NONDESTRUCTIVE TESTING

HANDBOOK

Third Edition

Volume 8

Magnetic Testing

Technical Editor
David G. Moore

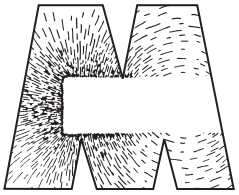
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American Society for Nondestructive Testing

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ASNT exists to create a safer world by promoting the profession and technologies of nondestructive testing.

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President's Foreword

Preface

Nondestructive testing (NDT) is a caring, science based profession dedicated to creating a safer world. This gives ASNT its moral authority and a noble system of ethics. We could not have a better mission than creating a safer world. NDT saves lives by protecting the public. Our mission brings us unique assets and is the source of our strength.

Safety is not an abstract issue but a concrete reality that touches individuals and communities. The issues we address are of value to every person on earth. This makes our work matter and gives us universal relevance, based on a clear and common value system. The NDT profession has a strong ethical foundation, a unique source of ASNT's strength as a professional society. These assets give us the power to attain the most and the best results.

Industry experts, technicians, researchers, equipment manufacturers, trainers, students, educators and staff — all represent diverse disciplines and schools of thought. The true heroes are the NDT workers, whose caring work ethic is an inspiration to us all. They are determined to make the world a safer place, and they work with impressive dedication and often under difficult conditions. The world needs many, many more of them, working together to make this world safer.

ASNT is an organization recognized for what it does, as well as what it says. Technology transfer and the dissemination of information are things ASNT has always done well, especially when members work in partnership within our Society. Today, collaboration to achieve ASNT goals is no longer simply an asset: it is a necessity.

The work our volunteers and staff do in certification programs, publications and training materials directly affects the quality of the workers, the development of new technology and the utilization of NDT by industry. The biggest challenge the NDT industry faces is the shortage of personnel — a shortage that is projected to become greater. Training is needed to qualify people, and training and reference materials like the *NDT Handbook* are important for reference and for training of more inspectors. The *NDT Handbook* is one of the most significant contributions of ASNT's Technical and Education Council.

On behalf of ASNT, I thank all the volunteers who worked together to create this book.

Victor Hernandez
ASNT President, 2007-2008

Foreword

Aims of a Handbook

The volume you are holding in your hand is the eighth in the third edition of the *Nondestructive Testing Handbook*. In the beginning of each volume, ASNT has stated the purposes and nature of the *NDT Handbook* series.

Handbooks exist in many disciplines of science and technology, and certain features set them apart from other reference works. A handbook should ideally provide the basic knowledge necessary for an understanding of the technology, including both scientific principles and means of application. The third edition of the Nondestructive Testing Handbook provides this knowledge through method specific volumes.

The typical reader may be assumed to have completed a few years of college toward a degree in engineering or science and has the background of an elementary physics or mechanics course. Additionally, this volume allows for computer based media that enhances all levels of education and training.

Standards, specifications, recommended practices and inspection procedures are discussed for instructional purposes, but at a level of generalization that is illustrative rather than comprehensive. Standards writing bodies take great pains to ensure that their documents are definitive in wording and technical accuracy. People writing contracts or procedures should consult the actual standards when appropriate.

Those who design qualifying examinations or study material for them draw on ASNT handbooks as a quick and convenient way of approximating the body of knowledge. Committees and individuals who write or anticipate questions are selective in what they draw from any source. The parts of a handbook that give scientific background, for instance, may have little bearing on a practical examination except to provide the physical foundation to assist handling of more challenging tasks. Other parts of a handbook are specific to a certain industry. This handbook provides a collection of perspectives on its subject to broaden its value and convenience to the nondestructive testing community.

The present volume is a worthy addition to the third edition. The editors, technical editors, ASNT staff, many contributors and reviewers worked together to bring the project to completion. For their scholarship and dedication, I thank them all.

Richard H. Bossi
Handbook Development Director

Preface

In industry and in this book, the term *flux leakage testing* is usually reserved for magnetic tests that do not use particles. Some readers may be surprised to learn that magnetic particle testing is actually a technique of flux leakage testing, the difference being that the particles are the indicating means.

This is primarily a book about magnetic particle testing. Yet a hundred pages in this volume — chapters on magnetism, magnetization, magnetic field measurement and demagnetization — all apply equally well to flux leakage testing. Parts of other chapters (on fundamentals, applications and the glossary) cover it, too.

In terms of physical principles, magnetic techniques are electromagnetic techniques, like eddy current testing, except that the test object is magnetized. For this reason, magnetic test objects are ferromagnetic, able to be magnetized. Magnetic particle testing can be used on iron and most steels but not on, say, aluminum or composites.

Magnetic particle testing is one of the oldest and one of the most widely used methods of nondestructive testing. It does not require as much training as the volumetric methods, ultrasonic or radiographic testing. In this, it resembles liquid penetrant testing, another surface method with which it is sometimes paired in training programs and literature. The same ASNT committee in 2008 covers both magnetic particle testing and liquid penetrant testing. Both these major methods provide visible indications of surface discontinuities. Neither requires as much training or equipment as the volumetric methods. And neither uses microprocessors as much as does, say, ultrasonic or eddy current testing.

The future for magnetic testing in the twenty-first century is bright. Its straightforward applications and results will help the world to maintain structural welds in infrastructure. And new construction and manufacturing in every industry will have the reliability of its ferromagnetic materials checked by magnetic tests.

It is the earnest wish of the volunteers in ASNT's Technical Council that this book will help ASNT to achieve its mission, making the world safer. To this end, and for this project, I thank all the contributors, reviewers and staff who created this book.

David G. Moore
Sandia National Laboratory

Editor's Preface

A perusal of early patents and trade journals of the steel industry — and early here means before 1930 — shows that the term *magnetic testing* was loosely used to describe a variety of electromagnetic test equipment, including eddy current instruments, magnetic flux leakage devices and funny looking permeance testers that resembled treadle driven sewing machines. Some of these devices would later be replaced by hand held instruments no more imposing than a scouting compass.

The *NDT Handbook* avoids using any company's name, but no discussion of magnetic particle testing would be complete without mentioning Magnaflux Corporation, which dominated the method so completely in the twentieth century that the method was widely known as *magnafluxing*.

In the 1930s, Magnaflux provided printed instructions to its clients. In 1938, its vice president, F.B. Doane, provided a comprehensive treatment of the subject: *Principles of Magnaflux*.

That book was followed in 1959 by the first edition of ASNT's *Nondestructive Testing Handbook*. That edition had three sections on magnetic particle testing and, immediately following them, two on flux leakage testing.

That handbook was followed in 1967 by *Principles of Magnetic Particle Testing* by Magnaflux's Carl Betz. Betz's book updated the one by F.B. Doane and is still valued for its lucid explanations of a technical subject. The method was on a firm scientific footing and was widely accepted.

In 1989, ASNT published a massive work, the *Nondestructive Testing Handbook, second edition:* Vol. 6, *Magnetic Particle Testing*. Scores of ASNT volunteers contributed to and reviewed the volume. Without fanfare, fully a fourth of the volume was applicable to flux leakage testing.

The present volume is the third edition of that work and includes all the information in the second edition — all that is still current, that is. References have been updated throughout the volume, especially significant where published standards are concerned. Much of the information about documentation, artificial discontinuities and illumination is new.

This volume's technical review is especially indebted to close attention by volunteers from the United States Metric Association. A fourth of ASNT's membership and half of its certification holders are overseas. Gradually and irrevocably, the United States is changing to international units of measurement. The accuracy and omnipresence of international units in the third edition of the *NDT Handbook* help to ensure that the series will be of value both to the world that ASNT serves and to posterity.

Likewise, alloys are identified according to the Unified Numbering System.

It is a privilege to work with ASNT volunteers, without whom there would be no handbook.

I would personally like to thank members of ASNT staff who helped to make this book better. The support of Timothy Jones, for administration, and Joy Grimm, for graphics, are gratefully acknowledged. Hollis Humphries supervised graphics, proofed the book and produced its CD-ROM version. Paul McIntire edited the second edition volume, from which this volume was derived.

People listed as contributors in the acknowledgments below were also reviewers but are listed once, as contributors.

Patrick O. Moore
NDT Handbook Editor

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CHAPTER 1

Introduction to Magnetic Testing

Marvin W. Trimm, Savannah River National Laboratory, Aiken, South Carolina (Part 2)

Arthur R. Lindgren, South Pasadena, Florida (Part 4)

PART 1. Nondestructive Testing

Scope of Nondestructive Testing

Nondestructive testing is a materials science concerned with all aspects of quality and serviceability of materials and structures. The science of nondestructive testing incorporates all the technology for process monitoring and for detection and measurement of significant properties, including discontinuities, in items ranging from research test objects to finished hardware and products in service. Nondestructive testing examines materials and structures without impairment of serviceability and reveals hidden properties and discontinuities.

Nondestructive testing is becoming increasingly vital in the effective conduct of research, development, design and manufacturing programs. Only with appropriate nondestructive testing can the benefits of advanced materials science be fully realized. The information required for appreciating the broad scope of nondestructive testing is available in many publications and reports.

Definition

Nondestructive testing (NDT) has been defined as those methods used to test a part or material or system without impairing its future usefulness.[1] The term is generally applied to nonmedical investigations of material integrity.

Nondestructive testing is used to investigate specifically the material integrity or properties of a test object. A number of other technologies — for instance, radio astronomy, voltage and amperage measurement and rheometry (flow measurement) — are nondestructive but are not used specifically to evaluate material properties. Radar and sonar are classified as nondestructive testing when used to inspect dams, for instance, but not when used to chart a river bottom.

Nondestructive testing asks "Is there something wrong with this material?" In contrast, performance and proof tests ask "Does this component work?" It is not considered nondestructive testing when an inspector checks a circuit by running electric current through it. Hydrostatic pressure testing is a form of proof testing that sometimes destroys the test object.

A gray area in the definition of *nondestructive testing* is the phrase *future usefulness*. Some material investigations involve taking a sample of the test object for a test that is inherently destructive. A noncritical part of a pressure vessel may be scraped or shaved to get a sample for electron microscopy, for example. Although future usefulness of the vessel is not impaired by the loss of material, the procedure is inherently destructive and the shaving itself — in one sense the true test object — has been removed from service permanently.

The idea of future usefulness is relevant to the quality control practice of sampling. Sampling (that is, less than 100 percent testing to draw inferences about the unsampled lots) *is* nondestructive testing if the tested sample is returned to service. If steel bolts are tested to verify their alloy and are then returned to service, then the test is nondestructive. In contrast, even if spectroscopy in the chemical testing of many fluids is inherently nondestructive, the testing is destructive if the samples are poured down the drain after testing.

Nondestructive testing is not confined to crack detection. Other anomalies include porosity, wall thinning from corrosion and many sorts of disbonds. Nondestructive material characterization is a field concerned with properties including material identification and microstructural characteristics — such as resin curing, case hardening and stress — that directly influence the service life of the test object.

Methods and Techniques

Nondestructive testing has also been defined by listing or classifying the various techniques.[1-3] This approach to *nondestructive testing* is practical in that it typically highlights methods in use by industry.

In the *Nondestructive Testing Handbook,* the word *method* is used for a group of test techniques that share a form of probing energy. The ultrasonic test method, for example, uses acoustic waves at a frequency higher than audible sound. Infrared and thermal testing and radiographic testing are two test methods that use electromagnetic radiation, each in a defined wavelength range. The word

technique, in contrast, denotes a way of adapting the method to the application. Through-transmission immersion testing is a technique of the ultrasonic method, for example.

Purposes of Nondestructive Testing

Since the 1920s, the art of testing without destroying the test object has developed from a laboratory curiosity to an indispensable tool of fabrication, construction, manufacturing and maintenance processes. No longer is visual testing of materials, parts and complete products the principal means of determining adequate quality. Nondestructive tests in great variety are in worldwide use to detect variations in structure, minute changes in surface finish, the presence of cracks or other physical discontinuities, to measure the thickness of materials and coatings and to determine other characteristics of industrial products. Scientists and engineers of many countries have contributed greatly to nondestructive test development and applications.

How is nondestructive testing useful? Why do thousands of industrial concerns buy the test equipment, pay the subsequent operating costs of the testing and even reshape manufacturing processes to fit the needs and findings of nondestructive testing? Modern nondestructive tests are used by manufacturers (1) to ensure product integrity and in turn reliability, (2) to avoid failures, prevent accidents and save human life (Figs. 1 and 2), (3) to make a profit for the user, (4) to ensure customer satisfaction and maintain the manufacturer's reputation, (5) to aid in better product design, (6) to control manufacturing processes, (7) to lower manufacturing costs, (8) to maintain uniform quality levels and (9) to ensure operational readiness.

These reasons for widespread and profitable nondestructive testing are sufficient in themselves but parallel developments have contributed to the technology's growth and acceptance.

Increased Demand on Machines

In the interest of greater performance and reduced cost for materials, the design engineer is often under pressure to reduce weight. Weight can be saved sometimes by substituting aluminum alloys, magnesium alloys or composite materials for steel or iron but such light parts may not be the same size or design as those they replace. The tendency is also to reduce the size. These pressures on the designer have subjected parts of all sorts to increased stress levels. Even such commonplace objects as sewing machines, sauce pans and luggage are also lighter and more heavily loaded than ever before. The stress to be supported is known as *dynamic stress* or *dynamic loading,* as opposed to static stress. It often fluctuates and reverses at low or high frequencies. Frequency of stress reversals increases with the speeds of modern machines, so components tend to fatigue and fail more rapidly.

Another cause of increased stress on modern products is a reduction in the safety factor. An engineer designs with certain known loads in mind. On the supposition that materials and workmanship are never perfect, a safety factor of 2, 3, 5 or 10 is applied. However, a lower factor is often used that depends on considerations such as cost or weight.

New demands on machinery have also stimulated the development and use of

Figure 1. Fatigue cracks contributed to damage to aircraft fuselage in flight (April 1988).

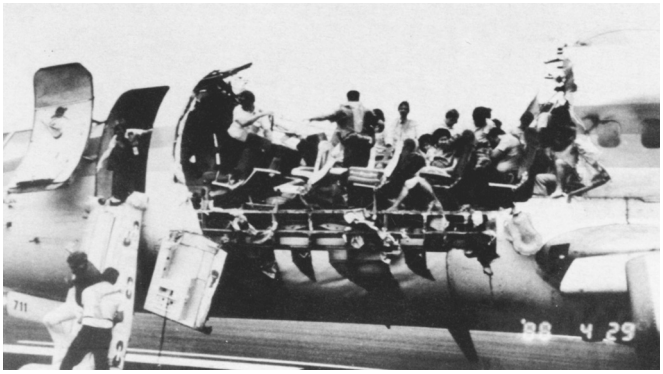


Figure 2. Boilers operate with high internal steam pressure. Material discontinuities can lead to sudden, violent failure with possible injury to people and damage to property.



new materials whose operating characteristics and performances are not completely known. These new materials could create greater and potentially dangerous problems. For example, an aircraft part was built from an alloy whose work hardening, notch resistance and fatigue life were not well known. After relatively short periods of service, some of the aircraft using these parts suffered disastrous failures. Sufficient and proper nondestructive tests could have saved many lives.

As technology improves and as service requirements increase, machines are subjected to greater variations and extremes of all kinds of stress, creating an increasing demand for stronger or more damage tolerant materials.

Engineering Demands for Sounder Materials

Another justification for nondestructive tests is the designer's demand for sounder materials. As size and weight decrease and the factor of safety is lowered, more emphasis is placed on better raw material control and higher quality of materials, manufacturing processes and workmanship.

An interesting fact is that a producer of raw material or of a finished product sometimes does not improve quality or performance until that improvement is demanded by the customer. The pressure of the customer is transferred to implementation of improved design or manufacturing. Nondestructive testing is frequently called on to confirm delivery of this new quality level.

Public Demands for Greater Safety

The demands and expectations of the public for greater safety are widespread. Review the record of the courts in granting high awards to injured persons. Consider the outcry for greater automobile safety as evidenced by the required automotive safety belts and the demand for air bags, blowout proof tires and antilock braking systems. The publicly supported activities of the National Safety Council, Underwriters Laboratories, the Occupational Safety and Health Administration, the Federal Aviation Administration and other agencies around the world are only a few of the ways in which this demand for safety is expressed. It has been expressed directly by passengers who cancel reservations following a serious aircraft accident. This demand for personal safety has been another strong force in the development of nondestructive tests.

Rising Costs of Failure

Aside from awards to the injured or to estates of the deceased and aside from costs to the public (because of evacuations occasioned by chemical leaks, for example), there are other factors in the rising costs of mechanical failure.

These costs are increasing for many reasons. Some important ones are (1) greater costs of materials and labor, (2) greater costs of complex parts, (3) greater costs because of the complexity of assemblies, (4) a greater probability that failure of one part will cause failure of others because of overloads, (5) the probability that the failure of one part will damage other parts of high value and (6) part failure in an integrated automatic production machine, shutting down an entire high speed production line. In the past, when production was carried out on many separate machines, the broken one could be bypassed until repaired. Today, one machine is often tied into the production cycles of several others. Loss of such production is one of the greatest losses resulting from part failure.

Classification of Methods

The National Materials Advisory Board (NMAB) Ad Hoc Committee on Nondestructive Evaluation classified techniques into six major method categories: visual, penetrating radiation, magnetic-electrical, mechanical vibration, thermal and chemical/electrochemical.[3] A modified version of their system is presented in Table 1.[1]

Each method can be completely characterized in terms of five principal factors: (1) energy source or medium used to probe the object (such as X-rays, ultrasonic waves or thermal radiation), (2) nature of the signals, image or signature resulting from interaction with the object (attenuation of X-rays or reflection of ultrasound, for example), (3) means of detecting or sensing resultant signals (photoemulsion, piezoelectric crystal or inductance coil), (4) means of indicating or recording signals (meter deflection, oscilloscope trace or radiograph) and (5) basis for interpreting the results (direct or indirect indication, qualitative or quantitative and pertinent dependencies).

The objective of each method is to provide information about one or more of the following material parameters: (1) discontinuities and separations (such as cracks, voids, inclusions and delaminations), (2) structure or malstructure (such as crystalline structure, grain size, segregation and misalignment), (3) dimensions and metrology (such as thickness, diameter, gap size and

discontinuity size), (4) physical and mechanical properties (such as reflectivity, conductivity, elastic modulus and sonic velocity), (5) composition and chemical analysis (such as alloy identification, impurities and elemental distributions), (6) stress and dynamic response (such as residual stress, crack growth, wear and vibration), (7) signature analysis (such as image content, frequency spectrum and field configuration) and (8) heat sources.

Material characteristics in Table 1 are further defined in Table 2 with respect to specific objectives and specific attributes to be measured, detected and defined.

The limitations of a method include conditions (such as access, physical contact and surface preparation) and requirements to adapt the probe to the test object. Other factors limit the detection or characterization of discontinuities or attributes and limit interpretation of signals or images.

Classification by Test Object

Nondestructive test techniques may be classified according to how they detect indications relative to the surface of a test object. Surface methods include liquid penetrant testing, visual testing and moiré testing. Surface/near-surface methods include tap, holographic, shearographic, magnetic particle and electromagnetic testing. When surface or near-surface methods are applied during intermediate manufacturing, they provide preliminary assurance that volumetric methods performed on the completed object or component will reveal few rejectable discontinuities. Volumetric methods include radiography, ultrasonic testing and acoustic emission testing. Through-boundary techniques include leak testing, some infrared thermographic techniques, airborne ultrasonic testing and certain techniques of acoustic emission testing. Other less easily classified methods are material identification, vibration analysis and strain gaging.

No one nondestructive test method is all revealing. In some cases, one method or technique may be adequate for testing a specific object or component. However, in most cases, it takes a series of test methods to do a complete nondestructive test of an object or component. For example, if surface cracks must be detected and eliminated and if the object or component is made of ferromagnetic material, then magnetic particle testing would be the appropriate choice. If the material is aluminum or titanium, then the choice would be liquid penetrant or electromagnetic testing. However, if internal discontinuities are to be detected, then ultrasonic testing or radiography would be chosen. The exact technique in each case depends on the thickness and nature of the material and the types of discontinuities that must be detected.

TABLE 1. Nondestructive test method categories.

Categories	Test Objectives
Basic Categories	
Mechanical and optical	color; cracks; dimensions; film thickness; gaging; reflectivity; strain distribution and magnitude; surface finish; surface flaws; through-cracks
Penetrating radiation	cracks; density and chemistry variations; elemental distribution; foreign objects; inclusions; microporosity; misalignment; missing parts; segregation; service degradation; shrinkage; thickness; voids
Electromagnetic and electronic	alloy content; anisotropy; cavities; cold work; local strain, hardness; composition; contamination; corrosion; cracks; crack depth; crystal structure; electrical conductivities; flakes; heat treatment; hot tears; inclusions; ion concentrations; laps; lattice strain; layer thickness; moisture content; polarization; seams; segregation; shrinkage; state of cure; tensile strength; thickness; disbonds; voids
Sonic and ultrasonic	crack initiation and propagation; cracks, voids; damping factor; degree of cure; degree of impregnation; degree of sintering; delaminations; density; dimensions; elastic moduli; grain size; inclusions; mechanical degradation; misalignment; porosity; radiation degradation; structure of composites; surface stress; tensile, shear and compressive strength; disbonds; wear
Infrared and thermal	anisotropy, bonding; composition; emissivity; heat contours; plating thickness; porosity; reflectivity; stress; thermal conductivity; thickness; voids; cracks; delaminations; heat treatment; state of cure; moisture; corrosion
Chemical and analytical	alloy identification; composition; cracks; elemental analysis and distribution; grain size; inclusions; macrostructure; porosity; segregation; surface anomalies
Auxiliary Categories	
Image generation	dimensional variations; dynamic performance; anomaly characterization and definition; anomaly distribution; anomaly propagation; magnetic field configurations
Signal image analysis	data selection, processing and display; anomaly mapping, correlation and identification; image enhancement; separation of multiple variables; signature analysis

Nondestructive Testing's Value

In manufacturing, nondestructive testing may be accepted reluctantly because its contribution to profits may not be obvious to management. Nondestructive testing is sometimes thought of only as a cost item and can be curtailed by industry downsizing. When a company cuts costs, two vulnerable areas are quality and safety. When bidding contract work, companies add profit margin to all cost items, including nondestructive testing, so a profit should be made on the

TABLE 2. Objectives of nondestructive test methods.

Objectives	Attributes Measured or Detected
Discontinuities and Separations	
Surface anomalies	roughness, scratches, gouges, crazing, pitting, imbedded foreign material
Surface connected anomalies	cracks, porosity, pinholes, laps, seams, folds, inclusions
Internal anomalies	cracks, separations, hot tears, cold shuts, shrinkage, voids, lack of fusion, pores, cavities, delaminations, disbonds, poor bonds, inclusions, segregations
Structure	
Microstructure	molecular structure; crystalline structure and/or strain; lattice structure; strain; dislocation; vacancy; deformation
Matrix structure	grain structure, size, orientation and phase; sinter and porosity; impregnation; filler and/or reinforcement distribution; anisotropy; heterogeneity; segregation
Small structural anomalies	leaks (lack of seal or through-holes), poor fit, poor contact, loose parts, loose particles, foreign objects
Gross structural anomalies	assembly errors; misalignment; poor spacing or ordering; deformation; malformation; missing parts
Dimensions and Measures	
Displacement; position	linear measurement; separation; gap size; discontinuity size, depth, location and orientation
Dimensional variations	unevenness; nonuniformity; eccentricity; shape and contour; size and mass variations
Thickness; density	film, coating, layer, plating, wall and sheet thickness; density or thickness variations
Physical and Mechanical Properties	
Electrical properties	resistivity; conductivity; dielectric constant and dissipation factor
Magnetic properties	polarization; permeability; ferromagnetism; cohesive force, susceptibility
Thermal properties	conductivity; thermal time constant and thermoelectric potential; diffusivity; effusivity; specific heat
Mechanical properties	compressive, shear and tensile strength (and moduli); Poisson's ratio; sonic speed; hardness; temper and embrittlement
Surface properties	color, reflectivity, refraction index, emissivity
Chemical Composition and Analysis	
Elemental analysis	detection, identification, distribution and/or profile
Impurity concentrations	contamination, depletion, doping and diffusants
Metallurgical content	variation; alloy identification, verification and sorting
Physiochemical state	moisture content; degree of cure; ion concentrations and corrosion; reaction products
Stress and Dynamic Response	
Stress, strain, fatigue	heat treatment, annealing and cold work effects; stress and strain; fatigue damage and residual life
Mechanical damage	wear, spalling, erosion, friction effects
Chemical damage	corrosion, stress corrosion, phase transformation
Other damage	radiation damage and high frequency voltage breakdown
Dynamic performance	crack initiation, crack propagation, plastic deformation, creep, excessive motion, vibration, damping, timing of events, any anomalous behavior
Signature Analysis	
Electromagnetic field	potential; intensity; field distribution and pattern
Thermal field	isotherms, heat contours, temperatures, heat flow, temperature distribution, heat leaks, hot spots, contrast
Acoustic signature	noise, vibration characteristics, frequency amplitude, harmonic spectrum, harmonic analysis, sonic emissions, ultrasonic emissions
Radioactive signature	distribution and diffusion of isotopes and tracers
Signal or image analysis	image enhancement and quantization; pattern recognition; densitometry; signal classification, separation and correlation; discontinuity identification, definition (size and shape) and distribution analysis; discontinuity mapping and display

nondestructive testing. The attitude toward nondestructive testing is positive when management understands its value.

Nondestructive testing should be used as a control mechanism to ensure that manufacturing processes are within design performance requirements. When used properly, nondestructive testing saves money for the manufacturer. Rather than costing the manufacturer money, nondestructive testing should add profits to the manufacturing process.

Other Nondestructive Test Methods

To optimize nondestructive testing, it is necessary first to understand the principles and applications of all the methods. This volume features magnetic testing, especially magnetic particle testing (Fig. 3) — one of many nondestructive test methods. The following section briefly describes major methods and the applications associated with them.

Visual Testing

Principles. Visual testing (Fig. 4) is the observation of a test object, either directly with the eyes or indirectly using optical instruments, by an inspector to evaluate the presence of surface anomalies and the object's conformance to specification. Visual testing should be the first nondestructive test method applied to an item. The test procedure is to clear obstructions from the surface, provide adequate illumination and observe. A prerequisite necessary for competent visual testing of an object is knowledge of the manufacturing processes by which it was made, of its service history and of its potential failure modes, as well as related industry experience.

Applications. Visual testing is widely used on a variety of objects to detect surface discontinuities associated with various structural failure mechanisms. Even when other nondestructive tests are performed, visual tests often provide a useful supplement. When the eddy current testing of process tubing is performed, for example, visual testing is often performed to verify and more closely examine the surface condition. The following discontinuities may be detected by a simple visual test: surface discontinuities, cracks, misalignment, warping, corrosion, wear and physical damage.

Liquid Penetrant Testing

Principles. Liquid penetrant testing (Fig. 5) reveals discontinuities open to the surfaces of solid and nonporous materials. Indications of a wide variety of discontinuity sizes can be found regardless of the configuration of the test object and regardless of discontinuity orientations. Liquid penetrants seep into various types of minute surface openings by capillary action. The cavities of interest can be very small, often invisible to the unaided eye. The ability of a given liquid to flow over a surface and enter surface cavities depends on the following: cleanliness of the surface, surface tension of the liquid, configuration of the cavity, contact angle of the liquid, ability of the liquid to wet the surface, cleanliness of the cavity and size of the surface opening of the cavity.

Applications. The principal industrial uses of liquid penetrant testing include postfabrication testing, receiving testing, in-process testing and quality control, testing for maintenance and overhaul in the transportation industries, in-plant and machinery maintenance testing and testing of large components. The following are some of the typically detected discontinuities: surface discontinuities, seams, cracks, laps, porosity and leak paths.

FIGURE 3. Test object used by A.V. de Forest to demonstrate the magnetic particle technique.

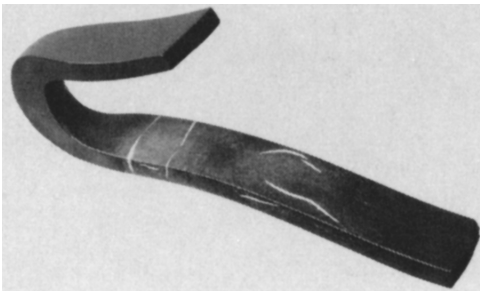


FIGURE 4. Visual test using a borescope to view interior of cylinder.



Magnetic Particle Testing

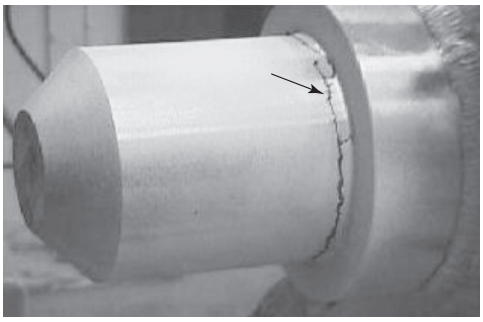
Principles. Magnetic particle testing (Fig. 3) is a method of locating surface and near-surface discontinuities in ferromagnetic materials. It depends on the fact that when the test object is magnetized, discontinuities that lie in a direction generally transverse to the direction of the magnetic field will cause a magnetic flux leakage field to be formed at and above the surface of the test object. The presence of this leakage field and therefore the presence of the discontinuity is detected with fine ferromagnetic particles applied over the surface, with some of the particles being gathered and held to form an outline of the discontinuity. This generally indicates its location, size, shape and extent. Magnetic particles are applied over a surface as dry particles or as wet particles in a liquid carrier such as water or oil.

Applications. The principal industrial uses of magnetic particle testing include final, receiving and in-process testing; testing for quality control; testing for maintenance and overhaul in the transportation industries; testing for plant and machinery maintenance; and testing of large components. Some discontinuities typically detected are surface discontinuities, seams, cracks and laps.

Eddy Current Testing

Principles. Based on electromagnetic induction, eddy current testing is perhaps the best known of the techniques in the electromagnetic test method. Eddy current testing is used to identify or differentiate among a wide variety of physical, structural and metallurgical conditions in electrically conductive ferromagnetic and nonferromagnetic metals and metal test objects. The method is based on indirect measurement and on correlation between the instrument reading and the structural characteristics and serviceability of the test objects.

FIGURE 5. Liquid penetrant indication of cracking.



With a basic system, the test object is placed within or next to an electric coil in which high frequency alternating current is flowing. This excitation current establishes an electromagnetic field around the coil. This primary field causes eddy currents to flow in the test object because of electromagnetic induction (Fig. 6). Inversely, the eddy currents affected by all characteristics (conductivity, permeability, thickness, discontinuities and geometry) of the test object create a secondary magnetic field that opposes the primary field. This interaction affects the coil impedance and can be displayed in various ways.

Eddy currents flow in closed loops in the test object. Their two most important characteristics, amplitude and phase, are influenced by the arrangement and characteristics of the instrumentation and test object. For example, during the test of a tube, the eddy currents flow symmetrically in the tube when discontinuities are not present. However, when a crack is present, then the eddy current flow is impeded and changed in direction, causing significant changes in the associated electromagnetic field.

Applications. An important industrial use of eddy current testing is on heat exchanger tubing. For example, eddy current testing is often specified for thin wall tubing in pressurized water reactors, steam generators, turbine condensers and air conditioning heat exchangers. Eddy current testing is also used in aircraft maintenance. The following are some of the typical material characteristics that may affect conductivity and be evaluated by eddy current testing: cracks, inclusions, dents and holes; grain size; heat treatment; coating and material thickness; composition, conductivity or permeability; and alloy composition.

Radiographic Testing

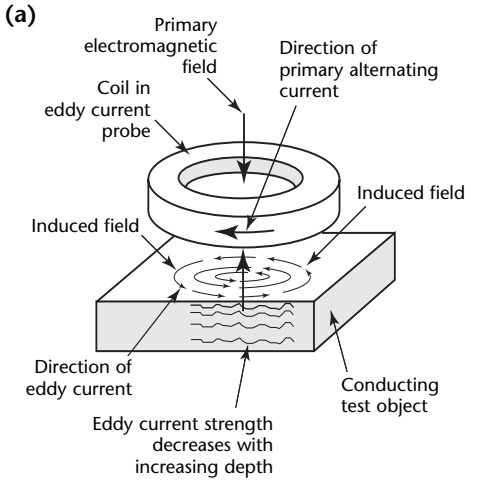
Principles. Radiographic testing (Fig. 7) is based on the test object's attenuation of penetrating radiation — either electromagnetic radiation of very short wavelength or particulate radiation (X-rays, gamma rays and neutrons). Different portions of an object absorb different amounts of penetrating radiation because of differences in density and variations in thickness of the test object or differences in absorption characteristics caused by variation in composition. These variations in the attenuation of the penetrating radiation can be monitored by detecting the unattenuated radiation that passes through the object.

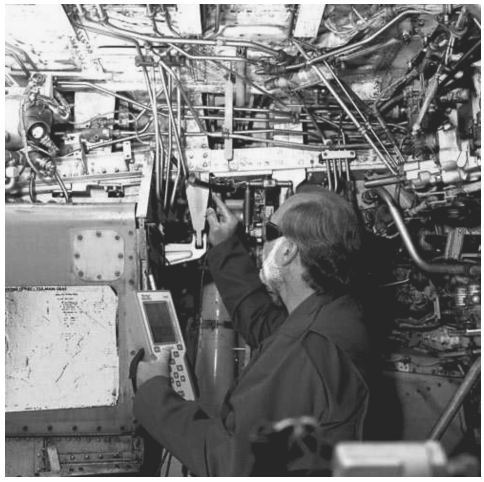
This monitoring may be in different forms. The traditional form is through radiation sensitive film. Radioscopic sensors provide digital images. X-ray computed tomography is a

three-dimensional, volumetric radiographic technique.

Applications. The principal industrial uses of radiographic testing involve testing of castings and weldments, particularly where there is a critical need to ensure freedom from internal discontinuities. Radiographic testing is often specified for thick wall castings and for weldments in steam power equipment (boiler and turbine components and assemblies). The method can also be used on forgings and mechanical assemblies, although with mechanical assemblies radiographic testing is usually limited to testing for conditions and proper placement of components. Radiographic testing is used to detect inclusions, lack of fusion, cracks, corrosion, porosity, leak paths, missing or incomplete components and debris.

FIGURE 6. Electromagnetic testing: (a) representative setup for eddy current test; (b) inservice detection of discontinuities.





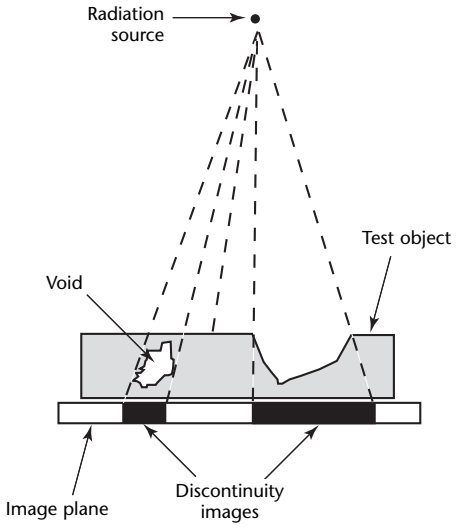
Acoustic Emission Testing

Principles. Acoustic emissions are stress waves produced by sudden movement in stressed materials. The classic sources of acoustic emission are crack growth and plastic deformation. Sudden movement at the source produces a stress wave that radiates out into the test object and excites a sensitive piezoelectric sensor. As the stress in the material is raised, emissions are generated. The signals from one or more sensors are amplified and measured to produce data for display and interpretation.

The source of acoustic emission energy is the elastic stress field in the material. Without stress, there is no emission. Therefore, an acoustic emission test (Fig. 8) is usually carried out during a controlled loading of the test object. This can be a proof load before service; a controlled variation of load while the structure is in service; a fatigue, pressure or creep test; or a complex loading program. Often, a structure is going to be loaded hydrostatically anyway during service and acoustic emission testing is used because it gives valuable additional information about the expected performance of the structure under load. Other times, acoustic emission testing is selected for reasons of economy or safety and loading is applied specifically for the acoustic emission test.

Applications. Acoustic emission is a natural phenomenon occurring in the widest range of materials, structures and processes. The largest scale events observed with acoustic emission testing

FIGURE 7. Representative setup for radiographic testing.



are seismic; the smallest are microscopic dislocations in stressed metals.

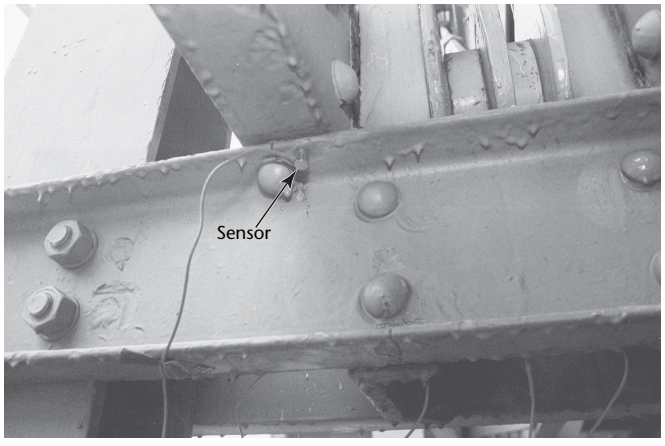
The equipment used is highly sensitive to any kind of movement in its operating frequency (typically 20 to 1200 kHz). The equipment can detect not only crack growth and material deformation but also such processes as solidification, friction, impact, flow and phase transformations. Therefore, acoustic emission testing is also used for in-process weld monitoring, for detecting tool touch and tool wear during automatic machining, for detecting wear and loss of lubrication in rotating equipment, for detecting loose parts and loose particles, for preservice proof testing and for detecting and monitoring leaks, cavitation and flow.

Ultrasonic Testing

Principles. In ultrasonic testing (Fig. 9), beams of acoustic waves at a frequency too high to hear are introduced into a material for the detection of surface and subsurface discontinuities. These acoustic waves travel through the material with some energy loss (attenuation) and are reflected and refracted at interfaces. The echoes are then analyzed to define and locate discontinuities.

Applications. Ultrasonic testing is widely used in metals, principally for thickness measurement and discontinuity detection. This method can be used to detect internal discontinuities in most engineering metals and alloys. Bonds produced by welding, brazing, soldering and adhesives can also be ultrasonically tested. Inline techniques have been developed for monitoring and classifying materials as acceptable, salvageable or scrap and for process control. Also tested are piping and pressure vessels, nuclear systems, motor vehicles, machinery, railroad stock and bridges.

FIGURE 8. Acoustic emission monitoring of floor beam on suspension bridge.



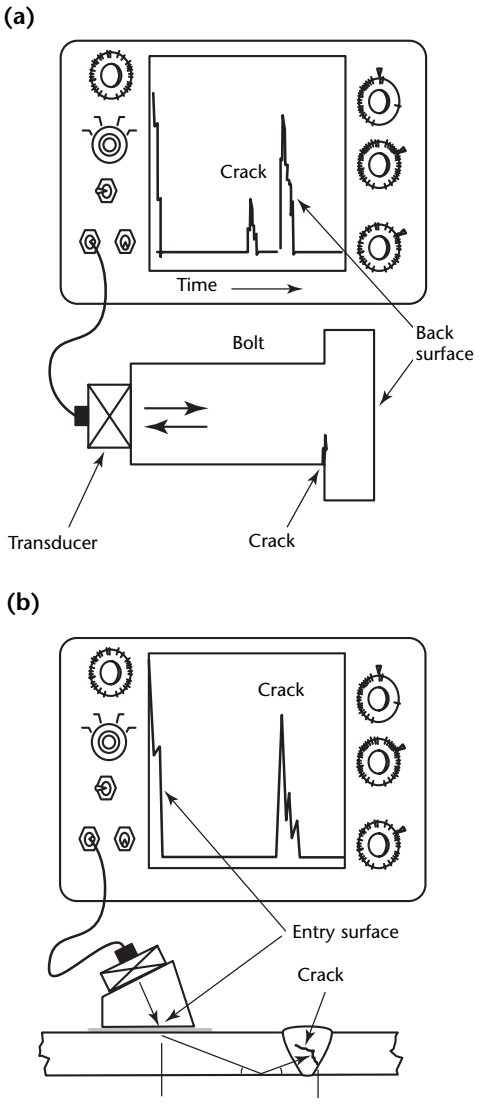
Leak Testing

Principles. Leak testing is concerned with the flow of liquids or gases from pressurized components or into evacuated components. The principles of leak testing involve the physics of liquids or gases flowing through a barrier where a pressure differential or capillary action exists.

Leak testing encompasses procedures that fall into these basic functions: leak location, leakage measurement and leakage monitoring. There are several subsidiary methods of leak testing, entailing tracer gas detection (Fig. 10), pressure change measurement, observation of bubble formation, acoustic emission leak testing and other principles.

Applications. Like other forms of nondestructive testing, leak testing affects

FIGURE 9. Classic setups for ultrasonic testing: (a) longitudinal wave technique; (b) transverse wave technique.



the safety and performance of a product. Reliable leak testing decreases costs by reducing the number of reworked products, warranty repairs and liability claims. The most common reasons for performing a leak test are to prevent the loss of costly materials or energy, to prevent contamination of the environment, to ensure component or system reliability and to prevent an explosion or fire.

Infrared and Thermal Testing

Principles. Conduction, convection and radiation are the primary mechanisms of heat transfer in an object or system. Electromagnetic radiation is emitted from all bodies to a degree that depends on their energy state.

Thermal testing involves the measurement or mapping of surface temperatures when heat flows from, to or through a test object. Temperature differentials on a surface, or changes in surface temperature with time, are related to heat flow patterns and can be used to detect discontinuities or to determine the heat transfer characteristics of an object. For example, during the operation of an electrical breaker, a hot spot detected at an electrical termination may be caused by a loose or corroded connection (Fig. 11). The resistance to electrical flow through the connection produces an increase in surface temperature of the connection.

Applications. There are two basic categories of infrared and thermal test applications: electrical and mechanical. The specific applications within these two categories are numerous.

Electrical applications include transmission and distribution lines, transformers, disconnects, switches, fuses, relays, breakers, motor windings, capacitor banks, cable trays, bus taps and other components and subsystems.

Mechanical applications include insulation (in boilers, furnaces, kilns, piping, ducts, vessels, refrigerated trucks and systems, tank cars and elsewhere), friction in rotating equipment (bearings, couplings, gears, gearboxes, conveyor belts, pumps, compressors and other components) and fluid flow (steam lines; heat exchangers; tank fluid levels; exothermic reactions; composite structures; heating, ventilation and air conditioning systems; leaks above and below ground; cooling and heating; tube blockages; environmental assessment of thermal discharge; boiler or furnace air leakage; condenser or turbine system leakage; pumps; compressors; and other system applications).

Other Methods

There are many other methods of nondestructive testing, including optical methods such as holography, shearography and moiré imaging; material identification methods such as chemical spot testing, spark testing and spectroscopy; strain gaging; and acoustic methods such as vibration analysis and tapping.

FIGURE 10. Leakage measurement dynamic leak testing using vacuum pumping: (a) pressurized system mode for leak testing of smaller components; (b) pressurized envelope mode for leak testing of larger volume systems.

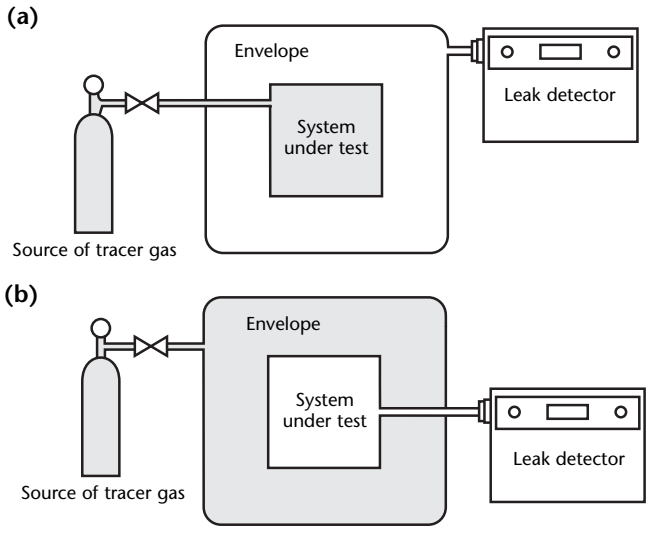
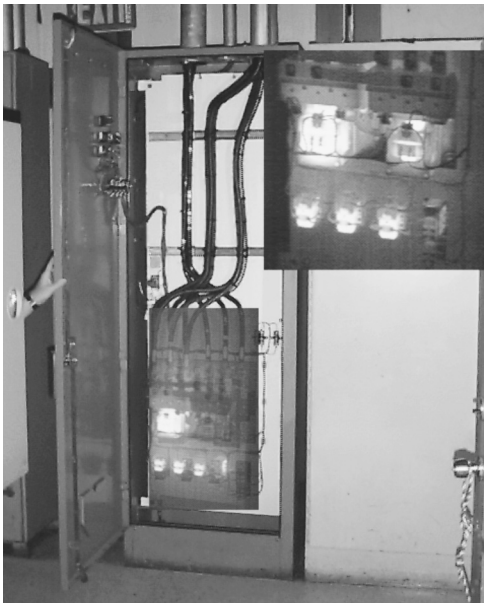


FIGURE 11. Infrared thermography of automatic transfer switches for an emergency diesel generator. Hot spots appear bright in thermogram (inset).



PART 2. Management of Magnetic Particle Testing

Selection of Magnetic Particle Testing[4]

Magnetic particle testing is an important method within the broad field of nondestructive testing. Magnetic particle testing is typically used to locate surface and near-surface discontinuities in ferromagnetic materials. When a part being inspected is magnetized, the flux flows through the part and discontinuities that lie generally transverse to the lines of flux will cause some of the flux lines to concentrate and leave the surface of the part. When this occurs, if finely divided ferromagnetic particles are correctly applied on the surface of the part, the particles (dry or wet) will be attracted to these leakage fields. When this occurs, an indication of the discontinuity is formed on the surface. This indication indicates the size, shape and location of the discontinuity on or near the surface.

Magnetic particle test equipment is designed to detect structural characteristics of a part. These characteristics range from simple surface discontinuities on flat surfaces to various fabrication or inservice discontinuities in complex geometries.

As a result, specific applications have been developed using magnetic particle testing, such as the following: detecting discontinuities in fabricated structures such as airframes, piping and pressure vessels, ships, bridges, motor vehicles and machinery and predicting the impending failure in highly stressed components exposed to the various modes of fatigue.

Advantages

The magnetic particle method is a sensitive means of locating surface cracks in ferromagnetic materials. There is little or no limitation on the size or shape of the part being inspected. Discontinuities that do not actually break through the surface are also indicated in many cases by this method, although certain limitations must be recognized and understood. Indications are created on the surface of the part at the location of the flux leakage. These indications provide a graphic representation of the actual discontinuity. Typically, elaborate precleaning is not necessary and some discontinuities filled with foreign material can be detected. The following are the primary advantages typically associated with magnetic particle testing: (1) economy, (2) speed, (3) sensitivity, (4) versatility, (5) applicability to irregular shapes, (6) field mobility, (7) minimal training requirements and (8) minimal equipment requirements.

Limitations

The primary limitation of magnetic particle testing is that the test object must be ferromagnetic. Because of the relationship between the discontinuity and lines of flux, the test must be performed in two directions. Magnetic particle testing may be limited by component geometry (size, contour, surface roughness, complexity and discontinuity orientation) and undesirable internal structure characteristics (permeability differences of joined material, pressed fit components and others). Because some wet magnetic particle techniques require liquid suspension for the particles, component compatibility with the liquid and test object temperature can become a factor. Demagnetization after the testing is often required because of future fabrication or end use. Another limitation for some components is possible overheating (introduction of large currents because of the size of the part) or production of arc strikes on finished surfaces. For proper interpretation of indications, a final limitation is the inspector's skill with the technique used and the inspector's knowledge of test object characteristics.

Management of Magnetic Particle Testing Programs

Management of a magnetic particle testing program requires consideration of many items before it can produce the desired results. Six basic questions must be answered before a program can be implemented effectively.

1. Is the program needed?
2. Are qualified personnel available?
3. Are qualified and approved procedures in place? Are regulatory requirements in place that mandate program characteristics?

4. What is the magnitude of the program that will provide desired results?
5. What provisions must be made for personnel safety and for compliance with environmental regulations?
6. What is the performance date for a program to be fully implemented?
7. Is there a cost benefit of magnetic particle testing?
8. What are the available resources in material, personnel and money?

Once these questions are answered, then a recommendation can be made to select the type of inspection agency. Three primary types of agencies responsible for inspection are (1) service companies, (2) consultants and (3) in-house programs.

Although these are the main agency types, some programs may, routinely or as needed, require support personnel from a combination of two or more of these sources. Before a final decision is made, advantages and disadvantages of each agency type must be considered.

Service Companies

Once a service company is selected, responsibilities need to be defined.

1. Who will identify the components within the facility to be examined?
2. Will the contract be for time and materials or have a specific scope of work?
3. If a time and materials contract is awarded, who will monitor the time and materials charged?
4. If a scope of work is required, who is technically qualified to develop and approve it?
5. What products or documents (test reports, trending, recommendations, root cause analysis and others) will be provided once the tests are completed?
6. Who will evaluate and accept the product (test reports, trending, recommendations, root cause analysis and others) within the service company?
7. Do the service company workers possess qualifications and certifications required by contract and by applicable regulations?
8. Do the service company workers require site specific training (confined space entry, electrical safety, hazardous materials and others) or clearance to enter and work in the facility?
9. Does the service company retain any liability for test results?

Consultants

1. Will the contract be for time and materials or have a specific scope of work?
2. If a scope of work is required, who is technically qualified to develop and approve it?
3. Who will identify the required qualifications of the consultant?
4. Is the purpose of the consultant to develop or update a program or is it to oversee and evaluate the performance of an existing program?
5. Will the consultant have oversight responsibility for tests performed?
6. What products or documents (trending, recommendations, root cause analysis and others) are provided once the tests are completed?
7. Who will evaluate the consultant's performance (test reports, trending, recommendations, root cause analysis and other functions) within the sponsoring company?
8. Does the consultant possess qualifications and certifications required by contract and by applicable regulations?
9. Does the consultant require site specific training (confined space entry, electrical safety, hazardous materials and others) or clearance to enter and work in the facility?
10. Does the consultant retain any liability for test results?

In-House Programs

1. Who will determine the scope of the program, such as which techniques will be used?
2. What are the regulatory requirements (codes and standards) associated with program development and implementation?
3. Who will develop a cost benefit analysis for the program?
4. How much time and what resources are available to establish the program?
5. What are the qualification requirements (education, training, experience and others) for personnel?
6. Do program personnel require additional training (safety, confined space entry or others) or qualifications?
7. Are subject matter experts required to provide technical guidance during personnel development?
8. Are procedures required to perform work in the facility?
9. If procedures are required, who will develop, review and approve them?
10. Who will determine the technical specifications for test equipment?

Test Procedures for Magnetic Particle Testing

The conduct of test operations (in-house or contracted) should be performed in accordance with specific instructions from an expert. Specific instructions are typically written as a technical procedure. In many cases, codes and specifications will require that a technical procedure be developed for each individual test. In other cases, the same procedure is used repeatedly.

The procedure can take many forms. A procedure may comprise general instructions that address only major aspects of test techniques. Or a procedure may be written as a step-by-step process requiring a supervisor's or a qualified/certified worker's signature after each step. The following is a typical format for an industrial procedure.

1. The *purpose* identifies the intent of the procedure.
2. The *scope* establishes the latitude of items, tests and techniques covered and not covered by the procedure.
3. *References* are specific documents from which criteria are extracted or are documents satisfied by implementation of the procedure.
4. *Definitions* are needed for terms and abbreviations that are not common knowledge to people who will read the procedure.
5. Statements about *personnel requirements* address specific requirements to perform tasks in accordance with the procedure — issues such as personnel qualification, certification and access clearance.
6. Calibration requirements and model numbers of qualified *equipment* must be specified.
7. The test *procedure* provides a sequential process to be used to conduct test activities.
8. A *system performance* check is needed before a test. The check might be daily or detailed.
9. *Acceptance criteria* establish component characteristics that will identify the items suitable for service (initial use or continued service).
10. *Reports* (records) provide the means to document specific test techniques, equipment used, personnel, activity, date performed and test results.
11. *Attachments* may include (if required) items such as report forms, instrument calibration forms, qualified equipment matrix, schedules and others.

Once the procedure is written, an expert in the subject evaluates it. If the procedure meets identified requirements, the expert will approve it for use. Some codes and standards also require the procedure to be qualified — that is, demonstrated to the satisfaction of a representative of a regulatory body or jurisdictional authority.

Test Specifications for Magnetic Particle Testing[4]

A magnetic particle test specification must anticipate issues that arise during testing. A specification is product specific and may be tailored to comply with one or more standards. A specification can require more stringent limits than the standard(s) it was written to satisfy. In practice, a specification provides a list of testing parameters that describes the techniques for locating and categorizing discontinuities in a specific test object. A typical specification includes acceptance criteria and is required by the designer, buyer or manufacturer of the article it covers.

The generation of magnetic flux and the detection of its leakage are of primary concern for magnetic particle testing. Specifications are written to eliminate variables of human operators and system designs, to produce an accurate result regardless of who performs the magnetic particle test. Specifications must be written with a full knowledge of (1) magnetic particle test techniques, (2) a technique's individual sensitivities, (3) the test object design, (4) its material characteristics and (5) the discontinuities critical to the test object's service life. In most mature manufacturing applications, nondestructive tests are considered during design and such specifications are specified on the test object's original drawing.

Magnetic particle specifications are produced to standardize test results, not to eliminate the initiative of the technician. There is no substitute for an experienced operator who assumes personal responsibility for the quality and accuracy of the test.

Testing specifications are working documents that tell how to locate discontinuities in a specific test object. Even well established and successful specifications need periodic review and revision. The increased reliance on artificial discontinuity standards, on various types of field indicators and on ring standards is driven by incidents of catastrophic failure after magnetic particle testing failed to detect critical discontinuities. These unreliable tests were performed using practices found in early specifications. Subsequent field intensity measurements were performed in areas of known failure on test objects of similar

design. In some cases, there was no magnetic leakage field in the critical areas. In other cases, the fields were very low and not strong enough to hold magnetic particles. These empirical data indicated that the previous current level equations could be applied only to the simplest test object geometry and were unreliable for complex geometries. It is very important that this kind of knowledge be incorporated as quickly as possible into industry specifications.

Interpretation

Interpretation may be complex, especially before a procedure has been established. The interpreter must have a knowledge of the following: (1) the underlying physical process, including location of flux density and its orientation in the test item, (2) techniques and equipment, (3) details about the item being examined (configuration, material properties, fabrication process, potential discontinuities and anticipated service conditions) and (4) possible sources of false indications that might be mistaken for meaningful magnetic particle indications.

After interpretation, acceptance criteria and rejection criteria are applied in a phase called *evaluation*.

Reliability of Test Results

When a test is performed, there are four possible outcomes: (1) a rejectable discontinuity can be found when one is present, (2) a rejectable discontinuity can be missed even when one is present, (3) a rejectable discontinuity can be indicated when none is present and (4) no rejectable discontinuity is found when none is present. A reliable testing process and a qualified inspector should find all discontinuities of concern with no discontinuities missed (no errors as in case 2 above) and no false calls (case 3 above).

To approach this goal, the probability of finding a rejectable discontinuity must be high and the inspector must be both proficient in the testing process and motivated to perform with maximum efficiency. An ineffective inspector may accept test objects that contain discontinuities, with the result of possible inservice part failure. The same inspector may reject parts that do not contain rejectable discontinuities, with the result of unnecessary scrap and repair. Neither scenario is desirable.

Magnetic Particle Test Standards

Traditionally, the purpose of specifications and standards has been to define the requirements that goods or services must meet. As such, they are intended to be incorporated into contracts so that both the buyer and provider have a well defined description of what one will receive and the other will deliver.

Standards have undergone a process of peer review in industry and can be invoked with the force of law by contract or by government regulation. In contrast, a specification represents an employer's instructions to employees and is specific to a contract or workplace. Many a specification originates as a detailed description either as part of a purchaser's requirements or as part of a vendor's offer. Specifications may be incorporated into standards through the normal review process. Standards and specifications exist in three basic areas: equipment, processes and personnel.

1. Standards for magnetic particle equipment include criteria that address generation of magnetic field, orientation and flux density, continuous or residual fields and other things.
2. ASTM International and other organizations publish standards for test techniques. Some other standards are for quality assurance procedures and are not specific to a test method or even to testing in general. Tables 3 and 4 list standards used in magnetic testing. The United States Department of Defense has replaced most military specifications and standards with industry consensus specifications and standards. A source for nondestructive test standards is the *Annual Book of ASTM Standards*.[5]
3. Qualification and certification of testing personnel are discussed below with specific reference to recommendations of *ASNT Recommended Practice No. SNT-TC-1A*.[6]

Personnel Qualification and Certification

One of the most critical aspects of the test process is the qualification of testing personnel. Nondestructive testing is sometimes referred to as a *special process,* special in that it is difficult to determine the adequacy of a test by merely observing the process or the documentation it generates. The quality

TABLE 3. Some magnetic testing standards issued by organizations headquartered in the United States.

American Petroleum Institute (API)

API RP 5A5, *Field Inspection of New Casing, Tubing and Plain-End Drill Pipe* (2005). [From ISO 15463 (2003).]

API SPEC 5CT, *Specification for Casing and Tubing* (2006)

API SPEC 5D, *Specification for Drill Pipe* (2001)

API SPEC 5L, *Specification for Line Pipe* (2004)

API 5LU, Ultra High-Test Heat Treated Line Pipe (1980)

American Welding Society (AWS)

AWS D1.1M, *Structural Welding Code — Steel* (2006)

AWS D14.6M, *Welding of Rotating Elements of Equipment* (1995)

AWS FORM E-8, *Report of Magnetic-Particle Examination of Welds* (2000)

ASME (American Society of Mechanical Engineers) International

ASME B31.1, *Power Piping* (2008)

ASME B31.3, *Process Piping* (2006)

ASME BPVC-V, *Boiler and Pressure Vessel Code: Nondestructive Examination* (2007)

ASME BPVC-XI, *Boiler and Pressure Vessel Code: Rules for Inservice Inspection of Nuclear Power Plant Components* (2007)

ASTM (American Society for Testing and Materials) International

ASTM A 275M, *Standard Test Method for Magnetic Particle Examination of Steel Forgings* (2006)

ASTM A 456M-99, *Standard Specification for Magnetic Particle Examination of Large Crankshaft Forgings* (2003)

ASTM A 903/A 903M, *Standard Specification for Steel Castings, Surface Acceptance Standards, Magnetic Particle and Liquid Penetrant Inspection* (2003)

ASTM A 986/A 986M, *Standard Specification for Magnetic Particle Examination of Continuous Grain Flow Crankshaft Forgings* (2006)

ASTM A 996/A 996M, *Standard Specification for Magnetic Particle Examination of Steel Forgings Using Alternating Current* (2007)

ASTM A 1028, *Standard Specification for Stainless Steel Bars for Compressor and Turbine Airfoils* (2003)

ASTM D 93, *Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester* (2007)

ASTM D 445, *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)* (2006)

ASTM E 45, *Standard Test Methods for Determining the Inclusion Content of Steel* (2005)

ASTM E 125, *Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings* (2003)

ASTM E 570, *Standard Practice for Flux Leakage Examination of Ferromagnetic Steel Tubular Products* (2004)

ASTM E 709, *Standard Guide for Magnetic Particle Examination* (2001)

ASTM E 1316, *Standard Terminology for Nondestructive Examinations* (2007)

ASTM E 1444, *Standard Practice for Magnetic Particle Testing* (2005)

ASTM E 1571, *Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope* (2006)

ASTM E 2297, *Standard Guide for Use of UV-A and Visible Light Sources and Meters Used in the Liquid Penetrant and Magnetic Particle Methods* (2004)

Manufacturers Standardization Society of the Valve and Fittings Industry (MSS)

MSS SP 53, *Quality Standard for Steel Castings and Forgings for Valves, Flanges, and Fittings and Other Piping Components — Magnetic Particle Examination Method* (2007)

SAE (Society of Automotive Engineers) International

SAE AMS 2442, *Magnetic Particle Acceptance Criteria for Parts* (2007)

SAE AMS 2641A, *Vehicle, Magnetic Particle Inspection, Petroleum Base* (1996)

SAE AMS 3040C, *Magnetic Particles, Nonfluorescent, Dry Method* (2002)

SAE AMS 3041D, *Magnetic Particles, Nonfluorescent, Wet Method, Oil Vehicle, Ready-To-Use* (2002)

SAE AMS 3042D, *Magnetic Particles, Nonfluorescent, Wet Method, Dry Powder* (2002)

SAE AMS 3043C, *Magnetic Particles, Nonfluorescent, Wet Method, Oil Vehicle, Aerosol Packaged* (2002)

SAE AMS 3044E, *Magnetic Particles, Fluorescent, Wet Method, Dry Powder* (2002)

SAE AMS 3045D, *Magnetic Particles, Fluorescent, Wet Method, Oil Vehicle Ready-To-Use* (2002)

SAE AMS 3046E, *Magnetic Particles, Fluorescent, Wet Method, Oil Vehicle, Aerosol Packaged* (2002)

SAE AMS 3161B, *Oil, Odorless Heavy Solvent* (2001)

SAE AMSI 83387, *Inspection Process, Magnetic Rubber* (1999)

SAE AS 3071, *Acceptance Criteria — Magnetic Particle, Fluorescent Penetrant, and Contrast Dye Penetrant Inspection* (2004)

SAE AS 4792, *Water Conditioning Agents for Aqueous Magnetic Particle Inspection* (1993)

SAE AS 5282, *Tool Steel Ring for Magnetic Particle Inspection* (1998)

SAE AS 5371, *Reference Standards, Notched Shims for Magnetic Particle Inspection* (1998)

SAE AS 5447, *Acceptance Criteria for Nuts — Magnetic Particle, Fluorescent Penetrant, and Visible Penetrant Examination* (2004)

SAE AS 7114, *National Aerospace and Defense Contractors Accreditation Program (NADCAP) Requirements for Nondestructive Testing* (1997)

SAE J 420, *Magnetic Particle Inspection* (1991)

SAE MAM 2300D, *Steel Cleanliness, Premium Aircraft-Quality Magnetic Particle Inspection Procedure, Metric (SI) Measurement* (2007)

SAE MAM 2301C, *Steel Cleanliness, Aircraft Quality Magnetic Particle Inspection Procedure, Metric SI Measurement* (2007)

SAE MAM 2303D, *Steel Cleanliness, Aircraft Quality, Martensitic Corrosion-Resistant Steels, Magnetic Particle Inspection Procedure, Metric SI Measurement* (2003)

SAE MAM 2304C, *Steel Cleanliness, Special Aircraft — Quality Magnetic Particle Inspection Procedure, Metric (SI) Measurement* (2003)

of the test largely depends on the skills and knowledge of the inspector.

The American Society for Nondestructive Testing (ASNT) has been a world leader in the qualification and certification of nondestructive testing personnel since the 1960s. (*Qualification* demonstrates that an individual has the required training, experience, knowledge and abilities; *certification* provides written testimony that an individual is qualified.) By the twenty-first century, the American Society for Nondestructive Testing had instituted three avenues and four major documents for the qualification and certification of nondestructive testing personnel.

1. Recommended Practice No. SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing,* provides guidelines to employers for personnel qualification and certification in nondestructive testing. This recommended practice identifies the attributes that should be considered when qualifying nondestructive testing personnel. It requires the employer to develop and implement a written practice, a procedure that details the specific process and any limitation in the qualification and certification of nondestructive testing personnel.[6]
2. ANSI/ASNT CP-189, *Standard for Qualification and Certification of Nondestructive Testing Personnel,* resembles SNT-TC-1A but establishes specific requirements for the qualification and certification of Level I and II nondestructive testing personnel. For Level III, CP-189 references an examination administered by the American Society for Nondestructive Testing. However, CP-189 is a consensus standard as defined by the American National Standards Institute (ANSI). It is recognized as the American standard for nondestructive testing. It is not considered a recommended practice; it is a national standard.[7]
3. ANSI/ASNT CP-105, *ASNT Standard Topical Outlines for Qualification of Nondestructive Testing Personnel* is a standard that establishes the minimum topical outline requirements for the qualification of nondestructive testing (NDT) personnel. The outlines in this single standard are referenced by both SNT-TC-1A and CP-189. CP-105 is a consensus standard of the American National Standards Institute (ANSI) and is recognized as an American standard for nondestructive testing. It is not considered a recommended practice; it is a national standard.[8]
4. The *ASNT Central Certification Program* (ACCP), unlike *SNT-TC-1A* and CP-189, is a third party certification process that identifies qualification and certification attributes for Level II and Level III nondestructive testing personnel. The American Society for Nondestructive Testing certifies that the individual has the skills and knowledge for many nondestructive test method applications. It does not remove the responsibility for the final determination of personnel qualification from the employer. The employer evaluates an individual's skills and knowledge for application of company procedures using designated techniques and equipment identified for specific tests. ACCP is not a standard or recommended practice; it is a service administered by the American Society for Nondestructive Testing.[9]

Excerpts from Recommended Practice No. SNT-TC-1A

To give an idea of the contents of these documents, the following items are excerpted from *Recommended Practice No. SNT-TC-1A*.[6] The original text is arranged in outline format and includes recommendations that are not specific to magnetic particle testing.

> **Scope** … This Recommended Practice has been prepared to establish guidelines for the qualification and certification of NDT personnel whose specific jobs require appropriate knowledge of the technical principles underlying the nondestructive tests they perform, witness, monitor, or evaluate. … This document provides guidelines for the establishment of a qualification and certification program. …
> **Written Practice** … The employer shall establish a written practice for the control and administration of NDT personnel training, examination, and certification. … The employer's written practice should describe the responsibility of each level of certification for determining the acceptability of materials or components in accordance with the applicable codes, standards, specifications and procedures. …
> **Education, Training, and Experience Requirements for Initial Qualification** … Candidates for certification in NDT should have sufficient education, training, and experience to ensure qualification in those NDT methods in which they are being considered for certification. … Table 6.3.1A [see Table 5 in this *Nondestructive Testing Handbook* chapter, for magnetic particle testing] lists recommended training and experience factors to be considered by the employer in establishing written practices for initial qualification of Level I and Level II individuals. …

Training Programs … Personnel being considered for initial certification should complete sufficient organized training to become thoroughly familiar with the principles and practices of the specified NDT method related to the level of certification desired and applicable to the processes to be used and the products to be tested. …

Examinations … For Level I and II personnel, a composite grade should be determined by simple averaging of the results of the general, specific and practical examinations … Examinations administered for qualification should result in a passing composite grade of at least 80 percent, with no individual examination having a passing grade less than 70 percent. …

TABLE 4. Some magnetic testing standards issued by organizations headquartered outside the United States.

Association Française de Normalisation [French Association for Standardization]

NF EN 1369, *Founding, Magnetic Particle Inspection* (1997)

NF EN ISO 9934-1, *Non-Destructive Testing — Magnetic Particle Testing; General Principles* (2002)

British Standards Institution

A-A-50751, *Magnetic Particle Process Control Kit* (1987)

A-A-59230, *Fluid, Magnetic Particle Inspection, Suspension* (2004)

BS 5138, *Specification for Magnetic Particle Flaw Inspection of Finished Machined Solid Forged and Drop Stamped Crankshafts* (1988)

BS 6072, *Method for Magnetic Particle Flaw Detection* (1986)

Canadian General Standard Board

CGSB 48-GP-8M, Certification of Nondestructive Testing Personnel (Magnetic Particle Method) (1992)

Deutsches Institut für Normung [German Institute for Standardization]

DIN 54132, *Non-Destructive Testing; Determining the Properties of Test Media for the Magnetic Particle Test* (1980)

DIN 54136 P1, *Non-Destructive Testing; Magnetic Leakage Flux Testing by Scanning with Probes, Principles* (1988)

DIN 25435 P2, *Inservice Inspections for Primary Circuit Components of Light Water Reactors; Magnetic Particle Methods* (1987)

European Committee for Standardization (CEN)

EN 1290, *Non-Destructive Testing of Welds — Magnetic Particle Testing of Welds* (2004)

EN 1291, *Non-Destructive Testing of Welds — Magnetic Particle Testing of Welds — Acceptance Levels* (2004)

EN 1369, *Founding — Magnetic Particle Inspection* (1997)

EN 9934, *Non-Destructive Testing — Magnetic Particle Testing* (2002)

EN 10228-1, *Non-Destructive Testing of Steel Forgings — Part 1: Magnetic Particle Inspection* (1999)

EN 10246-4, *Non-Destructive Testing of Steel Tubes, Part 4: Automatic Full Peripheral Magnetic Transducer/Flux Leakage Testing of Seamless Ferromagnetic Steel Tubes for the Detection of Transverse Imperfections* (2000)

EN 10246-5, *Non-Destructive Testing of Steel Tubes, Part 5: Automatic Full Peripheral Magnetic Transducer/Flux Leakage Testing of Seamless and Welded (except Submerged Arc-Welded) Ferromagnetic Steel Tubes for the Detection of Longitudinal Imperfections* (2000)

EN 10246-12, *Non-Destructive Testing of Steel Tubes, Part 12: Magnetic Particle Inspection of Seamless and Welded Ferromagnetic Steel Tubes for the Detection of Surface Imperfections* (2000)

EN 10246-18, *Non-Destructive Testing of Steel Tubes — Part 18: Magnetic Particle Inspection of Tubes Ends of Seamless and Welded Ferromagnetic Steel Tubes for the Detection of Laminar Imperfections* (2000)

Gosudarstvennye Standarty (State Standard) [Russian]

GOST 21105, *Non-Destructive Testing. Method of Magnetic Particle Testing* (1987)

International Organization for Standardization

ISO 3059, *Non-Destructive Testing — Penetrant Testing and Magnetic Particle Testing — Viewing Conditions* (2002)

ISO 4986, *Steel Castings — Magnetic Particle Inspection* (1992)

ISO 6933, *Railway Rolling Stock Material — Magnetic Particle Acceptance Testing* (1986)

ISO 9402, *Seamless and Welded (except Submerged Arc-Welded) Steel Tubes for Pressure Purposes — Full Peripheral Magnetic Transducer Flux Leakage Testing of Ferromagnetic Steel Tubes for the Detection of Longitudinal Imperfections* (1989)

ISO 9598, *Seamless Steel Tubes for Pressure Purposes — Full Peripheral Magnetic Transducer/Flux Leakage Testing of Ferromagnetic Steel Tubes for the Detection of Transverse Imperfections* (1989)

ISO 9934, *Non-Destructive Testing — Magnetic Particle Testing* (2004)

ISO 13664, *Seamless and Welded Steel Tubes for Pressure Purposes — Magnetic Particle Inspection of the Tube Ends for the Detection of Laminar Imperfections* (1997)

ISO 13665, *Seamless and Welded Steel Tubes for Pressure Purposes — Magnetic Particle Inspection of the Tube Body for the Detection of Surface Imperfections* (1997)

ISO 15463, *Petroleum and Natural Gas Industries — Field Inspection of New Casing, Tubing and Plain-End Drill Pipe* (2003)

ISO 17638, *Non-Destructive Testing of Welds — Magnetic Particle Testing* (2003)

ISO 23278, *Non-Destructive Testing of Welds — Magnetic Particle Testing of Welds — Acceptance Levels* (2006)

Japanese Standards Association

JIS G 0565, *Methods for Magnetic Particle Testing of Ferromagnetic Materials and Classification of Magnetic Particle Indications* (1992)

JIS Z 2319, *Methods for Magnetic Leakage Flux Testing* (2007)

JIS Z 2320, *Non-Destructive Testing — Magnetic Particle Testing* (2007)

JIS Z 2321, *AC Yoke Magnet for Magnetic Particle Testing* (2004)

JIS Z 2340, *Confirmation Method of Calibration by Visual Calibration Gauge on Magnetic Particle and the Liquid Penetrant Testing* (2007)

Practical [Examination] (for NDT Level I and II) … The candidate should demonstrate … ability to operate the necessary NDT equipment, record, and analyze the resultant information to the degree required. ... At least one flawed specimen should be tested and the results of the NDT analyzed by the candidate. …
Certification … Certification of all levels of NDT personnel is the responsibility of the employer. … Certification of NDT personnel shall be based on demonstration of satisfactory qualification in accordance with [sections on education, training, experience and examinations] as described in the employer's written practice. … Personnel certification records shall be maintained on file by the employer. …
Recertification … All levels of NDT personnel shall be recertified periodically in accordance with one of the [following:] continuing satisfactory technical performance [or reexamination] in those portions of the examinations … deemed necessary by the employer's NDT Level III. … Recommended maximum recertification intervals are 5 years for all certification levels.

These recommendations from the 2006 edition of *Recommended Practice No. SNT-TC-1A* are cited only to provide an idea of items that must be considered in the development of an in-house nondestructive testing program. Because the text above is excerpted, those developing a personnel qualification program should consult the complete text of *SNT-TC-1A* and other applicable procedures and practices. If an outside agency is contracted for magnetic particle test services, then the contractor must have a qualification and certification program to satisfy the codes and standards in force.

The minimum number of questions that should be administered in the written examination for magnetic particle test personnel is as follows: 40 questions in the general examination and 20 questions in the specific examination. The number of questions is the same for Level I and Level II personnel. Table 5 shows required hours of training for Level I and Level II.

TABLE 5. Recommended training and experience for magnetic testing personnel according to *Recommended Practice No. SNT-TC-1A.*[6]

	Level I	Level II
Magnetic particle testing		
High school graduate[a]	12 h	8 h
Two years of college[b]	8 h	4 h
Work experience[c]	70 h	210 h
Magnetic flux leakage testing[d]		
High school graduate[a]	16 h	12 h
Two years of college[b]	12 h	8 h
Work experience[c]	70 h	210 h

a. Or equivalent.
b. Completion with a passing grade of at least two years of engineering or science study in a university, college or technical school.
c. Minimum work experience per level. Note: For Level II certification, the experience shall consist of time as Level I or equivalent. If a person is being qualified directly to Level II with no time at Level I, the required experience shall consist of the sum of the times required for Level I and Level II and the required training shall consist of the sum of the hours required for Level I and Level II.
d. Magnetic particle training hours may be counted toward magnetic flux leakage training hours as defined in an employer's written practice.

Central Certification

Another standard that may be a source for compliance is published by the International Organization for Standardization (ISO). The work of preparing international standards is normally carried out through technical committees of this worldwide federation of national standards bodies. Each ISO member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and nongovernmental, in liaison with the International Organization for Standardization, also take part in the work.

Technical Committee ISO/TC 135, Non-Destructive Testing Subcommittee SC 7, Personnel Qualification, prepared international standard ISO 9712, *Non-Destructive Testing — Qualification and Certification of Personnel.*[10] In its statement of scope, ISO 9712 states that it "specifies the qualification and certification of personnel involved in non-destructive testing ... in one or more of the following methods: acoustic emission testing; eddy current testing; infrared thermographic testing; leak testing (hydraulic pressure tests excluded); magnetic particle testing; penetrant testing; radiographic testing; strain testing; ultrasonic testing; visual testing (direct unaided visual tests and visual tests carried out during the application of another NDT method are excluded)."

The International Organization for Standardization also publishes a standard for something called *limited certification.*[11] Inspectors whose actions are limited sometimes have limited training requirements. Limited certification would not be applicable to magnetic particle testing inspectors in the field, for example, but may be desired for operators of flux leakage units in steel mills.

PART 3. Safety in Magnetic Particle Testing

To manage a magnetic particle testing program, as with any testing program, the first obligation is to ensure safe working conditions. A safety checklist must not be confined to precautions mentioned in one publication, such as this handbook. The following text is provided to suggest safety considerations for magnetic testing applications and should not be referenced in place of actual safety regulations, recommended procedures or specifications. The following checklist includes some components of a safety program that demand serious consideration.

1. Before work is to begin, identify the safety and operational rules and codes applicable to the areas, equipment and systems to be tested.
2. Provide proper safety equipment (protective barriers, hard hats, safety harnesses, steel toed shoes, hearing protection and others).
3. Before the test, perform a thorough visual survey to determine all the hazards and to identify necessary safeguards to protect personnel and equipment.
4. Notify operative personnel to identify the location and specific material, equipment or systems to be tested. In addition, state, federal and company lockout/tagout procedures should be followed. Be aware of equipment that may be operated remotely or may be started by time delay.
5. Be aware of any potentially explosive atmospheres. Determine whether it is safe to take test equipment into the area.
6. Do not enter any roped off or no entry areas without permission and approval.
7. When working on or around moving or electrical equipment, the inspector should remove pens, watches, rings or objects in pockets that may touch (or fall into) energized equipment.
8. Know interplant communication and evacuation systems.
9. Never let unqualified personnel operate equipment independently from qualified supervision.
10. Keep a safe distance between the inspector and any energized equipment. In the United States, these distances can be found in documents from the Occupational Safety and Health Administration, the National Fire Prevention Association (*National Electric Code*),[12] the Institute of Electrical and Electronics Engineers (*National Electrical Safety Code*)[13] and other organizations.
11. Be aware of the personnel responsibilities before entering a confined space. All such areas must be tested satisfactorily for gas and oxygen levels before entry and periodically thereafter. If odors are noticed or if unusual sensations such as ear aches, dizziness or difficulty in breathing are experienced, leave the area immediately.

Safety requirements and standards are always in a state of review and revision. It is the responsibility of inspection managers to make sure that procedures and precautions are up-to-date and adequate for the safety of personnel.

Safety reviews should be conducted at least as often as the process control checks required for effective magnetic particle tests. There are many resources available for producing a successful safety program.

1. Equipment manufacturers provide detailed installation and operating instructions for new equipment.
2. Local and national government organizations provide standards for safety regulations. Before performing any fluorescent magnetic particle test procedure, contact the Occupational Safety and Health Administration (OSHA), the American National Standards Institute (ANSI), the American Conference of Governmental Industrial Hygienists (ACGIH) and the National Institute for Occupational Safety and Health (NIOSH).
3. Technical societies and special interest groups suggest recommended safety procedures for a variety of applications.
4. Manufacturing and other business facilities often have their own safety and health procedures.

Most facilities in the United States are required by law to follow the

requirements in applicable standards. Two occupational safety and health standards in the United States that should be reviewed are *Occupational Safety and Health Standards* for general industry[14] and the *Occupational Safety and Health Standards for the Construction Industry.*[15]

The resources above provide access to a wide range of required and recommended safety procedures. The immediate responsibility for safety lies with the individual performing the magnetic particle test. One of the first steps in developing an effective safety program is communicating pertinent data to the inspector and all other levels of the inspection team, from management through engineering to the inspectors. Personnel safety is always the first consideration for every job.

Test Environment

Some safety issues are independent of the test method. There are three categories of safety considerations for magnetic particle testing: (1) the inherent risks of the test site, (2) the potential dangers from an interaction between the test system and the testing environment and (3) the hazards possible from a magnetic particle testing system itself.

1. Magnetic particle tests are conducted in a variety of potentially dangerous sites: high on the superstructure of skyscrapers under construction, under water and in tightly confined pressure vessels. Testing personnel must first be made aware of the environment's particular safety requirements and must learn to operate within the site's own safety limits.
2. Magnetic particle test systems can react adversely with certain environmental conditions. Test systems using prods, for example, can be sources of electrical arcing. In the presence of explosive vapors or flammable gases, electrical hazards become doubly dangerous as the cause of ignition.
3. Safety considerations are needed for the test system itself, especially (a) cautions with electrical and mechanical systems and (b) care needed with petroleum distillates and other particle vehicles.

A magnetic particle test is typically performed in one of four environments with different electrical and mechanical safety considerations: (1) the controlled conditions of a testing facility, with relatively simple operating and safety procedures, (2) field sites in the presence of explosive gases below a prescribed minimum concentration, where electrical safety procedures can be like those for a controlled testing facility, (3) sites where explosive gas concentrations are known to be high, requiring stringent safety procedures and (4) underwater, requiring unique electrical and mechanical safety considerations.

Many applications of magnetic particle testing occur in difficult environments, such as refineries and offshore oil rigs. In refineries and chemical plants, there is often the danger of explosion caused by electrical components. In the case of offshore oil rigs, magnetic particle testing performed underwater calls for attention to the design and operation of the magnetizing circuitry. Not only are water hazards a cause for concern, but explosion hazards also must be addressed. Additionally, there are always the possibilities of exposure to hydrogen sulfide and potential well blowouts.

A dilemma that faces all equipment manufacturers is not having a thorough knowledge of the operating environments of their systems in service. Consider as an example some design questions asked about an alternating current magnetizing yoke. Can it be operated safely, even with frayed power cables, in some sections of a plant? Are there different organizations writing safety specifications for different industries' uses of the yoke? What differences are there between the safety specifications of different countries? What liability does the manufacturer have if such equipment causes a spark that results in an explosion? Do the manufacturer's operating instructions warn against operating in hazardous areas? Important aspects of the system design process should guard against potential accidents, but it is impossible to design for equipment misuse or compliance with all safety specifications.

Material Safety

Safety with Particle Vehicles

Most stationary magnetic particle test systems use a suspension of ferromagnetic particles in a liquid vehicle. The vehicle is often a petroleum distillate with its associated volatile characteristics. Oil based magnetic particle vehicles can be ignited by arcing of system cables or headstocks.

Some constituents of magnetic particle suspensions may cause skin irritation by removing natural oils. Unattended, the resultant drying and cracking of the skin may contribute to topical infections. Protective gloves are very effective and thorough washing of skin contact areas is always advised. Application of a

lanolin-based moisturizing lotion can also help restore oils leached from the skin by magnetic particle vehicles. Evaluation of the entire testing environment is required to provide adequate skin and clothing protection.

Potential Material Hazards

In the course of operation, magnetic particle test materials can have direct, unsafe effects on human operators (topical exposure to chemical solvents) or they can affect the environment in ways that are potentially hazardous (oil vehicle spills, for example).

The expendable materials used in magnetic particle tests consist of iron powders, mineral pigments, magnetic oxides, fluorescent organic pigments, petroleum distillate carriers, wetting agents, corrosion inhibitors and a variety of cleaning compounds and solvents. The chemicals are usually not dangerous but must be used with care.

Chemical substances should not be allowed prolonged contact with the skin. Wetting agents and solvents extract natural oils from the skin, causing inflammation and irritation. These chemicals should not be allowed to enter the mouth or eyes. Almost any compound other than water can irritate the eyes and many materials react with the tissues of mouth, throat and stomach. Solvent vapors, spray mists and dusts must not be inhaled. Vapors can irritate breathing passages and many kinds of vapors react immediately with the human nervous system.

The flammability of carrier vehicles and cleaning solvents must always be considered.

Material Safety Data Sheets

The United States Occupational Safety and Health Administration Hazard Communication Rule (29 CFR 1910.1200)[14] mandates a material safety data sheet (MSDS) for chemicals that contain hazardous ingredients. The sheet must be supplied to a customer with the initial shipment of any applicable chemical and must be updated whenever significant new information is discovered. Material safety data sheets must be available to the user of the product in the work area.

The format for the MSDS may be taken from the United States Department of Labor's nonmandatory form or it may be a supplier's individualized form. Alternate versions must meet regulatory requirements and must present all the required information.

Form Identification. The first section includes the product name as found on the container label; the name, address and telephone number of the manufacturer (or importer or distributor), who can provide additional information about the product; date of the form's preparation or its latest revision, to indicate the timeliness of its information; the name of the individual who completed the form and could serve as a source for further information.

Materials Listings. All the hazardous materials in the product are listed, with their breathing hazards. The American Conference of Governmental Industrial Hygienists (ACGIH) is an advisory group that recommends the threshold limit value (TLV), the concentration of a material that an individual can be exposed to without harm.

Physical Properties. Physical properties of the product can aggravate or diminish the effects of the hazards.

1. A volatile solvent (one having a low boiling point, high vapor pressure or high evaporation rate) is doubly hazardous because much of it will enter the breathing air during use. This may then require special ventilation or respiratory protection for inspectors. By comparison, a moderately toxic air pollutant may have such a high boiling point and low evaporation rate that very little of it can evaporate and enter the atmosphere.
2. The vapor density of a liquid is another important characteristic: vapors with high density tend to sink, accumulate and spread. Inspectors standing in the testing area may be unaware that a hazardous concentration of vapor exists at floor level. Most solvent vapors are denser than air and tend to settle. Chlorinated solvent vapors are much denser than air and their tendency to settle is pronounced.
3. Flammability is a physical property that should be considered along with density and solubility characteristics. Liquids that are insoluble in water and less dense than water will float. If such liquids are also flammable, water cannot extinguish their fire. If ignited, such liquids can float on a water surface, spread or travel with the water host.

Fire and Explosion Hazards. Many magnetic particle testing materials are incombustible solids and many of the liquid vehicles are actually treated water. However, some combustible liquid vehicles are in common use, and flash point is the accepted means for measuring their fire hazard. Flash point is defined as the lowest temperature at which a liquid

gives off gases sufficient to form an ignitible vapor at the liquid's surface. Flash point also depends on the concentration. The material safety data sheet lists recommended extinguishing media and special fire fighting procedures for hazardous or explosive materials. In addition, some chlorinated solvents break down under heat, producing very toxic substances such as carbon monoxide and phosgene gases.

Reactive Materials. The material safety data sheet lists materials that may be dangerously reactive. The intent is to warn about material compatibilities, as a guide for storage or use of the substances in mutual contact.

Health Hazards. Acute and chronic health conditions can accompany overexposure to hazardous materials. Of concern are the following: (1) carcinogens, (2) any chemical that may aggravate an existing medical condition, (3) symptoms of overexposure and (4) techniques of dealing with a spill.

Handling and Storage. Handling and storage precautions are based on good housekeeping and common sense.

1. Flammable, combustible or pressurized products should not be stored near heat sources. Chemical substances that are usually hard to ignite can burn vigorously if exposed to high temperatures such as those in a hot fire.
2. Careless exposures should be avoided — breathing dusts, vapors or spray mists, leaving them on the skin, or using the products around open flames are all basic but vitally important considerations.
3. Control measures are difficult to prescribe because the supplier usually is not familiar with the test environment or the exposure at each site. The organization that buys the material must add its own knowledge of in-house procedures to provide safety controls. For example, a slightly dusty product or a liquid that gives off some vapors may be nearly hazard free in an open and well ventilated area, requiring minimum protection and no special ventilation. The same product used in a more confined and poorly ventilated space (such as a small testing booth) may require approved respiratory protection or specially designed exhaust systems. Used inside a liquid storage tank or any enclosed compartment, the product's safe handling could mandate a full mask with an independent air supply. Tank entry safety programs must be used.
4. The amount of the material being used is a critical safety parameter. Ventilation and personal protection requirements are vastly different when a product is used occasionally or sparingly compared to continual or large volume use.

Magnetic particle materials must by law be well described in a material safety data sheet. However, the ultimate responsibility for a safe workplace rests with the organization that purchases the product and exposes its employees to it. Purchasers may expect material safety data sheet compliance from their suppliers but it is the purchasers' responsibility to use the information properly and to fully understand and alleviate the hazards involved.

The information needed in the material safety data sheet may change from year to year. The inspector needs to check the applicable regulations and other requirements periodically and update the data sheet as needed.

Equipment Safety

Proper installation of electrical components is a primary safety concern. In the presence of oil vehicles, electricity presents a fire hazard; in contact with water vehicles, electricity is a shock hazard. High amperage equipment should be electrically grounded.

When using prods for contact magnetization, involuntary motion by the inspector can cause an arc flash. Arcing can damage the eyes, provide an ignition source or produce surface damage on the test object. Under normal and adequate operating conditions, the inspector should never be exposed to electrical shock. Holding fixtures, such as clamping headstocks, must be operating reliably and predictably

In addition to the electrical system, mechanical systems also require attention for their safe operation. Many injuries have been caused by the failure of pneumatic or hydraulic components. Testing of material handling equipment on a scheduled basis is mandated by law and adequate recordkeeping is required.

The final system hazard is the ultraviolet radiation sources used for fluorescent magnetic particle testing. Several characteristics of these devices should be monitored. Most ultraviolet lamps operate at very high temperatures. Skin contact with these devices can cause injuries with the characteristics of both heat and radiational burning. Such burns are very painful and slow to heal. Ultraviolet radiation may also harm the human eye. The mercury vapor bulb used

in some lamps emits an intensity and wavelength of radiation that can permanently damage the retina. All lamps should be posted with appropriate warnings, and eye protection should be available for all testing personnel. The topic of ultraviolet radiation is discussed below in further detail.

Safety with Ultraviolet Radiation

Agencies sponsoring, contracting or overseeing tests using ultraviolet radiation have a responsibility to consult all applicable regulatory agencies and follow guidelines for personnel in the affected area. In the United States, the regulations and advice of the National Institute of Health and the Occupational Safety and Health Administration need to be observed.

Ultraviolet radiation sources are electrical components that get hot in use and emit ultraviolet radiation. They present a number of potential health and safety hazards. They can produce a severe electrical shock. Many models become very hot and can cause serious heat and radiation burns. In the presence of flammable vapors, heat from such an ultraviolet source can be sufficient for ignition of the gas. High intensity discharge lamps operate at pressures above atmospheric pressure and with impact can produce high velocity heated glass shards.

Despite these electrical and mechanical factors, the most serious safety concern is the more subtle and less understood hazard of ultraviolet radiation.

Ultraviolet Energy

Ultraviolet radiation is an invisible radiant energy produced by natural and artificial sources and is often accompanied by visible light and infrared radiation. Between X-rays and visible light, ultraviolet radiation occupies the portion of the electromagnetic spectrum in three ranges:

1. Wavelengths from 320 nm to 400 nm (the edge of the visible spectrum) are referred to as UV-A or long wave ultraviolet radiation. The UV-A wavelengths are used for fluorescent magnetic particle tests.
2. Wavelengths from 280 to 320 nm are known as *UV-B, midwave* or *erythemal ultraviolet* radiation, so named for its reddening effect on the skin. The UV-B wavelengths can cause sunburn and snow blindness. Such sources are not to be used for magnetic particle applications.
2. Wavelengths from 100 to 280 nm are known as *UV-C, actinic, germicidal or short wave ultraviolet* radiation. The UV-C radiation can cause severe burns and eye damage. In the presence of oxygen, such short wavelengths can also generate ozone, toxic if inhaled.

UV-B and UV-C ultraviolet radiation cause severe skin and eye damage after very short exposure. Do not use those shorter wavelength ranges for nondestructive testing.

Ultraviolet Radiation Hazards

Ultraviolet radiation and radiation sources present several hazards, including (1) electrocution or shock as with any electrical appliance, (2) fire or explosion as with any electrical or hot appliance, (3) radiation damage to eyes, (4) the possibility of cancer from overexposure and (5) radiation burns, like sunburn. The literature provided by equipment manufacturers needs to be studied carefully for safety precautions. In addition, various sources of information need to be consulted: workplace guidelines, requirements of standards and contracts, laws and codes in force, medical and health limitations particular to individual personnel, and agencies such as the United States Occupational Safety and Health Administration.

Projection Ultraviolet Sources

Medium Pressure, High Intensity Discharge Lamps. Spotlight and flood lamps are popular ultraviolet sources for industrial magnetic particle tests. Because the lens is made from clear glass, these lamps must be fitted with a filter suitable for transmitting the correct ultraviolet radiation while absorbing visible light and the hazardous short wavelength ultraviolet radiation. As with all high intensity discharge lamps, the filter also should be made of heat resisting glass. If the filter glass is cracked or broken, replace it immediately. Do not use a lamp with damaged filter glass. In addition to the safety hazard, unwanted visible light will reduce fluorescent contrast and diminish the effectiveness of the method.

External Reflector Lamps. A high intensity discharge lamp is available with a thin envelope of filter glass. External reflecting equipment is often provided for this lamp configuration because there is no internal reflection device. These lamps produce higher irradiances and smaller spot sizes than a typical 100 W spotlight. The bare quartz envelope produces dangerous short wave ultraviolet radiation and is very hazardous. If an ultraviolet bulb is cracked or punctured, turn it off and discard it

immediately. Hazardous radiation escapes from any opening in the bulb.

Ultraviolet Tubes. Ultraviolet tube sources are physically and often electrically similar to common fluorescent tubes. For some applications, ultraviolet tubes are used in large arrays close to the task. In addition to a few drops of mercury, the tube typically contains an inert gas or a mixture of inert gases at low pressure. On the inside surface of the glass tube is a phosphor, a white or blue powder. Ultraviolet tube sources produce an adequate intensity of radiation but cannot be focused. The irradiance is lower than that from medium pressure mercury vapor arc lamps, and tube sources should not be considered for critical magnetic particle tests. They are adequate for wide area irradiation.

Precautions

Precautions can prevent accidental exposure to ultraviolet radiation.

1. Signs should be posted in areas where ultraviolet radiation exists in excess of safe limits. Legal signage must display standard "caution, ultraviolet radiation" warnings and may contain additional health protection information. The color and size of such signs should meet federal and state requirements. In addition, equipment must be labeled to show its health and safety hazards.
2. Control of the environment is another critical safety measure. Equipment that produces ultraviolet radiation should be enclosed by partitions, screens or walls painted with nonreflective paint. Paint containing metallic particles should not be used.

Closing

Fluorescent magnetic particle testing is a simple and inexpensive nondestructive testing method. With appropriate precautions, the technique can be performed in a safe and effective manner.

PART 4. History of Magnetic Testing[16]

Early Flux Leakage Testing

Magnetic particle testing is so widely used that test bureaus and agencies administer it as a method apart from related electromagnetic techniques. In its science, however, magnetic particle testing is a technique of magnetic flux leakage testing — a technique distinguished by its very effective indicating means, the particles.

Flux leakage test techniques had their beginnings in the 1800s. In 1868, a British engineering publication reported that discontinuities were being located in gun barrels using a magnetic compass to register the flux.[17] In 1876, Charles Ryder obtained a patent to gage the carbon content of steel specimens.[18] In 1877, Anaxamander Herring obtained a patent for a test using a compass needle to detect anomalies in rails.[19] Early permeance testers, such as one by Charles Burrows (Fig. 12), were better suited for detection of variations of thickness or density rather than for identification and location of discontinuities.[20,21]

Flux leakage testing underwent further development in the twentieth century.[21-23] Its applications increased significantly with the introduction of magnetic particle testing in the 1930s. The following history concentrates on magnetic particle testing.[16,24]

Magnetic Particle Testing

Hoke

After World War I in 1918, William E. Hoke (a major in the United States Army and on assignment to the United States Bureau of Standards) was working on development of precision gage blocks as measurement standards. Hoke observed that metallic particles from hard steel parts being ground on a magnetic chuck sometimes formed patterns on the face of the part, patterns that frequently corresponded to cracks in the part's surface.

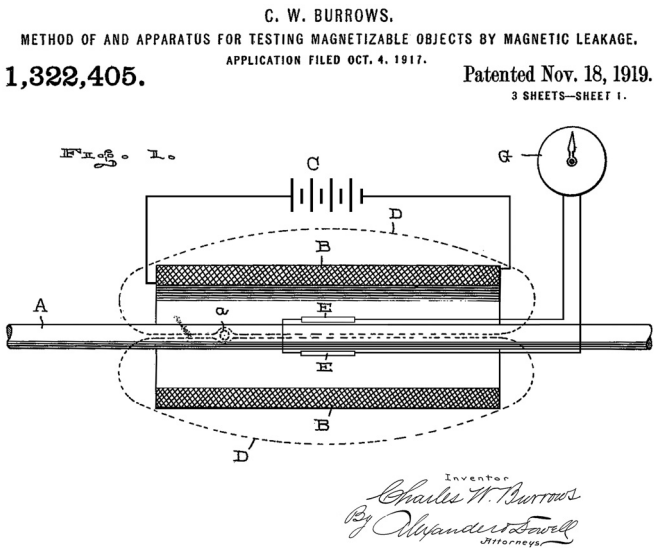
This alert observation marked the birth of magnetic particle testing (essentially, Hoke had recognized the basis for longitudinal magnetization). He applied for a patent issued in 1922 (Fig. 13)[25] but did not commercialize the idea.

De Forest

In the 1920s, Alfred V. de Forest was a research engineer, a consultant and a teacher at the Massachusetts Institute of Technology, Cambridge. The study of metals and their performance dominated his professional life. In 1928, de Forest was asked to investigate the cause of failure in some oil well drill pipe. His work on this project resulted in the magnetic particle test method (Figs. 14 and 15a).

De Forest recognized the possibilities of the method if it could be perfected to detect cracks in any direction. This meant that the direction of the magnetic field in the object could not be left to chance, neither could it be only longitudinal. The only means of magnetizing previously known were external magnets or coils carrying current. Alfred de Forest used a system that passed magnetizing current directly through the test object. This was

FIGURE 12. Drawing from United States Patent 1 322 405 by Burrows (1919).



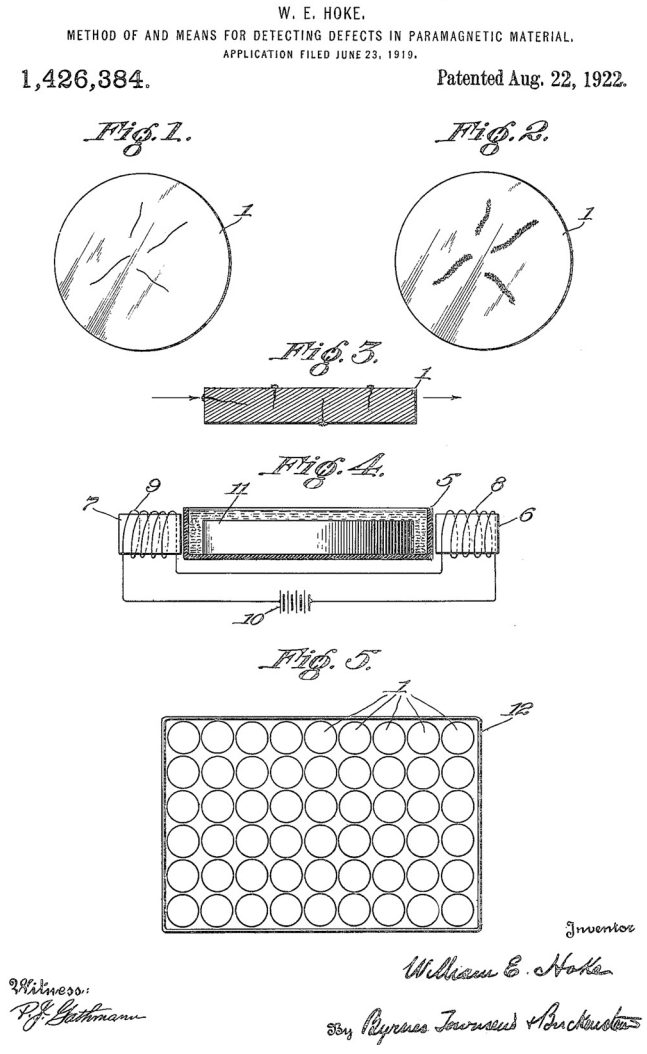
Legend

A. Magnetizable test object, such as steel rod or cable.
a. Discontinuity.
B. Solenoid.
C. Source of electric current.
D. Magnetic field.
E. Test coils.
G. Galvanometer or other indicating device.

circular magnetization, a technique that became widely used.

He also conceived of using magnetic powders with controlled size, shape and magnetic properties, essential for consistent and reliable results. Conflicts with Major Hoke's original patent were worked out the year de Forest met F.B. Doane (Fig. 15b), of Pittsburgh Testing Laboratories. That year, 1929, the partnership of A.V. de Forest Associates was formed. In 1934, de Forest's seminal patent on the method was issued[26] and the company became Magnaflux Corporation. In 1967, Carl Betz wrote that de Forest and Doane were individuals "who had the vision to see the value of a new idea and the courage and faith to

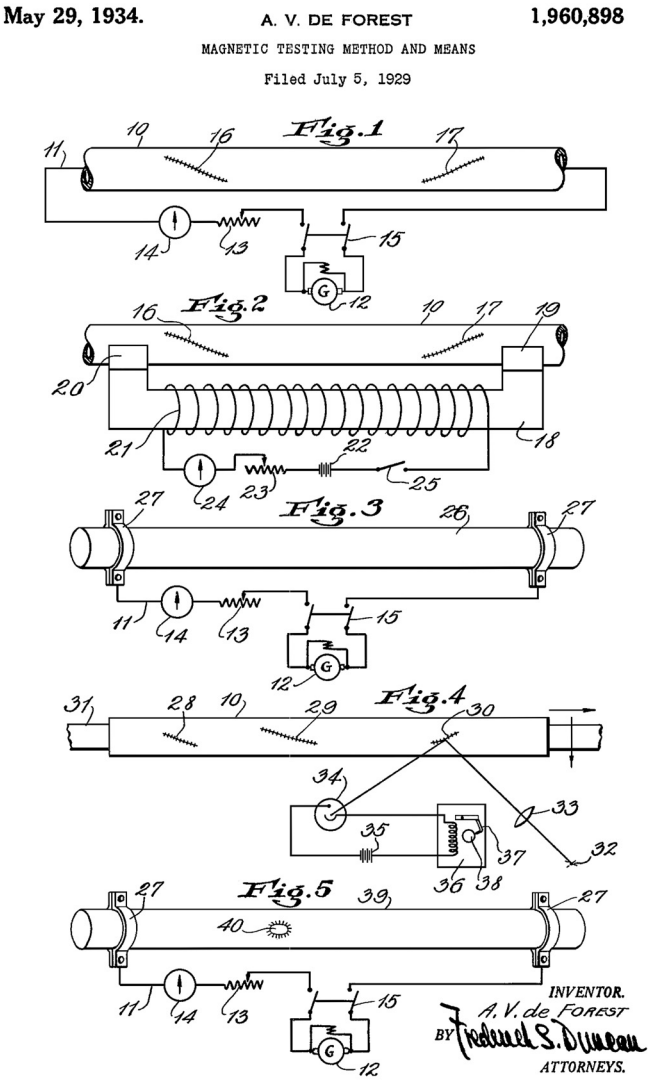
FIGURE 13. Drawings from United States Patent 1 426 384 by Hoke (1922).



Legend

1. Test object containing cracks.
5. Pan of diamagnetic medium.
6, 7. Electromagnetic cores.
8, 9. Solenoids.
10. Battery or other supply of current.
11. Test object.
12. Tray or pan to hold test object or objects.

FIGURE 14. Drawings from United States Patent 1 960 898 by de Forest (1934).



Legend

G. Galvanometer or other indicating device.
10. Steel tube or similar test object.
11. Conductor.
12. Source of electromotive force.
13, 23. Rheostat.
14, 24. Ammeter.
15, 25. Switch.
16, 17. Discontinuities.
18. Yoke.
19, 20. Contact poles of yoke.
21. Magnetizing winding.
22. Battery.
26. Round bar of magnetizable material.
27. Conducting clamps.
28-30. Groups of finely divided material.
31. Mandrel.
32. Light source.
33. Lens.
34. Photoelectric cell.

devote their lives to making this vision become a reality."[27]

Development in 1930s

Test System Development

In the early 1930s, de Forest and Doane showed great enthusiasm for their practical testing method. They set up a small laboratory and shop in Doane's basement and began making powder (then called *dust*). The pair produced a variety of particles, making it possible to inspect both smooth and rough surfaces, machined parts, castings or welds. The particles could be used for detecting discontinuities of various widths and depths and for detecting both surface and some subsurface discontinuities. These first particles were dry powders.

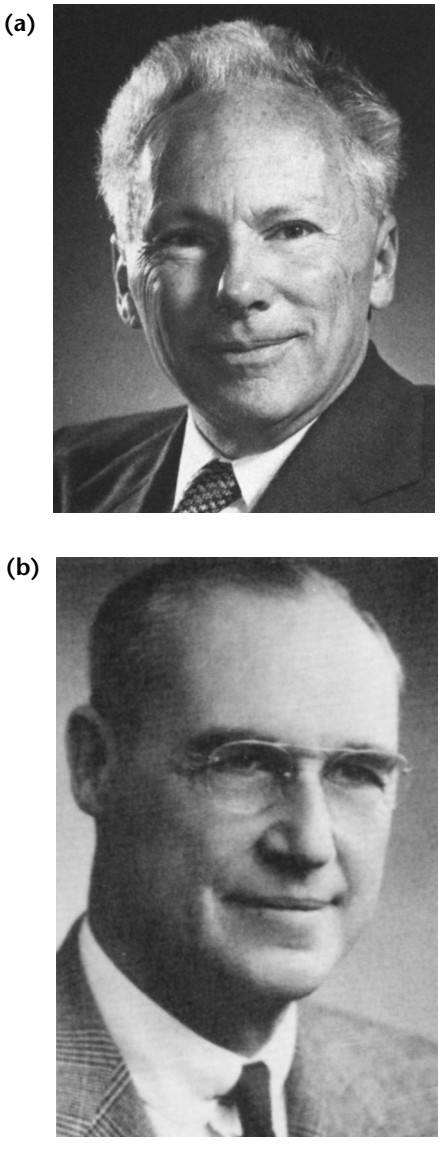
The wet (liquid suspension) technique was added in 1935. At the Wright Aeronautical Company in Paterson, New Jersey, black magnetic oxide was suspended in a light petroleum product similar to kerosene. At the same time, the General Electric Company in Schenectady, New York, began using finely ground mill scale suspended in light oil.

In 1936, a German patent was issued to F. Unger and R.S. Hilpert who suggested that magnetic particles could be suspended in water with wetting agents and rust inhibitors added. About two years later, there were important German developments in other areas of research.[28] Based on a desire to establish standardized magnetic particle test sensitivities, a magnetic test gage was developed at the Reichs Roentgenstelle at Berlin-Dahlem. With few modifications, the gage is the type known as the *berthold field gage*.[29]

In the United States, magnetic particle testing was introduced by Doane and de Forest to the Army Air Corps at Wright Field, Dayton, Ohio, and to the Navy at the Naval Aircraft Factory, Philadelphia, Pennsylvania. The test method was soon being used in suppliers' plants as well as aircraft repair centers. The original cracked sample used for demonstrating the effectiveness of magnetic particle testing is shown in Fig. 3. De Forest continually enjoyed the reaction of those who saw the particles attracted to the invisible cracks in his permanently magnetized sample.[30]

In the early 1930s, an experimental magnetizing fixture was first used to demonstrate the magnetic particle technique (Fig. 16). Figure 17 shows an assembly of electrical components like those built for early applications. This system used alternating current for magnetizing and was used to test tool steel bars. Figure 18 shows a unit used in the aircraft industry in the 1930s; it provided circular and longitudinal magnetization from storage battery power.

FIGURE 15. Pioneers of magnetic particle testing: (a) A.V. de Forest; (b) F.B. Doane.



Applications in 1930s

Railroads. The railroads were also early users of magnetic particle techniques, mainly for the location of fatigue cracks in axles and moving parts of steam locomotives.

A series of systems were designed in 1938 to inspect only one type of object (Fig. 19). This special design was built for the Denver and Rio Grande Western Railroad for the testing of railroad car axles. Many severe axle failures with

costly traffic delays and loss of equipment had been occurring nationwide. During the first few months of extensive magnetic particle testing, 45 percent of all moving locomotive parts were found to be defective. After two years of planned overhaul programs, failures due to fatigue cracking were virtually eliminated on the Denver and Rio Grande Western Railroad.

Steel. During this same time, the merchant steel mills were restricting spending because of the Great Depression and had not yet begun using magnetic particle tests. However, the method was accepted by specialty steel producers who made tool steel. This steel was more expensive and top quality was demanded. Seams in tool steel bars generally resulted in cracked tools, punches or dies. The labor cost of machining tools was high and specialty mills were often held responsible. Tool steel and alloy steel producers were among the early advocates of magnetic particle techniques.

Welds. In Germany, the magnetic particle test method was developing parallel with welding techniques and their use on steel structures. Magnetic particle techniques were used to locate cracks and to detect misalignments of plate edges. Alternating current prods and direct current yokes were reported to produce the best results.

Automobiles. The automobile industry became interested and by the end of the 1930s magnetic particle systems were

FIGURE 16. Experimental magnetic particle testing equipment used by F.B. Doane in 1930.

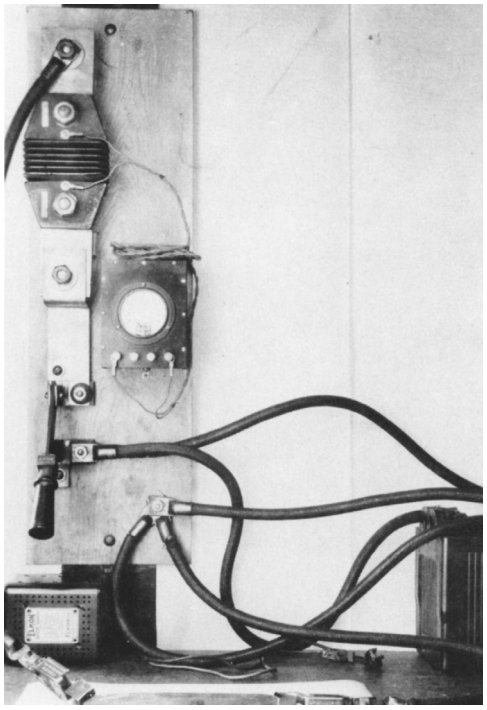


FIGURE 17. Alternating current magnetizing assembly (1933).

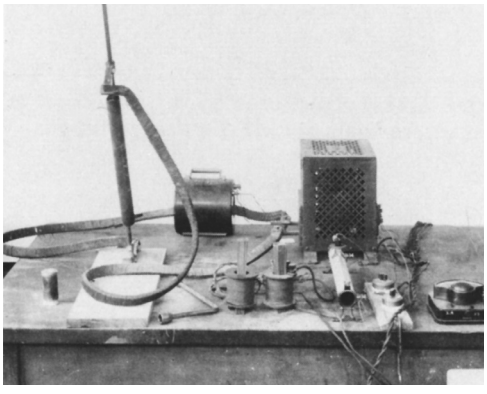
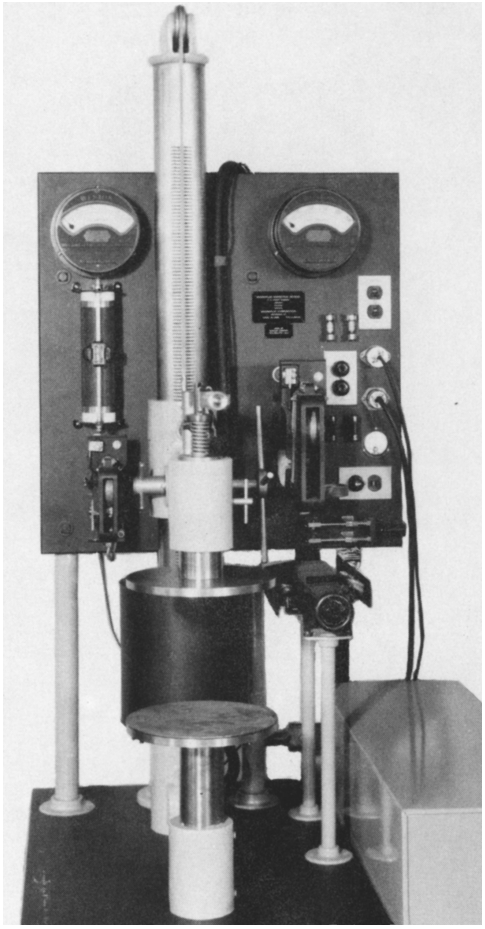


FIGURE 18. Storage battery unit used by aircraft industry from 1932 to 1940.



being used in metallurgical laboratories and in some receiving inspection departments on an experimental basis. The Greyhound Bus Company began its use of the method for the location of fatigue cracks in engine parts at overhaul.

Another early user was the Indianapolis Motor Speedway. In 1936, magnetic particle testing was made mandatory there for all steering parts. In that same year, more than 50 percent of the parts presented for testing were rejected. In 1948, Wilbur Shaw, president of the Speedway, stated that magnetic particle testing had contributed more to their safety record than any other single factor. He said that no accident at the track had been caused by a defective steering part since the test method was made compulsory. The first magnetic particle unit was sent to the Speedway in 1936 to eliminate serious spindle failures, which had been occurring during the two previous years. By 1962, although not mandatory, owners were submitting many engine parts for testing before practice runs. Many crankshafts were tested by the magnetic particle method and many magnesium wheels by the liquid penetrant method and were rejected before failure in service. These two methods have been widely used by the racing industry.

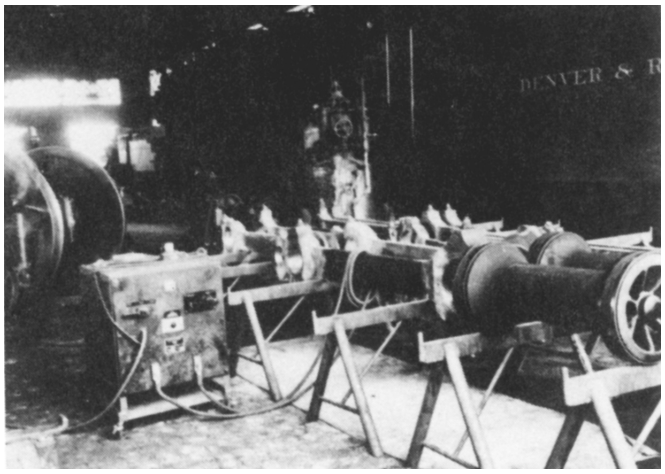
Aviation. Hamilton Standard Company used magnetic particles to test aircraft propellers. Pratt and Whitney, producer of aircraft engines, soon followed. Other airlines to use the method were American Airlines and United Airlines. Both the Army and the Navy recognized the value of the technique for locating fatigue cracks in engine parts, propellers and other highly stressed parts during periodic overhaul.

Around 1938, the Navy and Army Air Corps agreed on a standard magnetic particle system design to be used in their overhaul shops. It was a horizontal, wet technique, direct current machine, with storage batteries and battery charger. The amperage was controlled by a carbon pile rheostat. The unit bore the designation AN for Army and Navy.

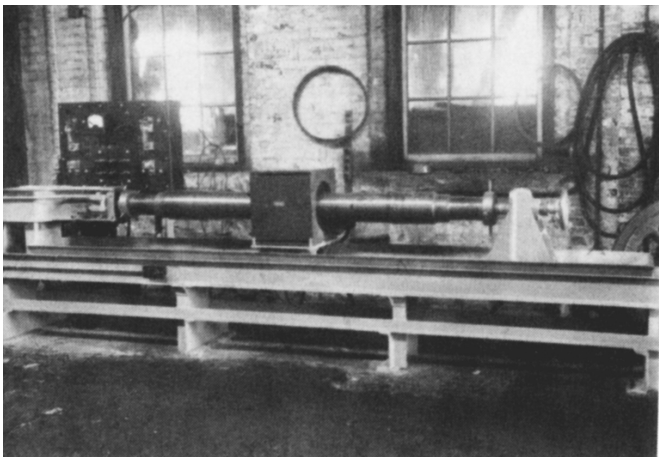
Electric Power. Early users also included steam power plants, which began scheduling the test method during maintenance of steam turbine blades, boilers and piping welds.

FIGURE 19. Magnetic particle testing of railroad car axles: (a) mobile unit (1937); (b) stationary unit (1938).

(a)



(b)



Improvements in Magnetizing Equipment

Until the mid 1930s, most magnetic particle inspectors made their own magnetizing equipment. About 1934, Doane introduced the low voltage, 60 Hz alternating current unit for steel mill bar stock testing. Before then, most magnetizing equipment used direct current from storage batteries. The unit had a transformer with two taps in the primary coil so that, by knife switches, the output from the secondary could be adjusted. Several machines of this type were designed to test heavy equipment in the railroads and other industries. One of these (shown in Fig. 19a in a railroad maintenance shop) is the prototype of today's mobile power packs. It operated from a 220/440 V, 60 Hz power supply and delivered up to 3000 A of low voltage magnetizing current through flexible cables. The unit was made mobile, on wheels, because it was easier to move the testing system than heavy railroad parts.

Demagnetizers. Before 1939, demagnetizers had been both crude and cumbersome. The use of alternating current for magnetization required special

design efforts to attain closer current control. Research eventually produced a thirty-point motorized tap switch that provided close control of the magnetizing current. This was a significant development that also provided the capability of rapid and automatic demagnetization of objects through a succession of short shots of alternating current at diminishing amperages. Larger objects could be demagnetized while still in place on the magnetizing unit.

Alternating Current Yoke. The 1930s saw the introduction of the alternating current electromagnetic yoke. The yoke was limited then as it is today to the location of surface discontinuities and found its first uses as a preventive maintenance tool. The yoke was also reportedly used in the metallurgical laboratory of a steel mill as a means of locating discontinuities in sample disks 50 mm (2 in.) thick, cut from each end of forging quality billets.

Growth in 1940s

War

The 1940s began with growing emphasis on military procurement. Purchasing groups came to the United States from Europe to buy military hardware. The major manufacturers expanded production of weapons, vehicles and aircraft. Foundries, forging plants, machine tool and gear manufacturers, steel mills, landing gear producers — all were affected.

As production increased, the need increased for magnetic particle testing. Makers of tractors and diesel engines also became users of the technique. Suppliers of castings and forgings showed genuine interest in the testing method. Many machine tool and turbine manufacturers purchased testing equipment for their metallurgical laboratories or testing departments. Military specifications required magnetic particle testing.

World War II created a need for not only more magnetic particle testing but also testing equipment that could rapidly handle mass produced parts. Special purpose handling systems were designed for larger and heavier objects (steel propeller blades, propeller hubs, engine cylinders and engine mounts) and some of these systems were partially automated.

Up to this time, magnetic particle testing had been used on many types of welded structures, particularly welded aircraft assemblies. However, on heavier welds, radiography was the accepted nondestructive testing method and was called for in the American Society of Mechanical Engineer's Boiler and Pressure Vessel Code.

Because of the war, American shipbuilding soared and so did the future of magnetic particle testing methods, for the ships and their weaponry. The most common naval weapon was the 127 mm (5 in.) gun for destroyers and aircraft carriers. The gun's mounts were made of heavy steel plate welded together to form a fixed and a rotating platform; the welds were up to 150 mm (6 in.) thick. Magnetic particle testing found an immediate application for locating inclusions and laminations that interfered with crack-free root weld passes before depositing more weld metal. Direct current testing with prods and an automatic powder blower also originated at this time.

The pace of production and the haste of all involved, including the military, caused a great deal of overinspection during the war. The first military specification on AN bolts required 100 percent testing in both directions, even though circumferential discontinuities were the only ones of importance. Many usable bolts were scrapped because of minor seams or inclusions.[30] In the years after the war, proposed military specifications were usually reviewed by the potential users before being issued. This reduced but did not eliminate the problem of overinspection. There were still important differences between drawing specifications and floor inspection requirements.

Direct Current and Quick Break Designs

The superiority of direct current magnetization for locating subsurface discontinuities had long been recognized. However, battery maintenance represented a growing problem because of the need for larger and heavier duty units. In 1941, the AN battery powered series of wet horizontal test machines was replaced on the assembly line by rectifier powered machines.

When a coil is used to impart a longitudinal field in a bar shaped object, special circuitry is required to ensure sufficient field near the ends of the test object for detection of circumferential discontinuities. The condition or effect required has been called *quick break* or *fast break*. Battery powered units had this feature built in.

Special quick break design considerations are required on rectifier powered machines. The lack of this special design can be catastrophic — one automobile producer dropped their sixty car per hour production rate to zero when steel conveyor pins began breaking in one

of their main lines. The magnetic particle test of these pins had been performed with war surplus systems built before the quick break phenomenon was recognized.

This one occurrence was followed by others in the years following the war. Most of the trouble was caused by maintenance personnel who innocently removed what appeared to be an extra breaker in the circuit of their machines. It is important that all units using a coil for magnetizing be checked periodically to ensure that quick break is operating properly. In the 1960s, a device for quickly verifying the presence of this feature was introduced.

Fluorescent Magnetic Particle Testing

In 1941, the magnetic particle testing method took a significant step forward with the introduction of fluorescent magnetic particles. The first fluorescent powders consisted of loosely bound agglomerates of magnetic powders and separate fluorescent powders. The two tended to be trapped together to form fluorescent indications. The agglomerated mixture was an improvement over visible powder but was still not completely satisfactory.

After experimental work by a number of individuals and groups, Robert Switzer and Joseph Switzer (Fig. 20) combined magnetic and fluorescent materials. The brothers developed a method of coating magnetic particles with fluorescent material and this greatly enhanced the particles' visibility. Pure black against pure white offers a 25:1 contrast ratio. Fluorescence in darkness offers contrast ratios as high as 1000:1. Fluorescent particles can therefore be fewer in number while offering a sizable increase in sensitivity for detection of fine discontinuities. The bonding process had another advantage: it allowed water instead of oil or kerosene as a suspension vehicle.

Years later, it was revealed that magnetic particle testing and fluorescent penetrant testing helped in building the first atomic bomb, in the Manhattan Project.[30] These test methods were also vital factors in the building of the atomic reactor beneath the stands of Stagg Field at the University of Chicago. A.V. de Forest used both test methods on various pieces of the reactor and the containers for the uranium fuel. Since then, both methods have been involved in many facets of the military and civilian use of atomic energy.

FIGURE 20. Joseph Switzer (left) and Robert Switzer.



Peacetime Production and Developments

Alfred de Forest said many times, "the closer the test can be brought to the hot steel, the more economical it is."[31] In other words, catch the discontinuity early and save money. During the war, nondestructive testing activities had been directed toward supplying the needs of war materiel contractors and military agencies. After the war, most metalworking firms continued to emphasize production, not testing or intensive quality control and all the nondestructive testing techniques, including the magnetic particle method, had to be reintroduced. This was done by selling the realities and advantages of accurate testing. It was a slow educational process, but by 1950 a consumer oriented economy had helped shift the emphasis toward quality. Peacetime manufacturing for profit in the late 1940s saw an increasing acceptance of nondestructive testing.

Developments in the hardware of magnetic particle testing helped improve accuracy and, in turn, the quality of products. In the 1930s, a mobile power pack for weld testing had used direct current for magnetization. This provided a penetrating magnetic field (designed to supplement radiography for detecting subsurface discontinuities) but restricted the mobility of the magnetic particles. A method of magnetizing called *surge magnetization* followed in the 1940s. It was possible, by suitable current control

and switching devices, to provide a very high current for a short period (less than a second) and to then reduce the current without interrupting it to a much lower steady value.

Surge magnetizing was used for many years to allow deeper penetration yet did nothing for powder mobility. After the war, half-wave magnetizing current provided increased penetration and increased powder mobility. Despite the refinement of radiographic techniques and the introduction of ultrasound, half-wave magnetic particle testing became widely used for the detection of both surface and near surface discontinuities in welds.

With the means available for magnetizing heavy cross sections in welds, castings and forgings, the rather simple technique of passing test objects through an alternating current coil for demagnetization was no longer always adequate. A demagnetizer that found wide acceptance during this period was one that could be built into any direct current power pack. A thirty-point switch and a set of breakers provided reversing and decreasing direct current at one reversal per second. This procedure was necessary for applications such as demagnetizing heavy crankshafts used in truck and off-road equipment.

The postwar years were most dramatic for the railroads. During this period, many inspectors learned what the term copper penetration meant: molten alloys from the bearings of railroad axle journals penetrated the grain boundaries of the heated journal. This provided the starting point for fatigue cracks and eventual axle failure. The condition could not be found visually nor with dry magnetic particles but was readily seen with fluorescent magnetic particle testing.

During the 1940s, developments also began in the utility industries and the petrochemical industries. Firms laying pipelines, for example, began using magnetic particle testing on welds made in the field, particularly on the tie-in welds made after dropping the pipe sections into place below ground level.

Many other applications in the twentieth century are discussed in detail elsewhere.[16]

Education

The 1940s also witnessed the beginning of nondestructive testing symposiums and schools for industry. Every magnetic particle testing system put into operation required operators and inspectors, so people were hired by the thousands and assigned to inspection work. Many of them knew little about the equipment, the inspection method or what an operator was expected to do. Military documents required contractors to train inspection personnel in both theory and applications. Government inspectors then administered written and practical examinations before assigning government certification. Compounding the training problem was a shortage of supervisors and instructors.

Schools were soon established in important industrial centers. For the magnetic particle technique, Magnaflux Corporation offered lecture courses, generally three days long. During the war, more than 55 of their courses were presented to about five thousand people. After the war, permanent schools were established by many nondestructive testing firms, each specializing in the methods they knew best. Most nondestructive testing innovators, including pioneers like Phil Johnson, had a common philosophy: every defect has a cause — educated and constructive inspectors can suggest a cure.

The Society for Nondestructive Testing (SNT) became very active during the 1950s. One of its important contributions was the publication of the *Nondestructive Testing Handbook*. Volume 2 of the first edition includes chapters on electrified particle and magnetic particle tests, test indications, principles and equipment. Work on the *Nondestructive Testing Handbook* began in 1950 and was continued by its editor, Robert C. McMaster, until its publication in 1959. The second edition devoted an entire volume to magnetic particle testing, including many pages applicable to flux leakage testing either with or without particles. Titled simply *Magnetic Particle Testing*, that volume was issued in 1989 by the publisher, which had changed its name to the American Society for Nondestructive Testing.[4]

Industry Challenges

The magnetic particle method continued to develop after 1950 in a number of ways, including the following: (1) mobility of test equipment, (2) automation, (3) fluorescent illumination, (4) electronic gaging of magnetic fields, (5) custom configurations for various applications and (6) refinements contributing to speed, safety, and repeatability of results. These developments are discussed in detail elsewhere.[16]

PART 5. Measurement Units for Magnetic Testing

Origin of SI System

In 1960, the General Conference on Weights and Measures established the International System of Units. *Le Systéme International d'Unités* (SI) was designed so that a single set of measurement units could be used by all branches of science, engineering and the general public. Without SI, the *Nondestructive Testing Handbook* series would contain a confusing mix of obsolete centimeter gram second (CGS) units, inch pound units and the units preferred by certain localities or scientific specialties.

SI is the modern version of the metric system and ends the division between metric units used by scientists and metric units used by engineers and the public. Scientists have given up their units based on centimeter and gram and engineers have abandoned the kilogram-force in favor of the newton. Electrical engineers have retained the ampere, volt and ohm but changed all units related to magnetism.

Table 6 lists the seven SI base units. Table 7 lists derived units with special names. Table 8 gives examples of conversions to SI units. In SI, the unit of time is the second (s) but hour (h) is recognized for use with SI.

For more information, the reader is referred to the information available through national standards organizations and specialized information compiled by technical organizations.[32-35]

Multipliers

In science and engineering, very large or very small numbers with units are expressed by using the SI multipliers, prefixes of 10^3 intervals (Table 9). The multiplier becomes a property of the SI unit. For example, a millimeter (mm) is 0.001 meter (m). The volume unit cubic centimeter (cm^3) is $(0.01\ m)^3$ or $10^{-6}\ m^3$. Unit submultiples such as the centimeter, decimeter, dekameter and hectometer are avoided in scientific and technical uses of SI because of their variance from the convenient 10^3 or 10^{-3} intervals that make equations easy to manipulate.

In SI, the distinction between upper and lower case letters is meaningful and should be observed. For example, the meanings of the prefix *m* (milli) and the prefix *M* (mega) differ by nine orders of magnitude.

TABLE 6. SI base units.

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

TABLE 7. SI derived units with special names.[a]

Quantity	Units	Symbol	Relation to Other SI Units[b]
Capacitance	farad	F	$C \cdot V^{-1}$
Catalytic activity	katal	kat	$s^{-1} \cdot mol$
Conductance	siemens	S	$A \cdot V^{-1}$
Energy	joule	J	$N \cdot m$
Frequency (periodic)	hertz	Hz	$1 \cdot s^{-1}$
Force	newton	N	$kg \cdot m \cdot s^{-2}$
Inductance	henry	H	$Wb \cdot A^{-1}$
Illuminance	lux	lx	$lm \cdot m^{-2}$
Luminous flux	lumen	lm	$cd \cdot sr$
Electric charge	coulomb	C	$A \cdot s$
Electric potential[c]	volt	V	$W \cdot A^{-1}$
Electric resistance	ohm	Ω	$V \cdot A^{-1}$
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	$Wb \cdot m^{-2}$
Plane angle	radian	rad	1
Power	watt	W	$J \cdot s^{-1}$
Pressure (stress)	pascal	Pa	$N \cdot m^{-2}$
Radiation absorbed dose	gray	Gy	$J \cdot kg^{-1}$
Radiation dose equivalent	sievert	Sv	$J \cdot kg^{-1}$
Radioactivity	becquerel	Bq	$1 \cdot s^{-1}$
Solid angle	steradian	sr	1
Temperature	degree celsius	°C	K
Time[a]	hour	h	3600 s
Volume[a]	liter	L	dm^3

a. Hour and liter are not SI units but are accepted for use with SI.
b. Number one (1) expresses a dimensionless relationship.
c. Electromotive force.

Table 8. Examples of conversions to SI units.

Quantity	Measurement in Non-SI Unit	Multiply by	To Get Measurement in SI Unit
Angle	minute (min)	$2.908\,882 \times 10^{-4}$	radian (rad)
	degree (deg)	$1.745\,329 \times 10^{-2}$	radian (rad)
Area	square inch ($in.^2$)	645	square millimeter (mm^2)
Distance	angstrom (Å)	0.1	nanometer (nm)
	inch (in.)	25.4	millimeter (mm)
Energy	British thermal unit (BTU)	1.055	kilojoule (kJ)
	calorie (cal), thermochemical	4.184	joule (J)
Power	British thermal unit per hour ($BTU \cdot h^{-1}$)	0.293	watt (W)
Specific heat	British thermal unit per pound degree fahrenheit ($BTU \cdot lb_m^{-1} \cdot °F^{-1}$)	4.19	kilojoule per kilogram per kelvin ($kJ \cdot kg^{-1} \cdot K^{-1}$)
Force	pound force	4.448	newton (N)
Torque (couple)	foot-pound ($ft\text{-}lb_f$)	1.36	newton meter (N·m)
Pressure	pound force per square inch ($lb_f \cdot in.^{-2}$)	6.89	kilopascal (kPa)
Frequency (cycle)	cycle per minute	60^{-1}	hertz (Hz)
Illuminance	footcandle (ftc)	10.76	lux (lx)
	phot (ph)	10 000	lux (lx)
Luminance	candela per square foot ($cd \cdot ft^{-2}$)	10.76	candela per square meter ($cd \cdot m^{-2}$)
	candela per square inch ($cd \cdot in.^{-2}$)	1 550	candela per square meter ($cd \cdot m^{-2}$)
	footlambert (ftl)	3.426	candela per square meter ($cd \cdot m^{-2}$)
	lambert	3 183 (= 10 000 ÷ π)	candela per square meter ($cd \cdot m^{-2}$)
	nit (nt)	1	candela per square meter ($cd \cdot m^{-2}$)
	stilb (sb)	10 000	candela per square meter ($cd \cdot m^{-2}$)
Radioactivity	curie (Ci)	37	gigabecquerel (GBq)
Ionizing radiation exposure	roentgen (R)	0.258	millicoulomb per kilogram ($mC \cdot kg^{-1}$)
Mass	pound (lb_m)	0.454	kilogram (kg)
Temperature (increment)	degree fahrenheit (°F)	0.556	kelvin (K) or degree celsius (°C)
Temperature (scale)	degree fahrenheit (°F)	(°F – 32) ÷ 1.8	degree celsius (°C)
Temperature (scale)	degree fahrenheit (°F)	(°F – 32) ÷ 1.8 + 273.15	kelvin (K)

Table 9. SI prefixes and multipliers.

Prefix	Symbol	Multiplier
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto[a]	h	10^{2}
deka[a]	da	10
deci[a]	d	10^{-1}
centi[a]	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

a. Avoid these prefixes (except in dm^3 and cm^3) for science and engineering.

SI Units for Magnetic Testing

In magnetic testing, units are mainly for magnetism, visible light and ultraviolet radiation. The SI units include the weber (Wb), the tesla (T) and several derived units. Originally, these units were developed by scientists using the CGS (centimeter gram second) metric system. For magnetic theories, the introduction of SI meant the removal of intermediate units (such as the unit pole) and made possible a direct conversion from flux per second to voltage.

Electromagnetics

Table 10 gives examples of CGS units not accepted for use with the SI. Furthermore, no other units of the various CGS systems of units, which includes the CGS electrostatic, CGS electromagnetic and CGS gaussian systems, are accepted for use with SI except such units as the centimeter (cm), gram (g) and second (s) that are also defined in SI.

The oersted, gauss and maxwell are part of the electromagnetic

three-dimensional CGS system. When only mechanical and electric quantities are considered, these three units cannot strictly speaking be compared each to the corresponding unit of SI, which has four dimensions. The SI units include the weber (Wb) and the tesla (T).

Magnetic Field Intensity. The ampere per meter replaces the oersted. Magnetic field intensity (magnetic field strength) is expressed in ampere per meter ($A \cdot m^{-1}$). One ampere per meter ($A \cdot m^{-1}$) equals about one eightieth of an oersted (Oe). The relationship is $1\,Oe = 1000 \cdot (4\pi)^{-1}\,A \cdot m^{-1} = 79.57747\,A \cdot m^{-1}$. $1\,A \cdot m^{-1} = 0.013\,Oe = 13\,mOe$.

Magnetic Flux Density. The tesla replaces the gauss. Magnetic flux density is expressed in weber per square meter ($Wb \cdot m^{-2}$), or tesla (T), to indicate flux per unit area. One tesla equals ten thousand gauss (G): $1\,T = 10^4\,G = 10\,kG$. $1\,G = 10^{-4}\,T = 0.1\,mT$. Tesla is a large unit and is often used with the SI multipliers (Table 9).

Magnetic Flux. The weber replaces the maxwell. One weber (Wb) equals 10^8 maxwell (Mx): $1\,Wb = 100\,MMx$. $1\,Mx = 10^{-8}\,Wb = 0.01\,\mu Wb = 10\,nWb$.

Illumination

The intensity of light — that is, of visible radiation — was formerly measured in footcandles (ftc) and is now expressed in lux (lx): 1 ftc = 10 lx.

Although visible radiation is sometimes expressed in watts per square meter, photometric units such as lux should never be applied to ultraviolet radiation.

Ultraviolet Radiation

The term light is widely used for electromagnetic radiation in the visible part of the spectrum. The term black light, however, should not be used for ultraviolet radiation, because (1) the term has become ambiguous, sometimes denoting the ultraviolet lamp and sometimes its radiation, (2) the term black here merely means invisible and not a spectral hue and (3) ultraviolet radiation is not light any more than X-rays are.

Ultraviolet radiation is divided into three ranges: UV-A (320 to 400 nm), UV-B (280 to 320 nm) and UV-C (100 to 280 nm). This is analogous to the segmentation of visible light into the wavelengths that produce the colors. Blue light, for example, generally has

TABLE 10. Units from centimeter gram second (CGS) system of units and not accepted for use with SI. Factor to convert each CGS unit to SI unit is given.

Physical Quantity	CGS Unit	Multiply by	SI Unit	SI Symbol
Basic CGS Units				
Magnetic field intensity	oersted (Oe)	$10^3 \times (4\pi)^{-1}$	ampere per meter	$A \cdot m^{-1}$
Magnetic flux	maxwell (Mx)	10^{-8}	weber	Wb
Magnetic flux density	gauss (G)	10^{-4}	tesla	T
Magnetic potential difference	gilbert (Gb)	$10 \times (4\pi)^{-1}$	ampere	A
Electromagnetic CGS Units				
Capacitance	abfarad	10^9	farad	F
Charge	abcoulomb	10	coulomb	C
Conductance	abmho	10^9	siemens	S
Current	abampere	10	ampere	A
Inductance	abhenry	10^{-9}	henry	H
Magnetic field intensity	abampere per centimeter	10^3	ampere per meter	$A \cdot m^{-1}$
Potential	abvolt	10^{-8}	volt	V
Resistance	abohm	10^{-9}	ohm	Ω
Electrostatic CGS Units				
Capacitance	statfarad	$1.112\,650 \times 10^{-12}$	farad	F
Charge	statcoulomb	3.3356×10^{-10}	coulomb	C
Conductance	statmho	$1.112\,65 \times 10^{-12}$	siemens	S
Current	statampere	$3.335\,641 \times 10^{-11}$	ampere	A
Inductance	stathenry	$8.987\,552 \times 10^{11}$	henry	H
Potential	statvolt	$2.997\,925 \times 10^2$	volt	V
Resistance	statohm	$8.987\,55 \times 10^{11}$	ohm	Ω

wavelengths between 455 and 492 nm. Yellow light is between 577 and 597 nm. The analogy to visible radiation might help those first learning to measure ultraviolet radiation. A certain intensity of yellow light will produce on a surface a certain illuminance measured in lux. In the same way, a certain amount of ultraviolet radiation will produce an irradiance on a test surface. Irradiance is a time dependent measure of the amount of energy falling on a prescribed surface area. Because ultraviolet radiation is invisible (not the same wavelengths as light), photometric measurement units such as the footcandle, lumen and lux do not apply.

Ultraviolet irradiance is expressed in watts per square meter ($W \cdot m^{-2}$) or, more commonly (to avoid exponents), microwatts per square centimeter ($\mu W \cdot cm^{-2}$). One unit of irradiance ($1\ \mu W \cdot cm^{-2}$) is the power (microwatt) falling on one square centimeter (cm^{-2}) of surface area. At higher irradiance, the milliwatt per square centimeter ($mW \cdot cm^{-2}$) is sometimes used: $1000\ \mu W \cdot cm^{-2} = 1\ mW \cdot cm^{-2}$, and $1\ \mu W \cdot cm^{-2} = 1 \times 10^{10}\ W \cdot m^{-2}$.

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2

CHAPTER

Fundamentals of Magnetic Testing[1,2]

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PART 1. Introduction to Magnetic Tests

Magnetic testing is part of the widely used family of electromagnetic nondestructive testing. The theory and practice of electromagnetic techniques are discussed elsewhere in the *NDT Handbook*.[1] When used with other methods, magnetic tests can provide a quick and relatively inexpensive assessment of the integrity of ferromagnetic materials.

Magnetic particle testing is in fact a variation of flux leakage testing that uses particles to produce indications. Because of the prevalence of tests specifically using particles, magnetic particle testing is usually treated as a separate method by industry and in the literature. The term *flux leakage testing,* also called *diverted flux testing,* is then meant to exclude tests with particles.

The magnetic circuit and the means for producing the magnetizing force that causes magnetic flux leakage are described below. Theories developed for surface and subsurface discontinuities are outlined along with some results that can be expected.

Industrial Uses[3]

Magnetic testing is used in many industries to find a wide variety of discontinuities. Much of the world's production of ferromagnetic steel is tested by magnetic or electromagnetic techniques. Steel is tested many times before it is used and some steel products are tested during use for safety and reliability and to maximize their length of service.

Production Testing

Typical applications of magnetic flux leakage testing are by the steel producer, where blooms, billets, rods, bars, tubes and ropes are tested to establish the integrity of the final product. In many instances, the end user will not accept delivery of steel product without testing by the mill and independent agencies.

Receiving Testing

The end user often uses magnetic flux leakage tests before fabrication. This test ensures the manufacturer's claim that the product is within agreed specifications. Such tests are frequently performed by independent testing companies or the end user's quality assurance department. Oil field tubular goods are often tested at this stage.

Inservice Testing

Good examples of inservice applications are the testing of used wire rope, installed tubing, or retrieved oil field tubular goods by independent facilities. Many laboratories also use magnetic techniques (along with metallurgical sectioning and other techniques) for the assessment of steel products and prediction of failure modes.

Steps in Magnetic Testing

There are four steps in magnetic testing: (1) magnetize the test object so that discontinuities perturb the flux, (2) scan the surface of the test object with a magnetic flux sensitive detector, (3) process the raw data from these detectors in a manner that best accentuates discontinuity signals and (4) present the test results clearly for interpretation. The following discussion deals with the first step, producing the magnetizing force.

Magnetic Particle Testing

Principles

Magnetic particle testing is a nondestructive method of revealing surface and subsurface discontinuities in magnetizable materials. It may be applied to raw materials such as billets, bars and shapes; during processes such as forming, machining, heat treating and electroplating; and in testing for service related discontinuities.

The testing method is based on the principle that magnetic flux in a magnetized object is locally distorted by the presence of a discontinuity. This distortion causes some of the magnetic field to exit and reenter the test object at the discontinuity. This phenomenon is called *magnetic flux leakage (MFL).* Flux leakage is capable of attracting finely divided particles of magnetic materials that in turn form an outline or indication of the discontinuity. The intensity or

curvature of magnetic flux leakage fields is critical in causing particles to remain held at an indication.

One of the objectives of magnetic particle testing is to detect discontinuities as early as possible in the processing sequence, thus avoiding the expenditure of effort on materials that will later be rejected. Practically every process, from the original production of metal from its ore to the last finishing operation, may introduce discontinuities. Magnetic particle testing can reveal many of these, preventing flawed components from entering service. Even though magnetic particle testing may be applied during and between processing operations, a final test is usually performed to ensure that all detrimental discontinuities have been detected. In welds with a tendency toward delayed cracking, there may be a specified time delay between the completion of welding and the final test.

The test itself consists of three basic operations: (1) establish a suitable magnetic flux in the test object; (2) apply magnetic particles in a dry powder or a liquid suspension; and (3) examine the test object under suitable lighting conditions, interpreting and evaluating the test indications (as in Fig. 1).

FIGURE 1. Forging laps in piston rods.



Capabilities and Limitations

Magnetic particle testing can reveal surface discontinuities, including those too small or too tight to be seen with the unaided eye. Magnetic particle indications form on an object's surface above a discontinuity and show the location and approximate size of the discontinuity. Magnetic particle tests can also reveal discontinuities that are slightly below the surface, depending on their size.

There are limits on this ability to locate subsurface discontinuities. These limits are determined by the intensity of the applied field and by the discontinuity's depth, size, type and shape. In some cases, special techniques or equipment can improve the test's ability to detect subsurface discontinuities.

Magnetic particle testing is for ferromagnetic materials only: it cannot be used on nonmagnetic materials, including glass, ceramics, plastics or such common metals as aluminum, magnesium, copper and austenitic stainless steel alloys.

In addition, there are certain positional limitations: a magnetic field is directional and for best results must be perpendicular to the discontinuity. This generally requires magnetizing operations in different directions to detect discontinuities. Objects with large cross sections may require a very high current to generate a magnetic field adequate for magnetic particle tests. A final limitation is that a demagnetization procedure is usually required following the magnetic particle process.

Knowledge of limitations can be helpful to managers, supervisors and personnel outside nondestructive testing who require general information on the magnetic particle testing process. It may also be helpful for introductory studies by individuals already using magnetic particle testing or those preparing for advanced training in the technique.

PART 2. Magnetic Field Theory

Magnetic Domains

Materials that can be magnetized possess atoms that group into magnetically saturated regions called *magnetic domains*. These domains have a positive and negative polarity at opposite ends. In macroscopically unmagnetized material, the domains are randomly oriented, usually parallel with the crystalline axes of the material, resulting in zero net magnetization.

When the material is subjected to a magnetic field, the domains attempt to align themselves parallel with the external magnetic field. The material then acts as a magnet. Figure 2 illustrates the domain alignment in nonmagnetized and magnetized material.

Magnetic Poles

A magnet has the property of attracting ferromagnetic materials. The ability to attract (or repel) is not uniform over the surface of a magnet but is concentrated at localized areas called *poles*. In every magnet, there are two or more poles with opposite polarities. These poles are attracted to the Earth's magnetic poles and therefore are called *north* and *south poles*.

Figure 3 can be duplicated by placing a sheet of paper over a bar magnet and sprinkling iron particles on the paper. It shows the magnetic field leaving and entering the ends or poles of the magnet. This characteristic pattern illustrates the term *lines of force* used to describe a magnetic flux field. There are a number of important properties associated with lines of force.

1. They form continuous loops that are never broken but must complete themselves through some path.
2. They do not cross one another.
3. They are considered to have direction, leaving from the north pole and traveling through air to the south pole, where they reenter the magnet and return through the magnet to the north pole.
4. Their density decreases with increasing distance from the poles.
5. They seek the path of least magnetic resistance or reluctance in completing their loops.

When a bar magnet is broken into two or more pieces, new magnetic poles are formed. The opposing poles attract one another as shown in Fig. 4.

If the center piece in Fig. 4 is reversed so that similar poles are adjacent, the lines of force repel one magnet from the other. If one of the bars is small enough, the lines of force can cause it to rotate so that unlike poles are again adjacent. This illustrates the most basic rule of magnetism: unlike poles attract and like poles repel.

FIGURE 2. Orientation of magnetic domains: (a) in nonmagnetized material; (b) in magnetized material.

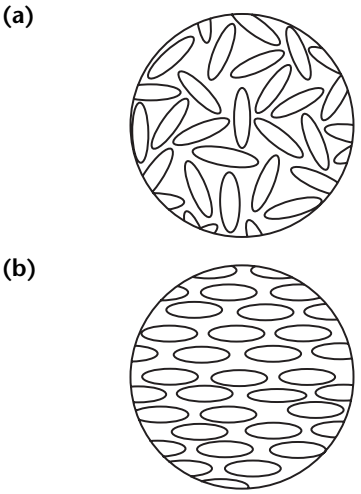
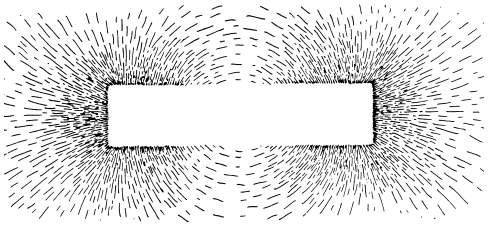


FIGURE 3. Magnetic field surrounding bar magnet.



Types of Magnetic Materials

All materials are affected to some degree by magnetic fields. Matter is made up of atoms with a positively charged nucleus surrounded by a field or cloud of negatively charged electrons. The electron field is in continual motion, spinning around the nucleus. When the material is subjected to a magnetic field, the electron orbits are distorted to some degree. The amount of this distortion (or the corresponding change in magnetic characteristics) when subjected to an external magnetic field provides a means of classifying materials into three main groups: diamagnetic, paramagnetic or ferromagnetic.

Diamagnetic Materials

The term *diamagnetic* refers to a substance whose magnetic permeability is slightly less than that of air. When a dimagnetic object is placed in an intense magnetic field, the induced magnetism is in a direction opposite to that of iron. Diamagnetic materials include mercury, gold, bismuth and zinc.

Paramagnetic Materials

Paramagnetic describes a substance whose permeability is slightly greater than that of air or unity. When such materials are placed in an intense magnetic field, there is a slight alignment of the electron spin in the direction of the magnetic flux flow. This alignment exists only as long as the paramagnetic material is in the external magnetic field.

Aluminum, platinum, copper and wood are paramagnetic materials

Ferromagnetic Materials

Ferromagnetic substances have a permeability that is much greater than that of air. When placed in an external magnetic field, the magnetic domains align parallel with the external field and remain aligned for some period of time after removal from the field. Ferromagnetism can only be explained via the domain theory. Paramagnetic and diamagnetic materials do not contain such domains.

This continued alignment after removal from the external field is called *retentivity* and can be an important property in some magnetic particle testing procedures.

Some examples of ferromagnetic materials are iron, cobalt, nickel and gadolinium.

Sources of Magnetism

Permanent Magnets

Permanent magnets are produced by heat treating specially formulated alloys in an intense magnetic field. During heat treatment, the magnetic domains become aligned and remain aligned after removal of the external field. Permanent magnets are essential to modern technology; their applications include magnetos, direct current motors, telephones, loud speakers and many electric instruments.

Common examples of permanent magnetic materials include alloys of aluminum, nickel and cobalt (alnico); copper, nickel and cobalt (cunico); copper, nickel and iron (cunife); and cobalt and molybdenum (comol). Supermagnet materials such as neodymium-iron-boron and samarium-cobalt are now common.

Magnetic Field of the Earth

The planet Earth is itself a huge magnet, with north and south poles slightly displaced from the Earth's axis. This displacement results in a slight deviation between geographic north and magnetic north.

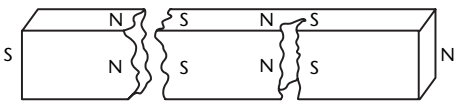
As a magnet, the Earth is surrounded by magnetic lines of force as shown in Fig. 5. These lines of force make up what is sometimes called the *earth field* and they can cause problems in both magnetizing and demagnetizing of ferromagnetic test objects. The earth field is weak, on the order of 0.03 mT (0.3 G).

Movement of ferromagnetic objects through the earth field can induce slight magnetization. This is a problem in aircraft where magnetized components can affect the compasses used in navigation. Similarly, demagnetizing can be difficult if certain objects, usually long shafts, are not oriented from east to west during the demagnetization process.

Mechanically Induced Magnetism

Cold working of some ferromagnetic materials, either by forming operations or during service, can magnetize the objects.

FIGURE 4. Broken bar magnet illustrating locations of newly formed magnetic poles.

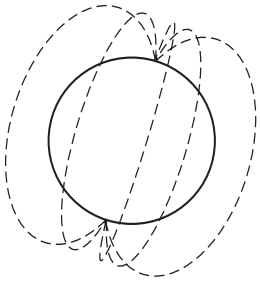


Legend
N = north
S = south

When mechanically induced magnetization occurs as a result of forming operations, it can be removed by subjecting the magnetized object to a routine demagnetization process.

It can be difficult to remove mechanically induced magnetization resulting from cold working. Disassembly is usually impractical and demagnetization must be accomplished using portable yokes or cable coils. The operation is complicated when other ferromagnetic components are near the magnetized object: the demagnetizing operation can magnetize adjacent objects and a sequence of demagnetizing operations must then be performed.

FIGURE 5. Magnetic field of Earth.



PART 3. Magnetic Flux and Flux Leakage

Circular Magnetic Fields

The most familiar type of magnet is the horseshoe shape shown in Fig. 6a. It contains both a north and south pole with the lines of magnetic flux leaving the north pole and traveling through air to reenter the magnet at the south pole. Ferromagnetic materials are only attracted and held at or between the poles of a horseshoe magnet.

If the ends of such a magnet are bent so that they are closer together (Fig. 6b), the poles still exist and the magnetic flux still leaves and reenters at the poles. In such a case, however, the lines of force are closer and more dense. The number of lines of flux per unit area is called *magnetic flux density* and is measured in tesla or gauss.

If the magnetic flux density is high enough, ferromagnetic particles are strongly attracted and can even bridge the physical gap between poles that are close enough together. The area where the flux lines leave the pole, travel through air and reenter the magnet is called a *magnetic flux leakage field*.

When the ends of a magnet are bent together and the poles are fused to form a ring (Fig. 6c), the magnet no longer attracts or holds ferromagnetic materials (there are no magnetic poles and no flux leakage field). The magnetic flux lines still exist but they are completely contained within the magnet. In this condition, the magnet is said to contain a circular magnetic field or to be *circularly magnetized*.

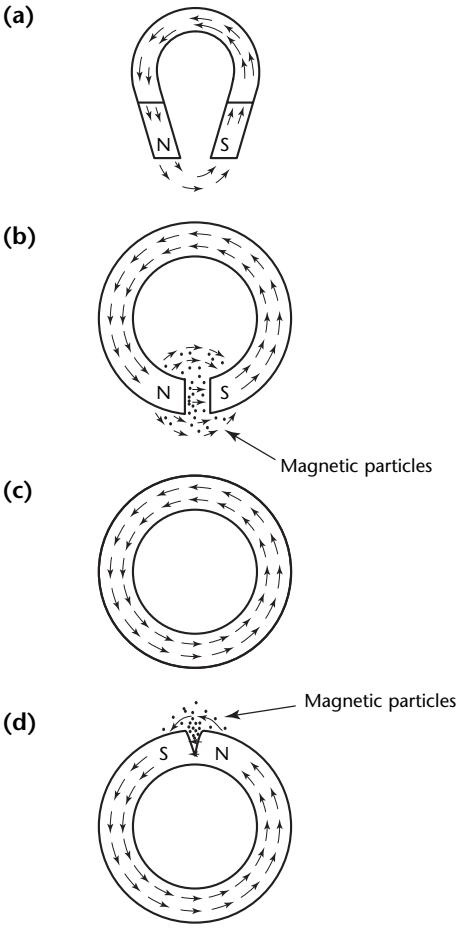
If a crack crosses the magnetic flux lines in a circularly magnetized object, north and south poles are immediately created on either side of the discontinuity. This forces a portion of the magnetic flux into the surrounding air, creating a flux leakage field that attracts magnetic particles (Fig. 6d) and forms a crack indication.

Longitudinal Magnetization

If a horseshoe magnet is straightened, a bar magnet is formed with north and south poles (Fig. 7a). Magnetic flux flows through the magnet and exits or enters at the poles. Magnetic poles can be thought of as occurring wherever field lines enter and leave a magnetized object. Ferromagnetic materials are attracted only to the poles and such an object is said to have a longitudinal field or to be *longitudinally magnetized*.

If these magnetic flux lines are interrupted by a discontinuity, additional north and south poles are formed on either side of the interruption (Fig. 7b).

FIGURE 6. Horseshoe magnet illustrating fundamental properties of magnetism: (a) direction of magnetic flux; (b) magnetic flux in air around poles (moving poles close together raises magnetic flux density); (c) fusing poles, forming a circularly magnetized object; (d) discontinuity in circularly magnetized object and its resulting flux leakage field.



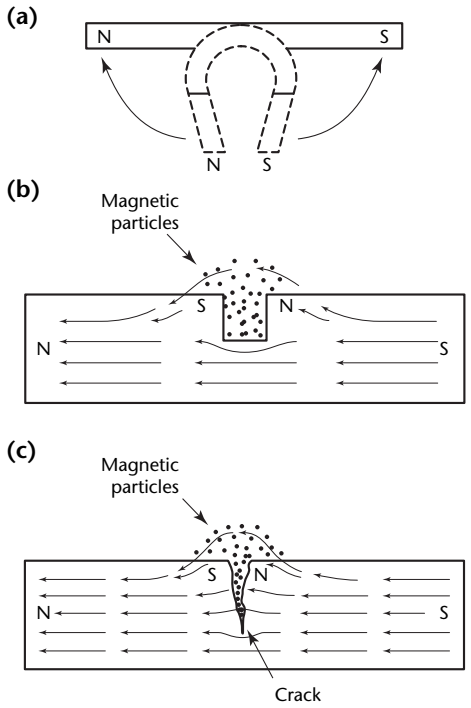
Such secondary poles and their associated flux leakage fields can attract magnetic particles. Even if the discontinuity is a very narrow crack, it will still create magnetic poles (Fig. 7c) that hold magnetic materials (the magnetic flux leakage field is still finite).

Magnetic Field Intensity

The intensity of a flux leakage field from a discontinuity depends on several factors: (1) the number of magnetic flux lines, (2) the depth of the discontinuity and (3) the width of the discontinuity's air gap at the surface (the distance between the magnetic poles).

The intensity and curvature of the leakage field determines the number of magnetic particles that can be attracted to form a test indication. The greater the leakage field intensity, the denser the indication, so long as the magnetic flux leakage field is highly curved.

FIGURE 7. Bar magnet illustrating longitudinal magnetization: (a) horseshoe magnet straightened into bar magnet with north and south poles; (b) bar magnet containing machined slot and corresponding flux leakage field; (c) crack in longitudinally magnetized object, producing poles that attract and hold magnetic particles.



Subsurface Discontinuities

A slot such as a keyway on the backside of an object creates new magnetic poles that distort the internal flux flow. If the slot is close enough to the surface, some magnetic flux lines may be forced to exit and reenter the magnetized object at the surface. The resulting leakage field can form a magnetic particle test indication.

Size and intensity of the indication depends on: (1) the proximity of the slot to the top surface; (2) the size and orientation of the slot; and (3) the intensity and distribution of the magnetic flux field. A similar effect occurs if the discontinuity is completely internal to the object. Figure 8 is an illustration of a keyway on the far side of a bar and Fig. 9 illustrates a midwall discontinuity.

Effect of Discontinuity Orientation

The orientation of a discontinuity in a magnetized object is a major factor in the intensity of the magnetic flux leakage field that is formed. This applies to both surface and internal discontinuities. The most intense magnetic flux leakage field is formed when the discontinuity is perpendicular to the magnetic flux flow. If the discontinuity is not perpendicular, the intensity of the magnetic flux leakage field is reduced and disappears entirely when the discontinuity is parallel to the magnetic flux flow.

FIGURE 8. Slot or keyway on reverse side of magnetized bar.

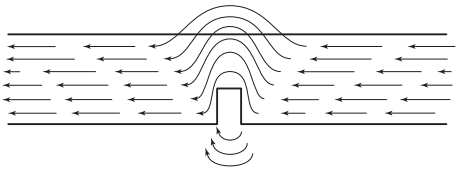


FIGURE 9. Internal or midwall discontinuity in magnetized test object. There may or may not be magnetic flux leakage, depending on value of flux in object.

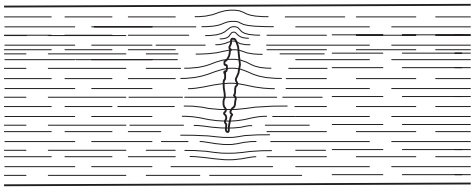
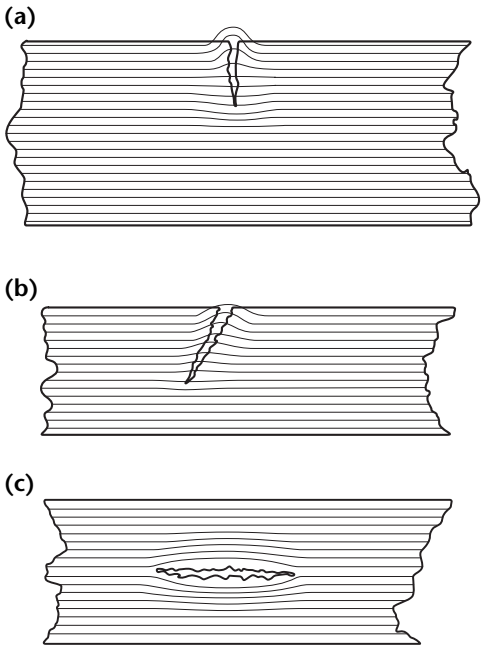


Figure 10 illustrates the effect of discontinuity orientation on the intensity of the magnetic flux leakage field.

Formation of Indications

When magnetic particles collect at a flux leakage site, they produce an indication visible to the unaided eye under the proper lighting conditions. Tighter magnetic flux leakage fields create the ideal conditions for particle attraction, the force on an individual particle being given by the product of terms involving the particle shape, the local value of the field intensity and a term involving the local curvature of the magnetic flux leakage field. Particles then tend to align end to end in this field. The stronger the ability to hold particles, the larger the indication.

FIGURE 10. Flux leakage fields from discontinuities with different orientations: (a) perpendicular to magnetic flux; (b) at 45 degree angle to magnetic flux; (c) parallel to magnetic flux.



PART 4. Electrically Induced Magnetism

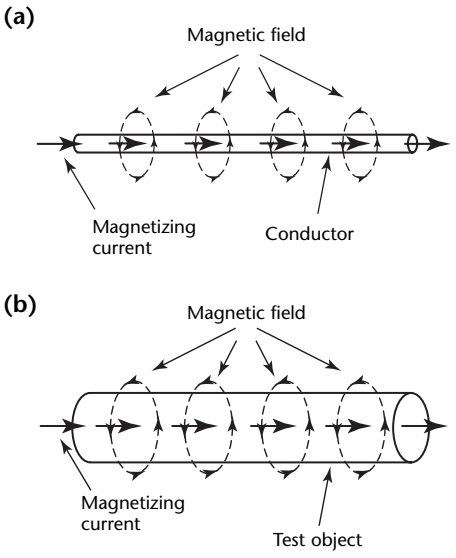
Circular Magnetization

When an electric current flows through a conductor such as a copper bar or wire, a magnetic field is formed around the conductor (Fig. 11a). The direction of the magnetic lines of force is always 90 degrees from the direction of current flow. When the conductor has a uniform shape, the flux density or number of lines of force per unit area is uniform along the length of the conductor and uniformly decreases as the distance from the conductor increases.

Because a ferromagnetized object is a large conductor, electric current flowing through the object forms a circular magnetic field. This magnetic field is known as *circumferential magnetization* because the magnetic flux lines form complete loops in the object (Fig. 11b).

A characteristic of circumferential magnetic fields is that the magnetic flux lines form complete loops without magnetic poles. Because magnetic particles are only attracted to and held where flux lines exit and enter the object surface, indications do not occur unless a discontinuity crosses the flux lines.

FIGURE 11. Magnetic field generated: (a) around conductor carrying electric current; (b) around ferromagnetic test object used as conductor.



Inducing Circular Magnetization in a Test Object

Figure 12 illustrates a method for inducing a circular field using a magnetic particle testing unit. The test object is clamped between the contact plates so that electric current passes through it.

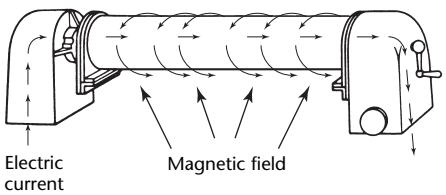
When tubes are tested by passing a current through them, the magnetic flux is zero at the inner surface or axis and is its maximum at the outside surface. The inside surface is often equally important when testing for discontinuities. Because a magnetic field surrounds a conductor, it is possible to induce a satisfactory field in the tube by inserting a copper bar or some other conductor through the tube and passing the current through the bar.

This method is called *internal conductor magnetization*. Figure 13 indicates a method employed for circular field inspection of short parts. For longer parts such as steel tubes, an insulated metal rod is run along the bore of the tube, exciting it with a high current. The rod should not touch the inside of the tube and the tube should be placed on wooden planks to isolate it from the ground. These measures should eliminate arc burns from magnetizing current grounding.

Magnetic Field Direction

The magnetic lines of force are always at right angles to the direction of the magnetizing current. One way to visualize the direction of the magnetic flux is to imagine the conductor held in your right hand with the thumb extended in the direction of the electric current flow. Your curved fingers then point in the direction of the magnetic flux flow. This is known as the *right hand rule* (Fig. 14).

FIGURE 12. Inducing circumferential magnetic field in object used as conductor.



Longitudinal Magnetization

Electric current can induce longitudinal fields in ferromagnetic materials. The magnetic field around a conductor is oriented lengthwise direction by forming the conductor into a coil (Fig. 15). The right hand rule shows that the magnetic field at any point within the coil is in a lengthwise direction.

When a ferromagnetic object is placed inside a coil carrying an electric current (Fig. 16), the magnetic flux lines concentrate themselves in a longitudinal direction. An object that has been longitudinally magnetized is characterized by poles close to each end where the field lines leave and enter the test object to form continuous loops around the associated current.

When a longitudinally magnetized object contains a transverse discontinuity, a leakage field is produced that attracts magnetic particles and forms an indication. Figure 17 illustrates a typical coil found on magnetic particle test systems used to locate transverse discontinuities.

FIGURE 13. Inducing circumferential magnetic field using internal conductor: (a) for tube with inside and outside surface discontinuities; (b) for multiple ring shapes with cracking on inside and outside surfaces.

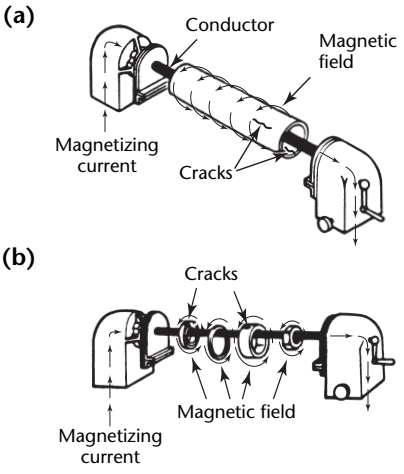
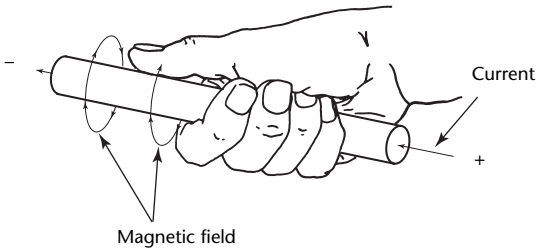


FIGURE 14. Right hand rule indicates direction of magnetic flux flow based on direction of magnetizing current.



Multidirectional Magnetization

When testing for discontinuities in different directions, it is standard practice to perform two tests, one with circular magnetization and the one with longitudinal. Two or more fields in different directions can be imposed on an object in rapid succession.

When this is done, magnetic particle indications are formed when discontinuities are favorably oriented to the direction of any field. Such indications persist as long as the rapid alternations of current continue.

FIGURE 15. Formation of longitudinal magnetic field using coiled conductor.

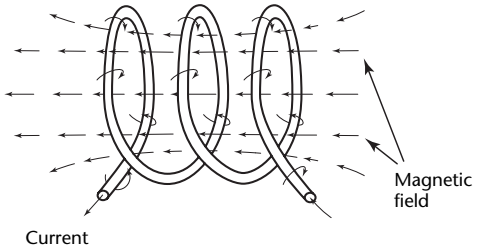


FIGURE 16. Test object containing longitudinal magnetic field induced by coil.

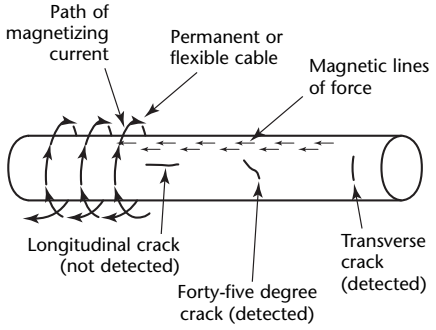
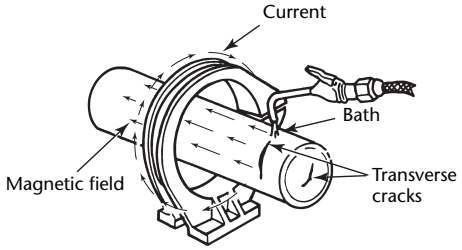


FIGURE 17. Formation of transverse discontinuity indication during longitudinal magnetization.



PART 5. Magnetic Particle Test Systems

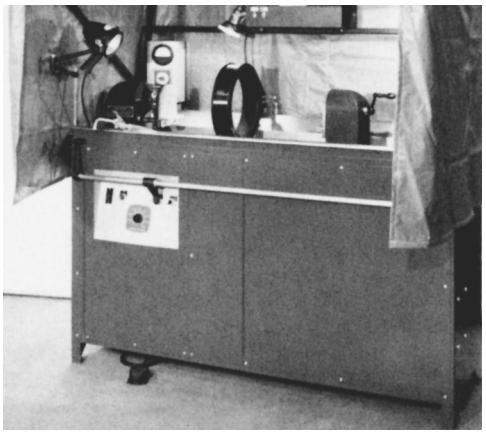
Stationary Magnetic Particle Test Systems

Wet method horizontal magnetic particle test systems typically consist of (1) a high current, low voltage magnetizing source; (2) head stock and tail stock for holding test objects and providing electrical contact for circumferential magnetization; (3) a movable coil for longitudinal magnetization; and (4) a particle suspension tank with an agitation system.

The basic components, along with magnetizing control indicators and ampere meters, are enclosed within a tabletop structural frame. Systems are available in a large number of sizes from a 25 mm (1 in.) contact plate opening up to systems that are 6 m (20 ft) long. The systems provide alternating current, direct current or a combination of the two, with maximum magnetizing current output from 1 to 10 kA. Figure 18 shows a typical stationary or wet horizontal unit.

Stationary magnetic particle systems include structures designed to be ergonomically healthful for the user. Control functions are positioned conveniently for the human body. Instrumentation includes liquid crystal displays for digital readouts of amperes achieved and smart knobs for fine tuning of settings. Magnetic particle stationary systems are designed for rugged durability and require practice to operate efficiently.

FIGURE 18. Typical wet horizontal magnetic particle test system.



A common cause of missed discontinuities is the misuse of the system parameters. The magnetic particle system requires an array of process controls and maintenance. An organization using a magnetic particle system should incorporate an intensive maintenance plan with a demanding training, qualification and certification program for individuals using the magnetic particle system. The maintenance plan should include daily process validation checks.

Power Packs

Power packs are the electrical sources needed to produce high amperage, low voltage magnetizing current. They are used to magnetize test objects such as castings and forgings that are too large to be placed in a stationary testing unit. The size and weight of power packs prevent moving them and test objects are accordingly transported to the test site. The rating or current output of commercial power packs varies widely but is typically from 6 to 20 kA of magnetizing current.

The current is applied by cable wraps, formed coils, clamps and prods. Most power pack units incorporate an adjustable current control, one or two ammeters and an automatic shot duration timer.

Mobile and Portable Testing Units

There are many applications where it is not possible to bring the test object to the magnetic particle system. Mobile units are one type of equipment that can be transported to the test site and still provide relatively high magnetizing currents. Traditional mobile units may be considered small versions of the power pack systems. Some mobile units have a magnetizing current output of 6 kA but most are limited by size considerations to between 3 and 4 kA. Transportability is also improved by restricting the types of magnetizing current to alternating current and half-wave direct current. Magnetizing current is applied to the test object by cable wraps, formed coils, prods and clamps. Oil field portable magnetizing

units can reach 15 kA by capacitor discharge through internal conductors or cable wraps.

The term *portable equipment* refers to compact, lightweight units that can be hand carried to the test site. Some portable units are mounted on wheeled carts to facilitate portability. Like stationary and mobile equipment, portable units come in a variety of sizes, shapes, weights and amperage outputs. The most common method of applying current with a portable unit is with prods or clamps. However, cable wraps and formed coils are also used in many applications. Reduced weight and size are achieved by omitting the step down transformer needed for demagnetization.

Prods and Yokes

Prods are magnetization accessories that may be used with stationary, power pack, mobile and portable units. They typically consist of a pair of copper bars 12 to 20 mm (0.5 to 0.75 in.) in diameter with handles and connecting cables. One of the prod handles has a trigger to remotely activate the magnetizing current from the unit's mainframe. Prods set up a circular magnetic field that diminishes in intensity as the distance between prods increases (Fig. 19). Prods are avoided with components that can be damaged by arcing.

Yokes are often cable connected to a mobile or portable unit that provides the magnetizing current. A yoke designed with a self-contained magnetizing source is often called a *hand probe*. Hand probes contain small transformers that generate low voltage and high current. Yokes usually contain a magnetizing coil with a core of laminated transformer iron. Attached to the core are legs that may either be fixed or articulated. When magnetizing current is applied to the coil, a longitudinal magnetic field is created in the core and transmitted to the legs. When coupled to a test object, a longitudinal magnetic field is generated between the poles as shown in Fig. 20.

Yokes are often specified by their lifting ability or the surface field they create midway between their poles, as measured with a tesla meter.

FIGURE 19. Circular magnetic field generated around magnetizing prods.

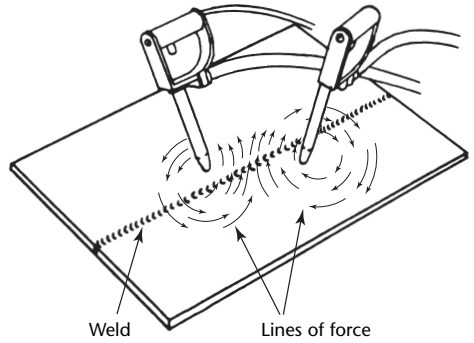
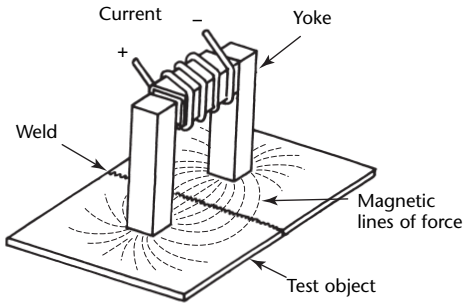


FIGURE 20. Longitudinal magnetic field generated by yoke.



PART 6. Ferromagnetic Material Characteristics

Magnetic Flux and Units of Measure

A magnetic field is made up of flux lines within and surrounding a magnetized object or a conductor carrying an electric current. The term *magnetic flux* is used when referring to all of the lines of flux in a given area. Flux per unit area is called *magnetic flux density* (the number of lines of flux passing transversely through a unit area). Flux density in a magnetized object will decrease with distance. Flux density is greatest at the poles.

There can be some confusion about the units of measure used to define these magnetic quantities. The unit of magnetic flux was originally called a *maxwell* with one maxwell being one line of flux. The unit of flux density was the *gauss* with one gauss equal to one maxwell per square centimeter. In 1930, the International Electrotechnical Commission redefined and renamed the gauss as an *oersted*, or the intensity of a magnetic field in which a unit magnetic pole experiences a force of one dyne.[3]

In 1960, the International Organization for Standardization released ISO 1000: *The International System of Units (SI)*. This document standardizes the metric units for magnetic flux. Flux intensity is measured using the weber (Wb) with one weber equal to 10^8 lines of flux. The flux density unit is the *tesla* (T) or one weber per square meter ($Wb \cdot m^{-2}$); 1 $Wb \cdot m^{-2}$ = 1 T = 10 000 gauss (10 kG).

Magnetic Hysteresis

All ferromagnetic materials have certain magnetic properties specific to that material. Most of these properties are described by a magnetic hysteresis curve. The data for the hysteresis curve are collected by placing a bar of ferromagnetic material in a coil and applying an alternating current. By increasing the magnetizing field intensity H in small increments and measuring the flux density B at each increment, the relationship between magnetic field intensity and flux density can be plotted.

The relationship between magnetic field intensity and flux density is not linear for ferromagnetic materials. A specific change in H may produce a smaller or larger change in B as shown in Fig. 21, the initial curve for an unmagnetized piece of steel. Starting at point O (zero magnetic field intensity and zero magnetic flux) and increasing H in small increments, the flux density in the material increases quite rapidly at first, then gradually slows until point P_1 is reached. At point P_1, the material becomes magnetically saturated. Beyond the *saturation point*, increases in magnetic field intensity do not increase the flux density in the material. In diagrams of full hysteresis loops, the curve OP_1 is often drawn as a dashed line because it occurs only during the initial magnetization of an unmagnetized material. It is referred to as the *virgin curve* of the material (Fig. 21a).

When the magnetic field intensity is reduced to zero (B_r in Fig. 21b), the flux density slowly decreases. It lags the field intensity and does not reach zero. The amount of flux density remaining in the material (line B_1O) is called *residual magnetism* or *remanence*. The ability of ferromagnetic materials to retain a certain amount of magnetism is called *retentivity*.

Removal of residual magnetism requires the application of a magnetic field intensity in an opposite or negative direction, of force equal or greater than used to saturate the test object (Fig. 21c). When the magnetic field intensity is first reversed and only a small amount is applied, the flux density slowly decreases. As additional reverse field intensity is applied, the rate of reduction in flux density (line $-H_cO$) increases until it is almost a straight line (point $-H_c$) where B equals zero.

The amount of magnetic field intensity necessary to reduce the flux density to zero is called *coercive force*. Coercive force is a factor in demagnetization and is also very important in eddy current testing of ferromagnetic materials.

As the reversed magnetic field intensity is increased beyond point $-H_c$, the magnetic flux changes its polarity and initially increases quite rapidly. It then gradually slows until point P_2 is reached (Fig. 21). This is the reverse polarity saturation point and additional magnetic field intensity will not produce an increase in flux density.

When the reversed magnetic field intensity is reduced to zero (point $-B_r$ in Fig. 21), the flux density again lags the magnetic field intensity, leaving residual magnetism in the material (line $-B_rO$). The flux densities of the residual magnetism from the straight and reversed polarities are equal (line B_1O is equal to line B_1O).

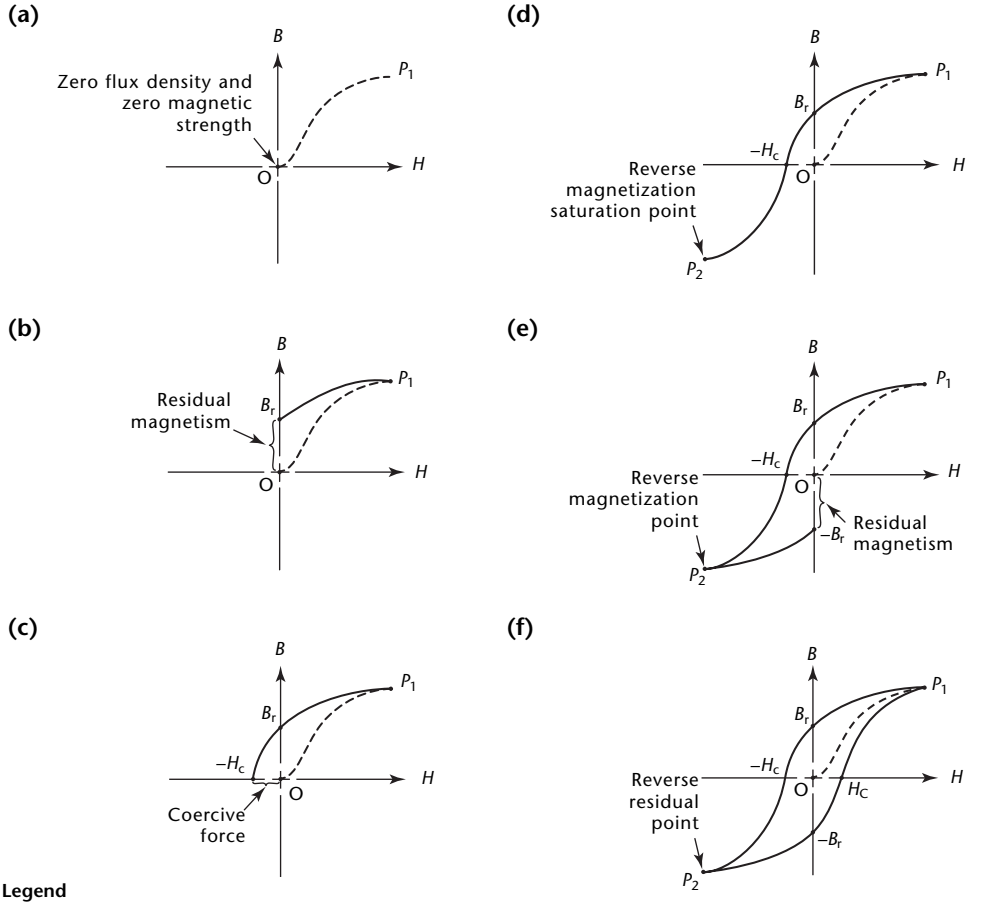
Removal of the reversed polarity residual magnetism requires application of magnetic field intensity in the original direction. Flux density drops to zero at point H_c in Fig. 21 with the application of coercive force H_cO. Continuing to increase the field intensity results in the magnetic polarity changing back to its original direction. This completes the hysteresis loop (note that the lower curve is a mirror image of the upper curve).

The hysteresis cycle repeats in this loop until the level of demagnetization is acceptable. An initial cycle illustrates the physical characteristics of permeability.

Magnetic Domains

When saturation is achieved, the magnetic domains are all aligned. When the magnetizing force is removed and the ferromagnetic component is at its remanent field state, some of the domains stay aligned while some return to random positioning. When coercive force is applied and the remanent field is at B (Fig. 21b) and the magnetizing force is at negative, the oriented domains rotate 90 degrees from initial orientation. When negative saturation is accomplished, the magnetic domains are 180 degrees out of original alignment. This effect continues as long as demagnetization continues using a reversing polarity.

FIGURE 21. Hysteresis data for unmagnetized steel: (a) virgin curve of hysteresis loop; (b) hysteresis loop showing residual magnetism; (c) hysteresis loop showing coercive force; (d) hysteresis loop showing reverse saturation point; (e) hysteresis loop showing reverse residual magnetism; (f) complete hysteresis loop.



Legend

B = magnetic flux density
H = magnetic field intensity
O = origin before magnetization
P = saturation point

Magnetic Permeability

One of the most important properties of magnetic materials is *permeability.* Permeability can be thought of as the ease with which materials can be magnetized. More specifically, permeability is the ratio of the flux density to the magnetic field intensity (*B* divided by *H*). Figure 22a is the virgin curve of a high permeability material and Fig. 22b is the curve of a low permeability material.

The reciprocal of permeability is *reluctance,* defined as the resistance of a material to changes in magnetic field intensity.

Magnetic properties and hysteresis loops vary widely between materials and material conditions. They are affected by temperature, chemical composition, microstructure and grain size. Figure 23a is a hysteresis loop for hardened steel and the loop is typical of a material with low permeability, high reluctance, high retentivity and high residual magnetism that requires high coercive force for removal. Figure 23b is the hysteresis loop for an annealed low carbon steel. It is typical of a material with high permeability, low reluctance, low retentivity and low residual magnetism that requires a low coercive force for removal.

FIGURE 22. Magnetic permeability curves: (a) high permeability virgin curve; (b) low permeability virgin curve.

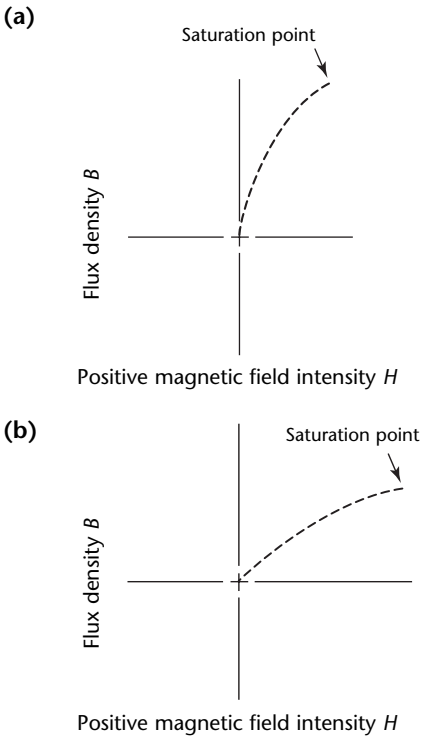
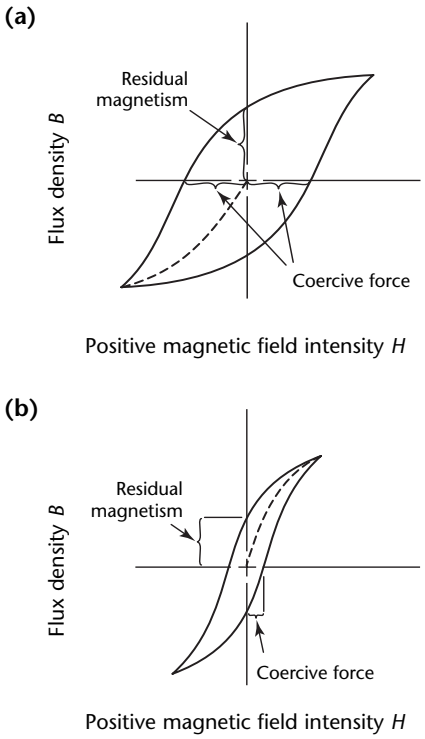


FIGURE 23. Hysteresis loops: (a) hardened steel hysteresis loop; (b) annealed low carbon steel hysteresis loop.



PART 7. Types of Magnetizing Current

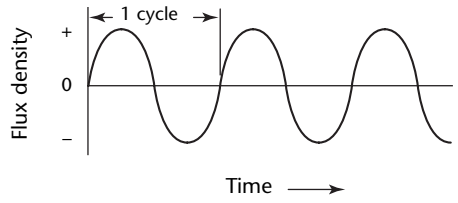
In the early days of magnetic particle testing, it was believed that the best current for magnetization was direct current from storage batteries. As knowledge of the magnetic particle process expanded and electrical circuitry continued to advance, many types of magnetizing currents became available: alternating current, half-wave direct current and full-wave direct current. The terms *half-wave rectified direct current* and *full-wave rectified direct current* are used for alternating current rectified to produce half-wave and full-wave direct current.

Alternating Current

Alternating current is useful in many applications because it is commercially available in voltages ranging from 120 to 440 V. Electrical circuitry to produce alternating magnetizing current is simple and relatively inexpensive because it only requires transforming commercial power into low voltage, high amperage magnetizing current.

In the United States and some other countries, alternating current alternates sixty times in a second. Many other countries have standardized fifty alternations per second. The alternations are called *cycles*. One hertz (Hz) equals one cycle per second and 60 Hz is sixty cycles per second. Figure 24 shows the waveform of alternating current. In one cycle, the current flows from zero to a maximum positive value and then drops back to zero. At zero, it reverses direction and goes to a maximum negative peak and returns to zero. The curve is symmetrical with the positive and negative lobes being mirror images.

FIGURE 24. Waveform of alternating current.



There are three primary advantages to using alternating current as a magnetizing source. First, the current reversal causes an inductive effect that concentrates the magnetizing flux at the object surface (called the *skin effect*) and provides enhanced indications of surface discontinuities. This is especially important for inspection of irregularly shaped components, such as crankshafts. Magnetic fields produced by alternating current are also much easier to remove during demagnetization. A third advantage is that the pulsing effect of the flux caused by the current reversals agitates the particles applied to the test object surface. By increasing particle mobility, this agitation allows more particles to collect at flux leakage points and so increases the size and visibility of discontinuity indications.

Concentration of the flux at the test object surface can be a disadvantage also because most subsurface discontinuities are not detected. Another disadvantage is that some specifications do not allow alternating current on plated components when the coating is thicker than 0.08 mm (0.003 in.). It is hard to determine when the flux in a test object is at peak; it depends on when in the magnetizing cycle the current is turned off.

Alternating current is more effective than direct current on objects with thick nonmetallic coatings.

Half-Wave Direct Current

When single-phase alternating current is passed through a simple rectifier, the reversed flow of current is blocked or clipped. This produces a series of current pulses that start at zero, reach a maximum point, drop back to zero and then pause until the next positive cycle begins. The result is a varying current that flows only in one direction. Figure 25 shows the waveform for half-wave direct current.

Half-wave direct current has penetrating power comparable to single-phase full-wave direct current. Half-wave current has a flux density of zero at the center of a test object and the density increases until it reaches a maximum at the object surface. The pulsing effect of the rectified wave produces maximum mobility for the

magnetic particles; dry method tests are enhanced by this effect. Another distinct advantage of half-wave direct current is the simplicity of its electrical components. It can be easily combined with portable and mobile alternating current equipment for weld, construction and casting tests.

One of the disadvantages of half-wave magnetization is the problem in demagnetization: the current does not reverse so it cannot be used for demagnetizing. Alternating current can be used to remove some residual magnetism but the skin effect of alternating current and the deeper penetration of half-wave direct current cause incomplete demagnetization.

Full-Wave Direct Current

Electrical circuits can rectify and invert so that so that the number of positive pulses is doubled. Figure 26 shows the waveform of single-phase full-wave rectified alternating current. The resulting current is called *single-phase full-wave direct current.*

Single-phase full-wave direct current has essentially the same penetrating ability as three-phase full-wave direct current. The current fluctuation causes a skin effect that is not significant. It is also possible to incorporate switching devices in the circuit that reverse the current flow. This permits built-in reversing direct current demagnetization. Because of its simpler components, the initial cost of single-phase full-wave direct current equipment is much less than that of three-phase full-wave equipment.

One disadvantage of single-phase units is the input power requirement. Single phase equipment requires 1.73 times more input current than three-phase units. This becomes very significant at higher magnetizing currents where input values can exceed 600 A.

FIGURE 25. Half-wave direct current waveform.

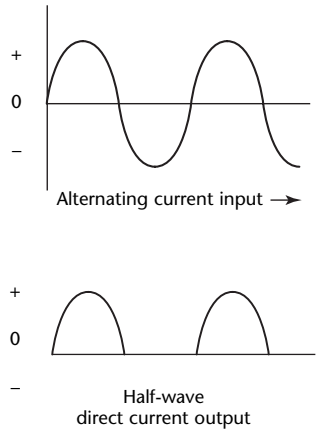
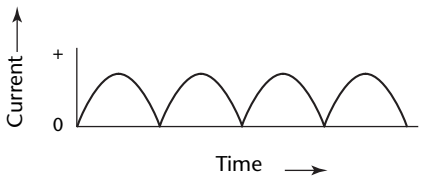


FIGURE 26. Single-phase full-wave direct current waveform.



Three-Phase Full-Wave Direct Current

Commercial electric power, especially at 220 and 440 V, is provided as three-phase alternating current with each phase providing part of the total current. Figure 27 shows the time relation of three-phase alternating current. Three-phase full-wave magnetic particle equipment rectifies all three alternating current phases and inverts the negative flow to a positive direction, producing a nearly flat line direct current magnetizing current. Figure 28 shows the waveform of three-phase full-wave direct current.

Three-phase full-wave direct current has all of the advantages of single-phase full-wave direct current plus some additional benefits. The current draw on the power line is spread over three phases, reducing the demand by nearly half. The demand on the line is also balanced, with

FIGURE 27. Waveform of three-phase alternating current.

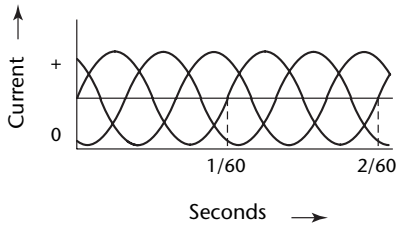
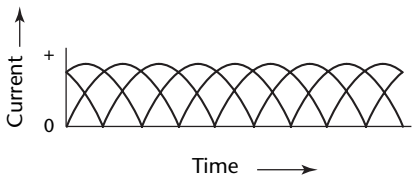


FIGURE 28. Three-phase full-wave direct current waveform.



each leg providing part of the current (single-phase pulls all of the current from one leg, resulting in an unbalanced line). Many power companies charge a higher rate to customers with unbalanced, high current requirements. The three-phase design also permits incorporating a *quick break* circuit that improves the formation of indications at the ends of longitudinally magnetized test objects.

Demagnetization

Objects that have been magnetic particle tested retain some magnetism. The amount of residual magnetism depends on the material and its condition. Low carbon steel in the annealed condition retains little or no magnetism while hardened alloy steels retain intense magnetic fields for long periods of time.

A metal may be demagnetized either by heating it to the curie temperature or by reverse electromagnetization. Reverse electromagnetization subjects a magnetized object to a magnetic force that is continually reversing its direction and gradually decreasing in intensity.

A common method of demagnetizing small objects is to pass them through a coil carrying alternating current or to place the object in the coil and gradually reduce the current to zero. The principle of demagnetizing with direct current is the same with alternating current. The magnetic field intensity or current must reverse serially and reduce gradually.

Demagnetization is discussed in detail elsewhere in this volume.

PART 8. Media and Processes in Magnetic Particle Testing

The formation of reliably visible discontinuity indications is essential to the magnetic particle testing method. An important factor in the formation and visibility of indications is the use of the proper magnetic particles to obtain the best indication from a particular discontinuity under the given conditions. Selection of the *wrong* particles can result in (1) failure to form indications, (2) the formation of indications too faint for detection or (3) a distorted pattern over the discontinuity and the resulting misinterpretations.

In magnetic particle tests, there are two classes of media that define the method: dry and wet. Dry method particles are applied without the addition of a carrier vehicle. Wet method particles are suspended in a liquid vehicle. The liquid vehicle may be water or a light petroleum distillate similar to kerosene.

Magnetic particles are also categorized by the type of pigment bonded to them to improve visibility. Visible particles are colored to produce a good contrast with the test surface under white or visible light. Fluorescent particles are coated with pigments that fluoresce when exposed to ultraviolet light. A third pigment category includes particles coated with a material that is both color contrasting under visible light and fluorescent when exposed to ultraviolet light.

Magnetic Particle Properties

The media used in magnetic particle testing consist of finely divided iron powder ferromagnetic oxides. The particles can be irregularly shaped, spheroidal, flakes or rod shaped (elongated). The properties of different materials, shapes and types vary widely and some are discussed below.

The level of particles in suspension should be maintained consistently, from 0.1 to 0.4 mL in a 100 mL settling test. For consistent results, the suspension vehicle must be changed frequently because of foreign material contamination.

Magnetic Permeability

Magnetic particles should have the highest possible permeability and the lowest possible retentivity. This allows their attraction only to low level leakage fields emanating from discontinuities. As the particles become magnetized, they then attract additional particles to bridge and outline the discontinuity, thus forming a visible indication.

Magnetic permeability alone does not produce a highly sensitive particle material. For example, iron based dry powders have a higher permeability than the oxides used in wet method suspensions. Yet a typical dry powder does not produce indications of extremely fine surface fatigue cracks that are easily detected with wet method suspensions. High permeability is desirable but is no more important than size, shape or the other critical properties. All of these characteristics are interrelated and must occur in appropriate ranges in order for high permeability to be of value.

Magnetic Retentivity

Materials used in dry method powders and wet method suspensions should have a low coercive force and low retentivity. If these properties were high in dry powders, the particles would become magnetized during manufacture or during their first use, reducing contrast and masking relevant discontinuity indications.

When wet method particles have a high coercive force, they are also easily magnetized, producing the same high level of background. Magnetized particles are attracted to any ferromagnetic material in the testing system (bath tank, plumbing system or rails) and this causes an extensive loss of particles from the suspension. Particle depletion creates process control problems and requires frequent additions of new particles to the bath.

Another disadvantage of magnetically retentive wet method particles is their tendency to clump, forming large clusters on the test object surface if warmth makes the pigment sticky.

Strongly magnetized particles form clusters and adhere to the test object surface as soon as bath agitation stops. Particles with low magnetic field intensity cluster more slowly while indications are

forming. The leakage field at the discontinuity draws the particles toward it and the clusters are constantly enlarging due to agglomeration. At the same time, the clusters sweep up nearby fine particles as they move toward the discontinuity.

Effects of Particle Size

The size and shape of magnetic particles play an important role in how they behave when subjected to a weak magnetic field such as that from a discontinuity. Large, heavy particles are not likely to be attracted and held by a weak leakage field as they move over the object surface. However, very small particles may adhere to the surface where there is no leakage field and thus form an objectionable background.

Dry Powder Particles

Within limits, sensitivity to very fine discontinuities typically increases as particle size decreases. Extremely small particles, on the order of a few micrometers, behave like dust. They settle and adhere to the object surface even though it may be very smooth. Extremely fine particles are very sensitive to low level leakage fields but are not desirable for production tests because of intense backgrounds that obscure or mask relevant indications.

Large particles are not as sensitive to fine discontinuities. However, in applications where it is desired to detect large discontinuities, powders containing only large particles may be used.

Many commercial dry powders are a carefully controlled mixture of particles containing a range of sizes. The smaller particles provide sensitivity and mobility while larger particles serve two purposes. They assist in building up indications at larger discontinuities and help reduce background by a sort of sweeping action, brushing finer particles from the test object surface. A balanced mixture containing a range of sizes provides sensitivity for both fine and large discontinuities, without disruptive backgrounds.

Wet Method Visible Particles

Particles used in a liquid suspension are usually much smaller than those used in dry powders. The smaller the discontinuity, the smaller the particles should be.

Larger particles are difficult to hold in suspension. Even 20 µm (0.0008 in.) particles tend to settle out of suspension rapidly and are stranded as the suspension drains off the test object. Stranded particles may line up in drainage lines that could be confused with discontinuity indications.

Wet Method Fluorescent Particles

Particles treated with a fluorescent pigment or some of the visible pigments differ in size and behavior from black or red (uncoated) visible particles. Fluorescent particles must be compounded and structured to prevent separation of the pigment and magnetic material during use. A mixture of loose pigment and unpigmented magnetic material produces a dense background and dim indications. In addition, the unpigmented magnetic particles may be attracted and held at leakage fields but their lack of contrasting color makes them difficult to see.

Producing fluorescent magnetic particles involves bonding pigment around each magnetic particle. The bonding must resist the solvent action of petroleum vehicles and surfactants and the abrasive action occurring in pumping and agitation systems. Some manufacturers encapsulate the bonded dye particle in a layer of resin. As a result of their processing, fluorescent particles have a definite size range that is maintained throughout the suspension's service cycle.

Effect of Particle Shape

Magnetic particles are available in a variety of shapes: spheres, elongated needles (or rods) and flakes. The shape of the particles affects how they form indications. When exposed to an external magnetic field, all particles tend to align along the flux lines. This tendency is much stronger with elongated particles such as the needle or rod shapes. Elongated shapes develop internal north and south poles more reliably than spheroid or globe shaped particles, because they have a smaller internal demagnetization field.

Because of the attraction of opposite poles, the north and south poles of these small magnets arrange the particles into strings. The result is the formation of more intense patterns in weaker flux leakage fields, as these magnetically formed strings of particles bridge the discontinuity. The superior effectiveness of elongated shapes over globular shapes is particularly noticeable in the detection of wide, shallow discontinuities and subsurface discontinuities. The leakage fields at such discontinuities are weaker and more diffuse. The formation of particle strings based on internal poles makes more intense indications.

Dry Powder Shapes

The superiority of elongated particles in diffuse magnetic fields holds true for dry powder testing. However, there is another effect that must be considered. Dry powders are often applied to object surfaces by releasing them out of mechanical or manual blowers. It is essential that the particles be dispersed as a uniform cloud that settles evenly over the object surface. Magnetic powder containing only elongated particles tends to become mechanically linked in its container and is then expelled in uneven clumps.

Wet Method Particle Shapes

The performance of particles suspended in a liquid vehicle is not as shape dependent as that of dry particles. The suspending liquid is much denser and more viscous than air; the movement of particles through the liquid is slowed so that they accumulate more reliably at discontinuities.

Because of this slower movement, wet method particles form minute elongated aggregates. Even unfavorable shapes align magnetically into elongated aggregates under the influence of local, low level leakage fields. In suspension, the particles are kept dispersed by mechanical agitation until they flow over the surface of the magnetized object. There is no need to add certain shapes to improve the dispersion of the particles.

Visibility and Contrast

Visibility and contrast are properties that must be considered when selecting a magnetic particle material for a specific testing application. Magnetic properties, size and shape may all be favorable for producing the best indication, but if an indication is formed and the inspector cannot see it, then the test procedure has failed.

Visibility and contrast are enhanced by choosing a particle color that is easy to see against the test object surface. The natural color of metallic powders is silver gray. The colors of iron oxides commonly used in wet method powders are black or red. Manufacturers bond pigments to the particles to produce a wide selection of other colors: white, black, red, blue and yellow, all with comparable magnetic properties.

The white or yellow colors provide good contrast against mill surface objects. They are not effective against the silver gray of grit blasted or chemically etched surfaces or against bright, polished machine ground surfaces. For those applications, black, red or blue is used. The choice of color depends on the surface colors of the test objects and on the prevailing test site lighting.

The ability to bond fluorescent dyes to magnetic powders has produced a particle material that provides the best possible visibility and contrast under proper lighting conditions. When test objects are examined in ultraviolet light, it is difficult not to see the light emitted by a few particles collected at a discontinuity.

Fluorescent particles are magnetically less sensitive than visible particles but the reduction in magnetic sensitivity is more than offset by the increase in visibility and contrast.

Visibility and contrast of fluorescent particles are directly related to the darkness of the testing site. In a totally darkened area, even a small amount of ultraviolet energy activates fluorescent dye to emit a noticeable amount of visible light. When the test site is partially darkened, the amount of required ultraviolet energy increases dramatically yet the emitted visible light is only barely noticeable, especially in the conventional yellow-to-green range.

Most military and commercial specifications require the test site to be darkened to 20 lx (2 ftc) or less, with a minimum ultraviolet intensity of 1000 $\mu W \cdot cm^{-2}$ at the test object surface.

Particle Mobility

When magnetic particles are applied to the surface of a magnetized object, the particles must move and collect at the leakage field of a discontinuity in order to form a visible indication. Any interference with this movement has an effect on the sensitivity of the test. Conditions promoting or interfering with particle mobility are different for dry and wet method particles.

Dry Powder Mobility

Dry particles should be applied in a way that permits them to reach the magnetized object surface in a uniform cloud with minimum motion. When this is properly done, the particles come under the influence of leakage fields while suspended in air and are then said to possess *three-dimensional mobility*. This condition can be approximated on surfaces that are vertical or overhead.

When particles are applied to horizontal surfaces, they settle directly onto the surface and do not have mobility in three dimensions. Some extension of mobility can be achieved by tapping or vibrating the test object, agitating the particles and allowing them to move

toward leakage fields. Alternating current and half-wave rectified alternating current (pulsed direct current) can give particles excellent mobility when compared to direct current magnetization.

Wet Method Particle Mobility

The suspension of particles in a liquid vehicle allows mobility for the particles in two dimensions when the suspension flows over the test object surface and in three dimensions when the test object is immersed in a magnetic particle bath.

Wet method particles have a tendency to settle out of the suspension either in the tank of the test system or on the test object surface short of the discontinuity. To be effective, wet method particles must move with the vehicle and must reach every surface that the vehicle contacts. The settling rate of particles is directly proportional: (1) to their dimensions and (2) to the difference between their density and the lower density of the liquid vehicle. Their settling rate is inversely proportional to the liquid's viscosity. As a result, the mobility of wet method particles is never ideal and must be balanced against the other factors important to wet method test results.

Media Selection

The choice between dry method and wet method techniques is influenced principally by the following considerations:

1. *Type of discontinuity* (surface or subsurface): for subsurface discontinuities, dry powder is usually more sensitive.
2. *Size of surface discontinuity*: wet method particles are usually best for fine or broad, shallow discontinuities.
3. *Convenience*: dry powder with portable half-wave equipment is easy to use for tests on site or in the field. Wet method particles packaged in aerosol spray cans are also effective for field spot tests.

The dry powder technique is superior for locating subsurface discontinuities, mainly because of the high permeability and favorable elongated shape of the particles. Alternating current with dry powder is excellent for surface cracks that are not too fine but this combination is of little value for cracks lying wholly beneath the surface.

When the requirement is to find extremely fine surface cracks, the wet method is superior, regardless of the magnetizing current in use. In some cases, direct current is considered advantageous because it also provides some indications of subsurface discontinuities. The wet method also offers the advantage of complete coverage of the object surface and good coverage of test objects with irregular shapes.

Visible or Fluorescent Particles

The decision between visible particles and fluorescent particles depends on convenience and equipment. Testing with visible particles can be accomplished under common shop lighting while fluorescent particles require a darkened area and an ultraviolet light source.

Both wet method visible and wet method fluorescent tests have about the same sensitivity, but under proper lighting conditions fluorescent indications are much easier to see.

Magnetic Particle Testing Processes

A test object may be magnetized first and particles applied after the magnetizing current has been stopped (called the *residual method*) or the object may be covered with particles while the magnetizing current is present (known as the *continuous method*). With test objects that have high magnetic retentivity, a combination of the residual and continuous methods is sometimes used.

Residual Test Method

In the residual method, the test object is magnetized, the magnetizing current is stopped and then the magnetic particles are applied. This method can only be used on materials having sufficient magnetic remanence. The residual magnetic field must be intense enough to produce discontinuity leakage fields sufficient for producing visible test indications. As a rule, the residual method is most reliable for detection of surface discontinuities.

Hard materials with high remanence are usually low in permeability, so higher than usual magnetizing currents may be necessary to obtain an adequate level of residual magnetism. This difference between hard steels and soft steels is usually not critical if only surface discontinuities are to be detected.

Either dry or wet method particle application can be used in the residual method. With the wet method, the magnetized test object may be immersed in an agitated bath of suspended magnetic particles or may be flooded with particle suspension in a curtain spray.

In the immersion technique, the intensity of discontinuity indications is directly affected by the object's dwell time in the bath. By leaving the object in the

bath for extended periods, leakage fields have time enough to attract and hold the maximum number of particles, even at fine discontinuities. If the test object has high retentivity, longer dwell time increases the sensitivity over that of the wet continuous method. Note that the location of the discontinuity on the object during immersion affects the accumulation of particles. Indications are more intense on upper horizontal surfaces and weaker on vertical or lower horizontal surfaces.

Care must be exercised when removing the test object from the bath or particle spray. Rapid movement can literally wash off indications held by weak discontinuity leakage fields.

Continuous Test Method

When a magnetizing current is applied to a ferromagnetic test object, the magnetic field rises to a maximum. Its value is derived from the magnetic field intensity and the magnetic permeability of the test object. When the magnetizing current is removed, the residual magnetic field in the object is always less than the field produced while the magnetizing current was applied. The amount of difference depends on the *BH* curve of the material. For these reasons, the continuous method, for any specific value of magnetizing current, is always more sensitive than the residual method.

Continuous magnetization is the only method possible for use on low carbon steels or iron having little retentivity. It is frequently used with alternating current on these materials because of the excellent mobility produced by alternating current.

With the wet method, the surface of the test object is flooded with particle suspension. The bath application and the magnetizing current are simultaneously stopped. The magnetic field intensity continues to affect particles in the bath as it drains. In some continuous method procedures, the magnetizing current remains on during interpretations.

The wet continuous method requires more operator attention than the residual method. If bath application continues, even momentarily, after the current is stopped, particles held by a discontinuity leakage field can be washed away. If there is a pause between stopping the bath application and applying the magnetizing current, the suspension can drain off the test object, leaving insufficient particles for producing discontinuity indications. Careless handling of the bath and current sequence can seriously hinder the production of reliable test results.

The highest possible sensitivity for very fine discontinuities is typically achieved by the following sequence: (1) immerse the test object in the bath, (2) pass magnetizing current through the object for a short time during immersion, (3) maintain the current during removal from the bath, (4) maintain the current during drainage of the suspension from the test object and (5) stop the magnetizing current.

Conclusion

Magnetic particle tests are effective nondestructive procedures for locating material discontinuities in ferromagnetic objects of all sizes and configurations. It is a flexible technique that can be performed under a variety of conditions, using a broad range of supplementary components.

Application of the magnetic particle method is deceptively simple — good test results can sometimes be produced with little more than practical experience. In fact, the development of the technique has been almost entirely empirical rather than theoretical.

However, the method is founded on the complex principles of electromagnetics and the magnetic interactions of at least three materials simultaneously. In addition, there is the critical consideration of the operator's ability to qualitatively and quantitatively evaluate the results of the inspection.

PART 9. Magnetic Test Techniques

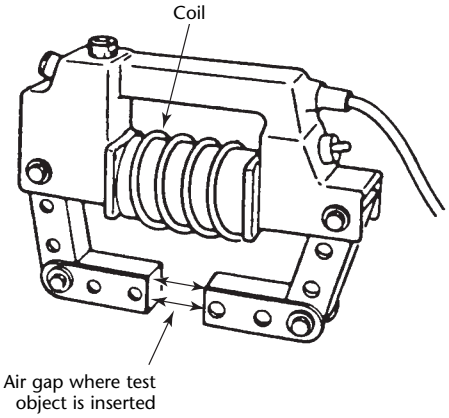
Successful testing requires the test object to be magnetized properly. The magnetization can be accomplished using one of several approaches: (1) permanent magnets, (2) electromagnets and (3) electric currents used to induce the required magnetic field.

Excitation systems that use permanent magnets offer the least flexibility. The major disadvantage with such systems lies in the fact that the excitation cannot be switched off. Because the magnetization is always turned on, it is difficult to insert and remove the test object from the test rig.

Electromagnets, as well as electric currents, are used extensively to magnetize the test object. Figure 29 shows an excitation system where the test object is part of a magnetic circuit energized by current passing through an excitation coil. The physics of magnetization are described elsewhere in this volume.

To obtain maximum sensitivity, it is necessary to ensure that the magnetic flux is perpendicular to the discontinuity. This direction is in contrast to the orientation in techniques that use an electric current for inspection of a test object, where it may be more advantageous to orient the direction of current so that a discontinuity would impede the current as much as possible. Because the orientation of the discontinuity is unknown, it is necessary to test twice with a yoke, in two directions perpendicular to each other. A grid is usually drawn on the test object to facilitate the tests.

FIGURE 29. Electromagnetic yoke for magnetizing of test object.

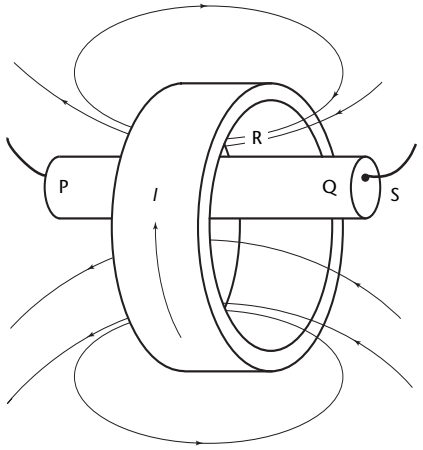


Magnetizing Coil

A commonly used encircling coil is shown in Fig. 30. The field direction follows the right hand rule. (The right hand rule states that, if someone grips a rod, holds it out and imagines an electric current flowing down the thumb, the induced circular field in the rod would flow in the direction that the fingers point.) With no test object present, the field lines form closed loops that encircle the current carrying conductors. The value of the field at any point has been established for a great many coil configurations. The value depends on the current in the coils, the number of turns and a geometrical factor. Calculation of the field from first principles is generally unnecessary for nondestructive testing; a hall element tesla meter will measure this field.

Two totally different situations, common in magnetic flux leakage testing, are described below.

FIGURE 30. Encircling coil using direct current to produce magnetizing force.



Legend

I = electric current
P, Q = points of discontinuities in example
R = point at which magnetic field intensity ***H*** is measured
S = point at which magnetic flux density ***B*** is measured

Testing in Active Field

In this technique, the test object is scanned by probes near position *R* in Fig. 30. Application of small fields is sufficient to cause magnetic flux leakage from transversely oriented surface breaking discontinuities. For subsurface discontinuities or those on the inside surface of tubes, larger fields are required. The inspector must experiment to optimize the applied field for the particular discontinuity.

Testing in Residual Field

Test objects are passed through the coil field and tested in the resulting residual field. Elongating the coil and placing the test object next to the inside surface of the coil will expose the test object to the largest field that the coil can produce.

This technique is often used in magnetic particle testing. The main problem to avoid is the induction of so much magnetic flux in the test object that the magnetic particles stand out like fur along the field lines that enter and leave the test object, especially close to its ends. Optimum conditions require that the test object be somewhat less than saturated. The inspector should experiment to optimize the coil field requirements for the test object because this field depends on test object geometry.

Applied Direct Current

If an electric current is used to magnetize the test object, it may be more advantageous to orient the direction of current in a manner where the presence of a discontinuity impedes the current flow as much as possible. Bars, billets and tubes are often magnetized by application of a direct current *I* to their ends (Fig. 31).

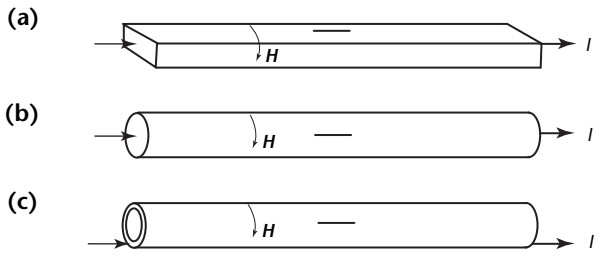
Figure 32 shows a system where the current *I* is passed directly through a tubular test object to magnetize the test object circularly. Figure 33 shows a central conductor energized by a current source to establish a circular magnetic field intensity in a tubular test object.

Capacitor Discharge Devices

For the circular magnetization of tubes or the longitudinal magnetization of the ends of elongated test objects, a capacitor discharge device is sometimes used.[4,5] The capacitor discharge unit represents a practical advance over battery packs and consists of a capacitor bank charged to a voltage *V* and then discharged through a rod, a cable and a silicon controlled rectifier of total resistance *R*. Typical configurations are shown in Fig. 34.

Larger capacitances at lower voltages provide better magnetization than smaller capacitances at higher voltages because larger capacitances at lower voltages lead to longer duration pulses and therefore to lower eddy currents. The lower voltage is an essential safety feature for outdoor use. A maximum of 50 V is recommended.[6]

FIGURE 31. Circumferential magnetization by application of direct current: (a) rectilinear bar; (b) round bar; (c) tube.



Legend
H = magnetic field intensity
I = electric current

FIGURE 32. Current carrying clamp electrodes used for testing ferromagnetic tubular objects with small diameters.

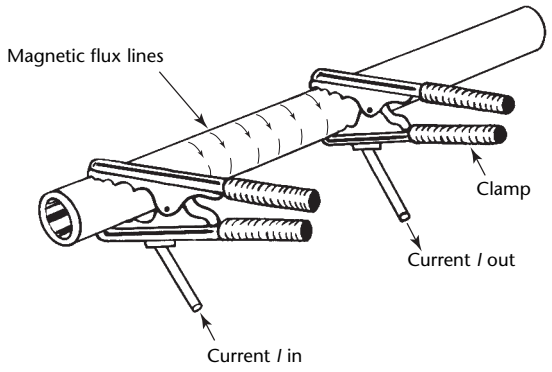
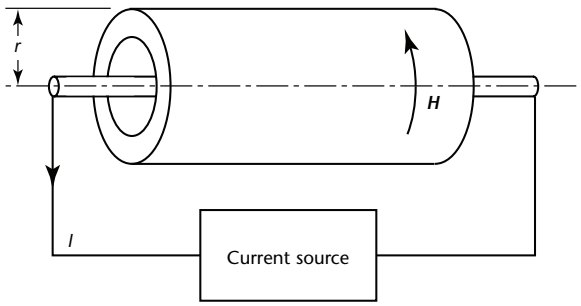


FIGURE 33. Simple technique for circumferential magnetization of ferromagnetic tube.

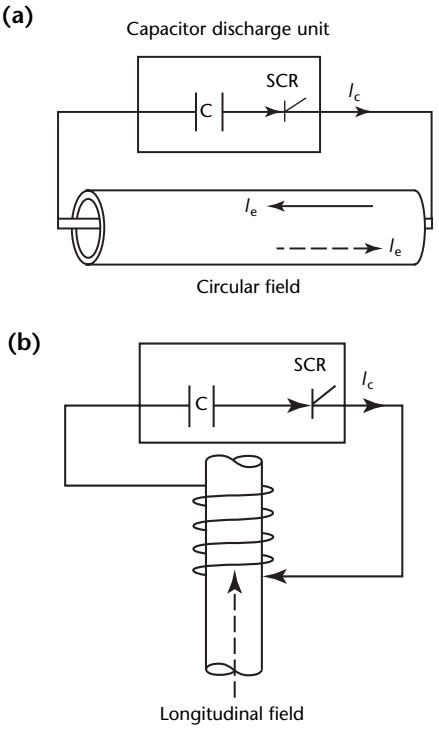


Legend
H = magnetic field intensity
I = electric current
r = tube radius

Magnitudes of Magnetic Flux Leakage Fields

The magnitude of the magnetic flux leakage field under active direct current excitation naturally depends on the applied field. An applied field of 3.2 to 4.0 kA·m^{-1} (40 to 50 Oe) inside the material can cause leakage fields with peak values of tens of millitesla (hundreds of gauss). However, in the case of residual induction, the magnetic flux leakage fields may be only a few hundred microtesla (a few gauss). Furthermore, with residual field excitation, an interesting field reversal may occur, depending on the value of the initial active field excitation and the dimensions of the discontinuity.

FIGURE 34. Capacitor discharge configurations causing magnetization perpendicular to current direction: (a) conductor internal to test object creates circular field; (b) flexible cable around test object creates longitudinal field.



Legend
C = capacitor
I_c = capacitor discharge current
I_e = eddy current
SCR = silicon controlled rectifier

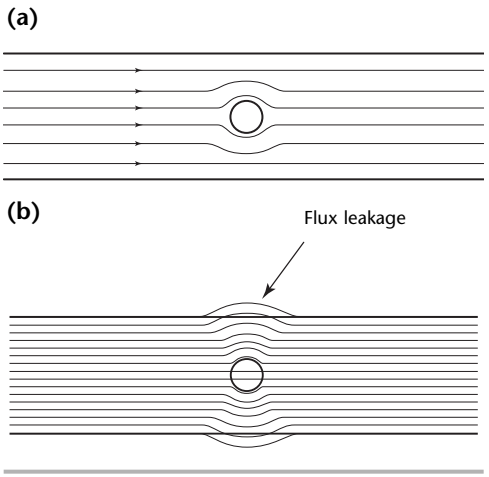
Optimal Operating Point

Consider raising the magnetization level in a block of steel containing a discontinuity (Fig. 35). At low flux density, the field lines tend to crowd together in the steel around the discontinuity rather than go through the nonmagnetic region of the discontinuity. The field lines are therefore more crowded above and below the discontinuity than they are on the left or right. The material can hold more flux as the permeability rises, so there is no significant leakage flux at the surfaces (Fig. 35a).

However, an increase in the number of lines causes permeability to fall. At about this point, magnetic flux leakage is first noticed at the surfaces. Although the lines are now closer together, representing a higher magnetic flux density, they do not have the ability to crowd closer together around the discontinuity where the permeability is low.

At higher values of applied field, the permeability continues to fall. It is, however, still large compared to the permeability of air, so the reluctance of the path through the discontinuity is still larger than through the metal. As a result, magnetic flux leakage at the outside surface helps provide a sufficiently high flux density in the material for the leakage of magnetic flux from discontinuities (Fig. 35b) while partially suppressing long range surface noise.

FIGURE 35. Effects of induction on magnetic flux lines at discontinuity: (a) no surface flux leakage occurs where magnetic flux lines are compressed at low levels of induction around discontinuity; (b) lack of compression at high magnetization results in surface magnetic flux leakage.



For residual field testing, it is best to ensure that the material is saturated. The magnetic field starts to decay as soon as the energizing current is removed.

Magnetic Test Probes

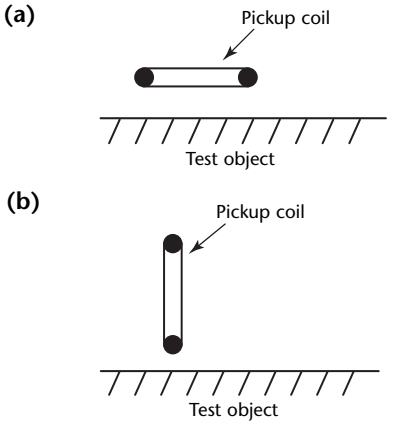
The purpose of probes for magnetic testing is to detect and possibly quantify the magnetic flux leakage field generated by heterogeneities in the test object. The leakage fields tend to be local and concentrated near the discontinuities. The leakage field can be divided into three orthogonal components: normal (vertical), tangential (horizontal) and axial directions. Probes are usually either designed or oriented to measure one of these components. Typical plots of these components near discontinuities are shown in this volume's chapter on probes.

A variety of probes (or transducers) are used in industry for detecting and measuring leakage fields.

Pickup Coils

One of the simplest and most popular means for detecting leakage fields is to use a pickup coil.[7] Pickup coils consist of very small coils that are either air cored or use a small ferrite core. The voltage induced in the coil is given by the rate of change of flux linkages associated with the pickup coil. Only the component of the flux parallel to the axis of the coil (or alternately perpendicular to the plane of the coil) is instrumental in inducing the voltage. This induction direction makes it possible to orient the pickup coil so as to measure any of the three leakage field components selectively (Fig. 36).

FIGURE 36. Effect of pickup coil orientation on sensitivity to components of magnetic flux density: (a) coil sensitive to normal component; (b) coil sensitive to tangential component.



The output of the pickup coil is proportional to the spatial gradient of the flux along the direction of the coil movement as well as the velocity of the coil. Two issues arise as a result.

1. It is essential that the probe scan velocity (relative to the test object) should be constant to avoid introducing artifacts into the signal through probe velocity variations.
2. The output is proportional to the spatial gradient of the flux in the direction of the coil.

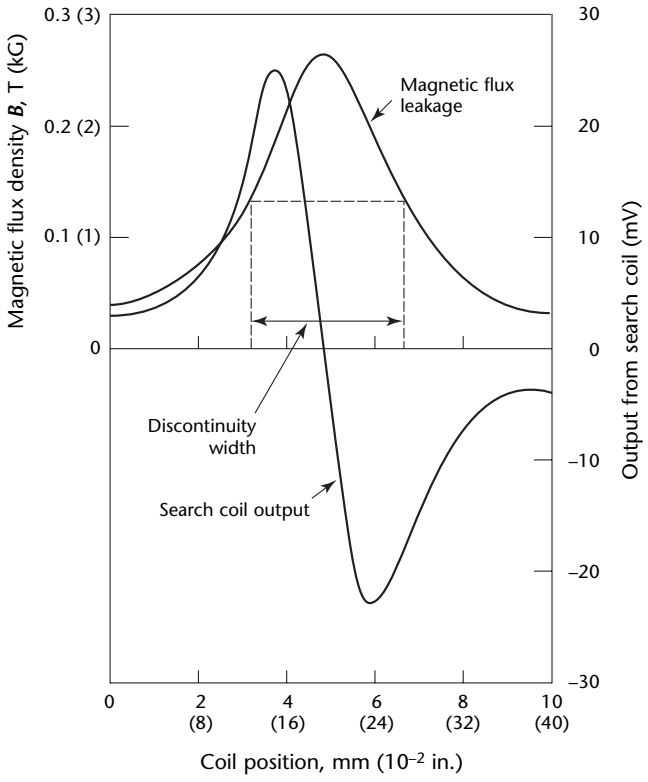
The output of the pickup coil can be integrated for measurement of the leakage flux density rather than of its gradient. Figure 37 shows the output of a pickup coil and the signal obtained after integrating the output.[8] The coil is used to measure, in units of tesla (or gauss), the magnetic flux density B leaking from a rectangular slot.

The sensitivity of the pickup coil can be improved by using a ferrite core. Tools for designing pickup coils, as well as predicting their performance, are described elsewhere in this volume.

Magnetodiodes

The magnetodiode is suitable for sensing leakage fields from discontinuities because of its small size and its high sensitivity.

FIGURE 37. Pickup coil and signal integrator (magnetic flux leakage) output for rectangular discontinuity.[7]



Because the coil probe is usually larger than the magnetodiode, it is less sensitive to longitudinally angled discontinuities than the magnetodiode is. However, the coil probe is better than the magnetodiode for large discontinuities, such as cavities.

Hall Effect Detectors

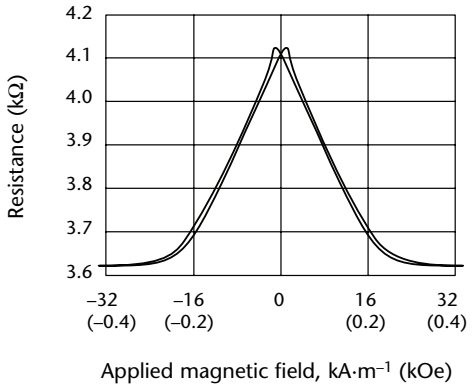
Hall effect detector probes are used extensively in industry for measuring magnetic flux leakage fields in units of tesla. Hall effect detector probes are described in this volume's chapter on probes for electromagnetic testing.

Giant Magnetoresistive Probes

Magnetic field sensitive devices called *giant magnetoresistive probes,*[9,10] at the most basic level, consist of a nonmagnetic layer sandwiched between two magnetic layers. The apparent resistivity of the structure varies depending on whether the direction of the electron spin is parallel or antiparallel to the moments of the magnetic layers. When the moments associated with the magnetic layers are aligned antiparallel, the electrons with spin in one direction (up) that are not scattered in one layer will be scattered in the other layer. This increases the resistance of the device. This is in contrast to the situation when the magnetic moments associated with the layers are parallel and the electrons that are not scattered in one layer are not scattered in the other layer, either.

Giant magnetoresistive probes use a biasing current to push the magnetic layers into an antiparallel moment state and the external field is used to overcome the effect of the bias. The resistance of the device, therefore, decreases with increasing field intensity values. Figure 38 shows a typical response of a giant magnetoresistive probe.

FIGURE 38. Resistance versus applied field for 2 µm (8×10^{-5} in.) wide strip of antiferromagnetically coupled, multilayer test object composed of 14 percent giant magnetoresistive material.[9]



Magnetic Tape

For the testing of flat surfaces, magnetic tape can be used. The tape is pressed to the surface of the magnetized billet and then scanned by small probes before being erased. This technique is sometimes called *magnetography*.

In automated systems, magnetic tape can be fed from a spool. The signals can be read and the tape can be erased and reused.

Unfortunately, the tangential leakage field intensity at the surface of the material is not constant. To optimize the response, the amplification of the signals can be varied.

Scabs or slivers projecting from the test surface can easily tear the tape

Magnetic Particles

Magnetic particles are the most popular means used in industry for making magnetic indications. The descriptions below are cursory.

Magnetic particle testing involves the application of magnetic particles to the test object before or after it is magnetized. The ferromagnetic particles preferentially adhere to the surface of the test object in areas where the flux is *diverted,* or *leaks out.* The magnetic flux leakage near discontinuities causes the magnetic particles to accumulate in the region and in some cases form an outline of the discontinuity. Heterogeneities can therefore be detected by looking for indications of magnetic particle accumulations on the surface of the test object either with the naked eye or through a camera. The indications are easier to see if the particles are bright and reflective. Alternately, particles that fluoresce under ultraviolet or visible radiation may be used. The test object has to be viewed under appropriate levels of illumination with radiation of appropriate wavelength (visible, ultraviolet or other).

Application Techniques

Magnetic particles are applied to the surface by two different techniques in industry.

Dry Testing. Dry techniques use particles applied in the form of a fine stream or a cloud. They consist of high permeability ferromagnetic particles coated with either reflective or fluorescent pigments. The particle size is chosen according to the

dimensions of the discontinuity sought. Particle diameters range from ≤50 to 180 µm (≤0.002 to 0.007 in.). Finer particles are used for detecting smaller discontinuities where the leakage intensity is low. Dry techniques are used extensively for testing welds and castings where discontinuities of interest are relatively large.

Wet Testing. Wet techniques are used for detecting relatively fine cracks. The magnetic particles are suspended in a liquid (usually oil or water) that can be sprayed on the test object. Particle sizes are significantly smaller than those used with dry techniques and vary in size within a normal distribution, with most particles measuring from 5 to 20 µm (2×10^{-4} to 8×10^{-4} in.). As in the case of dry powders, the ferromagnetic particles are coated with either reflective or fluorescent pigments.

Imaging of Magnetic Particle Indications

The magnetic particle distribution can be examined visually after illuminating the surface or the surface can be scanned with a flying spot system[11,12] or imaged with a charge coupled device camera.

Flying Spot Scanners. To illuminate the test object, flying spot scanners use a narrow beam of radiation — visible light for nonfluorescent particles and ultraviolet radiation for fluorescent ones. The source of the beam is usually a laser. The wavelength of the beam is chosen carefully to excite the pigment of the magnetic particles. The incidence of the radiation beam on the test object can be varied by moving the scanning mirror.

The photocell does not sense any light when the test object is scanned by the narrow radiation beam until the beam is directly incident on the magnetic particles adhering to the test object near a discontinuity. When this occurs, a large amount of light is emitted, called *fluorescence* if excited by ultraviolet radiation. The fluorescence is detected by a single phototube equipped with a filter that renders the system blind to the radiation from the irradiating source. The output of the photocell is suitably amplified, digitized and processed by a computer.

Charge Coupled Devices. An alternative approach is to flood the test object with radiation whose wavelength is carefully chosen to excite the pigment of the magnetic particles. Charge coupled device cameras,[13,14] equipped with optical filters that render the camera blind to radiation from the source but are transparent to light emitted by the magnetic particles, can be used to image the surface very rapidly.

In very simple terms, charge coupled devices each consist of a two-dimensional array of tiny pixels that each accumulates a charge corresponding to the number of photons incident on it. When a readout pulse is applied to the device, the accumulated charge is transferred from the pixel to a holding or charge transfer cell. The charge transfer cells are connected in a manner that allows them to function as a bucket brigade or shift register. The charges can, therefore, be serially clocked out through a charge-to-voltage amplifier that produces a video signal.

In practice, charge coupled device cameras can be interfaced to a personal computer through frame grabbers, which are commercially available. Vendors of frame grabbers usually provide software that can be executed on the personal computer to process the image. Image processing software can be used to improve contrast, highlight the edges of a discontinuity or to minimize noise in the image.

Test Calculations

In determining the magnetic flux leakage from a discontinuity, certain conditions must be known: (1) the discontinuity's location with respect to the surfaces from which measurements are made, (2) the relative permeability of the material containing the discontinuity and (3) the levels of magnetic field intensity H and magnetic flux density B in the vicinity of the discontinuity. Even with this knowledge, the solution of the applicable field equations (derived from Maxwell's equations of electromagnetism) is difficult and is generally impossible in closed algebraic form. Under certain circumstances, such as those of discontinuity shapes that are easy to handle mathematically, relatively simple equations can be derived for the magnetic flux leakage if simplifying assumptions are made. This simplification does not apply to subsurface inclusions.

Finite Element Techniques

An advance in magnetic theory since 1980 has been the introduction of finite element computer codes to the solution of magnetostatic problems. Such codes came originally from a desire to minimize electrical losses from electromagnetic machinery but soon found application in magnetic flux leakage theory. The advantage of such codes is that, once set up, discontinuity leakage fields can be calculated by computer for any size and

shape of discontinuity, under any magnetization condition, so long as the ***BH*** curve for the material is known.

In the models of magnetic flux leakage discussed so far, the implicit assumptions are (1) that the field within a discontinuity is uniform and (2) that the nonlinear magnetization characteristic (***BH*** curve) of the tested material can be ignored. Much of the early pioneering work in magnetic flux leakage modeling used these assumptions to obtain closed form solutions for leakage fields.

The solutions of classical problems in electrostatics have been well known to physicists for almost a century and their magnetostatic analogs were used to approximate discontinuity leakage fields. Such techniques work reasonably well when the permeability around a discontinuity is constant or when nonlinear permeability effects can be ignored. The major problem that remains is how to deal with real discontinuity shapes often impossible to handle by classical techniques.

Such deficiencies are overcome by the use of computer programs written to allow for nonlinear permeability effects around oddly shaped discontinuities. Specifically, computerized finite element techniques, originally developed for studying magnetic flux distributions in electromagnetic machinery, have also been developed for nondestructive testing. Both active and residual excitation are discussed above. The extension of the technique to include eddy currents is detailed elsewhere.

Part 10. Techniques of Magnetic Testing[15]

Magnetic flux leakage testing is a commonly used technique. Signals from probes are processed electronically and presented to indicate discontinuities. Although some techniques of magnetic flux leakage testing may not be as sophisticated as others, it is probable that more ferromagnetic material is tested with magnetic flux leakage than with any other technique.

Magnetizing techniques have evolved to suit the geometry of the test objects. The techniques include yokes, coils, the application of current to the test object and conductors that carry current through hollow test objects. Many situations exist in which current cannot be applied directly to the test object because of the possibility of arc burns. Design considerations for magnetization of test objects often require minimizing the reluctance of the magnetic circuit, consisting of (1) the test object, (2) the magnetizing system and (3) any air gaps that might be present.

Test Object Configurations

Short Asymmetrical Objects

A short test object with little or no symmetry may be magnetized to saturation by passing current through it or by placing it in an encircling coil. If hollow, a conductor can be passed through the test object and magnetization achieved by any of the standard techniques (these include half-wave and full-wave rectified alternating current, pure direct current from battery packs or pulses from capacitor discharge systems). For irregularly shaped test objects, testing by wet or dry magnetic particles is often performed, especially if specifications require that only surface breaking discontinuities be found.

Elongated Objects

The cylindrical symmetry of elongated test objects such as wire rope permits a relatively simple flux loop to magnetize a relatively short section of the rope. Encircling probes are placed at some distance from the rope to permit the passage of splices. Such systems are also suited for pumping well sucker rods and other elongated oil field test objects.

After a well is drilled, the sides of the well are lined with a relatively thin steel casing material, which is then cemented in. This casing can be tested only from the inside surface. The cylindrical geometry of the casing permits the flux loop to be easily calculated so that magnetic saturation of the well casing is achieved.

As with inservice well casing, buried pipelines are accessible only from the inside surface. The magnetic flux loop is the same as for the well casing test system. In this case, a drive mechanism must be provided to propel the test system through the pipeline.

Threaded Regions of Pipe

An area that requires special attention during the inservice testing of drill pipe is the threaded region of the pin and box connections. Common problems that occur in these regions include fatigue cracking at the roots of the threads and stretching of the thread metal. Automated systems that use both active and residual magnetic flux techniques can be used for detecting such discontinuities.

Ball Bearings and Races

Systems have been built for the magnetization of both steel ball bearings and their races. One such system uses specially fabricated hall elements as detectors.

Relatively Flat Surfaces

The testing of welded regions between flat or curved plates is often performed using a magnetizing yoke. Probe systems include coils, hall effect detectors, magnetic particles and magnetic tape.

Discontinuity Mechanisms

In the metal forming industry, discontinuities commonly found by magnetic flux leakage include overlaps, seams, quench cracks, gouges, rolled-in slugs and subsurface inclusions. In the case of tubular goods, internal mandrel marks (plug scores) can also be identified when they result in remaining wall

thicknesses below some specified minimum. Small marks of the same type can also act as stress raisers: cracking can originate from them during quench and temper procedures. Depending on the use to which the material is put, subsurface discontinuities such as porosity and laminations may also be detrimental. Such discontinuities may be acceptable in welds where there are no cyclic stresses but may cause injurious cracking when such stresses are present.

In the metal processing industries, grinding especially can lead to surface cracking and to some changes in surface metallurgy. Such discontinuities as cracking have traditionally been found by magnetic flux leakage techniques, especially wet magnetic particle testing.

Service induced discontinuities include cracks, corrosion pitting, stress induced metallurgy changes and erosion from turbulent fluid flow or metal-to-metal contact. In those materials placed in tension and under torque, fatigue cracking is likely to occur. A discontinuity that arises from metal-to-metal wear is sucker rod wear in tubing from producing oil wells. Here, the pumping rod can rub against the inner surface of the tube and both the rod and tube wear thin. In wire rope, the outer strands will break after wearing thin and inner strands sometimes break at discontinuities present when the rope was made. Railroad rails are subject to cyclic stresses that can cause cracking to originate from otherwise benign internal discontinuities.

Loss of metal caused by a conducting fluid near two slightly dissimilar metals is a very common form of corrosion. The dissimilarity can be quite small, as for example, at the heat treated end of a rod or tube. The result is preferential corrosion by electrolytic processes, compounded by erosion from a contained flowing fluid. Such loss mechanisms are common in subterranean pipelines, installed petroleum well casing and in refinery and chemical plant tubing.

The stretching and cracking of threads is a common problem. For example, when tubing, casing and drill pipe are overtorqued at the coupling, the threads exist in their plastic region. This causes metallurgical changes in the metal and can create regions where stress corrosion cracking takes place in highly stressed areas at a faster rate than in areas of less stress. Couplings between tubes are a good example of places where material may be highly stressed. Drill pipe threads are a good example of places where such stress causes plastic deformation and thread root cracking.

Typical Magnetic Techniques

Short Parts

For many short test objects, the most convenient probe is magnetic particles. The test object can be inspected for surface breaking discontinuities during or after it has been magnetized to saturation. For active field testing, the test object can be placed in a coil carrying alternating current and sprayed with magnetic particles. Or it can be magnetized to saturation by a direct current coil and the resulting residual induction can be shown with magnetic particles. In the latter case, the induction in the test object can be measured with a flux meter. Wet particles perform better than dry ones because there is less tendency for the wet particles to *fur* (that is, to stand up like short hairs) along the field lines that leave the test object. These techniques will detect transversely oriented, tight discontinuities.

The magnetic flux leakage field intensity from a tight crack is roughly proportional to the magnetic field intensity H_g across the crack, multiplied by crack width L_g. If the test is performed in residual induction, the value of H_g (which depends on the local value of the demagnetization field in the test object) will vary along the test object. Thus, the sensitivity of the technique to discontinuities of the same geometry varies along the length of the test object.

For longitudinally oriented discontinuities, the test object must be magnetized circumferentially. If the test object is solid, then current can be passed through the test object, the surface field intensity being given by Ampere's law:

$$\textbf{(1)} \quad \oint \boldsymbol{H}\, d\ell = I$$

where $d\ell$ is an element of length (meter), $\boldsymbol{H}$ is the magnetic field intensity (ampere per meter) and I is the current (ampere) in the test object.

If the test object is a cylindrical bar, the symmetry of the situation allows $\boldsymbol{H}$ to be constant around the circumference, so the closed integral reduces:

$$\textbf{(2)} \quad 2\pi R\boldsymbol{H} = I$$

or:

$$\textbf{(3)} \quad \boldsymbol{H} = \frac{I}{2\pi R}$$

where R is the radius (meter) of the cylindrical test object. A surface field intensity that creates an acceptable magnetic flux leakage field from the minimum sized discontinuity must be used. Such fields are often created by specifying the amperage per meter of the test object's outside diameter.

Transverse Discontinuities

Because of the demagnetizing effect at the end of a tube, automated magnetic flux leakage test systems do not generally perform well when scanning for transverse discontinuities at the ends of tubes. The normal component H_y of the field outside the tube is large and can obscure discontinuity signals. Test specifications for such regions often include the requirement of additional longitudinal magnetization at the tube ends and subsequent magnetic particle tests during residual induction. This situation is equivalent to the magnetization and testing of short test objects as outlined above.

The flux lines must be continuous and must therefore have a relatively short path in the metal. Large values of the magnetizing force at the center of the coil are usually specified. Such values depend on the weight per unit length of the test object because this quantity affects the ratio of length L to diameter D. Where the test object is a tube, the $L \cdot D^{-1}$ ratio is given by the length between the poles divided by twice the wall thickness of the tube. (The distance L from pole to pole can be longer or shorter than the actual length of the test object and must be estimated by the operator.) As a rough example, with L = 460 mm (18 in.) and D = 19 mm (0.75 in.), the $L \cdot D^{-1}$ ratio is 24.

The effective permeability of the metal under test is small because of the large demagnetization field created in the test object by the physical end of the test object. An empirical formula is often used to calculate approximately the effective permeability μ:

$$\mu = 6\frac{L}{D} - 5 \quad \textbf{(4)}$$

so effective permeability μ = 139 in the above example.

For wet magnetic particle testing, the surface tension of the fluids that carry the particles is large enough to confine the particles to the surface of the test object. This is not the case with dry particles, which have the tendency to stand up like fur along lines of magnetizing force.

In many instances, it may be better to use some other test technique for transverse discontinuities, such as ultrasonic or eddy current techniques.

Alternating Current versus Direct Current Magnetization

Alternating current magnetization is more suitable for detection of outer surface discontinuities because it concentrates the magnetic flux at the surface. For equal magnetizing forces, an alternating current field is better for detecting outside surface imperfections but a direct current field is better for detecting imperfections below the surface.

In practice, the ends of tubes are tested for transverse discontinuities by the following magnetic flux leakage techniques.

1. Where there is a direct current active field from an encircling coil, magnetic particles are applied to the tested material while it is maintained at a high level of magnetic induction by a direct current field in the coil. This technique is particularly effective for internal cracks. Fatigue cracks in drill pipe are often found by this technique.
2. Where there is an alternating current active field from an encircling coil, magnetic particles are applied to the tested material while it lies inside a coil carrying alternating current. Using 50 or 60 Hz alternating current, the penetration of the magnetic field into the material is small and the technique is good only for the detection of outside surface discontinuities.

When tests for both outer surface and inner surface discontinuities are necessary, it may be best to test first for outer surface discontinuities with an alternating current field, then for inner surface discontinuities with a direct current field.

Liftoff Control of Scanning Head

To obtain a stable detection of discontinuities, liftoff between the probe and the surface of the material must be kept constant. Usually liftoff is kept constant by contact of the probe with the surface but the probe tends to wear with this technique. A magnetic floating technique has been used for noncontact scanning. In this technique, liftoff is measured by a gap probe and the probe holder is moved by a coil motor, controlled by the gap signal.[16] This system and related technology are described in this volume's chapter on primary metals applications.

PART 11. Magnetic Testing Applications

Discontinuities[2]

For magnetic testing, discontinuities may be broadly categorized according to their origin in the stages of fabrication and service.

1. *Primary production and processing tests* are used to inspect the stages of processing from pouring and solidification of the ingot to production of basic shapes, including sheet, bar, pipe, tubing, forgings and castings. These tests are typically used to locate two discontinuity subgroups: (a) those formed during solidification are called *inherent discontinuities*; (b) those formed during mill reduction are called *primary processing discontinuities*.
2. *Secondary processing,* or *manufacturing and fabrication tests,* are used to inspect the results of processes that convert raw stock into finished components. Forming, machining, welding and heat treating discontinuities are detected.
3. *Service tests* are widely used for detecting overstress and fatigue cracking. Magnetic particle tests are *not* used to detect corrosion, deformation or wear, three of the most common service induced problems. Flux leakage testing, however, can be used to detect material loss resulting from corrosion or abrasion — in wire rope, for example.

Discontinuities caused during manufacture include cracks, seams, forging laps, laminations and inclusions.

1. Cracking occurs when quenched steel cools too rapidly.
2. Seams occur in several ways, depending on when they originate during fabrication.
3. Discontinuities such as piping or inclusions within a bloom or billet can be elongated until they emerge as long tight seams or gouges during initial forming processes. They may later be closed with additional forming.
4. Their metallurgical structures are often different but the origin of manufactured discontinuities is not usually taken into account when rejecting a part.
5. Forging laps occur when gouges or fins created in one metal working process are rolled over at an angle to the surface in subsequent processes.
6. Inclusions are pieces of nonmagnetic or nonmetallic materials embedded inside the metal during cooling. Inclusions are not necessarily detrimental to the use of the material.
7. The pouring and cooling processes can also result in lack of fusion within the steel. Such regions may be worked into internal laminations.

Discontinuities in used materials include fatigue cracks, pitting, corrosion, erosion and abrasive wear.

Much steel is acceptable to the producer's quality assurance department if no discontinuities are found or if discontinuities are considered to be of a depth or size less than some prescribed maximum. Specifications exist for the acceptance or rejection of such materials and such specifications sometimes lead to debate between the producer and the end user. Discontinuities can either remain benign or can grow and cause premature failure of the part. Abrasive wear can turn benign subsurface discontinuities into detrimental surface breaking discontinuities.

For used materials, fatigue cracking commonly occurs as the material is cyclically stressed. Fatigue cracks grow rapidly under stress or in the presence of corrosive materials such as hydrogen sulfide, chlorides, carbon dioxide and water. For example, drill pipe failure from fatigue often initiates at the bases of pits, at tong marks or in regions where the tube has been worn by abrasion. Pitting is caused by corrosion and erosion between the steel and a surrounding or containing fluid. Abrasive wear occurs in many steel structures. Good examples are (1) the wear on drill pipe caused by hard formations when drilling crooked holes or (2) the wear on both the sucker rod and the producing tubing in rod pumping oil wells. Specifications exist for the maximum permitted wear under these and other circumstances. In many instances, such induced damage is first found by automated magnetic techniques.

Basic Ferromagnetic Materials Production

In the production of ferrous alloys, iron ore is converted to steel in one or more furnaces where it is melted and refined and where alloying elements are added. While in the liquid state, the metal is poured into a mold and allowed to solidify into a shape typically called an *ingot* or is continuously cast.

Ingots are quite large and must be formed into more manageable shapes by hot working through a series of rolls or mills. These semifinished shapes are called *blooms, billets* or *slabs,* depending on size and shape. A bloom is an intermediate product, rectangular in shape with a cross sectional area typically larger than 0.02 m^2 (36 $in.^2$). A billet can be round or square with a cross sectional area from 1600 mm^2 to 0.02 m^2 (2.5 to 36 $in.^2$). A slab is an intermediate shape between an ingot and a plate with a width at least twice its thickness.

Inherent Discontinuities

This group of discontinuities occurs during the initial melting and refining processes and during solidification from the molten state. Such discontinuities are present before rolling or forging is performed to produce intermediate shapes.

Pipe

When molten metal is continuously cast or poured into a mold, solidification progresses gradually, starting at the sides and progressing upward and inward. There is progressive shrinkage during solidification. For ingots, the last metal to solidify is at the top and center of the mold. Because of the shrinkage, there is typically insufficient liquid metal remaining to fill the mold and a depression or cavity is formed.

In addition, impurities such as oxides and entrapped gases tend to migrate to the center and top of a mold and may become embedded in the last portions to solidify. After solidification, the upper portion is cut off or cropped and discarded, removing most of the shrinkage cavity and impurities. However, if the cavity is deeper than normal or if the cropping is short, some of the unsound metal will show up in the intermediate shape as a void called *pipe*. Pipe is almost always centered in the semifinished shape and is undesirable for most purposes.

Nonmetallic Inclusions

All steel contains nonmetallic matter that mainly originates in deoxidizing materials added to the molten metal during the refining operation. These additives are easily oxidized metals such as aluminum, silicon, manganese and others. The oxides and sulfides of the metals make up the majority of nonmetallic inclusions. When finely divided and well distributed, these discontinuities are often not objectionable.

However, sometimes the additives collect during solidification and form large clumps in an ingot. During primary processing these large clumps are rolled out into long discontinuities called *stringers*. In highly stressed components, stringers can act as nucleation points for fatigue cracking. In certain test objects, stringers are acceptable in a limited amount. Government and industry specifications on steel cleanliness define the amount of inclusions or stringers that may be accepted.

The addition of lead or sulfur to molten steel is a common practice for the alloys known as *free machining steels*. These alloys contain a large number of nonmetallic inclusions that break or chip during machining operations. Magnetic particle tests of free machining alloys often indicate an alarming number of discontinuities that are not considered detrimental in service.

Blowholes

As molten steel is poured into an ingot and solidification commences, there is an evolution of gases. These gases rise through the liquid in the form of bubbles and many escape or migrate to the cropped portion of the ingot.

However, some gases can be trapped in the ingot, forming the discontinuities known as *blowholes*. Most blowholes are clean and will weld or fuse shut during primary and secondary rolling. Those near the surface may have an oxidized skin and will not fuse, appearing as seams in the rolled, forged or extruded product. Oxidized blowholes in the interior of slabs appear as laminations in plate products.

Ingot Cracks

Contraction of the metal during solidification and cooling of the ingot generates significant surface stresses and internal stresses that can result in cracking. If the cracks are internal and no air reaches them, they are usually welded shut during rolling and do not result in discontinuities. If they are open to the air or otherwise become oxidized, they will not seal but remain in the finished product.

During the rolling of an ingot into a billet, oxidized cracks form long seams. It is common practice to use magnetic particle tests of billets before additional processing. Such preprocessing tests permit the removal of seams by grinding, chipping or flame scarfing. If not removed before rolling or working, seams are further elongated in finished shapes and this may make the final product unsuitable for many applications.

Primary Processing Discontinuities

When steel ingots are worked down to shapes such as billets, slabs and forging blanks, some inherent discontinuities may remain in the finished product. In addition, rolling or forming operations may themselves introduce other discontinuities. The primary processes considered here include the hot working and cold working methods of producing shapes such as plate, bar, rod, wire, tubing and pipe.

Forging and casting are also included in this category because they typically require additional machining or other subsequent processing. All the primary processes have the potential for introducing discontinuities into clean metal.

Seams

Seams in bar, rod, pipe, wire and tubing are usually objectionable. They originate from ingot cracks and despite preprocessing tests, some cracks can be overlooked or incompletely removed.

Rolling and drawing operations can also produce seams in the finished product. If the reduction on any of the rolling passes is too great, an overfill may then produce a projection from the billet. This projection can be folded or lapped on subsequent passes, producing a long deep seam.

The reverse also occurs if the shape does not fill the rolls, resulting in a depression or surface groove. On subsequent rolling passes, this underfill produces a seam running the full length of the shape. Seams originating from overfilled rolls usually emerge at an acute angle to the surface. Seams caused by underfilled rolls are likely to be normal to or perpendicular to the surface.

Seams or die marks can be introduced by defective or dirty dies during drawing operations. Such seams are often fairly shallow and may not be objectionable, especially when subsequent machining removes the seam. Seams are always objectionable in components that experience repeated or cyclic stresses in service. These seams can initiate fatigue cracks.

Laminations

Laminations in plate, sheet and strip are formed when blowholes or internal cracks are not fused shut during rolling but are flattened and enlarged. Laminations are large and potentially troublesome areas of horizontal discontinuity.

Magnetic particle testing detects lamination only when it reaches and breaks the edges of a plate. Laminations that are completely internal to the test object typically lie parallel to its surface and cannot be detected by magnetic particle procedures.

Cupping

Cupping occurs during drawing or extruding operations when the interior of the shape does not flow as rapidly as the surface. The result is a series of internal ruptures that are serious whenever they occur. Cupping can be detected by the magnetic particle method only when it is severe and approaches the surface.

Cooling Cracks

Bar stock is hot rolled and then placed on a bed or cooling table and allowed to reach room temperature. During cooling, thermal stresses may be set up by uneven rates of temperature change within the material. These stresses can be sufficient for generating cracks.

Cooling cracks are generally longitudinal but because they tend to curve around the object shape, they are not necessarily straight. Such cracks may be long and often vary in depth along their length. Magnetic particle indications of cooling cracks therefore can vary in intensity (heavier where the crack is deepest).

Forging Discontinuities

Forgings are produced from an ingot, a billet or forging blank that is heated to the plastic flow temperature and then pressed or hammered between dies into the desired shape. This hot working process can produce a number of discontinuities, some of which are described below.

Flakes

Flakes are internal ruptures that some believe are caused by cooling too rapidly. Another theory is that flakes are caused by the release of hydrogen gas during cooling.

Flakes usually occur in fairly heavy sections and some alloys are more susceptible than others. These ruptures are usually well below the surface, typically more than halfway between the surface and the center. Because of their positioning, flakes are not detectable by magnetic particle techniques unless machining brings the discontinuity close to the surface.

Forging Bursts

When steel is worked at improper temperatures, it can crack or rupture. Reducing a cross section too rapidly can also cause forging bursts or severe cracking.

Forging bursts may be internal or surface anomalies. When at or near the surface, they can be detected by the magnetic particle method. Internal bursts are not generally detected with magnetic particles unless machining brings them near the surface.

Forging Laps

During the forging operation, there are several factors that can cause the surface of the object to fold or lap. Because this is a surface phenomenon, exposed to air, laps are oxidized and do not fuse when squeezed into the object (Fig. 1).

Forging laps are difficult to detect by any nondestructive testing method. They lie at only slight angles to the surface and may be fairly shallow. Forging laps are almost always objectionable because they serve as fatigue crack initiation points.

Flash Line Tears

As the dies close in the final stage of the forging process, a small amount of metal is extruded between the dies. This extruded metal is called *flash* and must be removed by trimming.

If the trimming is not done or not done properly, cracks or tears can occur along the flash line. Flash line tears are reliably detected by magnetic particle testing.

Casting Discontinuities

Castings are produced by pouring molten metal into molds. The combination of high temperatures, complex shapes, liquid metal flow and problematic mold materials can cause a number of discontinuities peculiar to castings. Some of these are described below.

Cold Shuts

Cold shuts originate during pouring of the metal when a portion of the molten liquid solidifies before joining with the remaining liquid. The presence of an oxidized surface, even though it is liquid or near liquid, prevents fusion when two surfaces meet. This condition can result from splashing, interrupted pouring or the meeting of two streams of metal coming from different directions.

Cold shuts can be shallow skin effects or can extend quite deeply into the casting. Shallow cold shuts called *scabs* can be removed by grinding. Deep cold shuts cannot be repaired.

Hot Tears and Shrinkage Cracks

Hot tears are surface cracks that occur during cooling after the metal has solidified. They are caused by thermal stresses generated during uneven cooling. Hot tears usually originate at abrupt changes in cross section where thin sections cool more rapidly than adjacent heavier masses.

Shrinkage cracks are also surface cracks that occur after the metal cools. They are caused by the contraction or reduction in volume that the casting experiences during solidification.

Weldment Discontinuities

Welding can be considered a localized casting process that involves the melting of both base and filler metal. Welds are subject to the same type of discontinuities as castings but on a slightly different scale. In addition, other discontinuities may be formed as a result of improper welding practices. Some of the discontinuities peculiar to weldments are described below.

Lack of Fusion and Lack of Penetration

Failure to melt the base metal results in a void between the base and filler materials. This lack of fusion can be detected by magnetic particle methods if it is close enough to the weld surface.

With lack of penetration, the root area of the weld is inadequately filled. Magnetic particle testing does not generally detect lack of penetration.

Heat Affected Zone Cracks and Crater Cracks

Cracks in the base metal adjacent to the weld bead can be caused by the thermal stresses of both melting and cooling. Such cracks are usually parallel to the weld bead. Heat affected zone cracking is easily detected by magnetic particle testing.

Cracks in the weld bead caused by stresses from solidification or uneven

cooling are called *crater cracks*. Cracks caused by solidification usually occur in the final weld puddle. Cracks caused by uneven cooling occur in the thin portion at the junction of two beads. Magnetic particle testing is widely used to detect crater cracks.

Manufacturing and Fabrication Discontinuities

Discontinuities associated with various finishing operations, e.g., machining, heat treating or grinding are described below.

Machining Tears

Machining tears occur if a tool bit drags metal from the surface rather than cutting it. The primary cause of this is improperly shaped or dull cutting edges on the bit.

Soft or ductile metals such as low carbon steel are more susceptible to machining tears than harder medium carbon and high carbon steels. Machining tears are surface discontinuities and are reliably detected by magnetic particle testing.

Heat Treating Cracks

When steels are heated and quenched (or otherwise heat treated) to produce properties for strength or wear, cracking may occur if the operation is not suited to the material or the shape of the object. The most common sort of such cracking is *quench cracking,* which occurs when the metal is heated above the critical transition point and is then rapidly cooled by immersing it in a cold medium such as water, oil or air.

Cracks are likely to occur at locations where the object changes shape from a thin to a thick cross section, at fillets or notches. The edges of keyways and roots of splines or threads are also susceptible to quench cracking.

Cracks can also originate if the metal is heated too rapidly, causing uneven expansion at changes of cross section. In addition, rapidly increasing heat can cause cracking at corners, where heat is absorbed from three surfaces and is therefore absorbed much more rapidly than by the body of the object. Corner cracking can also occur during quenching because of thermal stresses from uneven cooling.

Straightening and Grinding Cracks

The uneven stresses caused by heat treating frequently result in distortion or warping and the metal forms must be straightened into their intended shape. If the distortion is too great or the objects are very hard, cracking can occur during the straightening operation.

Surface cracks can also occur in hardened objects during improper grinding operations. Such thermal cracks are created by stresses from localized overheating of the surface under the grinding wheel. Overheating can be caused by using the wrong grinding wheel, a dull or glazed wheel, insufficient or poor coolant, feeding too rapidly or cutting too heavily. Grinding cracks are especially detrimental because they are perpendicular to the object surface and have sharp crack tips that propagate under repeated or cyclic loading.

Another type of discontinuity that may occur during grinding is cracking caused by residual stresses. Hardened objects may retain stresses that are not high enough to cause cracking. During grinding, localized heating added to entrapped stresses can cause surface ruptures. The resulting cracks are usually more severe and extensive than typical grinding cracks.

Plating, Pickling and Etching Cracks

Hardened surfaces are susceptible to cracking from electroplating, acid pickling or etching processes.

Acid pickling can weaken surface fibers of the metal, allowing internal stresses from the quenching operation to be relieved by crack formation. Another cracking mechanism is the interstitial absorption of hydrogen released by the acid etching or electrodeposition process. Absorption of nascent hydrogen adds to the internal stresses of the object and subsequently may cause cracking. This mechanism, called *hydrogen embrittlement,* can result in cracking during the etching or plating operation or at some later time when additional service stresses are applied.

Service Discontinuities

Discontinuities also occur from service conditions. Some discontinuities such as deformation and wear are not detected by the magnetic particle test, but the technique is useful for indicating the discontinuities listed below.

Overstress Cracking

All materials have load limits (called *ultimate strength*). When service stressing exceeds this limit, cracking occurs. Usually the failure is completed by surface fracture of the object. In this case, the crack is easy to detect and magnetic particle testing is not required. However,

there are instances where surfaces do not visibly separate and magnetic particle testing is needed to detect and locate the cracking.

Fatigue Cracking

Objects subjected to repeated alternating or fluctuating stresses above a specific level eventually develop a crack. The crack continues to grow until the object fractures. The stress level at which fatigue cracks develop is called the *fatigue strength* of the material and is well below the ultimate strength of the material. There is an inverse relationship between the number of stress applications (cycles) and the stress level necessary to initiate cracking: low cycles and high stress produce the same results as high cycles and low stress.

Another factor contributing to fatigue cracking is the presence of surface anomalies such as copper penetration sharp radii, nicks and tool marks. These act as stress raisers and lower both the number of cycles and the stress level needed to initiate cracking. Fatigue cracking typically occurs at the surface and is reliably detected by magnetic particle testing.

Corrosion

Magnetic particle procedures are not used to detect surface corrosion or pitting. However, there are secondary discontinuities that can be revealed by the magnetic particle method. When objects are under sustained stress, either internal or external, and are at the same time exposed to a corrosive atmosphere, a particular kind of cracking results. Known as *stress corrosion cracking,* this discontinuity is easily detected by magnetic particle testing.

Another occurrence related to corrosion is pitting. Pitting itself does not usually produce magnetic particle indications (in some applications, sharp edged pits can hold particles). Pitting can serve as a stress raiser and often initiates fatigue cracks. Fatigue cracks originating at corrosion pits are reliably detected by the magnetic particle method.

Applications of Magnetic Flux Leakage Testing

Wire Ropes

An interesting example of an elongated steel product inspected by magnetic flux leakage testing is wire rope. Such ropes are used in the construction, marine and oil production industries, in mining applications and elevators for personnel and raw material transportation. Testing is performed to determine cross sectional loss caused by corrosion and wear and to detect internal and external broken wires. The type of flux loop used (electromagnet or permanent magnet) can depend on the accessibility of the rope. Permanent magnets might be used where taking power to an electromagnet might cause logistic or safety problems.

By making suitable estimates of the parameters involved, a reasonably good estimate of the flux in the rope can be made. Because discontinuities can occur deep inside the rope material, it is essential to maintain the rope at a high value of magnetic flux density, 1.6 to 1.8 T (16 to 18 kG). Under these conditions, breaks in the inner regions of the rope will produce magnetic flux leakage at the surface of the rope.

The problem of detecting magnetic flux leakage from inner discontinuities is compounded by the need to maintain the magnetic probes far enough from the rope for splices in the rope to pass through the test head. Common probes include hall effect detectors and encircling coils.

The cross sectional area of the rope can be measured by sensing changes in the magnetic flux loop that occur when the rope gets thinner. The air gap becomes larger and so the value of the field intensity falls. This change can easily be sensed by placing hall effect probes anywhere within the magnetic circuit.

Internal Casing or Pipelines

The testing of inservice well casing or buried pipelines is often performed by magnetic flux leakage techniques. Various types of wall loss mechanisms occur, including internal and external pitting, erosion and corrosion caused by the proximity of dissimilar metals.

From the point of view of magnetizing the pipe metal in the longitudinal direction, the two methods are identical. The internal diameters and metal masses involved in the magnetic flux loop indicate that some form of active field excitation must be used. Internal diameters of typical production or transportation tubes range from about 100 mm (4 in.) to about 1.2 m (4 ft).

If the material is generally horizontal, some form of drive mechanism is required. Because the test device (a robotic crawler) may move at differing speeds, the magnetic flux leakage probe should have a signal response independent of velocity. For devices that operate vertically, such as petroleum well casing test systems, coil probes can be used if the tool is pulled from the bottom of the well at a constant speed. In both types of instrument, the

probes are mounted in pads pressed against the inner wall of the pipe.

Because both line pipe and casing are manufactured to outside diameter size, there is a range of inside diameters for each pipe size. Such ranges may be found in specifications. To make the air gap as small as possible, soft iron attachments can be screwed to the pole pieces.

For the pipeline crawler, a recorder package is added and the signals from discontinuities are tape recorded. When the tapes are retrieved and played back, the areas of damage are located. Pipe welds provide convenient magnetic markers. With the downhole tool, the magnetic flux leakage signals are sent up the wire line and processed in the logging truck at the wellhead.

A common problem with this and other magnetic flux leakage equipment is the need to determine whether the signals originate from discontinuities on the inside or the outside surface of the pipe. Production and transmission companies require this information because it lets them determine which form of corrosion control to use. The test shoes sometimes contain a high frequency eddy current probe system that responds only to inside surface discontinuities. Thus, the occurrence of both magnetic flux leakage and eddy current signals indicates an inside surface discontinuity whereas the occurrence of a magnetic flux leakage signal indicates only an outside surface discontinuity.

Problems with this form of testing include the following.

1. The magnetic flux leakage system cannot measure elongated changes in wall thickness, such as might occur with general erosion.
2. If there is a second string around the tested string, the additional metal contributes to the flux loop, especially in areas where the two strings touch.
3. A relatively large current must be sent down the wire line to raise the pipe wall to saturation. Temperatures in deep wells can exceed 200 °C (325 °F).
4. The tool may stick downhole or underground if external pressures cause the pipe to buckle.

Cannon Tubes

In elongated tubing, the presence of rifling affects the ability to perform a good test, especially for discontinuities that occur in the roots of the rifling. Despite the presence of extraneous signals from internal rifling, however, rifling causes a regular magnetic flux leakage signal that can be distinguished from discontinuity signals. As a simulated discontinuity is made narrower and shallower, the signal will eventually be indistinguishable from the rifle bore noise. In magnetic flux leakage testing, cannon tubes can be magnetized to saturation and scanned with hall elements to measure residual induction.

Round Bars and Tubes

In some test systems, round bars and tubes have been magnetized by an alternating current magnet and rotated under the magnet poles. Because the leakage flux from surface discontinuities is very weak and confined to a small area, the probes must be very sensitive and extremely small. The system uses a differential pair of magnetodiodes to sense leakage flux from the discontinuity. The differential output of these twin probes is amplified to separate the leakage flux from the background flux. In this system, pipes are fed spirally under the scanning station, which has an alternating current magnet and an array of probe pairs. The system usually has three scanning stations to increase the test rate.

In one similar system, round billets are rotated by a set of rollers while the billet surface is scanned by a transducer array moving straight along the billet axis. Seamless pipes and tubes are made from the round billets.

In another tube test system, the transducers rotate around the pipe as the pipe is conveyed longitudinally. Overlapping elliptical printed circuit coils are used instead of magnetodiodes and are coupled to electronic circuits by slip rings. The system can separate seams into categories according to crack depth.

Billets

A relatively common problem with square billets is elongated surface breaking cracks. By magnetizing the billet circumferentially, magnetic flux leakage can be induced in the resulting residual magnetic field.

Magnetic flux leakage systems for testing tubes exhibit the same general ability to classify seam depth. It is generally accepted that even with the lack of correlation between some of the instrument readings and the actual discontinuity depths, the automatic readout of these two systems still represents an improvement over visual or magnetic particle testing.

One technique, often called *magnetography,* for the detection of discontinuities uses a belt of flux sensitive material, magnetic tape, to record indications. Discontinuity fields magnetize the tape, which is then scanned with an array of microprobes or

hall effect detectors. Finally, the tape passes through an erase head before contacting the billet again. Because the field intensity at the corners is less than at the center of the flat billet face, a compensation circuit is required for equal sensitivity across the entire surface.

Damage Assessment

In most forms of magnetic flux leakage testing, discontinuity dimensions cannot be accurately measured by using the signals they produce. The final signal results from more than one dimension and perhaps from changes in the magnetic properties of the metal surrounding the discontinuity.

Signal shapes differ widely, depending on location, dimensions and magnetization level. It is therefore impossible to accurately assess the damage in the test object with existing equipment. Under special circumstances (for example, when surface breaking cracks can be assumed to share the same width and run normal to the material surface), it may be possible to correlate magnetic flux leakage signals and discontinuity depths. This correlation is normally impossible.

Commercially available equipment does not reconstruct all the desired discontinuity parameters from magnetic flux leakage signals. For example, the signal shape caused by a surface breaking forging lap is different from that caused by a perpendicular crack but no automated equipment uses this difference to distinguish between these discontinuities.

As with many forms of nondestructive testing, the detection of a discontinuity and subsequent followup by either nondestructive or destructive methods pose no serious problems for the inspector. Ultrasonic techniques, especially a combination of shear wave and compression wave techniques, work well for discontinuity assessment after magnetic flux leakage has detected them. In some cases, however, the discontinuity is forever hidden. Such is very often the case for corrosion in downhole and subterranean pipes.

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CHAPTER 3

Magnetism[1]

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PART 1. Fundamentals of Electromagnetism

Coulomb's Law

The nature of electromagnetism can be summarized by four vector quantities, their interaction, their relations with each other and with matter. These four time dependent vector quantities are referred to as *electromagnetic fields* and include: electric field intensity ***E***, electric flux density ***D***, magnetic field intensity ***H*** and magnetic flux density ***B***.

The study of electromagnetic fields begins with the study of basic laws of electricity and magnetism and with the use of some basic postulates. In particular, it is customary to start with Coulomb's law. This law states that *the force between two stationary charges is directly proportional to the size of the charges and is inversely proportional to the square of the distance between them*.

Adding Gauss' and Ampere's laws provides a complete set of relations describing all electrostatic, magnetostatic and induction phenomena, but not wave propagation. To include wave propagation in electromagnetic field equations, the displacement current (continuity equation) is added to Ampere's law. Doing so obtains Maxwell's equations.

Alternatively, Maxwell's equations may serve as the basic postulates and, because they form a complete set describing all electromagnetic phenomena, the required relations may be deduced. By choosing Maxwell's equations as the starting point, an assumption of the equations' accuracy is implicitly made. This is not more troublesome than assuming that Coulomb's law applies or that displacement currents exist. In either case, the proof of correctness is experimental. This is an important consideration: it specifically states that Maxwell's equations and therefore the electromagnetic field relations cannot be proven mathematically.

Use of Maxwell's Equations

Maxwell's equations do not take motion into account and therefore do not include the induction of currents due to motion. To do so, it is necessary to add the lorenz force equation and the so-called *constitutive relations*. It may also be useful to note that, by proper interpretation, relativistic effects can also be handled (this application is found in the literature).[2-6]

The approach in this chapter is to start with Maxwell's equations and derive from them all the necessary relations. In doing so, the equations are accepted as the basic postulates. In particular, at low frequencies, Maxwell's equations are identical to those of Coulomb, Faraday, Gauss and Ampere. The results derived here are general and, within the assumptions made in their derivation, apply to a wider range of applications. Only those electric and magnetic phenomena most directly related to nondestructive testing and, in particular, to magnetic particle testing are considered in detail here. Other electromagnetic phenomena are mentioned briefly for completeness of treatment.

Maxwell's equations are a set of nonlinear, coupled, first order, time dependent partial differential equations whose general solution is difficult to obtain. Some methods for the solution of the electromagnetic field equations are discussed below.

Measurement Units

One major source of confusion when applying electromagnetic field theory has been the units for measurement. Centimeter gram second (CGS) units, the electromagnetic system of units (EMU) and meter kilogram second ampere units (MKSA) are the most familiar, but other systems such as the absolute magnetic, the absolute electric and the so-called *normalized system* have also been used.

More disturbing is the fact that mixed units have also been used. For example, practitioners used to use MKSA units such as the ampere for electrical quantities and EMU units such as the gauss for magnetic quantities.

Only the International System (SI) of Units is used in this section. The benefit gained in consistency far outweighs any inconvenience.

Another problem encountered in practice is the confusion between *magnetic field intensity* ***H***, sometimes called *field strength,* and *magnetic flux density* ***B.*** The term *magnetic field* is often used for ***H*** or ***B*** or both, depending on the situation. To avoid such confusion, the quantity ***B*** is used consistently for the magnetic flux density while ***H*** is the magnetic field intensity. Similarly, ***E*** is the *electric field intensity* and ***D*** is the *electric flux density*.

PART 2. Field Relations and Maxwell's Equations

Maxwell's equations are summarized in Eq. 1 through Eq. 4 in differential form and in Eq. 5 through Eq. 8 in integral form. Equation 9 is the lorenz force equation which describes the interaction of electric and magnetic fields with electric charge:

(1) $$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

(2) $$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

(3) $$\nabla \cdot \boldsymbol{D} = \rho$$

(4) $$\nabla \cdot \boldsymbol{B} = 0$$

(5) $$\oint_c \boldsymbol{E} \cdot d\boldsymbol{\ell} = -\frac{d\Phi}{dt}$$

(6) $$\oint_c \boldsymbol{H} \cdot d\boldsymbol{\ell} = I + \int_S \frac{\partial \boldsymbol{D}}{\partial t} \cdot d\boldsymbol{s}$$

(7) $$\oint_s \boldsymbol{D} \cdot d\boldsymbol{s} = Q$$

(8) $$\oint_s \boldsymbol{B} \cdot d\boldsymbol{s} = 0$$

(9) $$\boldsymbol{F} = q\left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right)$$

where $d\boldsymbol{\ell}$ is differential length (meters), $d\boldsymbol{s}$ is differential area (square meters), $\boldsymbol{E}$ is electric field intensity ($V \cdot m^{-1}$), $\boldsymbol{F}$ is force (N), I is current (A), $\boldsymbol{J}$ is current density ($A \cdot m^{-2}$), q is electric charge (coulomb) v is charge velocity (meter per second) and ∇ is the del operator.

Equations 1 and 5 are a statement of Faraday's law of induction. Equations 2 and 6 are a modified form of Ampere's law. The addition of the displacement current term $\partial D \cdot (\partial t)^{-1}$ was Maxwell's contribution to the original laws of electricity. The displacement current, although often taken as an assumption, is nothing more than an expression that can be derived from the continuity equation. Equations 4 and 8 are Gauss' law for magnetic sources and they state the nonexistence of isolated magnetic charges or poles. Equations 3 and 7 are Gauss' law for electric charges.

At this point, the equations are neither linear nor nonlinear. This important behavior is determined through material properties and is not inherent in the equations. The material properties follow the constitutive relations:

(10) $$\boldsymbol{B} = \mu \boldsymbol{H}$$

(11) $$\boldsymbol{D} = \epsilon \boldsymbol{E}$$

(12) $$\boldsymbol{J} = \sigma \boldsymbol{E}$$

If any of these relations is nonlinear, the field relations are nonlinear. In particular, the permeability is known to be highly nonlinear for ferromagnetic materials. In some cases, the conductivity and permittivity ϵ may also be nonlinear.

The electric conductivity σ, magnetic permeability μ and the electric permittivity ϵ are generally tensor quantities. Although for many practical purposes it can be assumed that they are scalar quantities, materials are encountered in practice that behave differently. These exceptions are defined through linearity, homogeneity and isotropy of the materials. Only for linear, isotropic, homogeneous materials are the material properties single-valued scalar quantities.

Linearity, Homogeneity and Isotropy

A medium is said to be *homogeneous* if its properties do not vary from point to point within the material. A medium is *linear* in a property when that property remains constant as the field changes. The permeability of most nonmagnetic materials is considered to be independent of the field. These materials are usually considered to be linear in permeability. A material is *isotropic* if its properties are

independent of direction. This means that the permeability of an isotropic material must be the same in all three spatial directions.

A good example of an anisotropic material is a permanent magnet. Most materials, including iron, are anisotropic on the crystal level. Because these crystals are randomly oriented, it may often be assumed that a macroscopic material is isotropic. This is not necessarily the case for hard steels or for steels with large, preferred orientations.

Static Fields

By setting to zero all time derivatives in Maxwell's equations, the equations for the static electric and magnetic fields are obtained. The four equations become:

(13) $\nabla \times \boldsymbol{E} = 0$

(14) $\nabla \times \boldsymbol{H} = \boldsymbol{J}$

(15) $\nabla \cdot \boldsymbol{D} = \rho$

(16) $\nabla \cdot \boldsymbol{B} = 0$

(17) $\oint_c \boldsymbol{E} \cdot d\boldsymbol{\ell} = 0$

(18) $\oint_c \boldsymbol{H} \cdot d\boldsymbol{\ell} = I$

(19) $\oint_s \boldsymbol{D} \cdot d\boldsymbol{s} = Q$

(20) $\oint_s \boldsymbol{B} \cdot d\boldsymbol{s} = 0$

Equations 13 and 15 are the governing equations for electrostatic fields (Faraday's and Gauss' laws). Equations 14 and 16 are Ampere's and Gauss' (magnetic) laws for magnetostatic applications. Note that Eqs. 13 and 15 do not contain the magnetic field whereas Eqs. 14 and 16 do not depend on the electric field. Thus, the equations for electrostatics and magnetostatics are completely decoupled and electrical quantities can be calculated without resorting to the magnetic field and vice versa.

As with the general system of equations, the lorenz equation has to supplement these equations. Because of the decoupling of the two sets, the force equation (Eq. 9) should be used in its electrostatic form for electrostatic fields:

(21) $\boldsymbol{F} = q\boldsymbol{E}$

For magnetostatic fields, only the magnetic force exists:

(22) $\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$

The electric current or, more conveniently, the electric current density $\boldsymbol{J}$ is the source of the magnetic field intensity (Eq. 14).

Equation 18 is particularly useful because it allows the calculation of the magnetic field intensity and the determination of its direction. If the integration is taken such that the normal to the surface enclosed by the contour C is in the direction of the current, then the field is described by the right hand rule: if the current is in the direction of the thumb, the field is in the direction of the fingers (Fig. 1). The total current I in Eq. 18 is the current enclosed within the contour.

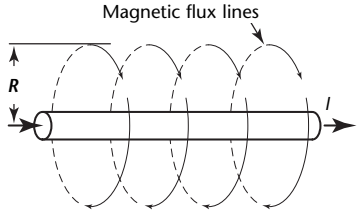
Magnetic Vector Potential

Equation 14 is a cross product and results in a vector quantity $\boldsymbol{J}$. Because the cross product of a vector is also a vector, the magnetic flux density $\boldsymbol{B}$ may be written as the curl (cross product) of another vector $\boldsymbol{A}$:

(23) $\boldsymbol{B} = \nabla \times \boldsymbol{A}$

Thus, Ampere's law (Eq. 14) can be written as:

FIGURE 1. Right hand rule: if the thumb of the right hand is in the direction of the current, the fingers show the direction of the magnetic field.



$$\textbf{(24)} \quad \nabla \times \frac{1}{\mu}(\nabla \times \boldsymbol{A}) = \boldsymbol{J}$$

The vector $\boldsymbol{A}$ is called a *magnetic vector potential*. For an isotropic linear medium, the following vector identity can be used to simplify this expression:

$$\textbf{(25)} \quad \nabla \times \nabla \times \boldsymbol{A} = \nabla(\nabla \cdot \boldsymbol{A}) - \nabla^2 \boldsymbol{A}$$

A vector is only defined when both its divergence and curl are specified. The divergence may be specified in different ways. The simplest is to set it equal to zero in Eq. 25. Ampere's law then becomes:

$$\textbf{(26)} \quad \nabla^2 \boldsymbol{A} = -\mu \boldsymbol{J}$$

which is the vector poisson equation.

Equation 23 defines the magnetic vector potential. This definition of the magnetic vector potential $\boldsymbol{A}$ allows the use of a simpler poisson equation instead of the original field equations.

Biot-Savart Law

The purpose of field relations is to solve field problems. Any of the relations obtained previously may be used for this purpose. In particular, Eq. 14 can be used for general field problems while Eq. 18 is useful for solution of highly symmetric problems. In problems where no such symmetry can be found but which are simple enough not to require the solution of the general Eq. 26, another method can be used. For these types of problems, the magnetic vector potential is used in still another form. Considering the current in a straight wire in Fig. 2, the following can be written at point *P:*

$$\textbf{(27)} \quad d\boldsymbol{A} = \frac{\mu I}{4\pi} \frac{d\boldsymbol{\ell}}{\boldsymbol{R}}$$

In Eq. 27, the definition of the magnetic vector potential in Eq. 23 has been used. In order to find the total magnetic vector potential, this differential is integrated over the closed contour formed by the current to obtain:

$$\textbf{(28)} \quad \boldsymbol{A} = \frac{\mu I}{4\pi} \oint_c \frac{d\boldsymbol{\ell}}{\boldsymbol{R}}$$

In order to find the field intensity or the flux density, it is necessary to find the curl of this expression by performing the operations in Eq. 23.

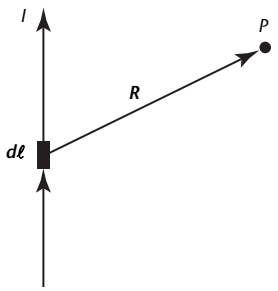
If the magnetic vector potential in Eq. 28 is substituted back into its definition, the following expression is obtained for the flux density:

$$\textbf{(29)} \quad \boldsymbol{B} = \frac{\mu I}{4\pi} \oint_c \frac{d\boldsymbol{\ell} \times \hat{\boldsymbol{R}}}{\boldsymbol{R}^2}$$

where $\hat{\boldsymbol{R}}$ denotes a unit vector in the direction of $\boldsymbol{R}$ in Fig. 2.

This expression, known as the *Biot-Savart law*, allows the calculation of the flux density directly. It is particularly useful for situations where the current paths are clear and the required contour integration is in the direction of the currents.

FIGURE 2. Straight current carrying wire and relation of current and field at point *P*.



PART 3. Electromagnetic Fields and Boundaries

Steady State Alternating Current Fields

Low frequency alternating current fields are unique in that a simpler form of Maxwell's equations can be used. The displacement current term ($\partial D \cdot \partial t^{-1}$) in Eq. 2 or Eq. 6 depends on frequency and is very small for low frequencies. In fact, this term may be neglected within conducting materials and for all frequencies below about $10E + 13$ Hz. If this assumption is introduced and the term neglected, the *pre-Maxwell* set of equations is obtained.

By introducing a phasor notation for all vectors, the time dependency is not explicitly used and the transformed system is both simpler in presentation and in solution. A general vector can be expressed as a phasor by the following definition:

$$\textbf{(30)} \quad A(x,y,z,t) = \text{real}\left[\tilde{A}(x,y,z)e^{j\omega t}\right]$$

where j is current density ($A \cdot m^{-2}$), t is time (seconds) and ω is angular frequency (radians per second).

Maxwell's equations (in differential form) can now be written as:

$$\textbf{(31)} \quad \nabla \times \tilde{\boldsymbol{E}} = -j\omega\tilde{\boldsymbol{B}}$$

$$\textbf{(32)} \quad \nabla \times \tilde{\boldsymbol{H}} = \tilde{\boldsymbol{J}} + j\omega\tilde{\boldsymbol{D}}$$

$$\textbf{(33)} \quad \nabla \cdot \tilde{\boldsymbol{D}} = \rho$$

$$\textbf{(34)} \quad \nabla \times \tilde{\boldsymbol{B}} = 0$$

In this form, all time derivatives were written as:

$$\textbf{(35)} \quad \frac{\partial \tilde{\boldsymbol{A}}}{\partial t} = j\omega\tilde{\boldsymbol{A}}$$

This version of Maxwell's equations is often called the *quasistatic form* and is very convenient for many alternating current calculations at low frequencies, including alternating current leakage fields. The following equation is obtained by a method similar to that used to obtain Eq. 26:

$$\textbf{(36)} \quad \nabla \times \frac{1}{\mu}\left(\nabla \times \tilde{\boldsymbol{A}}\right) = \tilde{\boldsymbol{J}} + j\sigma\omega\tilde{\boldsymbol{A}}$$

This equation, often called the *curl-curl equation* is a diffusion equation and is the basis of many analytical and numerical methods. By using the vector relation in Eq. 25, Eq. 36 can be written as:

$$\textbf{(37)} \quad \nabla^2\tilde{\boldsymbol{A}} - \nabla\left(\nabla \cdot \tilde{\boldsymbol{A}}\right) = -\mu\tilde{\boldsymbol{J}} + j\omega\mu\sigma\tilde{\boldsymbol{A}}$$

Here, the divergence of the magnetic vector potential may be chosen in any convenient, physically sound method. By choosing a zero divergence and rewriting the laplacian $\nabla^2\tilde{\boldsymbol{A}}$ in its differential form, a partial differential equation can be written for two-dimensional (Eq. 38), axisymmetric (Eq. 39) and three-dimensional geometries (Eq. 40). Equations 37 through 40 assume linear permeability:

$$\textbf{(38)} \quad \frac{1}{\mu}\left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right) = -J_s + j\omega\sigma A_z$$

$$\textbf{(39)} \quad \frac{1}{\mu}\left(\frac{\partial^2 A_\phi}{\partial r^2} + \frac{1}{r}\frac{\partial A_\phi}{\partial r} + \frac{\partial^2 A_\phi}{\partial z^2} - \frac{A_\phi}{r^2}\right) = -J_s + j\omega\sigma A_\phi$$

$$\textbf{(40)} \quad \frac{1}{\mu}\left(\frac{\partial^2 \tilde{\boldsymbol{A}}}{\partial x^2} + \frac{\partial^2 \tilde{\boldsymbol{A}}}{\partial y^2} + \frac{\partial^2 \tilde{\boldsymbol{A}}}{\partial z^2}\right) = -J_s + j\omega\sigma\tilde{\boldsymbol{A}}$$

These equations were obtained by substituting the magnetic vector potential in Maxwell's equations. Because other potentials (vectors or scalars) can be defined, the field equations may be obtained in terms of these functions or in terms of the original field quantities $\tilde{\boldsymbol{B}}$ and $\tilde{\boldsymbol{H}}$. A poissonian (or laplacian) form as in Eq. 40 is particularly useful because of the standard methods available for their solution.

Time Dependent Fields

Instead of neglecting terms in Maxwell's equations, if the complete sets in Eqs. 1 through 4 or Eqs. 5 through 8 are used, then the general time dependent form of Maxwell's equations is obtained. As was mentioned above, this form is completely general and, when combined with the appropriate boundary conditions, can be solved to obtain all electromagnetic phenomena, including those related to static fields. In practice, exact solutions are rarely obtained because of the complexity involved. Approximations or numerical methods are often required for the solutions of this type of problem.

Wave Propagation

When describing wave propagation, the time dependent form must be used. A wave equation may be obtained by using the definition of the magnetic vector potential in Eq. 23. By substituting this into Eqs. 1 and 2 and using the constitutive relations in Eqs. 10 and 11, the following equation is obtained for linear, isotropic material (where permeability μ is constant):

$$\textbf{(41)}\quad \nabla\times\nabla\times\boldsymbol{A} = \mu\boldsymbol{J} + \mu\epsilon\frac{\partial}{\partial t}\left(-\nabla V - \frac{\partial \boldsymbol{A}}{\partial t}\right)$$

where V is magnetic scalar potential (volt).

Using the vector identity in Eq. 25, Eq. 41 can be written as:

$$\textbf{(42)}\quad \nabla^2\boldsymbol{A} - \mu\epsilon\frac{\partial^2\boldsymbol{A}}{\partial t^2} = -\mu\boldsymbol{J} + \nabla\left(\nabla\cdot\boldsymbol{A} + \mu\epsilon\frac{\partial V}{\partial t}\right)$$

Because the magnetic vector potential requires the definition of the curl and the divergence, it is possible to define its divergence in whatever way the situation requires, if consistent with the field equation. The following form may be chosen:

$$\textbf{(43)}\quad \nabla\cdot\boldsymbol{A} + \mu\epsilon\frac{\partial V}{\partial t} = 0$$

Equation 42 then becomes:

$$\textbf{(44)}\quad \nabla^2\boldsymbol{A} - \mu\epsilon\frac{\partial^2\boldsymbol{A}}{\partial t^2} = -\mu\boldsymbol{J}$$

This is a heterogeneous wave equation for the magnetic vector potential. It is considered a wave equation because its solution represents waves traveling at a velocity $1\cdot(\mu\epsilon)^{-0.5}$.

This particular form was found by choosing to use the magnetic vector potential. Similar wave equations may be found in terms of the electric scalar potential (Eq. 45), the magnetic field intensity (Eq. 46) or the electric field intensity (Eq. 47):

$$\textbf{(45)}\quad \nabla^2 V - \mu\epsilon\frac{\partial^2 V}{\partial t^2} = -\frac{\rho}{\epsilon}$$

$$\textbf{(46)}\quad \nabla^2\boldsymbol{H} - \mu\epsilon\frac{\partial^2\boldsymbol{H}}{\partial t^2} = 0$$

$$\textbf{(47)}\quad \nabla^2\boldsymbol{E} - \mu\epsilon\frac{\partial^2\boldsymbol{E}}{\partial t^2} = 0$$

The last two equations were obtained under source-free conditions and are therefore homogeneous wave equations for the magnetic field intensity and electric field intensity respectively.

If phasors are used in Eqs. 46 and 47, instead of time dependent vectors, similar forms are obtained for wave equations where the time derivative is replaced by $j\omega$. Thus, the wave equations in Eq. 46 and 47 can be written as:

$$\textbf{(48)}\quad \nabla^2\widetilde{\boldsymbol{H}} - k^2\widetilde{\boldsymbol{H}} = 0$$

and:

$$\textbf{(49)}\quad \nabla^2\widetilde{\boldsymbol{E}} - k^2\widetilde{\boldsymbol{E}} = 0$$

where the constant k is defined as:

$$\textbf{(50)}\quad k = \omega\sqrt{\mu\epsilon}$$

These equations are known as the *homogeneous helmholz equations* and describe the harmonic form of the electromagnetic waves.

Skin Depth

In a linear isotropic material, after substitution of the constitutive relations in Eqs. 10 through 12 and using the vector identity in Eq. 25, Eqs. 1 and 2 become:

$$\textbf{(51)} \quad \nabla^2 \boldsymbol{E} - \sigma\mu \frac{\partial \boldsymbol{E}}{\partial t} - \epsilon\mu \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0$$

$$\textbf{(52)} \quad \nabla^2 \boldsymbol{H} - \sigma\mu \frac{\partial \boldsymbol{H}}{\partial t} - \epsilon\mu \frac{\partial^2 \boldsymbol{H}}{\partial t^2} = 0$$

Thus, $\boldsymbol{E}$ and $\boldsymbol{B}$ satisfy identical wave equations with a damping (dissipative) term proportional to the conductivity and magnetic permeability of the material. In a good conductor such as most metals, the second order derivative may be neglected for low frequencies since it is due to the displacement current in Maxwell's second equation. For example, Eq. 52 becomes:

$$\textbf{(53)} \quad \nabla^2 \boldsymbol{H} - \sigma\mu \frac{\partial \boldsymbol{H}}{\partial t} = 0$$

This is a simple diffusion equation. If an alternating magnetic field intensity $H_0 \exp(j\omega t)$ or $E_0(j\omega t)$ is applied parallel to the surface of the conductor, the electric field intensity $\boldsymbol{E}$ or the magnetic field intensity $\boldsymbol{H}$ is attenuated exponentially with distance below the surface. The attenuation is $\exp(-x \cdot \delta^{-1})$ where x is the distance below the surface and δ is the *skin depth* given by:

$$\textbf{(54)} \quad \delta = \sqrt{\frac{2}{\sigma\mu\omega}}$$

This is an important factor to consider for alternating current magnetic particle testing because, even at 60 Hz, the skin depth can be quite small. For example, for a typical ferromagnetic material with a conductivity $\sigma = 5 \times 10^6$, a relative permeability $\mu_r = 100$ and a frequency $f = 60$ Hz, the skin depth $\delta = 3$ mm. This is probably an overestimate because a linear material was assumed in the derivation.

For this reason, alternating current magnetic particle methods, such as the so-called *swinging field* methods, generally detect only discontinuities which are open to the surface. These methods are more sensitive to surface breaking discontinuities because the applied field is relatively more intense at the surface.

Electromagnetic Boundary Conditions

Electromagnetic fields behave differently in different materials. The constitutive relations in Eqs. 10 through 12 are a statement of this behavior. When different materials are present, the fields across the boundaries between these materials must undergo some changes to conform to both materials. In such cases, the field may experience a discontinuity at the boundary. In order to find the necessary conditions that apply at material boundaries, assume two different materials as in Fig. 3 and apply Maxwell's equations at the boundary. For convenience, the integral form is used. By doing so, the following four conditions are obtained:

$$\textbf{(55)} \quad E_{1\tau} = E_{2\tau}$$

$$\textbf{(56)} \quad \hat{\boldsymbol{n}} \times \left(H_{1\tau} - H_{2\tau}\right) = \tilde{\boldsymbol{J}}_s$$

$$\textbf{(57)} \quad \hat{\boldsymbol{n}} \cdot \left(D_{1n} - D_{2n}\right) = \rho_s$$

$$\textbf{(58)} \quad B_{1n} = B_{2n}$$

The boundary conditions are the same for the magnetostatic and time varying fields. These conditions are summarized as follows:

1 The tangential component of the electric field intensity E and the normal component of the magnetic flux density B are continuous across the boundary.
2. The normal component of the electric flux density D and the tangential component of the magnetic field intensity H are discontinuous across the boundary. The discontinuity depends on the existence of surface charges and currents. For situations where no such charges or currents exist, either component may be continuous, depending on the materials and the fields involved.

The four conditions presented in Eqs. 55 through 58 can be used in order to describe the fields in different materials and across their boundaries.

The four conditions are not entirely independent and should be specified with care. For example, in time varying fields, specification of the tangential component of E (Eq. 55) is equivalent to the specification of the normal component of B (Eq. 58). Similarly, specification of the

tangential component of H is equivalent to that of the normal component of D. Only two of the four may be specified independently (the tangential component of E and the tangential component of H or any other acceptable combination). Overspecification of boundary conditions may result in contradiction of conditions and may therefore be in error.

The boundary conditions in Eqs. 55 through 58 were obtained by using Maxwell's equations directly. In order to render these relations more useful, it is convenient to introduce the constitutive relations in these conditions and find the interface conditions for some special classes of common materials. Two such groups of materials often found in practice are:

1. boundary conditions between two lossless media (a lossless medium is one that has zero conductivity with arbitrary permittivity and permeability; two perfectly insulating materials are considered here); and
2. boundary conditions between a lossless material and a good conductor.

At the boundary between two good insulators, no current densities and free charges are normally present. Thus, all four components in Eqs. 55 through 58 are continuous. These then can be rewritten using the constitutive relations in Eqs. 10 and 12 as:

(59) $$\frac{D_{1\tau}}{D_{2\tau}} = \frac{\epsilon_1}{\epsilon_2}$$

(60) $$\frac{B_{1\tau}}{B_{2\tau}} = \frac{\mu_1}{\mu_2}$$

(61) $$\epsilon_1 E_{1n} = \epsilon_2 E_{2n}$$

(62) $$\mu_1 H_{1n} = \mu_2 H_{2n}$$

At the interface between a good conductor and an insulator, both surface current densities and free charges may exist. The electric field is zero inside a perfect conductor and both the tangential component of the electric field intensity and the normal component of the electric flux density must be zero inside the conductor. The boundary conditions (Eqs. 55 to 58) then become:

(63) $$E_{1\tau} = 0$$

(64) $$\hat{\boldsymbol{n}} \times \left(H_{1\tau} - H_{2\tau}\right) = \boldsymbol{J}_s$$

(65) $$\hat{\boldsymbol{n}} \cdot D_{1n} = \rho_s$$

(66) $$B_{1n} = B_{2n}$$

Note that while Eqs. 63 through 66 are correct for the static field, for the time varying field, both $\boldsymbol{B}$ and $\boldsymbol{H}$ must also be zero inside a perfect conductor. Thus, Eqs. 63 through 66 must be modified for the time varying case to:

(67) $$E_{1\tau} = E_{2\tau} = 0$$

When $H_{2\tau} = 0$, then:

(68) $$\hat{\boldsymbol{n}} \times H_{1\tau} = \boldsymbol{J}_s$$

When $D_{2n} = 0$, then:

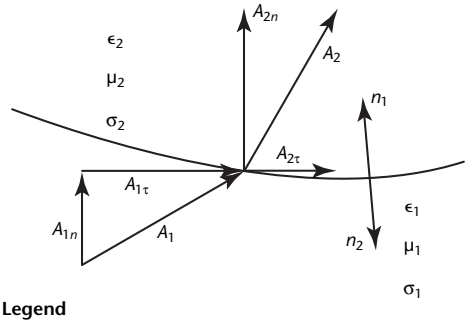
(69) $$\hat{\boldsymbol{n}} \cdot D_{1n} = \rho_s$$

(70) $$B_{1n} = B_{2n} = 0$$

Note that the boundary conditions in Eqs. 67 through 70 only apply for perfect conductors. This rarely arises except for simplified problems and for superconductors. In the case of a superconductor, these boundary conditions are also correct for the static field.

Proper application of the field equations and imposition of the correct

Figure 3. Boundary conditions between two materials.



Legend

A = magnetic vector potential
n = normal component of vector
ϵ = permittivity
μ = permeability
σ = conductivity

boundary conditions result in a correct solution to the field equations.

The Continuity Equation

Since charge cannot be destroyed or created, the only possible way to charge a body is through flow of charge from one point to another. This is stated mathematically by the continuity equation:

$$\textbf{(71)} \quad \nabla \cdot \boldsymbol{J} = -\frac{\partial \rho}{\partial t}$$

This often neglected relation is fundamental to understanding field behavior and is responsible for two important aspects of electromagnetic fields: Kirchoff's current law and the linking of electric and magnetic quantities. Observing that the continuity equation is in fact a statement of the divergence of the current density, the displacement current term in Maxwell's equations is shown to be a statement of the continuity equation or preservation of charge. Ampere's law, before Maxwell's modification is:

$$\textbf{(72)} \quad \nabla \times \boldsymbol{H} = \boldsymbol{J}$$

The divergence of the curl of a vector is zero (identically):

$$\textbf{(73)} \quad \nabla \cdot \left(\nabla \times \boldsymbol{H}\right) = 0$$

Thus, this equation can be written as:

$$\textbf{(74)} \quad \nabla \cdot \left(\nabla \times \boldsymbol{H}\right) = \nabla \cdot \boldsymbol{J} + \frac{\partial \rho}{\partial t} = 0$$

From Gauss' law (Maxwell's third equation), this can be written as:

$$\textbf{(75)} \quad \nabla \cdot \left(\nabla \times \boldsymbol{H}\right) = \nabla \cdot \left(\boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}\right)$$

And the following is the correct form of Ampere's law:

$$\textbf{(76)} \quad \nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

Note that this form is only necessary when both electric and magnetic quantities are present. The continuity equation need not be taken into account explicitly for purely electrostatic solutions because this implies static charges and therefore Eq. 71 is always satisfied implicitly. For direct current magnetic applications, Eq. 71 is again satisfied because any flow of charges is constant. The only time the equation needs to be introduced directly is when the displacement currents are large compared to conduction currents (at very high frequencies).

PART 4. Effect of Materials on Electromagnetic Fields

Material Properties and Constitutive Relations

Magnetic properties are important because of their effect on the behavior of materials under an external field (under active excitation) or when the external field is removed (residual magnetism). The magnetic properties are often discussed using the magnetic permeability of materials. This important quantity is defined through the constitutive relation in Eq. 10.

Permeability governs two important features of the magnetic field and therefore affects any application that uses the magnetic field. For ferromagnetic materials below saturation, flux density B is generally the quantity of interest and has higher values for high values of the permeability for a given source field intensity H. Secondly, the permeability also defines whether the field equation is linear or nonlinear.

The permeability of free space is $\mu_0 = 4\pi \times 10^{-7}\ H{\cdot}\mathrm{m}^{-1}$. Other materials may have larger or smaller permeabilities. Table 1 lists the relative permeabilities of some important materials.

The magnetic properties of materials are defined through the interaction of external magnetic fields and moving charges in the atoms of the material (static charges are not influenced by the magnetic field since no magnetic forces are produced in Lorenz' law). Atomic scale magnetic fields are produced inside the material through orbiting electrons. These orbiting electrons produce an equivalent current loop that has a magnetic moment:

$$\textbf{(77)} \quad \boldsymbol{m} = \hat{z} I \pi a^2$$

where πa^2 is the area of the loop, I is the equivalent current (Fig. 4a) and $\hat{z}$ is a unit vector normal to the plane of current flow.

Many such atomic scale loops or magnetic moments exist and the material volume contains a certain magnetic moment density. If N magnetic moments per unit volume are present, and if these moments are aligned in the same direction, a total magnetization is generated. The magnetization $\boldsymbol{M}$ is then given by:

TABLE 1. Relative permeabilities of magnetic materials. Values given for ferromagnetic materials represent approximate maximum relative permeabilities.

Magnetic Material	Relative Permeability
Diamagnetic materials	
Gold	0.999964
Silver	0.99998
Copper	0.999991
Lead	0.999983
Water	0.999991
Mercury	0.999968
Bismuth	0.99983
Paramagnetic materials	
Vacuum (nonmagnetic)	1.0
Air	1.00000036
Aluminum	1.000021
Ferromagnetic materials	
Cobalt (99 percent annealed)	250
Nickel (99 percent annealed)	600
Iron (99.8 percent annealed)	6000
Iron (99.95 percent annealed in hydrogen)	2.0×10^5
Nickel alloy	
Annealed nickel alloy (controlled cooling)[a]	1.0×10^6
Steel (0.9 percent carbon)	100
Iron (98.5 percent, cold rolled)	2000

a. By weight 79 percent nickel; 5 percent molybdenum; iron.

$$\textbf{(78)} \quad \boldsymbol{H}_{\mathrm{in}} = \boldsymbol{M} = N\boldsymbol{m}$$

The magnetic flux density of the material is then given by:

$$\textbf{(79)} \quad \boldsymbol{B}_{\mathrm{in}} = \mu \boldsymbol{M}$$

The terms $\boldsymbol{H}_{\mathrm{in}}$, $\boldsymbol{m}$ and $\boldsymbol{M}$ are vectors. This implies that a net magnetic field or flux density can only exist if these vectors are aligned in such a way that a total net vector $\boldsymbol{M}$ exists. If the independent vectors $\boldsymbol{m}$ are randomly oriented, as is often the case, the net magnetization is zero.

Materials

For the purposes of this chapter, three types of magnetic materials are important: *diamagnetic*, *paramagnetic* and *ferromagnetic*.

Diamagnetic Materials

In these materials, the internal magnetic field due to electrons is zero under normal conditions. In an external magnetic field, an imbalance occurs and a net internal field opposing the external field is produced. Thus, $\boldsymbol{M}$ in Eq. 78 is negative with respect to the applied field. The magnetization is proportional to the external field through a quantity called the *magnetic susceptibility* of the material x_m:

$$\textbf{(80)} \quad \boldsymbol{M} = x_m \boldsymbol{H}_{ex}$$

In terms of the applied flux density, this becomes:

$$\textbf{(81)} \quad \boldsymbol{B} = \mu_0 (1 + x_m) \boldsymbol{H}_{ex}$$

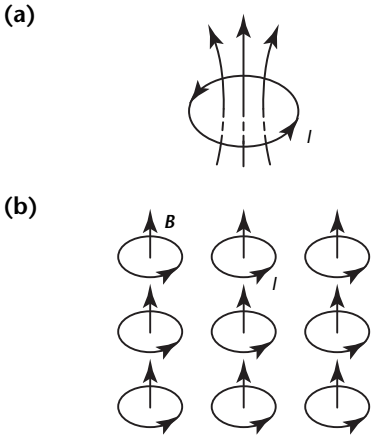
The magnetic permeability of any material can be written as:

$$\textbf{(82)} \quad \mu = \mu_0 (1 + x_m)$$

In diamagnetic materials, the magnetic susceptibility is very small and negative. Its magnitude is usually on the order of 10^{-5}. The net effect is that the relative permeabilities exhibited by diamagnetic materials are slightly smaller than 1.0. This group of materials includes many familiar metals including pure copper and lead.

Under special conditions such as temperatures less than –150 °C, some materials may become superconducting. An ideal superconductor has a magnetic susceptibility of –1 and a permeability of 0. A superconductor expels magnetic flux (the meissner effect) from its interior.

Figure 4. Representation of material properties: (a) field due to current loop; (b) current loops created by spinning electrons.



Legend
B = magnetic flux density
I = current

Paramagnetic Materials

This group of materials exhibits properties similar to diamagnetics except that the magnetic susceptibility is positive. In the presence of an applied magnetic field intensity, the atomic magnetic dipole moments can align to form a net magnetic dipole density. The effect is still relatively small, producing observed relative permeabilities slightly larger than 1.0.

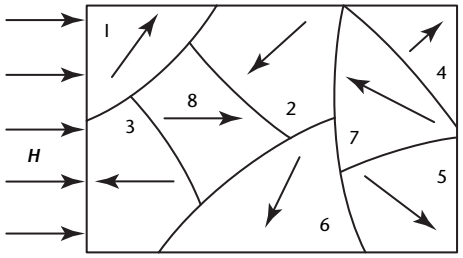
The permeability of paramagnetic materials remains constant over a large range of applied magnetic field intensities. Examples of materials in this group are air, aluminum and some stainless steels.

Ferromagnetic Materials

Ferromagnetic materials vary from diamagnetic and paramagnetic materials in two critical ways: (1) their susceptibility is very large and (2) there is a pronounced variation in the internal structure of their magnetic moments. In these materials, many atomic moments are aligned in a certain direction within a very small region called a *magnetic domain*. Neighboring domains have a similar structure, with the net magnetic domain in one direction. In the demagnetized state, the magnetic domains tend to be aligned randomly, exhibiting a net internal field that is either very small or zero.

This domain model is depicted in Fig. 5. When an external magnetic field is applied, those domains that have a net field aligned in the direction of the applied field grow in size while the other domains shrink. The internal field and the external field *H* are aligned in the same direction producing a larger total flux

Figure 5. Magnetic domains in ferromagnetic material: domain 8 is aligned with field and will grow as magnetic field intensity ***H*** is increased; domain 3 is aligned against field and will shrink as ***H*** is increased.



density B. The above argument is related to the hysteresis curve of a ferromagnetic material and explains why any such curve has a saturation region: beyond a certain field, all the magnetic domains are aligned with the field and an increase in the magnetic field intensity cannot increase the net magnetization. Materials typical of this group are iron, steels, nickel and some stainless steels. Table 1 summarizes some of the more important ferromagnetic materials and their permeabilities. Table 2 lists conductivities of various materials and Table 3 is a listing of dielectric constants.

TABLE 2. Electrical conductivities of some materials.

Material	Conductivity ($S \cdot m^{-1}$)
Silver	6.1×10^7
Copper (pure)	5.8×10^7
Gold	4.1×10^7
Aluminum	3.5×10^7
Tungsten	1.8×10^7
Brass	1.1×10^7
Iron (pure)	1.0×10^7
Soft steel	0.8×10^7
Carbon steel (1 percent carbon)	0.5×10^7
Nickel chromium stainless steel[a]	1.4×10^6
Nickel chromium alloy[b]	0.9×10^6
Mercury	1.0×10^6
Graphite	1.0×10^5
Carbon	3.0×10^4
Sea water	4.0
Germanium	2.3
Silicon	3.9×10^{-4}
Phenolic resin, cured	1.0×10^{-9}
Glass	1.0×10^{-12}
Rubber	1.0×10^{-13}
Mica	1.0×10^{-15}
Quartz	1.0×10^{-17}

a. 18 percent nickel, 8 percent chromium.
b. 80 percent nickel, 20 percent chromium.

As is evident from any hysteresis curve, the permeability of ferromagnetic materials is not constant but varies with the field. This is exhibited through the slope of the initial magnetization curve to which the permeability is tangent. Thus, most ferromagnetic materials are highly nonlinear materials.

TABLE 3. Dielectric constants (relative permittivities) for some materials.

Material	Relative Permittivity
Vacuum	1
Air	1.0006
Rubber	3
Paper	3
Phenolic resin, cured	5
Quartz	5
Glass	6
Mica	6
Water	81
Barium titanate	1200
Barium strontium titanate	10 000

PART 5. Magnetic Circuits and Hysteresis

Magnetic Circuits

The two equations that define the static magnetic field are Eq. 14 and Eq. 16. These are written below in differential and integral forms in terms of $\boldsymbol{B}$:

(83) $$\nabla \times \boldsymbol{B} = \mu \boldsymbol{J}$$

(84) $$\nabla \cdot \boldsymbol{B} = 0$$

(85) $$\oint_c \boldsymbol{B} \cdot d\boldsymbol{\ell} = \mu I$$

(86) $$\oint_s \boldsymbol{B} \cdot d\boldsymbol{s} = 0$$

These are Ampere's and Gauss' laws for the static field. They can also be viewed as defining a vector quantity $\boldsymbol{B}$ through its curl and divergence.

The line integral of the magnetic field intensity around a closed path is defined as a *magnetomotive force*.

(87) $$V_m = \oint_c \boldsymbol{H} \cdot d\boldsymbol{\ell} = NI$$

The units of the magnetomotive force are customarily expressed as *ampere turns* although the correct unit is the *ampere*. The modification from I to NI simply states that, if the total current inside the closed contour is divided into N wires, then the number of turns may be used for convenience.

Circuit Theory

A magnetomotive force $V_m = NI$ causes a magnetic flux Φ to exist within the closed contour mentioned in Eq. 87. If for any reason this flux is contained within a material, it may be assumed that a flux flows within the material. This concept allows flux to be treated much the same way as current and therefore circuit theory concepts may be used for the solution of some specific field problems.

To develop this concept, it is convenient to use a toroid (Fig. 6). The gap is assumed to be small and the flux densities inside the toroid and the gap are assumed to be the same. This assumption in effect neglects any fringing effects in the gap. If the field intensity is denoted in the gap as H_g and in the toroid as H_ℓ, then the fields can be calculated in terms of the flux density B_ℓ in the toroid and the permeabilities of the gap and of the toroid (μ_0 and μ) as:

(88) $$H_\ell = \frac{B_\ell}{\mu}$$

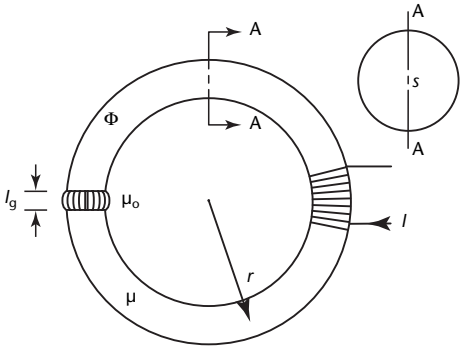
and:

(89) $$H_g = \frac{B_\ell}{\mu_0}$$

By substituting these in Eq. 87, the magnetic flux density is found to be related to gap lengths ℓ_g and the length $(2\pi r - \ell_g)$ of toroid material, where r is the mean radius of the toroid:

(90) $$B_\ell = \frac{\mu_0 \mu NI}{\mu_0 \left(2\pi r - \ell_g\right) + \mu \ell_g}$$

Figure 6. Toroid with air gap used to define magnetic circuit concept.



Legend
A = reference point
l_g = gap distance
r = radius of toroid
s = cross sectional area of toroid
μ = permeability
Φ = flux

If it is assumed that the magnetic flux density is uniform within a material (it is often uniform inside a toroid but rarely in other shapes), the flux can be calculated:

$$\textbf{(91)} \quad \Phi = Bs$$

The total flux through the toroid or the gap is therefore:

$$\textbf{(92)} \quad \Phi = \frac{NI}{\frac{2\pi r - \ell_g}{\mu s} + \frac{\ell_g}{\mu_0 s}}$$

Written in terms of the magnetomotive force V_m, the equation for the flux can be written as:

$$\textbf{(93)} \quad \Phi = \frac{V_m}{R_\ell + R_g}$$

where:

$$\textbf{(94)} \quad R_\ell = \frac{\ell_\ell}{\mu s}$$

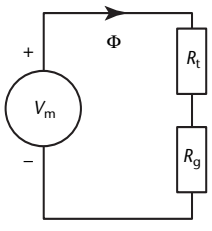
and:

$$\textbf{(95)} \quad R_g = \frac{\ell_g}{\mu_0 s}$$

The forms of Eqs. 94 and 95 are analogous to that of the direct current resistance ($R = \rho \ell \cdot a^{-1}$) and are therefore called *magnetic resistances* or *reluctances*. The reluctance of the gap is R_g and R_ℓ is the reluctance of the material in the toroid. The units for reluctance are 1 per henry ($1 \cdot H^{-1}$). Similarly, if magnetomotive force is considered analogous to voltage and flux analogous to current, Eq. 93 is analogous to Ohm's law.

For any closed magnetic path, the equation can be written as:

Figure 7. Equivalent magnetic circuit representation.



Legend
R_g = gap resistance
R_t = toroid resistance
V_m = magnetomotive force
Φ = flux

$$\textbf{(96)} \quad \sum_i N_i I_i = \sum_j R_j \Phi_j$$

Similarly, by using the divergence of the magnetic flux density $\nabla \cdot \boldsymbol{B} = 0$, the law for a junction is:

$$\textbf{(97)} \quad \sum_i \Phi_i = 0$$

For simplicity, an analogous magnetic circuit can be defined as in Fig. 7. Because of its simplicity, this approach has found considerable use in many areas, especially in devices with closed paths (transformers and machines). The approach is quite limited in scope because of the approximations used to derive the concept. First, the fringing effects cannot be neglected for large air gaps. Second, there are always some leakage fields that cannot be taken into account. Finally, the permeability has been assumed to be constant. In most cases of practical importance, the permeability of a material is field dependent (Eq. 98).

Hysteresis

The constitutive relation between the magnetic field intensity and the magnetic flux density is shown in Eq. 10. The behavior of the field within different materials has been described above. However, these do not describe all phenomena that exist within materials.

Inspecting Eq. 10 shows that by increasing the magnetic field intensity $\boldsymbol{H}$, the flux density $\boldsymbol{B}$ increases by a factor of μ. However, for ferromagnetic materials, Eq. 10 must be written as a nonlinear equation:

$$\textbf{(98)} \quad \boldsymbol{B} = \mu(H)\boldsymbol{H}$$

An alternative way to look at this phenomenon is to inspect the domain behavior of a ferromagnetic material. Initially, the domains are randomly oriented. As the applied field increases, domains begin to grow by displacing other domains and eventually occupying most of the material volume. Any further increase of the field has little effect on the domains and therefore has little effect on the flux density in the material; thus the permeability depends strongly on the applied field.

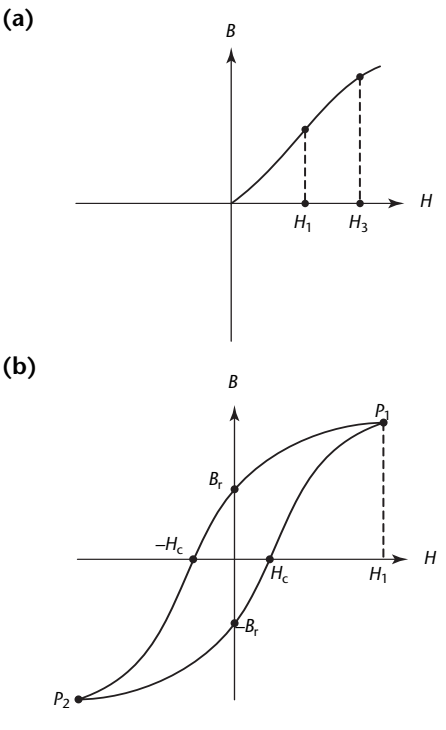
Magnetization Curves

A plot of the relation in Eq. 98 describing the flux density as a function of the field intensity is a useful way to look at

magnetic materials. For linear materials (materials for which the permeability is constant at any field value), this curve is a straight line whose slope is equal to the permeability. Ferromagnetic materials behave differently. The curves in Fig. 8 describe the behavior of iron. Initially, the applied field intensity is zero and so is the flux density.

As the field is increased, the flux density also increases but, unlike linear materials, the curve is not linear. At some field value H_1, the curve starts bending and the slope of the curve is reduced significantly. Any increase beyond the field H_3 increases the flux density but not at the same rate as at lower points on the curve. In fact, the slope in this section of the curve approaches unity, meaning that the relative permeability approaches 1. This region is called *saturation* and is dependent on the material tested. The whole curve described in Fig. 8a is called a *magnetization curve*. Since it starts with zero applied field it may also be called an *initial magnetization curve*.

Figure 8. Hysteresis curve: (a) initial magnetization curve; (b) hysteresis curve.



Legend
B = magnetic flux density
H = magnetic field intensity
P = saturation point

Hysteresis Curves

Reducing the applied field moves the curve to the left, rather than retracing the initial magnetization curve (Fig. 8b). The flux density is reduced up to the point B_r, where the applied field is zero. This residual flux is called *remanence* or *retentivity* and is typical of all ferromagnetic materials. Applying a reverse magnetic field further reduces the flux density to the point H_c, where an applied field intensity exists without an associated flux density. The field intensity at this point is called the *coercivity* or the *coercive force* of the material. Further increase in the negative field intensity traces the magnetization curve through point P_2 where a saturation point has again been reached, except that in this case the field intensity and the flux density are negative.

If the applied field is decreased to zero, a point symmetric to B_r is reached. Similarly, by increasing the applied field intensity to a value equal (but positive) to H_c, the flux density is again zero. Further increase in the field intensity brings it back to the point P_1. Repeating the process described above results in a retracing of the outer curve but not that of the initial magnetization curve. This unique magnetization curve is called the *hysteresis curve* and is typical of all ferromagnetic materials (hysteresis curves of different materials, including their coercive forces and remanence, are markedly different).

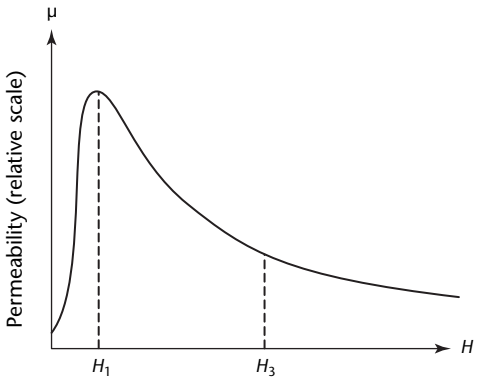
The slope of this curve at any point is the magnetic permeability. The slope is relatively high in the lower portions of the initial magnetization curve and is gradually reduced to unity. At this point, the material has reached magnetic saturation. A curve describing the slope of the initial magnetization curve of Fig. 8a is shown in Fig. 9. Figure 9 shows that for this material (iron), the initial relative permeability is low, increases gradually and then, as the field approaches saturation, decreases and approaches 1.

The hysteresis curve in Fig. 8b has four distinct sections described by the four quadrants of the coordinate system. Particularly important are the first and second. The curve in the first quadrant is created by an applied field or source and is therefore called a *magnetization curve*. In particular, the initial magnetization curve can only be described by starting with an unmagnetized sample of the material and then increasing the field within the material. This section of the curve is referred to as the active part of the curve. All direct current applications of magnetic particle testing that depend on active magnetization are governed by this section of the curve.

The second quadrant (with the limits at B_r and H_c) is called the *demagnetization curve*. It is important for two reasons. First, any magnetic material, after being magnetized, relaxes to the point B_r or more commonly to a point in the second quadrant. Secondly, this is the quadrant in which permanent magnets operate. The coercivity and remanence of ferromagnetic materials are very different from each other and define to a large extent the classification of magnetic materials. The coercivity and remanence of some important materials are shown in Table 4.

The area under the hysteresis curve represents energy. This is understood by referring to the poynting theorem. In devices such as transformers, this is a detrimental property because the energy is dissipated, primarily in the magnetic core of the device. In other cases, including permanent magnets or switching magnetic devices, this property is useful.

Figure 9. Initial permeability curve for iron.



Magnetization

In order to magnetize a sample, it is necessary to apply a magnetic field to the sample. The form in which this field is applied may vary depending on practical considerations but the same basic effect must be obtained: the field in the sample must be increased to a required value.

In general, if a sample is initially demagnetized, the field is gradually increased through the initial magnetization curve to a required point. If a residual method is being used, the field is reduced to zero and the material relaxes to a point in the second quadrant of the hysteresis loop. For previously magnetized samples, it is usually better to demagnetize the sample first and then to magnetize it to the required point.

Demagnetization

The hysteresis curve indicates that when the source of a field is reduced to zero, there is a remanent flux density in the material. This remanent or residual field is sometimes used for testing purposes but in many cases it is desirable to demagnetize a test object before a controlled field is applied or to demagnetize it after a test.

Demagnetization cannot be achieved simply by creating a field opposing the original source field. The demagnetization process is complicated by shape effects that usually cause different operating

TABLE 4. Coercivity and remanence of some important materials. Values for H_c and B_r are approximate and strongly depend on thermoelectrical history.

	Coercive Force H_c ($A \cdot m^{-1}$)	Remanent Flux Density B_r ($Wb \cdot m^{-2}$)	Saturation Flux Density B_s ($Wb \cdot m^{-2}$)
Soft magnetic materials			
Annealed nickel alloy (controlled cooling)[a]	0.2	10^{-4}	0.8
Nickel zinc ferrite	16	0	0.34
Silicon iron (4 percent silicon)	20	0.5	1.95
Iron (pure annealed)	100	1.2	2.16
Steel (0.9 percent carbon, hot rolled)	4000	1.0	2.0
Hard magnetic materials			
Carbon steel (0.9 percent carbon)	4000	1	—
Aluminum nickel alloy, type 5	44 000	1.2	—
Aluminum nickel alloy, type 8	126 000	1.04	—
Samarium cobalt	560 000	0.84	—

a. 79 percent nickel; 5 percent molybdenum; iron.

points to exist in different sections of the material (see the curve in Fig. 8).

Effective demagnetization of materials can be achieved by heating the material beyond the curie temperature and then cooling it in a zero field environment. Under most circumstances, this method is impractical because of the metallurgical effects associated with it.

A practical demagnetization approach is to cycle the material through the hysteresis curve while gradually reducing the magnetic field intensity to zero. The effect is shown in Fig. 10. If started with a high enough field intensity and reduced slowly, this procedure results in a properly demagnetized sample. In practice, demagnetization is performed by applying an alternating current field and gradually reducing its amplitude to zero. Complete demagnetization is usually a very time consuming process. In practical situations, it is usually limited to reducing the flux density to some acceptable level.

Minor Hysteresis Loops

It often happens while a sample is at some operating point on the hysteresis curve (either on the initial magnetization curve or on the outer loop) that a relatively small change in magnetization occurs. An example of this is a large direct current corresponding to a point on the hysteresis curve and a small alternating current superimposed on it.

Alternatively, if the magnetizing current is suddenly decreased and then increased again, the same effect is created. This situation results in a change in the hysteresis curve as shown in Fig. 11. Thus, a small oval curve similar to the hysteresis curve is described at the initial point. These loops are called *minor hysteresis loops* to distinguish them from the normal (or major) hysteresis loop. Because permeability is defined as the ratio of $|\boldsymbol{B}|$ and $|\boldsymbol{H}|$, the permeability of a minor loop may be defined as $\Delta B \cdot \Delta H^{-1}$:

$$\mu_{inc} = \frac{\Delta B}{\Delta H} \quad (99)$$

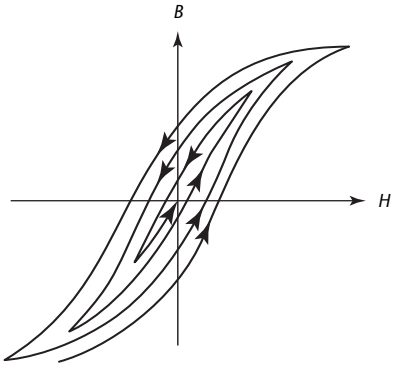
Also called an *incremental permeability*, this quantity depends on the location of the minor curve on the hysteresis loop and decreases as the normal magnetization increases. The slope of minor loops is always smaller than that of the major loop at a given point. Thus, the incremental permeability is lower than the normal permeability at any point on the hysteresis curve. As the material approaches saturation, the relative incremental permeability approaches unity.

Hysteresis Curve As Classifier

When applying electromagnetic fields, it is necessary to distinguish between applications, specialties and frequency ranges. For example, electromagnetic nondestructive testing is classified as a discipline separate from paleomagnetism (terrestrial magnetism), even though exactly the same principles are involved and, often, the same methods are used. Moreover, within each discipline different applications are distinguished.

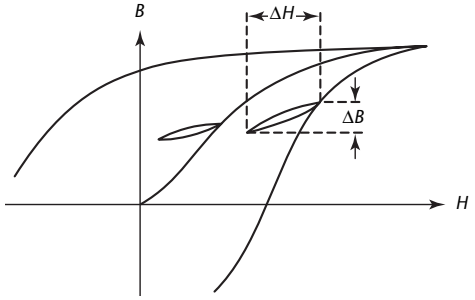
In nondestructive testing, *active leakage field*, *residual leakage field*, *eddy current* and other electromagnetic phenomena are used. This distinction helps focus the treatment of different problems. Often, the distinction parallels that of the various areas of electromagnetic fields: active leakage fields are associated with magnetostatics; residual leakage fields

Figure 10. Demagnetization of ferromagnetic materials.



Legend
B = magnetic flux density
H = magnetic field intensity

Figure 11. Major and minor hysteresis loops.



Legend
B = magnetic flux density
H = magnetic field intensity

with source-free magnetostatics; and eddy currents with steady state alternating current fields.

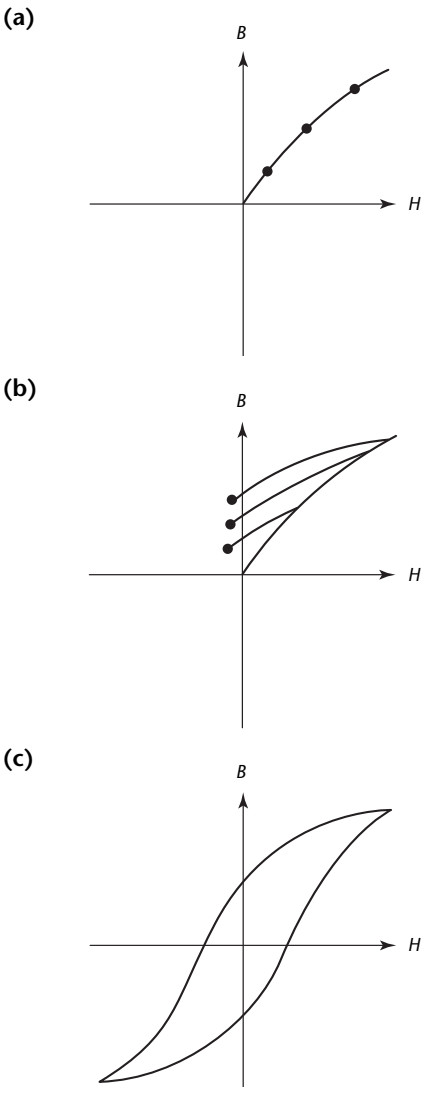
It is far more practical to distinguish between the various applications based on the point of operation on the hysteresis curve. This offers a visual description as well as some physical insight into the application.

Active leakage field methods are those that employ the initial magnetization curve (Fig. 12a). The point on the initial magnetization curve is obtained by increasing the current that increases intensity *H* from zero to some predetermined value. It is possible to apply a field to an initially magnetized sample but this is usually not done because of the difficulty in determining the exact operating point.

Residual leakage fields are obtained when an active excitation is removed and the operating points of the material are allowed to relax into the second quadrant (Fig. 12b). Similarly, alternating current leakage methods may be defined as those that employ a normal hysteresis curve. The operating point is on the major loop (Fig. 12c).

Eddy current methods require alternating current excitation but this is usually very low. In terms of the hysteresis curve, it may be said that the operating point is at the origin although small hysteresis loops are described around the origin as in Fig. 12c.

Figure 12. Classification of testing methods: (a) active leakage fields (direct current); (b) residual leakage fields; (c) alternating current operation.



Energy Lost in Hysteresis Cycle

The energy stored in the magnetic field is given as a volume integral of an energy density *w*:

$$\textbf{(100)}\quad W = \int_v w\,dv$$

After integrating over the hysteresis curve or over any part of it, the area under the curve may be written as:

$$\textbf{(101)}\quad w = \int_0^B H\,dB$$

The units of this integral are those of a volume energy density and, under linearity assumptions ($dB = \mu dH$), the energy density becomes $w = 0.5\ \mu H^2$.

If this is then integrated over the volume of material in which the magnetic field exists, the total work done by external sources can be written as:

$$\textbf{(102)}\quad W = \int_v \left(\int_0^B H\,dB \right) dv$$

The fact that energy is transformed in the process becomes apparent by considering that work needs to be performed in order to change the magnetic field in the volume of a material. The expression in Eq. 102 is the work done for a complete cycle over the hysteresis loop. If the field changes at a certain frequency, the energy per cycle in Eq. 102 must be multiplied by the frequency to obtain:

(103) $P_d = Wf$

This equation is exact but of limited use because it requires integration over the hysteresis loop. Being a complex function and in many cases only known experimentally, the hysteresis loop is difficult to integrate. For practical purposes, an approximate expression in terms of the maximum induced flux density B_{max} is often used. The dissipated power is:

(104) $P_d = \eta f B_{max}^{1.6}$

This expression is credited to Charles Steinmetz and assumes that the constant η is known. It ranges from 0.001 for silicon steels to about 0.03 for hard steels. It is an experimental value and the equation is only correct for relatively large saturation fields (above 0.1 T, or 1 kG). For low saturation flux densities, the equation cannot be used.

Eddy Current Losses

In addition to hysteresis losses, the change in flux density inside conducting materials generates induced electromagnetic forces in those materials. The existence of this electromagnetic force, and the relatively large conductivity of most metals, results in a relatively large current flowing inside the material in a path that is a mirror image of the source generating the field. It is difficult to calculate the eddy current generated for any particular situation but the relative quantity involved is easy to obtain.

For any conductor, the electric field due to the induced electromagnetic force is directly proportional to the magnetic field as:

(105) $\boldsymbol{E} \propto \frac{d\boldsymbol{B}}{dt} \propto f\boldsymbol{B}$

The dissipated energy due to heating losses (I^2R) is related to the square of the electric field. In terms of Eq. 105 and the magnetic field, this becomes:

(106) $\sigma E^2 \propto \sigma f^2 B^2$

This relation clearly indicates that the losses due to eddy currents can be very large, especially for large flux densities and higher frequencies. Eddy current losses may be reduced: (1) by reducing the conductivity of the materials involved (ferrites); (2) by special alloying to produce very narrow hysteresis curves (silicon steels); and (3) by breaking the eddy current paths (laminated cores).

The total losses in magnetic materials due to hysteresis and eddy current losses can be summarized in terms of the actual field as:

(107) $P_d = Nf + k\frac{B^2 f^2}{\rho}$

where N is the number of turns.

In terms of the saturation flux density B_{max}, total losses may be written as:

(108) $P_d = k_1 f B_{max}^{1.6} + k_2 f^2 \frac{B_{max}^2}{\rho}$

The constants k, k_1 and k_2 depend on geometry as well as on material properties.

PART 6. Characteristics of Electromagnetic Fields

Energy in Electromagnetic Field

In order to examine the energy in a magnetic field it is convenient to look first at the general time dependent expression for energy. This expression includes stored magnetic energy, stored electric energy and dissipated energy. The following vector identity is used:

$$\textbf{(109)}\quad \nabla\cdot(\boldsymbol{E}\times\boldsymbol{H}) = \boldsymbol{H}\cdot\nabla\times\boldsymbol{E} - \boldsymbol{E}\cdot\nabla\times\boldsymbol{H}$$

Into this expression, a substitution is made: the expression for the curl of $\boldsymbol{E}$ and $\boldsymbol{H}$ from Maxwell's first and second equations:

$$\textbf{(110)}\quad \nabla\cdot(\boldsymbol{E}\times\boldsymbol{H}) = -\boldsymbol{H}\frac{\partial\boldsymbol{B}}{\partial t} - \boldsymbol{E}\cdot\frac{\partial\boldsymbol{D}}{\partial t} - \boldsymbol{E}\cdot\boldsymbol{J}$$

Assuming the energy flows in a volume v bounded by an area s, it is then possible to integrate this expression over the volume v. Before this, transform the left side from a volume integral to an area integral using a divergence theorem.

$$\textbf{(111)}\quad \oint_s(\boldsymbol{E}\times\boldsymbol{H})\cdot\partial\boldsymbol{s} = -\frac{\partial}{\partial t}\int_v\left(\frac{\boldsymbol{H}\cdot\boldsymbol{B}}{2}+\frac{\boldsymbol{E}\cdot\boldsymbol{D}}{2}\right)\times dv - \int_v \boldsymbol{E}\cdot\boldsymbol{J}dv$$

The left side of the expression represents the total flow of energy through the area bounding the volume. The expression $\boldsymbol{E}\times\boldsymbol{H}$ is a power density with units of $W\cdot m^{-2}$. The power density is called a *poynting vector*:

$$\textbf{(112)}\quad \boldsymbol{P} = \boldsymbol{E}\times\boldsymbol{H}$$

The advantage of such an expression is that it also indicates the direction of the energy flow, information that is important for wave propagation calculations.

The first term on the right side of Eq. 111 represents the time rate of increase in the potential or stored energy in the system. It has two components: the stored magnetic energy and the stored electric energy. These energy densities reduce to simpler expressions for the static electric and magnetic fields:

$$\textbf{(113)}\quad w_e = \frac{\epsilon E^2}{2}$$

$$\textbf{(114)}\quad w_m = \frac{\mu H^2}{2}$$

The second term on the right side of Eq. 111 is the power dissipated and the power due to sources that may exist in the volume v. If no such sources exist, this term represents ohmic losses.

The poynting theorem describes all of a system's energy relations: electrostatic, magnetostatic or time dependent. Because the cross product between the electric field and the magnetic field is taken, these two quantities must be related, otherwise the results have no meaning.

The expression in Eq. 111 is an instantaneous quantity. For practical purposes, a time averaged quantity is more useful. This can be done by averaging over a time T (usually a cycle of the alternating current field):

$$\textbf{(115)}\quad P_{av} = \frac{1}{T}\int_0^T P(t)dt$$

Force in Magnetic Field

The force in the magnetic field is governed by the lorenz force equation given in Eq. 9. For the purposes here, the electric force (Coulomb's law) $\boldsymbol{F}_e = q\boldsymbol{E}$ is not important and was removed from the equation. This in effect assumes that the charge q only experiences a magnetic force:

$$\textbf{(116)}\quad \boldsymbol{F} = q(\boldsymbol{v}\times\boldsymbol{B})$$

Here, $\boldsymbol{v}$ is the velocity of the charge. While forces on charges are important in themselves, the force on current carrying

conductors is more important in conjunction with magnetic fields. If it is assumed that an element of conductor $d\ell$, with a cross sectional area s carries N charge particles per unit volume moving with an average velocity v, then the magnetic force that this conductor experiences is:

$$\textbf{(117)}\quad d\boldsymbol{F} = Nqs|v|\boldsymbol{d\ell} \times \boldsymbol{B}$$

Since $Nqsv$ is the total current in the conductor, the magnetic force becomes:

$$\textbf{(118)}\quad d\boldsymbol{F} = I\boldsymbol{d\ell} \times \boldsymbol{B}$$

To obtain the force due the complete conductor, integration is taken over the length of the conductor:

$$\textbf{(119)}\quad \boldsymbol{F} = I\oint_{C} \boldsymbol{d\ell} \times \boldsymbol{B}$$

Another important consideration is that of the force exerted on a current carrying conductor due to the field of a second conductor. This is treated by assuming that the field B is due to one conductor. If there are two conductors, the force on conductor 1 due to the field of conductor 2 is:

$$\textbf{(120)}\quad F_{21} = \frac{\mu}{4\pi} I_1 I_2 \oint_{C_1}\oint_{C_2} \frac{\boldsymbol{d\ell}_1 \times \left(\boldsymbol{d\ell}_2 \times \hat{\boldsymbol{R}}_{21}\right)}{R_{21}^2}$$

Similarly, the force on conductor 2 due to conductor 1 is:

$$\textbf{(121)}\quad F_{12} = \frac{\mu}{4\pi} I_2 I_1 \oint_{C_2}\oint_{C_1} \frac{\boldsymbol{d\ell}_2 \times \left(\boldsymbol{d\ell}_1 \times \hat{\boldsymbol{R}}_{12}\right)}{R_{12}^2}$$

In these equations, the integration is assumed to be over the entire (closed) path of the currents. This is not merely a convenience but is required to ensure that the forces F_{12} and F_{21} are equal and opposite in direction. In other words, integration over part of the contours violates Newton's third law (action and reaction forces).

Forces in the magnetic field may also be expressed in terms of the energy stored in the magnetic field. A system's mechanical work is done at the expense of its potential energy, so that:

$$\textbf{(122)}\quad \boldsymbol{F} \cdot \boldsymbol{d\ell} = -\left(\nabla\omega\right) \cdot \boldsymbol{d\ell}$$

where ω is angular frequency (radians per second).

The force due to this reduction in the stored energy is therefore:

$$\textbf{(123)}\quad \boldsymbol{F} = -\nabla\omega$$

This expression for the force is particularly convenient when the actual current distributions are not known or are too complicated to permit calculation of the flux densities of each current separately.

Because the magnetic field energy may be expressed in terms of inductances (Eq. 131), the force in the magnetic field may also be expressed in terms of inductances. Thus, for example, the force between two conductors carrying currents I_1 and I_2, having inductances L_1, L_2 and mutual inductance L_{12} can be written as:

$$\textbf{(124)}\quad \boldsymbol{F} = I_1 I_2 \left(\nabla L_{12}\right)$$

The stored energy is calculated as:

$$\textbf{(125)}\quad W = \frac{1}{2}L_1 I_1^2 + L_{12} I_1 I_2 + \frac{1}{2}L_2 I_2^2$$

Torque in Magnetic Field

The torque on a current carrying system may be calculated by using the definition of torque: the product of force and the moment arm length. For simplicity, consider the square loop in Fig. 13. If this definition is used, the torque is equal to:

$$\textbf{(126)}\quad \boldsymbol{T} = \hat{\boldsymbol{s}} I s B \sin\theta$$

where s is the area of the loop and $\boldsymbol{s}$ is a unit vector normal to the plane of the current loop. The product of current and area is defined as a magnetic moment m.

$$\textbf{(127)}\quad \boldsymbol{m} = I\boldsymbol{s}$$

The magnetic moment has a direction normal to the area s and in the direction described by the right hand rule. Thus, torque is a vector quantity and can be written as:

$$\textbf{(128)}\quad \boldsymbol{T} = \boldsymbol{m} \times \boldsymbol{B}$$

Inductance

Inductance is a property of the arrangement of conductors in a system. It is a measure of the flux linked within the circuit when excited and a measure of the magnetic energy stored in the system of conductors. Flux linkage is defined as the flux that links the whole system of conductors, multiplied by the number of conductors or turns in the system. For a simple solenoid, this is defined as:

$$\textbf{(129)}\quad \Lambda = N\Phi = N\int_s \boldsymbol{B}\cdot\boldsymbol{ds}$$

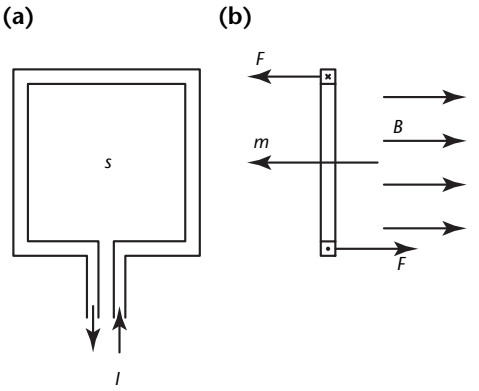
In effect, this includes only the flux that passes through the center of the solenoid. The integration is over the cross sectional area of the solenoid. A more complicated definition can be used, one that includes flux linkages that do not link all the conductors, but this has little practical use because of the difficulties in calculation.If the system under consideration is linear, the field is directly proportional to the current and the inductance in henries (H) of a system (a coil) may be defined as the ratio of the flux linkage and the current:

$$\textbf{(130)}\quad L = \frac{N\int_s \boldsymbol{B}\cdot\boldsymbol{ds}}{I}$$

The inductance in Eq. 130 can be calculated, provided that the flux linkages can be obtained. In many practical situations, it is more convenient to use an energy relation.

$$\textbf{(131)}\quad W = L\frac{I^2}{2}$$

Figure 13. (a) Rectangular loop; (b) direction of forces and torque on rotating loop.



Legend

B = magnetic flux density
F = mechanical force
m = magnetic movement (Eq. 127)
I = current
s = area within loop

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4

CHAPTER

Magnetization[1]

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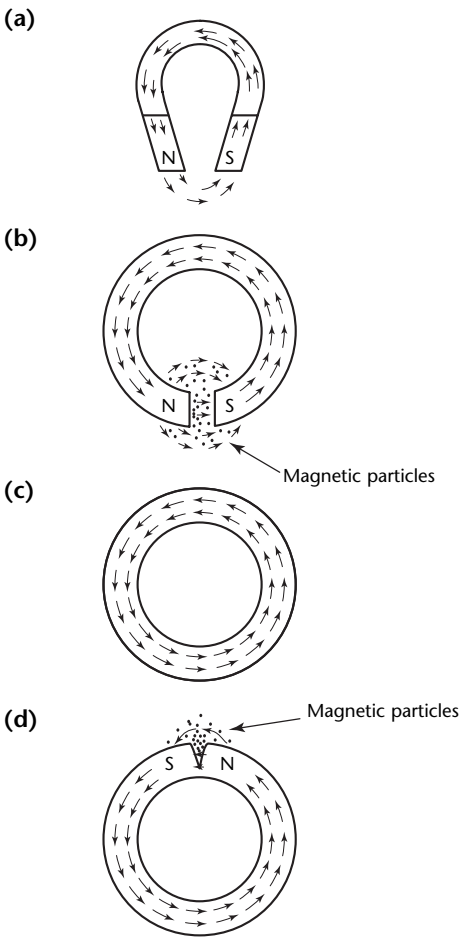
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PART 1. Description of Magnetic Fields

The magnetic particle testing method uses magnetic fields to reveal material discontinuities in ferromagnetic materials. The common horseshoe magnet attracts most ferritic materials to its ends or poles. Magnetic lines of flux flow from the south pole through the magnet to the north pole as illustrated in Fig. 1a.

Magnets attract certain materials at the poles, where the lines of flux leave or enter the magnet. When magnetic material is placed across the poles of a horseshoe magnet, the lines of flux flow from the north pole of the magnet through the material to the south pole. Magnetic lines of flux flow preferentially through magnetic material rather than nonmagnetic material or air.

FIGURE 1. Magnetism in various shapes: (a) horseshoe magnet; (b) ring magnet with air gap; (c) closed magnetized ring; (d) magnetic particles attracted to radial crack in circularly magnetized object.



Magnetized Ring

If a horseshoe magnet is bent so that its poles are close together (Fig. 1b), the poles still attract magnetic materials. Iron filings or other magnetic materials cling to the poles and bridge the gap between them. In the absence of a slot, the magnetic flux lines are enclosed within the ring (Fig. 1c). No external poles exist, and magnetic particles dusted over the ring are not attracted to the ring even though there are magnetic flux lines through it. Magnetized materials attract externally only when poles exist. A ring magnetized in this manner is said to contain a circular magnetic field which is wholly within the object.

Small changes in the cross section of the ring or in the permeability of its material may cause external flux and the attraction of magnetic particles.

Effect of Cracks

A radial crack in a circularly magnetized object creates north and south magnetic poles at the edges of the crack. This forces some of the magnetic lines of force out of the metal path. These disrupted lines of force are called *magnetic flux leakage*. Magnetic particles are attracted to the poles created by such a crack, forming an indication of the discontinuity in the metal test object (Fig. 1d).

Bar Magnet

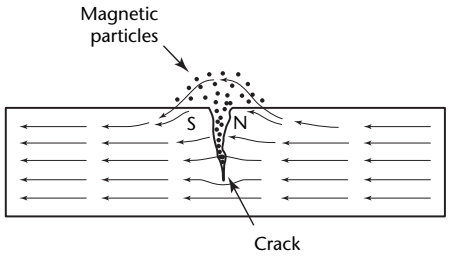
When a horseshoe magnet is straightened, it becomes a bar magnet with poles at each end. Magnetic flux lines exist through the bar from the south pole to the north pole but the flux density is not uniform along the bar. Magnetic particles are attracted to any location where flux emerges and particularly to the ends of the magnet where the concentration of

external flux lines is greatest. Since the magnetic flux within a bar magnet may run the length of the bar, it is said to be *longitudinally magnetized* or to contain a *longitudinal field*.

Effect of Cracks in Magnetized Bar

A crack in a bar magnet (Fig. 2) distorts the magnetic flux lines of force and creates poles on either side of the crack. These poles attract magnetic particles to form an indication of the crack. The intensity of poles formed at a crack depends on the number of magnetic flux lines interrupted. A crack at right angles to the magnetic lines of force interrupts more flux lines and creates stronger poles than a crack more nearly parallel to the flux lines. Test indications of maximum size are formed when discontinuities are at right angles to the magnetic lines of flux and the discontinuity is at the surface.

FIGURE 2. Straightening horseshoe magnet results in bar magnet: crack in bar magnet creates magnetic poles that attract magnetic particles outside the bar.



PART 2. Magnetization with Electric Current

Electric currents are used to create or induce magnetic fields in electrically conducting materials. Since it is possible to alter the directions of magnetic fields by controlling the direction of the electrical magnetizing current, the arrangement of current paths is used to induce magnetic flux lines at right angles to expected discontinuities in the test object.

Circular Magnetization

Electric current passing through a straight conductor (a wire or bar, for example) creates a circumferential magnetic field around that conductor (Fig. 3). The magnetic lines of force are always at right angles to the direction of the current that induces the magnetic field.

To determine the direction taken by magnetic lines of force around a conductor, imagine that the conductor is grasped with the right hand so that the thumb points in the direction of the electric current. The fingers then point in the direction taken by the magnetic field lines, surrounding the conductor. This is known as *Fleming's right hand rule*.

The passage of current induces a magnetic field intensity in the conductor as well as in surrounding space. An object magnetized in this manner is said to have a *circular field* or to be *circularly magnetized* (Fig. 3).

Circular Magnetization of Solid Test Objects

To induce a circular magnetic field in a solid test object, current may be passed through the object. This creates poles on both sides of discontinuities that are parallel to the length of the test object. These poles attract fine magnetic particles and form an indication of the discontinuity (Fig. 4a). It is also possible to generate a circular field in localized areas of the object using prods to pass current through the area being tested (Fig. 4b).

The prod electrodes (generally solid copper or braided copper tips) are first pressed firmly against the test object. The magnetizing current is passed through the prods and into the area of the object in contact with the prods. This establishes a circular magnetic field in the test object around and between each prod electrode.

The use of alternating current limits the prod technique to the detection of

FIGURE 3. Circumferential magnetic field surrounding straight conductor carrying electric current.

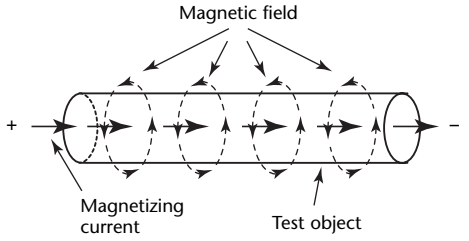
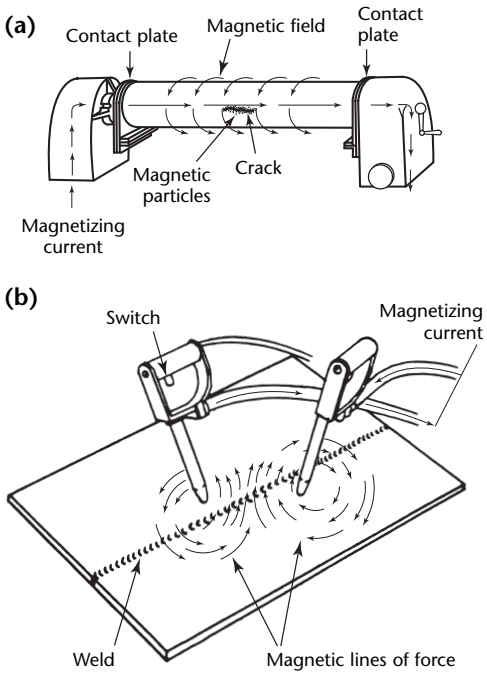


FIGURE 4. Circular magnetization of typical test objects: (a) circular magnetization caused by passing electric current from contact plates through test object; (b) production of localized circular field by passing electric current between contact prods.



surface discontinuities. Half-wave rectified direct current is more desirable here because its greater depth of penetration helps indicate near surface discontinuities.

The prod technique generally is used with dry magnetic particle materials because of increased particle mobility on rough surfaces and better penetration. In the United States, wet magnetic particles are not normally used with the prod technique because of electrical and fire hazards. In Europe, wet particles are regularly used with prods to achieve higher sensitivity. Care should be taken to maintain clean prod tips, to minimize heating at the point of contact and to prevent arc strikes and local heating of the test surface. Aluminum or copper braided tip prods or pads (rather than solid copper tips) are recommended because of the possibility of copper penetration if arcing occurs.

A remote control switch should be built into the prod handles to permit control of the current after positioning and before removing, to minimize arcing. Additional magnets, called *leeches*, can be attached to prod electrodes for the same purpose.

Circular Magnetization with Prods

In circular magnetization with prods, the field intensity is proportional to the current used but varies with prod spacing and the thickness of the section being tested. A magnetizing current of 90 to 110 A for each 25 mm (1 in.) of prod spacing is recommended for material under 20 mm (0.75 in.) thick. A magnetizing current of 100 to 125 A for each 25 mm (1 in.) of prod spacing is recommended for material over 20 mm (0.75 in.) in thickness. Prolonged energizing cycles may cause localized overheating. Prod spacing should not exceed 200 mm (8 in.).

Prod spacing less than 75 mm (3 in.) is usually not practical because the particles tend to band around the prods, making interpretation difficult.

Circular Magnetization with Direct Contact

Figure 5 shows the direct contact technique for producing circular fields in a ring to indicate circumferential cracks. To achieve a reliable examination of the entire cylindrical surface, two magnetizations are required.

This is done because the points of contact (where the current enters and leaves the ring) are not adequately magnetized for discontinuity indication. The ring must therefore be turned 90 degrees and then retested.

Circular Magnetization with Induced Current

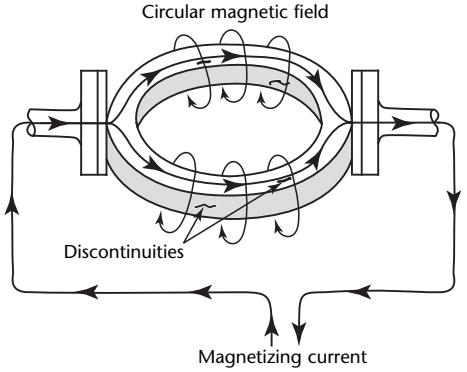
A current flowing circumferentially around the ring can be induced by making the ring a single-turn, short circuited secondary transformer (Fig. 6 illustrates this effect). To accomplish this effect, a standard magnetizing coil can be used.

The ring is placed inside the coil with its axis parallel to that of the coil. When the coil is energized with alternating current, the arrangement constitutes an air core transformer. The magnetizing coil is the primary circuit and the ring is the single-turn secondary circuit. The total current induced in the ring is greatly increased by inserting a laminated core of ferromagnetic material through the ring.

For materials with high magnetic retentivity, direct current can be applied in the technique known as *quick break* and the objects may then be tested by the residual technique. Quick break is when a direct current field is caused to collapse suddenly due to an abruptly interrupted magnetizing current. The circular field generated by the induced current leaves the test object with a strong residual induction. A bearing race is a good example of the type of object that can be tested advantageously by this technique.

For test objects made of soft material, with little retentivity, the continuous technique must be used and the collapsing direct current field technique is not applicable. By using alternating current (or half-wave direct current) in the magnetizing coil, the current may be left on and an alternating current (or half-wave direct current) of the same frequency as the magnetizing current is induced in the ring. This current should be allowed to flow long enough to produce indications by the continuous technique.

FIGURE 5. Direct contact method of magnetizing ring shaped test objects to locate circumferential discontinuities.



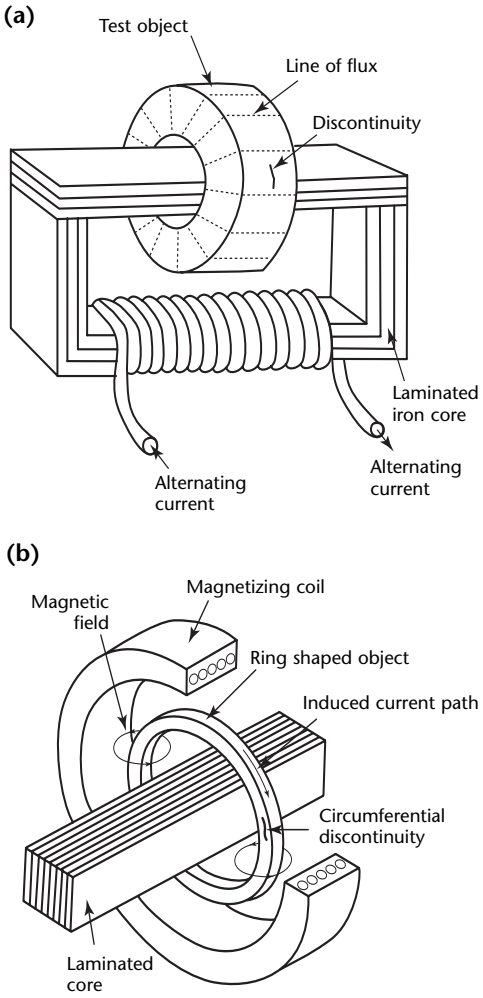
Circular Magnetization of Hollow Test Objects

With hollow objects or tubes, the inside surfaces may be as important for testing as the outside surfaces. When such an object is circularly magnetized (by passing the magnetizing current through it), no magnetic flux is produced on the inside surface.

Since a magnetic field surrounds a current carrying conductor, it is possible to induce a satisfactory magnetic field by sliding the test object onto an internal conducting bar (Fig. 7a). Passing current through the bar induces a circular magnetic field throughout the volume of the test object.

When a conducting bar is not available, an electrical cable may be passed through the test object and connected to receptacles in the magnetic particle unit (Fig. 7b). For large diameter cylinders, the cable can be brought back on the outside of the test object, then threaded through again — the second pass through increases the effective field by a factor of two. For long finished tubes, uninsulated conductors are not permitted because of arc burns.

FIGURE 6. Magnetizing with induced current method to locate circular discontinuities in ring shaped objects: (a) magnetizing core; (b) magnetizing coil.

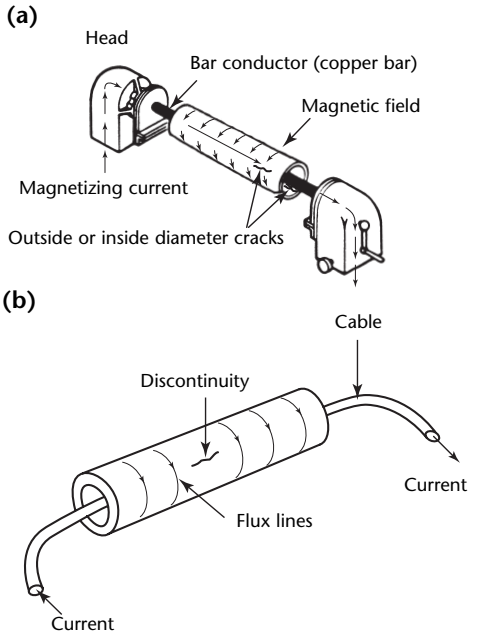


Longitudinal Magnetization

Electrical current can be used to create a longitudinal magnetic field in magnetic materials. When electric current is passed through a coil, a magnetic field is established lengthwise or longitudinally within the coil (Fig. 8).

The nature and direction of this field are the result of the field around the conductor which forms the turns of the coil. Application of the right hand rule to the conductor at any point in the coil (Fig. 8a) shows that the field within the coil is longitudinal.

FIGURE 7. Circular magnetization of cylindrical objects by using an internal current carrying conductor: (a) internal bar conductor; (b) internal cable conductor.

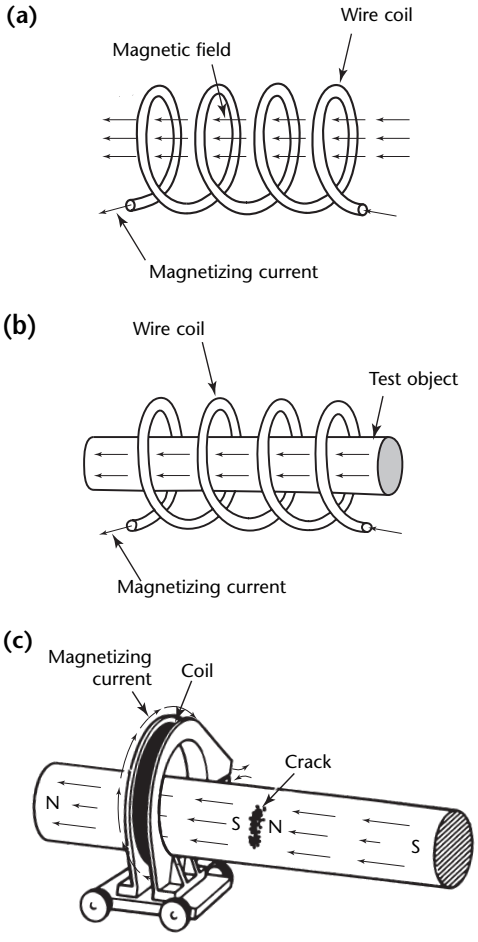


Coil Magnetization

When ferromagnetic material is placed within a coil, most of the magnetic lines of force created by the electric current concentrate themselves in the test object and induce longitudinal magnetization (Fig. 8b).

Testing of a long cylindrical object with longitudinal magnetization is shown in Fig. 8c. With a transverse discontinuity in the test object, magnetic poles are formed on both sides of the crack. These poles attract magnetic particles to form an indication of the discontinuity. Figure 8c shows that a magnetic field has been induced at right angles to the discontinuity.

FIGURE 8. Longitudinal or coil magnetization: (a) longitudinal magnetic flux within current carrying magnetizing coil; (b) longitudinal magnetization with coil; (c) typical arrangement of coil and test object for longitudinal magnetization.



Legend
N = north pole
S = south pole

Test objects too large to fit in a fixed coil can be magnetized longitudinally by making a coil from several turns of flexible cable (Fig. 8b). The use of portable magnetizing equipment with cables and prods or clamps has broadened the use of magnetic particle testing — there is no theoretical limit to the size of the object that can be tested in this manner.

Field Flow Magnetization

Another means of producing a longitudinal field in a test object is the field flow technique. Here, the field is produced by electromagnets and passed through objects as if they were the keepers in a yoke. (A keeper is magnetic filler put next to a pole to reduce the air gap.) The field is almost wholly contained within the test object.[2]

While there is theoretically no limit to the length of a test object that can be magnetized this way, as a practical matter with an alternating current source, power requirements limit the effective length to about 1.3 m (4 ft). However, special techniques using direct current have accomplished longitudinal magnetization in one step for lengths over 3 m (10 ft).

The field flow (or yoke) technique may have some advantages over the current flow (coil) technique in some production applications because: (1) moving a magnetizing coil several times may be impractical and time consuming, (2) test objects with length-to-diameter ratios less than 3:1 require no special handling and (3) a consistent field wholly contained within a test object may be required. Frequently the field flow technique is indicated in multidirectional magnetization.

A reference standard called a *quantitive quality indicator* containing known artificial discontinuities should be located in the center of the test object during setup to ensure adequate field intensity along its entire length.

PART 3. Factors Controlling Magnetization

Factors that should be considered when selecting a technique of magnetization include: (1) alloy, shape and condition of the test object, (2) type of magnetizing current, (3) direction of the magnetic field, (4) sequence of operations, (5) value of the flux density, (6) desired throughput and (7) type of discontinuities anticipated. Material properties, current type and direction of the magnetic field are covered below.

Material Properties

The alloy, its heat treatment, cold working and other conditioning treatments determine the magnetic permeability of a test object. It is necessary to consider these when selecting the sequence of operations, the value of flux density or the magnetic field intensity. They, in turn, affect selection of the magnetization means.

The size and shape of the test object determine the most practical technique of magnetization with the available equipment. The surface condition of the test object influences the selection of particles as well as the magnetization means. Surface coatings such as paint, chemical conversion or lacquer coatings are poor electrical conductors and affect testing because it is difficult or impossible to pass magnetizing current through such coatings. Whenever a test object can be properly magnetized with an induced technique, coating thickness is a concern for the inspector.

Types of Magnetizing Current

Many types of magnetizing current can be used for each type of testing (Fig. 9).[1] Most magnetizing equipment since 1990 is solid state, controlled by thermistors.[2,3] Full-wave rectified alternating current with three-phase bridge circuitry is shown in Fig. 9a. With a ripple of 5 percent, nearly the entire cross section can be magnetically saturated. This means that the probability of detecting subsurface discontinuities may be improved over other forms of current. Because only ohmic resistance is involved, large lengths can be tested at high current values.

Half-wave rectified alternating current with a single-phase circuit is shown in Fig. 9b. The direct current proportion amounts to about 30 percent of the peak value.

Figure 9c shows full-wave rectified alternating current with a single-phase bridge circuit. The direct current proportion amounts to about 64 percent of peak value.

Alternating current with a frequency of 50 to 60 Hz (Fig. 9d) shows excellent uniform magnetization of the surface even with large changes of cross section. Penetration depth is frequency dependent and equals about 2 mm at 50 Hz (skin effect). There is rapid reduction in indication sensitivity with increasing depth when using alternating current magnetization.

Pulsed current is illustrated in Fig. 9e. Because of the pulse train at predetermined intervals, the danger of heating from current flow at the contact points is minimized. Thin walled test objects can therefore be tested using higher currents.

Impulse current is normally used with the residual technique (Fig. 9f). The magnetization effect results from a high intensity single-current pulse of short duration (millisecond range).

Direct Current Magnetization

Direct current obtained from storage batteries was first believed to be the most desirable current to use for magnetic particle testing because direct current penetrates more deeply into test specimens than alternating current. The big disadvantage of storage batteries as a source of current is that there is a definite limit to the magnitude and duration of current that can be drawn from a battery before recharging. Battery maintenance is costly and can be a source of trouble.

Today, direct current is generally produced with silicon diode rectification. Current obtained by passing three-phase alternating current through special rectifiers is called simply *rectified current*.

A three-phase circuit demands lower power consumption to achieve an equivalent current density.

Half-Wave Rectified Magnetizing Current

Half-wave rectified current is the most effective current to use for the detection of subsurface and surface discontinuities when dry magnetic particles are used. This type of current is produced by putting single-phase alternating current through a rectifier. The rectifier is a nonlinear electronic component that permits unimpeded current flow in one direction and thus simulates direct current characteristics for purposes of testing. Half-wave rectified current imparts a very noticeable pulse to the particles. This gives them mobility, aids in the formation of indications and helps prevent the formation of nonrelevant indications.

Alternating Current Magnetization

Alternating current at line frequency is the most effective current to use for the detection of surface discontinuities, particularly fatigue cracks.

An advantage of alternating current testing is the ease with which test objects can be demagnetized.

It is important that alternating current testing equipment be built to include proper current controls.

Choosing Alternating or Direct Current[2,3]

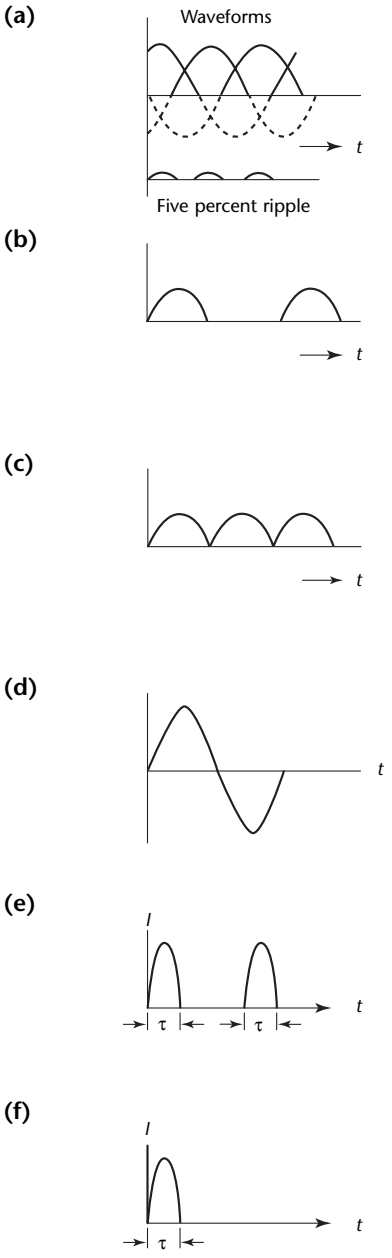
A direct current is distributed uniformly across the entire cross section of the test object. The field and flux density it creates are maximum at the outer surface and zero along the object's central axis, as required by Ampere's law. An alternating current field is forced to the surface because of the skin effect. This fact has technical consequences for the current flow in a billet of square cross section, for example. Figure 10 shows the difference in field intensity distribution along the test object surface in cases of alternating and direct current.

For direct current flow, the magnetic field near the billet corners is considerably lower than in the middle of each side; it is nearly constant in the case of an alternating current field. For corner cracks to be accurately indicated by direct current fields, an overmagnetization in the center area of each side may be unavoidable. With the alternating current technique, the same field intensity is obtained across the surface of the billet at half the current density.

Figure 11 shows the distribution of field intensity on the surface of a stepped sample. The difference in magnetic field intensity for the largest and smallest cross section is much greater in the case of direct current magnetization.

For the same value of direct current, the field intensity is inversely proportional to the square of the diameter: an alternating current field is

FIGURE 9. Theoretical types of current used for magnetic particle testing: (a) full-wave rectified alternating current with three-phase bridge circuit; (b) half-wave rectified alternating current with single-phase circuit; (c) full-wave rectified alternating current and single-phase bridge circuit; (d) alternating current at frequency of 50 to 60 Hz; (e) pulsed current; (f) impulse current.



inversely proportional only to the diameter. When maximum and minimum field intensities for a specimen are given in test specifications, a complicated test object can often be inspected only in sections, if the test is carried out with a direct current magnetic field.

More obviously, this effect can be seen on objects with sudden enlargements in cross section. In camshafts, for example, the alternating current field (in accordance with the skin effect) follows the contour; the direct current field follows a more direct path. As a consequence, alternating current systems are often found at airline and automotive overhaul stations, where surface fatigue cracks can occur at various locations on complex shapes such as landing gear and actuating mechanism components.

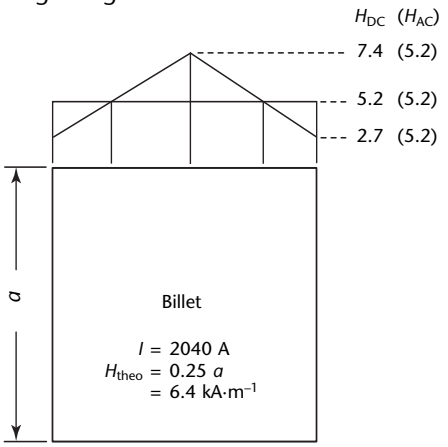
Furthermore, the magnetic pole areas at the ends of a test object are much smaller with an alternating current field. The indications of cracks near the contacting area are much better with an alternating current field.

An advantage of the direct current field is its increased depth of penetration. This provides the ability to test for subsurface cracks with magnetic particle techniques. Such tests are generally used to find cracks under chromium plating, subsurface cracks in flash welds and lack of root penetration or lack of fusion in weldments.

Extensive research has shown that the depth effect not only depends on the distance of the crack from the surface but also on the crack's shape, size and its relations to the test object dimensions. The indications from subsurface cracks are relatively blurred and indefinite and can be recognized reliably only on a sufficiently smooth surface.

Direct current field magnetization cannot guarantee the ability to indicate all subsurface discontinuities, particularly as depth increases. Magnetic particle testing should be for detecting surface or near surface discontinuities. Wet technique indications of discontinuities deeper than 0.2 mm (0.01 in.) should be relied on only when other nondestructive testing techniques cannot be used.

FIGURE 10. Tangential magnetic field intensity (kA·m^{-1}) on surface of current flow in square billets (f = 50 Hz). Current flow is through length of billet.



Legend

a = distance = 80 mm (3 in.)
H_{AC} = alternating current magnetic field intensity (A·m^{-1})
H_{DC} = direct current magnetic field intensity (A·m^{-1})
H_{theo} = theoretical magnetic field intensity (A·m^{-1})
I = electric current (A)

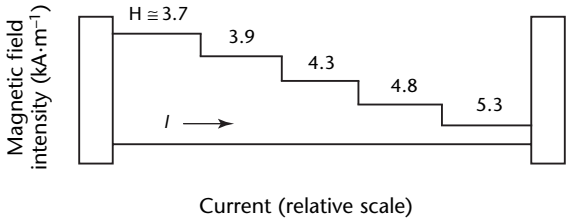
Depth of Penetration[5]

Figure 12 is a plot of threshold values for the magnetizing currents necessary to produce a readable indication of holes in a tool steel ring standard. Holes parallel to the cylindrical surface are drilled 1.8 mm (0.07 in.) in diameter at increasing depths below the surface. The depths vary from 1.8 to 21 mm (0.07 to 0.84 in.), in 1.8 mm (0.07 in.) increments, from hole 1 to hole 12.

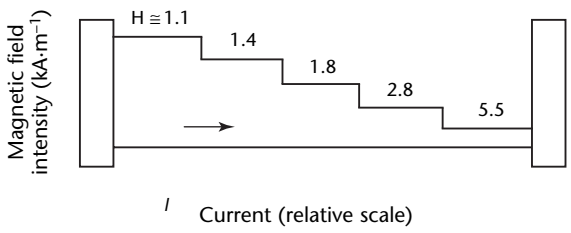
The results plotted in Fig. 12 were obtained using the dry continuous testing technique with an internal conductor using 60 Hz alternating current, and three forms of direct current: (1) direct current

FIGURE 11. Distribution of field intensity on surface of stepped sample: (a) alternating current field; (b) direct current field.

(a)



(b)



Legend

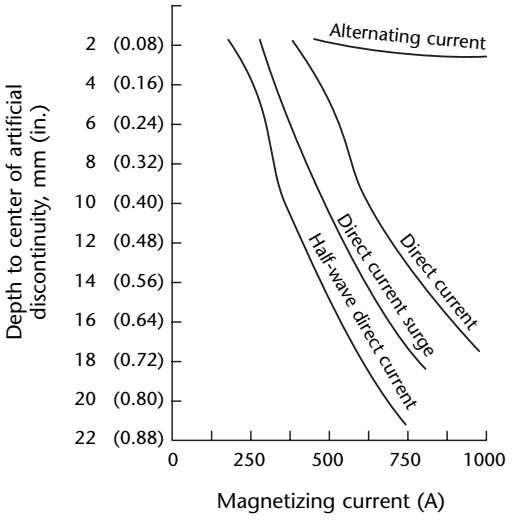
H = magnetic field intensity (A·m^{-1})
I = electric current (A)

from batteries, (2) three-phase rectified alternating current with surge and (3) half-wave rectified single-phase alternating current.

The alternating current test required about 475 A to indicate hole 1 and over 1000 A to indicate hole 2. Hole 3 could not be shown at any available alternating current value. Hole 2 was indicated with 475 A straight direct current, with 275 A full-wave rectified alternating current preceded by a surge of double this amount, and by 175 A using half-wave rectified alternating current. Half-wave rectified alternating current of 750 A indicated hole 12, while 975 A of direct current from batteries was needed to indicate hole 10.

These comparisons verify the importance of choosing the right current for producing the best indications. The comparisons also show how current should vary, depending on the nature and location of the discontinuities.

FIGURE 12. Comparison of sensitivity of alternating current, direct current, direct current with surge and half-wave rectified current for locating discontinuities wholly below surface of test object. Threshold indications produced using dry particles and continuous magnetization on unhardened tool steel ring with artificial discontinuity diameter of 1.8 mm (0.07 in.).[5]



PART 4. Direction of Magnetic Field

The proper orientation of the magnetic flux in relation to the direction of a discontinuity is the most important factor affecting discontinuity detection, even more than the magnitude of the magnetizing current.

For reliable testing, the magnetic flux should be at right angles to the discontinuity. If the magnetic flux is parallel to the discontinuity, there is little magnetic leakage: if an indication is formed at all, it is likely to be extremely small or indefinite. To ensure that proper field direction exists at the desired magnitude, reference standards containing artificial discontinuities are needed.

Circular Magnetization

Fundamentals of Circular Magnetization

The magnetizing technique that is easiest to control is circular magnetization. This is the technique in which the magnetizing current is passed directly through the test object, setting up circular magnetic field lines at right angles to the direction of current flow (Fig. 4a).

A good way to circularly magnetize the outer regions of a test object is to place the object between the contact plates of a stationary magnetic particle testing system. Care should be taken to clamp the test object firmly between contact plates made of lead or copper. Copper pads are coated with thermal rubber to reduce arcing. Enough of the object's surface area must contact the plates to permit passage of the magnetizing current without burning. As the area of the surface decreases, the probability of burning increases.

On irregular test objects, it may be helpful to use copper braid contact pads between the objects and plates to prevent overheating. When testing objects with irregular cross section, it may be necessary to circularly magnetize with a low current to inspect the thin areas. A technique specific to the application must be devised to pass a higher current through the heavier sections for testing of those areas.

Prod Magnetization of Large Test Objects

When an object is too big to fit into available test equipment, the test object (or areas of it) can be circularly magnetized by either of two means.

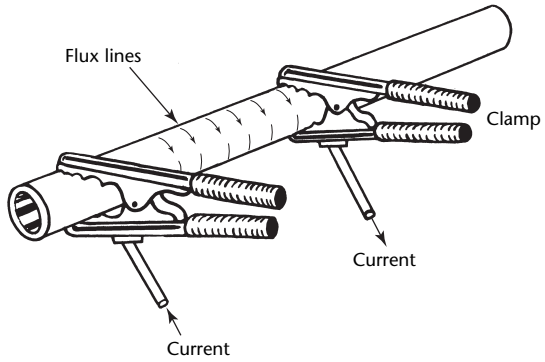
One means is to use prod contacts with cables to transmit the magnetizing current from the source to the test object (Fig. 4b). Prods are attached to the ends of the cables so that magnetizing current can be passed through the test object or through an area of it. Portable equipment should have a remote control switch on the prods, enabling the operator to control the current while moving the prods or viewing the test indications.

Another means of local magnetization is to use contact clamps with cables, particularly when the test objects are relatively small in diameter. Tubular structures can be tested this way by positioning the clamps so that the current passes through the area of interest and along the line of suspected discontinuities (Fig. 13).

Internal Conductor Magnetization

In a tubular test object, a circular magnetic field may be set up by passing current through the tube itself; no field is induced on the inside surface of the tube. If the test object is hollow or has holes through which an internal conductor can be passed, it is best to induce a circular magnetic field in the object by passing the magnetizing current through the conductor. Circular magnetization with a

FIGURE 13. Current carrying clamp electrodes used for testing tubular objects with small diameters.



central conductor has the following advantages over passing current through the test object itself.

1. It induces flux at the inside diameter of the test object, permitting testing of inner as well as outer surfaces.
2. Direct electrical contact is not made with the test object, thereby eliminating the likelihood of burning.
3. Several small ring shaped test objects (washers or nuts, for example) can be suspended on the same conductor and tested for transverse discontinuities in groups (Fig. 14).

Capacitor Discharge Circular Magnetization

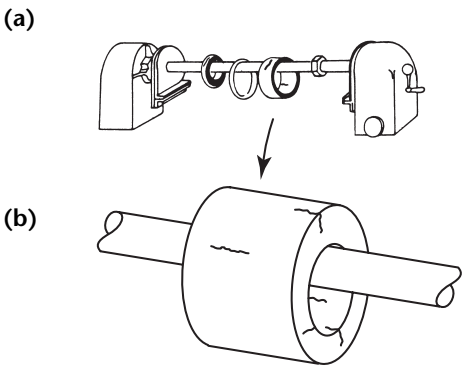
Capacitor discharge techniques are used for the circumferential magnetization of oil field pipes. The technique is discussed in detail elsewhere is this volume.

Limitations of Parallel Magnetization

A circular magnetic field surrounds any electrical conductor and this is the magnetic principle underlying circular magnetization with an internal conductor. Knowing this, some operators have assumed that they can induce a circular field in a test object by placing it next to instead of around a conductor. This is not true.

Some field is induced in the test object by such a procedure, but because a portion of the magnetic flux path is in air, the field in the object is greatly reduced, distorted and unevenly distributed. This procedure is sometimes called *parallel magnetization*. It is not dependable and should not be used.

FIGURE 14. Internal conductor method used to produce circular magnetization: (a) several ring shaped test objects magnetized simultaneously; (b) closeup of ring with cracks in several locations and orientations.



Longitudinal Magnetization

A longitudinal field can be induced in a test object by placing the object in a fixed current carrying coil. The coil may be mounted on the rails of a stationary unit or attached by cables to a portable unit (Fig. 8). The effective magnetic field induced by a coil extends from 150 to 220 mm (6 to 9 in.) beyond either end of the coil. Depending on fill-factor, if the test object is long, it is necessary to magnetize and test it in sections along its length.

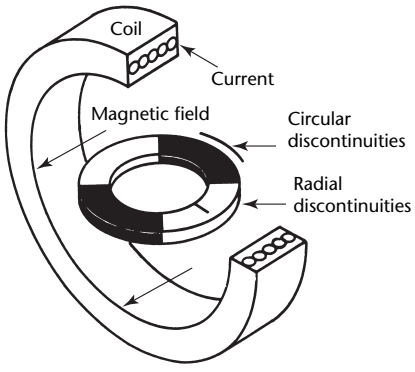
Longitudinal magnetization with portable equipment is accomplished by wrapping current carrying cable in a coil around the test object. Portable, alternating current coils are commercially available.

Important Considerations in Coil Magnetization

To induce an adequate longitudinal magnetic field with a coil, the long dimension of the test object should be at least twice as great as its short dimension or end pieces should be added and the long axis of the test object should be parallel to the coil axis. This is especially true in the case of irregularly shaped test objects, because the shape of the object affects the direction of the induced flux.

When a wheel, smaller in diameter than a coil, is placed in the coil (as shown in Fig. 15), a field is induced in the white areas of the test object in such a direction that radial discontinuities create

FIGURE 15. Coil magnetization of circular shape. Radial discontinuities will be indicated only in white areas; to reveal radial discontinuities in dark areas, test object must be rotated 90 degrees and remagnetized. Circular discontinuities will be indicated in shaded areas; to reveal circular discontinuities in white areas, part must be rotated 90 deg and remagnetized.



indications. However, radial cracks in the shaded areas of the test object are parallel (or nearly so) to the induced magnetic field, so that few or no indications are formed. Furthermore, magnetic poles and attractive forces occur in these areas. To indicate radial discontinuities in the shaded areas, it is necessary to rotate the test object through 90 degrees and remagnetize it, although this technique is not recommended.

The detection of radial cracks in a test object of this shape is more accurately and rapidly done using an internal conductor (Fig. 14). Better techniques for finding circumferential discontinuities in ring shaped test objects are shown in Figs. 5 and 6. Ring shaped objects, disks, wheels or races are best checked for circumferential cracks using the induced technique of Fig. 6. An iron core, for example, is used with a coil surrounding it to produce a toroidal field. This technique has an advantage over the direct contact technique (Fig. 5) in that no danger of arcing or burning exists, and the field is constant throughout the test object.

Yoke Magnetization

A longitudinal magnetic field can be induced in a test object or in a limited area of an object by using a handheld yoke. A yoke is a *U* shaped piece of soft magnetic material, either solid or laminated, around which is wound a coil carrying the magnetizing current (Fig. 16).

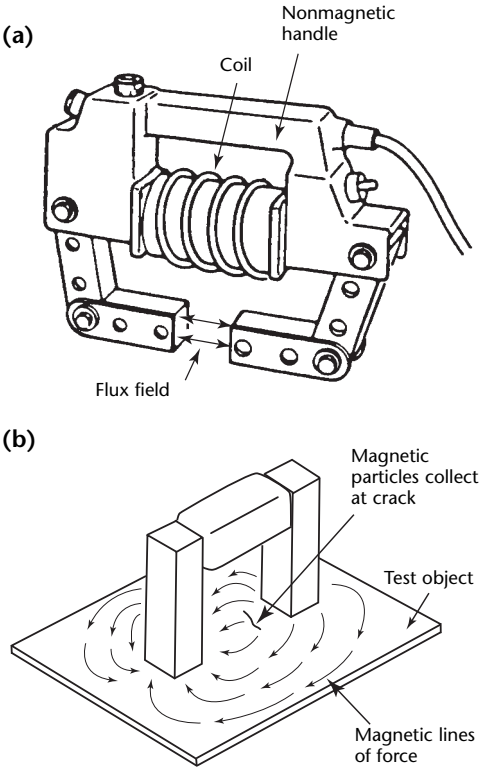
When a test object is placed across the opening of the *U* shape and the coil is energized, the object completes the path of the magnetic lines of force. This sets up a longitudinal field in the test object between the ends of the yoke. Permanent magnetic yokes can also be used to create a longitudinal magnetic field (Fig. 16b). Such yokes are often specified by their lifting power or by the tangential field intensity midway between the legs.

Combined Circular and Longitudinal Magnetization

Complete testing for discontinuities in different directions requires that two or more magnetizations and tests be performed. The test object should first be circularly magnetized and examined for indications, then longitudinally magnetized and inspected. Demagnetization is the final step.

It is critical to remember that discontinuities are best detected when they are at right angles to the magnetic lines of force.

FIGURE 16. Longitudinal lines of force induced by yoke magnet: (a) electrically energized yoke magnet; (b) permanent magnet yoke.



PART 5. Multidirectional Magnetization[6,7]

With all magnetizing techniques, discontinuities perpendicular to the magnetic flux are optimally indicated. However, discontinuity detection depends on flux density and the properties of the testing medium (Table 1).[8,9]

It is true that magnetic excitation also permits the detection of discontinuities that are not exactly perpendicular to the flux direction. In this case, the lines of flux can be decomposed into two components, one of them parallel and the other perpendicular to the direction of the crack. The perpendicular component contributes to the indication of the discontinuity. In some cases, even cracks appearing to be parallel to the flux direction may be weakly indicated. The reason is that most cracks are ragged in outline (intercrystalline cracks) so that some sections may be properly oriented for detection. However, at best cracks can only be detected when the angle between them and the direction of magnetization is more than 30 degrees. Experiments suggest the optimum angle is over 50 degrees.[10]

Combined Direct Current Fields

When a direct current magnetic field of a certain direction and intensity is superimposed on one of a different direction and intensity, both fields can be combined to form another field as shown in Fig. 17. Physically, the resulting field is formed by the addition of the two magnetic field vectors. The resulting field has a direction and intensity different from either of the primary fields, and is therefore very difficult to predict, especially when induced in complex shapes.

Two or three field directions may be superimposed by sequencing. If the fields vary in intensity with time, a swinging vector field is created. It is essential that multiple imposed fields be balanced in intensity, duration or both.

FIGURE 17. Superimposition of direct current magnetic fields: (a) addition of field vectors; (b) relationship of field directions.

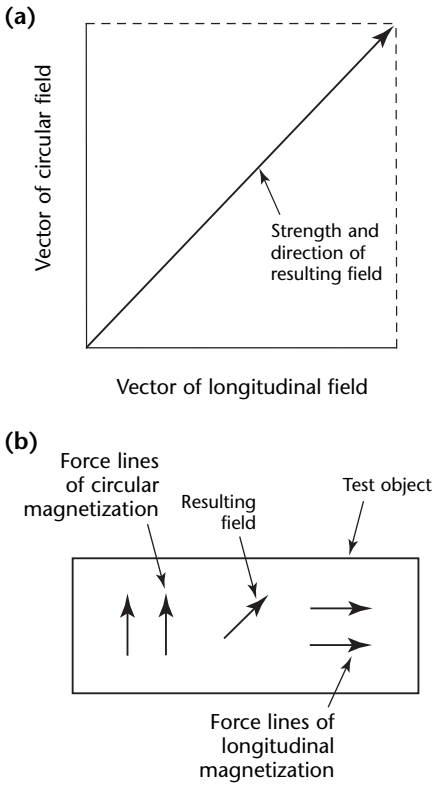


TABLE 1. Techniques for multidirectional magnetization.

Technique	Means
Circular magnetization technique	current flow technique (for solid and tubular test objects)
	internal conductor technique (recommended for tubular test objects)
Longitudinal magnetization technique	yoke or coil magnetization
Current induction technique	circulating current induced in ring using laminated core and influence of fluctuating longitudinal alternating current yoke field (Fig. 6)
Combination for single, overall test	yoke or coil magnetization with current flow or internal conductor technique
	internal conductor with current induction technique

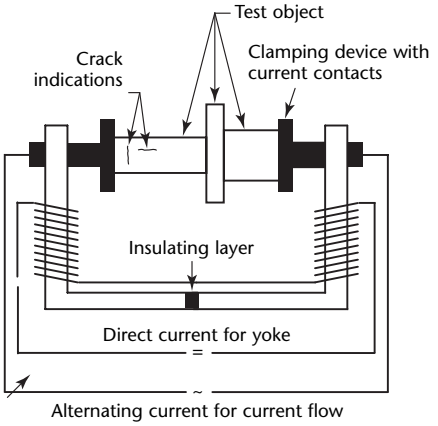
Combined Direct Current and Alternating Current Fields

For combined direct and alternating current magnetic particle testing, two perpendicular magnetic fields are superimposed in such a way that the resulting field changes its direction with time (generally in rhythm with the alternating frequency). The direction change again occurs in such a way that, for at least a short time, some field component is perpendicular to any existing crack direction. This in turn causes a magnetic particle accumulation and subsequent detection.

In the case of a combination of direct current yoke (or coil) with an alternating current flow (Fig. 18), the resulting field swings around the axis of the test object (Fig. 19). This combination of static and dynamic fields results in a vector swinging over an angle. The magnetic vector swings around the position of the direct current field and, in any given position, a sufficient component of it is at right angles to a possible discontinuity. If both fields have the same intensity, a total angle range of ±45 degrees (totally 90 degrees) is covered.

The disadvantages of direct current yokes are that (1) stray fields may form at the rounded ends of the test objects or at cross-sectional differences between the yoke and the object and (2) considerable field reduction occurs with large cross-sectional changes of the test object. Similar situations can also occur with coil magnetization.

FIGURE 18. Complete discontinuity detection by traditional swinging field technique (combination of direct current yoke and alternating current head current flow).



Combined Alternating Current Fields

It can be advantageous to magnetize in two directions with alternating current fields. An effective combination for periodic alternation of the resulting field vector cannot be realized if the two fields are in phase or in counter phase.

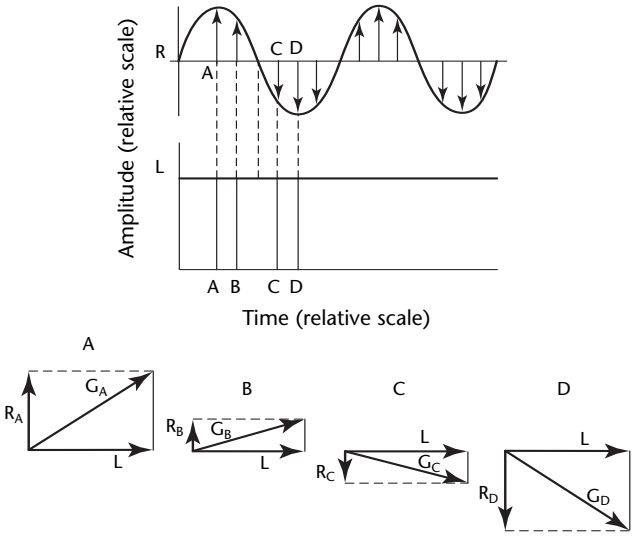
At a phase shift between 50 and 130 degrees, a rotating magnetizing vector of sufficient uniformity can be obtained. At a phase shift of 90 degrees and for equal field intensities, a circularly rotating vector is generated, as illustrated in Fig. 20. When three-phase current from the mains of a phase shift of 120 degrees is used, the behavior is similar (elliptical rotation).

Yoke for Combined Alternating Current Fields[1,6]

For structural reasons, a direct current yoke of solid steel has been used for many years to indicate transverse cracks. Alternating current yokes have recently been used but they must be assembled from laminated transformer sheet to prevent eddy current losses. These constructions are more expensive than direct current yokes.

Alternating current yokes are usually built to operate over limited clamping lengths, because a longitudinally oriented alternating current field is reduced with increasing clamping lengths.

FIGURE 19. Combined crack detection by circular alternating current and longitudinal direct current field.



Legend
G = vector of resultant field (at times ABCD)
L = vector of longitudinal magnetization
R = vector of circular magnetization

An alternating current yoke has several advantages.

1. Field distribution is uniform, even over test objects with geometrically complicated shapes and over changes of cross section.
2. Induced field flow is possible.
3. Demagnetization of the test object is simple and rapid.
4. Testing times are short.

With clamping lengths from 900 mm to 1200 mm (36 to 48 in.), longitudinal magnetization may better be achieved using a movable alternating current coil.

Testing Procedures with Multidirectional Magnetization[6]

With multidirectional magnetization techniques, the resulting magnetic field changes its direction in the rhythm of the frequency of the current application, becoming alternately perpendicular to certain cracks. However, the direction of such a vector is also parallel to a particular crack for a very short time. For this reason, when using the multidirectional technique, the application of the testing medium must always take place during magnetization. An indication previously established cannot be held by magnetic force and could theoretically be flushed away by the testing fluid. The procedure does possess a certain inertia: the magnetic vector has already left the parallel direction when the particles begin to move away.

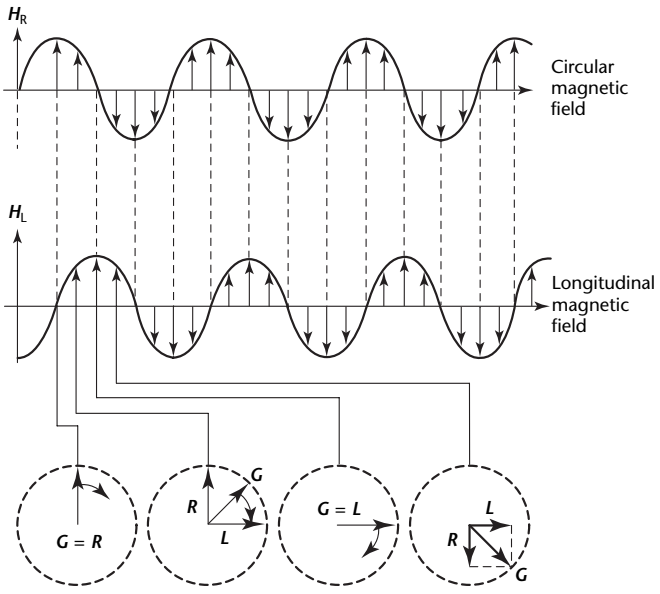
Experience in Germany and more recently in the United States indicates two advantages for the multidirectional magnetization technique. The technique can detect very small discontinuities because at some period in the magnetization cycle the field vector is normal to the discontinuity direction. Also, in comparison with the single magnetization procedures (head and coil magnetizations), the combined current technique presents considerable economic advantages since it requires only one processing step instead of two or more.[11,12]

Combined Auxiliary Magnetization

An exceptional variation of the multidirectional magnetization technique is called *combined auxiliary magnetization*, used for cylindrical test objects. Here, the auxiliary alternating current flow technique is combined with the alternating current induction technique (Fig. 21). A magnetizing bar is put through the test object. This laminated steel, copper coated bar serves as both a current conductor and a phase shifted magnetic field conductor.

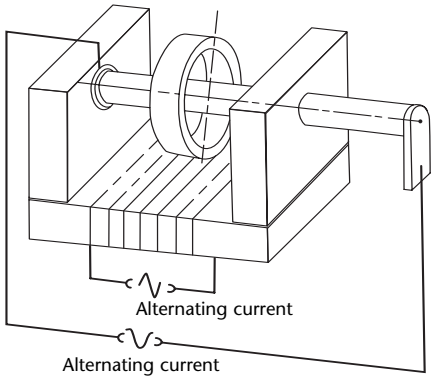
This reliable technique is noncontacting, pole free and can indicate cracks of any direction on inside surfaces, outside surfaces and face areas of cylindrical test objects. Combined auxiliary magnetization can be carried out only by systems equipped with an alternating current yoke — contributing still further to the trend toward alternating current yoke techniques (Table 1).

FIGURE 20. Alteration of the magnetic field by combination of two phase shifted alternating current fields (rotating vector).



Legend
G = vector of resultant field
H = magnetic field intensity (A·m^{-1})
L = vector of longitudinal field
R = vector of circular field

FIGURE 21. Combined auxiliary magnetization by combination of alternating current flow and current induction techniques.



PART 6. Circumferential Magnetization of Pipe

The drilling and production of natural hydrocarbons generally require that the tubular product (casing, tubing and drill pipe) be tested for discontinuities. Magnetic flux leakage techniques are the most commonly used tests for detection of outer and inner surface discontinuities. Ultrasonic testing is used for regions difficult to inspect with magnetic flux leakage.

A common form of testing for longitudinally oriented, surface breaking, tight discontinuities (seams, laps and cracks) involves magnetization of the tube circumferentially by the internal conductor technique, followed by testing with some form of magnetic flux leakage sensor. The use of ferroprobes, coils and solid state sensors for this application is summarized elsewhere in the *Nondestructive Testing Handbook*.[13] The text below deals with the magnetization of oil field tubes and treats magnetic particles as the sensor.

Specifications for Testing Oil Field Tubulars

Specifications and recommended practices for the testing of oil field materials are written by oil companies and the American Petroleum Institute (API).[14–17]

Magnetization Techniques for Oil Field Applications

Two distinct techniques[18] are used for the circumferential magnetization of tubes up to 14 m (45 ft) long (Fig. 22). Both techniques use an insulated rod (generally made from aluminum although this is not required) which passes through the bore of the tube. In Fig. 22a, the rod is reasonably well centered in the bore and fed with some form of direct current. In mill installations, this might be full-wave or half-wave rectified alternating current with the subsequent test being done using wet fluorescent magnetic particles.

In field operations, banks of batteries have been used for current. When the magnetizing current is pure direct current, the magnetic field intensity H at the outer surface of the tube, when the conductor is centered within the bore, is given in amperes per meter by:

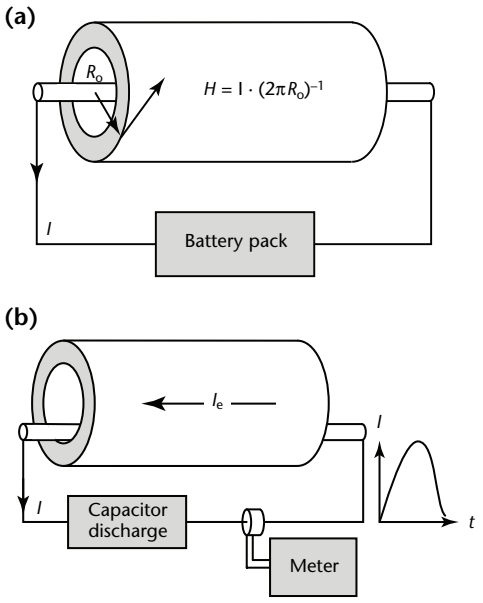
$$\textbf{(1)} \qquad H = \frac{I}{2\pi R_0}$$

where I is the current (amperes) and R_o is the outer radius of the tube (meters).

Figure 23 illustrates some of the values used in this discussion. In Eq. 1, the field intensity is given in amperes per meter because R_o is expressed in meters. However, this field intensity is sometimes measured with a hall element tesla meter, and because one gauss is numerically equal to one oersted in air, conversion to gaussian units yields:

$$\textbf{(2)} \qquad H = \frac{2I}{10R_0}$$

FIGURE 22. Two techniques for establishing circumferential magnetization in elongated tubes: (a) central conductor with battery pack to provide high current; (b) internal conductor with capacitor discharge system. Peak and duration meter may be used to measure pulse amplitude and duration.



Legend

H = magnetic field intensity ($A \cdot m^{-1}$)
I = electric current (A)
I_e = electric current (A) induced in cylinder
R_o = outer radius (m)
t = time (s)

where I is in amperes and R_0 is in centimeters.

The second magnetization technique is shown in Fig. 22b. The motive force is provided by a capacitor discharge unit.[19] The effect of rod centralization is minimal and has been shown to affect field intensity by 4.2 percent for pipe larger than 340 mm (13.37 in.).[20] Magnetization by this technique obeys no scientifically simple rules because the rapid rise of rod current during magnetization causes the induction of an eddy current in the tube and this detrimentally affects penetration of the magnetizing field intensity into the material.

The direction of the induced eddy current I_e with respect to the rod current I is shown in Fig. 23 for a centered rod. By Lenz's law, the eddy current induced on the inner surface of the tube must create a field within the material which opposes the field caused by the rod current I. The field intensity H at some radius r at some instant, whereas the rod and eddy current fields are finite, is given in amperes per meter by:

$$\textbf{(3)} \qquad H = \frac{I}{2\pi r} + H_e$$

The H_e term is the field intensity created by the eddy current itself.

Eddy Current Effect

In considering Fig. 23, Ampere's law indicates that the field at the radius r is caused by the currents inside that radius (rod current and inner wall eddy current). The outer wall eddy current is the return loop for the inner wall eddy current, and plays no role in the theory so far outlined. However, since it does represent an unwanted current flowing in the tube, its presence does lead to two very practical considerations.

First, pipes being magnetized before testing should be insulated from each other by an air gap. If this does not occur, then the outer surface eddy current can jump from protrusions in the pipe being magnetized to the next pipe in the string. The resulting arc can cause burns on both tubes. This in turn can cause hard spots on the materials at which corrosion might preferentially occur. This is particularly to be avoided with corrosion resistant materials, some of which require a hardness less than 22 on the rockwell C scale for longevity in corrosive environments.

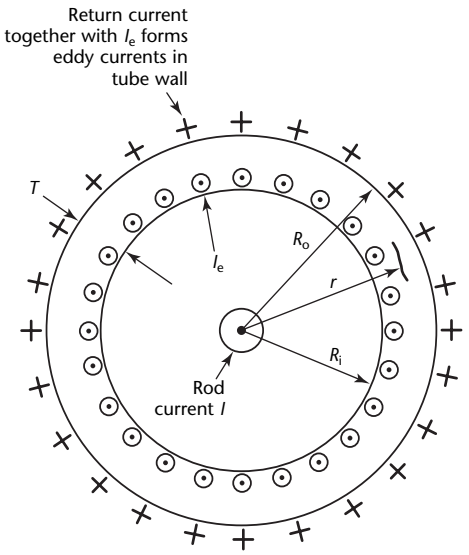
Secondly, the material should be insulated from the metal racks that carry it. If pipe racks are not insulated with a layer of nonconductive material (rubber or wood, for example), then the outside diameter surface eddy current can flow to ground through the rack and there is a real possibility of arc burn at the point of contact.

BH Curve in Setting Specifications

There is an important fact about the magnetization of test objects by the capacitor discharge, internal conductor technique: the ring sample *BH* curve governs the flux density value in the material. In effect, knowing the *BH* properties of the material from a ring sample investigation allows field intensity levels to be set. Figure 24 shows the *BH* properties of two typical oil field tubular materials: a 620 MPa (90 000 $lb_f \cdot in.^{-2}$) proprietary material and a 390 MPa (55 000 $lb_f \cdot in.^{-2}$) casing material.

The important point that can be made from these curves is that after application of about 3200 $A \cdot m^{-1}$ (40 Oe), the materials are effectively saturated.[21] It is generally true of oil field tubular materials that 3200 to 4000 $A \cdot m^{-1}$ (40 to 50 Oe) are required within the material to magnetize to a level sufficient for subsequent residual induction testing. It is required that this field intensity level be reached at

FIGURE 23. Eddy current I_e created in steel tube at beginning of pulse I in rod centered within bore of tube. Direction of I_e on inner surface opposes that of I; outer surface forms return path.



Legend

I = electric current (A) in rod
I_e = eddy current (A) induced on inner surface
r = radius (m) from axis to point inside tube wall
R_i = radius (m) from axis to tube inner surface
R_o = radius (m) from axis to outer surface
T = wall thickness

each point in the tube wall, despite the demagnetizing effect of the eddy current.

This requirement does not lead to a simple current equation that can be used by a typical operator in the field (experimental specifications found effective in saturating tubes are presented below).

Typical Requirements for Direct Current Magnetization

If the central conductor technique is used for the magnetization of tubes, then the values given in Table 2 reflect the magnetizing field at the outside diameter of either 3200 A·m^{-1} (40 Oe) for I_1 or 4800 A·m^{-1} (60 Oe) for I_2 for typical pipe sizes. Because the magnetization uses direct current, the wall thickness, mass per meter (weight per foot) and tube grade — which affect the magnetic and electrical properties of the material — do not affect the field intensity. The actual value used is often determined by specifications, as agreed between the manufacturer of the material and the user. A typical specification is given by:

$$\text{(4)} \quad I = 7500\,D\,[\text{mm}] = 300\,D\,[\text{in.}]$$

where D is tube diameter. This *amperes per diameter unit* specification is equivalent to 3760 A·m^{-1} (47 Oe) at the tube surface. It can be seen from Fig. 24 that such a field intensity raises the value of the flux density in the tube to a high level, so that after the field has fallen to zero, the flux density in the material is at a value close to remanence (B_r).

Full-Wave and Half-Wave Rectified Alternating Current

For the central conductor technique outlined above, some form of rectified alternating current is often used. It should be noted that such current waveforms induce eddy currents in the test object. The field intensity waveform at the outer surface can be seen by positioning a hall element to detect the field and feeding the output of the tesla meter to an oscilloscope.

Pulsed Current Magnetization

Internal conductor magnetization (using single pulses of current) differs from direct current or continuous magnetization by the central conductor technique because

FIGURE 24. Curves of magnetizing force H versus flux density B: (a) high strength tube steel material is a sour gas grade of special chemistry and heat treatment; (b) lower strength oil field casing. Dashed lines indicate that the materials are magnetized almost to saturation by application of 3.2 to 4.0 kA·m^{-1}.

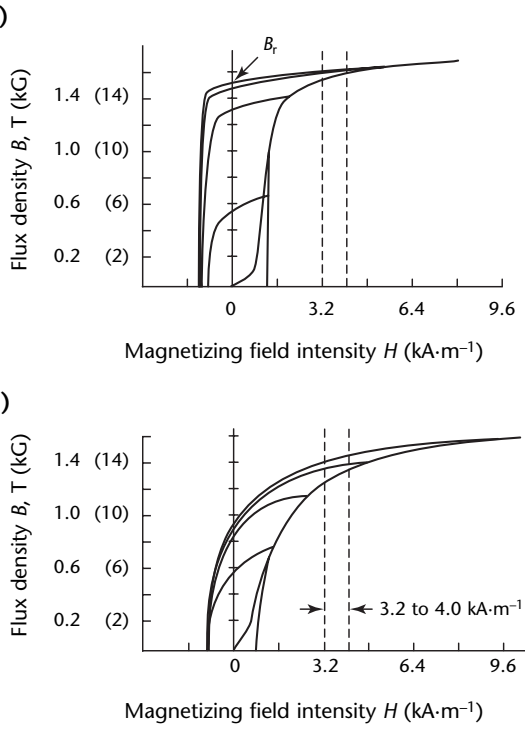


TABLE 2. Current requirements for direct current magnetization of oil field tubes. Direct current or long pulse (> 0.5 s) only. Not valid for capacitor discharge magnetization.

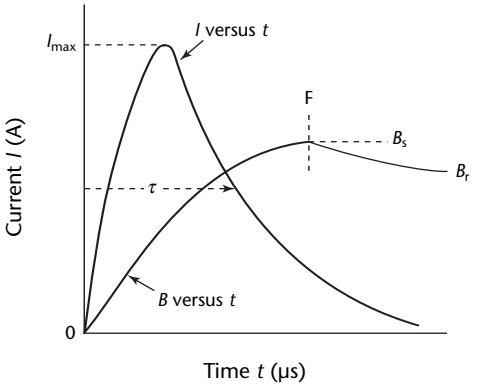
Tube Diameter		I_1[a]	I_2[b]
mm	(in.)	(A)	(A)
60	(2.4)	600	910
73	(2.9)	730	1100
89	(3.5)	890	1340
102	(4.0)	1020	1530
114	(4.5)	1150	1720
127	(5.0)	1280	1910
140	(5.5)	1400	2100
168	(6.6)	1690	2530
178	(7.0)	1790	2680
194	(7.6)	1940	2920
219	(8.6)	2200	3300
244	(9.6)	2450	3680
273	(10.8)	2740	4110
298	(11.8)	3000	4500
340	(13.4)	3410	5120

a. 3.2 kA·m^{-1} (40 Oe) at outside diameter.
b. 4.8 kA·m^{-1} (60 Oe) at outside diameter.

account must be made for the fact that the induced eddy current may not have time to die away before the field intensity from the conductor current dies away. Figure 25 shows two time variations that are measurable for single pulses, such as are provided by capacitor discharge units. The first variation is that of the magnetizing current (I versus t). In this variation, a relatively rapid rise of current to its maximum value I_{max} is followed by a much slower fall toward zero, the entire pulse length being on the order of 200 ms. This time variation is the response to the discharge of a capacitor C, initially charged to V_0 volts through a resistor R in a circuit containing inductance L. A simple mathematical analysis is provided later.

The second variation is that of the average bulk flux density within the material (B versus t). This quantity rises at a much slower rate than $I(t)$ due to the shielding effect of I_e. A high level of magnetization is reached when the flux density at the point F is close to the material's saturation value B_s. The consequences of conditions shown in Fig. 25 are that deep magnetization of the tube only occurs when the detrimental effect of the eddy current is overcome by elongating the electrical pulse in time so that the magnetizing current is still effective as the eddy current is dying away.

FIGURE 25. Plots of capacitor discharge internal conductor current (I versus t) and average flux density induced (B versus t) in tube. I_{max} and t are measured with peak and duration meter. Flux density peaks well after current.



Legend

B = magnetizing flux density
B_r = point of flux density lower than saturation
B_s = point of magnetic saturation
F = high magnetization point
I = current (A)
I_{max} = maximum current (A)
t = time (s)
τ = mean lifetime (s)

The fall in induction from F to B_r is that which is normally expected when the magnetizing field intensity falls to zero, as it does after the passage of a pulse. This is determined by the BH curve for the material undergoing magnetization. Should the point F not represent saturation (B_s), then the material reaches some average bulk flux density lower than B_r. This is often not a problem: while the surfaces are magnetized sufficiently for longitudinally oriented discontinuities to hold magnetic particles, no information of the interior condition is required. However, when relatively thin elongated tubulars can be tested from the outside surface only, saturation of the material is necessary for inside diameter discontinuities to produce magnetic flux leakage at the outside diameter.

Practical Testing Situations

Commonly encountered testing situations for the magnetization or remagnetization of tubes are discussed below, including
(1) material at unknown induction,
(2) material at zero induction and
(3) material not saturated by pulse.

The magnetic condition in which a sample arrives is often not known to the inspector, who must assume the worst possible case: the material is at saturation in a direction directly opposed to that caused by the magnetic particle test equipment. This is resolved by taking the material from an unknown value of remanence in one direction to remanence in the other direction as is shown in the schematic BH curve for the material (Fig. 26).

A material might also arrive with an induction between zero and $-B_r$ and it is desired to perform testing at $+B_r$. During magnetization, the material should take the path $-B_rH_cPB_sB_r$. That is, through saturation B_s to remanence B_r.

In the case of material initially at zero induction, the tube is at 0 on Fig. 26 and during magnetization takes the path OPB_sB_r.

In cases where the pulse is insufficiently strong, the material may follow a magnetization path such as $-B_rH_cPQ$ or OPQ. It is then essential to pulse more than once. A possible magnetization path during a second pulse is QB_sB_r. The net final induction is raised as shown.

Analysis of Pulse Current Magnetization

In the text below, an analysis of the pulse current internal conductor technique for

magnetizing elongated tubes is presented. Simplified equations are given for the types of current pulses available for magnetization. From the theoretical viewpoint, the current pulse time dependence (I versus t of Fig. 25) is discussed and then formulas are presented for the inductance experienced by the magnetizing circuit.

These formulas illustrate the dependence of such inductances (1) on the average value of the differential permeability $dB \cdot (dH)^{-1}$ of the object under magnetization and (2) between the field intensity and flux density limits imposed by the exciting current and BH properties of the material.

Current Pulse Time Dependence

For inductance capacitance resistance circuits, the time variation of the current pulse obeys the equation:

$$\textbf{(5)} \qquad \frac{d(LI)}{dt} + IR + \int I\frac{dt}{C} = 0$$

The three terms on the left of Eq. 5 represent the instantaneous voltages across the inductance, the resistance and the capacitance in the circuit (Fig. 22b). The inductance in the circuit is mainly that of the rod tube system, because by careful design the presence of additional inductance between cables and ground can be minimized. Because inductance is time dependent, it is included in the derivative term. The resistance is the combined resistance of the rod, cables and their connection, and any internal resistance in the capacitor discharge box. Resistance in the discharge box may be due to the forward resistance of a silicon controlled rectifier included to eliminate the possibility of current oscillation. The capacitance of the system is generally in the region of 2 to 8 F.

Equation 5 has three solutions if the time dependence of L is ignored. These solutions depend on the relative values of L, C and R.

$$\textbf{(6)} \qquad I = \frac{2V_o}{\sqrt{\frac{4L}{C} - R^2}} \exp(-\beta t) \sin\sqrt{\frac{4L}{C} - R^2}\, t$$

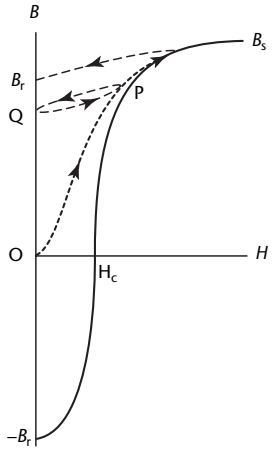
$$\textbf{(7)} \qquad I = V_o C(\beta^2 t)\exp(-\beta t)$$

$$\textbf{(8)} \qquad I = \frac{2V_o}{\sqrt{R^2 - \frac{4L}{C}}} \exp(-\beta t) \sin h\sqrt{R^2 - \frac{4L}{C}}\, t$$

where V_o is the voltage to which the capacitor bank is charged and $\beta = R \cdot (2L)^{-1}$.

The solution to Eq. 6 is oscillatory, but the presence of the *SCR* limits the pulse to only the first positive-going peak. This is shown in Fig. 27. In this example, the pulse has a length of 17 ms and reaches 10 500 A. Such pulses are ideal for magnetizing objects of low electrical conductivity, such as ferrite magnets. However, with highly conducting materials such as steel tubes, the initial

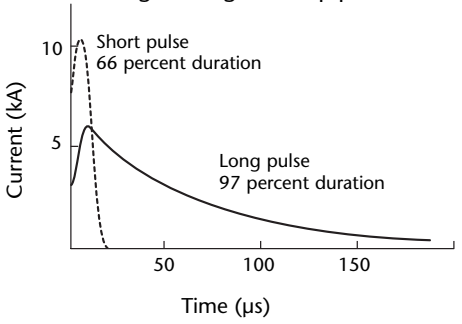
FIGURE 26. Possible paths taken by circumferentially magnetized material from various initial magnetization conditions to saturation B_s and then remanence B_r in known direction. Point P indicates weak pulse followed by second pulse.



Legend

B = magnetic flux density
H = magnetic field intensity
H_c,O,P,Q = reference points
——— = material at remanence in opposite direction
--------- = material at zero induction

FIGURE 27. Typical pulses from capacitor discharge systems: long pulse is more effective in magnetizing of line pipe.



rapid current rise (up to millions of amperes per second) induces a shield of eddy currents that does not permit field penetration into the bulk of the material. The net effect of this is a magnetized outer layer only.

The exponential solution (Eq. 7) is known in its mechanical analog as *critical damping*. It is difficult to achieve in this situation because it depends on the value of *L* which in turn is dependent on the physical and magnetic parameters of the test object. The formula for the inductance of a tube is given below.

The sin *h* solution (Eq. 8) leads to the longest pulses because there is no oscillation. Pulses of full length up to 160 ms are commonly used in the oil tube testing industry.

Definition of Pulse Length

It has become commonplace to define the length of such pulses as the time taken for the pulse to reach 0.5 I_{max} during decay τ (Fig. 25). Both I_{max} and τ are measurable with an inductive ammeter or peak and duration meter (Fig. 22b). Such pulses are effective in magnetizing tubular test objects because the field intensity from the rod current is still high as the eddy current in the test object dies away, so that penetration of the field into the bulk of the material occurs.

Since the inductance is a function of time, a full solution for the variation of the pulse current $I(t)$ can only be obtained by modeling the effect that the induced eddy current has on the instantaneous value of *L*. Experimental evidence indicates that, at least for elongated tubes, the physics of the magnetization process can be illustrated by a discussion of the constant *L* case.

Typical Values for *L, C* and *R*

In the design of a capacitor discharge pulsing system, it is essential to aim at a pulse that has sufficient length to deeply magnetize the material. There are two reasons for this. First, the material to be tested may arrive at the test site in a longitudinally magnetized condition and it may be necessary to remagnetize it circumferentially prior to testing. Second, some specifications call for relatively low emergent longitudinal field intensities at the ends of such elongated test objects. Rotation of the bulk flux density into the circumferential direction may be simplest way to achieve this.

An additional consideration unrelated to the physics of the magnetization of the test object is the safety of the system in both installed and field situations. The *National Electric Code* should be consulted for details. However, it appears essential for field use to limit the charging voltage of the capacitor bank to 50 V. The tendency of this restriction is to add capacitance to the system.

The resistance of the magnetization system is a factor in permitting high currents to flow. It is minimized for field use by using parallel strands of 11.7 mm (0.46 in.) diameter (AWG [American wire gage] 0000) copper welding cable for the connections between the rod and the capacitance discharge box. The rod is made of aluminum (mainly because of the continued need to make and break the rod) but any highly conductive material would work equally well. The requirement of elongating the pulse length to ensure the presence of its field after eddy currents have died away far outweighs the requirement of minimizing the overall resistance of the magnetizing circuit. Typical values, which might include that of 5 m (16 ft) of cable and 15 m (49 ft) of rod, are 1 to 5 mΩ.

The capacitance within the capacitance discharge supply is generally within the range of 2 to 8 F, which is comparatively large. This occurs because of the need to maintain relatively low voltages around the circuit and to elongate the pulse.

While the values *R* and *C* can be controlled by the manufacturer, the value of *L* cannot, mainly because it depends on the test object undergoing magnetization. In the case of tubulars, the inductance is given by:

$$\textbf{(9)} \quad L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{R_o}{R_i}$$

where $dB\cdot(dH)^{-1}$ is the differential permeability, ℓ is the length of the tube, R_o is the outer radius and R_i is the inner radius (Fig. 23).

It often occurs that the wall thickness *T* is much smaller than the average radius of the tube. Under these circumstances, Eq. 9 may be converted to:

$$\textbf{(10)} \quad L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{r+\frac{T}{2}}{r-\frac{T}{2}}$$

which reduces to:

$$\textbf{(11)} \quad L \cong \frac{\ell T}{2\pi r}\left(\frac{dB}{dH}\right)$$

Using the International System of Units (SI), Eq. 11 becomes:

$$\textbf{(12)} \quad L \cong 0.16\left(\frac{\ell T}{r}\right)\left(\frac{dB}{dH}\right)$$

where r is $0.5(R_o + R_i)$. All lengths are in meters and $dB{\cdot}(dH)^{-1}$ is dimensionless.

The inductance of thin walled tubes is seen from Eq. 11 to be proportional to the length ℓ and wall thickness T of the tube, and inversely proportional to its radius or diameter. Neither of these physical parameters nor the value of $dB{\cdot}(dH)^{-1}$ can be controlled by the designer of the magnetizing equipment.

For much of the tubular product used in oil fields, the value of $T{\cdot}(R)^{-1}$ does not vary a great deal, perhaps only by a factor of two. The average value of $dB{\cdot}(dH)^{-1}$ encountered during magnetization can be seen from Fig. 26 to vary widely, depending on (1) the point P reached on the *BH* curve by the material during magnetization and (2) the starting point for magnetization (anywhere from $-B_r$ to *Q* on the *B* axis). Examples of typical inductances follow.

Example 1. Pipe magnetized to saturation following the path $-B_rH_cPQ$. Flux density B_r at point B_r = 1.2 T (12 kG); dH = 2400 A·m^{-1} (30 Oe); ℓ = 10 m (33 ft); P = 1.2 T (12 kG); r = 136.5 mm (5.4 in.); T = 12.6 mm (0.5 in.).

Here, dB is 24 000 G, so $dB{\cdot}(dH)^{-1}$ = 800, and $L = (2 \times 10^{-7})(10\text{ m})(12.6\text{ mm})(800){\cdot}(136.5)^{-1}$ mm = 148 μH.

Example 2. Same tube as example 1 is taken from *Q* through *P* and B_s to B_r by a second pulse. B_s = 1.5 *T* (15 kG); dH = 4000 A·m^{-1} (50 Oe); *Q* = 1.0 *T* (10 kG).

The average value of $dB{\cdot}(dH)^{-1}$ is now only 100. Dividing the value obtained in example 1 by 8, the ratio of the two values of $dB{\cdot}(dH)^{-1}$ exhibited by the steel yields: L = 18.5 μH.

Example 3. Pipe is initially unmagnetized follows path OPB_sB_r with: B_s = 1.5 *T* (15 kG) = 9.09 m (30 ft); dH = 3200 A·m^{-1} (40 Oe); R = 27.7 mm (1.1 in.); T = 4.83 mm (0.2 in.).

Consequently, $L = (2 \times 10^{-7})(9.09\text{ m})(4.83\text{ mm})(15\,000{\cdot}(40)^{-1}){\cdot}(27.7)^{-1}$ mm = 119 μH.

The relatively large change in inductance exhibited by the tube in examples 1 and 3 affects the shape of the pulse waveform, notably the easily measurable parameters of peak current I_{max} and pulse duration τ. These parameters are shown in Fig. 25.

Design Considerations

Good equipment design must include user input about the material being magnetized. The worst case for the internal and external resistances of the magnetizing system should be known to the manufacturer and worst values of inductance should be investigated. Under no circumstances should peak currents be stated for the purpose of magnetization without an electrical and magnetic load being used for the system evaluation.

Depending on the use of the equipment, the relevant **regulations should be consulted about insulation, isolation, explosion proofing, intrinsic safety and purging.** Such regulations are found in a variety of places, depending on the use of the product. Notable among these are the Occupational Safety and Health Administration (OSHA), the National Institute of Occupational Safety and Health (NIOSH), the *Code of Federal Regulations* (CFR) and a variety of international specifications, many of which are much more stringent than those in the United States.

Equipment designers should particularly note the requirements of the Canadian standards when designing for Canada. The requirements of the United Kingdom, Norway and Germany are applicable when designing for the North Sea.

Magnetization Recommendations

Tubular product has such wide limits of diameter and wall thickness that it is difficult to provide a universal specification for the measurable parameters of current pulses for a high level of residual induction. However, broad guidelines based on research with a variety of tubes indicate that the values given in Table 2 provide adequate magnetization.

Pulse Duration

In Table 3, pulses are classified by duration. Long duration pulses are those in excess of 100 ms. For such pulses, the induced eddy current can be assumed to have died away while the magnetizing field intensity is still high enough to cause saturation. Moderate duration pulses are those between 40 and 100 ms. For magnetization, the longevity of the induced eddy current is acknowledged by its effect on the tube (shown through the use of the lineal mass of the tube rather than the outer diameter). Short pulses are those below 40 ms. The maximum current

requirement for the single short pulse compared to that for the single moderate pulse is higher for the same lineal mass of tube. In effect, the higher current causes a larger magnetizing field intensity in an attempt to overcome the eddy current.

Should it be necessary to use two such pulses, the peak current requirement falls because the material is partially magnetized. If the peak current can only reach I_{max} = 180 (W), then two such pulses are required. Should the pulse be of insufficient magnitude to magnetize the tube with two pulses, then a third pulse is necessary so that the three pulses meet the requirement of I_{max} = 145 (W).

These requirements are designed to ensure that the bulk induction following the pulses is at least 90 percent of the remanence value. In most cases it is higher.

Current Pulse Effectiveness

There are two techniques used to evaluate the effectiveness of a current pulse. A third technique, which detects surface fields only, is also outlined here. The first technique is a variation on the rowland ring technique for the evaluation of the magnetic parameters of magnetizable materials and involves the measurement of magnetic flux. The second technique is an indirect technique using an inductive ammeter (peak and duration meter). The third technique uses simulated contact discontinuities.

Flux Meter

Magnetic flux meters measure the total magnetic flux threading an area defined by a search coil. In the case of circumferential magnetization of a hollow product by the internal conductor technique, the search coil can be a single-turn coil through the test object. Flux changes are given by:

$$\Delta\Phi = A\Delta B \quad (13)$$

where $\Delta\phi$ is changes in flux, A is the area of the test object perpendicular to the search coil ($A = T\ell$), where ℓ is tube length, and ΔB is the change in flux density of the test object induced during magnetization.

Commercially available flux meters can generally be compensated for the test object area so that the device can be made to read the average flux density directly. A problem with this approach to the measurement of the final flux density is that the initial flux density in the test object, with respect to the vector direction of the search coil, must be zero. This problem occurs because, when flux changes are to be measured, the initial value must be known. However, if the tube shown in Fig. 28 is initially unmagnetized or the prior magnetization is longitudinal, then the flux meter reads the average density of induced circumferential magnetization.

Should the output of the flux meter be presented on an oscilloscope, it should be noted that flux values (caused by the passage of a pulse) between the beginning and the end of the magnetization process represent the flux linked by the single-turn coil and contain the effect of the flux in the air between the terminals of the flux meter.

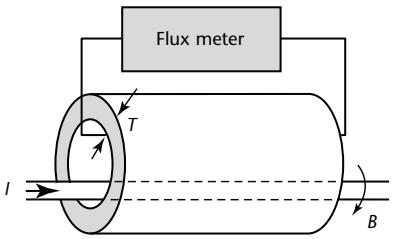
During the pulse, the air field caused by the current I in the rod and eddy currents I_e in the test object affects the instantaneous flux meter reading. When these currents have died away, only flux perpendicular to the single-turn coil affects the final result. If the operator has time to wind more than one turn around the test object, the resulting error in final

TABLE 3. Pulse classification by duration with current requirement.

Magnetization	Duration (ms)	Current Requirement
Long pulse	> 100	$I = 11.8\ D_1$
		$I = 300\ D_2$
Moderate pulse	40 to 100	$I = 74\ W_1$
		$I = 110\ W_2$
Single short pulse	0 to 40	$I = 161\ W_1$
		$I = 240\ W_2$
Double short pulse	0 to 40	$I = 121\ W_1$
		$I = 180\ W_2$
Triple short pulse	0 to 40	$I = 97\ W_1$
		$I = 145\ W_2$

D_1 = outer diameter (mm)
D_2 = outer diameter (in.)
I = current (A)
W_1 = tube weight (kg·m^{-1})
W_2 = tube weight (lb·ft^{-1})

FIGURE 28. Measuring of flux density induced in circumferential direction by techniques shown in Fig. 22.



Legend
B = magnetic flux
I = electric current
T = wall thickness

bulk flux can be reduced. However, for the purpose of establishing the presence of a residual induction in the test object to excite magnetic flux leakage from discontinuities, this procedure is not necessary.

Inductive Ammeter

In an inductive ammeter or peak and duration meter, as shown in Fig. 22b, the pickup coil is threaded onto any convenient part of the magnetizing circuit and when the pulse is fired the meter reads the peak current (I_{max} of Fig. 25) and the duration of the pulse (τ of Fig. 25).[21]

Saturation of the material occurs when successive readings on the ammeter are identical. This can be explained as follows. When the first pulse is fired, the material exhibits its highest value of $dB \cdot (dH)^{-1}$ because of the inclusion of the steep part of the *BH* curve into the value of *L* (Fig. 27). The average value of $dB \cdot (dH)^{-1}$ is effective in determining the value of the inductance in Eqs. 6 to 8. This value is relatively large compared to what the material might exhibit during a second pulse. In effect, the second pulse experiences a lower inductance than the first pulse.

The effect of the lowered inductance experienced by a second pulse is to permit the peak current I_{max} to reach a higher value than it reached on the first pulse — in effect, the material is different — but the system response is also to lower the duration τ. By monitoring I_{max} and τ, it is possible for inspectors to determine the relative degree of magnetization of the test object.

Simulated Test Discontinuity

Flexible laminated strips of high permeability material are commercially available and these may be placed in intimate contact with the test object after magnetization. Such strips contain three test discontinuities encapsulated in brass so that the liftoff between the test object and the strip is minimized to that of the brass encapsulation.

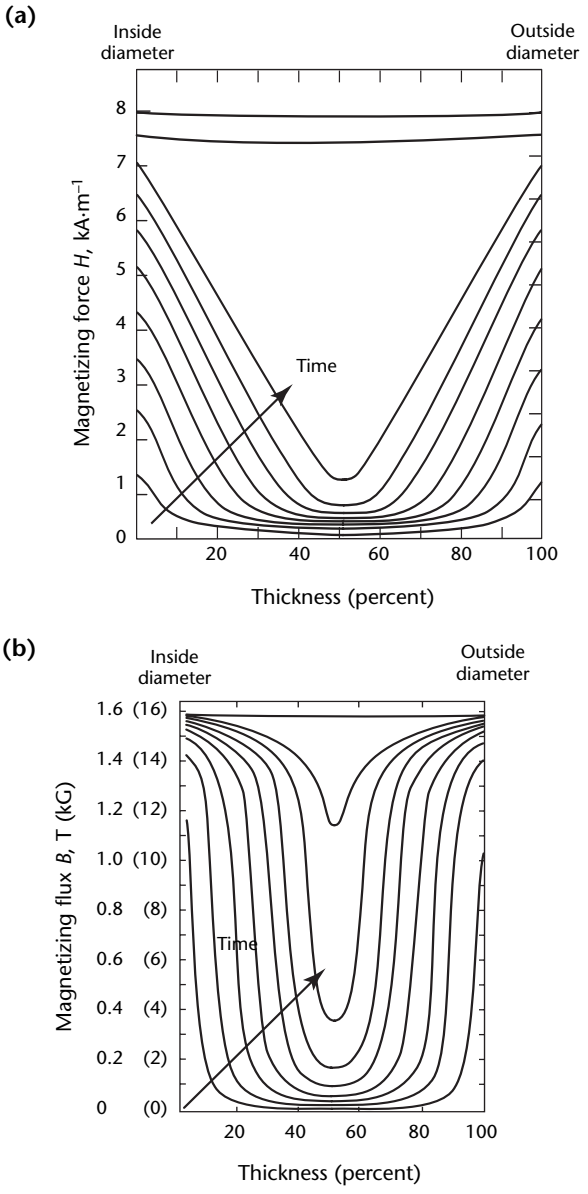
Under such circumstances, the magnetized material shares flux with the strip and, if the test discontinuities give an indication with magnetic particles, then so will a similarly sized discontinuity in the test object.

Use of Inductive Ammeters

When magnetizing with pulse techniques, the value of the material's field intensity *H* and flux density *B* both change with time. In Fig. 29, the horizontal axes show the percent distance from the inside diameter surface to the outside diameter surface. The vertical axes show either the fraction of *H* required to saturate the material or the flux density *B*. The lowest lines indicate time from the very start of the pulse. The uppermost lines indicate the field intensity and flux density levels at later time increments.

It can be seen from Fig. 29 that three phenomena occur during pulse magnetization: (1) both inner and outer surfaces are rapidly magnetized, (2) the midwall region is the last part of the material to be magnetized and (3) the midwall region can be left with a low

FIGURE 29. Plots of tube wall thickness: (a) versus magnetizing force; (b) versus resultant flux density. Lower lines represent field and induction at beginning of pulse (time proceeds up to the figures); central (midwall) regions are the last to be magnetized.



state of magnetization if the pulse field intensity is insufficient to saturate the material.

This last phenomenon contributes to magnetic fields from discontinuities at one surface, producing no leakage field at the other surface, when the material is not saturated. The leakage field into the midwall section of the material merely raises the local magnetization level to a higher degree.

During magnetization, if parts of the material do not reach a field intensity level that ensures saturation (at the point P in Fig. 26), then the ensuing bulk residual flux density is low and the material requires additional pulses to saturate it. The magnetization process calls for the highest values of the inductance L in Eqs. 5 through 12 during the first pulse and lower values during subsequent pulses. The general effect of a high value of inductance is to lower the value of I_{max} and elongate the value of τ.

In order to show that this is the case, and to limit the necessary mathematical computation, Eq. 7 is selected and from it the closed form results for I_{max} and τ are found. First, the time t (in seconds) at which I_{max} occurs is found by differentiation of Eq. 7 to be:

$$\textbf{(14)} \quad t = \frac{2L}{R}$$

where L is self inductance (henry) and R is resistance (ohm).

When this value is used in Eq. 7, the result for I_{max} is:

$$\textbf{(15)} \quad I_{max} = V_0 C \frac{R}{2Le}$$

where C is capacitance (farad) and V_0 is voltage.

This result indicates that the value of I_{max} is inversely proportional to that of L (the greater is L, the lower is I_{max}). To find τ, $I(t)$ must be set at 0.5 I_{max}. The result in seconds is:

$$\textbf{(16)} \quad \tau = 5.36 \frac{L}{R}$$

In this case, the pulse duration as defined by τ is proportional to the value of L. Larger values of L, such as are found for the initial pulse, lead to the longest pulse durations.

The *B-H* curve indicates that the lowest value of inductance that can occur under these magnetization conditions is that exhibited by saturated material, when the value of $dB \cdot (dH)^{-1}$ is at its lowest (Eq. 11). If two identical readings are obtained from an inductive ammeter as shown in Fig. 22, the material must be exhibiting its lowest inductance to the magnetizing circuit and must therefore be at remanence B_r.

Operation of Inductive Ammeters

The inductive ammeter is a microprocessor based instrument that employs an inductive pickup coil. This coil contains a large number of turns wound onto a nonconducting nonmagnetic ring shaped core. It is threaded onto the cables from the capacitor discharge system or onto the rod itself. When a pulse is fired, the flux caused by the current surge links with the ring and the voltage induced in the coil (Fig. 30) is given by:

$$\textbf{(17)} \quad E = \left(2 \times 10^{-7}\right) Nd \frac{dI}{dt} \ln \frac{b}{a}$$

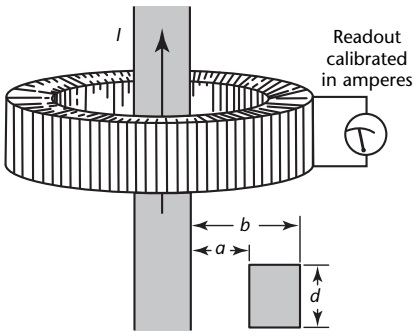
where a is the inner radius of the ring; and b is the outer radius of the ring; d is the axial length of the ring; $dI \cdot (dt)^{-1}$ is the rate of change of the current; N is the number of turns in the ring.

This equation is derived from Faraday's law of induction. To provide a signal related to the current itself, Eq. 17 must be integrated:

$$\textbf{(18)} \quad e = \int E \cdot dt = \left[\left(2 \times 10^{-7}\right) Nd \ln \frac{b}{a}\right] I$$

Here, e is the output voltage of the integration circuit. Because all the terms in the brackets are known, the output of the integration of the induced voltage is proportional to the instantaneous current, and the instrument can be calibrated to read current. Electronic circuits are used to measure the peak current I_{max} and the pulse duration τ.

FIGURE 30. Diagram of inductive pickup coil (dimensions used in Eq. 17).



PART 7. Magnetic Flux in Test Objects with Complex Shapes

When a discontinuity lies perpendicular to the magnetic field and is at or near the surface of an adequately magnetized test object, the leakage field attracts and holds magnetic particles applied to the test object surface. The capturing and holding power of the leakage field is determined by both the magnitude of the magnetic flux in the test object and the relative orientation of the discontinuity and flux. The gradient and magnitude of the leakage field are important for indication formation. There is, however, disagreement on whether the axial or tangential component is the one of interest.

There are rules used to define the current needed and how it is applied to produce the desired direction and flux density in the test object. Those rules, along with recommended particle concentrations, are specified in military and commercial specifications. Unfortunately, many complex ferromagnetic aircraft components have varying cross sections, large cutouts and protruding extremities. With these, it is difficult to apply empirical rules that guarantee effective testing of the object in its entirety.

The testing of the object shown in Fig. 31 has been detailed in the literature.[13] The direction and intensity of the external flux fields are measured using circular and longitudinal magnetization by means of a transverse hall probe tesla meter. The magnitude of the current pulse is determined from empirical rules in order to ascertain the validity of the rule in each case. The determination of the field direction and magnitude does not reveal the magnetic field level required for crack detection but does uncover problem areas caused by part geometry. Locations having cross-sectional areas significantly larger than those where the current enters the test object exhibit fields whose magnitudes are extremely low compared to those at the entry area (points 5, 6 and 7 in Fig. 31).

Magnetization was performed using full-wave direct current techniques. Low fields were also observed in deep cutouts (between points 6 and 7 of Fig. 31) and at the extremity areas not directly in the path of the current flow (points 4, 6 and 7 of Fig. 31). Any area producing a field of less than 10^{-3} T (10 G) was deemed inadequately magnetized. It was also determined that when the current branched into different directions at an intersection, the field at this intersection was zero (Fig. 32 and points 1, 2, 3 and 5 of Fig. 31). These particular areas required additional tests using portable electromagnetic yokes.

When dealing with complex test objects, initial investigations concerning the direction of the flux field and adequacy of field intensity should be determined using artificial discontinuity

FIGURE 31. Complex shape of steel forging for aircraft. Numbers are cited in text.

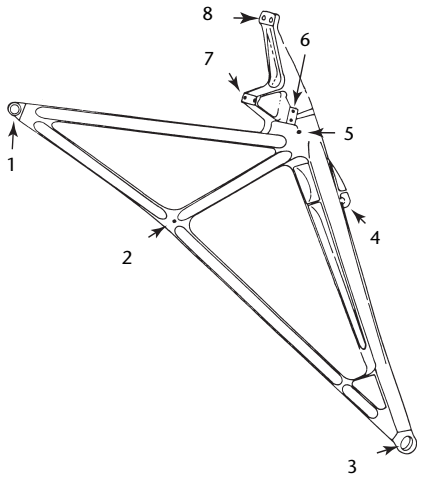
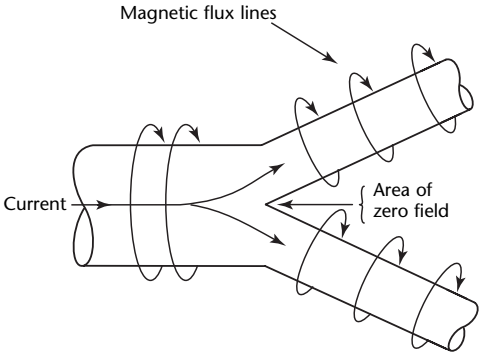


FIGURE 32. Typical geometry problem in magnetic particle testing.



shims placed at a sufficient number of locations on the test object. Special techniques are required to establish adequate field intensity and direction in some areas of the test object. The techniques should be documented for future reference when identical objects are to be tested. In cases of high production rates, special magnetizing tools may need to be fabricated to achieve reliable testing of the entire test object. This is important because areas containing changes in shape or thickness are likely locations for development of cracks during fabrication or service.

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CHAPTER 5

Magnetic Leakage Field Measurements[1]

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PART 1. Fundamentals of Magnetic Flux Leakage Fields

Magnetic particle testing is not an isolated technical discipline. It is a combination of two distinct nondestructive testing techniques: magnetic flux leakage testing and visual testing. The basic principle of the magnetic particle technique is to magnetize an object to a flux density that causes magnetic flux leakage from a discontinuity. Powdered ferromagnetic material is then passed through the leakage field and those particles held over the discontinuity are visually interpreted by the operator.

From a theoretical point of view, the only difference between magnetic flux leakage testing and magnetic particle testing is the use of iron or iron oxides as a sensor. In effect, magnetic particles may be considered a commonly used form of sensor for the detection of magnetic flux leakage (sometimes called *stray fields*).

The key to ideal magnetic particle testing is to provide the highest sensitivity to the smallest discontinuities by a careful combination of: (1) applied magnetic field intensity $H(t)$, (2) flux density $B(t)$ in the test object, (3) particle size and application method and (4) optimal viewing conditions. In order to do this, experiments are necessary with all of the parameters. The best combination is then chosen for a particular application.

Writers of specifications have often over-generalized this empirical process in order to provide the magnetic particle test operator with a set of rules that govern all situations. This generalization can lead to inappropriate specifications for certain magnetic particle tests.

There are many forms of magnetic field sensors, including the hall element, the magnetodiode, the ferroprobe and the sensor coil.[2,3] Tape recorder heads are magnetic sensors, as are the triaxial flux gate magnetometers that are orbited above the Earth to detect very small changes in magnetic fields. The purpose of this chapter is to provide details about the use of sensors in measuring and detecting fields for magnetic nondestructive tests.

Induction of Magnetic Flux Leakage

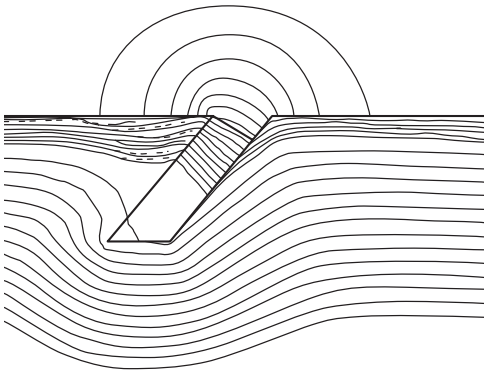
The essence of all magnetic flux leakage testing is to induce a magnetic flux density $B(t)$ around a discontinuity. The flux density may or may not be time dependent but should be at such a level that some of the flux is displaced by the discontinuity's higher magnetic reluctance. The displaced flux is forced out of the object's surface into the surrounding environment (air or water), where it can be detected (Fig. 1).[4]

Magnetizing Current

To induce flux leakage, magnetizing current can be passed through the test object by direct contact. This is commonly done but because of the danger of arc burns, it is not always recommended (Fig. 2). Insulated current carrying rods or cables may be used, by passing them through holes in the test object. Other alternatives are the use of coils to carry the current around the test object and the use of electromagnets or permanent magnets applied to the test object.[5]

When current is present, there is an associated field intensity $H(t)$ that raises localized areas to various flux density $\boldsymbol{B}(t)$ values, based on the ***BH*** properties of the test material. Figure 1 shows a computer simulation of field lines in and above a material at some value below magnetic saturation, as can be seen from the bending of the field lines under the discontinuity.[4]

FIGURE 1. Field lines around, through and above discontinuity (an oblique slot), as computed by finite element computer model. The magnetic flux leakage field is asymmetric.[4]



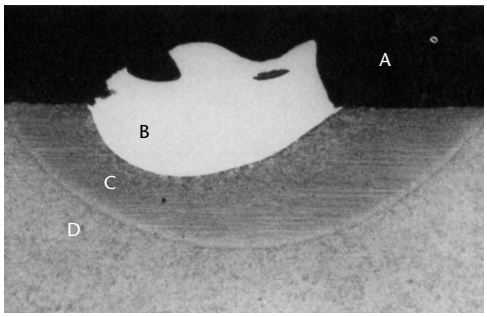
Effect of Flux Leakage on False Indications

In a magnetic particle test, it is important to raise the field intensity and flux density in the object to a level that produces magnetic flux leakage sufficient for holding particles in place over discontinuities. On the other hand, excessive magnetization causes particles to stick to minor surface leakages not caused by discontinuities.

If such surface leakage occurs (Fig. 3) and attracts large numbers of particles, the result is a false indication and the test object is said to be over magnetized for this inspection. It may then be necessary to verify the test results with another nondestructive testing method. Such false indications may result from local permeability changes which are caused by local stresses in the test object. In some cases, the magnetic flux leakage field might be caused by a subsurface material discontinuity and it may not be possible to distinguish the cause of the leakage without the use of additional nondestructive testing technology.

One way around this problem of excessive magnetization is to localize magnetizing fields at the object surface. This can be done using alternating current fields and the corresponding skin effect. As a rule, skin depth (also called *standard depth of penetration*) for 60 Hz alternating current fields in steel is typically about 1 mm (0.04 in.), depending on the permeability and electrical conductivity of the test object. The field intensity falls to e^{-1} of its surface value, or 37 percent, at this depth. At two skin depths, field intensity falls to e^{-2} or 13 percent of its surface value. Magnetic flux leakage from discontinuities depends on the value of $H(t)$ and, in turn, on how large a $B(t)$ value the field intensity causes around the discontinuity.

FIGURE 2. Micrograph of typical arc burn on surface of steel pipe, caused by direct contact magnetization.



Legend
A. Air.
B. Molten metal, solidified.
C. Steel, burnt and recrystallized.
D. Steel not burnt.

Why Particle Indications Form

Surface-breaking discontinuities best detected by magnetic particle tests are those that expel the optimal magnetic flux leakage for the technique. To gain a clearer insight of this, it is necessary to understand three sets of variables: (1) how discontinuity parameters affect the external magnetic flux leakage, (2) how magnetic field parameters affect the external flux leakage field and (3) how the sensor reacts to passing through such fields.

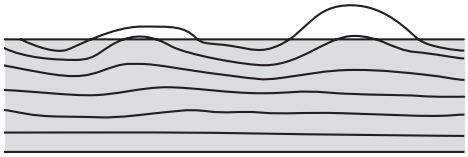
Discontinuity Parameters

The discontinuity characteristics that are critical to the formation of magnetic particle indications include depth, width, and angle to the object surface. The effects of discontinuity width on the topography of the magnetic flux leakage field have been described in what might be termed classical approaches[6–8] where the discontinuity may be replaced by arrays of poles. Higher ambient field intensities or flux densities are included within such models by increasing the pole densities that give rise to the magnetic flux leakage fields. More recently, computer models have been developed[4,9] to explain how magnetic flux leakage fields are related to discontinuity parameters (Fig. 1 is an example of such work).

In cases where the discontinuity is narrow and surface breaking (seams, laps, quench cracks and grind tears), the magnetic flux leakage field near the mouth of the discontinuity is highly curved (Fig. 4). The activating field intensity may be quite small (a few amperes per meter) or, after saturating the test object, inspection can be performed with the resulting residual induction.

In the case of subsurface discontinuities (inclusions and

FIGURE 3. Minor surface flux leakage from variations in local magnetic permeability may be source of false test indications.



laminations), the magnetic flux leakage field at the inspected surface (Fig. 5) is much less curved. Relatively high values of field intensity and flux density within the object are required for testing. This lack of leakage field curvature is due to saturation and greatly reduces the particles' ability to stick to such indications.

Magnetic Field Parameters

The properties of the magnetic field that most affect flux leakage include the field intensity, local *BH* properties and the angle to the discontinuity opening. The leakage field's ability to attract magnetic particles is determined by several additional factors. These include (1) the magnetic forces between the magnetic flux leakage field and the particle, (2) image forces between a magnetized particle and its magnetic image in the surface plane of the test object, (3) gravitational forces that may act to pull the particle into or out of the magnetic flux leakage field and (4) surface tension forces between the particle vehicle and the object surface (wet method tests).[10]

Some of these forces may in turn vary with: discontinuity orientation; the Earth's gravitational field; particle shape and size (in effect, with particle effective permeability); and with the particles' containing medium.

The magnetic force F_m (N) that holds a single particle to a magnetic flux leakage field is determined by the vector relation in Eqs. 1a and 1b. Strictly speaking, the magnetostatic force F_m acts on a magnetic dipole with a spatially constant moment $\boldsymbol{m}$ (such as a magnetic particle or a current carrying loop with a length much smaller than the scale over which the field is varying) in a magnetic leakage field $\boldsymbol{H}$:

$$\textbf{(1a)} \quad F_m = m \cdot \nabla \boldsymbol{H}$$

where $\boldsymbol{H}$ is the ambient leakage field intensity ($A \cdot m^{-1}$) and $\nabla \boldsymbol{H}$ is the gradient of the field ($A \cdot m^{-2}$).

In the special circumstance where the particle's moment is directly proportional to the magnetic leakage field, Eq. 1a can be rewritten:

$$\textbf{(1b)} \quad F_m = K\left(\boldsymbol{H} \cdot \nabla \boldsymbol{H}\right)$$

where K is a mathematical constant ($N \cdot m^3 \cdot A^{-2}$).

It can be seen from Eq. 1 that magnetic force F_m depends on local field intensity $\boldsymbol{H}$ and how it changes over the length of the particle $\nabla \boldsymbol{H}$. For surface discontinuities, $\nabla \boldsymbol{H}$ is large (because the field is highly curved), while $\boldsymbol{H}$ itself need not be large. For subsurface discontinuities, $\nabla \boldsymbol{H}$ is relatively small and $\boldsymbol{H}$ itself must be raised to compensate for the small change. Unfortunately, raising $\boldsymbol{H}$ will also raise surface noise.

In other forms of magnetic flux leakage testing, the flux density is raised to a higher level than is common with magnetic particle testing and nonrelevant indications (noise) are in some way recognized. For example, the signals that noise induces in flux sensitive detectors may be filtered out. Magnetic flux leakage testing is therefore not limited by a human inability to distinguish real from apparent discontinuities. It is limited by an electronic inability to perform the same function.

FIGURE 4. Highly curved magnetic field from narrow, surface breaking discontinuity.

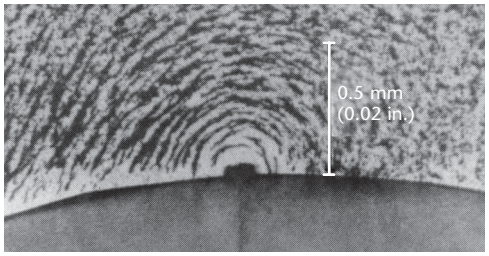
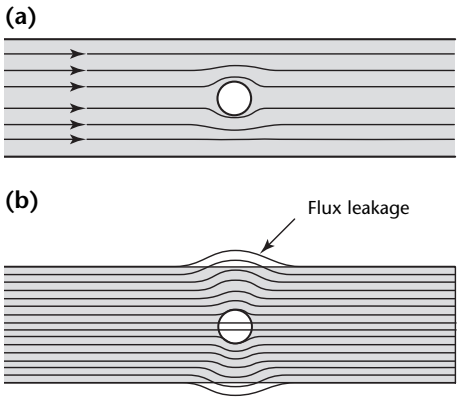


FIGURE 5. Effects of induction on flux lines in presence of discontinuity: (a) compression of flux lines at low levels of induction around discontinuity, so that no surface flux leakage occurs; (b) lack of compression at high induction, showing some broad surface magnetic flux leakage.



PART 2. Flux Sensitive Devices

Described below are flux sensitive devices used in magnetic nondestructive testing. The sensors detailed here measure either magnetic fields or their gradients.

Research[11] indicates that a lack of discontinuity detection can be blamed on the magnetizing method, the particles used, and the capability of the inspector. The important question that must be answered before beginning any magnetic particle test is: *what is the best possible combination of magnetizing means, particle shape, type and size, and operator training to detect a discontinuity of a specific size every time?* Commonly accepted magnetization methods may not always be the best. Flux measurement devices can help provide more accurate information about the test procedure.

Commonly used magnetic flux sensitive devices include: (1) a long straight wire passing through a magnetic field, (2) the search coil, (3) search coil derivatives such as *C* and *E* cores, (4) the hall element, (5) the magnetodiode, (6) the ferroprobe and (7) the flux gate magnetometer. For sensors in categories 1 through 3, the output signal depends on some form of time variation for the ambient field intensity. Sensors in categories 4 through 7 are not time dependent.

A long straight wire passing through a magnetic field is not used for nondestructive testing, but it is a crucial concept for understanding the signal developed in coil sensors as they pass through magnetic flux leakage patterns.

Voltage Developed between Ends of Straight Wire

As shown in Fig. 6, two conducting wires *PQ* and *RS* are placed at right angles to a magnetic field (shaded area) of constant flux density *B* directed toward the reader. Let another free wire *AA′* be moved to position *CC′*, a distance Δx away. The area swept out by the wire is then:

$$\textbf{(2)} \quad dA = L\Delta x$$

where *dA* is the area swept out by the moving wire (square meters), *L* is the length of the wire between *PQ* and *RS* (meters) and Δx is the distance between position *AA′* and *CC′* (meters). The magnetic flux interrupted by the wire is:

$$\textbf{(3)} \quad \Delta\Phi = \boldsymbol{B} \cdot \hat{n} d\boldsymbol{A}$$

where $\boldsymbol{B}$ is the magnetic flux density (tesla), $\hat{n}$ is the unit vector for the area *dA* and $\Delta\Phi$ is the interrupted magnetic flux (weber). The two equations together give:

$$\textbf{(4)} \quad \Delta\Phi = L\boldsymbol{B} \cdot \hat{n}\Delta x$$

Faraday's law of induction states that an electromotive force *e* will be induced in the wire and its magnitude is given by the relation:

$$\textbf{(5)} \quad e = -\frac{d\Phi}{dt}$$

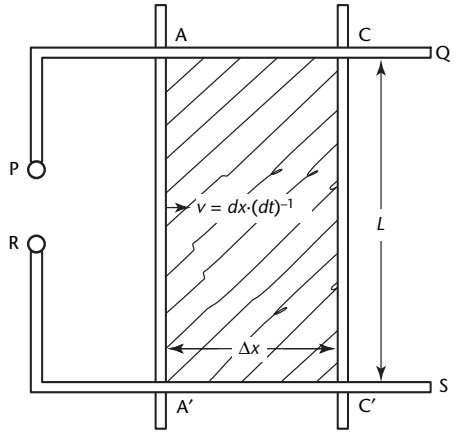
This is the rate at which the magnetic flux is cut. Eliminating the flux between Eqs. 4 and 5, and taking the component of $\boldsymbol{B}$ perpendicular to $\hat{n}dA$ gives:

$$\textbf{(6)} \quad e = -BL\frac{dx}{dt}$$

Finally, since $dx \cdot dt^{-1}$ is actually the velocity *v* of the wire, the induced electromotive force becomes:

$$\textbf{(7a)} \quad e = -BLv$$

FIGURE 6. Wire cutting magnetic flux between A-A′ and C-C′.



As an example calculation, consider a truck traveling north at 100 km·h^{-1}. If the length of the truck's axle is 2 m (6.6 ft) and the vertical component of the Earth's magnetic field intensity is 3×10^{-5} Wb·m^{-2} (0.3 G), then from Eq. 7 the electromotive force between the ends of the axle is:

$$\textbf{(7b)} \quad e = \left(3\times10^{-5}\ \text{Wb}\cdot\text{m}^{-2}\right)(2\ \text{m}) \times \left(\frac{100\,000}{60\times60}\ \text{m}\cdot\text{s}^{-2}\right) = 1.7\times10^{-3}\ \text{V}$$

This example indicates the magnitude of voltages induced when metal objects move in relatively small magnetic fields. As another example, compute the electromotive force generated between the ends of a 10 mm long wire when moving at 500 mm·s^{-1} through a field of 1.6×10^{-3} Wb·m^{-2} (16 kG).

$$\textbf{(7c)} \quad e = \left(1.6\times10^{-3}\ \text{Wb}\cdot\text{m}^{-2}\right) \times (0.01\ \text{m})\left(0.5\ \text{m}\cdot\text{s}^{-1}\right) = 8\times10^{-6}\ \text{V}$$

It is unusual for $\boldsymbol{B}$ to be at right angles to v and under such circumstances a more general form of Eq. 7 is required:

$$\textbf{(8)} \quad e = \int (\boldsymbol{v}\times\boldsymbol{B})\,d\boldsymbol{l}$$

where $\boldsymbol{v} \times \boldsymbol{B}$ is the vector cross product of the wire velocity and the flux density through which it passes. Numerically, this is ($\boldsymbol{vB}$) sin θ, where θ is the smaller angle between $\boldsymbol{v}$ and $\boldsymbol{B}$. The integral is taken along the length of the wire because the local value of $\boldsymbol{B}$ (through which each segment of wire is passing) may vary.

In magnetic nondestructive testing, wires in the form of coils are moved in a controlled fashion over a test surface so that the value of v is known and Eq. 8 can then be written as:

$$\textbf{(9)} \quad e = -v\int B_{\perp}\,dl$$

where $B_{\perp}$ is the perpendicular component of the magnetic field, such as the magnetic flux leakage field shown in Fig. 1.

The tangential flux density B_t plays no role in the development of the electromotive force in the conductor because sin θ is zero for this field component.

The electromotive force developed between A and A' appears across PR (Fig. 6) and can be measured with a sensitive voltmeter. No current flows if P and R are not connected. Furthermore, in the general case of conductor motion through magnetic fields, the variation of $\boldsymbol{B}$ along the conductor must be known so that the integral of Eq. 9 can be computed.

Example of a Straight Wire Signal

The electromotive force generated in the leading edge of the coil shown in Fig. 7 is deduced from the perpendicular field component of a tight crack. The simplest approximation for this magnetic flux leakage field is:[6,7]

$$\textbf{(10)} \quad B_t = \left(\frac{B_g L_g}{\pi}\right)\frac{y}{x^2+y^2}$$

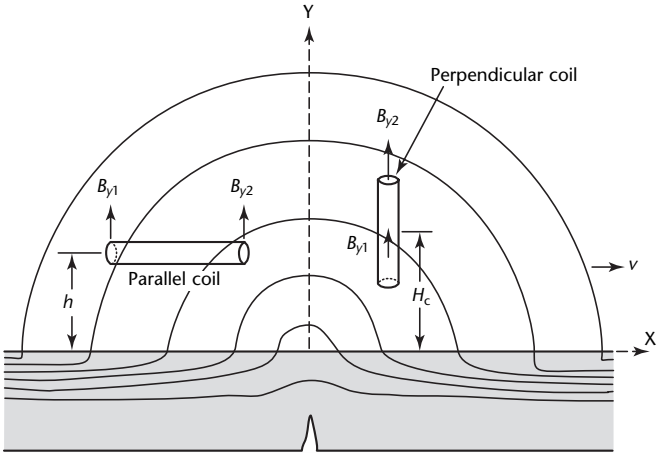
and:

$$\textbf{(11)} \quad B_{\perp} = \left(\frac{B_g L_g}{\pi}\right)\frac{x}{x^2+y^2}$$

where B_g is the flux density deep within the discontinuity (weber per square meter); L_g is the width of the discontinuity (meter).

The origin of coordinates is the mouth of the discontinuity. If the length L of the wire is parallel to and shorter than the

FIGURE 7. Parallel and perpendicular coils cutting magnetic flux leakage fields from discontinuity at speed *v*. For discontinuity fields longer than coil, coil outputs are as given in Legend for $E_{\parallel}$ and $E_{\perp}$.



Legend

B_y = leakage as measured in vertical direction
B = magnetic flux leakage (T)
$E_{\parallel}$ = parallel coil output, where $E_{\parallel} \propto (B_{y1} - B_{y2})Lv$
$E_{\perp}$ = perpendicular coil output, where $E_{\perp} \propto (B_{y1} - B_{y2})Lv$
H_c = liftoff measured to center of coil (m)
h = constant sensor liftoff (m)
L = coil length into page (m)
v = speed of coil relative to test object (m·s^{-1})
X = horizontal axis
Y = vertical axis

discontinuity opening, then the electromotive force developed between the ends of the wire is taken from Eqs. 10 and 11 as:

$$\textbf{(12)} \quad e = -\left(\frac{B_g L_g L v}{\pi}\right)\frac{x}{x^2 + y^2}$$

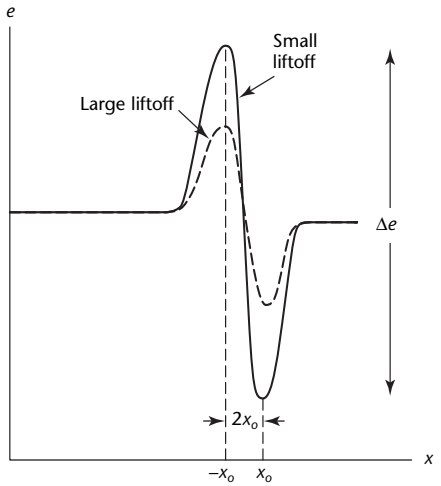
In traditional magnetic flux leakage testing equipment, the value of y is maintained at some constant value h (liftoff of the sensor). The form of the electromotive force is shown in Fig. 8 for increasing value of liftoff h. From Eq. 12, the magnitude of the electromotive force is shown to depend linearly on (1) the value of $B_g L_g$ (the magnetomotive force of the discontinuity), (2) L (the length of the wire, provided that the aforementioned conditions are met) and (3) v (the relative velocity between the object and the conductor).

The dependence on liftoff can be seen by differentiating Eq. 12 for the turning points ($x_o = \pm h$) and using these values to compute the swing Δe in e. The result is:

$$\textbf{(13)} \quad \Delta e = \frac{B_g L_g L v}{\pi h}$$

In this field approximation, the swing in voltage as the conductor passes through the magnetic flux leakage field is inversely proportional to the liftoff.

FIGURE 8. Electromotive force developed between ends of conductor passing at constant speed through leakage field such as Eqs. 11 and 12.



Legend

e = electromotive force signal (V)
x = lateral distance (meter)

Simple Pickup Coils

Figure 7 shows two commonly used pickup coils: parallel and perpendicular. In some cases, the turns of these coils are wound onto small blocks of ferrite to increase the value of $B_\perp$ above its air value ($B_\perp$ is the flux leakage component perpendicular to the test surface). Air core coils are discussed below.

Perpendicular Coil

With a one-turn coil passing at speed v through the same magnetic flux leakage field as above, the signal electromotive force is the difference between the two electromotive forces developed in the branches:

$$\textbf{(14)} \quad e = -\frac{B_g L_g L v}{\pi}(x) \times \left[\frac{1}{x^2 + h_1^2} - \frac{1}{x^2 + h_2^2}\right]$$

where h_1 and h_2 are the liftoffs of the two branches.

If the coil has N turns and a width of $2b$, then $h_1 = H_c + b$ and $h_2 = H - b$ (the liftoff H_c is measured to the center of the coil). The electromotive force then becomes:

$$\textbf{(15)} \quad e = -\frac{B_g L_g L N v x}{\pi}\left[\frac{1}{x^2 + (H_c + b)^2} - \frac{1}{x^2 + (H_c - b)^2}\right]$$

The results of varying h and b are shown in Fig. 9 where the electromotive force is similar in form to that of the straight wire. The turning points in the electromotive force are given by the solution to Eq. 16.

$$\textbf{(16)} \quad x_0^2 = \frac{\sqrt{2H_c^4 - (H_c b)^2 + b^4 - (H_c^2 + b^2)^2}}{3}$$

For example, when $b = 0.5\ H_c$, then the turning points are $x_o = \pm 0.74H$ and $2x_o$ (the distance between the turning points) is $1.49H_c$. The swing in signal e is difficult to compute in closed algebraic form.

Parallel Coil

When the coil is oriented so that one set of wires follows another, then the output signal is the difference between the

signals developed in the leading and trailing branches:

$$\textbf{(17)} \quad e = -\left[B_{\perp L} - B_{\perp T}\right] Lv$$

Using Eq. 11 for the leading and trailing edge fields ($B_{\perp L}$ and $B_{\perp T}$), substitute $x_L = x - b$ and $x_T = x + b$ for the leading and trailing edge distances from the center of the coil:

$$\textbf{(18)} \quad e = \left(\frac{2bNB_g L_g Lv}{\pi}\right) \times \frac{h^2 + b^2 - x^2}{\left[(x+b)^2 + h^2\right]\left[(x-b)^2 + h^2\right]}$$

The form of Eq. 18 is shown in Fig. 10. The dashed lines are voltages induced in the leading and trailing edges. The solid line is their difference or the form of the electromotive force. The signal consists of a major peak at $x = 0$ and two smaller side peaks. The roots of Eq. 11 occur at $x_o = \pm(h^2 + b^2)^{0.5}$ so that the distance between the points at which $e = 0$ is given:

$$\textbf{(19)} \quad 2x_o = 2\sqrt{h^2 + b^2}$$

The maximum value of the coil signal occurs at $x = 0$ and is proportional to $b \cdot (h^2 + b^2)^{-1}$. Differentiation with respect to b indicates that the coil signal is maximized when $b = h$. Thus when the half-width of the coil is equal to the liftoff, the coil output voltage is maximized with respect to the magnetic flux leakage from the discontinuity. This argument also indicates that this type of coil discriminates against relatively long range material surface noise such as might be caused by local permeability variations.

Ferrite Cores in Coils

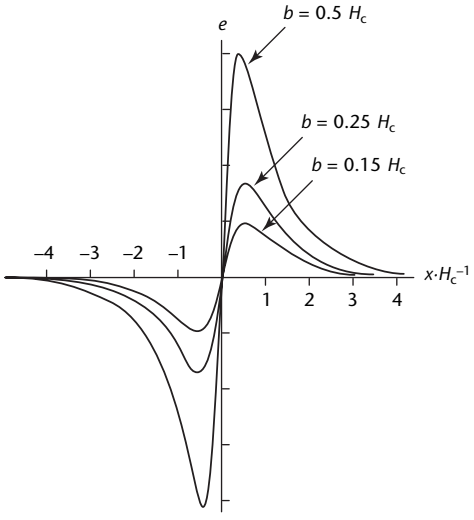
Ferrites are useful in pickup coils because they not only provide support for the wire turns but they also amplify the flux density through the coil windings by a value equal to the effective permeability of the ferrite.

For small pieces of ferrite (Fig. 11) where the dimensional (length to depth) ratio is small, the effective permeability of the ferrite may vary from the low teens to the thousands. The advantage of using ferrite occurs not only in this amplification but also in the fact that ferrites have very low electrical conductivities, minimizing detrimental eddy current effects in them.

Electronic Considerations for Coil Voltages

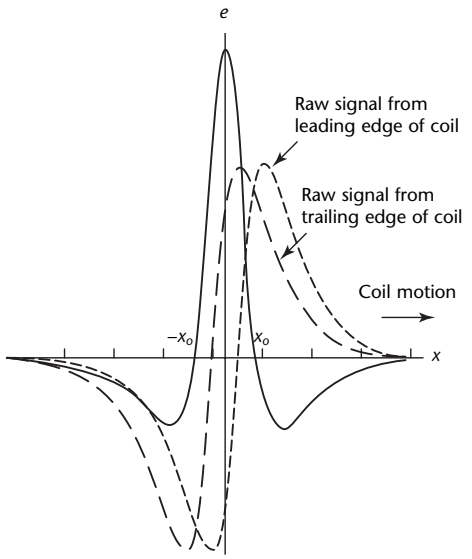
It is essential that pickup coils are used to generate voltages and not currents. Once

FIGURE 9. Form of voltage signal developed in perpendicular coil when passing at constant speed through magnetic leakage field.[2]



Legend
b = half of coil width (m)
e = signal (V)
H_c = liftoff (m) measured to center of coil
x = lateral distance (m)

FIGURE 10. Electromotive force induced in parallel coil by passing it through magnetic flux leakage field such as in Eq. 18. Coil potential (volts) is difference between leading and trailing edge signals.



Legend
e = signal (V)
x = lateral distance (m)

a current is allowed to flow in a coil, it creates its own magnetic field, one that can interfere with the field under investigation. The output of such coils is therefore generally fed to an operational amplifier of high impedance.

Coil Applications and Derivatives

Examples of coils as detectors for magnetic flux leakage are presented in the *Nondestructive Testing Handbook* on electromagnetic testing. Such coils can be connected in series adding, series opposing (a figure eight), overlapping and many other configurations.

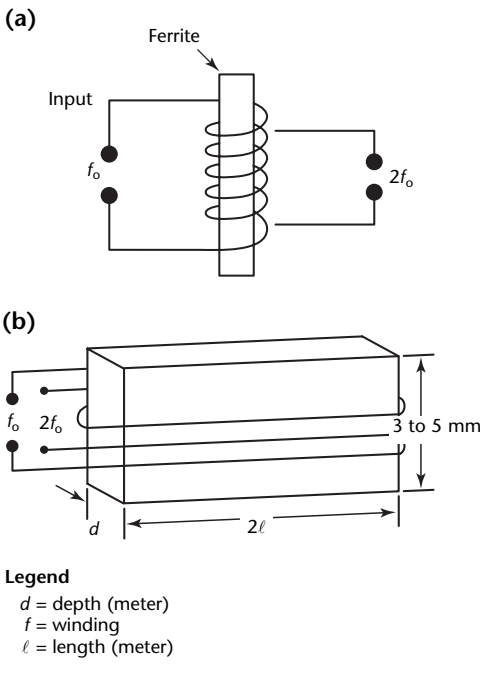
Search coils are often wound on ferrite cores to increase the flux through them (Fig. 11 shows two common configurations). A detailed discussion of such sensors is given in the electromagnetic testing volume.

Hall Element Sensors

Hall elements are slices of semiconductor material. When a current is passed through them and they are placed in a magnetic field, then a voltage develops across two of the faces of the element. The voltage is proportional to the magnetic flux density $\boldsymbol{B}$.

A solid state tesla meter is made up of the electronic components needed to supply current to a hall element, to detect and measure the resulting voltage and to then convert it to the measured field value.

FIGURE 11. Ferrite cored magnetic flux leakage detector coil systems: (a) configuration one; (b) configuration two.



Theory of Hall Element Operation

Electrically conducting solids are almost transparent to the flow of conduction electrons because the ions in the element lattice do not deflect conduction electrons as might be expected from a typical billiard ball model. As current is fed into one end of an element (Fig. 12), electrons are deflected toward one side of the element, in accordance with the lorentz force F:

$$\boldsymbol{F} = -e\left(\boldsymbol{E} + v \times \boldsymbol{B}\right) \quad \textbf{(20)}$$

where B is applied flux density (tesla), E is electric field intensity (volt per meter) on the particle, e is electronic charge (coulomb) and v is velocity of the particle (meter per second).

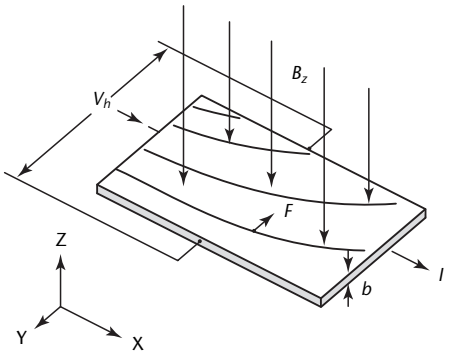
The term $v \times B$ is a vector cross product and is itself a vector at right angles to both v and B. Its direction determines which side of the element the electrons are deflected toward. The theory of solid state physics provides a voltage V_h across the element:[2]

$$V_h = \frac{R_h I B_z}{b} \quad \textbf{(21)}$$

where b is the thickness of the element in the direction of the magnetic field (meter), B_z is the component of the applied field at right angles to the current (webers per square meter), I is the applied current (amperes) and R_h is the hall coefficient ($A^{-1} \cdot s^{-1}$).

In general, if the element is placed at an angle to the field B, such that $B_z = B \cos \theta$, then the cosine of the angle must be found. Normally, the crystal is rotated

FIGURE 12. Magnetic flux, drive current and hall effect voltage relationship (see Eqs. 20 and 21).



until the maximum tesla meter reading is found. At that point, $\theta = 0$ because $\cos\theta = 1$.

The value the hall coefficient R_h is determined by the interaction of charge carriers with the crystal lattice. In a metal element, it would be given by:

$$\textbf{(22)} \quad R_h = -\frac{1}{ne}$$

where e is the charge on the electron (-1.6×10^{-19} C) and n is the electron concentration.

Metals do not make good hall sensors because their hall coefficients are too low. As can be seen in Eq. 21, the larger the hall coefficient, the larger the hall voltage. Investigations of hall coefficients for many substances have shown that combinations of elements from groups III and V of the periodic table give the highest hall voltages and have the least sensitivity to changes in temperature. Also, the charge carrier for these groups is more likely to be a hole rather than an electron.

Excitation of Hall Elements

Where contacts occur between two dissimilar metals such as the current and voltage attachments on the hall crystal, thermoelectric electromotive forces are generated.

If direct current is used to excite the crystal, the voltage read by circuitry following the voltage contacts is the sum of the hall voltage *and* the thermoelectric voltage. For this reason, hall element crystal excitation is usually performed with 25 to 350 mA alternating current.

Manufacture of Hall Elements

Bulk hall elements are generally bismuth doped semiconductors such as indium antimonide (InSb). These are produced by solid state crystal growth technology, cut into small rectangular blocks and have current and voltage leads attached before being encapsulated. Typical sizes are as small as 0.8 mm (0.03 in.) long by 0.4 mm (0.015 in.) wide by 0.5 mm (0.02 in.) thick.[5]

Vapor deposited hall elements have been reported for use in the testing of ball bearings by the magnetic flux technique.[12] In this application, bismuth was evaporated onto an alumina substrate. A newer development is to combine the hall sensor, its power supply and an amplifier on one chip. Figure 13 shows configurations of typical hall sensors and their specifications.

Applications of Hall Elements

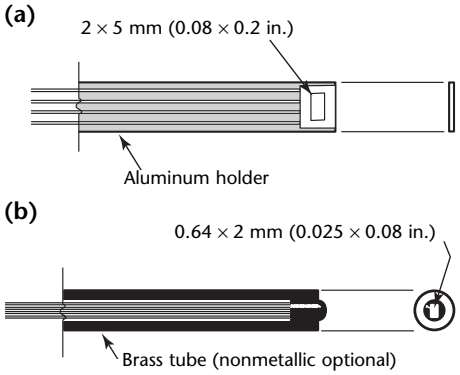
Hall elements are used with tesla meters or other devices to detect or measure magnetic fields. Typical configurations are shown in Fig. 14. In Fig. 14a, the hall sensor is held a fixed distance from a current carrying wire and the tesla meter measures the field intensity created by the current. In the case of pulsed currents, the peak current can be measured with a peak reading tesla meter.

In Fig. 14b, a ferrite ring is added to measure small fields or currents. The high permeability of the ferrite aids in creating a high B value in the vicinity of the sensor's active area. Figure 14c, 14d and 14e show combinations of hall elements and ferrite flux concentrator configurations used in magnetic flux leakage testing.

The level of external field just outside a partially demagnetized material may best be measured with a hall element meter. Figure 15 shows an inspector checking the external field level with a tesla meter after partial demagnetization of the test object, a 270 mm (10.75 in.) diameter steel tube.

Crossed hall elements can also be used. Such configurations are used to check welds or to reconstruct the total field from the measured components.[13]

FIGURE 13. Typical hall element probes: (a) flat; (b) axial.



Magnetodiodes

The magnetodiode is a solid state device whose resistance changes with field intensity. The device consists of positive and negative zones within a semiconductor, separated by a region of material that has been modified to create a recombination zone (Fig. 16). Its frequency response is flat from direct current to 3 kHz and the device is stable without temperature dependence from –10 to 50 °C (15 to 120 °F).

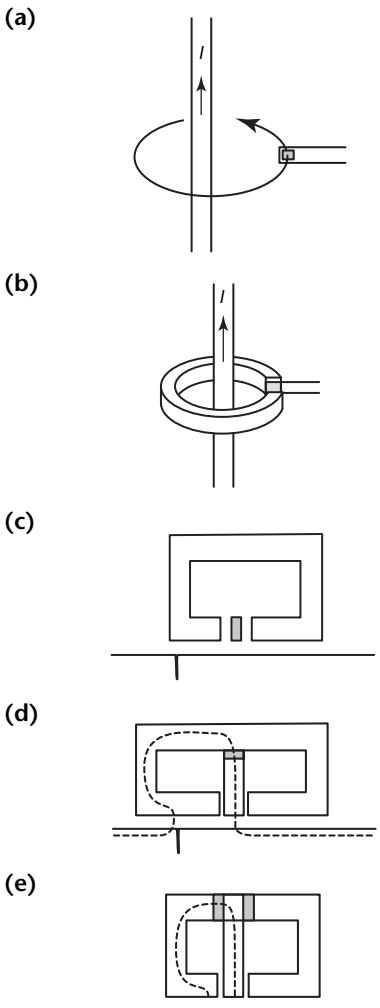
Applications of Magnetodiodes

Magnetodiodes have been used for detecting magnetic flux leakage from discontinuities in tubes.[3] The magnetic flux leakage is excited by alternating current electromagnets arranged to detect either internal or external surface breaking discontinuities. The system illustrates the general principles of magnetic flux leakage testing.[1]

Sensors are connected differentially to eliminate signals from the applied field and from relatively long range variations in surface field intensity. This system and magnetic flux leakage systems like it are used to rapidly evaluate the surface condition of tubes and can detect tight discontinuities with a depth of only 0.1 mm (0.004 in.).

Magnetic particle testing is often used to inspect such tubes but while it is extremely sensitive to outer surface, tight discontinuities, its use for inner surface discontinuities requires a viewing device.

FIGURE 14. Hall element configurations: (a) sensor at fixed distance from wire; (b) ferrite core; (c) free standing flux concentrator; (d) symmetrically positioned contacting concentrator; (e) asymmetric contacting concentrator.



Ferroprobes

Ferroprobes (also called *foerster microprobes*) take many forms but for the purposes of nondestructive testing they generally consist of cylindrical or rectangular ferrite upon which one or two coils are wound (Fig. 11).

Flux gate magnetometers are used to detect small changes in the Earth's magnetic field. As might be used by geophysical prospectors, these devices consist of ferrite rings carrying many coil configurations.

Both of these devices are based on the same physical laws as a tape recorder head or any other ferrite cored magnetic field pickup. The difference between the two is that ferroprobes are activated at high frequency.

Typically, one coil is excited with alternating current at a frequency f. The voltage induced in a second coil at frequency $2f$ is then detected. This secondary signal carries information about the scanned magnetic flux leakage field. Figure 17 is an example of the tangential magnetic flux leakage field taken with such a probe over an angle slot in residual induction at a liftoff of 1 mm (0.04 in.).[8]

Ferrite cores might be solid or hollow, to reduce eddy currents in the ferrite.

FIGURE 15. Checking external field level with tesla meter after partial demagnetization.



Large Volume Magnetic Field Indicators[14]

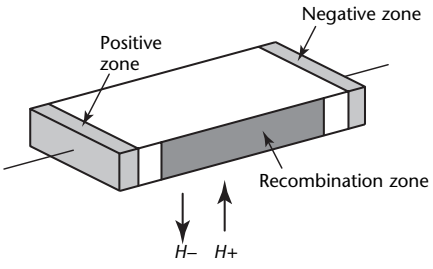
Bulk Field Indicators

The field measurement systems discussed above are designed and used for the assessment of magnetic leakage fields from material discontinuities. In all cases, the active sensing area of such a device is very small. In the case of the hall element, which is rectangular in shape, it is possible to integrate the field over the active area of the hall crystal, and so compensate for it. Then, by taking measurements at controlled distances above a magnetized surface, it is possible to extrapolate the field values to that at the surface. Once this is done, the electromagnetic boundary conditions indicate the magnetic field intensity just inside the surface.

The following text relates to the detection or measurement of magnetic fields over much larger areas, since the active area of the sensor is larger than that used for leakage field testing. The instruments are handheld, moving magnet sensors used to measure bulk external fields at a relatively high liftoff from the test object. They are often used as a practical check on the external demagnetization state of an object. Their use to detect magnetic field intensity within coils should be discouraged, since the coil field may remagnetize the moving magnetics. Note that these devices do not measure leakage fields from discontinuities.

A bulk magnetic field indicator can be used to measure the value of a uniform magnetic induction field in air. Because the relative magnetic permeability of air is 1, this reading is also the numerical equivalent of the magnetic field intensity of air.

FIGURE 16. Diagram of magnetodiode, showing positive and negative zones in intrinsic semiconductor material. Changes in magnetic field intensity *H* perpendicular to surface alters resistance in recombination zone.



The magnetic field indicator is also used to determine the existence of a magnetic field external to a ferromagnetic object. To do this, the indicator is oriented against the object's surface and moved to the position that gives the maximum external field reading.

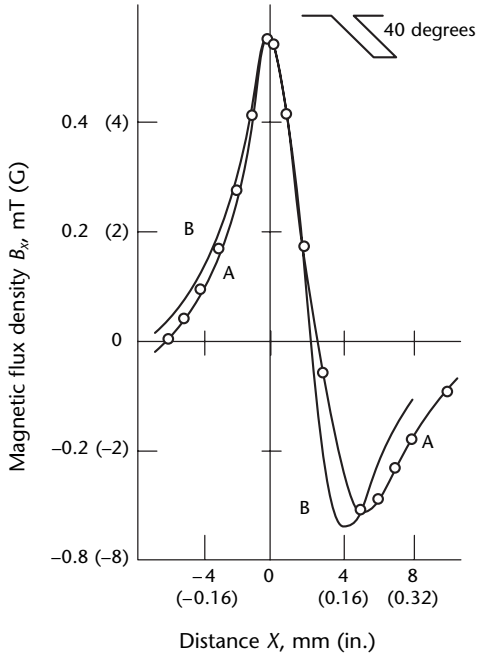
Bulk Field Indicator Construction

Many magnetic field indicators are round, about 64 mm (2.5 in.) in diameter with thicknesses of 13 to 25 mm (0.5 to 1 in.). The indicators commonly used for checking external field levels after magnetic particle tests have a range of about 1 to 2 mT (10 to 20 G) in divisions of 0.05 to 0.1 mT (0.5 to 1 G). Positive readings are north and negative readings are south (Fig. 18).

A key component of the magnetic field indicator is a small movable field sensing magnet. The magnet is mounted so it is free to rotate. Its angular deflection is shown by the movement of a pointer.

A second key component is a fixed permanent magnet. Its magnetic field intensity limits the useful range of the unit by providing a restraining force to prevent the sensing magnet from rotating freely. With no external magnetic field, these two magnets stay antiparallel to each other and the pointer remains in a

FIGURE 17. Tangential magnetic flux leakage fields in saturated residual induction over 40 degree slot.[8]



Legend

A. Experimental data at 1 mm (0.04 in.) liftoff.
B. Model with increased charge on acute face of slot.

neutral position, registering a zero reading (Fig. 18b).

The field indicator is designed so that the net magnetic field from these two magnets is weak outside the device. Placing the indicator on an unmagnetized object does not induce poles on the object sufficient for causing inaccurate meter readings.

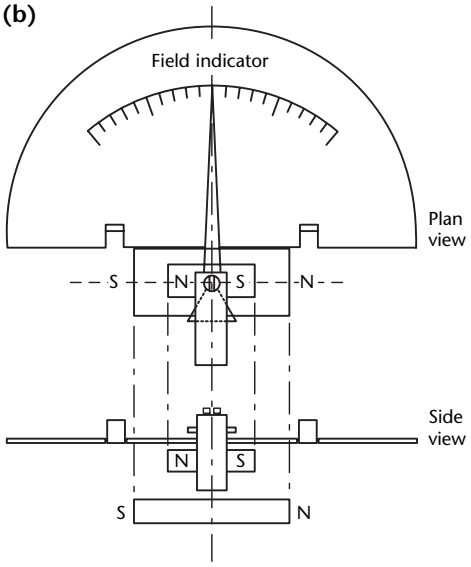
In principle, magnetic field indicators could use a coiled spring instead of a calibrated magnet to return the pointer to zero once the external field is removed. However, slight changes in the sensing magnet's intensity would then require recalibration of the unit. Also, a strongly poled sensing magnet, when placed very close to an unmagnetized object, could induce localized poles and cause inaccurate readings.

FIGURE 18. Typical magnetic field indicator: (a) photograph; (b) diagram. Distance from pivoting point of sensing magnet to closest point on edge of casing is about 18 mm (0.75 in.). Size, shape, material, magnetic field intensity and relative positions of sensing magnet and reference magnet vary with manufacturer.

(a)



(b)



Principles of Field Indicator Operation

A fixed magnet inside the device's housing sets up a reference magnetic field. A small movable sensing magnet is mounted inside this field. If a nearby object also sets up a magnetic field in the same area, the field sensing magnet rotates into a direction parallel to the resulting, combined magnetic field.

The instrument's pointer is attached to the sensing magnet and correspondingly rotates into a direction perpendicular to the resulting field. If the external field changes polarity, the pointer rotates in the opposite direction and the reading's algebraic sign changes. If the magnetic field indicator is rotated through 180 degrees about its pointer's zero direction, there is no algebraic sign change in the reading (the scale is also rotated 180 degrees).

However, in practice a reverse of polarity or rotation of the indicator often produces a change in a reading's magnitude unless the external field is perpendicular to the reference field.

Calibration and Use of Field Indicators

Generally, there are two ways to calibrate magnetic field indicators. These calibration methods provide two distinct ways of using the devices.

The most common calibration method correlates the angular deflection θ of the indicator's pointer with the magnitude B of a uniform external field whose direction is parallel to the zero direction of the pointer. To measure a uniform field, the field indicator is positioned so that the zero direction of the pointer is parallel to the field.

Used in this manner, the field B from an external object is perpendicular to the reference field B^* inside the magnetic field indicator. Or as depicted in Fig. 19:

$$\textbf{(23)} \quad B = B^* \tan \theta$$

For a small deflection, B^* may be considered uniform and a large θ indicates a relatively strong B. To keep within a practical calibrated scale when θ is between +45 and –45 degrees, the measured field must be weaker than the reference field (B less than B^*).

In many applications, B may not be perpendicular to B^*. For example, the

direction of B may be unknown or the field could be nonuniform. In a case like this, the magnetic field indicator is positioned against the object's surface and oriented in such a way that the directional marking on the device's casing is near to and perpendicular to the object's surface. Because the field is not necessarily normal to the object's surface, the reading can be less or greater than the actual value, depending on whether the field makes an acute or obtuse angle with the reference field (α and β in Fig. 20).

The alternate way of calibrating correlates the uniform field value B with the maximum deflection ϕ of the magnetic field indicator's pointer. The value of ϕ is obtained by orienting the instrument inside the field B. As shown in Fig. 21, the field vector B changes its direction relative to the field vector B^* and their resulting vector traces out a circular path of radius B centered at the tip of B^*.

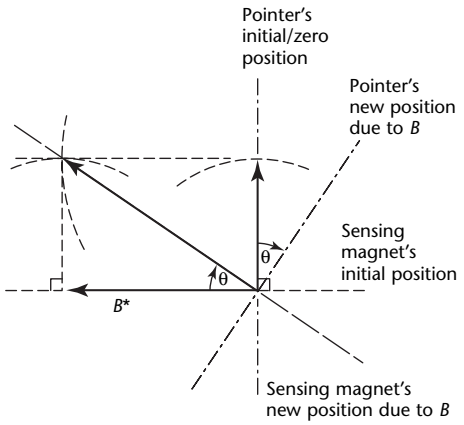
For B less than B^* and for a maximum deflection ϕ, the resulting field vector is tangential to this circular path. It follows that the field B is actually parallel to the pointer (Fig. 21). When $B < B^*$, Eq. 24 is valid.

(24) $B = B^* \sin \phi$

Note the differences between Eqs. 23 and 24. When measuring very weak fields, these two calibration methods are about the same and the pointer's angular deflection is approximately linear with the uniform field's magnitude ($\theta = B \cdot B^* = \phi$ for a small $B \cdot B^*$). In general, for the same uniform field B:

(25) $\phi > \theta$

FIGURE 19. Pointer deflection θ in first calibration type. B is perpendicular to B^* and $\tan \theta = B \cdot B^{*-1}$.



As a consequence of this inequality, the scale of the second type of calibration is generally wider if marked on the same arc inside the same magnetic field indicator. When using an instrument that is calibrated in the second way, the unit is often rotated to verify that the readings are maximized. Sometimes this is inconvenient for objects with complicated geometry because a rotation of the device may move its sensing magnet away from the area of interest.

If magnetic field indicators of the first type are used as if they had the second type of calibration (maximizing their readings by rotation) then the resulting maximum values are actually greater than the true field values. Sometimes, in this way, an estimate can be made for the size of a uniform or nearly uniform field, even though its direction is unknown.

FIGURE 20. Pointer deflection α and β when B is not perpendicular to B^* ($\alpha < \theta < \beta$).

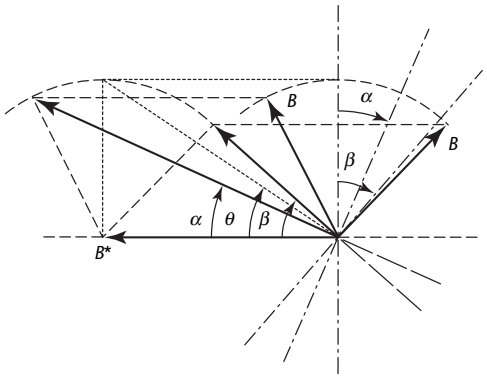
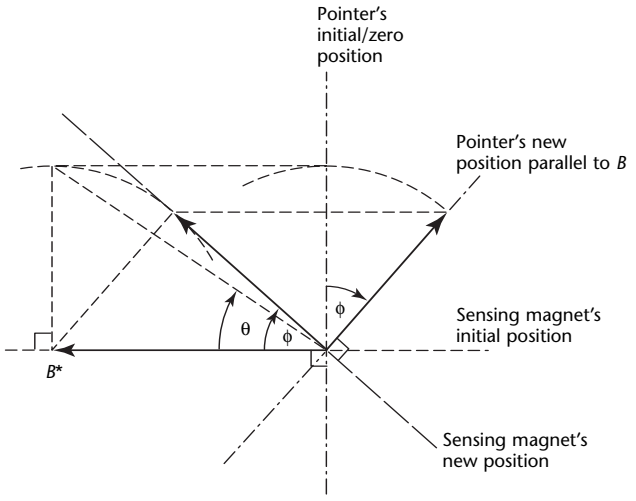


FIGURE 21. Pointer deflection ϕ in second calibration type. B and the pointer are parallel and ϕ is at maximum ($B^* > B$ and $\phi > \theta$).



When measuring a nonuniform field, the reading of a magnetic field indicator is at best the average field value over the area covered by the sensing magnet. For example, assume that the flux lines from an external magnetic source are almost parallel with the special directional marking on the magnetic field indicator. The two ends of the magnetic field indicator's field sensing magnet may still experience deflection forces of different magnitudes because of different field values and the resulting pointer deflection is an average of the two field values.

Measuring of Residual Fields

The primary function of a field indicator is to measure the external magnetic field intensity close to an object, but not every kind of residual magnetism can be detected by these instruments.

In a circularly magnetized object, where residual flux lines are circumferential and form closed loops inside the material, the induction is significantly different from zero but the field may not produce poles outside the object. Such a circular field does not produce significant readings in magnetic field indicators. Circularly magnetized objects do not attract or deflect magnetic materials during normal use unless surface discontinuities occur in the magnetized object, producing strong external poles.

Consider a cylinder with flat ends that has been longitudinally magnetized. A magnetic field indicator is placed against the cylinder's end surface and the directional marking on the indicator's casing is lined up with the length of the test object. The indicator is aligned normal to the cylinder's surface and a reading is taken.

If a demagnetization procedure has been properly performed, the indicator reading will be 0.1 mT (1 G) or less. Similar readings obtained on the side of the cylinder (with the directional marking perpendicular to the side surface) should be about zero. Sometimes, if residual magnetism is high, a nonmagnetic spacer is placed between the object and the magnetic field indicator and relative readings are obtained.

For a cylinder that is large compared to the indicator's size, measurements made at the center of the end surface are close to the actual values immediately beneath the surface of the object. The reason for this accuracy is that the magnetic fluxes immediately inside and outside the cylinder's end are perpendicular to the end surface and the perpendicular component of the magnetic induction field across the boundary surface is continuous, according to electromagnetic field theory.

However, the same accuracy is not possible for geometries with sharp corners or for objects that are small compared to the size of the indicator. In these instances, the measured field may not be uniform (the direction and density of the flux lines vary across a small distance) and a tangential component exists. It is known from electromagnetic field theory that the tangential component of magnetic induction may not be continuous when crossing the boundary surface between two media of different permeabilities. Therefore, the magnetic induction inside and outside the object may not be the same.

When the test object has an irregular shape or the residual field readings are large, one way to test external magnetism is to scan the entire surface of the object with a magnetic field indicator. Maximum readings occur at locations where significant external poles exist.

At such maximum reading locations, the field indicator can be used to determine if the field is normal to the object's surface. The field indicator is positioned against the object and oriented with its directional marking normal to the surface. The device is rotated through 180 degrees about the directional marking (normal to the object's surface). During rotation, variations of the indicator reading are noted.

If the rotation does not affect the indicator reading, then the reading is the true field value and the true field is normal to the object's surface at this location. If the field is not perpendicular to the object's surface, it is likely that, at a certain time during rotation, the actual field vector will have no projection along the direction of the indicator's reference field, and the reading at that time will be exactly the component of the field normal to the object's surface. In other words, the normal component of the field at this location will be no greater than the largest value observed in the rotation. More precisely, it is in between the readings obtained at the beginning and at the end of the rotation and is no greater than the average of these two values. If the same value appears twice during rotation, then it must be the normal component of the field.

In most applications, the purpose of external residual field measurement is to ensure that the objects are free of magnetic poles that detract from serviceability. The exact value of the external residual magnetism may not be critical, so long as it is lower than a limit predetermined by the user's empirical data.

Checking Indicator Reading Accuracy

If inconsistent results occur in matching magnetic field indicators, it is likely that some of the devices are malfunctioning. Certain indicator malfunctions are easy to detect, such as an imbalanced or damaged pointer, or mechanical failures at the support of the sensing magnet and pointer assembly. High mechanical impact or sudden exposure to a strong magnetic field are among the less obvious causes for erratic readings.

A magnetic field indicator can also become inaccurate if its magnetization is changed by exposure to a strong direct current or a decaying alternating current field. If the fixed reference magnets become partially demagnetized, the unit can give readings much larger than a good unit's results (smaller B^* in Eq. 23). If an indicator's magnetic components are totally demagnetized, its pointer may not return to the zero position, remaining virtually anywhere on the scale.

Two different field indicators may give different results at the same location on the test object. However, these differences alone do not indicate that one of the field indicators is malfunctioning. The sensing magnets of different devices may have different sizes and their location inside the units may be different. They may therefore not be measuring the field at exactly the same location. In addition, reference fields inside the units may also differ.

In a highly nonuniform field, readings may not vary in the same ratio as varying measurement locations. As a result, it may not be possible to verify the accuracy of a magnetic field indicator by comparing its readings to a known reference unit (other field measurement devices may be equally inaccurate in the nonuniform field). The best way to test the accuracy of a particular device is to perform reference comparisons in uniform or nearly uniform magnetic fields.

To set up a uniform magnetic field for calibration, a helmholtz coil may be used. This device contains two parallel coils separated at a distance equal to their radius and connected in series adding mode. In about 30 percent of the volume between the two coils, there is a very uniform magnetic field parallel to their axes. The field value can either be measured with an appropriate meter or calculated from the coils' dimensions and the value of applied direct current (in Eq. 26, $x \cdot R^{-1}$ is 0.5 and B_o is replaced with $2B_o$).

In addition to the helmholtz coil or commercial calibration fixtures, an approximately uniform magnetic field may be established using a large direct current coil. Over a small distance along the coil's axis, a magnetic field can be considered nearly uniform. As examples, Table 1 shows a set of magnetic field values for a five-turn coil of 300 mm (12 in.) diameter carrying 1500 A direct current. The table values were calculated using the following equations.

$$\textbf{(26)} \quad B = \frac{B_o}{\left[1+\left(\frac{x}{R}\right)^2\right]^{3/2}}$$

where B_o is the magnetic field at the center of the coil (millitesla), R is coil radius (meters) and x is distance (meters) from the center of coil along the axis.

$$\textbf{(27)} \quad B_o = \mu_o\left(\frac{NI}{2R}\right)$$

where I is applied direct current (amperes), N is number of turns in the coil and μ_o is the permeability constant ($4\pi \times 10^{-7}$).

Sometimes, the Earth's magnetic field can indicate a meter's accuracy: the Earth's field is about 0.05 mT (0.5 G). If the indicator's accuracy is within ±0.03 mT (0.3 G), then with proper north/south and horizontal orientations, the device should be able to register an approximate reading of the Earth's field, provided there are no other magnetic objects nearby.

The best magnetic field indicators are precision calibrated. Their accuracy may also be less susceptible to the influence of a strong magnetic field. In some applications, less costly magnetic field indicators may be used to do measurements. Precision calibrated units are then used as reference standards, verifying the readings of the less costly devices. Periodically, the reference devices are returned to the manufacturers for calibration.

Table 1. Magnetic flux densities for five-turn coil carrying direct current, compared with linear distance from coil center.

Distance from Coil Center		Measured Value	
m	(ft)	mT	(G)
0	0	31.0	(309.0)
0.45	(1.5)	1.0	(9.8)
0.9	(3.0)	0.14	(1.4)
1.0	(3.3)	0.1	(1.0)

Use of Magnetic Field Indicator

A magnetic field indicator is a convenient low cost tool for measuring the residual external field intensity of ferromagnetic objects. To measure a uniform field, indicators are often calibrated in a way that requires the operator to align a special directional marking (line or arrow on the device's casing) with the field's known direction.

For an external flux measurement, the field indicator is positioned against the object with its directional marking near to and perpendicular to the object's surface. This positioning is based on the fact that flux lines are expected to be perpendicular to the object's surface at the location of significant poles.

In cases where the field direction is uncertain, the indicator may be rotated about its directional marking, which is in turn positioned normal to the object's surface. The rotation moves through 180 degrees to get a maximum reading. The component of the magnetic field normal to the object's surface is no greater than the maximum value registered during rotation and no greater than the average of the readings at the beginning and the end of rotation. If the rotation does not affect the reading, then the field is perpendicular to the object's surface and the reading is the field's true value.

For a nonuniform field, the reading of the magnetic field indicator is an average value (at the spot where the indicator's field sensing magnet is located).

Good magnetic field indicators have sound mechanical supports for their reading pointers and these supports cannot be easily damaged. Their magnetic components cannot be easily demagnetized by strong external fields. Also, they do not induce significant magnetic poles on the objects they test.

For an accurate calibration of a field indicator, a uniform magnetic field may be provided by a helmholtz coil. For a quick check of calibration, various approximate, uniform field values along the axis of a large direct current coil may be used.

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CHAPTER 6

Equipment for Magnetic Particle Testing

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PART 1. Basic Magnetic Particle Equipment[1]

Magnetic particle test equipment can be as small as a handheld yoke or as large as billet testing units in steel mills. Magnetic particle systems have evolved from the small and simple units first produced. Improvements parallel developments in other technologies and include computer control and improved materials for particles, coatings and vehicles. In its fundamentals, the magnetic particle testing technique has not changed much since the 1930s. Changes have occurred in three areas: (1) magnetic particle materials, (2) test system configurations and (3) components automated for manufacturing and production.[2,3]

Magnetic particle test systems must fulfill two basic requirements: (1) accurate testing based on amperage requirements, test object size, magnetic field levels and suitable testing area and (2) testing with or without operator intervention at a rate required by the particular production facility. In turn, these two requirements determine the size, shape, speed and configuration of the magnetic particle testing system.

Effect of Test Parameters on Equipment Choice

Production Speed

Some magnetic particle testing systems operate at slow production speeds, often as low as a few large components per day. In other instances, the testing equipment is an integral component of a production line, processing and testing hundreds of objects per hour.

If only because of handling considerations, these two applications require completely different types of testing systems, designed and built to accommodate their specific uses.

Test Sensitivity

In some high production applications, the magnetic particle testing system is used as a product screening device: any indication of a discontinuity becomes cause for rejection. Once removed from the production line, the rejected object may then be reevaluated or reworked as needed.

In applications such as aerospace or plant maintenance, magnetic particle tests need to be very sensitive. Extremely small discontinuities must be detected, and correspondingly small test indications must be produced for evaluation and interpretation.

For some applications, high sensitivity is actually a problem: excess leakage fields produce false indications and dense backgrounds. The magnetic particle test sensitivity must be set to indicate discontinuities within a range of severity appropriate to the application.

Configuration of Test System

Ten considerations help configure a magnetic particle testing system for a specific application: (1) particle type (wet or dry), (2) magnetization requirements of the test object, (3) degree of automation required, (4) demagnetization requirements, (5) current requirements, (6) test object size and corresponding test system size, (7) electrical power availability, (8) air supply requirements, (9) accessories needed for the application and (10) test specifications requiring verification.

Each of these considerations is affected by other testing or manufacturing parameters. Magnetization, for instance, may need to be achieved with alternating current, half-wave rectified alternating current, full-wave rectified alternating current or single-phase rectified alternating current, depending on test object and test purpose. As another example, demagnetization requirements are determined by the test object's subsequent use and the magnetization means. In addition, demagnetization may need to be performed within the main testing system or at a separate station.

Before selecting the test equipment, there must be a thorough understanding of the magnetic particle technique, its capabilities and limitations. This understanding is applied to the requirements of the test objects and their anticipated discontinuities. The test object's magnetic characteristics, geometry and intended service affect the choice of the magnetic particle system. Finally, the test system must be configured and installed so that it is an integral part of the existing production facility.

The text that follows is a general view of magnetic particle testing systems and can guide specific applications.

Part 2. Wet Horizontal Equipment[1]

The magnetic particle equipment most commonly used for production testing is the wet horizontal unit (Fig. 1). The nominal length of such a unit is determined by the size of the object that can fit in its clamps. Lengths of 1 to 4 m (3 to 12 ft) are used for most applications. Many other system lengths have been designed, some for objects as small as aerospace bolts a few millimeters in length. On the other end of the scale, very long systems have been built for testing steel billets, gun tubes, oil field pipe or railroad engine crankshafts.

Figure 1. Wet horizontal magnetic particle bench unit.



Positioning of Test Object

Before magnetic particle testing, the object is clamped between a headstock and an adjustable tailstock that moves horizontally along rails in the unit's bed.

The headstock secures the test object by means of a compressed air cylinder. An electrically operated switch, often a foot switch, controls the throw of the headstock air cylinder.

The tailstock's position may be controlled by a gear screw and manual crank or, in some smaller units, the tailstock is simply pushed into position along the bed. Some systems use motor driven tailstocks but these are slow and are normally used only in special applications.

Magnetization Procedures

A wet horizontal testing system can magnetize circularly by direct contact and longitudinally with a yoke or encircling coil.

Once the test object is clamped into position, electrical current is passed through it or through a conductor to induce a field. For longitudinal magnetization, most horizontal systems have a magnetizing coil on a horizontal rail. While the test object is being loaded, the coil is clear of the headstock and tailstock. After circular magnetization, the coil is moved to encircle the object. On test objects over 450 mm (18 in.) long, the encircling coil must be repositioned in 350 to 425 mm (14 to 17 in.) increments. With yoke procedures, longitudinal fields are set up along the entire length of the test object, with no need for repositioning. A suitable reference standard with known discontinuities should be used to ensure adequate field intensity at the midpoint of the test object, or notched shims or quantitative quality indicators (QQIs) can be placed in the areas of interest to verify field directions and intensities (Fig. 2).[4]

Following each magnetization procedure, the test object is examined using wet magnetic particle techniques. Large test objects remain on the unit's bed. Many wet horizontal testing systems are equipped also for demagnetization.

Alternating and Direct Current Systems

Wet horizontal units used for in-service and in-process testing are usually single-phase alternating current systems. Alternating current equipment is less expensive because costly rectifying circuitry and associated cooling systems are not required. In addition, a separate demagnetizing unit is not necessary with alternating current units and test objects are demagnetized in position on the unit.

Aerospace codes and many manufacturing standards specify direct current magnetic particle testing equipment. These are usually three-phase full-wave rectified alternating current systems. In the early days of the magnetic

particle method, direct current was supplied by a bank of acid storage batteries that were often inefficient and unreliable. In 1941, the rectifier circuit was developed, producing unidirectional current from alternating current and replacing the troublesome battery bank.

Alternating versus Direct Current Equipment

There are many differences between the basic circuitry in direct and alternating current magnetic particle testing systems.

One difference is that direct current equipment often has a current timer preset for 0.5 s duration so that a low duty cycle can be used. The timer may be bypassed and is adjustable. Test systems using fully rectified alternating current require augmented cooling. Fans help fulfill the cooling requirements of the rectifier circuits. Such systems may offer demagnetization using reversing direct current with step down procedures or alternating current demagnetizing circuits with rapid decay.

Because alternating current produces a skin effect (with penetration depth dependent on line frequency), the resulting magnetic field follows the contour of the test object. With direct current magnetization, the current and the resulting field follow the path of least resistance, which is not necessarily the location of discontinuities. Therefore, alternating current equipment is often chosen because of an improved probability of detection. In addition, an equivalent relative field intensity in an alternating current system requires only about half of the current used by a direct current system.

FIGURE 2. Field indicators: (a) pie gage; (b) notched shims.

(a)



(b)



Wet Horizontal System Components

The rated magnetizing output and duty cycle of wet horizontal systems vary with the model and manufacturer. Alternating current equipment usually has a maximum output of 1.5 to 3 kA with some rated as high as 6 kA. Full-wave rectified alternating current equipment usually has a 2, 4 or 6 kA rating. For larger test objects, long systems can be

TABLE 1. Components of typical wet horizontal magnetic particle testing unit.

Hood	encloses the unit for ultraviolet radiation
Instrument pedestal	holds meters and other controls
Ammeter	measures amperage of direct current
Adjustable timer	controls elapsed time of magnetizing current
Visible light source	provides illumination
Switches	control fan and visible light
Coil	provides longitudinal magnetization
Contact plate	provides circuit connection at tailstock
Tailstock	adjustable to test object length
Crank	adjusts tailstock position
Curtain	encloses hood to restrict visible light
Actuator bar	triggers actuator to operate magnetizing current
Transfer switch	selects coil or head shot magnetization
Push button	starts and stops magnetizing current
Current control	selects current levels
Foot switch	controls air pressure valve for headstock contact plate
Actuator	connects to actuator bar to operate magnetizing current
Power indicator	indicates when power supply to unit is active
Pump switch	activates pump for magnetic particle suspension
Shelves	are headstock and tailstock contact plates to support test objects
Hose	delivers magnetic particle suspension
Nozzle	applies magnetic particle suspension to test object
Contact plate	connects circuit at headstock
Headstock	supports air cylinder that operates contact plate
Swing arm	allows positioning of ultraviolet lamp
Ultraviolet source	provides ultraviolet radiation
Reference standard	indicates the direction, penetration and intensity of field

manufactured with 10 kA or more direct current.

Table 1 lists the components of a typical wet horizontal magnetic particle testing system. Table 2 lists some accessories.

Test Systems outside North America

Magnetic particle testing systems used outside North America differ in several ways. First, because of demand for alternating current, nearly all systems are designed for use with single-phase input. Where applicable, rectified circuitry is generally half-wave rectified alternating current. Single-phase equipment is appreciably less costly to build than the three-phase rectified systems used in the United States. Single-phase equipment must have primary current double that of a three-phase system for the same secondary or magnetizing current output.

The main advantage of three-phase rectified alternating current is that the demanded theoretical power usage is lower. However, because most testing applications have a 10 percent duty cycle (0.5 s on and 5.0 s off), the saving in power is insignificant. Single-phase magnetizing current provides far greater particle mobility for dry and wet particles.

The second important difference, especially in European systems, is the nearly universal use of yokes rather than coils for developing a longitudinal field in test objects. Many European systems have no magnetizing coil mounted on the unit.

A third difference is that most of the electrical or electronic components are separated from the mechanical or handling portions of a system. In many countries, this separation is a code requirement with safety to personnel as justification. Note that since 1950, no instance of electrocution has been traced to a magnetic particle apparatus, mainly because secondary (magnetizing) circuits produce relatively low voltage.

Multidirectional Test Systems

Multidirectional testing systems provide magnetizing current in two or more directions. Because it is desired for the particles to move freely in the suspension, wet fluorescent particles are usually used in multidirectional systems.

Conventional magnetization in one direction is accomplished in a multidirectional unit by energizing a specially designed circuit. In addition, one, two or three circuits can be individually energized in rapid succession. These quickly changing magnetizing currents produce overall magnetization of the test object, allowing complete coverage of potential discontinuities.

TABLE 2. Accessories for magnetic particle tests in quality control.

Ultraviolet radiation meter	measures ultraviolet radiation intensity with digital or analog readout; may also include sensor for visible light
Test meter	measures amperage output of magnetic particle unit; must be compatible with unit's current
Centrifuge tube	tests concentration of magnetic particle suspension
Tool steel ring standard	verifies accuracy of test setup
Field indicator	provides relative measurement of residual magnetism
Calibrated field indicator	provides actual measurement of residual magnetism
Magnetic field indicator	indicates direction of magnetic field
Hall effect meter	measures magnetic fields in either dynamic or static modes
Reference standard	indicates the direction, penetration and intensity of field

Multidirectional test systems may be designed for very specific applications — the steel blades in jet engines, for example. For this particular test, the third phase of three-phase alternating current is used to provide a circular field directed through the dovetail of the blade. The circular field adds to a longitudinal field supplied by a coil, giving increased magnetic field intensity in the blade's critical dovetail area.

Theoretically, multidirectional magnetization can be applied in a majority of production applications with improvements in resolution and cost. Suitable reference standards with known discontinuities must be used for setup of multidirectional tests. When properly applied with assurance of adequate field and directional balance, improvements in discontinuity detection can be as high as 30 percent over typical unidirectional applications. Reduction in labor costs can exceed 60 percent when compared to conventional test procedures on wet horizontal equipment.

Time studies have indicated that forgings weighing 2.25 to 9 kg (5 to 20 lb) require about 35 percent less time for multidirectional tests because of reductions in handling and testing times. Test objects with multiple apertures are also likely candidates for significant reductions in labor costs when tested with multidirectional methods. Labor savings up to 90 percent have been reported on tests of plates in shipbuilding through heavy duty multidirectional power packs.

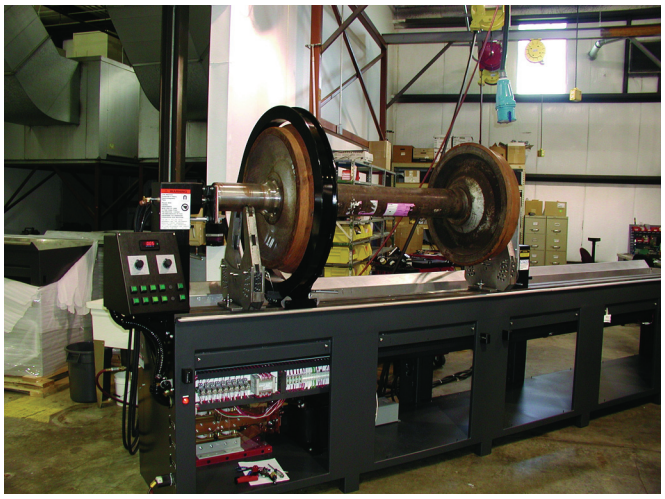
Part 3. Stationary Magnetic Particle Equipment[1]

Many different stationary bench units are available for specific magnetic particle testing applications. The size of the test system is determined by the size of anticipated test objects. Larger models are commonly used for heavy components such as diesel engine crankshafts, landing gear sections, gun barrels or railroad wheels (Fig. 3).

Stationary magnetic particle units are generally designed to operate from a 440 V three-phase alternating current source and to deliver alternating or rectified magnetizing current. Current control is often infinitely variable. In older units, the current was manually controlled with a step switch. Because of expanding requirements for close and repetitive control over current density, filtering of the power source may be necessary.

With the increasing use of programmable logic controllers, some stationary bench units can be programmed with the current test settings for various parts. With programmable logic, the operator recalls the part file and the machine automatically sets itself to the stored settings. Programmed settings ensure that identical parts are tested the same way on different occasions and by different operators.

Figure 3. Horizontal magnetic particle system for fluorescent testing of railroad wheels.



Direct Current Magnetizing Equipment

For magnetic particle testing of large, complex castings, welded structures or plate, overall magnetization with high magnetizing current is economical. The maximum output for such applications is usually rated around 12 kA.

Multidirectional magnetization is often used through two or three magnetizing circuits, making it possible to detect discontinuities in all directions in a setup. This multidirectional magnetization can be done mechanically or electronically. Electronic switching provides faster rise time and programmable cycles for reliability.

Equipment listed in Table 2 is used for monitoring test parameters for quality control inspections. The accessories listed in Table 3 are used in production installations.

Table 3. Accessories for production magnetic particle testing unit.

Hand spray gun	applies wet method suspension
Powder spray bulb	applies dry powder materials
Contact block	enables cables with bench unit
Cables	connect with lug terminals or slip (either-end) joints to portable or bench units; have 9 and 12 mm (2/0 and 4/0 American Wire Gage) diameters
Contact clamps	connect electric cables to test object
Prods	connect electric cables to test object (commonly for tests of welds or large objects)
Split coil	provides longitudinal magnetization with mobile units
Central conductor set	includes central conductors in several sizes for bench units
Test object supports	come as headstock, tailstock and rail mounted supports in various sizes for tubing, bars and shaft shapes
Transport truck	carries portable testing units and accessories
Contact pads, copper mesh	ensure contact with test objects (some models have rubber cushion backing and V shaped blocks)
Connectors, slip joint	connect quickly to prods, clamps, cables and contact block
Small part adapters	lets small objects be tested in standard wet horizontal unit

Automated Magnetic Particle Systems

Automatic or semiautomatic magnetic particle testing in most cases requires magnetization in two directions to detect randomly oriented discontinuities. Because two magnetic fields cannot exist simultaneously in one test object, it is necessary to switch from one direction to the other.

Electronic switching provides advantages in this configuration, as in others. Current can be switched several times per second and is often triggered by the line frequency. In this way, the test object is both circularly and longitudinally magnetized. Switching triggered by the line frequency lets the field direction vary at high speed.

Automated techniques are discussed in more detail below.

FIGURE 4. Portable magnetic particle testing: (a) particles applied to weld; (b) excess particles blown from area of interest.

(a)



(b)



Quick Break Magnetization

Quick break magnetization is needed in three-phase full-wave rectified systems using coils for direct current magnetization. When an object is placed in a coil and magnetized, the field lines leave the test object near the north pole and reenter near the south pole. The lines of force may be normal to the surface at the ends of the test object. A discontinuity near the end of the object may therefore be hard to detect with magnetic particles.

To overcome this problem, the direct current applied to the coil is quickly turned off. The rapid collapse of the magnetic field creates low frequency eddy currents within the object in a direction favorable for the detection of transverse discontinuities at the ends of the object.

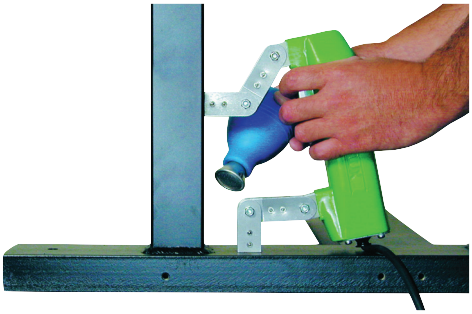
Prods (Fig. 4), a yoke (Fig. 5) or the field flow technique makes quick break magnetization unnecessary because the test object is part of the magnetic circuit. Periodic checking of the break is critical: on electronically triggered equipment, a malfunctioning firing module could result in quick break failure.

FIGURE 5. Yokes for magnetic particle testing: (a) instrument; (b) flexible legs adapted to weld.

(a)



(b)



PART 4. Mobile Magnetic Particle Equipment[1]

Mobile magnetic particle testing systems have outputs up to 20 kA and may be designed to deliver alternating current, direct current, half-wave rectified or pulse current. Table 4 lists the components of a typical mobile magnetic particle test unit. In systems before 1970, the current was adjusted with a thirty-point step switch. Some units have infinitely variable current and push button demagnetization.

In Europe, mobile systems are used as power packs for stationary testing units. This precaution is required because installing heavy duty electrical equipment under a kerosene or water suspension tank is prohibited.

Mobile equipment is widely used for many types of magnetic particle testing. The advantage of these system configurations is that they can be moved to the test site, whether that is a flight line, a refining tank, large plant machinery or a structural steel weldment. The advantage of a mobile system's high amperage is its ability to inspect large castings, forgings, welds or any other test object requiring strong magnetizing field intensities.

Current and Voltage Parameters

For certain applications, prods (Figs. 4 and 6) or clamps are used with mobile magnetic particle equipment. A solenoid, a cable wrapped into a coil, may be used for longitudinal magnetization or demagnetization (Fig. 7). A cable or, with clamps, a ferromagnetic bar can serve as an internal conductor for magnetization.

Mobile power packs operate on 230 or 460 V single-phase alternating current. Most units manufactured through the 1970s had a maximum output of 2 or 3 kA of half-wave alternating current or single-phase alternating current. Systems are now available with 4 and 6 kA half-wave alternating current and single-phase alternating current outputs or a range of pulse outputs.

In a typical system, an operator uses a front panel or terminal to select alternating or direct current.

Cables and Connectors

Cable length can be varied and many applications require lengths exceeding 30 m (100 ft). Mobile system cables are usually fitted with slip joint connectors at either end. Cables are connected to the test system, prods, clamps or to each other to lengthen the magnetizing circuit. Some high amperage systems use bolted terminals to permit high currents without overheating.

A 12 mm diameter (4/0 American Wire Gage) flexible rubber coated cable is most commonly used for mobile magnetic particle applications. For easier handling, 9 mm diameter (2/0 American Wire Gage) cabling is sometimes used for connections to prods. With short cables 5 to 10 m (15 to 30 ft) long, mobile equipment delivers close to its rated amperage. As the cables (magnetizing circuits) are extended, the amperage available at the test point is considerably decreased. For example, a 4 kA unit with two 30 m (100 ft) cables in the magnetizing circuit delivers about 1 kA at the test point, because of internal resistance of the secondary circuit.

The input power cable to a mobile unit can be almost any convenient length with little or no loss in output. Often the input cable is fitted with a heavy duty contact plug for connection to 230 or 460 V outlets. These outlets are commonly available for welding equipment and other heavy machinery. Mobile magnetic particle equipment may also be operated from alternating current generators.

As the cables and connectors become worn or overheated, their electrical resistance increases and current is reduced.

Input and Output Current Requirements

Mobile magnetic particle testing units can be operated on 230 or 460 V single-phase alternating current. The operating voltage is easily changed through an access port that exposes the terminals. Jumpers are alternately positioned to change the transformer connections and vary the input requirements. With either voltage input, the output rating is the same.

Mobile test systems with 6 kA output are not available with 230 V input and, because of high primary current requirements, must be operated on 440 to

460 V alternating current. Units once used tap switches. Since the 1980s, infinitely variable current control lets the operator establish the proper field intensity in a part. The intensity determines the current output for either alternating current or half-wave alternating current.

For demagnetization, mobile magnetic particle testing units use a decaying alternating current or a ramp demagnetizing system.

Operation of Mobile Testing Units

Remote Operation

A cable may be connected to a four-point outlet to let the operator control the mobile unit remotely. When using prods, a microswitch for controlling current flow may be in the prod handle. With clamps, coils or an internal conductor, a special remote switch station is available or the prod switch may be used.

Solid state units allow remote control of power, current and demagnetization. A second 120 V outlet is sometimes provided for remote power to alerts, powder blowers, grinders and other accessories.

Demagnetization

Demagnetizing can be accomplished in several ways with a mobile system. The choice of technique depends on the test object and magnetization means. Small objects can be demagnetized by selecting alternating current and forming a coil with the cables. The object is drawn through the coil while the coil is energized. The test object must be moved sufficiently far from the coil to outdistance the coil's magnetic field, usually about 1 m (3 ft).

For larger test objects, demagnetization is achieved by touching the surface with the energized coil and then moving the coil away from the test object.

An alternate means of demagnetization uses demagnetizing current flowing through the test object. Cables are connected to the object with clamps. With solid state equipment, the decay current or ramp current reducing system is used. With older equipment or tap switch units, demagnetization is done in successive steps. An internal conductor can also be used for demagnetization if the test object geometry lends itself to such procedures.

Demagnetization is discussed in more detail elsewhere in this volume.

TABLE 4. Components of typical mobile magnetic particle testing unit.

Lifting hooks	position the unit with crane
Current control	adjusts alternating or direct current intensity
Line switch	provides power to unit
Power indicator	indicates power to unit
Remote switch	allows remote control
Common connector	provides one side of output current
Power outlet	provides 120 V for accessories (powder blower, grinder, lamps)
Half-wave connector	with common connector, supplies half-wave alternating current to cables
Current connector	with common connector, supplies alternating current to cables
Cables	supply current to prods (12 mm diameter [4/0 American Wire Gage] cable)
Connector	uses either-end slip joint connector for additional cable or accessories
Remote control	stops or starts magnetizing and demagnetizing current
Casters	provide mobility (two swivel and two fixed)
Current light	indicates current is on for output circuit
Ammeter	indicates amperage in alternating or half-wave current circuits
Louvers	ventilate electrical equipment
Recess	stores cable and accessories

Maintenance of Mobile Testing Systems

Some critical maintenance procedures are required for mobile magnetic particle testing systems. For instance, the cooling intake of the unit must be kept clean to permit the free flow of air, especially if the unit is moved into a dirty testing environment.

Prod tips are another source of concern. They may become corroded or burned, hindering good contact with the test object. Defective prod tips can produce arc burns, sources of cracking. Similarly, clamps should have good copper mesh gripping points.

Frayed cables and continuous overheating decrease the conductivity of the cable. This produces heat, increases resistance and reduces the amperage available for testing. Connectors and cable joints should be tight and solid to avoid overheating.

PART 5. Portable Magnetic Particle Equipment[1]

Handheld Equipment

Portable magnetic particle equipment is practical for testing objects in the field, so it is often used for testing structural welds (Fig. 4).

The simplest and perhaps most common magnetic particle test system is a handheld magnetic yoke (Fig. 5). For small test objects (automotive parts, for example) surface discontinuities can be reliably detected at low production rates with a portable magnetic yoke. Yokes are also used for magnetic particle tests of welds, especially when arc strikes cannot be tolerated. It is difficult to prevent arc strikes when current is applied directly with prods.

Yokes operate on alternating current at standard line voltage, either 120 V or 240 V. For areas where a shock hazard exists, yokes can be made to operate at 42 V. The typical electromagnetic yoke's articulated legs assist positioning on complex shapes.

Yokes with four poles have been developed. By switching the poles in pairs at right angles to each other, discontinuity detection in all directions can be performed in a single setup.

Portable System Configurations

Larger equipment is needed for a higher magnetizing current or a higher duty cycle. Magnetic particle test systems often require heavy transformers and, excluding the magnetizing cables, can easily weigh 34 kg (75 lb). For that reason, portable units are sometimes mounted on carts and so become mobile.

Portable systems may operate from a 120, 240, 480 or 380 V single-phase source. Magnetizing output currents range from 400 to 2000 A for alternating current or half-wave rectified alternating current applications. Dual prods (Fig. 6) or clamps are used for direct contact magnetization. Fixed coils are available for mobile applications; most cables connect at either end, letting the operator manually form a magnetizing coil from a standard cable (Fig. 7).

Current and Voltage Parameters

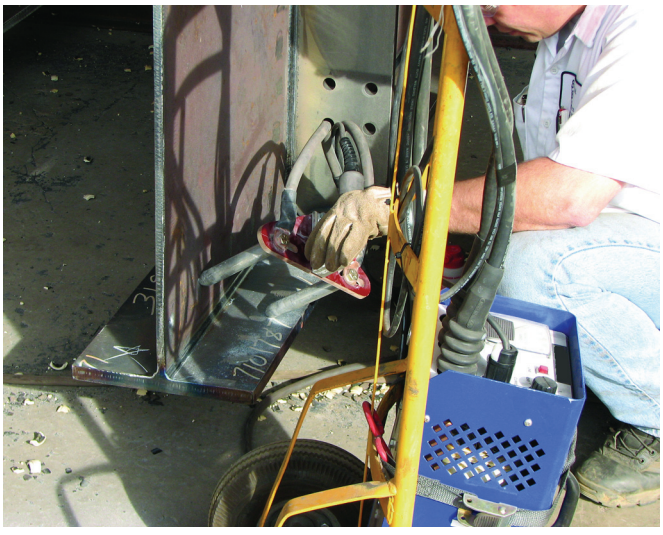
Portable systems vary greatly in electrical parameters. Lighter weight units are usually designed to operate on 120 V single-phase alternating current. Output amperage of these units can vary from 400 to 900 A, depending on the model and manufacturer. Because the usual limit on 120V is 30 A, outputs over 1.0 kA require a 240 or 480 V unit. Most portable magnetic particle testing systems contain half-wave rectified alternating current and alternating current output.

FIGURE 6. Handheld prods for magnetic particle testing: (a) of casting; (b) of bridge girder weld.

(a)



(b)



Either two or three connectors are provided for dual output systems: a common connector, one connector for half-wave rectified and a third connector for alternating current. Output is controlled with a tap switch or a potentiometer. A single ammeter serves to measure both the alternating current and the half-wave output.

Accessories and Components

Table 5 and Figs. 4 to 7 illustrate the components of a portable magnetic particle test system.

Accessories such as prods, clamps and cables for portable systems are similar to their counterparts for mobile testing units. Cable lengths for portable systems are usually limited to 10 m (30 ft) or two 5 m (15 ft) cables.

With the portable systems, demagnetization is accomplished using (1) manual alternating current step down or (2) a coil formed from cables using alternating current. When step down demagnetization is used, connection to the test object is made using clamps or an internal conductor.

A 120 V coil is useful for longitudinal magnetization. The coil consists of many turns of fine wire; a switch closes the circuit when the coil is connected to 120 V alternating current. The coil is primarily for testing elongated objects such as spindles or axles. The coil can also be used to demagnetize many kinds of test objects.

A capacitance discharge portable system, although it operates much like a standard portable unit, weighs considerably less and can use lighter, smaller magnetizing cables. The input voltage is low in capacitance discharge units, providing the additional benefit of increased operator safety.

Yokes

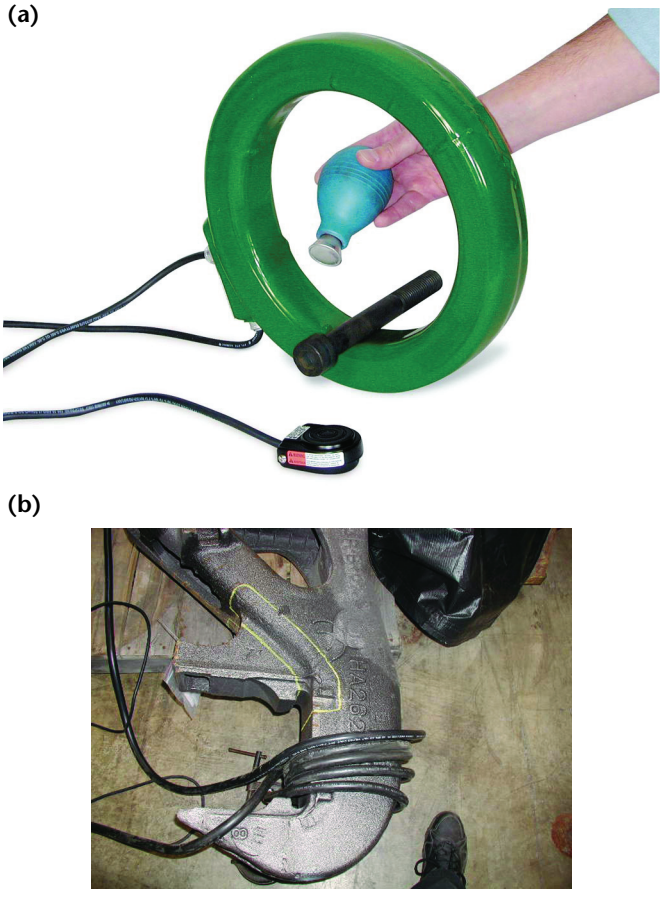
Magnetic particle yokes have a multiple-turn coil wrapped around an assembly of soft iron laminations. A power cord and switch are part of the typical yoke design. In service, the yoke is placed on the test object and energized. Magnetic particles are applied between and adjacent to the ends of the yoke. A magnetic field is set up between the poles of the yoke. To find discontinuities in both directions, the yoke is rotated 90 degrees and the operation is repeated.

In the middle of the twentieth century, alternating current yokes had a rigid U shape. A more useful design has the ends of the U jointed so that wider or narrower objects can be tested more efficiently (Fig. 5b). A rectifier is sometimes used with the yoke, providing a direct current field for penetration below the test surface.

TABLE 5. Components of typical portable magnetic particle testing unit.

Current control	provides adjustable or tap switch
Cables	need extra flexibility to connect to prods
Prods	make in-line electrical contact with test object
Handle	positions and transports unit
Half-wave connector	with common connector, supplies half-wave alternating current to cables
Remote receptacle	enables remote cabling hookup
Common connector	either-end connector for one side of output current
Power indicator	indicates when power supply to unit is on
Current connector	with common connector, supplies alternating current to cables
Control cable	connects to prod remote switch
Ammeter	measures alternating and half-wave current output

FIGURE 7. Coils for circumferential magnetization: (a) solenoid; (b) improvised to fit crimper connector of railroad car.



PART 6. Magnetic Particle Testing Power Pack Systems[1]

A power pack, a large portable battery, is used to set up magnetizing fields when an object is too big for the available stationary testing unit. Many magnetic particle systems in production environments have a power pack as part of their design. The electrical components of the magnetizing and demagnetizing circuits are generally part of the power pack. Timing circuits adapted to the particular production line are included.

Power pack timing circuits are designed for specific applications. This might be hundreds of objects per hour in the automotive industry or an object per minute in the steel industry. In other applications, the power pack could have timers that control the length of the current application to meet product specifications. Power pack design is usually dictated by the production requirements of the products being tested.

Power Pack Applications

Steel Industry

In the steel industry, magnetic particle testing is applied to products as diverse as billets, blooms, bars and tubing. Magnetic particle technology is used to test semifinished products and is sometimes applied at an intermediate stage of manufacture for process control.

A steel mill testing system typically uses a power pack that supplies magnetizing current to contacting fixtures. Depending on the test object's size, amperage as high as 20 kA full-wave direct current may be used. The test system is like a large bench unit, featuring a means of magnetically contacting the test object after positioning. Steel mill test equipment includes handling systems for positioning steel objects measuring from 12 to 20 m (40 to 60 ft) long.

After magnetization, the object is rotated and positioned for testing. Magnetic particle test results determine where the test object goes next: a grinding station, a secondary rolling operation or a shipping point.

For most magnetic particle tests, steel mills use wet fluorescent techniques. The standard steel mill test system includes a power pack, circulating pumps, a filtering system and application nozzles.

Automotive Industry

In the automotive industry, important components such as spindles, connecting rods and crankshafts are routinely tested with magnetic particle techniques. System configuration is based on a power pack for the magnetizing current. Timing circuits are vital in the power pack: magnetizing current must be applied at a specific time during the test object's conveyance through the system.

Magnetization may be circular or longitudinal and is routinely followed by demagnetization. Small test objects are demagnetized with an alternating current coil encircling the conveyor. On some systems, the operator drops the test object through a coil after testing. For large test objects, special contact demagnetizing circuitry is designed as integral to the power pack.

Large Castings

A multidirectional technique described below, also known as the *swinging field* technique, is applied for large, heavy castings. The power pack used in this technique can supply up to three separate magnetizing circuits. Contact is made by cables clamped to the test object and the circuits are arranged so that magnetizing current crosses the test object in three different directions. The power pack supplies timing circuitry for shifting current flow from circuit to circuit. In some applications, one of the three magnetizing circuits is used to form a coil, providing longitudinal magnetization in the test object. Demagnetizing circuitry, usually reversing direct current, can be a feature of this power pack unit.

The swinging field technique is an overall testing approach that uses wet fluorescent magnetic particle suspensions to test the entire surface of large cast objects. In a foundry, for example, this technique can save as much as 90 percent of the labor and time required to inspect an object with prods. In addition, areas can be tested that are inaccessible to prods.

Other Power Pack Applications

Full-wave direct current power packs are used for energizing bench units. These systems are usually designed for testing large objects such as landing gear forgings. A full-wave power pack is also useful when large weldments are tested. Instead of prods, the test object is contacted with clamps and magnetizing current is passed along the length of the weld. After this first test, the clamps are repositioned, contacting the object so that current is passed perpendicular to the weld line.

Multidirectional Field Power Packs

In some systems, a power pack is used to supply a circular field to the test object then within milliseconds the field is changed to longitudinal. This *swinging field* sequence is continuous and very fast because it can be based on the reversals of the 60 Hz power supplied to the unit.

For example, an elapsed time of 0.5 s allows 15 circular field shots and 15 longitudinal field shots. The resulting magnetic field sweeps across the test object and crosses the plane of a discontinuity regardless of its orientation.

Often, wet fluorescent magnetic particles are used with this magnetization method. The suspension is applied to the test object as the magnetic field swings across the material. The rapidly changing field requires high mobility from the particles and that in turn recommends the free, small particles used in wet fluorescent suspensions.

PART 7. Automation of Magnetic Particle Testing[2]

Test Object Handling for Magnetic Particle Tests

Manual Handling with Automated Testing

The simplest automation of the magnetic particle test procedure occurs when test objects are manually positioned in the test system and the magnetizing process then proceeds without operator intervention.

Consistency is achieved with this level of automation (1) by providing accurate levels of magnetizing current or field, (2) by producing accurate timing of magnetizing field or current flow and (3) by applying consistent volumes of magnetic bath in the same manner and the same direction for each test object. This consistency of processing considerably improves both the quality and efficiency of the testing. To include this kind of automation in a standard magnetic particle testing system is relatively simple and can be achieved inexpensively with electronic current leveling devices and electronic timers.

Fully Automated Handling

Fully automated magnetic particle testing systems can be cost justified only when large volumes of similarly sized and similarly shaped test objects are inspected. To move from simple to complete automation requires the installation of mechanical handling systems that feed test objects through the testing machine. Automatic scanning after magnetization and sorting is complex and costly.

Handling in a manufacturing operation forms a large part of the typical production cost: in the United States, the cost of handling is often more than half of the total cost.[5] More than any other single factor, materials handling offers an opportunity for cutting production costs and increasing productivity.

In planning a fully automated testing system, labor costs may not be the most important factor. Other considerations are safety, space and quality.

Safety. Statistics indicate that a very large portion of industrial accidents happen during the movement of materials. Many of these accidents can be prevented by the use of mechanical handling systems.

Space Utilization. It is often possible to increase output from the same amount of space by a mechanical handling system. Such automation ensures the flow of objects from process to process and eliminates the need for temporary storage spaces before and after each manufacturing process.

Quality Control. Accurate control of handling system speed ensures that each test object receives the same treatment. Counters can be installed to monitor system speeds and this information may be stored on-site or delivered to a remote controlling center.

Fully automated magnetic particle testing systems are designed for a specific manufacturing site so that the testing system is compatible with existing manufacturing facilities. For example, the system for moving objects through manufacturing operations may be an overhead conveyor or a roller track. The testing system must be designed as an integral part of the site's existing handling facility. It is equally important for the testing system to accommodate particular production rates, depending on whether the plant uses a batch system or continuous flow line production.

Another important design consideration is the size of the test objects. If large, they may be attached to or loaded onto the conveyor singly and are presented in that way to the testing system. Small objects are often loaded into baskets or fixtures and conveyed through the plant in these containers. On arrival at the magnetic particle testing system (which may have its own mechanism for presenting test objects into magnetizing positions), the fixtures can be unloaded singly by a simple robotic arm. Very small test objects (fasteners, for instance) may be singly presented into the testing system by means of a vibrating bowl feeder.

The most important considerations for successful design of a fully automated magnetic particle testing system are (1) reducing test object movement to a minimum, (2) mechanizing handling in a manner compatible with the rest of the manufacturing process and (3) controlling test object movement and the testing process with a single program installed in a programmable logic controller.

Monitoring of Automated Testing Equipment

Magnetic particle testing systems are designed to meet specific testing requirements for detectability of discontinuity location, direction and size. Also included in design considerations for automated systems are such parameters as test object symmetry, size, weight, configuration, magnetic properties and throughput requirements.

All of these factors influence the design of the load station, conveyor system, test object positioning fixtures, magnetizing method, magnetizing apparatus, bath application, test object manipulation, visual or automatic scanning testing stations, demagnetization apparatus, offloading and tested part segregation.

Automated Magnetizing

The proper magnetizing technique for a specific test object is fundamental. Selection of the type and level of magnetizing current may be dictated by the controlling process specifications. Alternating current, half-wave direct current and full-wave direct current, single-phase and three-phase, and single-shot all have their place in automated test systems.

In most manufacturing applications of magnetic particle testing, test objects are sequentially processed with circular and longitudinal magnetization using contact and coil techniques. This has long been standard practice for manually operated equipment and semiautomated systems as well as for automated tests.

This magnetization technique is reliable but slow for automated line throughput. Test objects magnetized in both the circular and longitudinal methods require (1) magnetizing in a circular direction, (2) testing and interpretation, (3) demagnetizing in some cases, (4) magnetizing in a longitudinal direction and (5) further testing and interpretation.

Multidirectional Magnetization

When automatically processing large numbers of similar test objects (automotive forgings or castings, for example), there is a critical need for performing magnetic particle tests at the highest reliable speed. This is done by using a system that indicates discontinuities in all directions with one magnetizing operation.

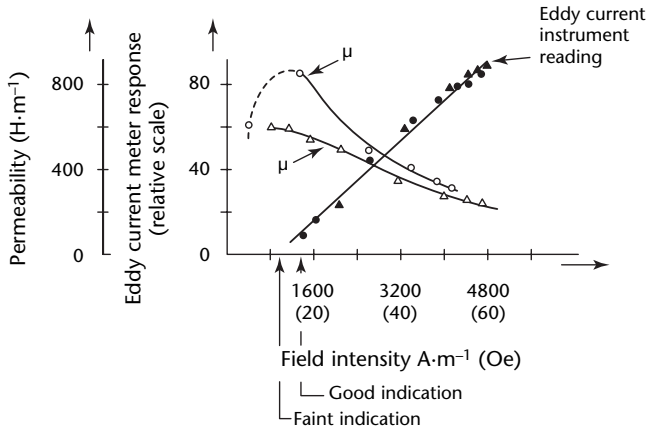
Several systems for this kind of testing have been implemented, including alternating current swinging field systems. In a typical alternating current swinging field, current is applied to the headstock and tailstock simultaneously, with a second alternating current 120 degrees out of phase with the first, applied to the coil. These currents are two phases of a three-phase electrical supply.

A multidirectional, contact and noncontact magnetization technique provides a significant increase in the speed with which magnetization can be established in a given test object. The implementation of electronic firing circuitry enables phase switching rise times on the order of 4 ms in a 0.5 s shot. Controlling the current level in each firing circuit is another valuable characteristic. Proper multidirectional magnetization can reduce magnetization time by half.

A test system design incorporating multidirectional magnetization techniques must account for the following considerations: (1) the intensity and direction of the magnetizing fields, (2) the sequencing of the magnetizing shots, (3) the duration of the overall shot and (4) the application of the magnetic bath and, in turn, the availability of magnetic particles on the test object and their freedom to move and form indications.

It takes considerable time and experimentation to ensure that all these parameters are correct. If the magnetic field intensities in different directions are not correctly adjusted relative to each other, test indications may not be distinct and significant discontinuities can be missed. Field intensity adjustments may not necessarily be accurate if a pie gage or other artificial discontinuity devices are used (Fig. 2). A multidirectional magnetic

FIGURE 8. Eddy current response versus magnetization curves for two sample test bars 13 × 25 × 150 mm (0.5 × 1 × 6 in.) with electron discharge machined notches at 0.6 μm (0.015 in.) depth.



Legend

● ○ = annealed to hardness of 64 rockwell-B

▲ △ = spheroidized to 91 rockwell-B

particle system should be set up using a magnetic field indicator (tesla meter) and a reference standard (a typical test object containing known discontinuities).

Computer Components of Automated Testing Systems

An automated magnetic particle testing system may be managed by programmable logic with the following features: (1) central processing program, (2) programmable memory, (3) input means, (4) output means and (5) a power supply.

The central processor uses instructions from the computer's memory. Among other functions, the central processor uses software for the following purposes: (1) to interrogate the status of the inputs, (2) to set or reset the outputs, (3) to perform counting and timing functions and (4) to monitor the system continuously for malfunction.

This kind of controller provides flexibility for testing and manufacturing. Magnetizing current levels, shot duration and magnetic bath application parameters can be easily monitored and changed. Test object identity and programming can be fed from an external computer, and data on inspected parts may be filed as test objects move through the system.

Monitoring for System Malfunction

With a totally automated magnetic particle testing system, it is critical to verify correct performance of the system. For instance, if the magnetizing current has not reached its full value because of bad contact, or if the magnetic bath concentration is low or high, test objects move through the system but discontinuities are not reliably indicated. Subsequent interpretation, manual or automatic, will consider this lack of indications to mean freedom from discontinuities.

It is essential therefore to monitor all the parameters of the magnetizing process and to detect malfunctions of transducers and other devices introduced into the system.

Malfunction. Malfunction systems are normally connected to alarms at two levels. A soft alarm warns of malfunction requiring operator intervention. The programmable controller may indicate that the concentration of the magnetic bath may have moved beyond preset limits or the magnetizing current may have dropped within ten percent of a preset value. Based on established procedure, the operator then decides whether to accept the test objects, to reprocess the test objects or to stop the system. A hard alarm immediately shuts down the system if a test object is jammed in the clamping mechanism, if the bath pump fails or if any part of the hardware or software fails.

Current Leveling. It is necessary to monitor a test system's current leveling device to ensure that it is operating correctly. The magnetizing power unit in an automated testing system includes current leveling capability to ensure that, when the current output control has been set, the precise amount of current is supplied at each shot. When the output current is kept consistent, a drop in current may be attributed to conditions external to the power unit (bad contact with the test object or loose cable connections, for example).

Magnetizing Current. Current passing through the test object or the coil must be monitored. Current levels at 90 to 100 percent of a preselected value should be acceptable in most tests. Current values at 80 to 90 percent should cause a soft alarm. Below 80 percent, a hard alarm should sound and the system should be shut down. These thresholds may be adjusted for different applications. Monitoring current levels for multidirectional magnetization is more complex because the current is flowing in any one direction only briefly. It is probably more efficient to integrate the current levels in each direction and average them over the duration of the current shot. Monitoring of the duration of the shot itself is also necessary but this can be a straightforward function of the programmable controller.

Bath. The concentration of magnetic particles in the bath is very important yet some systems have not monitored it. The programmable controller should monitor the magnetic bath application time, pump pressure and flow rate. Consistency in the application of the bath helps provide consistent, reproducible test results.

All of these monitoring steps — current level of the system, current level in the test object, bath concentration and dwell time — are important steps for verifying the operation of an automated testing system and, in turn, for ensuring the reliability of the system's test results.

Automating of Magnetic Particle Testing Procedure

In today's industrial environment, interest in automation for production operations, from basic fabrication to final assembly, is commonplace. Lower cost results from labor reduction, yield improvements and better quality. Better quality comes about because of the uniform manufacture by

automatic machines and from reduction of human error.

Automation can be used in magnetic particle testing by certain combinations of the following processes: (1) automatic handling and positioning of the test object, (2) automatic test object magnetization, (3) automatic timing of the bath application relative to the magnetization timing, (4) automatic detection and location of magnetic particle indications on the test object and (5) automatic interpretation (deciding if indications are caused by discontinuities).

Process Monitoring

Full automation comprises more than automatic scanning. The term *automatic scanning* refers to automated observation. When the magnetic particle testing process is fully automated, all steps are performed automatically and there is no inspector. Processing, observation and interpretation are performed and monitored by an automatic apparatus.

Partial automation is achieved when certain operations are automated. For example, it is common to use automatic cleaning and bath application tied to automatic magnetization and still use inspectors to observe and interpret the indications.[6]

It is important for the inspector to verify that each stage of the testing procedure is performed properly. If full automation is used, automatic verification is required and maintenance of such components becomes a critical procedure. At production speeds, inoperative verification equipment can invalidate large numbers of magnetic particle tests. There are various ways to verify proper performance of processing stages.[7] The first decision in this and all verification processes is determining the need for verification. For example, if cleaning is critical to the accurate testing of a particular product, then the cleaning procedure must be verified. The next decision is determining the characteristics of interest (in this case, those that affect magnetic particle test results) and how they can be quantified.

Verification of Cleaning Operations

If a spray cleaning system is used, a flow meter may be used to monitor the cleaning bath as it moves through the pipes leading to the spray head. The flow meter should be placed as close to the spray head as possible and the signal generated by the flow meter should be compared with the signal to activate the flow valve. Timing differences occur but this is a good way to verify that valves are working and that the flow is enough. The cleaning solution should be also monitored to determine if the bath is uncontaminated and at proper concentration.

The cleaning of magnetic particle test specimens is usually not critical. Unlike liquid penetrant testing, magnetic particle tests are generally very forgiving of nonmagnetic dirt. For example, it is possible to have nonferritic foreign material contained in surface cracks and still do an excellent job of detecting these discontinuities with magnetic particle techniques. Good judgment and cost considerations determine how much cleaning is monitored.

Verification of Magnetization

Several approaches can verify magnetization. Current flowing during the correct magnetization time window is a good indication that the test object is being magnetized properly.[8] Further assurance occurs when the monitored current value falls within predetermined thresholds. Monitoring of the current time and value is straightforward. Flux shunting devices determine proper magnetization levels and can serve as references.

It is also possible to measure the normal and tangential components of the surface magnetic flux density with a hall effect device.[8] This measurement is a relative indicator of internal flux density for test objects with simple shapes. It is best to measure this value during the magnetization time window and use it to activate predetermined thresholds.

Another approach is to use an eddy current device to measure the change in relative permeability of the material being magnetized (Fig. 8). The optimum value of permeability is that value at the knee of the initial magnetization curve.[9] It is possible to monitor this point with eddy current techniques. As with other methods, predetermined values should be used, proper threshold levels should be set and permeance should be measured during magnetization.

Monitoring of Particle Bath

Low Retentivity Objects. Bath application is crucial for test objects with low magnetic retentivity. If such a test object has a smooth surface and bath continues to flow over developed indications after the magnetization cycle, it is probable that the developed magnetic particle indications will be washed off. In this situation, it is crucial that the magnetization cycle be carefully timed when determining the bath procedure.[8] Flow conditions should be checked and

cycles should be carefully adjusted to ensure that all bath flow has stopped in critical areas of the test object before the magnetization cycle ends. Then both the magnetization and bath cycles must be monitored to set thresholds to detect deviations. Flow can be monitored with a flow meter (Fig. 9) as close as possible to the spray heads. Photocells and acoustic path devices have also been used to measure flow rates.

High Retentivity Objects. If the test object has high magnetic retentivity or a rough surface, bath application is not as critical. If proper magnetization is used in a high retentivity test object, the magnetic leakage field around the discontinuity continues to exist and attract particles after the magnetizing current is shut off. In this case, discontinuity indications develop even if bath flow continues after the magnetization cycle. Multidirectional applied fields are not retained in test objects[8] (only one of the directions remains after the current is stopped). The usual compromise is to end magnetization with a field orientation covering the most critical discontinuity orientation. If alternating current magnetization is used, the current should be cut off at the same point in the cycle for every test object for consistency. For maximum retained field, the current should be cut off at zero or when it is decreasing from a maximum value (Fig. 10). If a coil or yoke is used for alternating current magnetization, it is easy to demagnetize the test object as it moves through the tapering field at the exit end of the coil or yoke.[8] As with low retentivity materials, little or no field is then retained around the discontinuity and indications might be washed off. However, if the test object's surface is rough, embedded particles may resist washing even if the test object is demagnetized. Remaining particles might indicate discontinuities.

Bath Coverage. It is vital for critical areas to be covered with magnetic particle bath. Positioning of the test object relative to the bath applicator is therefore very important. When an automatic loading system is used, it is possible for the test object to shift and critical areas are not then exposed to the bath. For this reason, test object positioning should be monitored by means of limit switches, photocells or acoustic path monitors.

Bath Concentration. In manual systems, magnetic particle concentration is monitored using a centrifuge (Fig. 11) in a settling test.[10] In automatic systems, it is possible to monitor particle levels with electromagnetic techniques, optical techniques and particle counters. A number of bath parameters may be checked at the same time by using a standard test object containing a known discontinuity. The reference standard is passed through the entire test system in front of each part being tested or in some

FIGURE 9. Typical magnetic particle bath flow versus magnetization time.

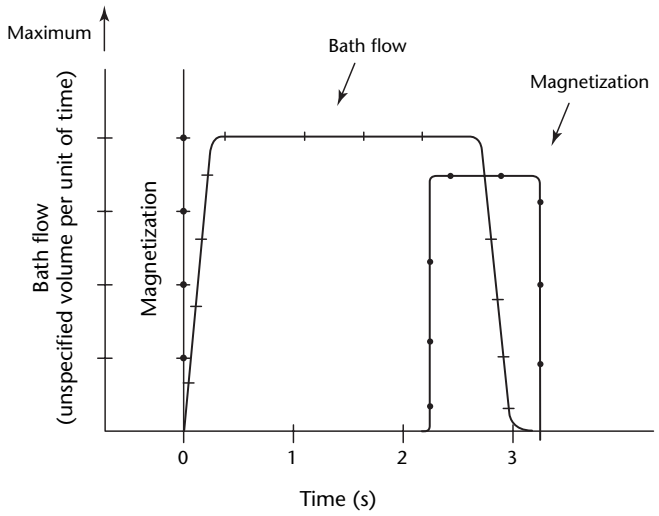
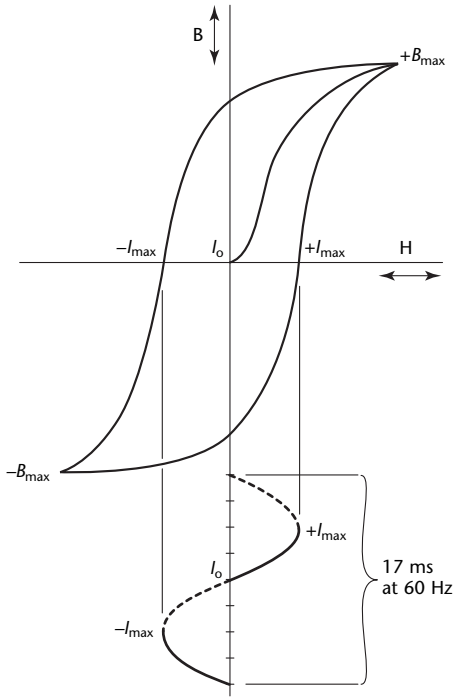


FIGURE 10. Flux density versus magnetizing current. To ensure maximum retained field, current should be shut off during the two parts of the waveform illustrated as solid lines. Shutoff must be at the same point for all test objects to ensure consistency.



Legend
I = current (A)
B = magnetic flux density (T)
H = magnetic field intensity (A·m^{-1})

frequent, repetitive manner. The standard is cleaned, magnetized, bathed and tested automatically. When the system is working correctly, the standard's indications confirm that test objects are being inspected properly.

Automated Scanning of Magnetic Particle Tests

Fluorescent magnetic particle indications are scanned to automate the viewing of test results. Automatic scanners usually comprise the following components: (1) a source of ultraviolet radiation, (2) a video camera, (3) a computer for imaging, (4) amplification and discrimination equipment to evaluate indications and (5) material handling accessories.

Material handling accessories are needed to move test objects to and from the scanner, to index or move the test objects under the scanner so that all desired areas are inspected uniformly and to mark or separate rejected test objects.

Automated Interpretation of Magnetic Particle Testing

Recognition of significant test indications and distinguishing them from background indications are generally the two most complex problems for an automated testing system. Background often appears as a foggy glow containing a number of isolated bright spots. Frequently, there are also some false indications that share the characteristics of discontinuities. These include tool marks, scratches, thread crests, valleys, hole edges and other anomalies.

A trained operator ignores nonrelevant indications and so should an automated system. This discrimination capability dramatically increases system complexity, yet most automated testing applications require pattern recognition capabilities including optical techniques, dedicated digital processing, microprocessor algorithms and neighborhood processing algorithms.

Optical Pattern Recognition

In laser inspection, a linear beam is aimed at a discontinuity and along the orientation of that discontinuity. Figure 12 illustrates the formation of this line of light using an anamorphic lens. An anamorphic lens is curved so that it focuses the collimated laser light into a line parallel to the lens axis. The beam's cross sectional width in the orthogonal direction is maintained because there is no focusing in that axis.

For optical pattern recognition, a phototube detects and integrates the fluorescent flash that occurs when the exciting beam is coincident with the indicated discontinuity. The need for parallel alignment of the beam with the discontinuity limits system flexibility.

A similar result can be obtained using a scanning laser system and integrating the output of the photodetector across the scan. This has the advantage of a larger depth of field (no optics are used for focusing) but requires more complex scanning and electronics.

Sensitivity is reduced if the beam and the discontinuity are not parallel. A parallel line of exciting radiation permits optical integration of the fluorescent light from the entire length of the indication. Slits of excitation illumination can permit optical pattern recognition for straight line indications in other orientations.

FIGURE 11. Centrifuge tube for monitoring of magnetic particle concentration.

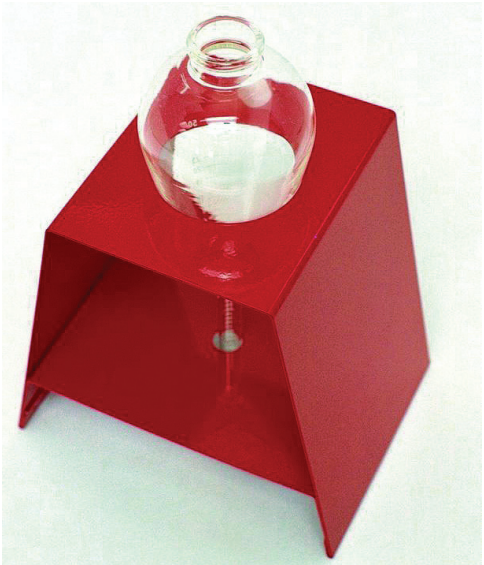
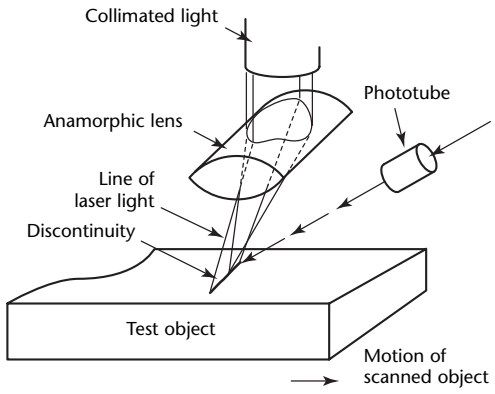


FIGURE 12. Optical pattern recognition of straight, linear fluorescent test indications.



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CHAPTER 7

Magnetic Particles[1]

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PART 1. Introduction

Magnetic particle testing is magnetic flux leakage testing in which the indications are produced by ferromagnetic particles applied to the test surface.

Magnetic particle testing provides a test indication very near actual material discontinuities, describing their size and shape on the test object surface. In this important way, the magnetic particle method differs from most other nondestructive tests. In other techniques, test indications are typically produced in a medium separate from the test object, as an oscilloscope trace, through an acoustic transducer or on radiographic film, for example. By outlining and precisely locating the discontinuity, magnetic particle indications are comparatively simple to interpret.

The magnetic particle test method is best suited for locating small surface discontinuities on ferromagnetic test objects. The technique may also indicate the presence of certain linear discontinuities slightly below an object's surface. The precise degree of the magnetic particle test sensitivity has not been firmly established, although this text discusses several applications that demonstrate how fine a crack may be reliably detected with careful testing procedures. In practical situations, absolute sensitivity is not as important as the probability of detection. This probability is a product of the magnetic particle characteristics, the magnetization technique, the level of magnetization, test environment lighting intensity and inspector training.

There are two types of magnetic particles in general commercial use: dry and wet. Dry particles are applied to the test surface as a solid suspension or as a cloud in air. Wet particles are applied as a suspension of particles in a liquid vehicle, either oil or water.

PART 2. Dry Technique Testing Materials

Dry Technique Particle Characteristics

Particles used in the dry technique of magnetic particle testing are manufactured to emphasize three sets of physical properties: (1) magnetic characteristics, (2) size and shape and (3) visibility.

Magnetic Properties

Nearly all dry magnetic powders are finely divided iron particles coated with pigments. These ferrous materials are chosen to provide the characteristics critical to magnetic particle test procedures. Primary among these are low magnetic retentivity, high magnetic permeability and low coercive force.

Low retentivity increases the dry powder's ability to clearly indicate discontinuities. If the particles retain magnetism (high magnetic retentivity), they adhere to each other and cannot be properly applied. When such particles reach the test object, they adhere to its surface and cause an intense background, masking discontinuity indications.

High magnetic permeability also increases the powder's ability to indicate discontinuities. Particles with high permeability are easily attracted to the small magnetic leakage fields from discontinuities, where they are trapped and retained for interpretation.

The concentration of the magnetic material in dry powders is a fourth critical consideration. Increasing the amount of magnetically inert pigment in a dry powder composition naturally lowers its magnetic sensitivity, or coercivity. Dry magnetic powders are therefore manufactured as a compromise between the primary need for sensitivity and the secondary need for high visibility.

Size and Shape

Particle size and shape are to some extent more critical than magnetic permeability for achieving sensitivity and ease of use in a dry powder. Magnetic powders are not simply an aggregate of metallic filings. The particles are made from carefully selected magnetic materials of specific size, shape, magnetic permeability and retentivity. They are designed to be used in air, not to be mixed with a liquid vehicle. Reclaiming dry powders is not recommended.

Fine dry particles that can pass through mesh sieve apertures of 50 µm (0.002 in.) diameter show much greater sensitivity to small discontinuities and their small leakage fields when compared to particles of 150 µm (0.006 in.). The coarser particles, nearly three times the diameter of the 50 µm (0.002 in.) mesh particles, are more than 20 times heavier and are too large to be held by weak leakage fields.

However, for two reasons, a dry testing powder cannot be made exclusively of small magnetic particles: (1) small particles adhere to all surface anomalies (oil traces, dampness, fingerprints or roughness), producing dense particle backgrounds and (2) the testing environment becomes extremely dusty and unsafe for the inspectors. As a result, a practical dry magnetic powder contains a range of particle sizes. Small particles are needed for sensitivity to fine discontinuities. Coarser particles are needed to bridge large discontinuities and to diminish the powder's dusty nature. In addition, large particles can reduce masking by dislodging the background often formed by fine particles.

Particle shape also has important effects on background, particle application and test results. Elongated particles (large length-to-diameter ratios) are easily attracted to leakage fields. When compared to particles of equal permeability but compact shape, long particles more readily form linear discontinuity indications, possibly because of their ability to easily achieve magnetic polarity. However, elongated particles cannot be used alone because of their tendency to mat and to form clusters hard to apply.

Particles with a compact shape flow easily, have high mobility and can be simply dispersed into clouds for proper application. As a result, the most sensitive dry powders contain both shapes, in a ratio determined by the test application and empirical data.

In SAE AMS 3040, *Magnetic Particles, Nonfluorescent, Dry Method,*[2] the upper size limit for sensitive dry particles is about 180 µm (0.007 in.) diameter. Larger particles can plug powder applicators and do not add sensitivity.

Not all dry powder test procedures require high sensitivity. In some applications, high sensitivity is actually detrimental to the testing procedure. In these circumstances, size and shape are less critical and the most important particle characteristic is low residual magnetism.

Visibility and Contrast

Dry technique magnetic testing powders are commercially available with three types of colors: (1) visible colors, for viewing under visible light, (2) fluorescent colors, for viewing under ultraviolet radiation and (3) daylight fluorescent colors. The daylight fluorescent powders fluoresce brightly in visible light, greatly amplifying their visible color.

The visible light powders are normally available in gray, red, black, yellow, blue and metallic pigments. This range of colors allows the user to choose the one that contrasts most strongly with the test object surface.

Fluorescent colors are seldom used in dry powder applications, partly because dry powder tests are typically performed on site or on large structures, making it difficult or impossible to enclose and darken the testing area. In addition, fluorescent dry powders often produce background that is bright enough to be objectionable.

Daylight fluorescent colors are occasionally used when a test indication's high visibility or contrast is more important than absolute sensitivity (fluorescent color augments the visible color and indications are extremely bright and visible). With these powders, there is no need for an enclosed, darkened test environment. In fact, the brighter the ambient light, the brighter the indications. Daylight, even in deep shadow, excites their fluorescence, as does blue mercury vapor lighting or the light from white fluorescent tubes. Ordinary incandescent lights work less effectively than white or blue light sources. However, the yellow light from sodium vapor lights does not excite fluorescence in daylight powders and cannot be used for this application.

In some applications, particle contrast may be enhanced by coating the test object surface with a thin white lacquer. The characteristics of the lacquer then become important considerations for the magnetic particle inspector. The white surface coating must dry immediately, lest it slow the testing procedure, and must be easily removed after the test to avoid delays and additional costs.

Dry Particle Uses

Dry magnetic particles are often used to test welds or castings for surface discontinuities. Dry powder is not recommended for the detection of fine discontinuities such as fatigue cracks or grinding checks. Wet technique testing is much more sensitive to small surface discontinuities.

Tests of Welds

In weld testing, the typical magnetic particle technique uses prods or yokes, with the inspector magnetizing and testing short overlapping lengths of the weld. The continuous magnetization technique is used (the magnetic field is continuously activated while the inspector applies the powder and removes the excess).

Automatic processing has been used for testing linear welds on large diameter pipe. However, most welded structures are shaped in ways that make them difficult to handle automatically. In addition, much weld testing is done on site and only portable testing systems can be used.

Direct current magnetization is usually preferred for weld testing because it penetrates more deeply and allows the indication of slightly subsurface linear discontinuities. Half-wave direct current also has the advantage of providing increased particle mobility and increased potential for forming accurate discontinuity indications while reducing background.

Tests of Castings

Dry particles are particularly useful for magnetic particle testing of large castings. Cast objects are normally tested using prods or yokes, with the test covering small overlapping areas. Large portable power supplies may be used. In these applications, the magnetization equipment is set up in advance, with connectors for through-current shots firmly clamped in place and coils or looped cables wound where needed. The current is applied throughout powder application making this a continuous technique. Because the test procedure may take several minutes on a large casting, all test system cabling must be properly rated to avoid excessive heating.

The choice of magnetizing current depends on the type of discontinuities being sought.

Application of Dry Magnetic Particles

Particle Applicators

Dry magnetic powders must be applied in a gentle stream or cloud. If applied too rapidly, the stream may dislodge indications already formed and will certainly build up too much background for easy removal or interpretation. If applied with too much velocity, typical particles gain too much momentum to be reliably trapped by discontinuity leakage fields. Manual and mechanized powder applicators can help provide proper density and speed of particle application.

The simplest and most common particle applicators are rubber bulbs or shaker bottles. For most magnetic particle applications, these simple devices provide the kind of application required for accurate testing. Mechanical powder blowers are another application option. They are designed to float a cloud of particles onto the test object surface and then to provide a gentle stream of air to remove the lightly held background particles. For best results, magnetizing current should be present throughout the application of particles and the removal of background.

Monitoring of Particle Application

Regardless of the applicator used, the inspector must carefully monitor the test object while particles are applied. It is critically important that powder application be done properly to ensure the reliability of the test. This is especially true if subsurface discontinuities are being sought. Their particle indications are weakly held and not well delineated, so that they are very susceptible to damage from particles applied later.

Particle Reuse

It is recommended that each batch of dry magnetic particles be used only once. There are occasions when reuse is permitted, but inspectors should understand the effects of frequent reuse.

Ferrous magnetic powders are dense (specific gravity of 7.68). When agitated in bulk, as in a powder blower or a bulb, a lot of shearing and abrasion results and wears off some pigment. Each reuse, with its additional rehandling, wears off more pigment. As a result, color and contrast diminish to the point that indications are not visible.

Reuse of magnetic powders also encourages fractionation, the separation of different sized particles from the composite. Particles sprayed over a test object are designed to have different sizes and to fall in different trajectories. Generally, finer particles float further away from the point of introduction. Unless great care is taken to collect all the particles, reused powders gradually become coarser and so less sensitive.

Particle Storage

The storage condition for dry technique powders is critical to their subsequent use. The primary environmental consideration is moisture. If magnetic particles are exposed to high levels of moisture, they immediately begin to form oxides. Rusting alters the color, but the major problem is that the particles adhere to each other, forming lumps or large masses useless for magnetic particle testing.

Though not severe, there are also limitations on the temperatures at which dry powders can be stored and used. Visible light powders work on surfaces as hot as 370 °C (700 °F). Near this temperature some particle materials become sticky. Others lose much of their color, although their magnetic properties remain intact and they can still indicate discontinuities. Beyond 370 °C (700 °F), magnetic powders can ignite and burn.

Fluorescent and daylight fluorescent powders lose their visible contrast at 150 °C (300 °F) and sometimes at lower temperatures. This occurs because the pigments are organic compounds that decompose or lose their ability to fluoresce at particular temperatures.

Other Considerations

Dry technique powders must not be used in wet technique applications. Dry particles are designed and manufactured at densities that work well in air but cause them to settle quickly out of liquid suspensions. In water, typical dry powders settle at rates around 152 $mm \cdot s^{-1}$ (6 $in. \cdot s^{-1}$) and accordingly cannot be kept suspended. In addition, dry powders are susceptible to oxidation when exposed to water.

Note also that ferrous powders in general and particularly many of their pigments have been classified as nuisance dusts by the Occupational Safety and Health Administration (OSHA) and must be handled accordingly.[3]

Viewing and Interpreting Dry Particle Test Indications

Producing a discontinuity indication is the first stage of a magnetic particle test. Viewing the indication and interpreting its meaning is the second important step, and both procedures depend critically on the characteristics of the magnetic particles and radiation intensities.

Visible Particle Light Intensities

ASTM E 1444, *Standard Practice for Magnetic Particle Testing,*[4] calls for minimum light intensities of 1000 lx (100 ftc) for magnetic particle testing with nonfluorescent powders. Other light level recommendations range from 800 to 2000 lx (80 to 200 ftc).

The optimal light level is often a compromise between operator fatigue and visibility. On bright or reflective surfaces, high light intensities can cause glare that interferes with interpretation. On darker surfaces or those covered with thin scale, rust or other staining, the 1000 lx (100 ftc) level may be barely adequate.

Fluorescent Particle Radiation Intensities

Because of their limited industrial application, there is little empirical data for radiation levels in dry fluorescent testing. In addition, there is presently no standard or specification for dry fluorescent intensity ranges. The few dry fluorescent powders that have had marginal applications were much brighter than typical wet technique powders. Their viewing conditions were correspondingly less demanding than the conditions for wet fluorescent particle viewing (see below).

Daylight fluorescent dry powders also have no specifications for required radiation intensities. Sunlight, shaded or direct, as well as artificial blue or white light all excite daylight fluorescent powders to a high level of brightness and visibility. Incandescent light is somewhat less effective and yellow sodium vapor light is totally ineffective. Daylight fluorescent powders also fluoresce brightly under ultraviolet radiation but cannot be recommended for this technique of viewing. They exhibit a high level of fluorescent background when viewed in the dark, high enough to nearly obliterate fine discontinuity indications. Testing under full visible light hides this background and keeps contrast high.

Dry Magnetic Particle Specifications

Although the manufacturers of dry magnetic powders have their own quality control tests, additional testing is often needed to prove conformance to user specifications. One important specification is SAE AMS 3040, *Magnetic Particles, Nonfluorescent, Dry Method.*[2] SAE AMS 3040 places an upper limit on particle size: 98 percent must be finer than a 180 µm (0.007 in.) diameter mesh. The specification also defines the limiting amount of loose pigment (in a test called magnetic properties) and specifies a minimum sensitivity: six indications visible on the tool steel ring standard.

Other techniques have been developed for dry magnetic particle testing of pipe, including recommendations for the dry particles.[5] Powder is required to have a range of particle sizes: at least 75 percent in mass should be finer than 125 µm (0.005 in.) mesh and at least 15 percent in mass should be finer than 44 µm (0.0017 in.) mesh.

This technique also outlines a magnetic permeability test that uses a cylindrical powder sample as the core of a simple transformer. For an 11 $kA \cdot m^{-1}$ (140 Oe) input in the primary circuit, at least 2.5 V shall show up across the secondary circuit, with the prescribed circuitry. Such tests are sensitive to the amount of powder packed into the cylinder and effectively put a ceiling on the amount of magnetically inert pigment that the powder can contain.

PART 3. Wet Technique Testing Materials

Wet Technique Particle Characteristics

In wet technique magnetic particle testing, particles over 25 µm (0.001 in.) in diameter are considered coarse. These large particles exhibit diminished sensitivity to fine surface cracks and produce no more than four indications on the tool steel ring standard. These coarse particles settle out of suspension in 5 to 15 min and are difficult to keep in suspension.

Sensitive wet technique particles range from 5 to 15 µm (0.0002 to 0.0006 in.) in diameter; unpigmented ferromagnetic oxide particles are an order of magnitude finer.

The small size and generally compact shape of wet technique particles dominate their behavior. Their size makes permeability measurements inexact and not useful. In addition, the size influences the brightness of fluorescent powders made from such particles.

Wet Particle Composition

Commercial wet technique particles are made from finely divided iron, from black iron oxide, from brown iron oxide and experimentally from ferrites, nickel and nickel alloys.

Black iron oxide or magnetite (Fe_3O_4) is available as ground ore or preferably as a fine synthetic powder. Brown iron oxide (gamma Fe_2O_3) is chemically identical to nonmagnetic red iron oxide (alpha Fe_2O_3) but has the same ferromagnetic cubic crystalline structure as magnetite.

Ferrites are hard ceramic materials difficult to make into fine powders. Some nickel alloy powders show good magnetic test sensitivity, if fine enough, but are slightly denser than iron and even harder to keep in suspension.

Fluorescent powders also contain fluorescent pigments as well as a binding resin to attach the fluorescent pigment to the ferromagnetic core.

Size and Shape

At sizes of 10 µm (4×10^{-4} in.) and under, practically all low retentivity ferromagnetic powders have a compact shape, with length-to-diameter ($L \cdot D^{-1}$) ratios around one, because the techniques of forming low retentive powders (grinding or precipitating from a highly agitated solution) preferentially break down long, narrow particles. Exceptions to this are the high retentivity, high coercive force oxides and ferrites used in magnetic tapes.

Fluorescent wet particles have a definite and measurable size, as do particles based on finely divided metallic iron. Synthetic iron oxides are more difficult to measure, with diameters around 0.1 µm (4×10^{-6} in.). They are almost too fine to settle out of suspension.

Because of their slight residual magnetism, oxide particles collect to form loose clusters that settle out of suspension much faster than individual particles. The degree of clustering depends on the intensity of agitation. At high agitation rates, the clusters are small. At low agitation rates, they become larger. Clusters can often be seen on smooth shiny test surfaces after bath application. In this quiescent state, the clusters grow large enough to be seen with the unaided eye, often tens of micrometers in diameter.

Magnetic Properties

Because metals and ferrites can be shaped into ideal toroidal samples of 100 percent density, their magnetic properties can be measured precisely. Powders cannot be accurately measured because samples cannot be made with densities higher than about 50 percent. As an example, pure iron has an initial permeability of 1000 at 8 $kA \cdot m^{-1}$ (100 Oe) field intensity. Pure iron has a maximum permeability around 5000. In laboratory tests, 10 µm (0.0004 in.) iron powder showed a permeability of about 10 (5 for iron oxides) at 8 $kA \cdot m^{-1}$ (100 Oe). With the lower field intensities associated with small leakage fields at discontinuities, permeabilities may well be lower still (the data above cannot be used to predict a ferromagnetic powder's behavior).

Because of their compact shape, the true material permeability of fine wet technique particles may not be of practical importance. However high the core material's permeability might be, the apparent permeability of the individual particles does not exceed a value of about 2.5. This is because of the large

demagnetization factor[6] associated with an $L{\cdot}D^{-1}$ ratio of one.

$$\text{(1)} \qquad \frac{1}{\mu} = \frac{1}{\mu'} - N_d = \frac{1}{\mu'} - \frac{N}{4\pi}$$

where N is the demagnetizing factor, N_d is the shape demagnetization factor, μ is the true permeability of the parent ferromagnetic material and μ' is the apparent permeability of the sample particle.

At lower material permeabilities, the apparent permeability decreases, becoming 2.0 at a material permeability of 10. The apparent permeability decreases rapidly at still lower permeabilities. As a result, magnetic particles made from very high permeability material are slightly more effective than those of moderate permeability values (about 20 to 100). The most important consideration is avoiding the use of particles with very low permeabilities.

True material permeability becomes important when two or more particles touch and align in a leakage field. The $L{\cdot}D^{-1}$ ratio of the joined particles begins to effectively exceed a value of one, and the demagnetization factor of the string of particles shrinks, allowing the string to become more effectively magnetized and more firmly attached to the sites of discontinuity leakage fields.

Visibility and Contrast

Wet technique particles are commercially available as fluorescent and nonfluorescent materials. Most nonfluorescent particles are simply ferromagnetic iron oxides, either black or brown. These are used in their natural color with no added pigment. As a result, these particles are very slightly more sensitive than the pigmented fluorescent particles. For this reason, the unpigmented iron oxides are preferred for some applications where sensitivity is more important than easy visibility. Bearing testing is an important application of these oxides: sensitivity is critical and the smooth reflective surface of the test objects gives the best possible contrast to the dark oxide particles.

On darker surfaces, indications from brown and black particles are very difficult to see and locate, though a thin white lacquer painted on the test surface can improve contrast, much as it does with dry powders.

Fluorescent magnetic particles are composites, containing a ferromagnetic core, a fluorescent pigment and preferably a binder to hold the composite together. The size of the particle strongly influences its fluorescent brightness, as the following data illustrate.

In 1 kg (2.2 lb) of 125 µm (0.005 in.) iron particles, the pigmented surface area is about 6 m^2 (65 ft^2) and can be made brightly fluorescent with very little pigment. A finer iron powder, about 40 µm (325 mesh or 0.0017 in.) has a surface area around 18 m^2 (190 ft^2). In 1 kg (2.2 lb) of a 6 µm (2.4×10^{-4} in.) oxide based powder, the pigmented surface area is about 420 m^2 (4500 ft^2). Because the inspector's eyes register the fluorescent pigment on the particle's surface, ultrafine particles require 30 to 60 times as much pigment as the coarser particles to achieve the same relative brightness. Such ratios make manufacturing of bright ultrafine particles impossible (the particle would contain virtually all pigment with a trace of ferromagnetic core and no electromagnetic sensitivity).

An important consideration in fluorescent particle contrast is its durability. In an agitation system where the bath constantly passes through a centrifugal pump, the particles are subjected to constant high speed impact and shearing action from the pump's impeller. This slowly breaks the particle down to fragments. In the extreme case, two kinds of particles are formed: (1) nonfluorescent magnetic fragments, which form indications that cannot be seen, and (2) nonmagnetic fluorescent fragments, which do not indicate discontinuities but which do cause background. In practice, baths never reach this stage of total deterioration, but as breakdown progresses, indications become dimmer while background fluorescence increases (indication-to-background contrast diminishes).

The onset of particle breakdown can be detected in an already operating bath by an extension of the settling test. Fluorescent fragments are both less dense and finer than the intact particles and settle out of suspension much more slowly, requiring 10 to 15 h. After a settling test is performed, allow the settling tube and sample to sit unagitated overnight. Loose fluorescent pigment will produce a thin, brightly fluorescent layer on top of the sediment. This is the *settling test,* described below.

No firm correlation has been made between the extent of particle breakdown, the relative amount of free pigment and the reliability of the bath. This settling test simply detects the occurrence of breakdown. The individual user can best relate the evident breakdown to the quality of the fluorescent magnetic particle bath.

Oil Vehicles for Wet Technique Particles

There are two kinds of vehicles used for wet technique testing: water and oil. Oil vehicles are preferred in certain applications: (1) where lack of corrosivity to ferrous alloys is vital (finished bearings and bearing races, for instance); (2) where water could pose an electrical hazard; (3) on some high strength alloys, where exposure to water may cause hydrogen embrittlement (hydrogen atoms from water can diffuse into the crystal structure of certain alloys and so cause embrittlement.

Water vehicles are preferred for the following reasons: (1) lower cost, (2) little fire hazard, (3) no petrochemical fumes, (4) quicker indication formation and (5) little clean up required on site.

History of Oil Vehicle Specifications

In the past, a variety of petroleum solvents and oils were written into magnetic particle testing specifications but most of these early oil vehicles were designed for other purposes. For example, federal specification P-D-680, *Dry Cleaning and Degreasing Solvent,*[7] and federal specification VV-K-220 (kerosene, deodorized)[8] were referenced in MIL-I-6868E (1976), *Magnetic Particle Inspection Process*.[9] These standards were all superseded.[10-12]

P-D-680 originally applied to nondestructive testing before high flash point fluids were required. This specification called for: (1) a minimum flash point of 59 °C (138 °F), (2) a low distillation range (no contemporary oil vehicle would meet this specification) and (3) two inappropriate, purely chemical tests (the doctor test and sulfuric acid absorption).[7]

The VV-K-220 document allowed a similarly low flash point and low distillation range and required a different sulfuric acid reactivity test.[8]

ASTM E 1444, like MIL-STD-1949A before it, calls for magnetic particle oil vehicles that met the requirements of AMS 3161 and DLA A-A-59230.[4,12-14]

SAE AMS 3161, *Odorless Heavy Solvent Inspection Oil,*[15] addresses viscosity, a specific concern of magnetic particle testing. Viscosity is measured as square meter per second ($m^2 \cdot s^{-1}$) and is often expressed in square millimeter per second ($mm^2 \cdot s^{-1}$) or its equivalent in the centimeter gram second system, centistokes (cSt). The specified viscosity of 2.0 to 2.3 $mm^2 \cdot s^{-1}$ is low, typical of light, volatile petroleum solvents with low flash points. The flash point minimum given in SAE AMS 3161 is only 65 °C (150 °F).[15]

Flash point is important for two reasons. Fire safety is the primary consideration: the Occupational Safety and Health Administration has placed costly restrictions on the use of lower flash point solvents in open tanks).[16-18] These restrictions may be avoided if the vehicle's flash point is over 93 °C (200 °F). Health considerations are less obvious but also important. Low flash point vehicles are more volatile than high flash solvents. A typical petroleum solvent having a flash point of 66 °C (150 °F) is much more volatile than one having a flash point of 93 °C (200 °F) or more, and burdens the inspector's breathing air with many times more solvent vapor.

The MIL-STD-1949A has been replaced by ASTM E 1444, *Standard Practice for Magnetic Particle Testing*.[4] The requirements for magnetic particle oil vehicles can be found in SAE AMS 3045 and SAE AMS 3046 documents.[19,20] DLA A-A-59230, *Fluid, Magnetic Particle Inspection, Suspension,* supersedes DOD F 87935, *Fluid, Magnetic Particle Inspection, Suspension Medium.* The requirements of DOD F 87935 were as follows.[14,21]

1. The maximum viscosity is 5.0 $mm^2 \cdot s^{-1}$ (5.0 cSt) at bath temperature, in accordance with ASTM D 445.[22]
2. The minimum flash point is 93 °C (200 °F), in accordance with ASTM D 93;[23]
3. The vehicle fluoresces no more than does the reference standard.
4. There is no odor.
5. Particulate matter is no greater than 0.5 $mg \cdot L^{-1}$, in accordance with ASTM D 2276.[24]
6. Total acid number is 0.015 $mg \cdot g^{-1}$ maximum, in accordance with ASTM D 3242. Acidity is expressed as the amount (milligram) of base (potassium hydroxide, KOH) needed to neutralize 1 g of the measured material.
7. The ASTM color number is 1.0 maximum, in accordance with ASTM D 1500.[25]

The requirements of AMS 2641 in 2007 were as follows.[26]

1. The minimum flash point is 93 °C (200 °F) for a Type I vehicle and is 60 to 93 °C (140 to 200 °F) for Type II vehicle (ASTM D 93).[23]
2. Viscosity must be no more than 3.0 $mm^2 \cdot s^{-1}$ (3.0 cSt) at 38 °C (100 °F); no more than 5.0 $mm^2 \cdot s^{-1}$ (5.0 cSt) at bath temperature, according to ASTM D 445.[22]
3. Fluorescence must be the same as specified in DOD F 87935.[21]

The AMS 2641 specification prescribes the same limits as DOD F 87935 on the

amount of particulate matter, acidity, odor (inoffensive) and visible color.[21,26]

Viscosity Check

Viscosity, a measure of a fluid's resistance to flow, is an important property of oil vehicles for magnetic particle testing. Contaminants from the surface of test objects build up in the particle suspension and increase its viscosity. Precleaning test objects to remove oil and grease helps resolve but does not eliminate this problem.

Depending on the specifications in force, viscosity measurements are usually performed monthly, often in specialized commercial laboratories. A 90 mL (3 oz) specimen from the tank is enough for this check.

If the viscosity exceeds specified values, the suspension is discarded and the tank is drained, cleaned and refilled with fresh suspension. The results of viscosity tests are reported in a log book, along with any third party reports.

Suspensions, solvents and similar materials must be discarded in compliance with federal, state and local laws.

Vehicles for Wet Technique Particles Water Conditioning

Water cannot by itself be used as a magnetic particle testing vehicle. It rusts ferrous alloys (including the testing equipment), it wets and covers test surfaces poorly and does not reliably disperse fluorescent magnetic particles. Water conditioners or wetting agents must be added to remedy these shortcomings.

Water conditioners are well covered in the ASTM E 1444 specification.[4] SAE AS 4792, *Water Conditioning Agents for Aqueous Magnetic Particle Inspection,*[27] requires only that a conditioned water vehicle (1) wet a test surface without the film of water breaking and (2) have an alkalinity not exceeding a pH of 10.0. (The term pH is used as a logarithmic measure of hydrogen cation concentration.[28] Water has a pH of 7; acid solutions have more hydrogen ions and a pH less than 7; alkaline solutions have fewer hydrogen ions and a pH greater than 7.)

Common sense indicates that a conditioned bath should not rust test objects and should not foam so as to interfere with the formation of indications. In magnetic particle tests, a water conditioner needs to perform the four following functions: (1) reliably wet and cover all test surfaces, (2) encourage wetting and dispersion of fluorescent particles, with their water repellent organic pigments and binders, (3) minimize foaming caused by wetting agents necessary in the bath and (4) retard rusting of test object surfaces.

Where the bath does not at first cover the test object surface, there can be no particles and no indication formation. Beyond this, the bath film must cover the test object surface (without breaking) throughout the magnetic particle test procedure. If the water film does break or peel from the surface to form separate drops, it also peels off particles in indications. The result is a poor and unreliable test.

Wetting Abilities

Different surfaces require different degrees of wetting. Steel billets, with porous, oxidized surfaces are easily wetted by untreated water. At the other extreme, very smooth surfaces covered with a trace of oil require very strong wetting ability. In such cases, surface tensions as low as 25 $mN \cdot m^{-1}$ (25 $dyn \cdot cm^{-1}$) may be required.

Magnetic iron oxides used in nonfluorescent wet technique baths are easily wetted by untreated water. However, fluorescent particles typically contain organic pigments and binding resins that tend to be water repellent. Fluorescent baths must therefore include treated water to achieve the wetting ability needed to cover common oily test surfaces and to adequately wet and disperse the fluorescent particles. When fine fluorescent magnetic particles are not wetted by the vehicle, they float on the bath surface like dust and no amount of agitation will disperse them.

Foaming Solutions

Because they contain powerful wetting agents, magnetic particle water baths easily generate stable foams when agitated at the surface. Masses of foam that reach the test surface during bath application slide to the lowest edge of the surface, erasing indications in their path. It is therefore important that water baths (1) do not foam excessively and (2) generate unstable foam that disappears quickly. Although careful formulation of a water conditioner can minimize foaming, full foam control occasionally requires antifoaming agents. Such agents cover the bath surface with a microscopically thin layer of an oily substance. Antifoaming agent concentrations are critical: if too much is present, it acts like an oily contaminant, coagulating the magnetic

particles and destroying the bath's wetting ability.

Corrosion Inhibition

Corrosion was at one time controlled by including small amounts of sodium nitrite or traces of sodium chromate in the magnetic particle bath. These chemicals have high levels of toxicity and, when present in the United States, must be listed by suppliers on "Materials Safety Data Sheets," as ordered by the Occupational Safety and Health Administration.[29] Sodium nitrite and sodium chromate are also among the waste water contaminants regulated by the Environmental Protection Agency. These safety restrictions limit the use of the chemicals, and alternative corrosion inhibitors may have found acceptance after 2008.

Water baths have never been expected to provide long term corrosion protection for the test object after testing is complete. Accomplishing this protection requires separate treatment after testing.

Bath Contamination

Both water and oil vehicles can be contaminated by solid materials, as in the discussion of settling tests, below. Introduced oil may also be a contaminant of water and oil baths. In addition, oil vehicles can be contaminated by water.

The most common form of contamination is oil in a water bath. This occurs in recirculating systems where bath runoff returns to the bath reservoir and oil on the test surface is washed into the water. When enough oil is present, it causes magnetic particles to congeal and also destroys the bath's wetting ability. Oil contamination can be avoided by effectively precleaning test objects. If this is not possible, stringent control of the bath is required and should include regular visual inspections and monitoring of production levels. Contaminated bath is discarded and replaced.

Highly fluorescent oil or grease on test object surfaces can easily dissolve into oil based magnetic particle baths. The accumulation of introduced oil produces a blue fluorescent background that can hinder discontinuity detection. Frequent inspection of the bath and monitoring of production levels are again the solutions, if precleaning is not possible.

Particle coagulation also occurs when water contaminates an oil bath. The condition is accompanied by a sticky buildup on the bath tank walls. Adding small (0.1 percent or less) amounts of a suitable oil soluble emulsifier will restore the bath. Emulsifiers must be added carefully: too much will markedly increase the bath's viscosity and fluorescence.

Brilliance and Contamination Checks

Each week that magnetic particle equipment is used, the brilliance of fluorescent suspension should be checked by comparing it to a fresh, unused sample. When a suspension is mixed, 200 mL can be retained in a dark glass bottle for reference.

Used suspension is compared with the unused sample under ultraviolet radiation. If the brilliance is noticeably different, the test system's tank should be drained, cleaned and refilled with fresh suspension. The results of these checks are recorded in the log book.

Contamination of the suspension by foreign matter should also be checked at least once a week. If the suspension is contaminated, the tank should be drained, cleaned and refilled with fresh suspension. The following procedure is used to verify contamination.

1. Run the circulating pump for 1800 s (30 min).
2. Fill a graduated 100 mL centrifuge tube with suspension and let it stand for 1800 s (30 min).
3. Examine the liquid above the precipitate under ultraviolet radiation. If the oil or water fluoresces green or yellow green, the tank should be drained, cleaned and refilled with fresh suspension.
4. Examine the precipitate. If two distinct layers are visible and if the top layer of contaminate exceeds 50 percent of the bottom layer's magnetic particles, then the tank is drained, cleaned and refilled with fresh suspension.
5. Record the results in the log book. Specifications may vary in the allowable ratio between particles and contaminant in the precipitate. Results of these tests are always logged in writing.

Because these tests together take at least 3600 s (60 min), it is normal to begin magnetic particle testing before the brilliance and contamination procedures are completed. If the suspension does not meet specification, objects tested during the 1800 s (30 min) must be retested with fresh suspension.

Bath Preparation

Wet magnetic particle baths may be mixed by the supplier or may be sold dry for mixing by the user. When the magnetic particle system contains a

recirculating bath, mixing is relatively easy.

Recirculating System Bath Preparation

After the liquid vehicle is added to the bath tank, the manufacturer's required amount of powder is added directly above the sump. The bath is allowed to recirculate for five minutes while the pump disperses the powder.

When a conditioning agent is needed for a water vehicle, the agent is added to the bath and dissolved before the magnetic powder is added. Because the conditioning agent must be dissolved before it becomes active, it is faster to begin the process with warm water.

Nonrecirculating System Bath Preparation

If the magnetic particle system has an air agitated bath, or if the bath is applied from spray guns, then bath preparation is more difficult. Magnetic particles often stick together during manufacture, storage or shipment and simple stirring does not separate them. Manually mixed baths are therefore susceptible to uneven distribution of particles and are unreliable for testing.

The best way to manually prepare a finely dispersed bath is to add premeasured powder to a small food blender along with enough oil or conditioned water to nearly fill the container. At low speed this takes about 30 s.

An alternative technique is to add premeasured powder to a small container along with enough liquid to form an easily worked paste. Mixing by hand precedes adding the paste to the bath.

Bath Maintenance

The effectiveness and reproducibility of a magnetic particle bath depend on its concentration. If the concentration is too low, indications will be weak and difficult to locate. If the concentration is too high, the background will be intense enough to camouflage indications. Correct particle concentrations fall between these extremes.

Keeping the concentration at a constant level eliminates one variable in the test: the indication-to-background contrast. It is important to monitor bath concentrations regularly throughout the testing cycle, not only after bath preparation. Suppliers of magnetic powders specify bath concentration both in mass of powder per volume of bath and also in settling volume ranges that result from these concentrations. Most industry standards specify only the acceptable settling volume.

Visible Particle Concentrations

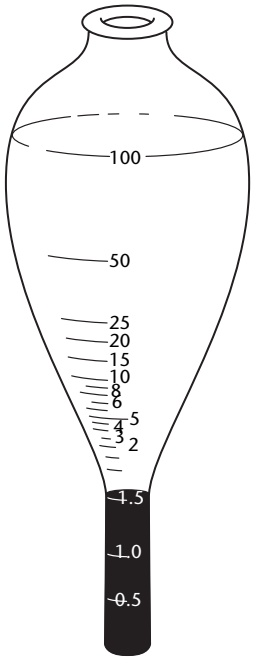
The Society of Automotive Engineers specifications AMS 3042 and AMS 3043 for visible wet technique particles call for settling volumes from 10 to 24 mL·L^{-1} or (using a 100 mL centrifuge tube) 1 to 2.4 mL (1 to 2.4 cm^3).[30,31] ASTM E 1444 calls for a range of 1.2 to 2.4 mL after 1800 s (30 min) settling in a vibration free location.[12]

All three standards specify the pear shaped tube of ASTM D 96, *Water and Sediments in Crude Oils* (Fig. 1 shows a similar settling tube).[32] The ASTM D 96 tube has a 1.5 mL (1.5 cm^3) stem graduated in 0.1 mL (0.1 cm^3) increments. The next graduation is at 2.0 mL (2.0 cm^3) in the conical portion of the tube. If the expected settling volume is in an inadequately graduated portion of the settling tube, a permanent mark should be made at the correct concentration so the bath can be kept constant without guesswork.

Fluorescent Particle Concentrations

SAE AMS 3044 and SAE AMS 3045 standards for wet particles specify concentrations for fluorescent particle baths but again the requirements differ slightly. The SAE AMS specifications call

FIGURE 1. Typical centrifuge tube used for magnetic particle settling tests.



for a range of 0.2 to 0.5 mL (0.2 to 0.5 cm^3) whereas the older specification MIL-STD-1949A had called for 0.1 to 0.4 mL (0.1 to 0.4 cm^3) settling volumes. The ASTM D 96 tube is required for either test. MIL-STD-1949A has been superseded by ASTM E 1444.[4,12,19,32,33]

Fluorescent particle baths are much more dilute than visible baths, so that all likely settling volumes fall within the graduated stem of the tube. More reproducibility for small settling volumes can be achieved if the tube has a 1 mL stem graduated in 50 µL intervals.

Particle Settling

Settling Ranges

It is not productive to assume that all concentrations within broad specified ranges are equally effective or desirable. For example, it has been shown that fluorescent particle concentrations around 2 $mL \cdot L^{-1}$ give the best results on a tool steel ring standard.[34] Higher concentrations produce backgrounds that obscure faint discontinuity indications. Lower concentrations produce indications too faint to be easily detected.

In another special case, it was found that increasing particle concentration from 1 to 4 $mL \cdot L^{-1}$ gives increasingly brighter indications with very little increase in background. In this application, clusters of very fine cracks were located under a chromium plate. The cracks were very close together (less than 0.5 mm apart) so that expanding indications totally depleted the narrow strips of background between the cracks, producing dense bright indications.

Some users prefer a substantial fluorescent background where it makes bath concentration measurements less frequent. Such modifications of recommended procedure are allowed only after firmly establishing and verifying the results of such tests for the individual application.

The broad concentration ranges outlined in most specifications cover the limits that are allowed and that may be required. Testing beyond either specified extreme may not produce the best results and higher or lower concentrations should be considered.

There is a strong tendency in some industries to test at the lowest possible concentration. Low concentrations are valid for economic reasons and also ensure that excessive background does not become a problem. One precaution is necessary for this approach: if particles are applied from a recirculating system where the excess bath returns to the reservoir, particle depletion is likely. Most magnetic particles adhere to the test object whereas most of the vehicle returns to the reservoir. The particle concentration decreases steadily with usage over time and may not be noticed by inspectors. For reliable, reproducible magnetic particle tests with low bath concentrations, the frequency of concentration tests must be increased.

Settling Test

Since the 1940s, a settling test has been used to measure magnetic particle bath concentrations.[35] It is a convenient technique that requires little equipment, a simple procedure and only 30 to 60 min to perform. Its accuracy is sometimes less than 80 percent but the levels of precision are appropriate for most applications.

ASTM E 1444 specifies that the filled settling tube be demagnetized before the settling test begins.[4] Because the magnetic condition of a bath can affect the speed of settling and the final settling volume, the demagnetization procedure is an effort to standardize the magnetic level of the bath regardless of its use.

Settling Parameters. It is essential that the settling test take place in a location free from vibration. The settling tube must be positioned in an area that is proven to be free of strong magnetic fields.

Freshly magnetized bath settles very rapidly, often in 900 s (15 min) or less. Magnetization causes the particles to clump together quickly and form large clusters that sink fast (agglomerated settling). However, these clusters form a much larger settling volume than if the individual particles were unmagnetized: the structure of the clusters cannot be compacted by gravity.

Speed of settling and settling volume depend on the particles' magnetization level, so the settling tube sample must be demagnetized. Vibration during settling does not affect the speed of settling but can compact the sediment to give falsely low settling volumes.

Settling Tube. Settling test equipment is simple: (1) a 100 mL pear shaped graduated glass centrifuge tube (Fig. 1), (2) a stand for supporting the tube vertically and (3) a timer to signal the end of the specified settling period.

The tube referenced in most specifications has a 1.5 mL (1.5 cm^3) stem graduated in 0.1 mL intervals. According to ASTM D 96, the maximum reading error of this tube is 30 µL.[32] Another common tube has a 1.0 mL stem graduated in 50 µL intervals. This configuration is easier to read for baths with small settling volumes, including most fluorescent particle baths.

For very dilute baths, even 0.05 mL intervals are too large. A tube with a 0.2 mL stem in 0.01 mL graduations gives the most reproducible results. This stem is very nearly the size of a capillary tube and is extremely difficult to clean after a settling test.

The typically specified tube is probably a compromise. It can be used to measure dilute fluorescent particle baths (under 0.2 mL with diminished accuracy) as well as more concentrated visible particle baths (also with diminished accuracy if the settling volume is over 1.5 mL). The three tubes do not show the same settling volumes for the same bath. Tubes with narrower stems show higher settling volumes. Hindered settling behavior mentioned below acts to retard settling in the more constricted stems.

Effect of Contaminants

Recirculating magnetic particle baths can pick up solid contaminants from three main sources. The first source includes solids washed into the bath from test object surfaces. Vapor phase degreasing, a common procedure for cleaning test objects before magnetic particle testing, does not remove nonoily contaminants such as sand, dust, lint or grit.

A second source is particulate matter in the testing atmosphere, matter that settles into the bath. The quantity of these solids is determined by the geographic location and the nature of the manufacturing facility, but some airborne particulates can be in quantities sufficient for increasing the settling test volume.

A third source, unique to water baths, is a highly dilute but bulky and gelatinous precipitate. The contaminant is caused by increasing water hardness in the bath as water is added to replace evaporation loss. Water hardness is determined by the concentration of certain salts, including calcium and magnesium. The resulting precipitate does not affect settling tests of baths with high particle concentrations because too little of it is present and the weight of the settled ferrous particles compacts it. In dilute baths (settling volumes of 0.1 mL or less in the 100 mL centrifuge tube), the precipitate adds bulk to the sediment and can give falsely high settling volume readings.

Contaminating particles do not necessarily settle out first or last to form obvious layers in the sediment. The effects of contamination contribute strongly to the low absolute accuracy of the settling test. Contamination of oil baths by water and contamination of water baths by oil tend to produce bulk sediments and substantial amounts of the magnetic particles adhering to the sloping walls of the settling tube.

Stages of Settling

The sedimentation of magnetic particles during the settling test consists of four separate but overlapping stages.[36]

The first stage is simple unhindered settling of the individual particles. This changes to agglomerated settling where their slight residual magnetism causes the particles to collect into larger and faster settling clumps. When most of the particles have settled into the narrowing portion of the centrifuge tube, hindered settling begins. In this stage, the local particle concentration is high enough that the falling particles get in each others way and restrict further settling. In addition, the upward flow of the displaced liquid now becomes rapid enough to further retard settling. The final stage is compact settling, where all the particles are in contact and apparently settled but the sediment slowly shrinks in volume as more liquid is displaced.

Condition of Vehicle after Settling

In its early versions, MIL-STD-1949[12] required that the supernatant liquid (the vehicle after settling) be essentially nonfluorescent. Naturally, fluorescence in the liquid vehicle can detract from the contrast of fluorescent indications. It can also signal the breakdown of fluorescent magnetic particles into their components. A fluorescent magnetic particle bath composed of unattached fluorescent pigment along with nonfluorescent particles, whose indications cannot be seen under ultraviolet radiation, is not usable and should be discarded.

Three different conditions can lead to fluorescence in the supernatant liquid after settling is complete, but not all of them indicate a substandard bath. Fluorescent oils or grease can be swept into the bath from test surfaces, making the whole liquid fluorescent. Particles can break apart, leaving tiny slow settling fragments of fluorescent but nonmagnetic pigment behind. Finally, some very small but complete particles can escape agglomeration and, settling at individually slow rates, may require another hour or more to finally settle out.

The fluorescing of a supernatant liquid is a warning to further monitor the condition of the bath. Is the blue fluorescence due to oils bright enough to interfere with indication contrast? If not, then it is not excessive. Does the

sediment after overnight settling show a bright fluorescent layer on top? If not, the particles have not been broken apart. Does the green fluorescent supernatant liquid give feeble indications because of the extremely low concentration of particles? If so, then the bath contains fine, slow settling but useful particles. The converse to any of the above answers indicates that the bath should be replaced.

ASTM E 1444[4] recommends that the graduated portion of the tube be viewed under both visible and ultraviolet radiation for contamination. If striations or bands are present in different colors and if they exceed 30 percent of the volume, the bath must be adjusted or replaced.

Various instruments are available to monitor bath concentrations automatically. Acceptance of these instruments is compromised by two disadvantages: (1) the much lower cost of simple settling test equipment and (2) the accuracy of continuous monitoring equipment can be compromised by certain kinds of bath contaminants.

Applications of Wet Magnetic Particles

Magnetization Techniques

Wet technique materials can be used in practically any kind of magnetic particle test, and they are most useful for indicating the fine surface cracks that dry powders cannot locate reliably.

Wet particles can be used with the residual and the continuous magnetization techniques. In the residual technique, the test object must have high magnetic retentivity. It is first magnetized, then the magnetizing source is removed and the object is dipped into an agitated magnetic particle bath. Agitation must be gentle or sometimes stopped during immersion to avoid dislodging indications. Longer immersion or exposure times yield larger indications, an advantage of the residual technique.

The continuous magnetization technique is more widely used, with slight variations in procedure that depend on the specific application. In the typical wet horizontal testing unit, the inspector flows agitated bath onto the test object from a hose. After the hose is shut off, the magnetizing field is activated. At this point, the bath is draining off test surfaces slowly enough to avoid dislodging indications. If these actions are not properly sequenced and bath is still being applied after the magnetizing current ceases, the continuous technique is no longer being used but rather the residual technique. This degrades the inspection and can actually nullify it if the test objects are of low magnetic retentivity.

Sample test objects are available to teach, as well as test, application technique. They feature a very low retentivity iron test object containing a discontinuity. If the sequencing of bath application and magnetization is not correct, the discontinuity is not indicated.

Automatic rather than manual bath application is preferred for multidirectional magnetization. Precise timing and sequencing are very important in this application, where the test object is exposed to various magnetic orientations to locate discontinuities positioned in various orientations throughout the object.

Because an object can retain only one magnetic field at a time, the fields are rapidly switched. The discontinuities indicated by the final field orientation are effectively located by a brief continuous technique. Discontinuities magnetized by earlier fields in the rapid sequence are subject to erasure if the bath flow is too rapid. This also explains why test objects with some surface roughness (13 root mean square or rougher) are better candidates for multidirectional testing than those with very smooth surfaces. By increasing friction, rougher surfaces not only slow the bath flow and drainage but also retain indications.

Means of Applying Wet Magnetic Particles

In on-site testing using portable or movable power supplies, wet magnetic particles are typically applied in a spray, with no provision for collecting or recovering excess bath. This technique avoids bath contamination from particulates present on the test object. Often, the continuous magnetization technique is used in this test, with the magnetizing current deliberately kept on throughout bath application.

Several means of spraying are available: aerosol cans, prepressurized spray guns and spray guns supplied from a separate container (a drum of bath or a pressurized spray pot).

Each of these devices has its own advantages and disadvantages. Aerosol cans free the testing process from the need for separate pressurized air, but the cans must be frequently shaken to keep the bath suspended. Prepressurized spray guns cost less than bath in aerosol cans but require pressurized air or carbon dioxide cartridges and must still be constantly agitated and therefore

continually shaken. Prepressurized guns are also much heavier than aerosol cans and handling can be strenuous. Spray guns supplied from separate containers often have recirculating systems immersed in the bath. These automatically keep the bath agitated and are quite effective where electrical power is available. Pressurized spray pots can be equipped to supply constant agitation and are handy where pressurized air is available.

Wet Magnetic Particles for Special Applications

Wet technique fluorescent particles can be used for nondestructive testing of underwater structures such as drilling or production platforms. Test procedures parallel those used on dry land plus some added complications.

First there are the personnel hazards: (1) exposing inspectors to deep underwater conditions for long periods and (2) the electrically conductive environment demands perfect insulation to avoid electrocution. Besides the safety aspects, the magnetic particle test procedure is itself complicated. Often the tests are performed in murky surroundings with poor visibility where currents can carry particles away from the test surface. Before testing can begin, the structure must be cleared of all sediment and other marine fouling.

The magnetic particle materials are usually special fluorescent powders that mix equally well with fresh water or sea water. The particle suspension is taken to the test site in a plastic bottle where it is applied near the magnetizing yoke commonly used for underwater tests. The particles are in concentrated aqueous slurry immediately diluted to normal particle concentrations by the surrounding water.

In another special application, thick, concentrated slurries of paramagnetic flakes in a viscous liquid are occasionally used to locate surface cracks. These reflective particles do not migrate to leakage fields but rotate in place to line up with the fields.

The inspector brushes the slurry onto the surface, producing a shiny film that stays in place and does not run or drip off. Where a leakage field exits, the particles present their dull edges to the surface, delineating cracks with dark lines on the otherwise bright surface. After this technique, cleanup is tedious.

Temperature Limits

Water Vehicles

Wet technique testing is susceptible to temperature limits that do not affect dry particle testing. Water baths change little in viscosity between the freezing and boiling points of water but do freeze on test surfaces colder than 0 °C (32 °F). Near subfreezing temperatures, water does not freeze instantly and magnetic particle indications have time to form before the water bath solidifies.

At lower temperatures, antifreeze must be added to keep the bath liquid. Antifreeze is useful only in those applications where high sensitivity is not desired, such as the testing of steel billets. Solutions of water and either ethylene glycol or methyl alcohol rapidly become far too viscous below freezing and drastically retard the formation of discontinuity indications.

The upper temperature limit of the test object in water baths has not been established as of 2007. At 100 °C (212 °F), water evaporates too quickly for indications to form and this can happen at somewhat lower temperatures as well.

Oil Vehicles

Oil baths, though still liquid below –18 °C (0 °F), increase noticeably in viscosity as the test piece or bath temperature decreases. Type I baths (defined in SAE AMS 2641) have a viscosity around 2.4 $mm^2 \cdot s^{-1}$ (2.4 cSt) at 38 °C (100 °F) and reach the 5 $mm^2 \cdot s^{-1}$ (5 cSt) limit at about 10 °C. (50 °F). Type II baths (also in SAE AMS 2641) have a viscosity around 2.7 $mm^2 \cdot s^{-1}$ (2.7 cSt) at 38 °C (100 °F) and reach the 5 $mm^2 \cdot s^{-1}$ (5 cSt) limit at approximately 13 °C (55 °F). These figures may vary with the source or manufacturer of the oil vehicle.[26]

The upper limit of practical temperature for oil baths is influenced more by health considerations than by fire hazards. When an oil bath is heated to its flash point (either in bulk or by contacting a test surface at this temperature), air in the immediate vicinity contains nearly 1 percent oil vapor by mass. The vapor condenses to a fine oily mist as the vapor cloud cools. A vapor or mist concentration at the 1 percent level is 100 times more than OSHA's permissible exposure limit of 100 $\mu L \cdot L^{-1}$.[3] This level can be considered hazardous. For health reasons, an oil bath should be used at maximum temperatures far below the flash point. Excellent ventilation is required for any use of an oil bath above 43 °C (110 °F).

Viewing Wet Technique Indications

Visible Lighting Specifications

Visible wet technique magnetic particle testing is subject to the same lighting requirements as dry particle testing in ASTM E 1444.[4] The minimum requirement is 1000 lx (100 ftc) at the testing surface.

Because the nonfluorescent particles are often used on fairly bright, reflective surfaces, glare can reduce contrast on dark surfaces. Lowering the light intensity, when not prohibited by specifications, can decrease glare but requires careful evaluation of the test results. Where specular reflection of the light source is not a problem for inspectors, the specification requirements should be followed in all cases.

Fluorescent Lighting Specifications

For fluorescent wet technique testing, ASTM E 1444[4] requires a minimum ultraviolet radiation intensity of 1000 $\mu W \cdot cm^{-2}$ at the test surface. Further, the maximum allowable visible light intensity at the surface is 20 lx (2 ftc) because visible light reflected from the test surface lowers the contrast of the fluorescent indications. Visible light intensity must be measured with the ultraviolet lamps switched on because ultraviolet radiation sources emit small amounts of visible light, primarily in the violet portions of the visible spectrum. This small amount of visible light, added to the ambient visible light already in the testing booth, can help lower a fluorescent indication's contrast.

The reliability of testing increases dramatically as the ultraviolet radiation intensity increases.[34] The probability of detection of 97 discontinuities on 37 test pieces has been shown to rise from 34 percent at 1000 $\mu W \cdot mm^{-2}$ to 100 percent at 4000 $\mu W \cdot cm^{-2}$.

PART 4. Magnetic Particle Sensitivity

The data below were compiled from application studies of magnetic particle process sensitivities. Discontinuity sizes were usually not known by the investigators. In five instances, the test objects were closely examined, sometimes with destructive techniques, to determine exactly what the magnetic particle technique was detecting.

Studies to Determine Wet Technique Particle Sensitivity

Discontinuity Size Limits for Carburized Steel

Case hardened (carburized) steel pins of unspecified size were tested with wet technique magnetic particles, both visible and fluorescent.[37] A direct current coil was used and crack depths were not measured. Some indications of fine transverse cracks were found.

Microscopic visual tests of the smooth test object surface showed crack widths ranging from 0.25 to 2.3 µm (1×10^{-5} to 9×10^{-5} in.). Such crack widths are typical of a surface under high compressive stress.

This range of widths could be considered the narrowest detectable discontinuity for a direct current test, which produces a magnetic field largely contained within the higher permeability core of this test object. An alternating current technique concentrates the magnetic field at the surface, possibly altering the detectable discontinuity size limit.

Discontinuity Size Limits for Nitrided Steel

Nitrided steel bushings of unspecified size were magnetic particle tested at 1 kA for grinding cracks.[1,37] The bushings had been nitrided to an average depth of 0.15 mm (0.006 in.).

The magnetic particle discontinuity sites were metallurgically examined and showed grinding cracks from 13 to 65 µm (0.0005 to 0.0025 in.) deep. Some quench cracks with depths from 0.05 to 0.13 mm (0.002 to 0.005 in.) were also detected with magnetic particle techniques. All cracking was normal to the surface.

Correlation of Discontinuity Size with Other Parameters

Several 20 mm (0.8 in.) high explosive projectiles were tested with fluorescent magnetic particles. The tests used direct current, a central conductor and a head shot, with current passing lengthwise through the projectiles. Though not a common application, two test reports present documented correlations of discontinuity size, location, magnetizing current and indication quality. The reports' original drawings are reproduced in Figs. 2 to 11.[1,38]

Correlation of Discontinuity Indication Brightness

A study of indication brightness versus seam depth was made on two 60 mm (2.4 in.) square steel billets. Ultraviolet photographs were taken at the ends of six billets at two continuous current settings and one residual current level.

Figures 12 to 18 show the brightness of magnetic particle indications for the various discontinuity depths. Although some clarity is lost in the reproduction process, the original photographs indicate a direct relationship between increased crack depth and increased indication brightness.[1,39]

Discontinuity Size Limits in Steel Billets

During processing, certain steel billets are heated to a temperature where the outer 0.4 mm (0.015 in.) oxidizes to form scale. Magnetic particle tests of such billets are concerned only with cracks likely to remain after scale removal. The goal of the study below was to lower the sensitivity of the testing technique to avoid detection of fine temporary cracks.

Test indications were established using a special low sensitivity fluorescent wet technique particle. These coarse particles had diameters from 25 to 50 µm (0.001 to 0.002 in.). Test indications were compared to those for commercial powders with diameters of 3 to 5 µm (0.0001 to 0.0002 in.). Figure 19 shows the test indications from standard sized particles. Figure 20 shows the results of tests with the coarse particles. The larger particles did exhibit depth discrimination, scarcely

indicating fine cracks. Crack depth was verified by grinding.

The low sensitivity particles indicated discontinuities with depths of 0.37 to 0.8 mm (0.015 to 0.033 in.) but did not consistently detect shallower cracks. By this criterion, surface discontinuities less than 0.37 mm (0.015 in.) in depth may be called fine cracks. Those deeper than 0.8 mm (0.033 in.) may be considered coarse cracks.

Dry Powder Sensitivity

Little information exists on the surface discontinuity sensitivity limits for dry magnetic particles. However, a typically sensitive dry powder contains by weight about 35 percent coarse particles, in the 25 to 50 µm (0.001 to 0.002 in.) diameter range. It is likely that this portion of the dry powder conglomerate has roughly the same sensitivity as the similarly sized coarse wet particles cited above.

Effect of Discontinuity Depth on Tangential Field Component

In a particle sensitivity study, measurements were recorded for the leakage fields emanating from a series of five milled slots. The slots were milled lengthwise down the center of one face of an 82 mm (3.25 in.) square steel billet.

Three of the slots were a constant 0.12 mm (0.07 in.) width, with depths of 0.38, 0.75 and 1.25 mm (0.015, 0.03 and 0.05 in.). The two other slots were a constant 0.75 mm (0.03 in.) depth with widths of 0.4 and 0.5 mm (0.016 and 0.021 in.). All measurements were made at a magnetizing current of 500 A using full-wave rectified direct current.

The tangential component of the leakage field H_t was measured with a meter operating in the differential mode. Errors in probe position were no greater than 0.5 mm (0.02 in.). Field intensity readings were estimated to be accurate to 40 $A \cdot m^{-1}$ (0.5 Oe). The results of this study are summarized in Table 1.

Note that H_t increases with the slot depth. The tangential component also increases with slot width, though possibly not in direct proportion. These slots are not particularly fine cracks but do indicate a downward trend of H_t for decreasing slot size. At distances beyond 0.5 mm (0.02 in.) from the slot center line, there is no reading for the tangential component.

Closing

The magnetic particle testing technique is extensively used in virtually all of the world's major industries — its successful application on any ferromagnetic material has ensured its position among the most valuable nondestructive testing techniques. Because it is so widely used, so simple to apply and so familiar, the complexity of magnetic particle testing is often underestimated.

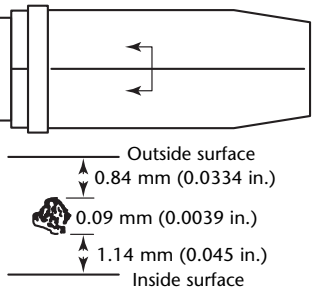
The technique is, in fact, founded on the complicated interactions of several electromagnetic fields and at least two separate materials for every test. The particles are magnetic field sensors and, as with any critical testing component, need to be fully understood for efficient and accurate use.

TABLE 1. Tangential magnetic field component at center line of milled reference slots.

Depth		Width		Liftoff		Magnetic Field Intensity (H_t)	
mm	(in.)	mm	(in.)	mm	(in.)	$A \cdot m^{-1}$	(Oe)
0.38	(0.015)	0.18	(0.007)	0		190	(2.4)
0.38	(0.015)	0.18	(0.007)	0.5	(0.02)	111	(1.4)
0.38	(0.015)	0.18	(0.007)	1.0	(0.04)	80	(1.0)
0.38	(0.015)	0.18	(0.007)	1.5	(0.06)	48	(0.6)
0.75	(0.03)	0.18	(0.007)	0		549	(6.9)
0.75	(0.03)	0.18	(0.007)	0.5	(0.02)	334	(4.2)
0.75	(0.03)	0.18	(0.007)	1.0	(0.04)	223	(2.8)
0.75	(0.03)	0.4	(0.016)	0		573	(7.2)
0.75	(0.03)	0.4	(0.016)	0.5	(0.02)	374	(4.7)
0.75	(0.03)	0.4	(0.016)	1.0	(0.04)	255	(3.2)
0.75	(0.03)	0.5	(0.021)	0		653	(8.2)
0.75	(0.03)	0.5	(0.021)	0.5	(0.02)	390	(4.9)
0.75	(0.03)	0.5	(0.021)	1.0	(0.04)	255	(3.2)
1.40	(0.057)	0.18	(0.007)	0		1274	(16.0)
1.40	(0.057)	0.18	(0.007)	0.5	(0.02)	892	(11.2)
1.40	(0.057)	0.18	(0.007)	1.0	(0.04)	573	(7.2)

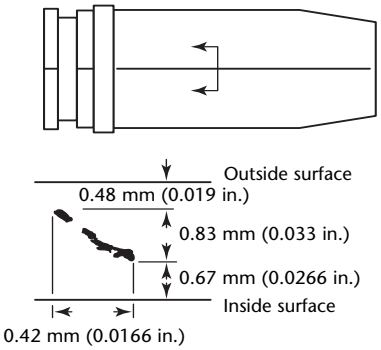
FIGURE 2. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.

(a)



Head	Central conductor
I_T = 1300 A	I_T = 1000 A
I_G = 1700 A	I_G = 1500 A
$I_{R:1000}$ = none	$I_{R:1000}$ = none

(b)



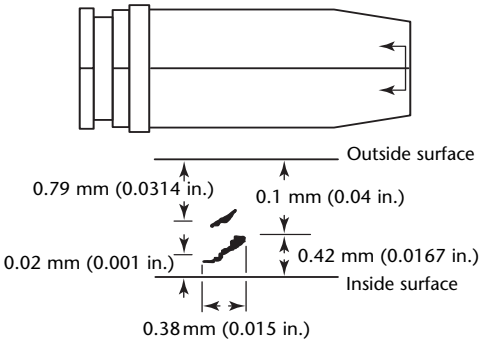
Head	Central conductor
I_T = 500 A	I_T = 200 A
I_G = 800 A	I_G = 400 A
$I_{R:1000}$ = none	$I_{R:1000}$ = none

Legend

I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

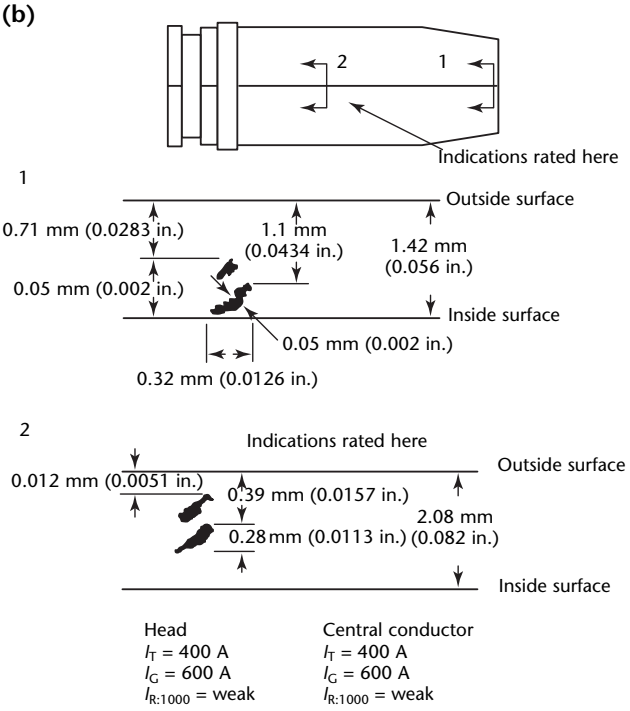
FIGURE 3. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.

(a)



Head	Central conductor
I_T = 300 A	I_T = 300 A
I_G = 500 A	I_G = 500 A
$I_{R:1000}$ = none	$I_{R:1000}$ = none

(b)

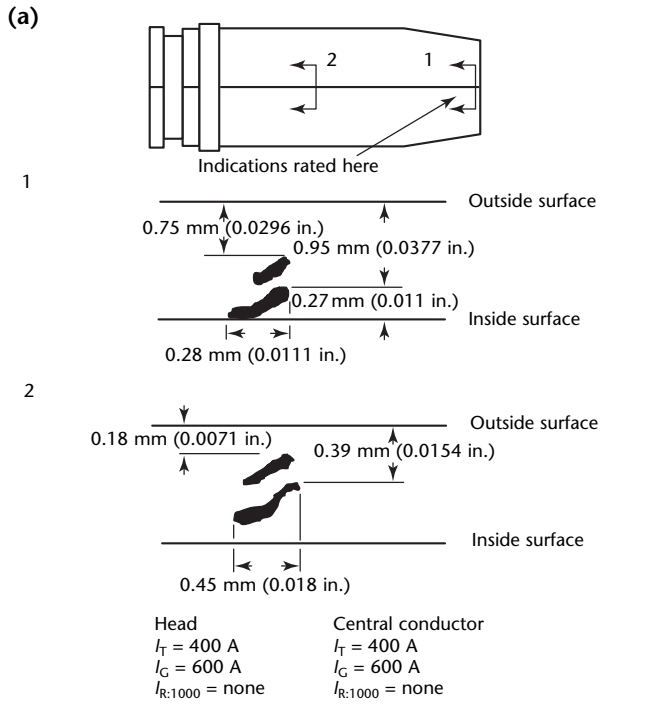


Head	Central conductor
I_T = 400 A	I_T = 400 A
I_G = 600 A	I_G = 600 A
$I_{R:1000}$ = weak	$I_{R:1000}$ = weak

Legend

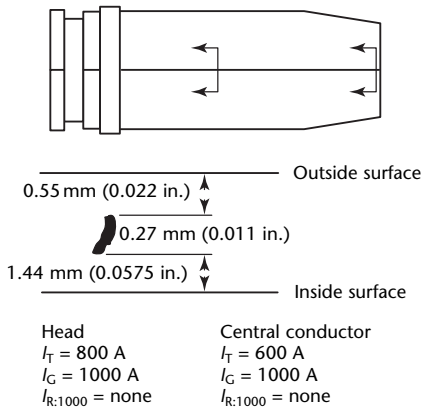
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 4. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings (a) first casing and test setup; (b) second casing and different setup.



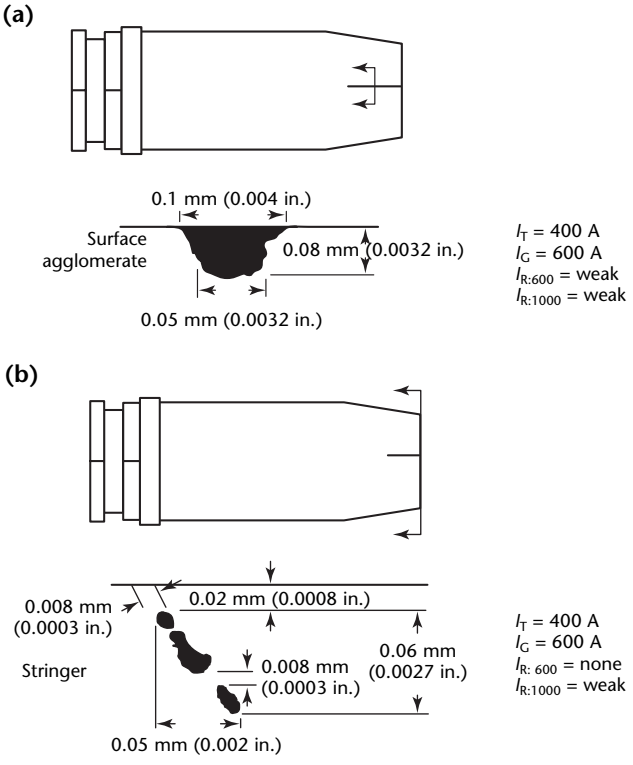
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 5. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casing.



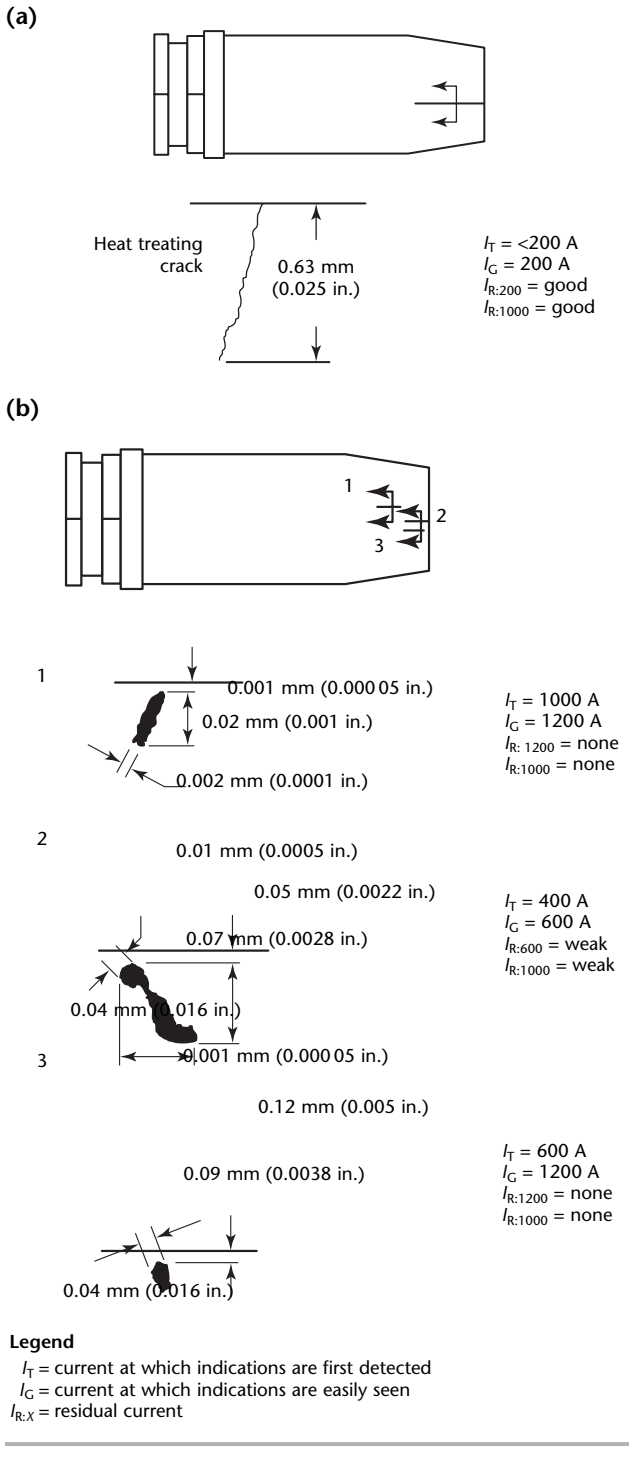
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 6. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



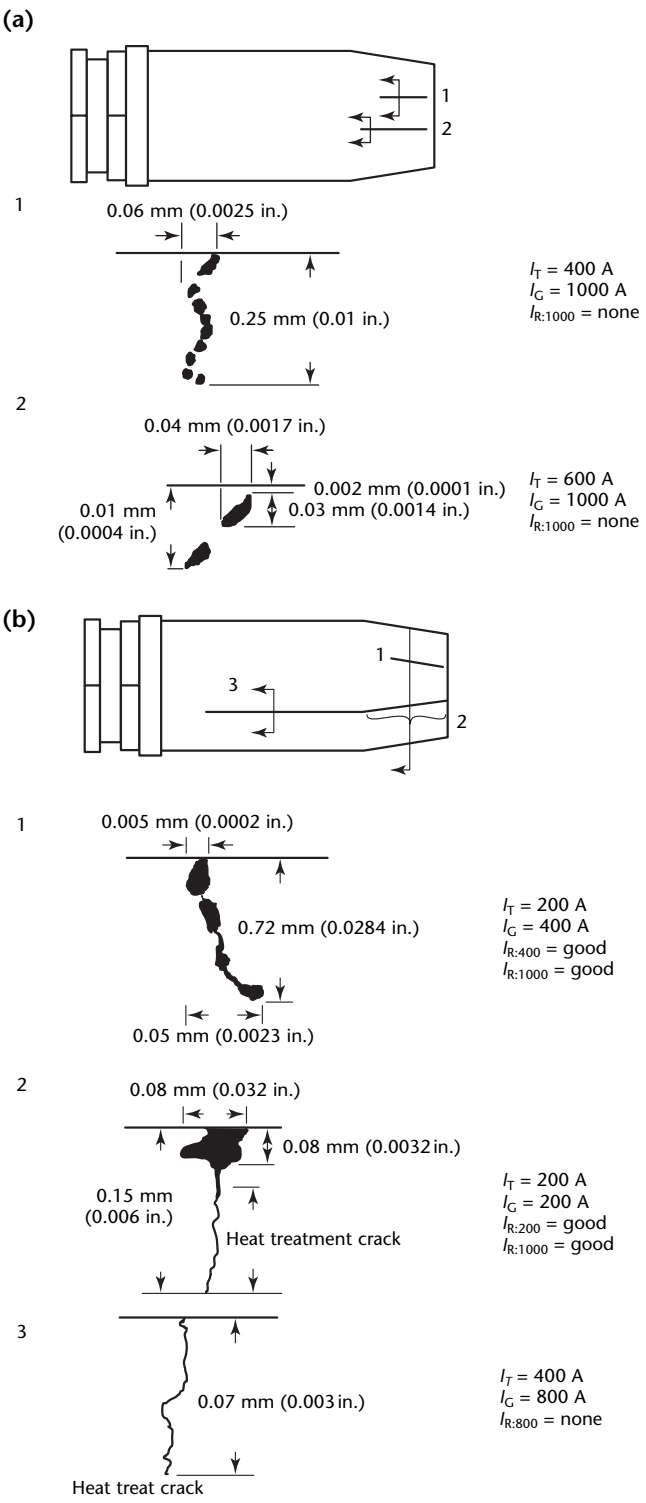
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 7. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



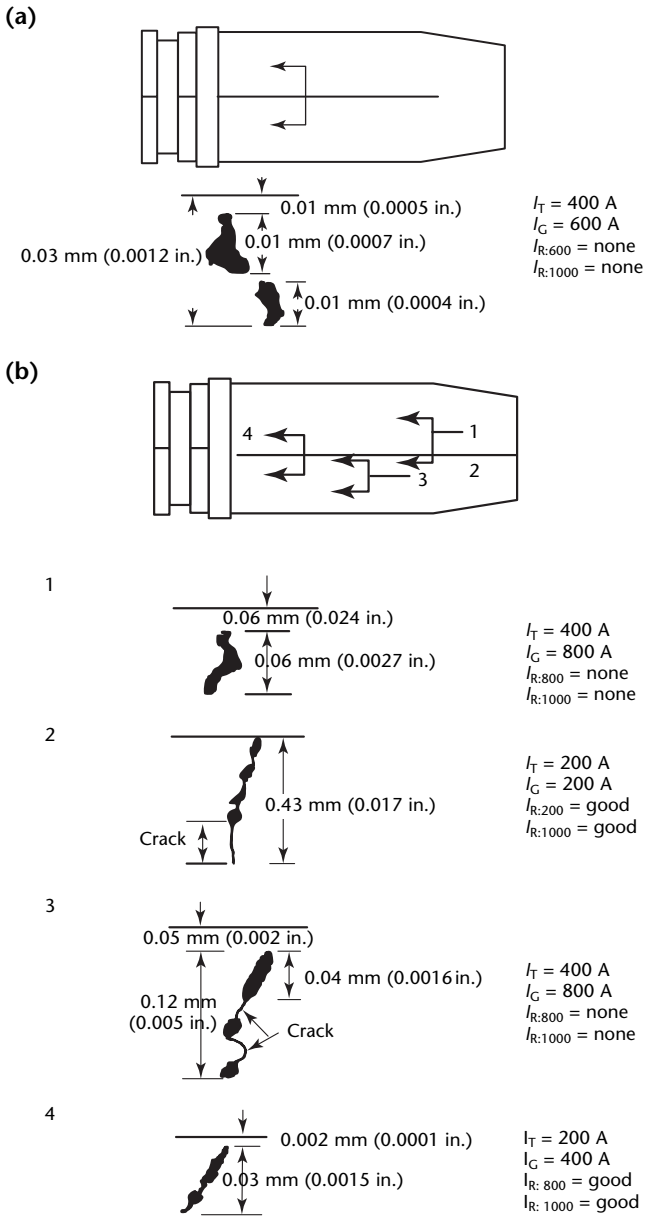
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 8. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



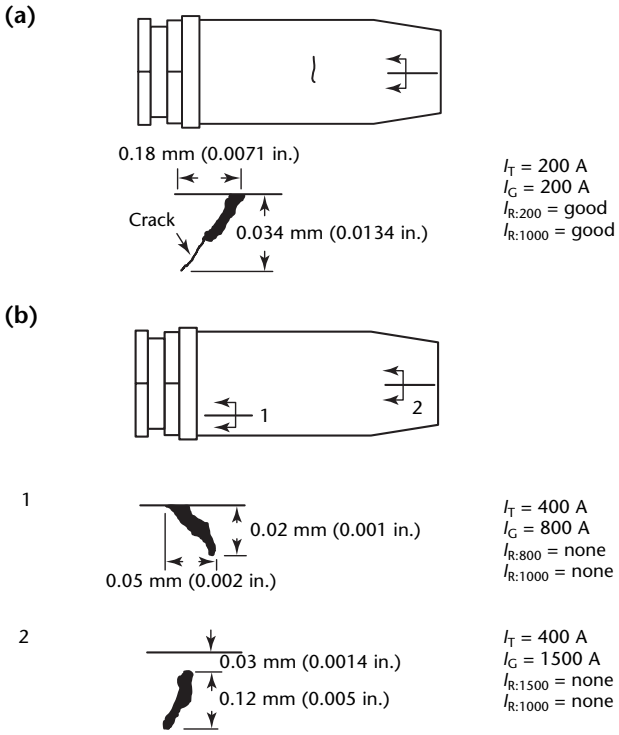
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 9. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



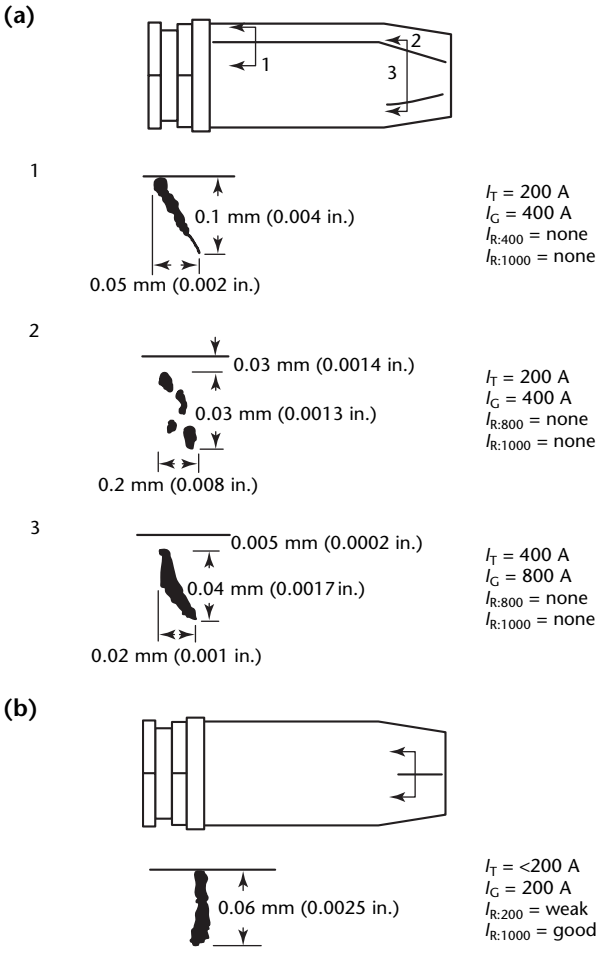
Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

FIGURE 10. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



Legend
I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

Figure 11. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings: (a) first casing and test setup; (b) second casing and different setup.



Legend

I_T = current at which indications are first detected
I_G = current at which indications are easily seen
$I_{R:X}$ = residual current

Figure 12. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

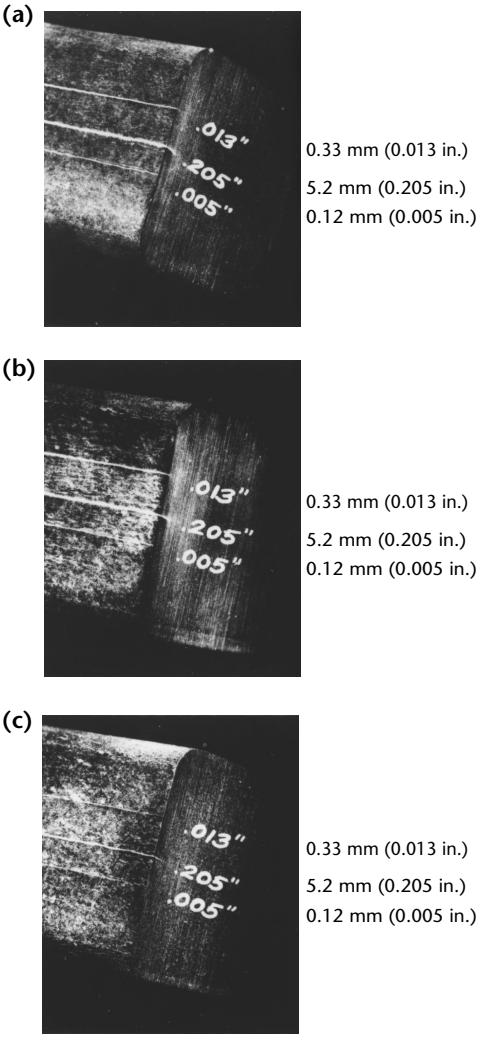


FIGURE 13. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

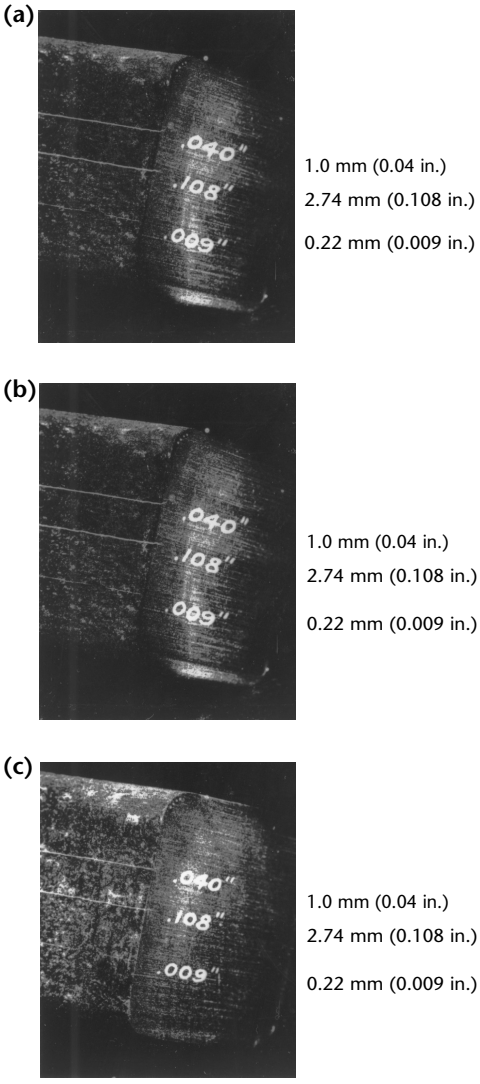


FIGURE 14. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

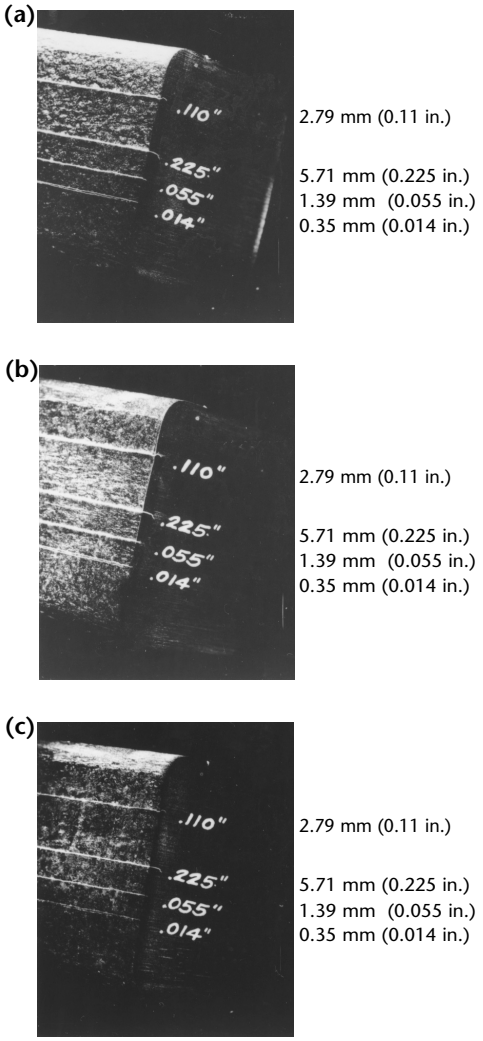


FIGURE 15. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

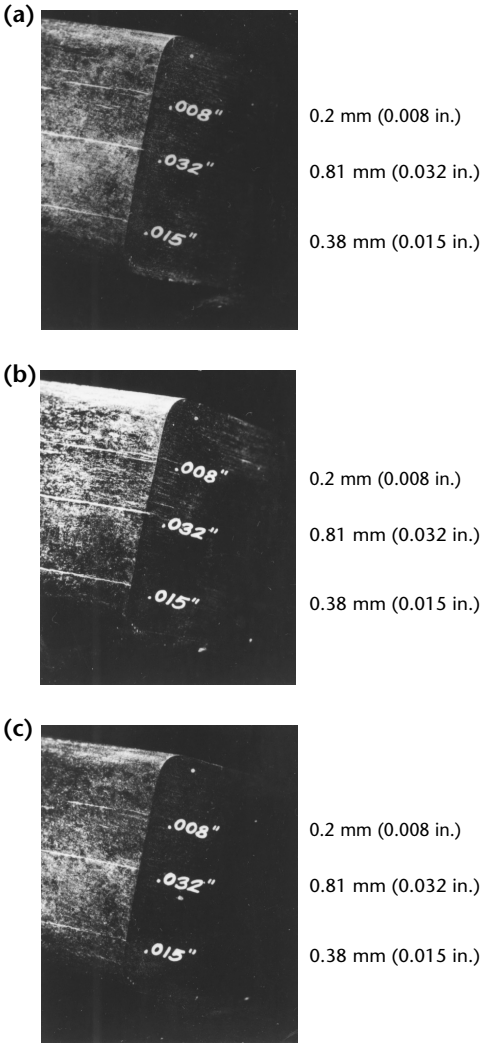


FIGURE 16. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

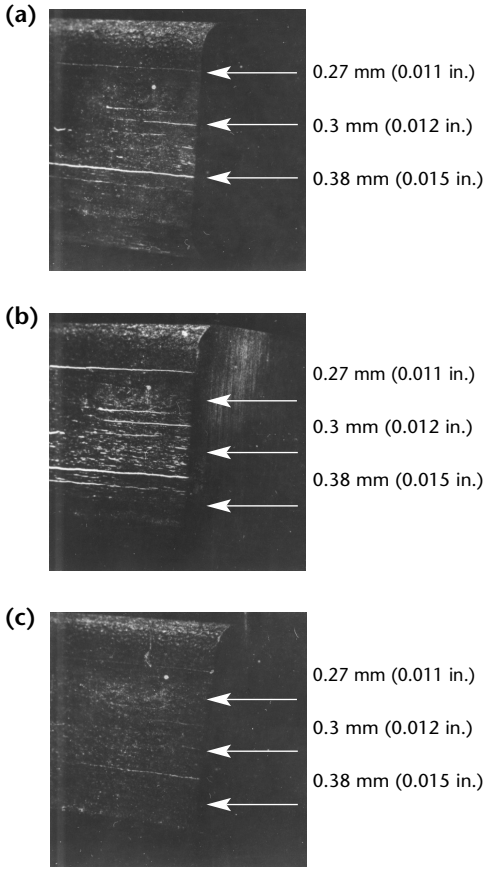


FIGURE 17. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

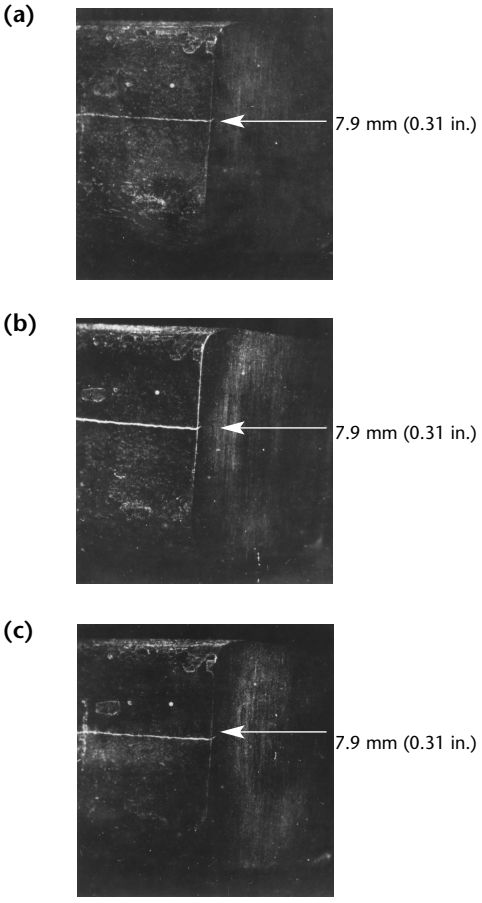


FIGURE 18. Ultraviolet photographs taken at ends of square steel billet for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; (c) residual direct current at 200 A.

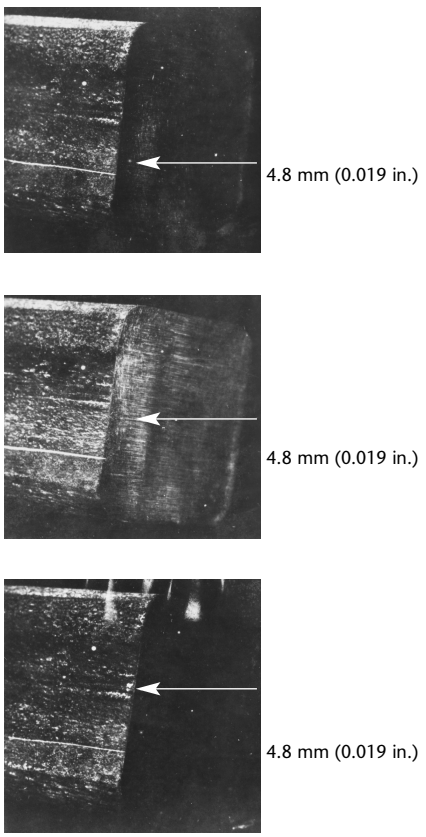


FIGURE 19. Standard sized fluorescent magnetic particles with bath concentrations at 1.25 g·L^{-1} used to test a 64 mm (2.5 in.) square steel billet at: (a) 300 A full-wave direct current; (b) 600 A full-wave direct current; (c) 1050 A full-wave direct current.

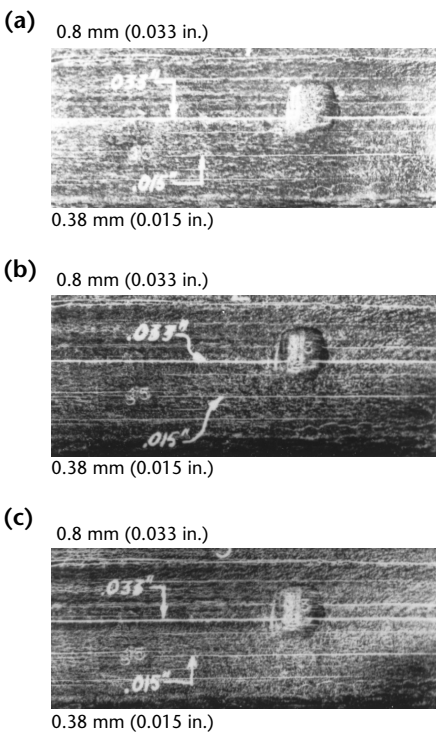
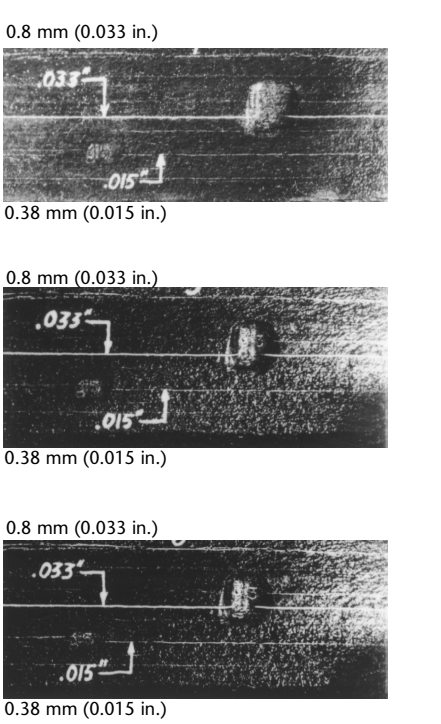


FIGURE 20. Coarse, large sized fluorescent magnetic particles with bath concentrations at 1.25 g·L^{-1} used to test a 64 mm (2.5 in.) square steel billet at: (a) 300 A full-wave direct current; (b) 600 A full-wave direct current; (c) 1050 A full-wave direct current.



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CHAPTER 8

Viewing of Magnetic Particle Tests

Charles H. Mazel, BlueLine NDT, Bedford, Massachusetts (Parts 1 and 4 to 7)

Henry J. Ridder, Atascadero, California (Parts 1 to 3)

J. Thomas Schmidt, Crystal Lake, Illinois (Parts 1 to 3)

PART 1. Detection of Magnetic Particle Indications[1]

Magnetic particle discontinuity indications on the surface of a test object serve no purpose until they are detected and interpreted. Until the early 1950s, all indications were detected by the eyes of the human inspector. In some cases, indications were recorded by photography, but no other mechanical or electronic detection systems existed.

Today, electrooptical devices can be used to detect indications and computers are then used to interpret the detected signals. Because these devices are costly and inflexible, their use is limited to high volume applications where speed and reproducibility justify cost. Nearly all magnetic particle tests still base their procedures on the human eye as a detector. To obtain the highly sensitive results the method is capable of, it is necessary to understand the operation and limitations of the eye.

Because all test results do not automatically indicate a rejectable discontinuity, it is also necessary to understand test indication interpretation. Some magnetic particle indications are relevant, others are not, and still others are false indications.

Light and Vision[2]

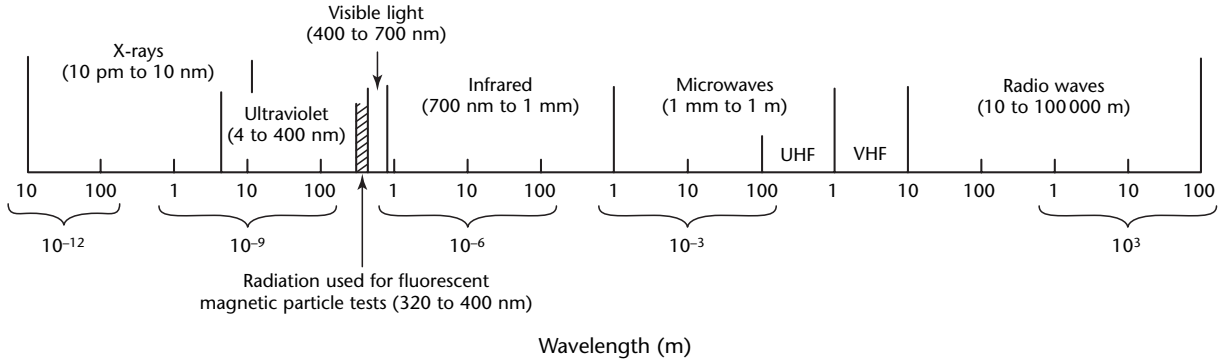
The kinds of electromagnetic radiation include X-rays, radio waves, ultraviolet radiation and thermal waves (Fig. 1). Each kind differs from the others in its wavelength or frequency. Light is also electromagnetic radiation but differs from other kinds in that radiation in its frequency band can be sensed by the human eye. Eyes can also distinguish colors — different frequency bands within the spectrum of visible light (Fig. 2).

Measurement Units for Magnetic Particle Testing

Light is measured in either radiometric or photometric units. Radiometric units are used where the energy levels of electromagnetic radiation are of interest, independent of human eyesight. Power is expressed in watts (W); in irradiance, (power per unit area) in watts per meter squared ($W \cdot m^{-2}$) or in microwatts per square centimeter ($\mu W \cdot cm^{-2}$) where $1\ W \cdot m^{-2} = 100\ \mu W \cdot cm^{-2}$. These units are frequently encountered when talking about the outputs of ultraviolet or other radiation sources that excite fluorescence.

Photometric units take into account the properties of human vision. They are needed because the eye is not equally sensitive to all wavelengths of light. Two light sources could have the same radiometric intensities but very different photometric intensities depending on their spectral properties. Photometric power is expressed in lumens (lm). Power per unit area, also called *illuminance*, is expressed in lumens per meter squared ($lm \cdot m^{-2}$), lux (lx) or footcandles (ftc) where $1\ lm \cdot m^{-2} = 1$ lx and 1 ftc = 10.76 lx. For convenience, a factor of 10 is used to relate footcandles and lux so that 1 ftc ≅ 10 lx. These units are frequently encountered in discussion of the required illumination level for visible light inspection or the allowable background

FIGURE 1. Electromagnetic spectrum, showing range of ultraviolet radiation used for fluorescent magnetic particle testing.



light for fluorescence inspection. Luminous intensity is the power per unit solid angle (as opposed to per unit area) and is expressed in lumens per steradian ($lm \cdot sr^{-1}$) or candela (cd), where $1\,lm \cdot sr^{-1} = 1$ cd. Another unit sometimes encountered is the luminous intensity per unit area, also called luminance, measured in lumens per steradian per meter squared ($lm \cdot sr^{-1} \cdot m^{-2}$) or candela per meter squared ($cd \cdot m^{-2}$). Lighting conditions were formerly described also in footlamberts (ftl), where 1 ftl = 3.426 $cd \cdot m^{-2}$.

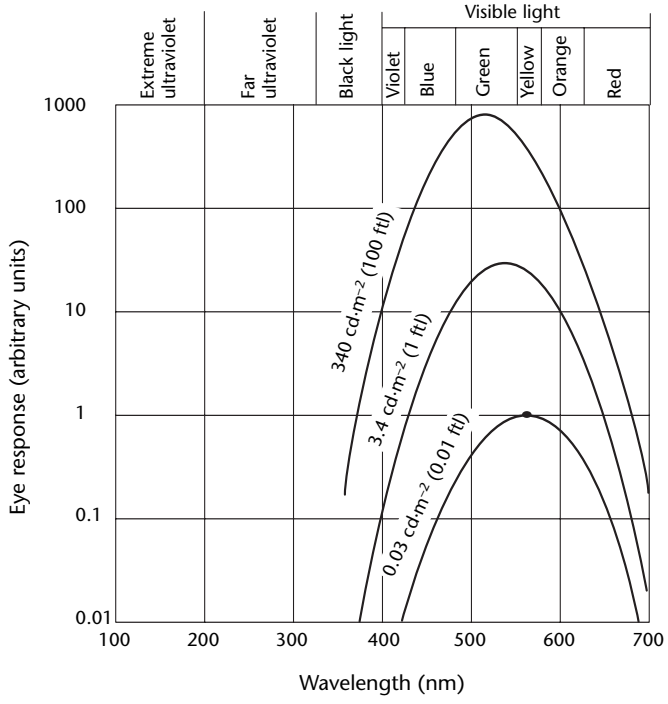
The troland is a unit used in ophthalmology to measure retinal luminance. Not a genuine measurement unit, it is a logarithmic expression of a physical quantity and is a product of brightness times pupil area.

Sensitivity of Eye

Vision acuity is the eye's relative ability to resolve detail. As shown in Fig. 3, vision acuity drops as the illumination (brightness) decreases. Light is detected in the retina by two types of photoreceptors, *rods* and *cones*.

The rods are more sensitive to light than the cones are but are insensitive to color. The cones provide the eye's color sensitivity. As brightness diminishes, the iris of the eye opens wider and the rods become preferential detectors because of their sensitivity to low light.

FIGURE 2. Average human eye response to various wavelengths at different light levels.



There are three varieties of spectral sensitivity in the cones, broadly characterized as red, green and blue, although they are relatively broad and overlapping. Different wavelengths of light will stimulate the three types of cones to varying degrees, producing the sensations of color. Vision at light levels at which the cones dominate is called *photopic vision*. As brightness diminishes, the iris of the eye opens wider and the rods become the preferential detectors because of their low light sensitivity. This is called *scotopic vision* and occurs under conditions of dark adaptation (3×10^{-5} $cd \cdot m^{-2}$). At low levels of illumination the eye is color blind because the rods are not color sensitive.

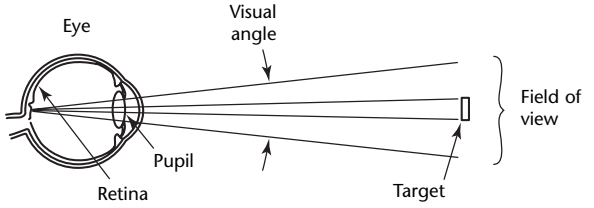
Color blindness is due to partial or complete loss of function of one or more of the three types of cone. This dysfunction can result in an inability to distinguish colors, and the exact nature of the problem will depend on which cone types are impaired. Color blindness can have significant impact on the ability to perform inspections.

The sensitivity of the eye to different wavelengths of light changes with the light level. Under photopic conditions, the maximum sensitivity is at about 555 nm whereas under scotopic conditions it is at about 510 nm. The human eye is relatively unresponsive to radiation at wavelengths shorter than 400 nm (Fig. 1). However, in the absence of longer wavelengths, the sensitivity of the eye to shorter wavelengths greatly increases.

Figure 2 shows the response of the average human eye under various lighting levels. The highest luminance level shown is 340 $cd \cdot m^{-2}$ (100 ftl) — a normal, brightly lit room.

The second light level, at 3.4 $cd \cdot m^{-2}$ (1 ftl), is about the average found in a darkened testing booth. Total darkness is never achieved in a typical testing booth, for the following reasons: (1) near ultraviolet sources also produce some blue and violet visible light and (2) most testing booths contain some sources of

FIGURE 3. Visibility of object is function of illumination, of image characteristics such as hue and of target's apparent size. Apparent size in monocular vision is measured as degree of visual angle.



fluorescence, often the inspector's clothing. At the 3.4 cd·m^{-2} ambient light level, the eye becomes sensitive to radiation in the 380 to 400 nm range. This is almost thirty times higher than the sensitivity in bright light conditions. The 380 to 400 nm radiation causes a deep blue visual sensation in the eye, plus greatly increased sensitivity in the blue region to the 405 nm spectral line of mercury vapor lamps. This does have the advantage of allowing the dark adapted inspector to move around the booth safely, accurately locating objects in the testing area.

The top response curve in Fig. 2 is the 0.03 cd·m^{-2} (0.01 ftl) level. Almost total darkness, this level is seldom encountered in magnetic particle testing. Under these conditions, the eye is over 800 times more sensitive than at normal levels and can respond to wavelengths down to 350 nm, where the cornea and lens of the eye fluoresce. The eye also detects the presence of longer wavelength visible light more easily at low background levels.

Dark Adaptation

The eye adjusts to changing light intensity by varying the size of the pupil and by changing the retinal sensitivity. This is an autonomic or reflex action in normal vision, but full adjustment to low level light does not occur instantly. The change from bright, visible light to the darkened environment needed for reliable fluorescent testing normally requires at least 300 s (5 min) for an average, healthy inspector.

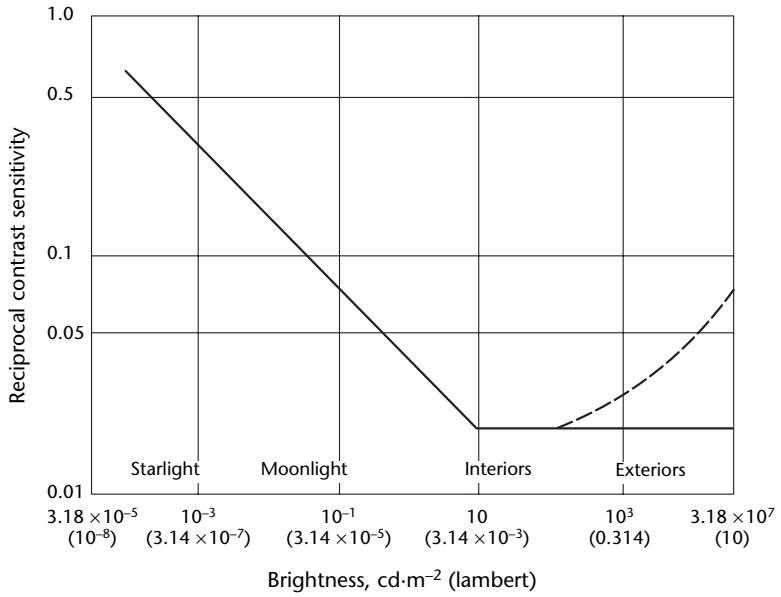
The time required for dark adaptation generally increases with increasing age of the inspector. Dark adaptation is not easily retained — there is a decided physiological safety advantage to having pupils that quickly adjust to bright light. Even very brief visible light exposure requires complete subsequent dark adaptation.

The brightness of the area surrounding the target of vision also affects visual acuity. Reducing the contrast of the background area reduces vision acuity (Fig. 4). Normally, vision acuity is determined for visible light illumination. Vision acuity for monochromatic light is higher for the yellow and yellow green wavelengths.

When light levels are reduced, the pupil of the eye expands in diameter to allow more light to enter and the retina of the eye becomes more sensitive. Further dark adaptation occurs below 0.002 cd·m^{-2} as the eye switches from cone (photopic) vision to rod (scotopic) vision. Figure 5 shows the variation in brightness discrimination that occurs with dark adaptation.

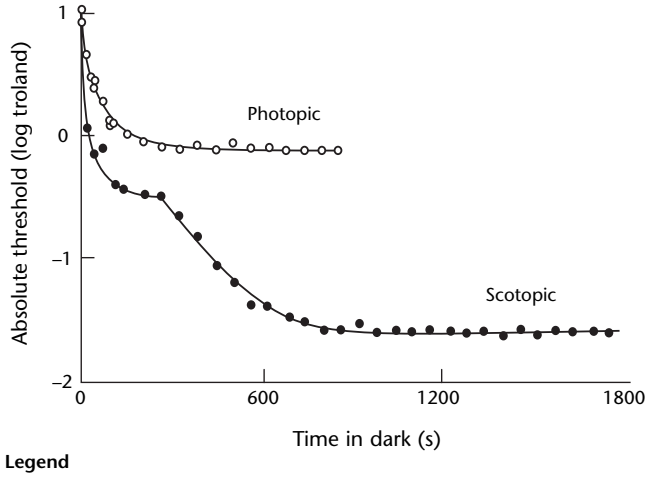
The change in perception by the human eye for varying conditions of illumination is shown schematically in Fig. 6. During dark adaptation, the eye is changing and cannot perform at maximum sensitivity in either vision condition. The time required for dark adaptation before testing varies with the individual and depends on the overall health and age of the inspector. A dark

FIGURE 4. Contrast sensitivity of human eye as function of field brightness. Dashed curve indicates contrast sensitivity for dark field.



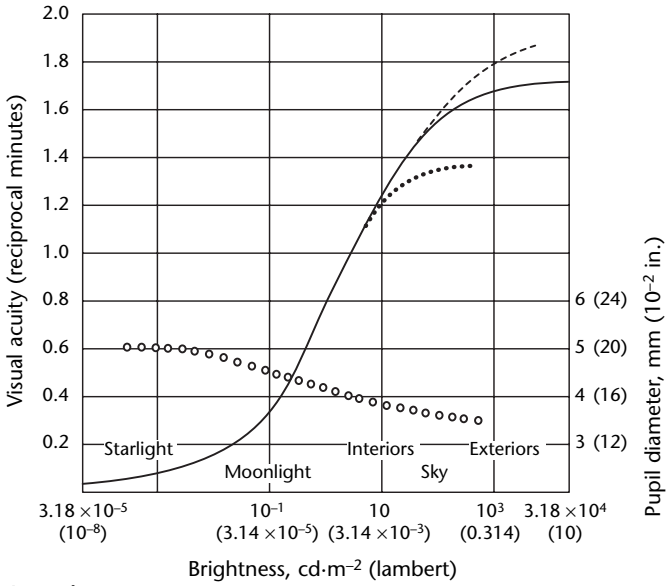
adaptation time of 300 s (5 min) is typically required for fluorescent magnetic particle testing with ultraviolet irradiation. Complete dark adaptation may take as long as 1200 s (20 min). Some specifications have required only 60 s (1 min) of dark adaptation before performing fluorescent magnetic particle tests.

FIGURE 5. Dark adaptation curves measured with 25 mm (1 in.) test stimulus after subject is preadapted for 5 min.



Legend
o—o—o = photopic preadapted to 6760 troland
●—●—● = scotopic preadapted to 389 troland

FIGURE 6. Visual acuity as function of object brightness.



Legend
——————— = acuity as function of object brightness
– – – – – – – – – – – – = acuity with increased background brightness
••••••••••••••••• = acuity with decreased background brightness
oooooooooooooo = pupil diameter

Retinal illuminance T is difficult to quantify outside of an optics laboratory, but the quasiunit troland helps describe dark adaption (Figs. 5 and 6). Retinal illuminance T relative to brightness is measured in trolands (Td):

$$\textbf{(1)} \quad T = L \times a$$

where L is photopic luminance (cd·m^{-2}) and a is pupil area (mm^2).[3] Because trolands are incremented geometrically, their measurement is expressed logarithmically.

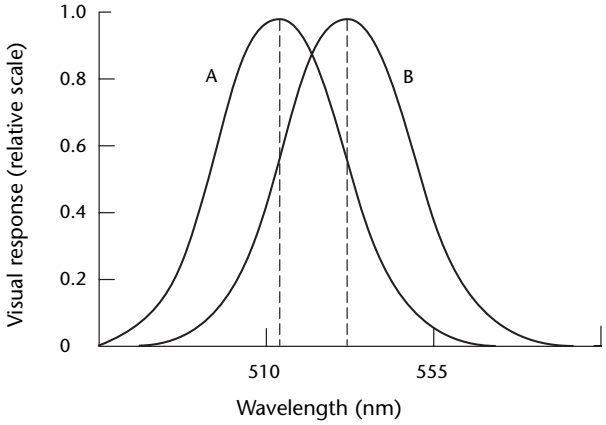
The maximum sensitivity of the eye shifts in wavelength during dark adaptation. Figure 7 shows the sensitivity of the eye as a function of light wavelength for normal levels of illumination and also for the dark adapted eye. As dark adaptation progresses, the peak sensitivity of the eye shifts toward the blue end of the visible spectrum with reduced sensitivity in the red. This shift results from the different chromatic sensitivities of the rods and cones.

Contrast of Magnetic Particle Indications

Illumination and Fluorescence[2]

Two kinds of light create contrast in magnetic particle testing — illumination and fluorescence. For each approach, it is useful to think in terms of a system of components chosen to work together to produce the desired results. Three components are common to both approaches: (1) particles that produce

FIGURE 7. Relative luminous efficiency curves for human eye showing response as function of incident light wavelength.



Legend
A = photopic vision with adequate illumination
B = scotopic vision with dark adapted eye and low illumination

visual contrast against their background when illuminated properly; (2) a light source that produces the needed illumination; (3) a means, generally the human eye, of viewing the inspection surface.

For fluorescent inspection, there is always an additional component: a barrier filter that blocks the reflected radiation while transmitting the fluorescence. When using ultraviolet radiation, it is not necessary to use an external barrier filter because we have ultraviolet blocking material naturally in our eyes. It is desirable to wear ultraviolet blocking glasses anyway, because the eye has a natural fluorescence that can reduce viewing contrast slightly. If wavelengths other than ultraviolet are used to stimulate fluorescence, barrier filter glasses may be necessary to see indications.

For inspection visibility, it is often desirable to add contrast paint as another component. Contrast paint should be added if there is not sufficient contrast between the magnetic particles and the natural color of the part inspected.

Creating Contrast[1,2]

The intent of magnetic particle testing is to find indications, and the inspection is generally done by a human observer. The better the visual contrast between the indication and everything that is not an indication (the background), the more likely the indication will be seen. Providing appropriate illumination and viewing conditions ensures adequate contrast for proper inspections.

Test indications can be seen because they contrast with the background. All detection devices, including the eye, work by detecting this contrast. In electronics, contrast is called signal-to-noise ratio. If there is enough energy present to operate a detector, then the greater the contrast, the more reliable is its detection. Two types of contrast are important to magnetic particle tests: brightness contrast and color contrast.

Brightness Contrast[1]

Brightness contrast is the amount of light reflected by one surface compared to that reflected by another adjacent surface. High brightness materials transmit or reflect most of the light striking them, a characteristic related to surface texture. Magnetic particle indications can be high or low brightness, so long as the background is the opposite brightness.

In the visible light test systems, indications are typically low brightness and the backgrounds are high brightness. The background may reflect 15 to 75 percent of incident light. Test indications may reflect 3 to 8 percent of incident light. Dividing an average background reflection of 45 percent by an average indication reflection of 5 percent produces a contrast ratio of 9:1.

If this indication is large enough to be resolved, a 9:1 contrast ratio is easily seen by the human eye and most other detectors. Contrast ratios as low as 1.25:1 can be detected, although the ratio should be at least 2:1 to achieve reasonable probability of detection.

In visible light test systems, there is sometimes a correlation between brightness and color of the particles: low brightness particles are often dark colored and high brightness particles are light colored.

In fluorescent systems, the indication is bright, both because it emits large amounts of visible light and because ultraviolet radiation is not visible to the eye. This makes a nonfluorescent background appear low in brightness and the contrast ratio is accordingly high. In a fully darkened viewing area, the effective contrast ratio can be 200:1 or higher.

Color Contrast[1]

The visible portion of the electromagnetic spectrum (Fig. 1) includes wavelengths between 400 and 700 nm. If all wavelengths are present in equal amounts, the light is white. If no wavelengths are present, the eye sees black. Light from 450 to 480 nm is pure or saturated blue. Light from 550 to 600 nm is pure or saturated red. If both wavelengths are present, the color is perceived as purple.

Few visible light sources produce pure light of any color. Generally, the light is predominantly of one color but also contains some of all the other visible wavelengths. As the proportion of white light (all wavelengths) to colored light (a specific range of wavelengths) increases, the color becomes less saturated or more impure.

Color contrast can be defined as the difference between two colors of equal brightness and it therefore includes both color (wavelength) and saturation (percentage of a certain wavelength). At the same brightness, two impure colors have very little contrast, while one pure color and one impure color may contrast strongly.

Color contrast contributes a small percentage to total visibility or total detectability, with brightness contrast making up the primary contribution. A pure red indication is not highly visible against a pure blue background of equal purity and brightness. In fact, such a situation can decrease detectability because of eye strain (red and blue

wavelengths focus at different points in the eye). Issues related to color blindness or to black-and-white imaging also make brightness contrast more reliable than color contrast.

In nondestructive testing, the magnetic particle material usually has a relatively pure color whereas the background is typically as nearly white or nearly black as possible. The main importance of color to detectability is its difference from the background.

Detection Devices[1]

There are three types of detection devices for magnetic particle testing: the human eye, imaging detectors (cameras) and nonimaging detectors (scanners).

Scanning Detectors

Scanners are nonimaging detection systems. In their simplest form, they consist of a radiation source, a means of moving the test object, a detector and signal processing equipment. In use, the radiation source illuminates the test object surface and the detector measures the radiation reflected or emitted from it. The test object is moved past the detector at a uniform speed, distance and orientation. If the measured amount of light changes significantly, an indication is detected.

Usually, the light source is focused or collimated into a narrow beam that moves over the test surface. Because only a small area is illuminated, it is possible to exactly locate any detected indication. It is also possible to focus the detector on a small area although mechanical alignment is harder.

Scanners may be built for either the visible or fluorescent technique. With the visible technique, the radiation source can emit any wavelength the detector can see. Lasers are often used as light sources because they produce narrow, intense beams. With visible systems, typically the reflection is high from the background and low from the indication. A sudden decrease in signal results from the presence of a particle indication.

With the fluorescent systems, the detector is covered by a filter that absorbs the wavelength of the light source but transmits the wavelengths produced by fluorescence in the particles. It is not necessary that either light be in the visible range, as long as the detector is sensitive to the emitted light.

The photoelectric detectors used in scanners seldom have the same color or brightness sensitivity as the human eye. It is necessary that the detector be sensitive to some of the emitted or reflected wavelengths. Filters are used to remove unwanted light and undesirable background.

Scanner systems are simpler than video systems. Scanners are optically and electronically less complicated and can be less costly. They are often designed with very sensitive detectors. A major advantage is the scanners' great depth of field. They usually have no lenses in the detector system and do not need to be focused.

Video Detectors

Video is used as a test indication detector in automated magnetic particle systems. Video cameras produce images that may include the test object as well as indications. This property allows sophisticated interpretation with a dedicated computer.

Video camera detector systems use broad field illumination sources that cover a large portion of the test object. Video is essentially sensitive to visible light so standard visible or ultraviolet radiation sources may be used. These sources may in turn be specially filtered or filters may also be placed over the camera lens. As with scanners, video does not have the same color sensitivity as the human eye, so care must be taken to guarantee the compatibility of light sources, camera and test materials.

Because of the higher contrast ratios, most video systems use fluorescent test techniques. In such tests, the radiation source and camera are filtered to transmit and receive the necessary wavelengths.

Human Eye As Detector

The term *radiation* refers both to visible light and ultraviolet radiation.

For magnetic particle tests, there are two important characteristics of visible light. Illumination is measured in lux (lx) or footcandles (ftc). Luminance or photometric brightness is measured in candela per square meter ($cd \cdot m^{-2}$) or footlamberts (ftl). For the purposes of visible magnetic particle tests, these two characteristics are practically equivalent.

The eye is the most common detector used in the magnetic particle testing industry. When considered simply as a component of the test system, the eye is widely available, highly sensitive, very flexible and interfaced to a sophisticated computing device that can produce instantaneous interpretations of test results.

The eye is sensitive to both color and brightness. However, it is not equally sensitive to brightness at all intensity levels and it is not equally sensitive to all colors. The human eye responds to all

wavelengths between 400 and 700 nm but it responds most strongly to the yellow green wavelengths in the center of the spectrum. The response curve is bell shaped, falling off to no response at about 400 and 700 nm (Fig. 2).

The eye changes its absolute and color sensitivity at different ambient light levels. Figure 2 shows this effect for three typical light levels: 340, 3.4 and 0.03 cd·m^{-2} (100, 1.0 and 0.01 ftl).

Light Conditions[1]

Bright Light Conditions

The 340 cd·m^{-2} (100 ftl) level is the amount of light found in a brightly lighted indoor room or outdoors on a bright day in deep shade. It is a light level often used for visible magnetic particle tests. It is also the level where the eye is considered fully adapted to bright light and where increased brightness does not cause further sensitivity change. Under these conditions, the peak sensitivity is at 555 nm and the eye is only 10 percent as sensitive to blue (470 nm) and red (650 nm) light. This means that blue and red appear only one tenth as bright as yellow green or that ten times as much blue and red light is needed to appear as bright as yellow green.

Figure 2 indicates why fluorescent particles are often green, yellow or orange. Because the peak response of the eye is to yellow, less light of this color is required for minimum visibility. Less exciting ultraviolet radiation (or less fluorescent dye surface area) is necessary for the indication to be visible. Green (520 nm) or orange (590 nm) produce 75 percent as much eye response as yellow. If a testing application requires one of these for color differentiation, the drop in brightness is often acceptable in exchange for the increased color contrast.

Low Light Conditions

At low light levels, the operating mode of the eye changes. The retina or sensory tissue in the eye is coated with two types of receptors: rods and cones. Cones are used in high brightness conditions and respond to color as well as brightness. Rods have much more sensitivity to light and are used in low brightness conditions, but they are do not detect color.

Cone vision (340 cd·m^{-2} or 100 ftl) is called *photopic* vision. Rod vision (0.03 cd·m^{-2} or 0.01 ftl) is called *scotopic* vision. The region in between, where both rods and cones are partially operative, is called *mesopic* vision. Full rod vision is about 800 times as sensitive to brightness as full cone vision but it is totally insensitive to color. The eye cannot see color in low light.

Although the dark adapted eye cannot distinguish or differentiate colors, it can detect certain wavelengths and is more sensitive to some colors than others. As the 0.03 cd·m^{-2} or 0.01 ftl curve shows, the maximum response wavelength shifts to 512 nm (blue green) and most sensitivity to red light is lost. However, sensitivity to blue and ultraviolet radiation increases. It is possible to see wavelengths as low as 350 nm in the absence of all other light.

Lighting in Typical Testing Conditions

In a magnetic particle testing booth, it is not possible to attain full darkness. Ultraviolet lamps emit some blue visible light and stray fluorescence or light leaks are almost unavoidable. The light level in most testing booths ranges between 1.7 and 14 cd·m^{-2} (0.5 and 4 ftl).

A good booth has about 3 cd·m^{-2} (1 ftl) of visible light on the test object surface. Figure 2 shows that peak eye response at this level is at 530 nm (green) and that light of 380 nm and above is visible. The figure also indicates that the eye is about 30 times as sensitive as in full bright conditions. Color is barely discernible and most test indications are perceived as blue white.

The eye does not adapt instantly to changes in light level. Moving from full bright adaptation to full dark adaptation can take as long as 1200 s (20 min). Going from full bright adaptation to the 3.4 cd·m^{-2} (1 ftl) level can take 120 s (2 min). If critical tests are being performed, the inspector should wait at least 120 s (2 min) after entering the booth before beginning the test. Less critical tests in lighter booths can often be done after 30 s (0.5 min) of adaptation.

With visible magnetic particles, testing should not be attempted with less than 100 lx (10 ftc). Between 300 and 1000 lx (30 and 100 ftc) is best for most visible testing applications. Critical tests of small discontinuities may require 1000 to 5000 lx (200 to 500 ftc). Extended testing at levels over 2000 lx (200 ftc) may produce eyestrain.

Fluorescent tests should be carried out in the darkest conditions possible. Specifications typically call for less than 20 lx (2 ftc) of visible light in the booth and in some cases the measurement must be made at the test site on the test object surface.

Rough magnetic particle tests can be made with up to 100 lx (10 ftc), but contrast levels and detectability are low. A light level of 500 lx (50 ftc) may be

acceptable if (1) a high level of ultraviolet irradiation is available, (2) bright fluorescent particles are being used and (3) high sensitivity is not required. In no case should fluorescent tests be attempted when the visible light level is higher than 1000 lx (100 ftc). Fluorescent tests should be done outdoors in daylight only if the test site can be partially darkened.

Personnel Vision Requirements[1]

To perform magnetic particle tests, the inspector must possess a certain level of vision acuity. Vision tests are typically done with near vision and all inspectors should be tested to ensure proper vision acuity. The American Society for Nondestructive Testing recommends a minimum ability to read a specified type size at specified distances.[4,5] The document also recommends that the inspector demonstrate the ability to differentiate between colors used in the magnetic particle test method.

Good close vision is required to properly perform magnetic particle tests. Good color vision may be helpful in visible light tests, but it is not as critically important for fluorescent tests because everyone loses some color vision in a dim testing booth.

PART 2. Interpretation of Indications[1]

Interpretation is the final stage of a magnetic particle test, but certain interpretation decisions must be made early in the process. Two of the most critical involve the appropriateness of the magnetic particle technique.

1. Is the test technique correct for the anticipated discontinuities?
2. Is the test technique appropriate for the test object?

Once these decisions are made, magnetic particle indications can be formed, detected and interpreted. If they represent discontinuities, their severity and effect on test object service can be determined.

Subsurface Discontinuities

Magnetic particle tests can be used to locate specific types of subsurface discontinuities in ferromagnetic materials, depending on (1) the type of magnetic particle equipment and the kind of magnetizing current, (2) the nature and characteristics of the discontinuity (its orientation and depth under the surface) and (3) the dimensions and shape of the test object. This ability to detect subsurface discontinuities should not be exaggerated. Other nondestructive test methods detect subsurface discontinuities better.

Dry particles reveal only major linear discontinuities (shrinkage cracks or incomplete penetration) — only if the discontinuity's depth below the object surface is less than 6 mm (0.25 in.). When the wet technique is used, the maximum depth below the surface is 0.2 mm (0.008 in.). These depth limits are based on empirical data and vary with type and size of the discontinuity, with the dimensions and shape of the test object and with the magnetic properties of the test object material.

Effect of Test Object Shape

The shape of a test object can cause magnetic flux lines to bypass some areas of the object surface. No flux leakage occurs in those areas and no particle indications are formed, despite the presence of possible discontinuities.

Sensors can and should be used to indicate the presence and direction of magnetic flux leakage, particularly with test objects having changes in cross section or unusual configurations. Sensors can also provide a relative value for the number of flux lines needed to obtain specified test reliability.

Selection of Technique

The fact that an object is ferromagnetic does not mean that magnetic particle testing is the best surface inspection method. The exceptions depend mainly on the size, shape and finish of the test object. For example, under some specifications, overmagnetization of finish machined objects can create high background, masking indications. In forgings, flow lines and particles accumulate at corners or grooves to produce nonrelevant indications.

In addition, if magnetizing current is applied to the test object by direct contact, there is a high probability of arcing and damage to fine surfaces. In aerospace components, for example, arcing inevitably causes minute cracks into which copper from contact pads can penetrate. Copper penetration is cause for rejection in virtually all aerospace components.

Evaluation of Indications

The first step in interpretation is to decide the character of a magnetic particle indication: is it relevant, nonrelevant or a false indication?

If it is relevant (representative of an actual material discontinuity), the indication is then evaluated, based on the data given in the acceptance criteria for that type of test object. If the test object is within the acceptance criteria, it can be accepted, even though a discontinuity is present. However, such acceptable discontinuities do not affect the quality, future use or service life of the test object. If the acceptance criteria are not met, the test object is rejected and a full report goes for further evaluation to a materials review board. Members of that board typically include quality assurance managers, engineers and in most cases a customer representative.

The review board decides future action for the test object: scrap, use as is, rework or repair. After rework or repair, the object is retested. Scrapped components are destroyed to prevent accidental use.

Some nonrelevant indications are caused by the shape of the test object — by magnetic leakage from sharp corners, splines, thread roots or magnetic writing, for instance. Nonrelevant indications are not cause for rejection but can mask actual discontinuities critical to the object's service life. Proper testing techniques reduce the occurrence of nonrelevant indications.

False indications are not caused by magnetic flux fields but by material obstructions and improper processing: dirt, fingerprints, gravity, scale or drain lines are examples. Proper housekeeping can prevent false indications. They are not cause for rejection but often require retesting before acceptance.

Nonrelevant indications are caused by magnetic leakage fields but they do not represent accidental discontinuities. Flux leakage may be caused by sharp corners, holes drilled close to the surface, threads, changes in the structure of the material, shrink fits or dissimilar metals. The main problems with nonrelevant indications are (1) that they can mask actual discontinuities and (2) that actual discontinuities can be interpreted as nonrelevant.

Metallurgical Properties

Alloy and hardness directly influence the magnetic properties of metals such as steel. Variations in hardness from cold working create localized variations in magnetic properties. Depending on the alloy, such variation can cause magnetic particles to form sharp, distinct patterns.

Heat affected zones near welds can give similar indications. Some of the tool steels with high retentivity and high coercive force are well known to produce sharp, well defined nonrelevant patterns. If such a condition occurs, magnetic particle test results should be verified by a method such as liquid penetrant or ultrasonic testing.

When a coupon is taken from such an area and metallurgically examined, a minor change in the grain structure is often visible. This change does not typically influence the strength of the test object but can cause nonrelevant particle indications. In some cases, high internal and external stresses cause variations in magnetic properties and so cause nonrelevant indications.

Contact Indications and Stamping Marks

Objects that touch each other during magnetization may set up local polarities at their surfaces and cause leakage fields. This happens most often when a number of objects on a central conductor are magnetized at the same time. Contact indications are sometimes called *magnetic writing*. Confusing particle patterns can be caused and, as with all nonrelevant indications, these patterns can mask relevant indications.

Numbers or letters stamped onto a component are sometimes ground out before magnetic particle testing. The changes to the structure caused by stamping are sometimes enough to cause changes in the metal's magnetic properties. Magnetic particles occasionally can indicate these magnetic changes and outline or indicate the previously stamped characters. This indication is nonrelevant but may be used to identify the test object.

Structural Indications

At abrupt changes in section of a magnetized object, there is an increase in internal flux density which in turn creates local external polarity and produces magnetic particle indications. Sharp corners, keyways, internal splines or holes close and parallel to the object surface are component design features that produce nonrelevant indications. Such indications are characterized by their width and lack of clarity. Their relationship to the object's design is usually apparent.

Again, the primary concern over structural indications is their ability to mask relevant discontinuity indications. When structural indications occur, the magnetic lines of force exit the material normal to the surface, an unfavorable orientation for the detection of discontinuities. Quick break magnetization can partially eliminate structural discontinuities.

A shrink fit may also be considered a structural indication. The interface between two objects gives a distinct magnetic particle indication that is apparently not related to the pressure used for the shrink fit operation.

Particle indications in the roots of threads are often caused by gravity rather than by a magnetic leakage field. Very careful examination of the threaded area is required to distinguish relevant from nonrelevant indications. In this case, relevant indications turn in a slightly transverse direction with a hook at the end of a crack.

Dissimilar Metals and Welded Joints

When two metals with different magnetic properties are fused together, the interface produces a sharp indication during magnetic particle testing. An automotive valve is typical of such a component: the valve body is fusion welded to a stem fabricated from a different metal. Under test, the fusion line shows up very clearly, making it impossible to inspect the weld for lack of bond. A supplementary ultrasonic test is required for complete inspection of an object such as a valve body, containing dissimilar metals.

In addition to indications that can occur in the heat affected zone of welds, nonrelevant particle indications can also appear in the weld reinforcement. Indications caused by abrupt changes in the crack's cross section can also occur at that location. A very thorough visual test with magnification or grinding of the weld cap is often necessary to supplement magnetic particle procedures for such test objects.

False Indications

Dirt and Scale

If a test object is improperly cleaned, foreign material may trap magnetic particles. Improper cleaning contributes to contamination of a wet particle suspension and causes drainage lines, forming patterns that resemble discontinuity indications. These indications do not reappear after the object is cleaned and retested, thereby establishing their false character.

Scale on the test object surface often produces false test indications, but the source of scale is easily accounted for. If scale is forced into the surface of the test object during forging, a significant discontinuity is formed and, depending on the stage of manufacture, can be relevant to service life.

Scratches and Burrs

Surface scratches and burrs trap magnetic particles and form patterns that may look like relevant indications. For example, these false indications can mimic a crack with an orientation transverse to the particle flow. Often, such indications can be distinguished from relevant indications by the lack of particle buildup. Verification at 10× magnification in visible light may sometimes prove necessary.

Scratches and burrs are classified as false indications, unless the scratches occur in notch sensitive and highly stressed materials, on polished surfaces or if burrs are found in threads and splines.

A good visual examination before the magnetic particle test generally locates these conditions. Because the indications are linear, they must be reported.

PART 3. Control of Wet Particles[1]

Note that the particles in suspension are an insignificant part of a testing operation's total cost. Frequently changing the magnetic particle suspension does not materially inflate the cost of testing. Even if the bath is changed each week, it is still a very small fraction of the total cost, when compared to equipment depreciation and labor.

Settling Test

Most wet magnetic particle installations depend on the settling test for control of particle concentrations in suspension. It is now possible to use this simple technique to detect other attributes in a particle bath.

Low signal-to-noise ratio is the principal reason for failure to detect fluorescent discontinuity indications: it is nearly impossible to detect fluorescent indications in high fluorescent backgrounds, for either automated tests or the human eye. The principal causes of low signal-to-noise ratio are (1) excessive current density, (2) excessive magnetic particles in suspension, (3) excessive fluorescent background in the vehicle or (4) excessive particle contamination. The settling test can detect the last three causes.

In a typical setting test done with fresh particles, a concentration of 0.15 to 0.25 mL particles should be found in a 100 mL centrifuge tube. A lower concentration, on the order of 0.1 mL, is usually satisfactory. Anything above 0.3 mL is excessive and should be avoided, even if specifications allow up to 0.5 mL.

The settling test may be used to determine two of the primary kinds of bath contamination: (1) loose fluorescent material from the particles themselves and (2) extraneous oils (such as cutting oils) that remain on the test object after cleaning. The degree of such contamination can be monitored with a centrifuge tube that retains an initial sample of the vehicle for reference purposes. This sample is compared to a concentration test after at least 3600 s (1 h) of settling.

Another source of contamination is sand from previous sand blasting, residue from grinding or shot dirt. These contamination sources are the result of inadequate precleaning and can be determined by comparing of settling tests.

Particle Control at Indication Site

Control of particles in suspension at the point of the discontinuity is vital. Fluorescent magnetic particles are used in the overwhelming number of applications (about 10 percent of the magnetic particle suspensions are nonfluorescent), so that fluorescent particle control is needed more often than control of visible particles. Ideally, a discontinuity should have a high contrast ratio under ultraviolet radiation. The indication should be sharp with virtually no background either from the particles or their vehicle.

The relative number of particles in suspension per unit volume should be controlled within close limits. This control is important because the basis for evaluation of an apparent discontinuity is typically the visual detection of particle accumulation. Mass fluorescence in the background of an indication can greatly diminish detectability by significantly lowering the contrast between background and indication.

Wet Concentration Test

After a maximum of 8 h (480 min), the concentration of a magnetic particle suspension should be measured: concentration must be proper before testing can continue. If there are insufficient particles in the suspension, no indications can form. Too many particles give a high background that can mask small indications.

The concentration is measured with a settling test.

1. Run the circulating pump for a minimum of thirty minutes.
2. Flow enough suspension through an applicator nozzle to ensure uniformity of the suspension.
3. Fill a thoroughly cleaned, 100 mL centrifuge tube to the 100 mL line with the suspension sample.

4. Allow the tube to stand away from magnetic fields and vibration for 3600 s (60 min) when oil is the vehicle, 1800 s (30 min) when water is the vehicle.
5. Verify the volume of settled particles on the tube's graduated scale. The precipitate volume should be 0.15 to 0.3 mL per 100 mL for fluorescent particles and 1.0 to 2.4 mL per 100 mL for black oxide particles.
6. Adjust the suspension concentration by adding particles or vehicle and repeat the settling test.
7. Repeat step 6 until the correct concentration is obtained.
8. Record each concentration reading in the log book.

Brilliance and Contamination Tests

Each week that magnetic particle equipment is used, the brilliance of fluorescent suspension should be checked by comparing it to a fresh, unused sample. Whenever suspension is mixed, a minimum of 200 mL should be retained in a dark glass bottle for reference.

Used suspension is compared with the unused sample under ultraviolet radiation. If the brilliance is noticeably different, the test system's tank should be drained, cleaned and refilled with fresh suspension. The results of these procedures are recorded in the log book.

Contamination of the suspension by foreign matter should also be checked at least once a week. If the suspension is contaminated, the tank should be drained, cleaned and refilled with fresh suspension. The following procedure is used to verify contamination.

1. Run the circulating pump for 1800 s (30 min).
2. Fill a graduated 100 mL centrifuge tube with suspension and allow it to stand for 1800 s (30 min).
3. Examine the liquid above the precipitate under ultraviolet radiation. If the oil or water fluoresces green or yellow green, the tank should be drained, cleaned and refilled with fresh suspension.
4. Examine the precipitate. If two distinct layers are visible and the top layer of contaminate exceeds 50 percent of the bottom layer's magnetic particles, then the tank is drained, cleaned and refilled with fresh suspension.
5. Record the results in the log book. Specifications may vary in the allowable ratio between particles and contaminant in the precipitate. Results of these tests are always logged in writing.

Because both of these tests take at least 1800 s (30 min), it is normal to begin magnetic particle testing before the brilliance and contamination procedures are completed. If the suspension does not meet specification, all objects tested during the 1800 s (30 min) must be retested with new suspension.

Viscosity Test

Viscosity is a measure of a fluid's resistance to flow and is an important property of the oil used as a vehicle for magnetic particle testing. There are two kinds of viscosity: dynamic and kinematic. Dynamic viscosity (or absolute viscosity) is not considered here. Kinematic viscosity is measured in square meters per second ($m^2 \cdot s^{-1}$) and was formerly measured in stokes (St), where one stokes equals 100 square millimeters per second: 1 cSt = 1 $mm^2 \cdot s^{-1}$ = 10^{-6} $m^2 \cdot s^{-1}$.

In general, viscosity is measured in specialized commercial laboratories. Common viscosity values for the vehicle used in magnetic particle suspensions must not exceed applicable regulations and safety standards,[6] which should be specified in the inspection contract.

Contaminants from the surface of test objects tend to build up in the particle suspension and increase its viscosity. Precleaning test objects to remove oil and grease mitigates but does not eliminate this problem. Depending on the specifications in force, viscosity measurements are usually performed monthly. A 90 mL (3 oz) specimen from the tank is sufficient for accurate appraisal.

If the viscosity exceeds specified values, the suspension is discarded and the tank is drained, cleaned and refilled with fresh suspension. The results of viscosity tests are reported in the log book (third party reports also are filed). Suspensions, solvents and similar materials must be discarded in compliance with federal, state and local laws.

PART 4. Magnetic Particle Tests Viewed under Visible Light[2]

Visible light inspection achieves contrast through particles that differ from the background in color, intensity or a combination of the two when illuminated with broadband white light. The background surface may be the natural state of the part being inspected, but if that surface does not provide sufficient contrast then a thin layer of contrast paint, generally white, should be used. Particles are available in a wide range of colors to suit a variety of inspection needs.

Light Sources for Visible Light Inspection

Visible light sources for magnetic particle tests are not significantly different from those used for other visual testing applications. Sunlight, incandescent lamps, fluorescent tubes or metal vapor arc lamps are satisfactory. The spectral characteristics of the light source are not significant as long as the output is broadband enough.

Some care needs to be taken with some white light sources, especially those using light emitting diodes. Light emitting diodes are semiconductor devices that emit light when a current passes through them. The light emission arises from differences in energy levels within the device and is a form of electroluminescence. Because of the nature of the electronic transition in the semiconductor, light emitting diodes emit light over a relatively small range of wavelengths. White light emitting diodes are actually narrow band blue light emitting diodes with a phosphor coating that absorbs the blue energy and reemits it over a broader wavelength range. These light emitting diodes are usually very deficient in red wavelengths and may not produce adequate contrast with red particles.

The recommended illumination intensity for visible inspections is 1000 lx (100 ftc) at the inspection surface, although particular inspections may specify more or less light. The intensity can be measured with meters calibrated in lux or footcandles. It is possible for there to be too much light. Too bright a light may overwhelm the inspector's vision, to the point where indications cannot be seen. Excessive light can also increase inspector fatigue.

Because a greater area is visible, floodlights offer an advantage for inspecting large and relatively flat surfaces. On intricate test objects where areas are accessible with difficulty, handheld spotlights may be more effective.

Particles for Visible Light Inspection

Particles for visible light inspection are available in a variety of colors, including red, yellow, green, blue, gray and black. The color may be selected to provide best contrast with the items to be inspected under the illumination conditions that will be used for the inspection.

Dual Particles

Some manufacturers offer particles called *dual use* particles, that is, particles that are designed for visible light inspections but also fluoresce. The fluorescence increases their brightness even in broadband white light but use of a supplemental fluorescence excitation source with these particles makes them even more conspicuous, improving detection sensitivity.

PART 5. Magnetic Particle Tests Viewed under Ultraviolet Radiation[2]

Fluorescence is a powerful technique for producing contrast and is the technique of choice for inspections that require high sensitivity. In the process of fluorescence, light is absorbed at one wavelength, or color, and reemitted at another. The strength of the technique lies in the fact that the light used to illuminate the surface and excite the fluorescence is invisible to the observer, so the indication is seen as a glowing area against a dark background. This contrast is greater than can be achieved with visible light techniques that depend on broadband reflection.

Principles of Fluorescence

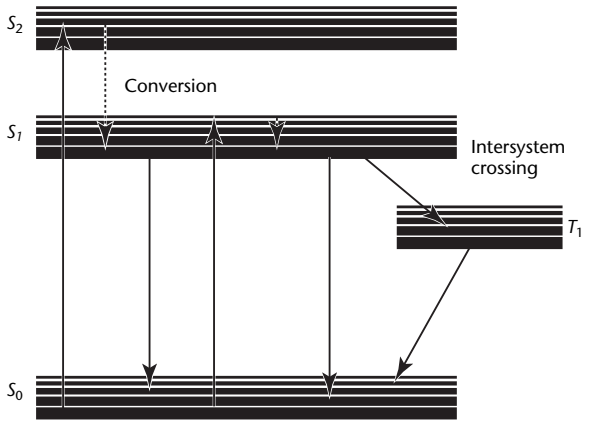
Fluorescence is a form of luminescence, the emission of light without heat. This is different from incandescence, in which a body emits light as a function of its temperature. Incandescence is what we see in a standard filament light bulb or a burner on an electric stove. In luminescence, an electron absorbs energy that shifts it from a lower to higher orbital (excited) state within the molecule and then releases that energy in the form of light when it returns to the ground state. There are many different types of luminescence, the difference among them being the source of the energy that promotes the electron to the excited state. In chemiluminescence, for example, the energy comes from a chemical reaction. This is what is happening in the glowing necklaces that are often seen at parties. Bioluminescence is a form of chemiluminescence that occurs in living organisms, such as fireflies. There are many other forms of luminescence.

Fluorescence is a form of luminescence in which the energy that produces the excited state electron comes from an absorbed photon of electromagnetic radiation. Fluorescence entails the absorption of electromagnetic radiation at one wavelength followed by its almost immediate reemission at a longer wavelength. The emission ceases as soon as the source of excitation is removed. Fluorescence does not require ultraviolet radiation: many forms of electromagnetic radiation can stimulate fluorescence.

Fluorescence is usually explained by the jablonski diagram (Fig. 8). A typical jablonski diagram shows the ground singlet state (S_0), two excited singlet states (S_1 and S_2), and a triplet state (T_1). The thicker horizontal lines in the figure represent electronic energy levels, while the thinner lines stacked above them represent vibrational and rotational energy states. Under normal conditions the electrons are in the lowest level of the S_0 ground state. The gaps between the energy levels represent discrete amounts of energy, and they determine the effectiveness of different wavelengths of electromagnetic radiation at producing fluorescence in a given molecule. The energy level of an incident photon corresponds to the energy of the gap between levels: the greater its energy, the more likely that a photon will be absorbed.

If an incoming photon is absorbed, it causes an electron to jump from the S_0 state to a higher excited state, such as S_1 or S_2. This transition is indicated by the vertical lines with arrows pointing up. This happens on a time scale of about 10^{-15} s. The jump may occur to one of the higher vibrational or rotational states within that energy level. The next thing that happens is that the excited state electron loses some of its energy to vibration within the molecule and drops

FIGURE 8. Jablonski diagram of processes involved in fluorescence.



Legend

S_0 = original, unexcited state of irradiated material
S_1 and S_2 = energized states of material
T_1 = triplet state (phosphorescence)

to the lowest energy level of the S_1 state. This process, called *internal conversion*, occurs on a time scale of about 10^{-12} s. Finally, the electron may fall to one of the sublevels of the S_0 state, emitting a photon of electromagnetic radiation in the process. This occurs on a time scale of about 10^{-9} s. Even though this is a very short time it is still on the order of a thousand times slower than the internal conversion process. Because some of the original incoming photon energy is lost to internal conversion, the energy of the emitted photon is less than that of the incident photon. The energy of a photon is directly related to its wavelength, and lower energy corresponds to a longer wavelength. This is the process that transforms one color of light to another. In practical terms, this means that there is shift in wavelength from the excitation light to the emitted light – from ultraviolet radiation to anywhere in the visible spectrum, from blue light to green/yellow/orange/red, from green light to yellow/orange/red and so on.

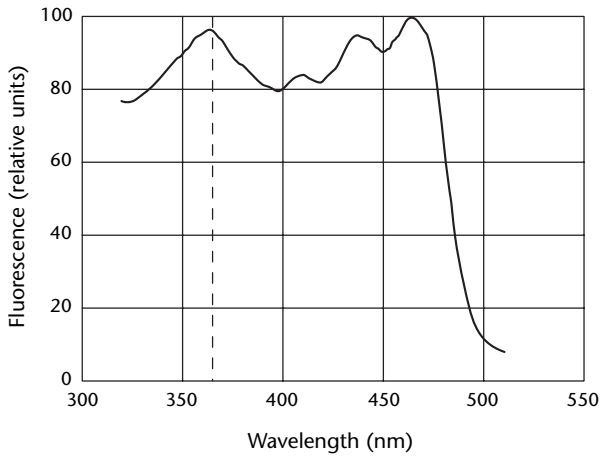
Fluorescence is not the only way that a molecule can lose its excited state energy, so not every photon absorption event produces a corresponding emitted photon. Fluorescence has competition from a number of other processes. The energy may be lost entirely to vibration (heat) within the molecule. Nonfluorescent magnetic particles absorb different wavelength ranges of light just as fluorescent particles do, but they do not lose that energy as fluorescence. The dyes that give color to clothes absorb light at different wavelengths. For this reason, darker clothes absorb more photons and heat up more than lighter clothes but without any fluorescence. Another possibility is that the excited state energy may be used to perform chemical changes, which is what happens in photosynthesis by plants. There are other deexcitation pathways.

Different molecules have different probabilities for the competing deexcitation processes. For magnetic particle testing, the more of the energy that comes out as fluorescence, the brighter the indication will appear. The *quantum yield* of a fluorescing substance is defined as the number of photons emitted divided by the number of photons absorbed, and particle manufacturers try to use materials with the highest quantum yields they can.

Excitation Spectrum

Because an electron can jump from the ground state to a variety of sublevels of excited states, more than one wavelength can be used to excite fluorescence. The *excitation spectrum* is a graph of the relative ability of different wavelengths of light to excite the fluorescence of a material. This ability can be measured with an instrument called a *spectrofluorometer*. In one common configuration, the spectrofluorometer contains an intense broadband light source, two monochromators (devices that can select narrow wavelength bands of the light) and a sensitive photodetector. One of the monochromators is positioned between the light source and the measured sample and is used to select the wavelength to excite the fluorescence. The other monochromator is in the light path between the sample and the detector and is used to select the wavelength of fluorescence emission to be measured. To measure the excitation spectrum, the emission monochromator is fixed at one wavelength at which the material fluoresces strongly and the excitation monochromator is scanned through a wide band of wavelengths. At each excitation wavelength, the intensity of the emitted fluorescence is measured. The result is a graph like the one in Fig. 9, which was measured from a commercially available fluorescent magnetic particle sample. The vertical dashed line in the graph is at 365 nm, the peak output of ultraviolet lamps usual in magnetic particle testing. The graph shows that this choice is good for making that particle fluoresce and that it is not the only wavelength that works.

FIGURE 9. Fluorescence excitation spectrum for ordinary fluorescent magnetic particles. Vertical dashed line is at 365 nm, the peak emission wavelength from ultraviolet lamps used for magnetic particle testing. Graph shows that 365 nm is excellent for exciting fluorescence from this particle but is not the only possibility.



Emission Spectrum

When the excited state electron falls from the lowest level of the S_1 excited state, it can go to one of the vibrational or rotational sublevels of the S_0 ground state. Transitions to different sublevels correspond to different amounts of energy difference, which in turn correspond to different wavelengths of fluorescent emission. Thus, the light emitted by fluorescence is not at a single wavelength but occurs over a range of wavelengths, described by the *emission spectrum*. This spectrum can be measured in the spectrofluorometer by setting the excitation monochromator at a fixed wavelength and scanning it through the desired range of wavelengths, measuring the intensity at each wavelength. The result is a graph like that in Fig. 10, measured from the same fluorescent magnetic particle sample for which the excitation spectrum is shown in Fig. 9.

Because of internal conversion, almost all fluorescence occurs from the lowest level of the S_1 excited state, no matter what excited state the electron originally reached. The practical implication of this is that the emission spectrum is independent of the particular wavelength of light that excites the fluorescence.

Phosphorescence

The diagram in Fig. 8 shows another possible electronic transition, from singlet state S_1 to a intermediate, lower energy state T_1. This is what is called the *triplet state*. The transition between S_1 and T_1 is called *intersystem crossing*. Electrons do not orbit in this zone, or shell. The intersystem crossing is caused by the interaction of electron's weak orbital coupling. If the electron reaches the triplet state, it will remain there awhile. This stasis results in phosphorescence, the property by which materials glow in the dark. With fluorescence, the emission of light ceases nanoseconds after the excitation light is removed, but with phosphorescence the release of photons persists much longer, for minutes or hours.

Fluorescent Indications[2]

Fluorescent magnetic particle indications should be inspected in a darkened area. The lower the level of ambient visible light, the more brilliant fluorescent indications will appear. This is important particularly when testing for very small discontinuities that may attract only a small number of fluorescent particles.

Visible Light Interference

The visible light intensity in a test area has a dramatic effect on performance and reliability. More visible light makes fluorescent indications harder to see, requiring higher ultraviolet irradiances to permit detection of indications. Table 1 lists several ambient visible light level equivalents. The results of laboratory tests on light levels for fine and coarse cracked panels and a dark adapted inspector are shown in Table 2.

Ultraviolet test booths typically cannot achieve visible light levels less than 10 to 20 lx (1 to 2 ftc) because ultraviolet lamps, even with filters, have some visible light output. In addition, the induced fluorescence from test objects, inspectors'

FIGURE 10. Fluorescence emission spectrum for same fluorescent magnetic particles as in Fig. 9. Emission peak is at 525 nm, in green part of spectrum.

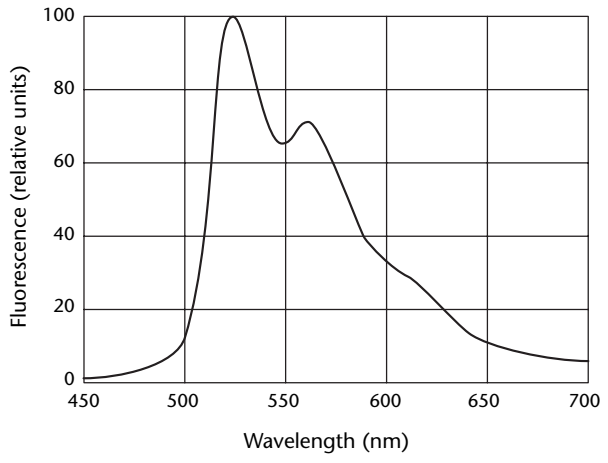


TABLE 1. Ambient light levels.

Visible Light Intensity		
lx	(ftc)	Light Level Equivalent
10	(1)	best ultraviolet testing booth
100	(10)	dim interior ambient lighting
1000	(100)	bright interior; deep shade under sun

TABLE 2. Empirically determined minimum light for discontinuity location with fluorescent magnetic particles.

Light Intensities for Small Discontinuities		Light Intensities for Large Discontinuities	
$W \cdot m^{-2}$	$\mu W \cdot cm^{-2}$	$W \cdot m^{-2}$	$\mu W \cdot cm^{-2}$
0.3	30	0.1	10
5	500	0.5	50
50	5000	5	500

clothing and spills of fluorescent material can add to visible light. It is important for the test station to be free of random fluorescent materials, whether or not they come from the test.

Eyeglasses

At present, there are no official federal regulations covering the permissible amount of ultraviolet exposure an inspector can receive during a work day. However, the American Conference of Governmental Industrial Hygienists has recommended the following limits for the ultraviolet spectral region from 315 to 400 nm: total radiant energy incident on unprotected skin or eyes, based on either measurement or output data shall not exceed (1) 1 $mW \cdot cm^{-2}$ for longer than 1000 s and (2) 1 $J \cdot cm^{-2}$ for less than 1000 s. These limits may be revised, so quality and safety personnel should check current guidelines.[6] Ultraviolet absorbing safety glasses can prevent ultraviolet radiation reflected from the part being inspected or from other surfaces in the inspection booth from reaching the eye.

Photosensitive (photochromic) eyeglasses darken in the presence of ultraviolet radiation. The darkening is proportional to the amount of incident radiation. Although this type of lens has advantages under sunlight, such glasses would decrease the intensity of the fluorescence emission reaching the eye and thus would interfere with fluorescent magnetic particle tests. These glasses are not permitted for use in the test area.

Wearing red lenses in lighted areas may aid subsequent dark adaptation. These glasses must be removed after entering the darkened testing booth and before viewing fluorescent indications.

Some commercial eyeglass frames fluoresce and can cause glare or unnecessary fluorescent background illumination. As with any object in the testing booth, glasses should be examined and care should be taken to eliminate extraneous sources of light.

Fluorescence of Eyes

It is possible that an inspector may experience a temporary clouding of vision if ultraviolet radiation is permitted to shine into the eye or if it is reflected into the eye from test object surfaces. This clouding occurs because the cornea, lens and the liquid in the eye (the vitreous humor) are also fluorescent materials. Under no circumstances should shorter wavelength ultraviolet radiation be allowed to shine or reflect into the eye.

Because of the eye's own fluorescence, ultraviolet sources in the testing area should be positioned so that neither direct nor reflected light shines into the operator's eyes. Ultraviolet absorbing eyeglasses should be worn if this fluorescence becomes a serious problem and are recommended to prevent unnecessary exposure of the eye to ultraviolet radiation. They are also helpful when viewing critical small particle indications. Such visors or glasses should block all ultraviolet radiation, and most violet and blue light, without diminishing the yellow/green test indication.

PART 6. Radiating Accessories for Magnetic Particle Testing[2]

Fluorescent Lamps

Fluorescent lamps produce light by bombarding gases with electrons from a cathode to produce ultraviolet energy. This energy excites within the lamp a fluorescent coating that in turn emits several wavelengths of visible and invisible light. Fluorescent lamps have adequate intensity and very even distribution, but their color balance is different from all other sources.

Fluorescent light appears white to the eye but has a very green tint on film. Filters are available to correct this light to approximate daylight. The filters are purple and should always be used when making color photographs under fluorescent light.

Sources for Photography of Fluorescent Indications

Fluorescent indications are normally photographed under illumination provided by mercury vapor ultraviolet lamps. These lamps are often used for inspection of magnetic particle test objects and may be spotlights or flood lamps. For fluorescent photography, the lamps are equipped with a black glass filter that cuts off all visible light except a small amount of violet. Such lamps are often used without a filter for space illumination in factory areas; it may sometimes be necessary to photograph visible indications using this source. Such light is extremely blue and a yellowish filter is required to obtain proper color balance with color film.

Mercury arc ultraviolet sources are often highly directional and spotty when photographed. They illuminate the area of an indication well but may not produce enough distributed light to photograph the rest of a large test object. In such cases, it may be necessary to use a visible light double exposure to show the test object. If this is done, the test object must be underexposed in visible light to retain good images of the indications. Such visible light exposures are made at a focal ratio, or relative aperture, at least two less than normal exposures.

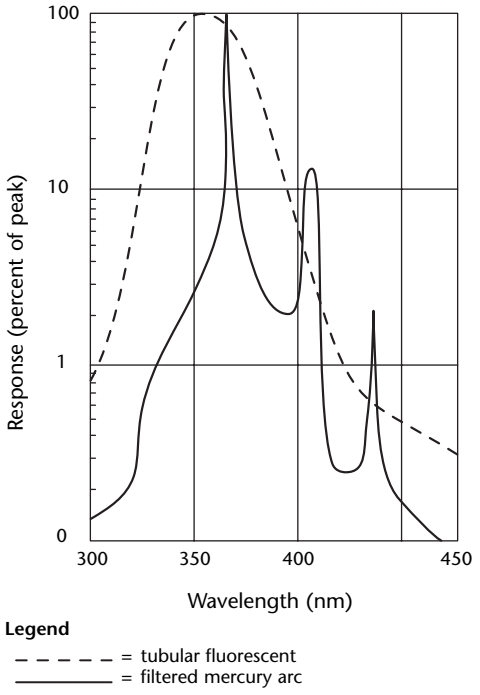
Tubular Ultraviolet Sources

Another radiation source used for fluorescence photography is sometimes called *tubular sources*. These are standard fluorescent fixtures equipped with special bulbs containing an ultraviolet emitting phosphor enveloped in ultraviolet transmitting black glass. Such lamps produce most of their light in the near ultraviolet spectrum but also have a considerable output of blue and violet visible light. Their output is unfocused, so they illuminate a large area without high intensity in any one spot.

Tubular sources can produce an acceptable photograph of a large area containing large, bright test indications, particularly if the camera is equipped with a filter that cuts off violet light. Such sources are not good for small or dim indications because (1) they have low spot intensity and (2) their large visible light output cuts contrast.

Figure 11 shows the spectral emission of ultraviolet radiation sources used in magnetic particle testing.

FIGURE 11. Spectral emission of mercury arc and tubular ultraviolet sources.



Mercury Arc Ultraviolet Lamps

The most common light source for fluorescent magnetic particle testing is a mercury arc bulb rated at 100 W. Ultraviolet lamps require an autotransformer to regulate current and step up voltage. The ultraviolet radiation source for fluorescent magnetic particle tests emits radiation with an intense peak at 365 nm. The ultraviolet output was formerly and incorrectly measured in footcandles with a visible radiation meter. Ultraviolet radiation meters are now available to measure the ultraviolet intensity directly at the testing point as watts per square meter or as microwatts per square centimeter.

A filter is placed over an ultraviolet radiation source for two reasons: (1) to block visible light, exposing the test object only to ultraviolet wavelengths and (2) to restrict the emission of ultraviolet wavelengths harmful to the human body. No magnetic particle test should be attempted without the filter in position. Damaged filters must be replaced immediately. Dirty filters seriously impede the emission of ultraviolet radiation — cleanliness is essential for accurate magnetic particle test results.

The 100 W mercury arc lamp requires about 600 s (10 min) to reach full intensity. To lengthen service life, the lamp should remain energized after warmup. It is good practice to keep ultraviolet lamps energized for the entire working day.

Ultraviolet lamps are sensitive to low voltage and voltage fluctuations. For this reason, they must be connected to voltage sources that have little fluctuation (within 5 percent of the voltage rated for the transformer). A tap switch in the transformer allows adjustment to several voltages.

Construction of Mercury Arc Lamp

Mercury arc lamps are gaseous discharge devices in which an electric arc takes place in a controlled atmosphere and emits light whose characteristics depend on the atmosphere.

The construction of a typical mercury arc bulb is shown in Fig. 12. The mercury is confined in a quartz or hard glass cartridge, and two main electrodes carry current to the arc stream (along the length of the cartridge). An auxiliary starting electrode and a current limiting resistor are also included in the electrical design. The entire assembly is sealed in an outer protective bulb that may either be evacuated, filled with air or filled with an inert gas, depending on the design of the bulb. The lamp is fed from a current regulating ballast reactance or transformer. This is required because the arc tube shows negative resistance characteristics and would quickly destroy itself if not throttled by an external device.

Energizing of Mercury Arc Lamp

When the lamp is first turned on, the mercury in the cartridge is not vaporous but is condensed in droplets on the inside of the tube. Under this condition, it would be difficult or impossible to strike the arc. To facilitate starting, a small amount of neon gas is incorporated into the cartridge and a starting electrode is sealed through an end of the tube near one of the main electrodes.

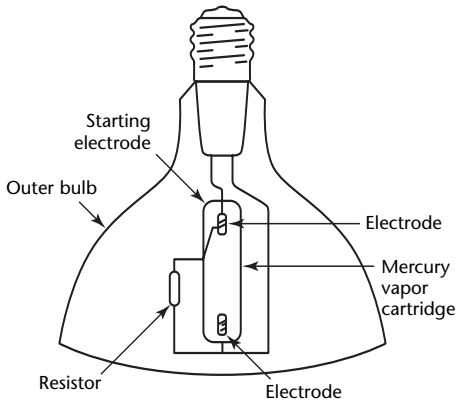
When voltage is first applied, a discharge from the starting electrode moves through the neon. This glow discharge carries a small current limited by the protective resistor but is sufficient to vaporize and ionize the mercury and eventually cause an arc to strike between the main electrodes. The heating and ionization process takes 300 to 900 s (5 to 15 min) after the lamp is first energized.

Spectral Characteristics of Mercury Arc Sources

One of the advantages of the mercury arc lamp is that its output can be controlled by design and manufacture. By proper choice of vapor pressure, spectral output can be varied from a few intense but widely scattered lines (when the pressures are near 1 mPa) to an almost continuous spectrum at about 10 MPa (100 atm).

At medium pressures from 100 to 1000 kPa (1 to 10 atm), the light output is about evenly distributed between the visible, near ultraviolet and far ultraviolet ranges. These medium pressure lamps have been used for magnetic particle

FIGURE 12. Mercury arc lamp construction.



testing. Figure 11 shows the spectral emission of two kinds of ultraviolet sources.

Transmission Characteristics of Ultraviolet Filters

Because a limited portion of the ultraviolet spectrum is needed for testing, the output radiation from a light source must be filtered. A commonly used and effective filter is made of heat resistant purple glass. A typical transmission curve for an ultraviolet filter peaks rather sharply near 360 nm and starts to rise again at about 700 nm.

Illumination Intensity of Mercury Arc Sources

An appropriately filtered 100 W ultraviolet bulb can produce up to about 3000 $\mu W \cdot cm^{-2}$ peak intensity at 450 mm (18 in.) from the test surface. The ultraviolet irradiance at the test surface can be altered by adjusting the distance between the ultraviolet source and the test object. Bringing the light source within 50 mm (2 in.) of the surface increases the intensity to over 30 000 $\mu W \cdot cm^{-2}$. Flood bulbs and those lamps provided with fluted filters generally provide substantially lower irradiance.

Because test surfaces can be blocked by lamp housings, the shortest practical source-to-object distance is about 50 mm (2 in.). A typical ultraviolet radiation test can meet most specifications with a distance of 380 mm (15 in.) and a minimum intensity not less than 1000 $\mu W \cdot cm^{-2}$.

Fixtures for Ultraviolet Sources

For several reasons, ultraviolet sources require a housing and fixturing: (1) to support the filter; (2) to prevent leakage of unwanted visible light; and (3) to permit positioning of the beam onto the test surface.

Various ultraviolet fixtures are commercially available. Some are small and portable. Others are mounted permanently inside a testing booth or on a production testing system. Figure 13 shows a portable ultraviolet lamp.

The 100 W lamp is small enough to be portable, although it is often mounted more or less permanently in a testing unit. These lamps come in a variety of configurations from various manufacturers, in spot and flood lamp types. Spot lamps are used almost exclusively to attain high intensities for localized use. As shown in Fig. 14, spot lamps produce an intense but narrow beam.

Output Varieties for Ultraviolet Sources

There are many mercury arc ultraviolet sources ranging down to a 2 W size. These have found certain very specialized uses in magnetic particle testing. They usually do not have built-in reflectors so their lower power is widely dispersed.

A 400 W ultraviolet source is also available. It is large and typically limited to a stationary mounting. The 400 W source produces a large amount of ultraviolet over a large area and is well adapted to illuminating a large area for quick location of large or medium sized indications. This source does not produce as high a maximum irradiance in any one area as the 100 W bulb.

A 125 W mercury vapor lamp is also regularly used in nondestructive testing, but several aerospace companies do not permit use of the 125 W source. The bulb has a filter built into its exterior glass shell. Because this is a pear shaped bulb, it has an exterior reflector. The bulb socket and handle are mounted on the reflector.

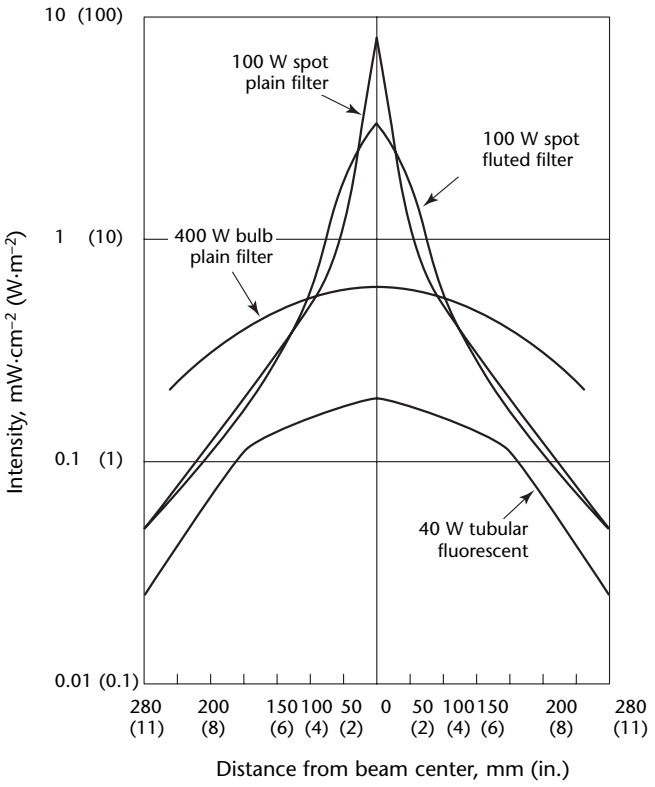
FIGURE 13. Portable ultraviolet lamp.



Although the 125 W bulb is bulkier than the 100 W model, it has a number of advantages. The 125 W lamps have less of a warmup period and come up to brilliance much faster. In addition, the 125 W bulb is much less susceptible to voltage variations.

There is still another ultraviolet source available, but it is not suitable for magnetic particle testing applications. It is an incandescent ultraviolet bulb in 75 and 150 W sizes. These are standard incandescent bulbs with a filter glass envelope. Measured on a standard ultraviolet meter, these sources produce ultraviolet irradiance similar to that of a 4 W fluorescent tubular source. In addition, the incandescent bulb produces nearly 30 times as much visible light as the fluorescent tubular sources. Experiments show that small discontinuity indications detected with other sources cannot be detected with incandescent ultraviolet sources. Large indications might be detectable but the high risk of missing indications makes incandescent ultraviolet bulbs unwise.

FIGURE 14. Intensity variations as function of distance from beam center for several ultraviolet sources.



Fluorescent Tubular Cold Discharge Ultraviolet Sources

Another type of ultraviolet radiation source for magnetic particle testing is the fluorescent tubular ultraviolet source. Electrically and mechanically, these standard fluorescent bulbs come with inputs from 2 to 60 W watts. They are cold discharge tubular lamps containing low pressure mercury vapor glow discharges. The primary radiation generated within the glass envelope is hard ultraviolet of 254 nm wavelength. The primary radiation is used to excite a special cerium activated calcium phosphate phosphor on the inside of the tube. This phosphor, when activated by ultraviolet radiation, emits ultraviolet radiation with a range of 320 to 440 nm, peaking at 360 nm.

Because a significant amount of visible light is emitted along with the ultraviolet, these bulbs are often made with a purple filter glass similar to that used over high pressure arc lamps. This filter greatly reduces the emitted ultraviolet but often still leaves an excessive amount of visible blue light, considering the relatively low intensity of its ultraviolet output. Figure 11 compares the spectral emission of the fluorescent tubular source to that of the high pressure mercury arc.

Selection of Tubular Lamps

Fluorescent tubular sources produce sufficient ultraviolet radiation but cannot be focused. The irradiance is much lower than that provided by the high pressure mercury arc lamps, so fluorescent tubular sources are inadequate for critical fluorescent magnetic particle tests.

Fluorescent tubular sources offer the significant advantages of instant starting, cool operation and low cost. Used in typical four-lamp fixtures, the 40 W tubular sources add up to 160 W and produce near ultraviolet radiation intensities of 1 to 5 $W \cdot m^{-2}$ at normal operating distances. Although fluorescent tubular sources may not meet certain specifications (ASTM E 1444,[7] for example), they are commonly used in industrial applications where stringent performance limits are not required.

Fluorescent tubular sources, especially in smaller sizes, are practical for battery powered, portable ultraviolet sources. Electrically, they are more efficient than high pressure mercury arc sources. More important, they start and reach full output in a few seconds rather than the 900 s (15 min) required by the high pressure arc.

Care of Ultraviolet Sources

Care should be taken to avoid breaking mercury vapor arc lamps. Mercury constitutes a significant health hazard. It is toxic and may also lead to cracking of aluminum and other metallic components that it contacts. Broken filters can permit exposure to dangerous hard radiation.

The output level of an ultraviolet source depends on the cleanliness of the filter, the applied voltage and the age of the bulb. To keep the output high, the filter should be periodically removed and cleaned, the voltage should be held constant and the bulb should be replaced when its output drops.

Low voltage can extinguish a mercury arc and gradually shorten the life of a bulb. Where line voltage is subject to wide fluctuations, with low points at 90 V or less, ultraviolet sources cannot be expected to operate properly (Fig. 15). High voltage surges also decrease bulb life. Line voltages above 130 V can cause very early burnouts.

On fluctuating power lines, specially designed constant voltage transformers are recommended to control voltage and extend the source's service life. An additional advantage is obtained by using such a transformer. Certain power lines are subject to sharp drops when heavy machinery is started, and the regulating transformer helps obviate cooling of ultraviolet sources before reignition.

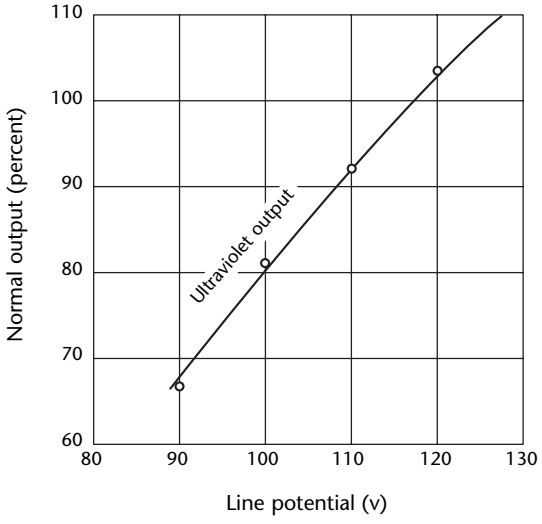
Service Life of Ultraviolet Bulbs

The ultraviolet output level of any bulb decreases with age. As a bulb nears the end of its life, output may drop as much as 75 percent. The service life of mercury arc ultraviolet bulbs varies widely, depending on their care and the original manufacturer. Nominal life expectancy is typically provided by the manufacturer (1000 h for a 100 W spot). For various reasons, the actual service life is less for a bulb in magnetic particle testing. The manufacturer's service life is an estimate based on a standard operating cycle in a fixed and ventilated position. Ultraviolet lamps used in magnetic particle testing are subject to numerous starts and shutoffs and to rough handling. In addition, because of filtering and portable housings, ultraviolet lamps for fluorescent tests often operate at higher than optimum temperatures.

The magnetic particle inspector can contribute to lamp life in two ways. One of these is to avoid operating ultraviolet sources above their rated voltage. Slight increases in voltage decrease lamp life substantially. In some tests, increasing supply voltage to between 125 and 130 V resulted in burned out lamps in as little as 48 h.

A second way to prolong the life of an ultraviolet source is to keep the number of starts as low as possible. Each time a lamp is started, a small amount of active material is removed from the electrodes. A single start is equivalent to several hours of continuous burning. It is generally more economical to leave lamps burning over rest periods and lunch hours than to turn them off and on again.

FIGURE 15. Variation in ultraviolet output of 100 W mercury arc lamp (normal power factor ballast and 117 V tap) as line voltage varies.



Ultraviolet Measurement

It is often difficult to determine the precise amount of ultraviolet radiation required to carry out a particular test. A suitable level can generally be determined by trials on reference standards with known discontinuities.

Fluorescent magnetic particle test interpretation may be considered a visual test, and most of the rules applicable to visible light testing apply. Because different amounts of ultraviolet radiation are necessary for different types of testing, some means of evaluating and specifying irradiance level is needed. Experience indicates that ultraviolet irradiance levels of 10 $W \cdot m^{-2}$ are generally adequate.

Selenium Cell Measurement of Ultraviolet Intensity

Beginning around 1942, selenium cell photoelectric meters were used to measure ultraviolet levels. The most common, easily used portable footcandle meters were designed for illumination engineers. It was discovered that if the filters were

removed from these meters, they became sensitive to ultraviolet radiation.

The lux or footcandle is a unit of visible light illuminance. It is defined in terms of the human eye's response under bright (photopic) conditions. There is no such thing as a footcandle of ultraviolet radiation. Ultraviolet radiation was incorrectly measured in footcandles for many years with unfiltered footcandle meters. Although unscientific, the results were reproducible.

In addition, such metering was always dependent on an uncontrolled portion of the spectral sensitivity of selenium. This part of the selenium response was of no concern to the manufacturer of the visible light meter and could have been changed at any time without notice and without effect on the visible light measurements. The effect on ultraviolet measurement could have been significant. Despite these disadvantages, no portable meter was then available to give true measurements in the near ultraviolet wavelength range.

Ultraviolet Meters

Ultraviolet energy is invisible electromagnetic radiation, similar to radio and infrared waves. These radiations are measured in energy per unit time or watts and frequently, as in the case of broadcast radio waves, in kilowatts. Ultraviolet power output can also be measured in watts but is more often stated in milliwatts (mW) or microwatts (µW). Although ultraviolet sources are commonly rated by their wattage, these figures are actually electrical energy input rather than optically radiated output. Because of conversion losses, the radiated output is much less than the input.

Measurement of ultraviolet irradiance requires equipment sensitive in that spectral region calibrated in watts per square meter ($W \cdot m^{-2}$), milliwatts per square centimeter ($mW \cdot cm^{-2}$) or microwatts per square centimeter ($\mu W \cdot cm^{-2}$). Such meters are typically filtered so that they respond only to the appropriate ultraviolet wavelengths (Fig. 16).

The ideal responsivity function for such a measurement in magnetic particle testing is a constant sensitivity from 320 to 400 nm (the near ultraviolet range) and zero sensitivity elsewhere. With such a responsivity, measurements can be accurate and straightforward. Unfortunately, large departures from this ideal responsivity are commonplace in ultraviolet meters. Detectors or filters needed for realizing the ideal are not available.

When the spectral distribution of a calibration lamp and the lamp to be measured are significantly different, the measured irradiance may err substantially. Some manufacturers sell equipment to calibrate radiometers primarily used with the 100 W parabolic ultraviolet source. Without a correction factor, such calibrated meters provide erroneous measurements.

All common industrial ultraviolet radiometers use a bandpass filter. Such filters have variable high transmission from 320 to 400 nm and much lower transmission elsewhere. An ultraviolet meter's ability to measure with minimal interference from other radiations is based on two characteristics: (1) its spectral flatness, the upper limit and constancy of its transmission in the ultraviolet region of interest, and (2) its blocking ability, the lower transmission limit that can be maintained at all other wavelengths. Interfering radiations, usually medium ultraviolet (ultraviolet B, 280 to 320 nm), visible (400 to 700 nm) and infrared (760 to 10^6 nm), can be particularly troublesome in magnetic particle testing.

Unfortunately, filters with sharp cut-on and sharp cut-off slopes are costly and unusual in magnetic particle testing meters. In addition, errors and confusion can be caused by radiometers with a spectral response wrong for the application. Military standards and other industry specifications clearly state that the spectral region of interest is 320 to 400 nm for magnetic particle tests. Typical spectra of lamps used in nondestructive testing are shown in Fig. 11.

Figure 16. Combined photometer and radiometer.



The excitation spectrum is such that some fluorescent magnetic particles increase in fluorescence efficiency beyond 380 nm. Also, the output of commonly used ultraviolet sources does not fall to zero at this wavelength. For these reasons, a meter whose sensitivity falls to zero at 380 nm may fail to explain why one type of lamp causes greater fluorescence than another type. The meter may also differ in relative readings from a radiometer with a spectral bandwidth extending to 400 nm. Using broader bandwidth radiometers generally gives a better indication of the quantity of usable ultraviolet.

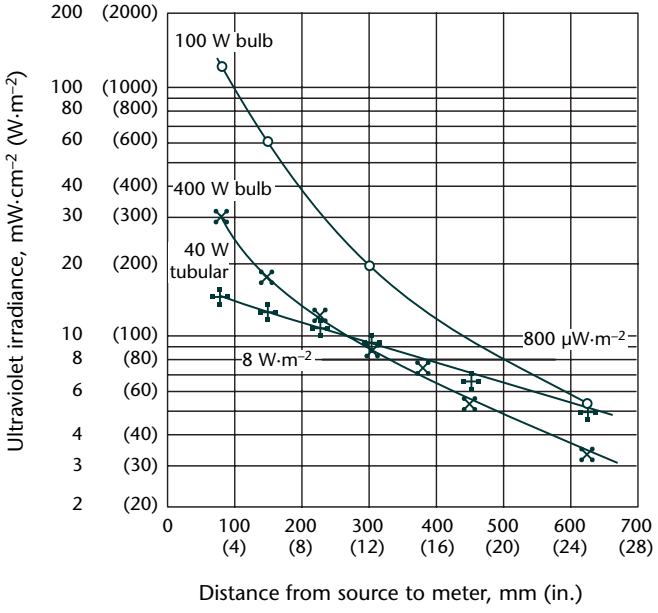
Units of Measure for Ultraviolet Sources

ASTM E 1444, *Standard Practice for Magnetic Particle Examination,*[7] calls for a minimum ultraviolet radiation intensity of 1000 μW·cm^{-2} (10 W·m^{-2}) at the test surface, with a maximum of 20 lx (2 ftc) of visible light in the testing area. Industry specifications vary.

As shown in Fig. 17, ultraviolet irradiances vary greatly with the distance between the light source and the radiometer and with the type and wattage of the source. Under normal conditions, irradiance does not vary as the inverse square of the distance. Ultraviolet sources are broad beam whereas the inverse square law applies to point sources.

Irradiance is an average over the area of the sensor, and most radiometers used in nondestructive testing have different sized apertures. For this reason, there may be some reading variations even if all sensors were similarly calibrated. The 100 W spot lamp used as a portable ultraviolet source produces a narrow beam of high intensity radiation, and some 125 W lamps can be even narrower. Such beams may not irradiate an entire area covered by a larger sensor, and measurements may then differ considerably from meters with smaller sensor areas.

FIGURE 17. Variations in ultraviolet irradiance with distance from source face for 400 W and 100 W tubular lamps.



Ultraviolet Radiometers

Ideally, the irradiance of a surface can be measured directly by placing a calibrated detector at that surface at any time, but this is usually not possible with radiometers. To avoid additional sources of error, it is essential that the complete area of the calibrated detector be irradiated. If at all possible, the detector should be oriented normally to the incident radiation to avoid modification of the detector's projected area and to minimize reflections from filters in front of the detector.

If it is not possible to have most of the incident radiation striking the detector perpendicularly, then an angular sensitivity plot for the detector system must be used to avoid large errors. Sensors with interference filters are especially prone to large errors if the irradiating source is tangential from the sensor face or if measurements are made close to extended sources.

A digital radiometer might have an uncalibrated, perforated metal plate transmitting for example 20 to 30 percent of the ultraviolet radiation striking it, depending on the geometry of the measurement. This transmission allows an effective scale extension up to (200 000 μW·cm^{-2}). The user would determine the multiplication factor of the metal attenuator under normal conditions. A radiometer could need a correction factor of 50 percent to measure fluorescent ultraviolet sources.

Not all meters are designed for the same range of conditions or for the particular conditions found in magnetic particle testing applications. Some meters are used in applications such as ultraviolet curing, photolithography or medical phototherapy where the spectral output of the source is very different from the sources used in magnetic particle testing.

Service Life of Ultraviolet Meters

Periodic recalibration is essential to maintain the reliability and accuracy of the ultraviolet meter. Apart from catastrophic events such as thermal or mechanical impact, the components of most radiometric sensors are subject to

deterioration, even with careful use. Ultraviolet filters are subject to aging effects, particularly those provided with the interference filters. Humidity and heat that build within the multilayer filter can irreversibly damage its transmission characteristics.

A plastic wavelength converter is used in most sensors to change the ultraviolet radiation to visible light closer to the peak sensitivity of the meter's photodiode. These converters undergo irreversible photochemical damage and must be replaced at regular intervals. Most manufacturers recommend recalibration every six months. If the meter is heavily used and under extreme environmental conditions, the recalibration period should be shortened.

PART 7. Alternative Ways to Excite Fluorescence

For fluorescent particle inspection, most standards specify ultraviolet radiation with a peak emission at 365 nm. Fluorescent particle inspection was enabled by and developed around the intense ultraviolet sources based on mercury vapor, which has an intense spectral emission line exactly at 365 nm. This led to the self-consistent system in which the particle manufacturers produce particles that fluoresce with adequate intensity when stimulated by these lamps. The particles do not necessarily have their maximum excitation exactly at 365 nm, but the excitation at that wavelength is strong enough that the particles perform well for inspections.

New sources of ultraviolet radiation are becoming available, including very high intensity lamps based on microdischarge technology and compact lamps based on ultraviolet light emitting diodes. The peak wavelength output of these sources is not necessarily at 365 nm. It is not even necessary that the excitation be in the ultraviolet range.

Blue Light Sources for Fluorescent Particle Inspection

The processes that underlie fluorescence of a material and discussed above may be excited by a range of wavelengths, not just one particular ideal wavelength. The excitation spectra for many of the fluorescent particles used regularly in nondestructive testing show that ultraviolet radiation is not needed to make them fluoresce. In some cases, other wavelengths of light are more efficient than ultraviolet at stimulating fluorescence.

Figure 18 shows the excitation spectrum for red fluorescent particles. Experience has demonstrated that this particle works well under ultraviolet radiation. The excitation spectrum shows that ultraviolet radiation near 365 nm is not the most efficient range for stimulating the fluorescence of this particle. The graph rises through the blue and has its peak in the green portion of the spectrum.

Even for a green fluorescent particle, ultraviolet might not be the ideal excitation wavelength. Figure 19 shows

FIGURE 18. Fluorescence excitation spectrum for ordinary red fluorescent magnetic particles. Ultraviolet radiation excites this particle well enough for practical use, but graph shows that blue and even green wavelengths would be more efficient at exciting fluorescence.

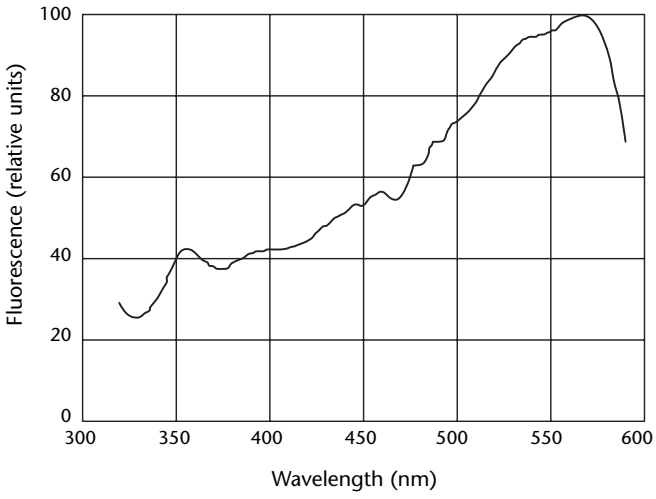
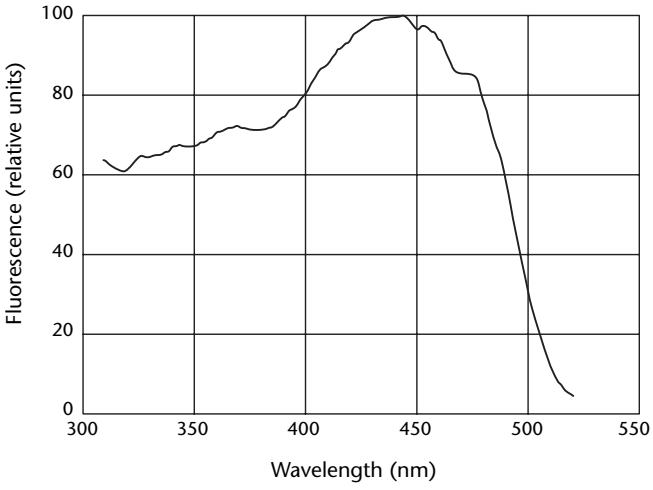


FIGURE 19. Fluorescence excitation spectrum for ordinary, green fluorescent magnetic particles. Ultraviolet excites this particle well enough for practical use, but graph shows that wavelengths in blue range would be more efficient at exciting fluorescence.



the excitation spectrum for another commercially available fluorescent magnetic particle. In this case, blue light in the 400 to 470 nm range is more efficient than ultraviolet radiation at exciting fluorescence.

For magnetic particle testing, fluorescence excitation lights have been introduced that use blue instead of ultraviolet radiation. These lights work because most of the available fluorescent magnetic particles have quite broad excitation spectra that extend well into the blue portion of the spectrum. The manufacturer of such alternative light sources must provide certification as to which particles can or cannot be used with the lights.

The additional challenge when using blue light for excitation is that, unlike ultraviolet radiation, blue light can be seen by humans. The intense blue light used for excitation would interfere with our ability to see the fluorescent indications, just the same as excess visible light in a fluorescent inspection area. This makes it necessary to use barrier filter glasses spectrally matched to the light source so that they block all of the reflected blue light while transmitting the fluorescence emission with high efficiency. For blue light, these would be yellow filter glasses with a sharp cut-off.

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CHAPTER 9

Recording of Magnetic Particle Indications

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PART 1. Basic Documentation[1]

Discontinuity indications formed by magnetic particle testing may be very visible on the surface of the test object at the time of the test but are seldom permanent or even durable. In many cases, it is desirable to make a permanent record of these indications. Sometimes, the record helps document and justify the return of a rejected part and in other cases the recorded indication helps prove that a discontinuity is small enough to be insignificant.

Indications may be recorded in two basic ways: (1) on the test object itself (often called *fixing*) or (2) on other media for storage remote from the test object. The text that follows includes data on fixing means, plus details on recording with media separate from the test object, including drawings and written descriptions, pressure sensitive tape transfers, alginate impressions, photography and magnetic rubber replicas.

Drawings and Written Descriptions

The simplest method of recording test indications is the written description. To be practical and meaningful, this written record must be detailed and descriptive. At the very least, it should include the sizes and locations of test indications.

Inspectors routinely keep written records to report their activities: dates, inspector' names, test locations and test results. If test objects are in a series, as in an assembly line, individual parts or batches of them can be numbered and identified in a report. If the test objects are part of a larger installation, such as plant equipment, the test locations can be identified by number on a map or diagram in the report. Additional information should be supplied as warranted by the application.

Drawings are often used in place of or as complements to written descriptions. Drawings can provide more information than written descriptions or they can be confusing, depending on the skill and dedication of the illustrator. If large numbers of similar test objects must be recorded by drawing, a master diagram can be prepared and copied. Indication records are then added to the copies by the magnetic particle inspector.

PART 2. Tape Transfers[1]

In the decades before digital photography (discussed below), a simple mechanical way to record magnetic particle indications was the tape transfer. This technique uses a piece of pressure sensitive tape pressed over the indication then lifted off and pressed onto a piece of paper that is kept as the test record. It is usually necessary to include some written description of the discontinuity location and orientation.

To make a good tape transfer, the test surface must be clean before the tape is positioned. Dust and dirt deactivate the adhesive if present in excessive amounts, as do water and oil. It is often necessary to clean the surface before the magnetic particle test is performed and again before the indication transfer is made.

Dry Technique Tape Transfers

Tape transfers are most easily made with dry magnetic particle tests. Large indications are usually produced with dry techniques and there is no moisture to resist the tape adhesive.

Excess magnetic powder is removed, usually by a gentle air flow, before the transfer is made. Once the indication is formed and the excess powder removed, a piece of tape sufficiently long to cover the desired area is pressed firmly over the indication. The tape is then lifted off the test object and pressed onto the paper backing that is retained as the record.

If fluorescent particles are used, dark colored paper (particularly black photographic paper) is the best backing. Most commercially available pressure sensitive tapes are fluorescent and greatly reduce contrast between the indication and the backing. If possible, nonfluorescent tape should be obtained for transfers with fluorescent particles.

Wet Technique Tape Transfers

Tape transfers can be made from wet indications but not as simply as from dry ones. The first requirement is that the object surface and the test indication be dry before the transfer is taken. The procedure is to form the indication normally, allow the excess bath to drain off and to then dry the surface before making the transfer. Wet surfaces prevent the tape from sticking properly and may dissolve the tape or adhesive.

Water Vehicle Tape Transfers

With water vehicle tests, the drying procedure can be fairly simple. Water dries quickly in a typical testing environment, leaving the test object surface in proper condition for a tape transfer.

If there is not enough time for the water vehicle to evaporate, or if the particle background is too dense, the test object can be gently rinsed with acetone. Acetone dissolves water and dries very quickly. It also rinses away some surface particles, performing the function of the dry technique air flow. However, caution must be exercised to avoid washing away indications.

Oil Vehicle Tape Transfers

With oil suspensions, drying is more difficult. Oil drains slower than water and dries much slower. With some very volatile oils, it may be possible to wait until the vehicle evaporates, but it is usually necessary to remove excess oil bath with a volatile solvent (petroleum ether, hexane or naphtha).

Rinsing with solvents must be done carefully to avoid loss of the indications and the solvent must be completely dry before the tape is placed.

Caution must be observed when using these solvents because some are very flammable. If possible, it is best to transport the processed test objects to a fume hood to rinse them. The area where rinsing is conducted must be well ventilated and free of sparks or other sources of ignition. Strict storage and handling restrictions apply to all flammable materials.

Wet Fluorescent Tape Transfers

Because wet technique particles are often fluorescent, the same procedures and precautions as mentioned for dry fluorescent particles must be observed. Black paper as a permanent backing for the retained tapes is particularly important.

Fluorescent indications may sometimes perform as visible light indications but their size and visibility are not ideal (particle concentrations are normally much lower than needed for white light visibility). Therefore, normal tape transfer techniques can provide low quality but usable transfers of fluorescent indications.

Archival Quality of Tape Transfers

Tape transfers of magnetic particle tests do deteriorate with time. The adhesive dries out and becomes brittle, and in some cases, so does the plastic tape base. The transfers then fall off the paper substrate and may be lost.

To minimize this problem, high quality translucent tapes should be used. Tape records should be stored in a cool and moist environment. Wrapping records in aluminum foil retards degradation of the tapes. Good tapes properly stored last at least five years and often longer. Serious deterioration may be expected from the best tape records in about ten years.

An alternative to tape transfers is digital photography, discussed below.

PART 3. Fixed Coatings for Test Indications[1]

A helpful but seldom used means of recording magnetic particle test indications is the fixing coating. These coatings are usually bulk materials that are gently sprayed onto the test object surface. The coatings can fix a discontinuity indication in one of two ways: (1) by binding the indication firmly in place on the test object or (2) by lifting the indication for preservation elsewhere, much like a tape transfer.

Only certain materials can be used as magnetic particle fixing coatings. Because test surfaces typically contain bath or other materials (scale, oil or water), a coating must adhere to the object surface in spite of contaminants. Specially formulated materials are required for this characteristic.

Application of Fixing Coatings

It is best to have the test object surface as clean and dry as possible before applying the coating. In production operations, this normally requires special drying equipment to complete the recording in a reasonable amount of time. Water baths are probably the easiest to fix because they have shorter drying times than other vehicles and because water does not emit noxious or flammable fumes.

Fixing on Test Object

One function of fixing coatings is to protect the test indications so that abrasion from mechanical handling does not damage the test result. Coatings designed for this purpose must be durable after drying.

Such coatings are typically applied by spray and may be water based or organic materials. The coating must dry before it can perform its protective function. In the interest of speed, drying equipment must often be provided.

Fixing for Removal from Test Object

The other type of fixing coating is designed to be stripped off the test object so that the actual indication is preserved elsewhere as a record of the test. These coatings are special materials containing a release agent that allows the dried coating to be lifted off the object surface. Usually a specially prepared pressure sensitive strip is pressed over the area and used to pick up the coating with its entrapped indication. The strip provides support for the coating and allows easier removal and storage.

With fluorescent indications, the usual precautions apply. Strips and coatings may be fluorescent and can compromise indication visibility.

Quality of Fixing Coatings

Test indications fixed to the test object retain their validity indefinitely while the test object is inactive. The characteristics of a normal service environment can quickly erode or mask typical test results fixed on the object surface. Fixed indications removed from the test object must be stored with the same precautions as tape transfer records. Humidity and temperature controls are needed to extend the life of fixed records.

The pressure sensitive strips used for removing a fixed indication are special grades of expensive materials. Their life expectancy is limited but longer than that of low grade tapes often used for simple tape transfers. The removed test indications may be mounted on paper backing, wrapped in foil and archived in a cool, moist environment.

PART 4. Alginate Impressions[1]

Alginate impression compounds are based on mixtures of potassium alginate, calcium sulfate, sequestering agents such as sodium phosphate, and fillers such as silica, diatomaceous earth or calcium carbonate. When the compound is mixed with a prescribed amount of water, a soft paste is formed. In 3 or 4 min, the paste becomes a rubbery solid with the characteristic of accurately conforming to and replicating, in negative, the surface to which it is applied. This physical record in one-to-one scale has proved valuable in many areas, as in dentistry.

The impression solid also absorbs and lifts particulate matter from the object surface and it is this absorption property that makes alginate compounds useful for recording magnetic particle indications. The primary benefit of these compounds is their ability to lift particle indications from test object locations that cannot be directly viewed by the inspector.

Application of Alginate Impression Techniques

To make alginate impressions, the test object is first processed through a typical magnetic particle test procedure. Discontinuity indications are allowed to form normally.

After the test, the alginate impression compound is mixed according to the instructions of the manufacturer. The mixed compound is immediately applied to the inspected part. The test object does not have to be dried before application of the recording media.

If the area of interest is a cavity, it should immediately be filled with the compound paste. If the area of interest is large or has a complex geometry, the recording compound can be applied to a thin polyethylene sheet and the sheet is then smoothed over the full test area. Movement of the sheet or excessively working the compound will smear the test indications.

After the paste sets into a solid, the magnetic particles are gently separated from the object by slowly peeling the polyethylene sheet away from the surface or gently dislodging the solid from its cavity. In a successful impression recording, the discontinuity indication is transferred to the compound material in its original size and shape. Test results may then be examined and interpreted at a convenient location remote from the test object surface.

Archival Quality of Alginate Impression Records

Because of their size, alginate impressions are difficult to retain for archival purposes. One procedure is to use the alginate impression to retrieve a discontinuity indication from an inaccessible location and to then photograph the indication for filing purposes. Supplementary documentation details the magnetic particle test technique, the impression recording procedure and the photographic data required for complete archival record keeping.

PART 5. Digital Photography and Image Archiving[2]

Digital photography is a valuable inspection tool. It can be used to record the test object in any method but is especially valuable to preserve test results in qualitative surface methods — liquid penetrant, magnetic particle and visual testing. Test results can be saved as an archive of the inspection, as is done with radiographs and ultrasonic displays.

In the twentieth century, articles about photography of surface tests featured advice specific to photographic film.[1,3,4] Digital techniques have obviated much of this information.

Also, in liquid penetrant and magnetic particle testing, surface indications have been documented by using transfers, strips of cellophane or transparent adhesive tape, to lift indications and attach them to reports.[1,5] These transfers had drawbacks: photocopy machines picked up glare from the tape, and lifting was impractical for wet techniques. Fluorescence itself would not be visible later and could not be photocopied. Film photography also kept the inspector from judging the adequacy of an image until the film was developed. Digital photography provides an immediate image so that a photograph can be retaken immediately if an image is unsatisfactory, without having to return to the site or repeat a test.

Documentation

Inspectors need to save images of test objects for various reasons — comparison, process control, training, documentation and quality assurance. Photographs demonstrate that the job was performed. The following measures can make photography a useful part of the inspection.

1. Few cameras let the operator name files, so keep a written log of photograph file names, who performed the tests, when, test parameters and any circumstances of interest.
2. Write information such as the test number, location and time — information like that used to identify radiographs — on a small card or piece of paper and place it by the test object within the camera's field of view. This step makes it easier to identify and sort test photographs later. A ruler or tape measure in the photograph will provide scale.
3. Photograph the reference standard at the time of inspection and include its image with the documentation.
4. Specify or describe photography in the written procedures.

The visible characteristics of photographs are affected by the photographer's choice of settings. Some options are hardware specific and can be selected at the moment a test is documented — zoom, for example. Camera models change every year: for desired settings, inspectors should consult the owner's manual of the camera used. A good rule of thumb is that the resulting image should provide visible information like that in the reference standards used for discontinuity evaluation.

Some conditions are controlled at the time of photography — illumination, for example. Some photographic settings can be modified later — a color image may be changed to gray scale for printing in a manual, for example.

Photographing of Indications

Photography is art. Digital technology has made it faster, easier and less expensive than it was in the twentieth century, but doing it well requires training and practice. Basic principles still apply, with changes due to the digital medium. Books are available on the subject.[6,7]

Compact Camera versus Reflex Cameras

There are two general types of digital cameras in use today. They are the single-lens reflex and the compact camera. The single lens reflex is more sophisticated and more versatile. Its special feature is that the scene is viewed through the lens by a system of mirrors and prisms. This gives a very clear view of 95 percent or more of the picture area. These cameras have a liquid crystal display on the back where images already in the camera and operational menus can be viewed. These cameras use interchangeable lenses allowing a large

selection of focal lengths. Most professionals use this type of camera.

The other type of camera is the compact camera. Here, the scene is viewed on the liquid crystal display on the back of the camera. Some of these cameras also allow viewing with another liquid crystal display in an eyepiece or by an optical viewer above the lens. This optical eyepiece shows only about two thirds of the picture area and does not exactly align with the lens, so this feature should not be used for scene selection in indication photography. Compact cameras are the normal consumer's choice because they are smaller, simpler and less expensive than the digital single lens reflex. They can often do an adequate job of indication photography.

Focal Length and Field of View

To capture maximum detail, the inspector wants the area of interest to be as large as possible within the camera's field of view. Many cameras offer optical zoom, letting the user move the lens telescopically to "zoom in on" a subject and capture more detail in a closeup. The same advantage can be achieved simply by moving closer to the subject. Some digital cameras achieve zoom inexpensively by something called *digital zoom,* which amounts to cropping the image; this expedient sacrifices details because not all the pixels are retained.

Camera focal length determines the angle of view and the depth of field. Short focal lengths give wide angles of view; long focal lengths give narrow angles of view. Short focal lengths give large depth of field; long focal lengths give small depth of field. The closer the subject is to the camera, the smaller the depth of field will be.

Indication photography is basically close-up or macro photography, *macro* meaning that the image is viewed in a scale larger than the original subject. For indication photography at close range, depth of field is a problem. Small depth of field may cause parts of the subject to be out of focus, making the photographic record unacceptable. Therefore, camera equipment and settings should be used that keep the indication in focus. Many *cameras have a setting for macro* photography that changes the lens to improve focus at close range. The macro setting does not alter the number of pixels.

In general, focal lengths should be short for indication photography. Short focal lengths maximize depth of field and permit closer working distances. On a digital lens single-reflex camera with typical midrange lens, the minimum focusing distance is around 500 mm (20 in.). Closer work needs a macro lens, close-up screw-on lenses or extension tube. Most compact cameras will focus down to 75 mm (3 in.) so special attachments are not necessary.

Very close-up photography usually means very limited depth of field. If a test exposure shows some desired areas are out of focus, depth of field can be increased by using a smaller lens aperture (higher f-stop). A smaller aperture may require a slower shutter speed and blurring from camera movement.

Digital cameras focus automatically, but the object of interest must be centered in the camera's field of view. Also, the range finder used for focusing in many cameras is acoustic and will not work through transparent obstacles such as window glass.

Illumination

Direct lighting from incandescent lamps can cause artifacts — light reflecting from the test object, for example, or refracted light creating glare in the camera lens. Indirect lighting and overhead illumination from fluorescent lamps help minimize this problem.

Anybody taking photographs outdoors is aware of light and avoids dark shadows. A portable flood lamp or camera flash may remedy dim lighting for a test.

Digital cameras adjust automatically to dim illumination, and subsequent image processing may salvage a dark photograph. However, a test should be performed only if reference standard indications are visible on-site and at the moment of inspection.

Digital cameras are so sensitive that flash is not often necessary. Flash illumination with digital cameras should be avoided at close range, less than 0.6 m (2 ft). Because most indication photographs will be made at this distance or closer, such photographs will be overexposed. Furthermore, in most cases the flash is very close to the camera lens and cannot be removed. Flash from such equipment is sometimes reflected directly back into the camera, producing glare. Therefore flash photographs of indications will normally be made only if all else fails.

Exposure Duration and Sensitivity

Because a macro image is enlarged, camera motion during exposure will be magnified and proper procedures are needed to avoid blurring. Briefer exposures and image stabilization help but do not eliminate the problem. Camera motion can be eliminated by using a tripod or by bracing the camera against a solid object. If this is not possible, one

must use the highest practical shutter speed. Even with image stabilization, shutter speed should not exceed 0.03 s. With a tripod, it is wise to use a cable release or self timer to avoid moving the camera while pressing the shutter release. The self timer function lets the camera release the shutter without motion from hand pressure.

Digital cameras let the sensitivity of the camera be adjusted over a very wide range. With film, sensitivity or exposure index could only be changed by changing the film, and even the most sensitive films were not as sensitive as the digital cameras. In more sensitive films, increased grain size causes spots in the picture. Unfortunately, digital cameras have the same problem. Photographs made with high exposure sensitivities also show graininess, called *noise*. This noise gets worse as sensitivity increases. True, one can make digital photographs in the dark, but the photographs may be so grainy as to be unacceptable. Thus, the photographer must compromise all the above factors to get acceptable indication photographs.

Effect of Exposure Duration on Contrast

The purpose of an indication is to make a discontinuity visible. This means making the indication contrast strongly with the background. Usually there is enough contrast, but for emphasis it is often desirable to increase this contrast. Most digital cameras can be set to give more contrast. However, it is often easier and more practical to adjust contrast with an image editing program in the computer.

Similarly, the inspector should try to expose the photograph properly. In indication photography, a bad exposure may be redone unless the inspector or the test object moves on before the problem is noticed. A great aid to getting proper exposure is the histogram display, usually available via the menu. The histogram appears as a mountain and valley profile in the display. The right side of the display indicates the amount of bright tones; the left side, dark tones. Ideally, the display should look like a mountain more or less in the middle. If the mountain is off to either side of the display, the photograph is either overexposed or underexposed. Should this be the case, reset the camera and retake the shot if possible.

Badly underexposed shots can often be brightened to a useable degree with image editing software, but excessive graininess may be present. Software can often make slightly overexposed shots useable with some loss of detail. Badly overexposed areas cannot be corrected and are lost. Therefore, if one must err in exposure with digital photography, underexposure is better than overexposure.

White Balance

Photographs can have unnatural tints. When the picture is taken, this effect can be mitigated through a control called *white balance* on digital cameras. Unrealistic tints can be removed so that objects that appear white on site are white in the image. If skin appears too pink or too green, for instance, then the problem may be corrected through white balance. The white balance control lets the photographer adjust the tint of an image by scrolling through a spectrum of tint options in a single dial and selecting the most realistic one.

Most digital cameras also have a way for the user to tell the camera under what type of illumination a photograph is being taken. White balance takes into account the colors of the light source and adjusts the relative amounts of red, green and blue primary colors so that neutral colors are correct before the image is recorded.

Color can be balanced again later, in image processing. The selection of the RAW file format, discussed below, makes this easier.

When photographing indications, color is often unimportant. Therefore, white balance is usually not critical as it is in most photography. In fact, gray scale (black and white) indication photographs may be preferable. Digital cameras normally record in color, but in some cases they can be set to produce gray scale. And it is easy for software to convert images to gray scale.

Photography is a process which has many variables. It is necessary to do some experimentation to get good results. As equipment becomes better, the process should become still easier and more accurate.

Fluorescence

In many cases, the indications to be photographed will be fluorescent. The magnetic particle inspector does not want to photograph ultraviolet radiation as such but instead wants to photograph the nonultraviolet radiation known as *fluorescence*. Ultraviolet radiation is invisible to the human eye; to be seen, its energy needs to be converted into visible light. A fluorescent magnetic particle indication is not ultraviolet, or else no one could see it. Similarly, photographs called *ultraviolet* are usually visible translations of ultraviolet originals.

As in night photography, the ambient area will be partially dark and bright

indications will stand out in the photograph. The following measures may help the inspector photograph fluorescent indications.

1. Try night camera settings if the image is taken in a dark area.
2. Notice if wavelengths or colors are being filtered or enhanced, either with hardware (by a screen at the lens, for instance) or digitally. A test object viewed with protective goggles may look different in a photograph.
3. Consult reference standards with known discontinuities to select camera settings and filters.
4. Keep notes about circumstances that might affect discontinuity evaluation.

Dark Background

To prevent a haze on dark background, the ultraviolet radiation must be filtered. A standard photographic ultraviolet radiation filter is effective for this purpose. If the camera has filter threads on the front of the lens, a filter of the proper size can easily be attached. Unfortunately, many compact cameras do not have such threads. In such cases, it is necessary to improvise. An ultraviolet filter can be held over the lens during exposure. It is also possible to tape a filter over the lens. However, most compact cameras have a battery saving feature which shuts off the camera after a short period, and often retracts the lens into the body at the same time. Tape placed around the lens body may then prevent the lens from retracting and cause a mechanical failure. If a filter is attached by tape, the tape should be on the camera body, not the lens. Also, the shutdown time might be adjustable via a menu to minimize the problem at the cost of decreased battery life.

When photographing fluorescent indications, the background should be dark but still visible. One should be able to see the test object as well as the indications. Usually, there is enough visible light leaking through the ultraviolet filters both on the lamp and the camera to make the test object visible. This illumination can often be adjusted with the image adjusting software. It is also possible to use a brief visible light exposure by turning on a white light in the area.

Pixels

Digital photographs are designed for a computer display. A display consists of a grid of squares called *picture elements*, or *pixels*. Displays range from 320 × 240 pixels to over 3840 × 2400. A standard display of 800 × 600 pixels is called a *super video graphics array*. It is superseded in most computers but remains popular in mobile devices.

Each pixel is part of a larger image, and more samples provide a more accurate representation of the original. Pixels are rectangular and on computer monitors are usually square. The square shape is an artifact of the display; the original electronic datum is dimensionless. Pixels may be translated into dots for printing. *Dot* and *pixel* are interchangeable terms: for example, dots per inch (DPI) and pixels per inch (PPI) are equivalent measures of resolution, discussed below.

There are two classes of graphic file formats. Line drawings use mathematical calculations called *vectors* to plot lines and are not considered here. Raster images, or bit mapped images, assign hue and intensity values to each pixel and are used for photography. Table 1 lists common file formats for digital images. Some cameras

Table 1. File formats of computer images.

Designation	Format
Lossless Raster Formats	
BMP	bit mapped picture
DIB	device independent bitmap
PIC	three-letter file extension for PICT
PCT	three-letter file extension for PICT
PICT	picture metafile
RAW	extension for undeveloped image from digital camera (virtually lossless)
TIF	three-letter file extension for TIFF
TIFF	tagged image file format
Lossy Raster Formats	
GIF	graphics interchange format, native to CompuServe® internet service provider
IFF	Interchange file format
JFF	JPEG file format
JFIF	JPEG file interchange format
JIF	JPEG image format
JPEG	Joint Photographic Experts Group, a standards organization
JPG	three-letter file extension for JPEG
PBM	portable bit map
PGM	portable gray map
PNG	portable network graphics
RAW	extension for undeveloped image from digital camera (virtually lossless)
XBM	X bit map
Vector Formats (for line drawings)	
CGM	computer graphics metafile
EMF	enhanced metafile, version of WMF
EPS	encapsulated postscript, native to Adobe® software
PDF	portable document format, native to Adobe® software
SVG	scalable vector graphics
SWF	Shockwave Flash®

use proprietary formats similar to these common file formats.

A *bit map* defines an image and color for all pixels in the image. TIFF and JPG files are bitmapped. A bit map does not need to contain color coded information for each pixel in every row. It needs to contain information indicating a new color as the display scans along the row. For this reason, an image with much solid color requires a small bit map.

The term *pixel* can also mean an element in a sensor array. An array is a group of adjacent receptors each of which records a single point of radiation and which together provide a composite picture. Such arrays are in cameras and other radiation detectors (X-ray fluoroscopes and infrared cameras) at various wavelengths.

File Formats

File formatting has been evolving rapidly with advances in digital technology. Several standards may be consulted or referenced for digital image archives.[8-11]

The file formats for digital photographs fall into two classes: lossy and lossless (Table 1). Lossy formats compress files to save hard disk space. A format is said to be *lossy* when digital information and hence image detail are lost. JPG files are lossy and are used in many digital cameras and web pages because their compression makes small files and because they can be viewed on personal computers. Lossless TIFF and PICT and nearly lossless RAW formats provide similar files but use more disk memory.

Inspectors who archive digital photographs need to be aware that converting files from a lossless to a lossy format (for example, from a TIFF to a JPG) can degrade images so that some details, such as crack tips, are harder to see. There are several occasions when this sort of image degradation can take place: (1) when a file is changed from a lossless to a lossy format, such as TIFF to JPG; (2) when a lossy image is converted to a file with lower size or resolution; (3) when an image is imported into a document created by a word processing or layout program. This reduction may be inadvertent, caused by program settings. Of course, an image conversion may have no effect on the usefulness of the resulting image: though degraded, it may still show all features of interest.

Procedures need to be clear so that they can be followed. The procedures describing how photographs are archived should include definitions of *lossy* and *lossless* and of file formats so that the results can be interpreted later.

The purpose of the camera RAW format is to record all of the exact data from the camera's sensor and any other metadata, such as time and camera settings. Camera RAW files are much larger than JPG files. Some RAW formats do not use compression; others implement lossy data compression to reduce file size without affecting image quality. Camera RAW formats avoid the compression artifacts inherent in JPG files. RAW files have many advantages over JPG files, including the following:

1. Image quality is higher.
2. RAW conversion software gives the user fine control of more parameters such as lightness, color balance, hue and saturation.
3. Edits are performed nondestructively, without degrading image quality.
4. The image is not compressed; if lossless, the maximum amount of image detail is always kept within the file.

Camera manufacturers use different versions of RAW format. As of 2008, there is no widely accepted standard for RAW format, so more specialized software may be required to open RAW files than to open standardized formats like JPG or TIFF. Cameras that support RAW files typically come with proprietary software for conversion of their RAW format to TIFF or JPG. To retrieve an image from a RAW file, the data must first be converted into a red, green and blue (RGB) image.

Because of proprietary formatting, some formats listed in Table 1 are in fact families of related formats. There are several forms of TIFF and of PNG, for example, and a given version may not work with a given program. Before using new equipment, the inspector will want to check that test images can be transferred to and viewed with hardware at the archiving location.

Image Characteristics

Many computer programs are widely available for processing digital images. They let the user adjust settings that, in the twentieth century, used to rely on the skill of a photographer at the moment of image capture or film development.

Color

Hue. A color is described by its hue, saturation and value (HSV). Hue is what is normally thought of as color. A digital color in a computer display is a blend of three primary hues: red, green and blue. Saturation is the intensity or dominance of a hue: a hue can be increased or diminished in an image just as black

versus white can be adjusted in an image through all shades of gray. Value is the lightness or darkness of a hue and is usually called *brightness* when the three hues are combined in white light. Image processing software permits the intensity and value of these hues to be adjusted independently within each image.

Conversion to Gray. If the image is converted to gray scale, as in a report printout, care must be taken that features of interest remain visible: a fluorescent nondestructive test indication in brilliant green may disappear entirely if it changes to a shade of gray like that in an adjacent area.

Color Balance. The camera setting of white balance, discussed above, can improve the realism of color photographs by preventing unnatural tints. Image processing programs also enable improvement of color balance. Program menus may refer to it by other terms, such as *color intensity* or *hue saturation*.

If a photograph is taken in a digital camera's RAW file format, image colors can be fixed without information loss. Most cameras take RAW photos in twelve-bit color (4096 shades per color) instead of eight-bit color (256 shades per color), enabling powerful balance adjustments without visible loss in quality.

Size

The more pixels in an image, the more information it carries. An image's quantity of pixels is its true size in the dimensionless electronic space of the computer.

To be viewed, the image must be translated to a medium such as a computer display or printed page, where details become visible to human eyes in order to be interpreted. In a process known as *scaling*, the pixels can be compressed or spread out to fit the desired viewing surface (Fig. 1). Scaling affects resolution, discussed below.

Image size and resolution are usually expressed in terms of image width, in the horizontal dimension. The size and resolution of the vertical scale can be manipulated independently but to prevent distortion usually undergo the same processes as the horizontal.

The number of pixels in an image can be decreased or increased in a step called *resampling* or *conversion*. Resampling cannot add more data to a photograph once it has been shot.

Resolution

The resolution of an image is its ability to distinguish small adjacent objects. Two thin adjacent lines appear as two thin lines, for instance, and not as one thicker line. Resolution depends on the number of pixels in the image and hence on its file size. In Fig. 2, two versions of the same image show the difference between high and low resolution. Details in an image cannot be restored simply by converting it to a higher resolution or from a lossy to a lossless format. Once an image's resolution is reduced, details are lost. If a display's resolution exceeds an image's resolution, the image will look blurry.

FIGURE 1. Example of scaling of digital image.

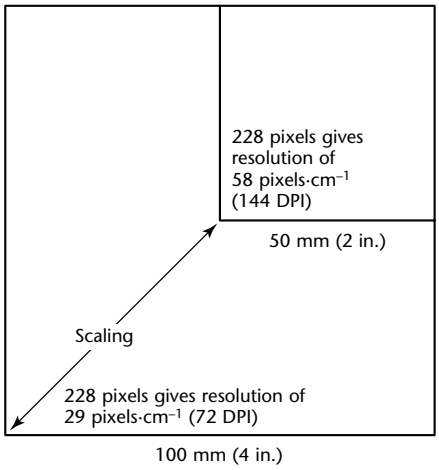
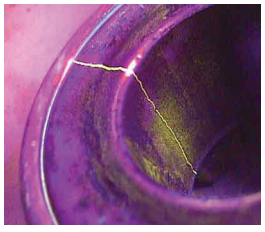
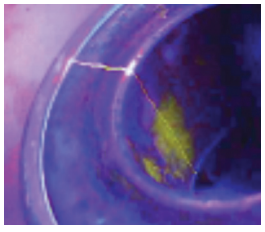


FIGURE 2. Visible light photograph showing magnetic particle indication under ultraviolet lamp: (a) high resolution, at 40 pixels·cm^{-1} (100 PPI); (b) low resolution, at 10 pixels·cm^{-1} (25 PPI). Lower resolution blurs details. Lowering resolution sometimes enhances contrast or increases hue intensity — side effects better achieved by image processes that do not sacrifice detail.

(a)



(b)



Resolution is measured in dots per inch (DPI) for printers or square pixels per inch (PPI) for computer displays, measured along the horizontal axis. Alternatives using SI metric units are to specify pixels per centimeter (pixels·cm^{-1}) or the pixel width in micrometers (μm).

Because the number of pixels in a scalable image is fixed, however, an expression of resolution is meaningless unless the viewed image size is also specified. If a given digital image is reduced to half its width, for instance, the number of pixels per unit of width and the resolution are doubled (Fig. 1). The data in the image file may remain the same, but smaller size makes details harder to see. Someone processing digital images must make decisions balancing image size versus resolution.

Brightness

Brightness is the common term for the luminance of light emitted by each pixel. Usually, one control setting adjusts brightness to affect all pixels in an image simultaneously. This parameter can be adjusted to compensate for poor visibility on overcast days. Too little brightness can make a picture dark as night, and too much brightness can make it washed out so no features stand out.

Saturation. In a color image, saturation is the intensity of a hue. A hue of zero saturation is black or gray. If all three hues have zero saturation, the image is colorless, black.

Contrast. The setting of contrast controls the degree of difference between light intensities at different points in the image. Like brightness, contrast is adjusted to affect all pixels in an image at once. As contrast is increased, for example, a dark indication becomes easier to see on a bright background and a bright indication becomes more visible on a dark background.

Contrast and brightness interact closely, and the inspector must sometimes adjust them to find the correct settings for each photograph. Figure 3 shows the effect of brightness and contrast on an image.

FIGURE 3. Photograph of cracked rod: (a) high contrast, high brightness; (b) high contrast, low brightness; (c) low contrast, high brightness; (d) low contrast, low brightness.

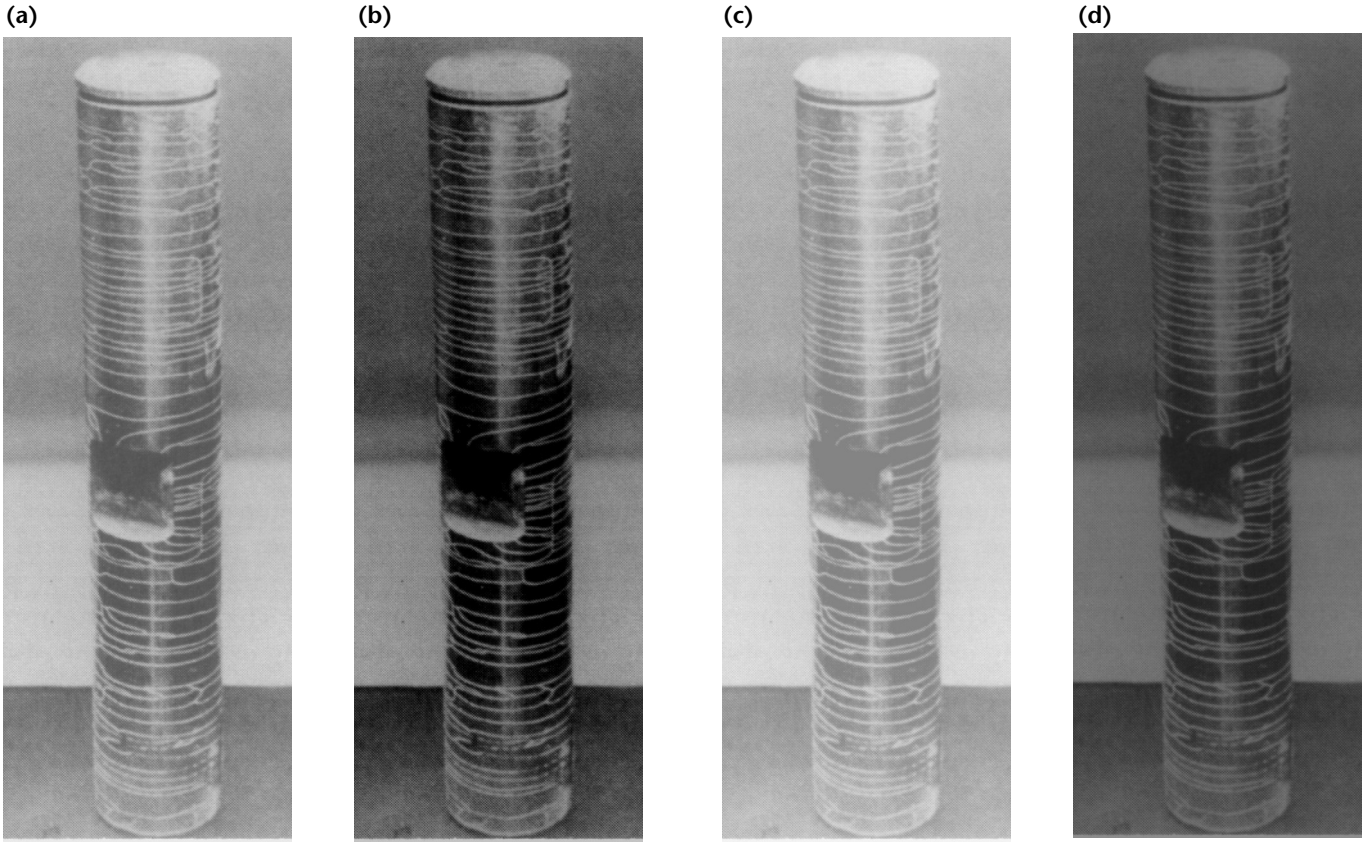


Image Integrity

Inspectors may be tempted to enhance images to justify accept/reject decisions. This temptation should be treated with caution. The inspector may consider several rules of thumb.

1. Local features including indications must not be exaggerated or obscured using image processing tools having descriptors such as *pencil, eraser, flood, spray* or *smudge*. These alterations of an image could be considered falsification of test results.
2. Image settings such as zoom, brightness and contrast may be freely adjusted, as photographers have done for generations.
3. A photograph of the reference standard should be included in the archive and used to evaluate modifications made to test images. How do the same modifications affect discontinuity visibility in the reference standard?

For some applications, a written statement on image processing may be a desirable part of an inspection procedure. Accept/reject decisions are usually made at the moment of inspection and in the presence of the test object. If some decisions are made later, that protocol can be documented in the procedure.

In some archives, a file's metadata, including its creation date, are part of its documentation. These metadata can be lost if an image is saved in another format.

Closing

In practice, the viewing quality of a digital photograph depends on several factors.

1. The vision acuity of the viewing human can be impaired by medical conditions such as myopia and color blindness.
2. The visibility of a shot is affected by things such as light and camera position.
3. The useful detail in an image is affected by its size and by its quality in terms of features such as contrast and resolution.

Technology has given the inspector options beyond the scope of the present discussion: (1) light measurement and illumination, (2) optical gaging and range finding, (3) photography sensitive to other wavelengths, including ultraviolet and infrared, and (4) video documentation of inspection, more for procedures than for indications. These and other options depend on hardware. The present discussion also does not consider marine environments or extremes of altitude or temperature.

Most inspectors already use a computer for communication, for research and for writing procedures. With the investment of a few hundred dollars for a camera and software, an inspector can add digital photography to the inspection options. With practice and planning, digital photography can be a valuable tool for inspection and quality control.

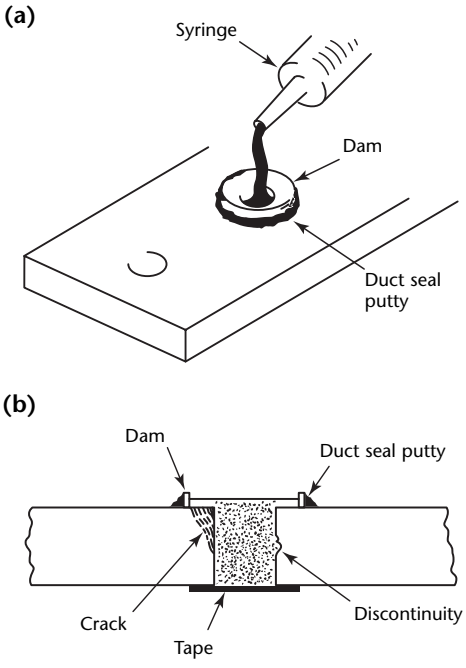
PART 6. Magnetic Rubber[1]

Magnetic rubber provides a nondestructive test technique for detecting cracks or other discontinuities on or near the surface of ferromagnetic materials. Magnetic rubber is a mixture of silicones and petroleum hydrocarbon distillate. Its controlled viscosity rubber base holds a dispersion of magnetic particles and cures at room temperature. The test object is magnetized with the uncured rubber covering the area of interest. The magnetic particles then migrate to the leakage field caused by a discontinuity.

As the rubber cures, discontinuity indications remain in place on the surface of the rubber touching the test object. After curing, the rubber is removed from the test object and the test results are interpreted in a convenient location.

The technique is described in SAE AMS I 83387.[12] Figures 4 to 6 depict the magnetic rubber inspection process. Figures 7 and 8 show the preparation for magnetic rubber tests of horizontal and vertical fastener holes.

FIGURE 4. Typical magnetic test using magnetic rubber: (a) rubber application; (b) cross section of inspected hole.



Its principal applications are in certain problem areas having (1) limited visual or mechanical accessibility, (2) coated surfaces, (3) complex shapes or poor surface conditions and (4) discontinuities that require magnification for detection and interpretation.

FIGURE 5. Magnetic leakage at material discontinuity causes particles in magnetic rubber to migrate and concentrate over discontinuity: (a) yoke positioning; (b) cross section of inspected hole.

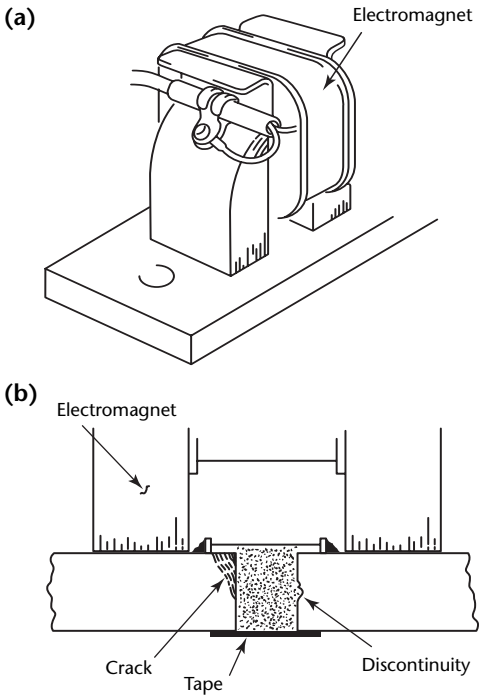
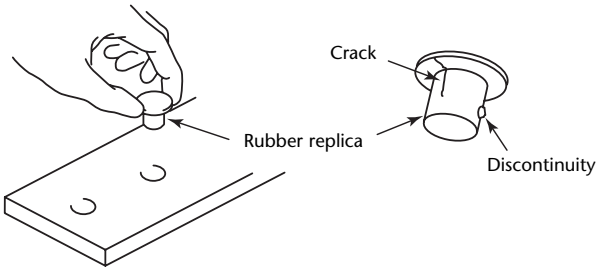


FIGURE 6. After curing, magnetic rubber replica is removed from test surface, revealing crack as dark line. Other surface discontinuities and conditions are also shown.



Magnetic Rubber Supplies

Magnetic rubber techniques require special supplies and equipment (Table 2) Necessary cleaning materials include organic solvents. The solvents must be able to dissolve oil and grease and must be stored with appropriate precautions. Water, air pressure and strong detergents may also be used for cleaning.

FIGURE 7. Horizontal hole preparation for magnetic rubber inspection.

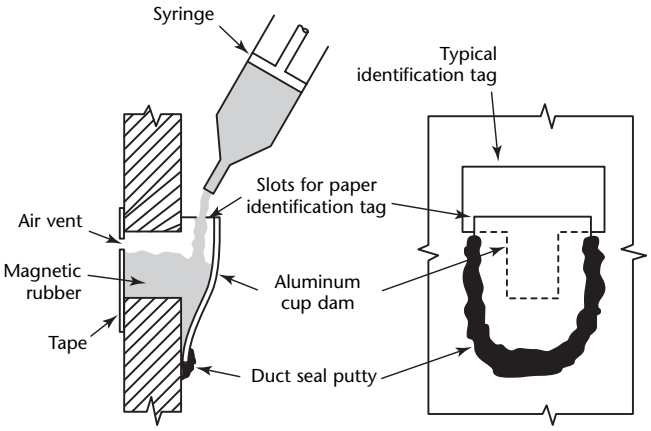
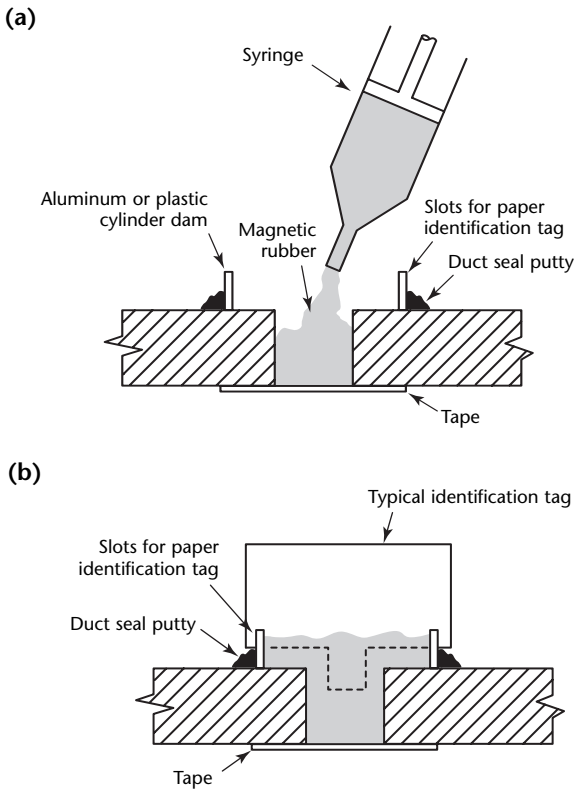


FIGURE 8. Vertical hole preparation for magnetic rubber inspection: (a) rubber application; (b) site identification.



There are three formulations of magnetic rubber (Tables 3 to 5). The more viscous and slower curing provides medium sensitivity. The one with lowest viscosity is most sensitive. A slightly more viscous and very slightly less sensitive formula has a yellow coloring agent. Yellow makes the indications more noticeable to the inspector reading the replica, thereby improving the probability of detection of very small cracks.

Magnetizing Equipment

Magnetic rubber test techniques require the same kinds of magnetizing systems used for dry technique magnetic particle tests. The system may include yoke, prods, clamps, coils or central conductors with alternating or direct current. The direct current yoke is preferred for magnetization. Permanent magnets may be used in certain applications.

TABLE 2. Materials and accessories for magnetic rubber inspection.

Basic Materials
- Magnetic rubber compound
- Catalysts (dibutyl tin dilaurate and stannous octoate)
- Cure stabilizer (water with acetone)
- Duct seal putty
- Masking or duct tape
- Aluminum foil
- Release agent (not silicone based) to help remove replicas

Material Preparation Accessories
- Small disposable cups (paper or plastic)
- Balance scale (0.1 to 1000 g)
- Disposable syringes, 20 to 50 mL (20 to 50 cm^3)
- Disposable stirrers

Optional Special Equipment
- Central conductor and dam (assorted sizes)
- Electromagnetic yoke with fixed or articulated legs
- Electronic magnetic field indicator (tesla meter)
- Geometric pole pieces that fit test object
- Mechanical shaker (such as paint shaker)
- Microscope (7× to 10×) for tiny indications
- Permanent bar magnets
- Vacuum chamber

TABLE 3. Magnetic rubber formulations.

Viscosity	Curing	Sensitivity
50 Pa·s (500 cP)	slow	medium
10.5 Pa·s (105 cP)	fast	high, colored
10 Pa·s (100 cP)	fast	high

Test Object Preparation

Using the chosen cleaning solvent, oil, grease and soils are removed from the test surface. Also remove metal burrs, smears and sharp edges. Be sure the surface is dry and free of loose debris before proceeding.

If needed, a central conductor and dam assembly (Fig. 9) are then installed and connected. Using tape, foil and duct seal putty, a reservoir is formed for the magnetic rubber. Virtually any test object configuration can be prepared for magnetic rubber inspection using a dam assembly. Upside down surfaces can be tested by building a reservoir beneath the test area and pressure filling it with magnetic rubber. A vent hole must be provided in the reservoir to prevent entrapment of air.

TABLE 4. Recommended magnetic field intensities and durations for magnetic rubber. Variations are required for specific applications.

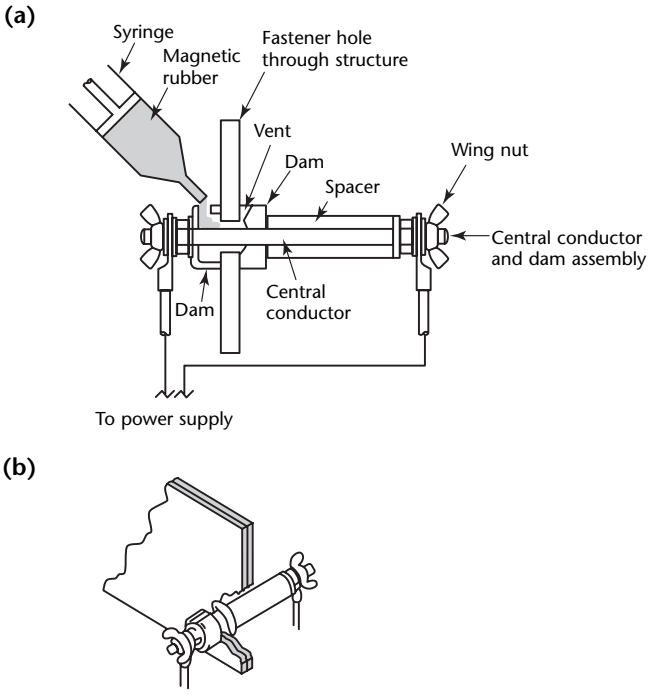
Tested Area	Viscosity Pa·s	(cP)	Field Intensity mT	(G)	Magnetization Duration in Each Direction (s)
Holes, uncoated	50	(500)	5 to 10	(50 to 100)	30
	10.5	(105)	3 to 5	(30 to 50)	30
	10	(100)	3 to 5	(30 to 50)	30
Holes, coated	same as uncoated		same as uncoated		longer than uncoated; depending on coating thickness
Surfaces, uncoated	50	(500)	15	(150)	60
	50	(500)	10	(100)	180
	50	(500)	5	(50)	600
	10	(100)	10	(100)	30
	10.5	(105)	5	(50)	60
	10.5	(105)	3	(30)	120
Holes, coated	same as uncoated		same as uncoated		longer than uncoated; depending on coating thickness

TABLE 5. Formula for magnetic rubber inspection material starting with 10 mL (10 cm^3) of rubber base.

T-12 Catalyst[a] (drops)	T-9 Catalyst[b] (drops)	Cure Stabilizer[c] (drops)	Pot Life (min)	Cure Time (min)
Formula for High Viscosity, 50 Pa·s (500 cP)				
10[d]	0[d]	2	8	60
5	0	2	15	120
2	0	2	30	240
Formula for Medium Viscosity, 10.5 Pa·s (105 cP)				
2	2	0	5	15 to 20
3	3	0	3	10 to 15
4	4	0	2	5 to 10
15[e]	0	2	10[e]	75[e]
Formula for Low Viscosity, 10 Pa·s (100 cP)				
1	1	0	5	15 to 20
2	2	0	3	10
15[e]	0	2	10[e]	75[e]

a. Dibutyl tin dilaurate.
b. Stannous octoate.
c. Water with acetone.
d. Do not use more catalyst than indicated for 1 h cure. Use only this catalyst system.
e. Very sensitive formula for long pot life.

FIGURE 9. Typical central conductor setup for magnetic rubber inspection of horizontal or vertical fastener holes: (a) cutaway view of fastener; (b) cross section through the fastener hole.

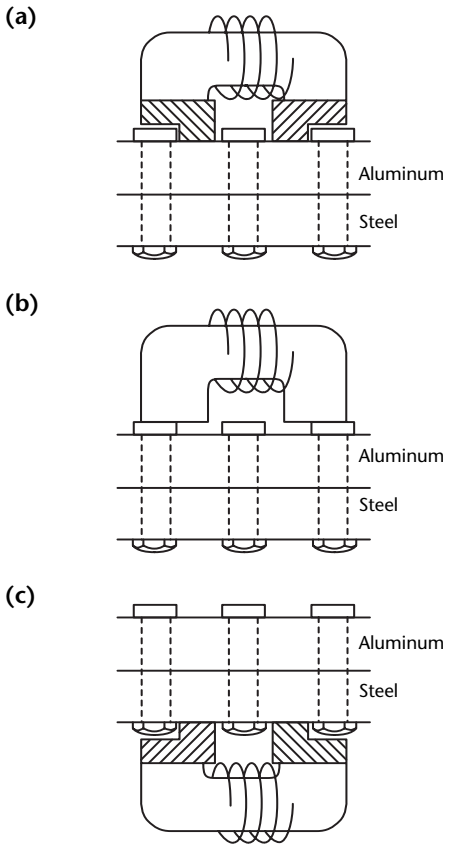


Magnetization and Current Parameters

Magnetization may be applied with (1) portable electromagnets or yokes, (2) central conductors, (3) conventional magnetic particle units with clamps, prods or coils or (4) permanent magnets. Direct current yokes are preferred. In areas of limited access, steel extensions or pole pieces may be used to extend the magnetic circuit to include the test object. Permanent magnets may be useful in certain specialized situations where test object shape makes magnetization with yokes difficult. The magnetic fields produced by permanent magnets are often quite low and sometimes unreliable. Permanent magnets should be used only if specific procedures have been developed using reference standards with known discontinuities.

Central conductors are best suited for fastener and attachment holes, particularly when there are layers of material requiring replication.

FIGURE 10. Good and bad magnetic contact for magnetic rubber inspection: (a) very little magnetic flux getting through aluminum to steel; (b) better magnetic field from leaving steel bolts in place; (c) best magnetic field from magnetizing from steel side.

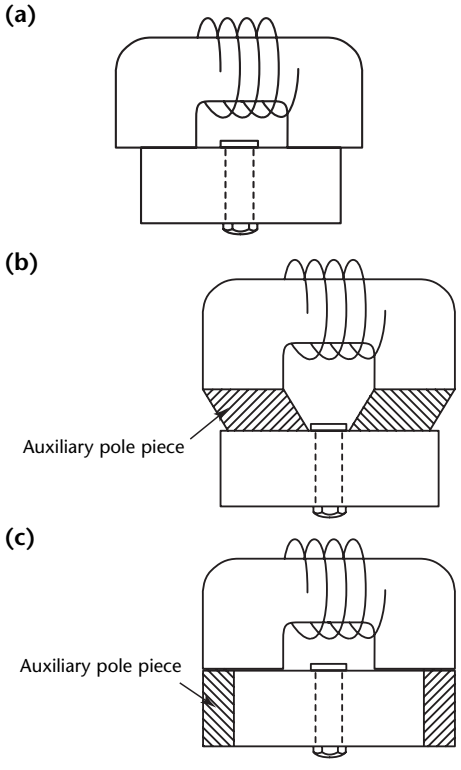


Good magnetic contact is critical. Magnetic field intensity is greatly reduced with poor contact between the test object and magnetizing yoke. To increase contact, auxiliary pole pieces may be machined from soft iron and attached to the poles of electromagnets. Pole pieces should be designed to have the smallest possible reduction of cross section consistent with space requirements. Figures 10 to 13 demonstrate good and bad magnetic contact arrangements and the use of pole pieces.

Magnetic field requirements include both field intensity, duration and direction of the field. Field intensity and duration are detailed in Table 4.

Determine the direction of the field. Cracks and other discontinuities are displayed more strongly when they lie perpendicular to the magnetic lines of force. When the discontinuity direction is uncertain, the magnetism should be applied from two directions to increase reliability: after magnetizing in one direction, the magnetization source is rotated 90 degrees and applied again. When the direction of a discontinuity is known, only one magnetizing direction is required.

FIGURE 11. Improved contact and improved magnetic field using pole pieces: (a) poor contact (field partially lost); (b) field improved with addition of pole pieces; (c) magnetic field and contact improved with correct pole piece configuration.



Measure the magnetic field intensity using a tesla meter by placing the probe in the hole or on the surface to be inspected. The transverse probe can measure the field parallel to the part surface and will be used most often.

Preparing and Applying of Magnetic Rubber

Magnetic rubber is prepared according to manufacturer specifications and is mixed only a few minutes or seconds before application.

First, to resuspend the magnetic particles, the base rubber is thoroughly mixed with a wooden tongue depressor or spatula. Mixing should continue until the material contains no streaks or color variations. Materials that have settled should be agitated by a mechanical shaker, such as a paint shaker.

Weigh or measure the specified amount of magnetic rubber into a paper cup or other disposable container. About 1 g of base material is equivalent to 1 mL (1 cm^3) of material. Do not measure out more material than can be used within the allowable magnetization period.

Deaerate the material if air bubbles are a problem. This is done by placing the mixed material in a vacuum chamber and reducing the pressure to between 85 and 100 kPa (25 to 30 in. Hg) for 60 to 120 s.

Catalyst and Stabilizer

The catalyst, stabilizer or both are added as in Table 5. Higher humidity or higher temperature will increase the cure rate. When temperature or humidity change, or when material from a different batch is used first, mixing a small test batch to determine optimum ratios of catalyst to base material is recommended. If the cure is too fast and the rubber starts to gel before magnetization is complete, the process will need to be repeated. Using a tongue depressor or equivalent, thoroughly stir the mixture. Avoid whipping air into the mixture.

Applying of Rubber to Test Object

When testing holes with scored surfaces, small diameters or unusual configurations, the test area may be coated with a thin layer of petrolatum, or release agent to aid removal of the replica. The release agent **must not** be of the silicone variety. Rubber may be applied by

FIGURE 12. Improved contact and improved magnetic field using pole pieces: (a) very poor contact (field partially lost); (b) radius magnetism much improved with pole piece.

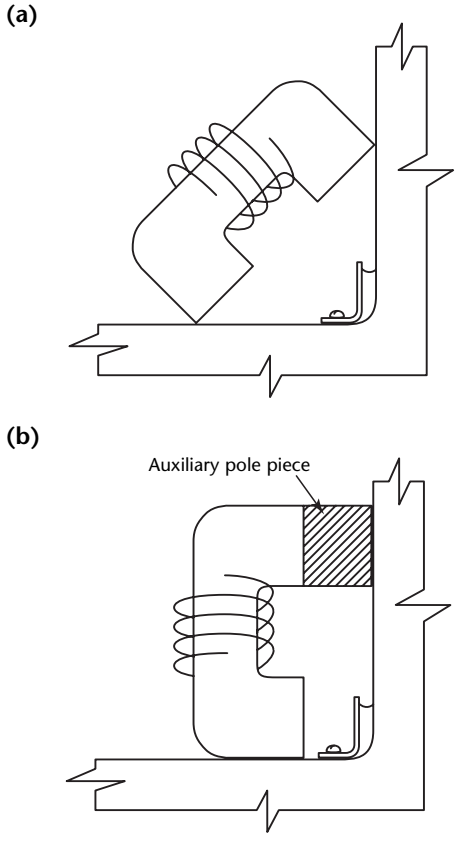
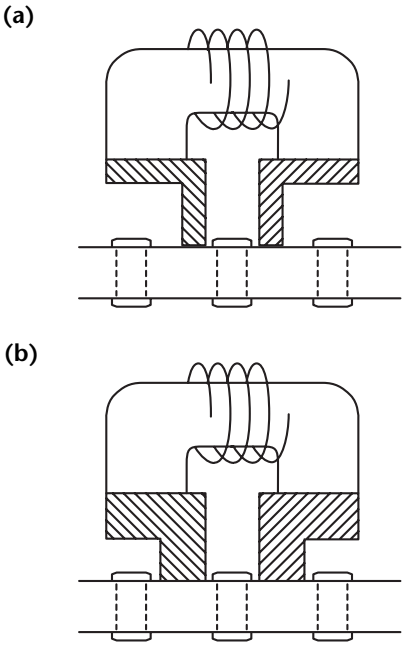


FIGURE 13. Correct positioning of pole pieces: (a) pole pieces reduce cross section unnecessarily; (b) greater cross section reduces loss of field.



pouring from the disposable container if sufficient access is available. Inaccessible areas, or overhead applications, may be filled with a disposable syringe. Such areas must be equipped with vent holes to let air escape and let rubber completely fill the cavity. These vent holes must often be closed with tape or putty after filling to prevent escape of the rubber compound

Magnetization commences and must be completed in the allotted time. Allow the magnetic rubber to cure for the time specified by the chosen formula. Avoid movement of the test object and contamination of the magnetic rubber while it cures. To determine that the magnetic rubber is completely cured, lightly touch the replica or the mixture remaining in the mixing container to check that it is no longer sticky.

To remove the replica, first remove tape, aluminum dam, duct seal putty and central conductor dam assembly, then carefully extract the replica from the test area. The replica must be identified by a tag or label or by placing it in a labeled container.

The replica is then visually examined for its condition and discontinuity indications. A low powered microscope (at least 10×) will aid in locating minute discontinuities in the inspection site. After inspection, test objects may be demagnetized per instructions and cleaned with solvent or vapor degreased if necessary.

Archival Quality of Magnetic Rubber Records

The magnetic rubber technique is not a means of recording indications from a typical magnetic particle test. It is a different test procedure, requiring its own test parameters and its own specialized equipment.

Advantages of the technique are as follows.

1. Inspections may be performed in areas of limited visual or mechanical access.
2. Inspections may be performed through paint, coatings and on parts of any shape.
3. Inspections may be performed using low levels of magnetization by varying cure times of the rubber.
4. Inspections may be performed in very small or threaded surfaces.
5. Magnetic rubber provides a permanent replica of the test object surface as well as the particle discontinuity indications. This record may be retained intact for as long as space is available. Magnetic rubber replicas may also be photographed for archival purposes.

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10

CHAPTER

Reference Standards for Magnetic Particle Testing[1]

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PART 1. Fundamentals of Reference Standards for Magnetic Particle Testing

Nondestructive tests are typically designed to reveal the presence of discontinuities or to measure specific properties in a structure or material. The discontinuity may be an anomaly in a homogeneous material or a change in one of the material's properties, such as thickness, hardness or density.

Before testing, some form of artificial discontinuity or reference standard is commonly used to verify the operation of a magnetic particle testing system. This verification is performed (1) to provide a sensitivity check of the testing procedure and (2) to establish a known correlation between the response of the test system, the magnitude of the material property or the severity of a discontinuity.

Magnetic particle testing uses magnetic fields to inspect ferromagnetic materials. Discontinuities in the material cause disturbances in the magnetic field which in turn produce a leakage flux. It is this leakage flux that permits the formation of particle indications. Both the direction and intensity of the magnetic field are critical in determining the sensitivity of the test procedure. Both of these factors are affected by the nature of the material, the test object geometry and the way in which the magnetic field is induced.

All of these parameters are interrelated to determine the direction and intensity of the magnetic field in a particular location in a test object. The mathematics of these interrelationships does not lend itself to straightforward, closed form solutions even for relatively simple geometries. A generalized solution for more complex test objects has not been obtained and would probably not completely solve the problem of establishing magnetic particle testing procedures.

Empirical Rules for Reference Standards

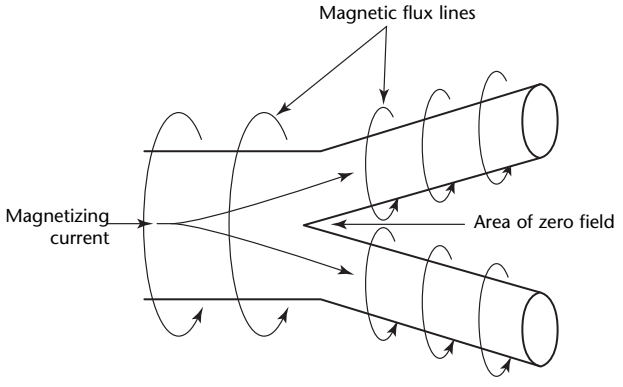
Perhaps more than any other nondestructive technique, magnetic particle testing has based its procedures on empirical data (rules of thumb) developed by trial and error in the early days of the technique. These rules have persisted through the years in various standards and specifications. The reliance on empirical data occurred because of the enormous complexity of magnetic fields and their interactions with ferromagnetic components. Unfortunately, rules of thumb have sometimes been used exclusively for determining the adequacy of certain test setups. As with most empirical data, the rules developed for magnetic particle testing should be used with caution and with an understanding of their limits. Caution dictates that regular system monitoring be used to verify acceptable test sensitivity — most existing formulas cause overmagnetization of some test objects.

It is easy to demonstrate the connection between misused rules of magnetization and inaccurate testing. Figure 1 shows where a null field is produced at the fork in a simple test object configuration. Failure to use some form of field intensity indicator to verify the presence of a valid magnetic flux could lead to inadequate testing of this critical area. Measurements with the means described here have shown a variation from 0.3 to 8.5 mT (3 to 85 G) within the same test object, because of its geometric differences.

Reliability Studies

The absence of magnetic field verification has led to widely varying test effectiveness. Two often cited reliability studies are excellent examples of the problems associated with the lack of a sensitivity check. The first of the studies[2] was the result of a round robin among four major aerospace contractors, two jet

FIGURE 1. Magnetic particle testing problem area in simple part geometry.



engine manufacturers, three landing gear manufacturers, one major forging supplier and a commercial test lab. Each company processed and tested 24 pedigreed specimens with known discontinuities. All of the discontinuities were considered detectable at that time in the technique's development.

The companies varied from less than 20 percent detection to over 90 percent. Only one of the eleven companies scored better than 60 percent of the discontinuities. At the time of its completion, the study drew few conclusions about the cause for this variability. Another study[3] concluded that the maximum probability of detection was 55 percent on jet turbine blades made of magnetic alloys. The reasons for the poor results were not individually assessed.

Needs for Known Indicator

The goal of system monitoring is to verify that the system is performing in the desired way and at the desired sensitivity. The most direct way to achieve this goal is to verify the system's ability to detect one or more known discontinuities. Ideally this would be done with a discontinuity of the smallest critical size in an exact duplicate of the test piece. This ideal is rarely if ever practical.

More often, some form of artificial discontinuity indicator is used. This reference standard is designed to help evaluate several aspects of a magnetic particle system's performance, including (1) testing the magnetizing equipment, (2) checking the sensitivity of the magnetic particle compound and (3) verifying the adequacy of a test procedure for detecting discontinuities of a predetermined magnitude.

System Evaluation

Unlike equipment for other nondestructive testing methods, magnetic particle testing systems give little evidence of malfunction. The absence of a test indication could mean (1) that tests were properly performed on samples without discontinuities or (2) that the testing system was not working and therefore not locating existing discontinuities.

As a result, some form of reference standard is needed to determine proper system performance and adequate sensitivity. Such a system evaluation tool should check for contamination of the magnetic particle bath, material visibility (loss of fluorescence on fluorescent oxides), particle concentration (for wet techniques), adequate particle mobility and the generation of an appropriate magnetic field.

System Standardization

When multiple variables can affect the outcome of a test, a means should be used to normalize or standardize the test. This ensures that consistent, repeatable results are achieved, independent of the machine, the operator or the time of the test.

The most direct way to achieve consistent results is to regularly use a reference standard to compare system sensitivity to preestablished tolerances. If the desired sensitivity is not achieved, testing should be stopped to allow required system adjustments.

Parametric Evaluations

It is at times useful to examine a system's sensitivity to changes in one or more variables. For example, to evaluate the effectiveness of magnetic particle testing on chromium plated components, it would be appropriate to investigate (1) the effect of various plating thicknesses, (2) the sensitivity of the test to changes in current levels or field intensity and (3) the effect of changes in the particle type or bath concentration.

Reference standards are used to study these changing parameters. Indications of the known discontinuities help determine the effect of the individual parameters on test sensitivity. The results of such studies are used to generate or modify testing procedures for the material and geometry of interest.

Technique Development

In the past, it was common for some operators to rely solely on empirical rules for establishing magnetic particle testing procedures. This practice frequently lead to overmagnetization, poor coverage, inappropriate selection of test geometries or some combination of all three disadvantages.

The selection of an appropriate test technique may be the single most important factor in the success of a magnetic particle test. Reference standards and artificial indications can significantly improve system performance and may also reduce the cost of testing by eliminating unnecessary configurations or scrap caused by excessive current. Reference standards used during technique development can quickly verify the completeness of coverage, the direction of magnetizing fields and the level of field intensities.

In many cases, it can be demonstrated that common rules of thumb produce field intensities far in excess of those

necessary for detecting particular discontinuities. Excessive field intensity might appear to provide a margin of safety for unknown effects of test object material and geometry. However, in many cases, this excess produces a significant field component normal to the test object surface. This in turn reduces particle mobility, increases particle background and actually reduces rather than enhances the sensitivity of the test. Reference standards are often used to regulate field intensity to avoid excess flux while achieving accurate indications.

Two kinds of artificial discontinuities are used for magnetic particle test systems: (1) those designed to indicate the adequacy of the field in an unknown test object and (2) those designed to measure the effectiveness of the testing system independent of the test object.

PART 2. Reference Standards for System Evaluation

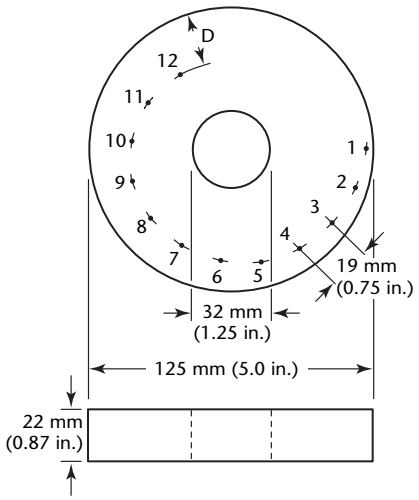
Reference standards may be used to evaluate the functionality or performance of a magnetic particle testing system. On a periodic basis, reference standards are used as test objects to monitor the system for changes in magnetic field production, particle concentration, visibility or contamination. It is helpful to have graduated discontinuities so that a numerical indicator of the system performance can be recorded and monitored.

Tool Steel Ring Standard

The tool steel ring is a commonly used and universally recognized reference standard for magnetic particle testing systems (Fig. 2 and Table 1) but essentially indicates only particle efficacy. Since its introduction in the 1940s, it appears in virtually all United States codes and specifications as the means for checking magnetic particle performance.[4]

The ring is widely used for measuring system performance for both wet and dry techniques. It is important, however, to recognize the ring's limits. For example, a current density level less than 20 percent of that usually applied (Table 2) is all that is needed to indicate a surface discontinuity 0.25 mm (0.01 in.) in length.

FIGURE 2. Tool steel ring standard (see Table 1).



The ring standard is used by passing a specified direct current through a conductor which in turn passes through the ring's center. The magnetic particle testing procedure (or system) is evaluated based on the number of holes detected at various current levels. The number of holes that should be detected at a

TABLE 1. Comparative dimensions for tool steel ring having diameter of 125 mm (5 in.) (Fig. 2). Hole diameters are 1.78 mm (0.07 in.) each.

Hole Number	Distance from Edge to Center of Hole	
	mm	(in.)
1	1.8	(0.07)
2	3.6	(0.14)
3	5.3	(0.21)
4	7.1	(0.28)
5	9.0	(0.35)
6	10.7	(0.42)
7	12.5	(0.49)
8	14.2	(0.56)
9	16.0	(0.63)
10	17.8	(0.70)
11	19.6	(0.77)
12	21.4	(0.84)

TABLE 2. Amperage and indications for test rings per SAE AS 5282.[7]

Suspension Type	Full-Wave or Half-Wave Direct Current (A)	Minimum Quantity of Holes
Wet fluorescent	500	3
	1000	5
	1500	6
	2500	7
	3500	9
Wet visible	500	3
	1000	4
	1500	5
	2500	6
	3500	8
Dry powder	500	4
	1000	6
	1500	7
	2500	8
	3500	9

particular current level is provided by written specifications (Tables 2 and 3).[5-7]

Standard test objects such as the ring have proven to be a valuable aid in controlling magnetic particle test system parameters.[8] However, in addition to magnetizing current level, other factors influence test results, including the properties of the particles, operator skill, magnetization level, direction of the magnetic fields produced and particle concentration. An evaluation of all the contributing factors requires the development of mathematical models[9] to describe their effect on the formation of test indications.[10]

Ring Standard Magnetic Fields

All magnetic leakage fields are a superposition of dipolar fields. This dipole character is usually evident when the field from the discontinuity is measured.[11,12] The field arising from a long cylindrical discontinuity in a linear isotropic medium can be exactly calculated and has a pure dipolar character. The coordinate system is defined in Fig. 3. The applied field has a value of H_0 and is in the X direction.

This is a classic problem in magnetostatics[13] whose solution in the region of permeability m_1 consists of the vector sum of the applied field H_0 with a dipole field centered at the origin. The dipole field can be written in polar coordinates as:

$$\textbf{(1)} \quad H_r = -m\frac{\cos\theta}{r^2}$$

$$\textbf{(2)} \quad H_\theta = -m\frac{\sin\theta}{r^2}$$

Figure 3 shows these variables. Dipole moment m of length along the cylinder axis is given by:

TABLE 3. Amperage and hole indication requirements for tool steel rings with hardness of 187 to 221 brinnell.

Suspension Type	Full-Wave or Half-Wave Direct Current (A)	Minimum Quantity of Holes
Wet fluorescent	1400	3
	2500	5
	3400	6
Wet visible	1400	3
	2500	5
	3400	6
Dry powder	1400	4
	2500	6
	3400	7

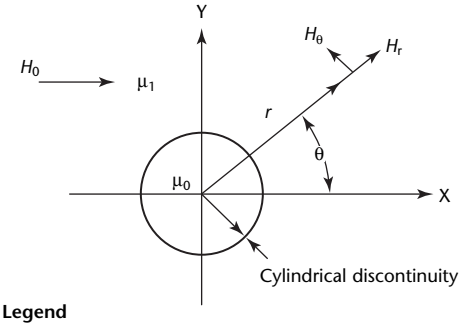
$$\textbf{(3)} \quad m = \frac{\mu_1 - \mu_0}{\mu_1 + \mu_0} H_0 a^2$$

The field from the cylindrical discontinuity is exactly that which would be obtained from a magnetic dipole m of intensity per unit length centered at the origin and pointing in the negative X direction (because $\mu_1 > \mu_0$), or that which would be obtained from a current dipole with a current separation product of $2\pi_m$ pointing in the negative Y direction.

Boundary Influence

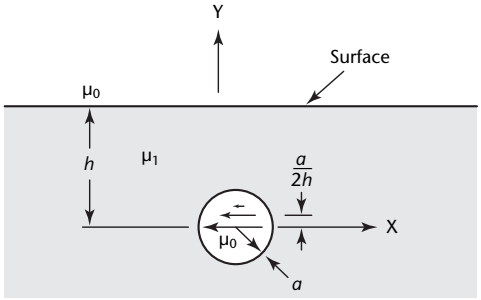
The field from a cylindrical discontinuity next to a plane boundary can be obtained by using the technique of images. The field above the plane surface is the sum of the fields from a dipole at the center of a discontinuity (Fig. 4) with intensity as

FIGURE 3. Coordinate system for cylindrical discontinuities.



Legend
H_0 = applied magnetic field intensity
H_r = axial magnetic field intensity
H_θ = radial magnetic field intensity
r = radial distance of field of interest
X,Y = directional axes
μ_0 = original permeability
μ_1 = permeability of test material

FIGURE 4. Dipole images for field from cylindrical discontinuity next to plane surface.



Legend
a = radius of cylindrical discontinuity
h = depth of discontinuity
X,Y = directional axes
μ_0 = original permeability
μ_1 = permeability of test material

given by Eq. 3 and an infinite series of images. To a good approximation, when $h > 2a$, all image dipoles are assumed to be at the center of the cylinder.[14] The field above the surface can then be described by Eqs. 1 and 2 (rather than by Eq. 3), with m given by:

$$(4) \quad m = \frac{2\mu_1}{\mu_1 + \mu_0} \times \left[1 + \left(\frac{\mu_1 - \mu_0}{\mu_1 + \mu_0}\right)^2 \left(\frac{a}{2h}\right)^2\right] \times H_0 a^2$$

Magnetic particle test materials generally have μ1 >> μ0. The major effect of the surface is an approximate doubling of the effective dipolar field from the first term on the right of Eq. 4 and a small increase from the second term (about 7 percent when h = 2a).

Sample Leakage Field Calculation

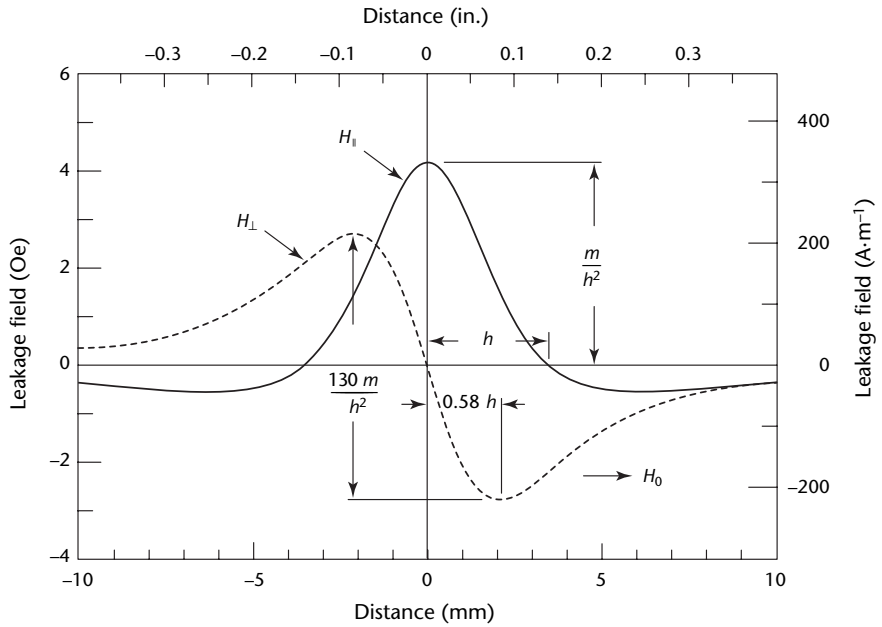
The calculated field from a subsurface cylindrical discontinuity (as obtained by Eqs. 1, 2 and 4) has the familiar form illustrated in Fig. 5. The illustration shows the components tangential and perpendicular to the surface (the most commonly measured components).

The numerical values are based on the hole depth (h = 3.56 mm or 0.14 in.) and hole radius (a = 0.89 mm or 0.03 in.) of hole 2 in the ring, with a central conductor current of 1000 A. This corresponds to an H_0 value of 2.5 kA·m^{-1} (31.5 Oe). This calculation applies to the ideal case of a linear isotropic magnetic medium with a high permeability, a two-dimensional geometry (a cylindrical discontinuity of infinite length) and a plane parallel boundary. Although the test ring of Fig. 2 deviates considerably from this ideal condition, comparison of measured leakage fields with the form shown in Fig. 5 reveals that the leakage fields from the ring can be closely approximated by Eqs. 1 and 2.

Consistency of Ring Standard

A discussion of magnetic particle bath quality says that specification SAE AS 5282, *Tool Steel Ring for Magnetic Particle Inspection,* "has identified and corrected inconsistencies that have clouded the usefulness of the ring in the past. Previously, baths were used to verify the rings which, in turn, were used to verify the baths. The use of a mechanism using magnetic probes to indicate the magnetic properties of a ring have eliminated this seeming conundrum and resulted in a much more uniform industry standard.

FIGURE 5. Calculated components of magnetic leakage field at surface of subsurface cylindrical discontinuity in linear isotropic magnetic medium with high permeability and with applied field in positive X direction.



Legend

h = depth of discontinuity
H_0 = applied magnetic field intensity
$H_\perp$ = perpendicular magnetic field intensity
$H_\parallel$ = parallel magnetic field intensity
m = dipole moment per unit length

Still, the procedure for magnetizing the ring and applying the bath needs to be uniformly administered for consistently meaningful observations."[7,15]

Reference Standard Test Blocks

Split Prism Test Block

The prism block shown in Fig. 6 is another reference standard containing an artificial discontinuity.[16] Truncated half-prisms are built with one face at an angle. When two such components are bolted together, an artificial crack is formed. The sloped surface of the block provides variable distances from the conductor.

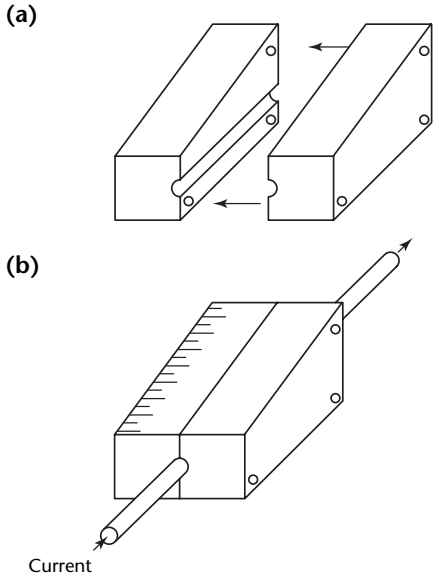
When current is passed through the conductor, the leakage field from the crack gradually weakens along the prism face. A current of specified amperage is applied through the conductor and the length of the magnetic particle indication is used to measure the test sensitivity.

Magnetized Test Blocks

Another version of the block standard consists of two ground steel blocks forming an artificial crack at their contact surfaces, similar to the discontinuity formation in the split prism test block. On one of the face ends, a small permanent magnet is fixed below a brass cover, causing magnetic flux leakage from the artificial discontinuity. This leakage field decreases with greater distance from the magnet, so that longer discontinuity indications reveal higher test sensitivity.

This same task can be fulfilled by another block standard using a slightly different test principle: a residually magnetized block is manufactured to contain a network of many different crack widths on its surface (Fig. 7). A typical standard of this type is 50 mm (2 in.) in diameter and 10 mm (0.4 in.) thick. Very fine cracks are situated between grosser discontinuities across the block standard's face. As an example of this standard's use, the loss of indications for the fine cracks (or their appearance as points rather than lines) indicates that the magnetic particle bath is no longer effective.

FIGURE 6. Prism sensitivity indicator: (a) separate blocks; (b) artificial crack.



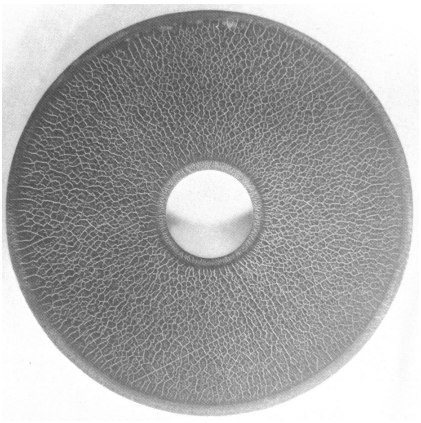
Other Tools for Performance Checks

For performance tests, in addition to tool steel rings and test blocks, ASTM E 709[6] lists several tools available to the inspector: the hall effect device, pie gage, shim and test plate. They can help to quickly confirm system settings. Some are also used during discontinuity evaluation to determine parameters such as field direction and are discussed in that context elsewhere in this chapter.

Test Plate

For performance tests, in addition to the tool steel ring, ASTM E 709[6] describes a test plate that should be of a composition and thickness like that of the test object. The test plate measures at least 250 × 300 mm (10 × 12 in.) and bears electro discharge machined notches like those in shims and pie gages.

FIGURE 7. Residually magnetized block standard.



PART 3. Magnetic Discontinuity Standards

Artificial discontinuity standards and magnetic field indicators of the shared flux type all have some common characteristics. The basic shared flux gage was developed by B. Berthold and was first used in Germany in the late 1930s to indicate magnetic field direction. Refinements have resulted in the pie gage, widely used in weld testing applications (specified by T9074-AS-GIB-010/271).[17] This device responds to applied magnetic fields independently of the test object.

On flat ferromagnetic surfaces, the shared flux devices respond well and verify magnetic field intensities that can detect surface discontinuities about 25 µm (0.001 in.) long and 10 µm (0.0004 in.) deep. On complex test objects with convex surfaces, the value of shared flux devices is limited and invariably results in overmagnetization when so applied.

Shared flux discontinuity standards should only be used with the continuous technique of particle application. When the continuous technique is not used, commercial pie gages may indicate a magnetic field, but this is evidently residual magnetism in some gages or possibly even physical entrapment of particles.

All artificial discontinuity standards can produce results comparable to a hall effect probe and tesla meter. A shim with 30 percent discontinuity depth and pie gages can indicate discontinuities 0.25 × 0.05 mm (0.01 × 0.002 in.) at 0.9 to 1.5 mT (9 to 15 G), depending on the permeability of the test object material.

Pie Gages and Flexible Laminated Strips

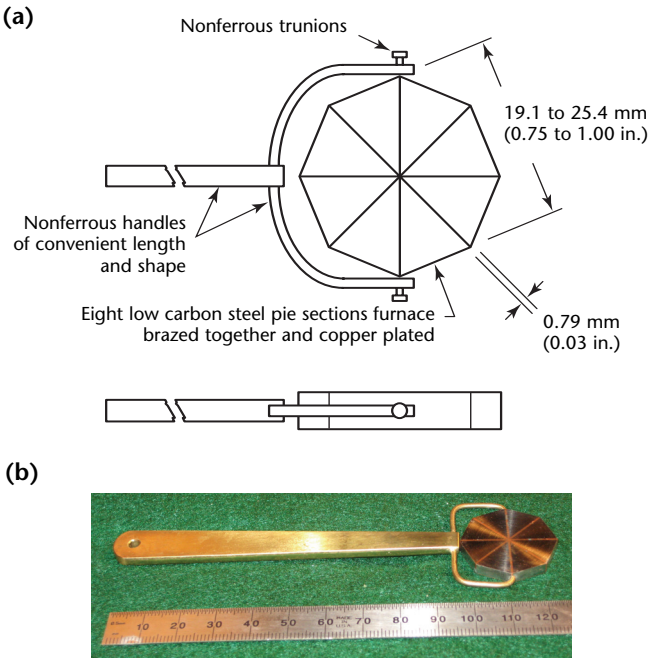
Pie Gages

The pie gage is a disk of highly permeable material divided into four, six or eight sections by nonferromagnetic material. The divisions serve as artificial discontinuities that radiate out in different directions from the center. The diameter of the gage is 18 to 25 mm (0.75 to 1.0 in.). The divisions between the low carbon steel pie sections are to be no greater than 0.8 mm (0.03 in.); the dividing interstices between sections are usually filled with epoxy or another inert material so they won't get clogged with particles or grime. The sections are furnace brazed and copper plated. The gage is placed on the test piece copper side up, and the test piece is magnetized. After particles are applied and the excess removed, the indications provide the inspector the orientation of the magnetic field. The pie gage as illustrated in Fig. 8 or the flexible laminated strips as shown in Fig. 9 may only be used as a tool to demonstrate the direction of the external magnetic field.

The principal application is on flat surfaces such as weldments or steel castings where dry powder is used with a yoke or prods. The pie gage is not recommended for precision parts with complex shapes, for wet techniques or for proving field magnitude. The gage should be demagnetized between readings.

The main advantages of the pie gage are that it is easy to use and it can be used indefinitely without deterioration. The pie gage's disadvantages are that it retains some residual magnetism so indications will prevail after removal of the source of magnetization, that it can only be used in

FIGURE 8. Pie gage magnetic field indicator: (a) diagram; (b) photograph.



relatively flat areas and that it cannot be reliably used for determination of balanced fields in multidirectional magnetization.

Flexible Laminated Strips

Flexible laminated strips, also known as *slotted strips,* are pieces of highly permeable ferromagnetic material with slots of different widths. These strips are typically used to ensure proper field direction during magnetic particle examination. They are placed on areas of interest on the test object as it is inspected. The longitudinal axis of the strip should be placed perpendicular to the direction of the magnetic field of interest to generate the strongest particle indications on the strip. A strip whose longitudinal axis is parallel to the applied field will not provide any particle indications. The indications produced on the strips assure the inspector that the proper field direction is obtained in the area of interest.

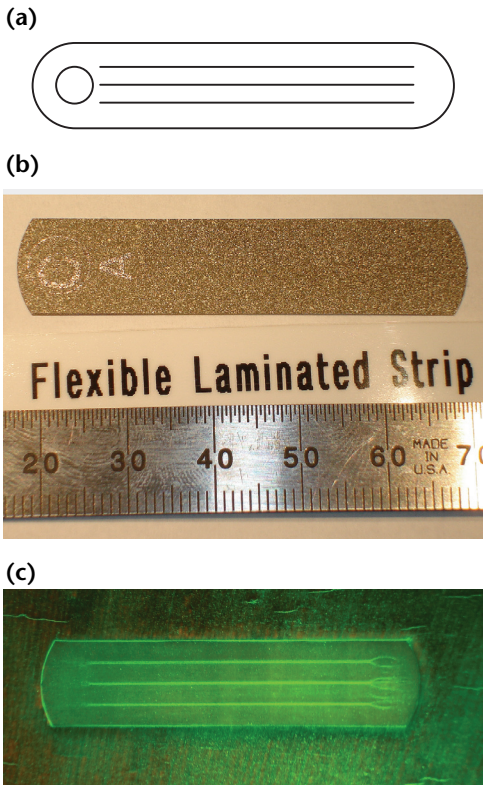
The strips are available in two types, for general and aerospace use. Both types of strip contain a steel layer sandwiched between two brass plates 0.05 µm (0.0020 in.) thick. The bottom brass layer acts as a liftoff of 0.05 mm (0.0020 in.) from the examination surface. The brass is nonmagnetic and functions only to provide liftoff and to protect the steel layer. The entire strip may have a polymeric coating for further protection. The longitudinal dimension of the strips is 50 mm (1.95 in.) and the width of the strip is 12 mm (0.47 in.).

Both types of strips (general and aerospace) contain three longitudinal slots in the center steel layer. The widths of the slots in the general strip are 191 µm (0.0075 in.), 229 µm (0.009 in.) and 254 µm (0.010 in.). The widths of the slots in the aerospace strip are 76 µm (0.003 in.), 102 µm (0.004 in.) and 127 µm (0.005 in.). Figure 9 shows the aerospace strip in visible light and under ultraviolet radiation.

Advantages of these strips are that they are relatively easily applied to the component, that they can be used successfully with either the wet or dry technique when using continuous magnetization, that they are repeatable as long as orientation to the magnetic field is maintained and that they can be used repetitively. Two disadvantages are that they cannot be bent to complex configuration and that they indicate discontinuities in only one direction, making them unsuitable for multidirectional fields.

Both pie gages and flexible laminated strips are used to determine the approximate orientation and, to a limited extent, indicate the adequacy of field intensity. However, they do not measure the internal field intensity of the test object. They merely detect external fields in the vicinity of the test object. The presence of multiple gaps at different orientations helps reveal the approximate orientation of the magnetic flux. Slots perpendicular to the flux lines produce the most distinct indications. Slots parallel to the flux lines produce little or nothing.

FIGURE 9. Slots are cut into center steel layer of flexible laminated strips: (a) diagram; (b) visible light photograph of aerospace strip; (c) photograph under ultraviolet irradiation.



Notched Shim Standards

Notched shim standards are widely used to establish proper field direction and ensure adequate field intensity during technique development in magnetic particle testing. The shims in Figs. 10 and 11 may be used to ensure the establishment and balance of fields in the multidirectional magnetization technique.

The shims are available in two thicknesses, 0.05 mm (0.002 in.) and 0.102 mm (0.004 in.). Thinner shims are used when the thicker shims cannot conform to the part surface in the area of interest. The shims are available in two

sizes, 19 mm (0.75 in.) square for Figs. 11 and 12 and 20 mm (0.79 in.) square for Fig. 13. The shims of Fig. 13 are cut, by the user, into four 10 mm (0.395 in.) square shims for use in restricted areas.

Shims are made of AMS 5062[18] or equivalent low carbon steel and must be used as specified in AS 5371.[19] Shims are placed in the areas of interest with notches toward the test surface. Use enough shims or place the shim in multiple areas to ensure that proper field directions and intensities are obtained.

These shim standards are often used with a tesla meter and a hall effect probe to establish the test procedure during technique development for a particular component. They are used with the wet technique only, and like other flux sharing devices, can only be used with continuous magnetization.

Some of the advantages of the shim standards are that they can be quantified and related to other parameters, that they can accommodate virtually any configuration with suitable selection and that they can be reused with careful application and removal practices. Some disadvantages are that the application process is somewhat slow, that the parts must be clean and dry, that shims cannot be used as a residual magnetism indicator as they are a flux sharing device, that they can be easily damaged with improper handling and that they will corrode if not cleaned and properly stored.

Figures 14 and 15 are photographs of some of these shims. Figure 14 shows fluorescent tests.

Another type of shim (sometimes called a *block*) has been used in Japan since the 1960s. These indicators help check the magnetic particle apparatus and suspension and the intensity and direction of effective magnetic field on the test surface.[20] The blocks are available in a variety of thicknesses and slot depths. Linear and circular slots are available. Circular slots are particularly effective when the direction of the magnetic flux is not known. The shims are taped to the test object (slotted side in close contact with the part), in areas where the intensity and direction of the magnetic field are in question. The slots share magnetic flux with the test object and simulate discontinuities slightly below the surface.

An American version of the Japanese shim is manufactured in 0.05 mm (0.002 in.) and 0.1 mm (0.004 in.) thicknesses, with discontinuity depths of 15, 30 and 60 percent of the shim thickness. The controlled discontinuities are available as either linear grooves or circular grooves. The circular

FIGURE 10. Shim indicators for magnetic field verification: (a) simple shim; (b) slotted strip.

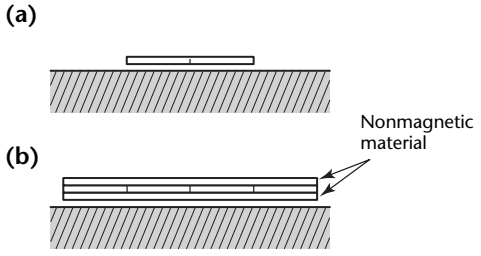
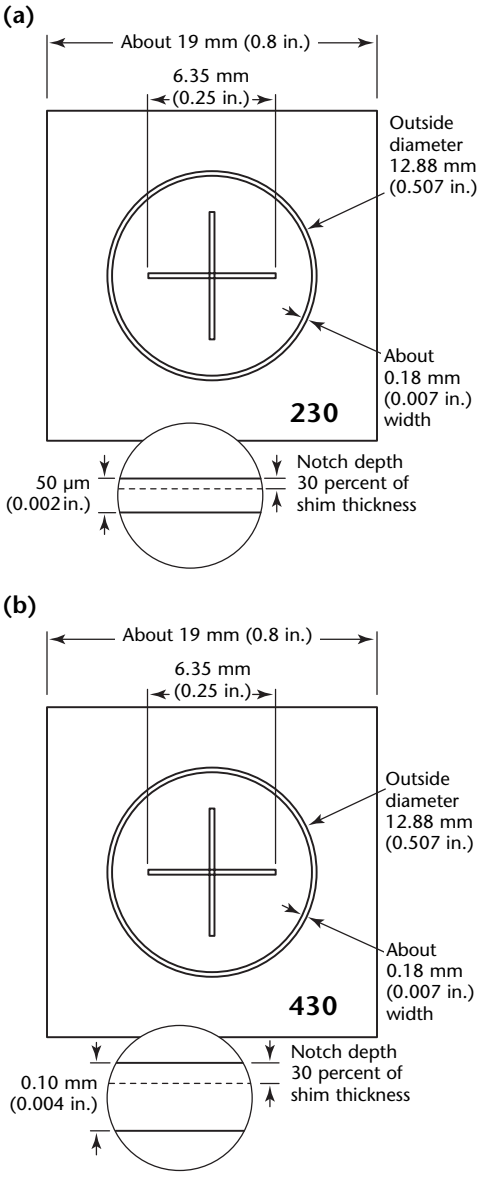
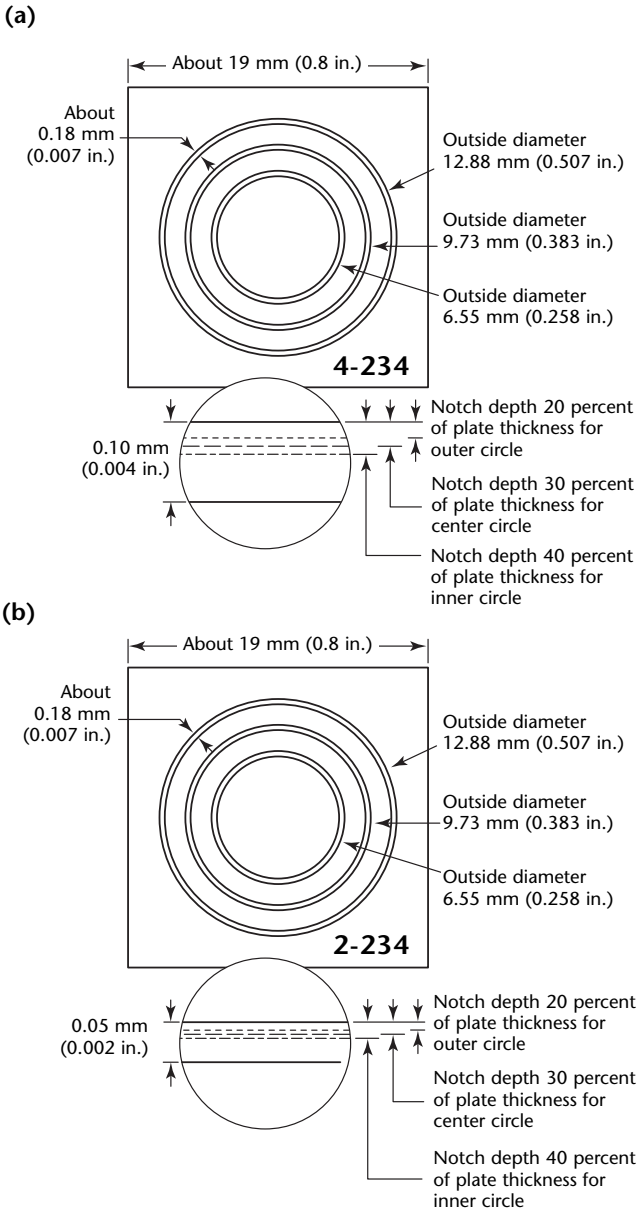


FIGURE 11. Shims for magnetic particle testing: (a) type CX-230, notch 30 percent of 50 µm (0.002 in.); (b) type CX4-430, notch 30 percent of thickness 0.10 mm (0.004 in.).



discontinuities have the added advantage of indicating the direction of maximum field intensity and the angular tolerance of sensitivity. Such shim standards can be used when setting up multidirectional magnetization to ensure that balanced fields exist in all directions at any given point in the test object during the magnetization cycle.

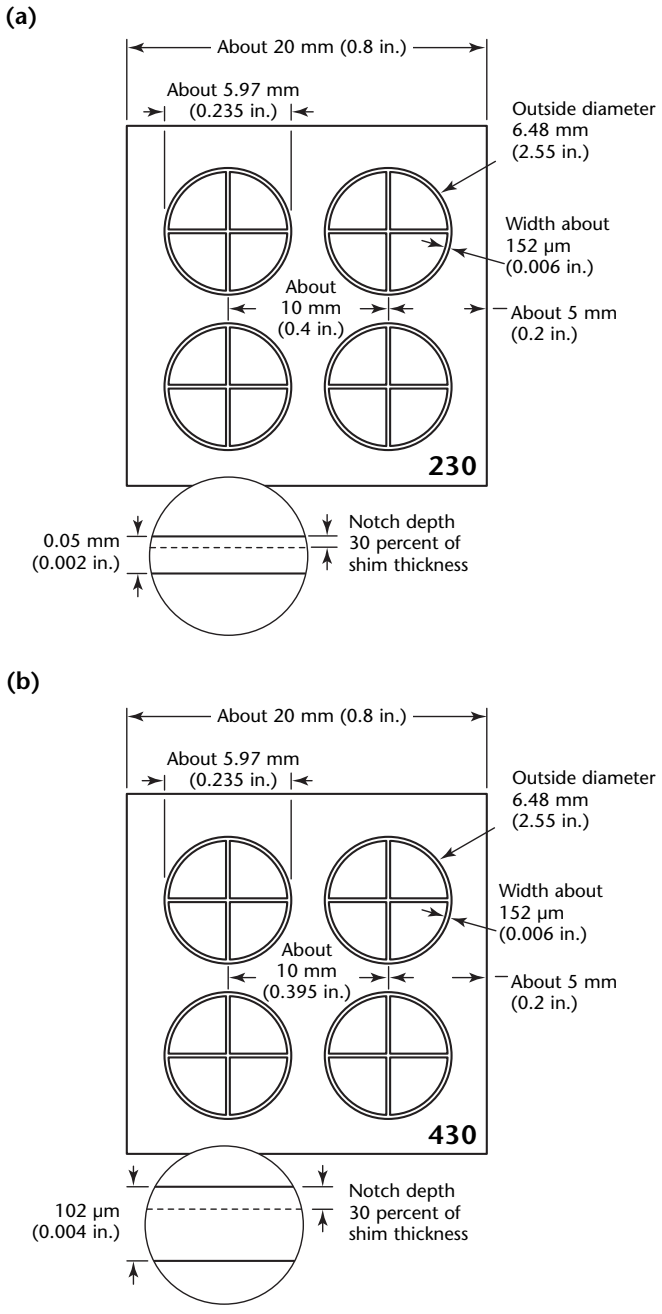
FIGURE 12. Shims for magnetic particle testing: (a) type 3C4-234, thickness 0.102 mm (0.004 in.); (b) type 3C2-234, thickness 0.05 mm (0.002 in.). Notch depth 20 percent for outer circle, 30 percent for center circle, 40 percent for inner circle.



Application of Shims

Shims are sometimes called *paste-on* discontinuities because they must be taped to the test object. Shims are used most often during the development of test procedures, where they help indicate the relative intensity and direction of a magnetic field for a particular test configuration.

FIGURE 13. Shims for magnetic particle testing: (a) type CX4-230, thickness 0.05 mm (0.002 in.); (b) type CX4-430, thickness 102 µm (0.004 in.). Notch depth 30 percent of shim thickness.



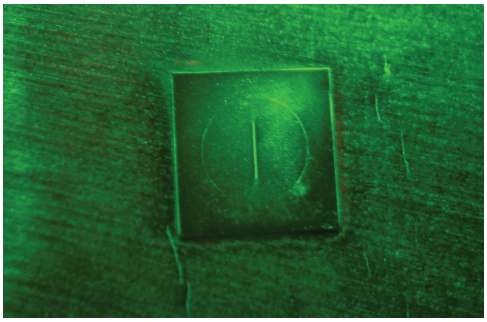
Because shims are often made of high permeability foils, they are generally small and flexible enough to fit into fairly complex test object geometries to help determine the adequacy of field intensity in these critical areas. Once the field distribution is found adequate, the testing procedure is recorded and the components are tested with the parameters established by the shims.

Magnetic Media

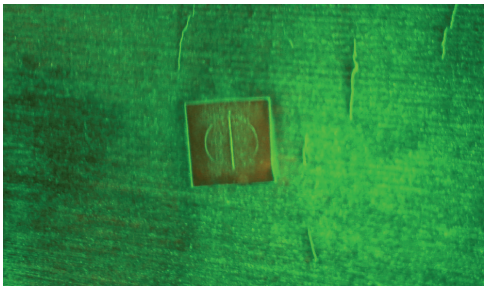
Encoded magnetic media — permanently magnetized devices or devices containing permanent magnets — are used to evaluate the performance of particle materials in a manner independent of system factors including magnetization.

FIGURE 14. Photographs of shims seen under ultraviolet irradiation: (a) CX4-430; (b) 3C2-234; (c) CX4-230.

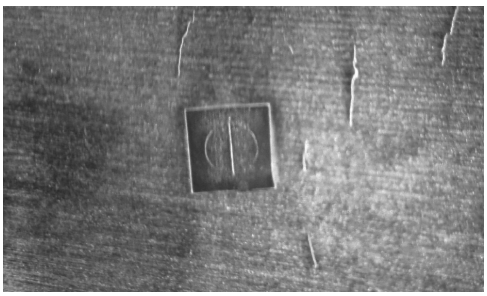
(a)



(b)



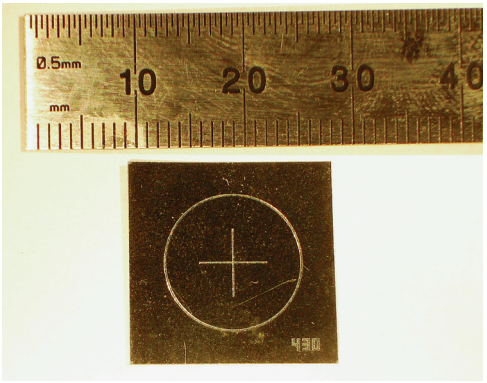
(c)



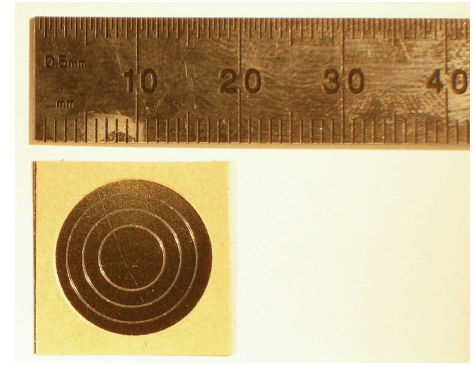
These devices can be used with either dry technique or wet technique materials. They can be used (1) to compare different materials to each other, (2) to check the visibility of materials under varying illumination conditions, (3) to track the performance of a material over time and (4) to make other relevant comparisons. With suitable care, the magnetization in these devices should not change over time. These devices should not be magnetized or demagnetized. Contact the

FIGURE 15. Visible light photographs of shims: (a) CX-430; (b) 3C2-234; (c) CX4-230.

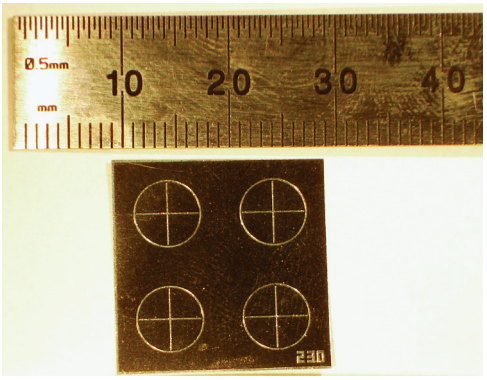
(a)



(b)



(c)



device manufacturer in regard to any magnetization or performance issues.

Magnetic Stripe Cards

A magnetic stripe card is an encoded magnetic medium for instantly evaluating the performance of magnetic particle test materials. ASTM standards recognize magnetic stripe cards as tools for evaluation of magnetic particle test materials.[5,6] Figure 16 shows samples of the encoded strips on a magnetic stripe card using dry particles and wet, fluorescent, magnetic particle materials.

The magnetic stripe contains two encoded tracks. The upper track is labeled from 0 to 10*X* when read from left to right. The lower track is a mirror image of the upper track and is labeled from 10*X* to 0 when read from left to right. Each track is magnetically encoded with a series of gradients that decrease in intensity in the direction of 0 to 10*X*. A more sensitive magnetic particle material will display a greater number of observable gradients or indications than a less sensitive material. The magnetic stripe card can be used to evaluate quantitatively the performance of magnetic particle materials by displaying the number of indications that can be observed after the powder or solution has been applied to the stripe. Particle sensitivity can be graded on the basis of the weakest visible indication.

The card can be exposed to fluid suspensions by pouring or spraying the bath over the card or by dipping the card in the bath and allowing excess fluid to drain off. Observations can be made immediately. The fluid may be allowed to evaporate, allowing permanent recording as described below. For dry powders, blow or sprinkle the powder over the card. Remove the excess powder by gently blowing over the stripe.

Using the scales printed next to the stripe, observe the number of visible indications. A reading may be recorded as the number of observable indications on either or both of the magnetic tracks. Both tracks should display close to the same number of indications, as long as the particle medium is evenly applied.

Permanent documentation is easy. Firmly press transparent tape over the dried indications and transfer the tape to the report form; or photograph the card. Records can be used to document bath conditions, make onsite bath standards and for other purposes.

Particle sensitivity can be determined immediately when particles are applied. Then the surface of the card must be cleaned of fluid and particles.

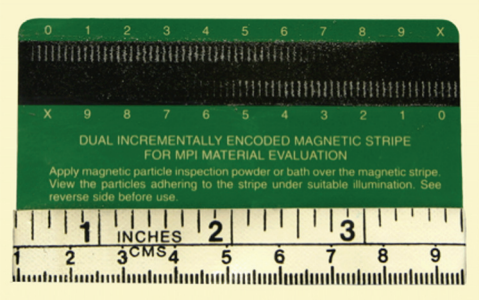
Precautions. The surface of the stripe card must be clean of any fluid or foreign matter before application of particles. The encoded strip shall not be remagnetized in any manner before use or demagnetized in any manner after use. When not in use the magnetic stripe card should be kept away from excessive heat and cold, and strong magnetic fields. For optimum performance, it should be used at room temperature. The stripe material has a coercivity of 2200 $A \cdot m^{-1}$ (2750 Oe). If indications are not visible, the particles must be verified with another card or test material before use. Under no circumstances will this strip replace the steel ring or the particle concentration tests for magnetic particle materials.

Permanent Magnets

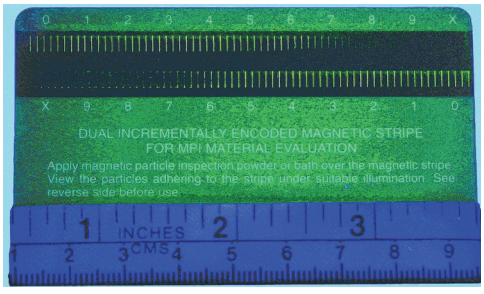
Ferromagnetic objects can be permanently magnetized and devices containing permanent magnets can be fabricated to provide and serve as qualitative indicators of magnetic particle sensitivity.

FIGURE 16. Particle indications of decaying encoded pattern (top track) and reverse decaying pattern (bottom track) on magnetic strip of magnetic strip card: (a) dry, visible light particles; (b) wet, fluorescent particles.

(a)



(b)



PART 4. Electromagnetic Reference Devices

Hall Effect Meters

Hall effect meters are commonly used to measure the intensity of the magnetizing force tangential to the surface of a test object (Fig. 17). The device measures not the magnetic flux *B* within the component but the corresponding magnetic field intensity *H* next to it. The hall effect meter is a relatively effective indicator and is in widespread use for establishing magnetic particle testing procedures. It effectively measures residual fields and indicates the direction of the remanence.

Various specifications call for different tesla (gauss) or ampere per meter (oersted) values in particular applications. Required values commonly range from 1.6 kA·m^{-1} (20 Oe) to 4.8 kA·m^{-1} (60 Oe) when the residual technique is used. A residual field less than 240 A·m^{-1} (3 Oe) usually does not attract conventional magnetic particles.

The voltage generated in the setup of Fig. 17a can be related to the external magnetic field:

$$V_h = \frac{IBR_h}{b} \quad (5)$$

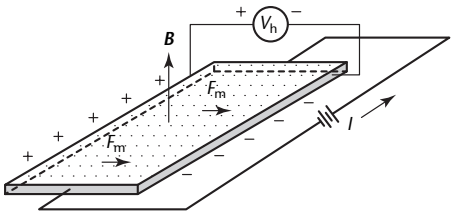
where *B* is the magnetic flux leakage density field component (tesla) at a right angle to the direct current in the hall element, *b* is the thickness (meter) of the hall element, *I* is the applied direct current (ampere), R_h is the hall coefficient of the hall element and V_h is the potential generated (volt).

Probes are available with either tangential (transverse) or axial sensing elements (Fig. 18). Probes can be purchased in a wide variety of sizes and configurations and with different measurement ranges. The probe is placed in the magnetic field such that the magnetic lines of force intersect the major dimensions of the sensing element at a right angle.

The advantages of hall effect devices are that they provide a quantitative measure of the intensity of magnetizing force tangential to the surface of a test object, that they can be used for measurement of residual magnetic fields and that they can be used repetitively. Their main disadvantages are that they must be periodically calibrated and that they cannot be used to establish the balance of fields in multidirectional applications.

FIGURE 17. Digital magnetic field indicator (tesla gage): (a) diagram; (b) photograph.

(a)



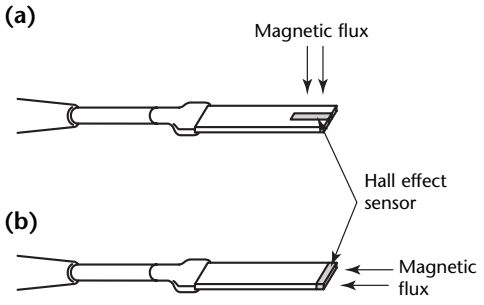
(b)



Legend

B = magnetic flux density (tesla)
F_m = magnetic force on electrons (newton)
I = primary current (ampere)
V_h = high potential (volt)

FIGURE 18. Hall effect probes: (a) tangential; (b) axial.



Eddy Current Devices

The ability of a material to hold electromagnetic energy in the form of eddy currents is a function of both the conductivity and permeability of the material. Because the permeability of a ferromagnetic material changes as the material is magnetized (from a relatively low initial permeability through a higher maximum value), the eddy current coil impedance also changes.

Several eddy current procedures have been developed to detect this change in permeability and thereby indicate the degree of magnetization. Because of poor repeatability, few of these procedures are widely used. The repeatability problem stems from the large number of variables that can affect eddy current response in a ferromagnetic material.

A magnetization level indicator has been developed to detect imbalance in the permeability along the lines of flux compared with the permeability transverse to the lines of flux as the material approaches magnetic saturation.

Magnetic Field Indicators

Field indicators are small mechanical devices, each with the shape of a hockey puck, that use a soft iron vane deflected by a magnetic field. The X-ray image in Fig. 19 shows the inside working of a field meter seen from the side. The vane is attached to a needle that rotates and moves the pointer along the scale. Field indicators can be adjusted and calibrated so that quantitative information can be obtained. However, the measurement range of field indicators is usually small due to the mechanics of the device. The one shown in Fig. 19 has a range from 2 mT (20 G) to –2 mT (–20 G). This limited range makes it best suited for measuring the residual magnetic field after demagnetization.

Closing

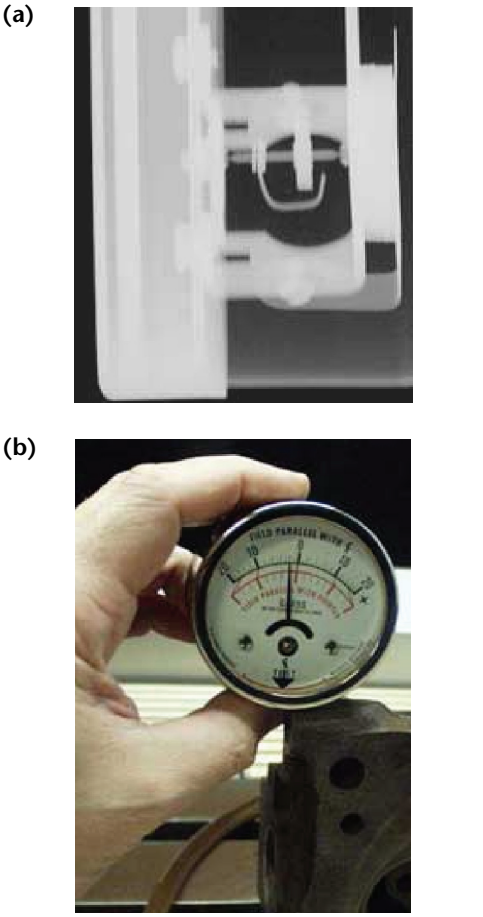
Magnetic particle testing historically relied on empirical guidelines for the development of test procedures. This practice led to widely varying discontinuity detection capabilities. Various codes and specifications have perpetuated the problem by citing rules of thumb for establishing procedures.

Several forms of reference standards are available for verifying procedures and for evaluating the performance of a magnetic particle testing system (as a whole or by components). Reference standards for this purpose are usually made of high permeability materials containing controlled graduations of artificial discontinuities. Reference standards are also available for evaluating the effectiveness of a magnetic particle test for a particular test object. These devices include a variety of shim configurations containing known discontinuities.

Electronic reference standards such as hall effect meters and eddy current devices can also be used to evaluate the adequacy of a test procedure.

Widespread use of reference standards and test discontinuities is needed to improve the consistency of magnetic particle tests and to increase the detection reliability of the technique.

FIGURE 19. Analog magnetic field indicator (tesla gage): (a) radiographic view from side; (b) photograph showing face plate.



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11

CHAPTER

Demagnetization[1]

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PART 1. Theory of Demagnetization[1,2]

Demagnetization is the process of removing magnetism from a ferromagnetic material. Ferrous materials usually retain some residual magnetism after the magnetizing current is removed. The amount of residual magnetism depends on (1) the retentivity of the material, (2) the coercive force of the material and (3) the intensity and direction of the magnetic field. A longitudinal residual field is often simple to detect with a tag wire or a field meter. A circular magnetic field is completely contained in the test object and may not exhibit the leakage fields and poles needed for typical detection means.

Complete demagnetization is virtually impossible to obtain. Consequently, the demagnetization process is actually a reduction of the residual field to a level that is appropriate for the test object's subsequent service or manufacture. Demagnetization is accomplished on the domain level by establishing or reestablishing random orientations in the material's magnetic domains.

The demagnetization process exposes the test object to a reversing magnetizing field that gradually diminishes in intensity. This causes a corresponding reversal and reduction in the magnetic field intensity in the object by scrambling the domains.

Need for Demagnetization[2]

Demagnetizing is often required for magnetic particle testing but may also be required for other reasons.

It is sometimes necessary to demagnetize an object before magnetic particle testing, particularly if the test object has a strong residual field from previous operations such as magnetic crane handling or from contact with a magnetic chuck.

When an object is magnetized for magnetic particle testing, the residual field might adversely affect later stages in its production. A residual field interferes with machining operations by causing chips to adhere to the test object and this is detrimental to both tool life and the object's finish. A magnetic field can also interfere with welding operations by actually shifting the arc and producing potentially defective welds. An important reason for demagnetizing is to clean the test object before it moves to any other surface related production step.

Residual fields can also interfere with the function of the test object after it is placed in service. Magnetized milling cutters, for instance, hold ferromagnetic chips and this not only interferes with the cutter's function but damages the surfaces of cut objects. Residual fields can interfere with certain magnetic instruments (compasses, for example) or with any number of sensitive electronic components. A residual magnetic field is particularly destructive to closely fitted moving components such as crankshafts, connecting rods and bearing surfaces.

When Demagnetization Is Not Needed

It is not always necessary to demagnetize after magnetic particle testing. Below are some factors that determine whether demagnetization is needed to reduce the residual magnetic field. These factors focus on the test object's subsequent manufacture and its service life.

When test objects have low magnetic retentivity (an automotive block, for example, or low carbon steel used for welded tanks), the residual field dissipates as soon as the magnetizing current is removed. Sometimes, this is also true in large structures and no demagnetization is required after magnetic particle testing.

Demagnetization occurs as a side effect of heat treatment if the test object temperature is taken to the curie point or above (about 750 °C or 1400 °F for steel). At the curie temperature, magnetic domains return to their random orientations and the material is demagnetized when it cools, making further demagnetization unnecessary.

Finally, when an object is remagnetized in a different direction to a level equal to or below its previous magnetization, then demagnetization is not required. Some early specifications required demagnetization between circular and longitudinal magnetization steps of magnetic particle tests. This was unnecessary for the accuracy of the test.

The written procedure document should specify if demagnetization is unneccessary.

Ferromagnetic Materials

Ferromagnetic materials are characterized by a relative ease of magnetization when exposed to a magnetizing force. This can be attributed to the relatively high magnetic permeability μ exhibited by these materials. Once magnetized, ferromagnetic material retains a level of magnetic flux density *B* after the magnetizing field intensity *H* has been removed. This remanent flux density is variously referred to as *residual flux*, *residual magnetis*m or the *residual field*. The magnitude of residual flux density is a function of the following factors: (1) the magnetic characteristics of the material, (2) the immediate history of the material's magnetization, (3) the intensity of the applied magnetizing field, (4) the direction of magnetization (longitudinal or circular) and (5) the test object's geometry.

See the introduction to this volume for information about measurement units.

Depending on the direction of the flux with respect to the surface of the test object, these lines may leave the object at one point and continue their path through air before reentering at another point. The points where magnetic lines of flux leave and reenter a ferromagnetic material are called *surface magnetic poles*. The north pole is near where flux lines leave the material. Flux lines reenter the material near to the south pole. Such fields emanating from a test object are called *leakage fields* and are the phenomena responsible for attracting nearby magnetic particles.

Requirement for Demagnetization

Test objects that retain a relatively strong residual flux density can be a source of problems during subsequent manufacturing processes or during service. Some typical problems are detailed below.

When subsequent machining is performed on a test object, the presence of a strong residual flux density can attract and hold chips or particles. This can adversely affect surface finish or tool life.

In an arc welding operation, the presence of strong leakage fields can deflect the arc away from its intended location. This phenomenon is sometimes called *arc blow*. Electron beam welding is also adversely affected by residual magnetism. Even leakage fields of moderate intensity can deflect the electron beam away from its intended target.

Plating quality also can be affected by residual magnetism. In an operation such as chrome plating on a steel surface, the presence of a strong residual magnetic field can divert the plating current away from its intended location. Such mishaps incur the expenses of the first faulty plating, of possible repair and of a second plating operation.

Inservice operation of an object may be impaired if it is the source of excessive leakage fields, attracting metallic chips or tramp particles. This condition can cause malfunctions in rotating assemblies such as bearings or excessive wear on bearing surfaces. Strong residual flux densities also may cause a substantial magnetic attraction between parts moving next to each other. This can produce increased friction or may in other ways interfere with the intended function of the component.

Cleaning operations for the removal of metallic chips and particles can be hampered by the presence of residual fields. This can be of special concern when cleaning objects that have internal openings such as oil passages.

Residual leakage fields can have a direct adverse effect on certain types of instrumentation. The magnetic compass aboard aircraft is an example, as are many electronic components.

Rotating shafts containing residual magnetism may act as electric generators with the Earth's magnetic field or other stray fields. The generated electricity can heat the shafts, causing operating losses and other service problems.

Finally, objects sometimes need to be demagnetized before using established magnetizing current levels for magnetic particle testing. Strong residual induction can lead to erroneous results and faulty test results because magnetic particles may not move freely on the test surface.

Demagnetization is not required when the test material exhibits very low magnetic remanence. Low carbon or nodular steels are included in this category. If the next manufacturing process calls for the object to be heated above the curie point, the material becomes nonmagnetic and demagnetization is accomplished by heating. At the curie point, steel temporarily transforms from ferromagnetic to paramagnetic and then cools with zero net induction.

If the part does not require additional machining and its intended function is not compromised by the presence of a residual field, then demagnetization is unnecessary.

Common Sources of Residual Magnetic Fields

Ferromagnetic material can become magnetized in a number of ways, intentionally and unintentionally.

Parts may be purposely magnetized to perform magnetic particle tests or to facilitate a magnetic flux leakage test. Magnetization may also come from biasing magnetic fields such as those used to negate the effects of permeability changes in eddy current tests.

Magnetic chucks are a common source of residual fields. Pronounced fields can be left in an object if a chuck's built-in demagnetizing cycle is faulty or inadequate. Prematurely removing test objects before completion of the demagnetizing cycle can also be a source of residual magnetism

Lift magnets are convenient material handling devices, but because they operate with direct current, they can leave strong residual fields in fabricated objects or in raw material. Physical contact with any permanent magnet or highly magnetized object (a machine table or fixture) can also establish a residual field.

Low frequency induction heating that is abruptly terminated can induce very strong residual flux density. The lower the frequency, the deeper the magnetizing field intensity penetrates into the material.

With certain orientations of high amperage cables, an electric arc welding operation can magnetize ferromagnetic material.

Residual magnetization can occur with improper operation of alternating current through a coil demagnetizer. This occurs when the coil current is terminated and the test object is still within the coil or within its influence. Penetration depth is determined by the frequency of the alternating current.

Finally, under certain conditions the Earth's magnetic field can impart a longitudinal residual field. This occurs only with low coercivity steels, usually when the object is shocked or vibrated while its long axis is parallel to the Earth's magnetic field. Such a residual field may become quite significant for long parts subjected to severe vibrations in service or transport. The intensity (horizontal component) of the Earth's field in the United States is about 16 $A \cdot m^{-1}$ (0.2 Oe). This is equivalent to the magnetic field intensity at the center of a 5 ampere-turn coil 300 mm (12 in.) in diameter.

Effect of Magnetic Field Origin on Demagnetization

The type of magnetizing source becomes significant when considering the nature of residual induction and its subsequent demagnetization.

Alternating currents tend to flow near the surface of a conductor. This *skin effect* produces residual fields that are surface oriented. Such fields respond well to demagnetization with alternating current.

There is practically no skin effect associated with a direct current magnetizing source and consequently the entire cross section of an object can be residually magnetized. Deep seated residual fields in larger objects may not be affected by alternating current demagnetizing techniques because the skin depth is only about 1 mm (0.04 in.) for steel of relative permeability 100 at 60 Hz.

Types of Residual Magnetic Fields

Longitudinal Magnetic Fields

Materials magnetized by a coil or solenoid sometimes can be left with a longitudinal residual induction. The field is oriented longitudinally, lengthwise, in the test object, and there is a high concentration of emergent fields at each end. These fields constitute poles, lines of magnetic flux entering or leaving the material.

Longitudinal magnetization is easily detected by field measuring devices such as the tesla meter or by the attraction of other ferromagnetic materials. Although this type of field can adversely affect subsequent machining, it is usually very responsive to demagnetizing techniques.

In some situations, such as magnetic particle testing of oil field tubes, leaving a circular induction in a pipe may be more advantageous than leaving a longitudinal induction.

Circular Magnetic Fields

Unlike longitudinal residual induction, circular residual induction can exhibit little or no external evidence of its presence. The flux may be entirely confined within the material, depending to some extent on part geometry and the magnetizing procedure.

For example, if magnetizing current is passed through a homogeneous length of ferromagnetic bar stock having a circular cross section, the resulting circular

residual flux density is for all practical purposes undetectable without altering the bar in some manner. Virtually no leakage fields emanate from its surface because the magnetic flux path is closed within the object. Because of this, the internal residual flux density ***B*** may be much stronger than the magnetization of the test object longitudinally in a coil or solenoid having a comparable magnetic field intensity ***H***.

The circular residual flux density becomes an apparent problem when the geometry of the object is altered by subsequent machining. For example, if a keyway is cut in a piece of shafting that is circularly magnetized, the circular field becomes quite evident. Strong leakage fields occur on either side of the keyway. All holes or slots cutting through a circular field produce magnetic poles that can attract materials such as chips or dust from subsequent machining.

Without special equipment, demagnetization of a circularly magnetized object can be very difficult. Confirmation of an adequate demagnetization level is an additional problem. Leakage field measuring devices are ineffective because there may not be an external leakage field to monitor. In this case, reorientation of the circular field into a longitudinal field before demagnetization may be advantageous in some instances when such a procedure is compatible with part geometry and size.

Multiple Magnetic Poles

Multiple magnetic poles can be induced in and retained by ferromagnetic material that has been exposed to direct current magnetization, as in a magnetic chuck or lift magnet. These fields can be pronounced and can take the form of alternate north and south poles at relatively close intervals. Demagnetization of multiple poles may be difficult using conventional alternating current through-coil procedures.

PART 2. Principles of Demagnetization

Ferromagnetic material differs from other material in that it contains magnetic domains, localized regions in which the atomic or molecular magnetic moments are aligned in parallel. When a material is not magnetized, the domains are randomly oriented and their respective magnetic inductions sum to zero. When the material is exposed to a magnetizing field intensity *H,* the domains tend to align with the applied magnetic field and add to the applied field.

When the magnetizing source *H* is removed, some of the magnetic domains remain in their new orientation rather than returning to the original random orientation and the material retains a certain level of residual magnetic field.

Magnetic Hysteresis

Magnetic hysteresis is a lag in the change of magnetization values in response to a change in the magnetizing force. There is a relationship (Fig. 1a) between the magnetic field intensity *H* (magnetizing source) and the magnetic flux density *B* (level of magnetization). When an unmagnetized material is magnetized by gradually increasing *H* from zero to $+H_m$, the level of magnetization *B* increases along the virgin magnetization curve to a maximum value corresponding to $+B_m$.

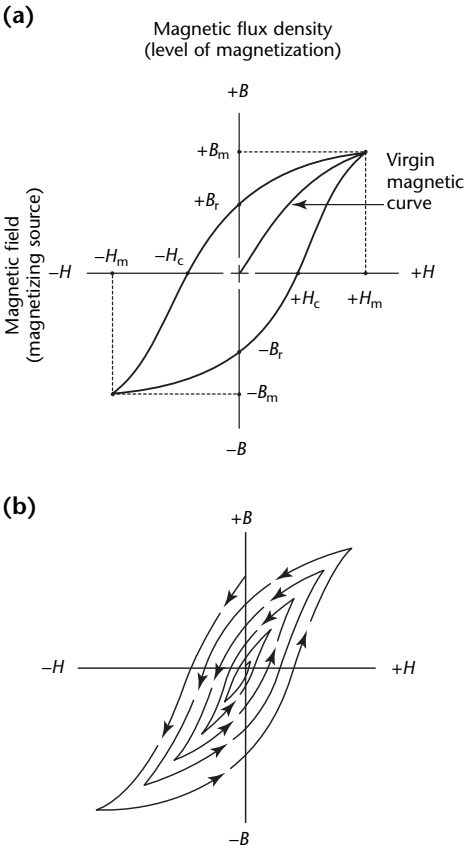
As *H* is reduced to zero, the level of *B* falls to $+B_r$ rather than zero. This level of retained magnetization ($+B_r$) is the remanent or residual field remaining in the material. As negative values of *H* (opposite polarity) are applied, the curve passes through $-H_c$ and on to H_m and reaches a magnetization level of $-B_m$. Reversing the applied field to a value of $+H_m$ completes the magnetic hysteresis loop.

Retentivity and Coercive Force

The value H_c is the coercive force and is an indicator of the difficulty involved in demagnetizing a material. The value of B_r is the material's retentivity and indicates the residual induction within a section of the material. As a rule, high coercive forces are associated with harder materials and low coercive forces with softer materials. Therefore, harder materials usually offer more resistance to demagnetization and require a higher demagnetizing field than softer materials.

No definition has been made for the dividing line between hard and soft materials. However, if $H_c >> 8000$ A·m^{-1} (100 Oe), then the material is typically considered hard. If $H_c << 400$ A·m^{-1} (5 Oe), then the material is considered soft. Coercive forces as large as 8×10^5 A·m^{-1} (10^4 Oe) and as small as 0.08 A·m^{-1} (10^{-3} Oe) have been observed.

FIGURE 1. Hysteresis curve: (a) showing reference points; (b) downcycling.



Legend

B = magnetic flux density
B_m = maximum magnetic flux density
B_r = residual magnetic flux density where $H = 0$
H = magnetic field intensity
H_c = magnetic field intensity where $B = 0$
H_m = maximum magnetic field intensity

The fact that an object retains a strong residual field B_r does not necessarily indicate a high coercive force H_c. Some materials retain an appreciable residual induction yet are easily demagnetized (transformer steels are an example). On the other hand, some materials that retain relatively weak residual fields can be extremely difficult to demagnetize because of a high coercive force.

Downcycling

Practically all demagnetizing techniques are based on a common procedure called *downcycling* — cyclical application of opposed magnetic fields of successively decreasing intensity.[3] A magnetizing field intensity H high enough to overcome the initial coercive force H_c is alternately reversed in polarity and gradually reduced to zero. The diminishing hysteresis curve in Fig. 1b illustrates this principle.

The value of the total coercive force H_c is often unknown and varies near the ends of the test object. However, it is always less than the maximum magnetizing force H_m value. This may serve as a guide in cases where the magnetizing field intensity H_m is known, as is sometimes the case in magnetic particle testing. Successful demagnetization procedures often start with an initial demagnetizing field that equals or exceeds that of the magnetizing force H_m.

An object may also be demagnetized by raising its temperature above the curie point. Although this technique provides thorough demagnetization, it is often impractical.

The magnetic field of the Earth can affect ferromagnetic objects but is weak, about 0.03 mT (0.3 G).

PART 3. Demagnetization Procedures

Alternating Current Demagnetization

Through-Coil Demagnetization[1,2]

Alternating current demagnetization with a specially built demagnetizing coil is the most convenient and widely used demagnetization method. Single-phase alternating current is used to power a multiturn coil. Various voltages (120, 240 or 480 V) are used, depending on availability and the application.

The simplicity of the alternating current through-coil technique makes it one of the most prevalent demagnetization means. The technique uses a coil powered from a current source alternating at line frequency (usually 60 Hz in the United States). As a test object is conveyed through the coil, it is subjected to an intense magnetic field within the coil. Operating at a fixed amplitude, the coil produces a continuously reversing magnetic field because of the cyclic, alternating current.

The typical demagnetization procedure comprises three main steps: (1) the test object is positioned within the coil, (2) the coil is energized to a predetermined level and (3) the test object is removed from the coil and placed outside the coil's magnetic field.

As the single-phase alternating current reverses in the coil, the magnetic field in the test object also reverses. As the object is moved out of the coil's magnetic field, the object's field is weakened as it is reversed. Moving the test object completely away from the coil (usually 1 m away) effectively demagnetizes the part. The current through the coil is maintained until the test object is completely out of the coil's field. If the current is stopped before this, or if the object's movement is stopped within the coil's field, residual magnetism could remain in the test material.

To facilitate handling, a small rolling carriage and track are often furnished with coil demagnetizing systems. The test object is positioned on the carriage next to the coil and pushed through the coil and beyond it to a neutral area.

Demagnetization of test shims may be performed by removing them slowly from one pole of an alternating current yoke.

The magnitude of the field can also be reduced by withdrawing a coil such as a cable coil away from a stationary test object. This technique is advantageous for high production rates because a properly designed coil can be continuously energized while a steady stream of test objects is conveyed through the coil opening. Typical alternating current through-coil demagnetizers are shown in Figs. 2 and 3.

FIGURE 2. Manually operated alternating current coil demagnetizer with roller carriage and automatic timer.

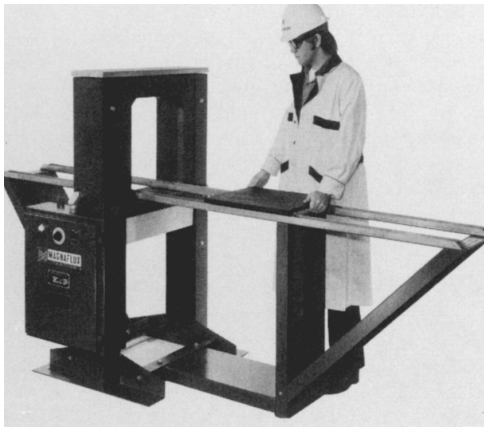
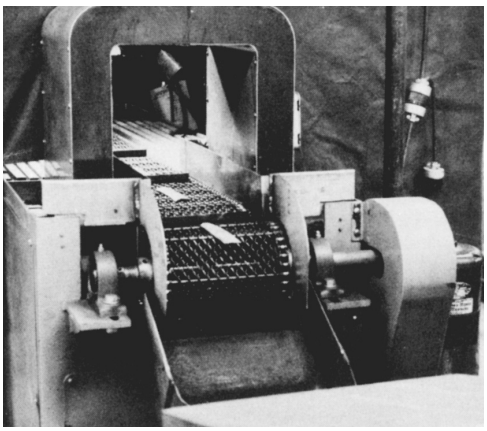


FIGURE 3. Production alternating current coil demagnetizer in magnetic particle testing conveyor unit.



Circular Field Demagnetization

Alternating current demagnetization may also be achieved with a circular magnetic field. The test object is placed between the contact points (headstock and tailstock) of a magnetizing system. An applied alternating current is gradually reduced to zero and this demagnetizes the object. The procedure is widely used with alternating and direct current systems designed for testing heavy objects.

Reducing alternating current was formerly done with a step down switch connected to a tapped power transformer. The step down was either a motorized switch or the manual current control tap switch of the magnetizing unit. Similar circuitry and procedures were used for mobile equipment, where contact with the object was made with cables and clamps.

A faster system of demagnetizing heavy objects with alternating current is the solid state decaying technique. The amperage flowing through the object is rapidly and smoothly reduced by the demagnetizing system's electronics.

Cable Wrap Technique

There are applications (such as large or immobile test objects) where a cable wrap, with an appropriate high amperage alternating current power source, can provide a convenient means of demagnetization. The high amperage power source must also incorporate a suitable current control to facilitate the gradual reduction of current from maximum to zero.

Portable or mobile alternating current power packs are available for such applications. Equipment of this type usually features stepless solid state current control. Some units incorporate special current decay circuitry that automatically reduces the current from maximum to zero in a matter of 3 or 4 s.

It is difficult to demagnetize the ends of line pipe in the field by using welding cables because the local *BH* curve at the end of a pipe is variable. The technician performing the demagnetization must have a good understanding of the process.

Through-Current Technique

Through-current demagnetization is a contact technique. High amperage alternating current is caused to flow directly through a test object starting at contact electrodes. The current control system must provide gradual reduction of current as required for demagnetization. A portable alternating current power pack used for cable wrap demagnetization may also be used for the through-current technique.

Direct Current Demagnetization[1,2]

Direct current demagnetization requires equipment with (1) a means of reversing the direction of current flow and (2) a means of gradually reducing the current level. A motorized 30-point tap switch connected to a tapped transformer is the most common current reduction means. The reducing voltage is fed into rectifiers with each tap setting.

Reversing Direct Current Contact Coil Technique

Reversing direct current contact coil demagnetization is usually associated with relatively large test objects that have been magnetized using a direct current magnetic field. It is also applicable in certain instances where alternating current demagnetization proves ineffective.

The technique requires high amperage direct current or full-wave rectified alternating current that can be directed to a coil or contact plate. There must also be provisions for reversing the polarity of the current and suitable means for gradually reducing its amplitude to zero.

The coil of a magnetic particle testing unit can be used for demagnetization, but a more effective technique is to put the demagnetizing current directly through the test object with what is called a *head shot*. Head shots are not permitted in some circumstances, such as for oil field tubular test objects.

The direct current is alternately reversed in polarity (direction) and reduced in amplitude to zero. Although fewer steps may provide satisfactory results, greater reliability is achieved by using about 30 reversals and current reductions to approach zero asymptotically.

The cycle is usually controlled automatically and requires about 30 s to complete. When using a coil, the test object should remain stationary within the coil until the demagnetizing cycle has been completed. When the contact technique is used, contact should be maintained until the cycle is completed. The direct current provides deep penetration and is usually very successful on objects otherwise difficult to demagnetize.

For economy, the reversing direct current demagnetizing feature is usually incorporated into the design of direct current horizontal wet magnetic particle testing units or relatively large stationary power packs.

Reversing Cable Wrap Technique

This technique is used for demagnetizing objects too large or heavy to process on a horizontal wet testing unit. The object to be demagnetized is wrapped with multiple turns of high amperage flexible cable, such as American Wire Gage 4\0 (12 mm [0.45 in.] in diameter), connected to a stationary direct current power pack.

The current is alternately reversed in direction and reduced in amplitude through multiple steps until the current reaches zero. This current is reduced usually by using built-in automatic circuitry similar to that designed into some wet testing units. Power packs that lack an automatic demagnetizing cycle can sometimes be used to accomplish demagnetization by manually interchanging cable connections (current reversal) and manipulating manual current controls (current reduction). However, this is time consuming and requires an appropriately fine current control to be successful — for example, demagnetizing the ends of a pipe in the field.

Pulsating Reversing Technique

A high amperage direct current coil demagnetizer has been designed to produce alternate pulses of positive and negative current. The pulses are generated at a fixed amplitude and a repetition rate of five to ten cycles per second. This permits relatively small objects to be demagnetized by the through-coil technique.

The object is subjected to a constantly reversing magnetic field as it passes through the coil and the magnitude of the effective field is reduced to zero as the object is gradually withdrawn from the coil. This mode of operation is identical to the alternating current through-coil technique described above, except for the reduced repetition rate (five to ten cycles per second rather than sixty cycles per second).

The lower repetition rate substantially reduces the skin effect with a corresponding increase in magnetic field penetration. Therefore, the technique provides additional demagnetizing capabilities on some relatively small test objects with thick cross sections that are difficult to handle with line frequency coil demagnetizers. Another standard mode of operation allows the object to remain stationary within the coil while the current gradually decays to zero.

Specialized Demagnetization

There is a wide variety of miscellaneous demagnetizing techniques that have specific applications designed around a specific test object.

Demagnetization with Yokes

A yoke configuration is sometimes used to demagnetize small objects having high coercive force. Yokes are also used for demagnetization of objects with small length-to-diameter ratios, including spheres with nearly perfect length-to-diameter ratios of 1. Yokes are usually designed for a specific type or range of test objects.

Some alternating current yokes are similar in operation to the alternating current coils: the test object is passed between or across the surfaces of the pole faces at maximum field intensity and are then withdrawn. Direct current yokes are sometimes used with reversing direct current techniques on specific objects requiring deep penetration. However, this process is inherently slow because of the associated high inductance of the circuit.

Some coil or yoke arrangements use damped oscillation to obtain the required reversing and diminishing field. The oscillation is derived from a special circuit design based on specific values of capacitance, inductance and resistance.

Demagnetization of Oil Field Tubes

Various testing processes involving direct current magnetization leave the test object with a significant longitudinal residual field. Demagnetization is usually required to eliminate any possibility of the field having an adverse effect on subsequent machining or welding. Some tubular products have lengths of 9 to 15 m (30 to 50 ft) — a formidable challenge to standard demagnetization procedures. Some unusual techniques have been used when facilities for full length demagnetization are not available.

One such procedure applies a bucking (opposite polarity) field at the ends of the object using a direct current coil positioned near the ends. By trial and error, magnetizing current to the coil is increased until external field readings are reduced to an acceptable level. The result is a redistribution of the field at each end of the tube. Unfortunately, mechanical agitation from handling or transport after this procedure can result in the redistribution of the longitudinal field and can reestablish strong leakage fields at the ends of the test object.

Another specialized demagnetization procedure uses a full length internal conductor and a unidirectional current pulse to reorient the longitudinal field and form a circular field. The magnitude of the circularly magnetizing current is increased until acceptable external field readings are achieved. While this is not demagnetization, it does reduce leakage fields to a level suitable for butt welding operations. It also creates the undesirable conditions associated with circular magnetization and hinders subsequent operations, including weld preparation or threading.

Overall demagnetization is the best solution for long tubes and this is usually carried out using some form of reversing direct current. For static conditions, an internal conductor is used with a conventional reversing direct current cycle. A cable, wrapped to give several internal conductors, could be used in place of the central conductor. However, when the object's length is taken into consideration, the central conductor approach is much more time efficient.

The advent of pulsating direct current equipment has led to dynamic demagnetizing systems for overall demagnetization of long test objects. In such systems, the object is conveyed through a special coil arrangement at speeds up to 1.5 $m \cdot s^{-1}$ (300 $ft \cdot min^{-1}$). The coil current consists of constant amplitude pulses of direct current alternating relative to polarity (positive and negative) at a rate of about five cycles per second.

Selection of Demagnetization Technique

Selecting a suitable demagnetization procedure is a matter of matching capabilities with the specific application. Each of the procedures discussed above has advantages and limitations based on test object size, hardness, production rate and source of magnetization (Table 1).

Limitations of Alternating Current Techniques

The alternating current through-coil technique is probably the most widely used demagnetization technique because of its simplicity and its adaptability to high production rates. However, the skin effect associated with alternating current magnetic fields results in limited penetration. Consequently, alternating current demagnetization may be ineffective for removing deep residual fields such as those from direct current magnetization.

This factor becomes significant on large test objects. As a rule, alternating current techniques can effectively demagnetize most objects with a cross section less than 50 mm (2 in.), regardless of the original magnetizing source. Larger test objects with deep residual fields usually require some form of reversing direct current demagnetization. If alternating current is the only source of magnetization, alternating current demagnetization is effective regardless of test object size.

TABLE 1. Demagnetizing method selection guide based on test object size, hardness and production rate for residual fields from direct current magnetizing source.

	Test Object Size			Material Hardness			Production Rate		
	Small[a]	Medium[b]	Large[c]	Soft	Medium	Hard	Low	Medium	High
Alternating Current (50 to 60 Hz)									
Through-coil	yes	maybe	no	yes	yes	no	yes	yes	yes
Cable wrap	no	maybe	maybe	yes	yes	no	yes	no	no
Through-current (30-point step down)	no	yes	no	yes	yes	no	yes	maybe	no
Through-current (current decay)	no	yes	no	yes	yes	no	yes	maybe	no
Yoke	yes	no	no	yes	yes	maybe	yes	no	no
Reversing Direct Current									
Through-coil (pulsating)	yes	yes	yes	yes	yes	yes	yes	yes	yes
Coil (30-point step down)	yes	yes	maybe	yes	yes	yes	yes	yes	no
Cable wrap (30-point step down)	no	maybe	yes	yes	yes	yes	yes	no	no
Through-current (30-point step down)	no	yes	yes	yes	yes	yes	yes	maybe	no

a. Hand held.
b. Diameter < 50 mm (2 in.).
c. Diameter > 50 mm (2 in.).

Maximum Effective Field Intensity

The maximum effective field intensity H_m of a particular demagnetization procedure is an important indicator of the procedure's capability. Basically, the H_m value must be sufficient to overcome the coercive force H_c associated with the material to be demagnetized. Generally, H_c increases with hardness.

Test object size and geometry (including the length-to-diameter ratio) are also factors that influence field intensity requirements. The demagnetization potential of a procedure inherently increases with field intensity capabilities. When related to various alternating current coil sizes with equal ampere turn ratings, the field intensity increases as coil size decreases.

Direct Current Demagnetization of Large Objects[1,2]

Alternating current does not penetrate ferromagnetic materials very deeply. For this reason, large test objects and those magnetized with direct current cannot be demagnetized with alternating current. Reversing direct current procedures are usually required when alternating current techniques prove inadequate.

For heavy objects, putting the demagnetizing current directly through the test object in a head shot is efficient because it breaks down longitudinal and circular fields. Head shot demagnetization is usually done with large power packs.

On production equipment, demagnetization circuitry can be a part of the test system design. For example, the unit's conveyor can pass through a demagnetizing coil beyond the test station or a circular magnetization shot can be incorporated into the conveyor operation.

For those difficult applications, reversing direct current has unexcelled demagnetization capabilities. Although production rate capabilities are limited, this is usually not a significant hindrance. Because larger objects are often involved, the associated production rates are relatively low. Almost any object can be demagnetized to an acceptable level with reversing direct current.

Demagnetizing Equipment

Alternating Current Demagnetization Equipment

Alternating current coil demagnetizers function only as demagnetizers. They are designed for operation at line voltage and line frequency. Most of these units are rated for intermittent duty but some are available for continuous duty. Various coil openings are commercially available.

Portable alternating current half-wave units are lightweight magnetization and demagnetization units used to power high amperage cables. Solid state stepless current control permits demagnetization by coil, cable wrap or contact techniques. Limited alternating current output usually restricts application of these systems to relatively small or medium sized objects.

Mobile alternating current half-wave units are heavy duty, dual output systems used with high amperage cables. Newer designs have solid state current control and built-in current decay circuitry. Relatively large test objects can be demagnetized by the coil, cable wrap or contact techniques.

Horizontal wet alternating current units with solid state current control feature current decay circuitry that can be used for demagnetizing either by the coil technique or the contact technique.

Reversing Direct Current Demagnetization Equipment

Equipment for reversing direct current demagnetization is often expensive. The reversing feature is commonly offered as an option on direct current magnetization equipment but separate units are also available. Some typical units are listed below.

Coil demagnetizers are designed for demagnetization only. A constant amplitude, high amperage direct current is directed through a fixed coil. The polarity of the current is continuously reversed at a fixed rate. Relatively small test objects may be demagnetized dynamically with the through-coil technique or statically with modified current decay techniques. Coil sizes may be limited.

Horizontal wet magnetization and demagnetization units permit objects to be magnetized, tested and demagnetized in place on the system. Demagnetization is based on automatic polarity reversal and a step down cycle using coil or contact techniques. These systems are suitable for relatively large test objects.[3]

Stationary magnetization and demagnetization power packs produce high amperage directed to the test object through flexible high amperage cables. Either the contact or cable wrap technique can be used to demagnetize large objects. The reversing direct current demagnetization process is automatically controlled through a fixed cycle.

Specially designed systems are available for applications that require high rates of productivity. Special power pack and coil configurations are available to demagnetize 9 to 15 m (30 to 50 ft) lengths of tubing on a continuous basis at rates up to 1.5 $m \cdot s^{-1}$ (300 $ft \cdot min^{-1}$).

PART 4. Typical Demagnetization Problems

Demagnetizing Field Intensity Too Weak

Demagnetizing capability is directly related to the technique's effective magnetic field intensity induced in the test object.

Conventional alternating current coils are usually rated in terms of ampere turns. However, for the same applied ampere turns, the intensity of the field increases as coil diameter decreases. It should be noted that the field intensity within a coil is greater near the inside wall than at the center.

Alternating Current Demagnetization after Direct Current Magnetization

Objects magnetized by a direct current source can be difficult if not impossible to adequately demagnetize with an alternating current process. This is more prevalent in test objects with diameters greater than 50 mm (2 in.) because of the pronounced skin effect associated with alternating current fields.

Deep interior residual magnetism remains unaffected by surface oriented alternating current fields. On such objects, some form of reversing direct current demagnetization must be used.

Test Object Orientation

Improper test object orientation relative to an alternating current demagnetizing coil can adversely affect demagnetization. For the best results, a test object should be passed through the coil lengthwise or with its longest axis perpendicular to the coil — that is, parallel to the coil's central axis.

Ring shaped test objects such as bearing races can be rolled through an alternating current coil to obtain the desired results. In a similar manner, objects with a complex configuration may require some form of rotation as they are passed through a demagnetizing coil.

Poor Length-to-Diameter Ratio

The ratio of an object's length to its diameter is as important to coil demagnetization as it is to coil magnetization. Values below 3:1 can be a problem, but the situation may be corrected by effectively increasing the length-to-diameter ratio.

This correction is done by adding ferromagnetic pole pieces at both ends of the object. Pole pieces should be about 150 mm (6 in.) long and nearly the same diameter as the object. With pole pieces in place, the assembly can be passed through the demagnetizing coil in the usual way. For large lots, it is sometimes convenient to pass the objects through the demagnetizing coil end to end in an unbroken chain.

Magnetic Shielding

Whenever possible, it is desirable to demagnetize an object before its assembly with other components. Once assembled, the test object may be adjacent to or surrounded by other ferromagnetic material. In such cases, the demagnetizing field may be shunted through the adjacent material rather than through the object itself and demagnetization will be ineffective.

Small objects should not be passed through a demagnetizing coil in bundles or layered in handling baskets. Test objects in the center of a stack are shielded from the demagnetizing field by the outer layer of material. For the same reason, ferromagnetic baskets or trays are not used.

Calibration of Field Indicators

Field indicators are convenient for monitoring of demagnetization, but obscure changes in calibration can cause problems. Inadvertently subjecting the device to a demagnetizing field can partially demagnetize the field indicator's internal permanent magnet and significantly increase the device's

sensitivity. Subsequent measurements would then falsely indicate that an established demagnetization process is inadequate. In such cases, the results of demagnetization should be verified with another device known to be accurate.

Demagnetization Specifications

Demagnetization specifications can cause serious production problems. Specifications are often written without accommodation to the practical limitations of the demagnetization process and its verification. For example, objects exhibiting a field indicator reading around 0.3 mT (3 G) usually will not have an adverse effect on subsequent machining or welding, instrumentation or end use.

Strictly specified limitations should be placed only on a limited number of demagnetization applications (particular test objects manufactured for specific service) as required by experience or laboratory data. To eliminate ambiguity, a specification should define how a reading is made — on the surface with a hall effect meter or with a field indicator of a specific design.

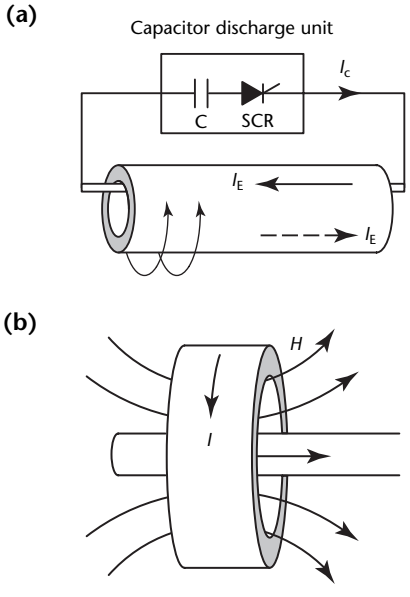
PART 5. Demagnetization of Elongated Test Objects

Much finished or semifinished tubular product is tested for surface breaking tight discontinuities by magnetic flux leakage. In the case of ferromagnetic oil field tubes, for example, the ends of the tube might first be tested for transversely oriented discontinuities, with the magnetic flux induced by placing the end of the tube in a coil. The tube is then tested for longitudinal discontinuities using circumferential induction from a current pulse along an internally placed conductor connected to a capacitor discharge system. Both of these techniques are shown in Fig. 4.

In some testing specifications, it is also required that the external longitudinal magnetic fields close to the ends of the tubular product (especially oil field transmission line pipe) be reduced to a value below a specified minimum after magnetic flux leakage testing.[4] The field is generally reduced so that such materials can more easily be welded.

Typically a specification might require that not more than 800 $A \cdot m^{-1}$ (10 Oe) be measured with a tesla meter at the ends of the material. After magnetic flux leakage testing for transversely oriented discontinuities, the magnetic field intensities emerging from the ends of tubes might easily be 40 $kA \cdot m^{-1}$ (500 Oe): demagnetization is essential.

FIGURE 4. Magnetization of elongated products as commonly practiced for oil field tubular tests: (a) circumferential magnetization of tube by capacitor discharge internal conductor; (b) longitudinal magnetization of end region using encircling coil.



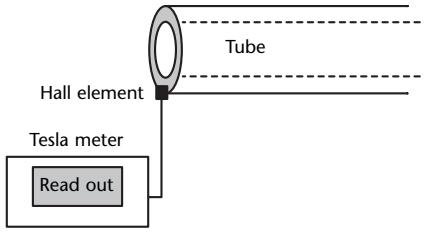
Legend
C = capacitor
H = lines of magnetic flux
I_c = comparator output current
I_E = induced current
SCR = silicon controlled rectifier

Circumferential Remagnetization

In some cases, after longitudinal magnetization has been established and transverse discontinuity testing completed, it is necessary to remagnetize only in the circumferential direction. The resulting magnetization then causes little or no external field. Tubes are easy to remagnetize by using the internal conductor technique[5] shown in Fig. 4a. The remaining longitudinal field intensity can be measured easily with a tesla meter as shown in Fig. 5.

In this test, a calibrated tesla meter is used to measure the maximum value of the magnetic field intensity at the end of the material. If it exceeds a specified value, additional shots from the capacitor discharge internal conductor are applied to reduce this emergent field. For this application, a tesla meter capable of reading up to 100 mT (1000 G) is preferred over other types of field indicators.

FIGURE 5. Hall element tesla meter measuring longitudinal magnetic field in air close to end of tube.



Angled Nature of Resulting Field

The presence of small axial field intensity at the end of a tube (or other elongated part) does not indicate that the tube is not circumferentially magnetized.[6] It merely indicates that the circumferential and axial flux densities involved form spiral flux lines, obeying a vector relationship such as that shown in Fig. 6.

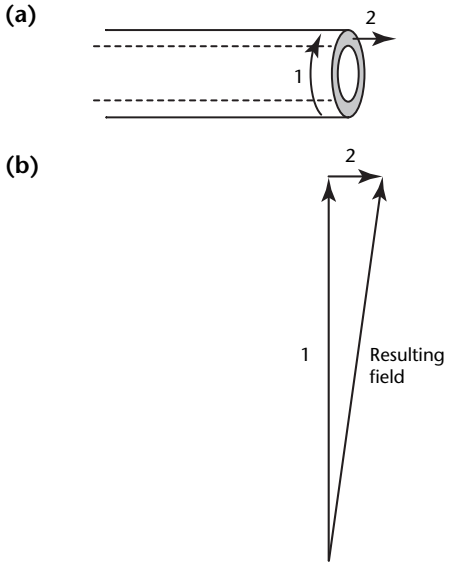
In this particular example, the material just inside the end of the tube is saturated with magnetic flux that is virtually circumferential at a value very close to the remanence B_r for the steel. Suppose that an external flux density of 1 mT (10 G) occurs for a material with a remanence of 1400 mT (14 kG). This flux density measurement was made with a tesla meter after attempted circumferential magnetization by the technique outlined above. The external flux density indicates that the direction of the flux inside the material is only $\tan^{-1}(1400^{-1})$ or 0.04 degrees from being perfectly circumferential.

Drill Pipe End Area Tests

When the threaded end of a pipe becomes strained longitudinally, the roots of the threads are particularly prone to cracking.[7] A commonly practiced magnetic flux leakage test is that of longitudinally magnetizing the ends of drill pipe (Fig. 4b) and looking for thread root cracks with wet fluorescent magnetic particles. Following such a test, the rotation of the flux into the circumferential direction might require several pulses from a capacitor discharge internal conductor system. Under such circumstances, longer pulses (25 ms) are more effective than shorter ones (3 ms).

In the resulting circumferential magnetization, the drill stem can be tested for longitudinally oriented discontinuities and the tool joints can be tested for heat check cracks with magnetic particle tests. The threads are also relatively easy to clean of particles.

FIGURE 6. Possible magnetic flux density configuration at end of tube: (a) emergent flux density is measurable with tesla meter but circumferential component is not; (b) resulting field within tube is almost circumferential here.



Legend

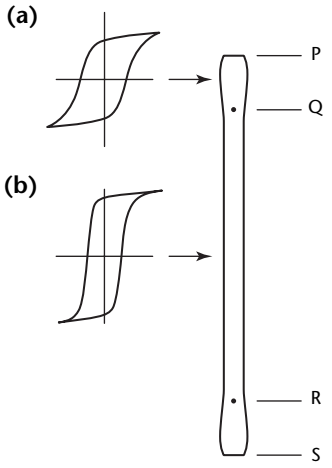
1. Circumferential field, 1.4 T (14 kG).
2. Longitudinal field, 1 mT (10 G).

Upset Area Problems

It is generally necessary to apply only 3.2 to 4 $kA \cdot m^{-1}$ (40 to 50 Oe) circumferentially to magnetize oil field tubular materials to a point near saturation. This is especially true of the region between the ends of the material (*Q-R* in Fig. 7). Some materials may require higher field intensity values to cause saturation — the *BH* curve for the material should be consulted.

However, before threading the ends of such tubes, it is sometimes necessary to bell or upset the ends (*P-Q* and *R-S*) of the material. This process may lock in existing magnetic fluxes from earlier tests, so the flux density at the ends can require a

FIGURE 7. Different circumferential magnetic field *BH* curves: (a) at the belled or upset ends of tubes; (b) at unworked center section of tube. Curve (a) shows lower flux density B_r and higher field intensity H_c than curve (b).



higher demagnetizing circumferential field than do the central regions of the tube. The difference is due to ineffective or incomplete stress relief at the ends after upsetting, which also causes the *BH* properties to differ from those of the central regions.

When this situation is encountered, a tesla meter can indicate the number of pulses required to rotate the flux within the upset areas.

Alternating Current Coil Demagnetization

After tubes have been longitudinally magnetized to saturation, the residual magnetic field is usually lowered with alternating current or direct current through a centralized, surrounding coil. With the alternating current technique, it is critical to know that, for a frequency of 60 Hz, the skin depth being demagnetized is only about 1 mm (0.04 in.). The effect of this form of demagnetization depends on (1) the intensity of the demagnetizing field at the surface of the test object, (2) the thickness of the material and (3) the material's *BH* properties.

In traditional demagnetization with alternating current, it is required that the test object be slowly removed axially from the demagnetizing coil and that the intensity of the field be enough to produce saturation in the direction opposed to the existing magnetization.

Because of the skin effect, the field intensity at any point within the material is lower than at the surface. If sufficiently high fields are to penetrate the material to cause demagnetization at that given point, the surface field amplitude must be several times higher than required to cause saturation. At five skin depths, about 5 mm (0.2 in.), one percent of the surface field remains. It is clear that the alternating current technique is confined to relatively thin or thin walled test objects and that some other form of demagnetization is needed for thicker materials.

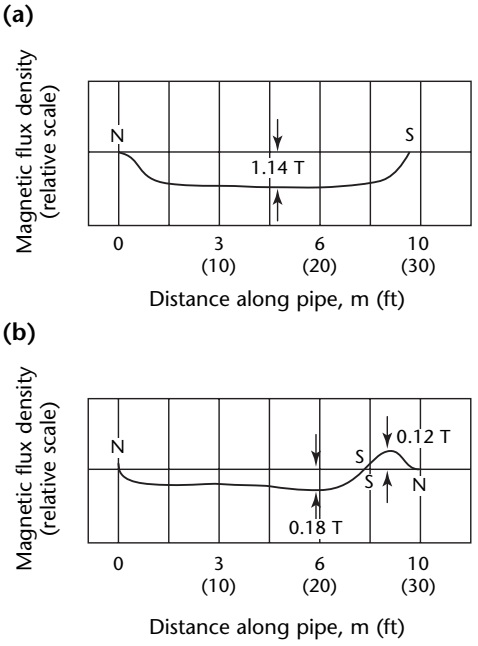
Direct Current Coil Demagnetization

Partial demagnetization of tubes is often accomplished by passing the tube through a coil in which the field intensity *H* opposes the direction of the residual induction in the material. Demagnetization current settings are obtained by trial and error because only the external fields at the ends of the tube are available to the inspector. Currently accepted practice is to adjust the demagnetizing field intensity to provide the minimum fields at either end of the test object. As shown in Fig. 8, this process leaves the flux density in the material at a high level.

The actual value of the axial flux density in the material is governed by two factors. The first is the local magnetic property or, in effect, just how high a value of flux density *B* can be sustained. The second is the proximity of the ends of the material (this affects the flux density through the demagnetizing field). The latter factor is very important within about 1 m (40 in.) of the tube ends and has a considerable effect on the local *BH* properties. The general effect is to lower the local permeability because of the internal demagnetizing field inside the test object.

As an example, the effect of direct current coil demagnetization on the axial flux density in a typical 10 m (30 ft) tube is shown in Fig. 8. As illustrated in Fig. 8a, the axial flux density of the tube after magnetization is relatively constant at 1.14 T (11.4 kG) except within about 1 m (40 in.) of either end. This flux density is

FIGURE 8. Axial bulk flux density in 10 m (30 ft) long tube: (a) after longitudinal magnetization to saturation; (b) after direct current coil demagnetization using constant current. Note remanent flux density (1.14 T or 11.4 KG), opposed dipole effect caused by demagnetization and values of flux densities in tube after demagnetization.



close to the remanence for the material, which varies with localized stress, chemical composition and other factors.

After demagnetization, in which only the external field is sampled at both ends of the tube, the remaining flux density within the material is as shown in Fig. 8b. The flux density for the majority of the material is relatively low and in the same direction as the saturated state. However, at one end of the tube the direction of the flux has been reversed by the coil field for roughly 1.4 m (4.4 ft). The demagnetized material then exists in an opposing dipole configuration, with poles as shown in the illustration.

When this form of demagnetization is used, the inspector must consider each application individually. The direct current required depends on the wall thickness of the tube. Passage of the material through an alternating current coil, perhaps of low frequency, further lowers the contained flux.

Flux Sensed Demagnetization

Traditional alternating current and direct current demagnetization techniques do not totally demagnetize an object; they merely reduce the bulk flux density to the value at which emergent fields are low enough not to hinder subsequent metalworking processes. The following information is provided to show that lower bulk flux values can be calculated by sensing the remaining flux and adjusting the demagnetization current to make the flux as small as possible.

A commonly used technique for sensing the flux density level in an elongated object is to jerk a loosely fitting coil from a position of flux linkage with the part to a position of no flux linkage. This is shown in Fig. 9. With the coil in position 1, the flux linkage with the magnetized object is given by:

$$\textbf{(1)} \qquad N\Phi = N \times \int \boldsymbol{B} \cdot \hat{\boldsymbol{n}} dA$$

where $\boldsymbol{B}$ is the flux density of the test object in the coil (tesla), N is the number of turns on the coil, $N\Phi$ is the flux linkage (weber turns) and $\int \hat{\boldsymbol{n}} dA$ is the area of the coil perpendicular to B (square meters).

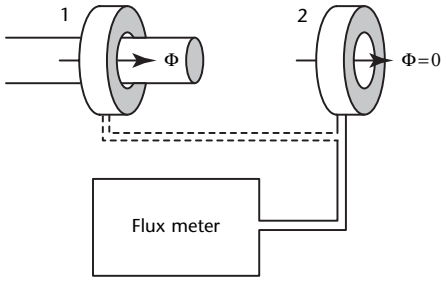
With the coil in position 2, the flux linkage is zero and the net change in flux linkage is $N\Phi B \cdot \int \hat{\boldsymbol{n}} dA$. When the voltage induced in the coil during this process is integrated with a flux meter, the output (suitably compensated for the value of A and N) is the average value of the flux density in the test object directly inside the coil at position 1.

Applying this theory to demagnetization, the test object is passed through a sensing coil and the output of the flux meter is used to compensate electronically for the current through the demagnetizing coil. This compensation produces a net flux density in the sensing coil, and therefore in the object, as close to zero as possible. This is shown schematically in Fig. 10.

Problems Associated with Partial Demagnetization

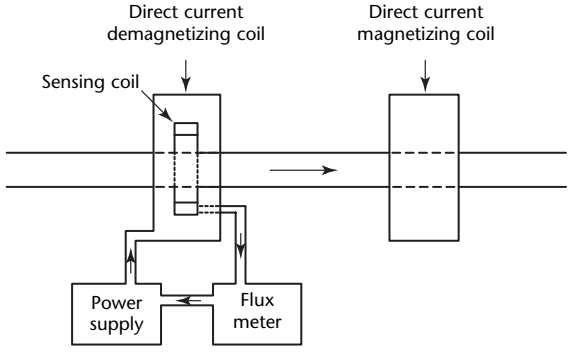
Partial demagnetization can lead to field problems when the material later appears to be highly magnetized. Because of the skin effect, surface demagnetization by the alternating current technique is at

FIGURE 9. Measurement of flux Φ at specific position close to end of elongated test object. Search coil is taken from position 1 to position 2 and resulting voltage is integrated within flux meter. Flux meter output is proportional to flux at position 1.



Legend
1. First position of coil.
2. Second position of coil.

FIGURE 10. Diagram for optimizing of direct current demagnetization of elongated test object. Sensing coil develops voltage as magnetized material passes through. Voltage is fed to flux meter. Meter's signal is proportional to flux density within test object and is used to control programmable power supply of demagnetizing coil.



best temporary. The bulk magnetization of the test object may lead to large external fields.

The alternative practice is local application of a direct current field that, although it may remove the flux from a small region, does not demagnetize the entire part. Unless the entire object can be completely demagnetized, presently accepted practice will continue: the flux is reduced in certain regions of the object so that externally applied field indicators show a low field. The end user will continue to accept material highly magnetized though appearing demagnetized. No specifications appear to exist for demagnetization procedures that lead to bulk flux reduction in previously magnetized objects. Here are two examples of situations where the lack of demagnetization can cause problems at a later date.

1. A common practice in the testing of oil field tubes is to reduce the bulk flux to the condition shown in Fig. 8b. Subsequent transportation and other mechanical vibrations can cause the external field to rise to levels unacceptable to the end user. Such levels cannot be caused by the Earth's magnetic field, only 0.02 mT (0.2 G), because the field intensity required to magnetize these materials is much larger than 0.02 mT.
2. A second common practice is to pass a longitudinally magnetized tube or rod through a coil carrying 50 or 60 Hz alternating current. Skin depth considerations reveal that the volume of material actually demagnetized is small. The material is left in a highly magnetized state, apart from a surface layer. Subsequent handling causes the reappearance of high external fields.

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12

CHAPTER

Magnetic Testing of Metals[1]

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PART 1. Casting Discontinuities

Discontinuities

Discontinuities are variations in the geometry or composition of an object. Such variations inherently affect the physical properties of the object and may in turn affect the object's service life. Not all discontinuities are defects. The definition of *defect* changes with the type of component, its construction, its materials and the specifications or codes in force. It should be well understood that a discontinuity harmless in one object may be critical in another.

Detection of discontinuities is a process that is largely dependent on the discontinuity's physical characteristics — in the case of cracks, a critical parameter is the ratio of surface opening to crack depth. However, crack depth and width are not the only factors affecting detectability; length and orientation to the surface are also important.

To better detect and interpret magnetic particle discontinuity indications, it is necessary to know the basic material characteristics of the test object. Furthermore, it is also important to consider how the material is produced, what manufacturing processes are used to form the finished product and what discontinuities are typically initiated by the processing operations.

During the various stages of material processing, certain discontinuities can be expected. Typically, a discontinuity is categorized by the stage of manufacturing or use in which it initiates: casting, forging, welding, processing and service. The text that follows describes discontinuities that may originate from the processing operations in each of the five stages. The listing is provided only for educational purposes and may not apply to all test objects.

Casting

When ferromagnetic materials are produced, molten metal solidifies into ingot form. During solidification, foreign materials and gas bubbles may be trapped in the ingot and form what is known as *inherent* discontinuities. Many of these are removed by cropping but a number of them can remain in the ingot. Such discontinuities then can be rolled, forged and sectioned along with the material in its subsequent processing operations.

Several inherent discontinuities occur commonly in ferromagnetic materials (Table 1).

Cold Shut

A cold shut is initiated during the metal casting process. It occurs because of imperfect fusion between two streams of metal that have converged. Cold shuts may also be attributed to surging, sluggish molten metal, an interruption in pouring or any factor that prevents fusion where two molten surfaces meet.

This discontinuity produces magnetic particle indications similar to those of cracks or seams with smooth or rounded edges similar to those of Fig. 1.

Pipe

During solidification, molten metal shrinks. In the case of a casting,[1] there eventually can be insufficient molten metal for completely filling the top of the mold. As a result, a cavity forms, usually in the shape of an inverted cone or cylinder (Fig. 2).

If this shrinkage cavity is not completely removed before rolling or forging into final shape, it becomes

TABLE 1. Discontinuities in ferromagnetic castings.

Discontinuity	Location	Cause
Cold shut	surface or subsurface	meeting of two streams of liquid metal that do not fuse
Hot tears	surface	adherence to the core or mold during the cooling process
Inclusions	surface or subsurface	contaminants introduced during casting process
Pipe	subsurface	absence of molten metal during final solidification
Porosity	surface or subsurface	entrapped gases during solidification of metal
Segregation	surface or subsurface	localized differences in material composition

elongated and appears as voids called *pipe* in the finished product. Pipe can also result from extrusion, caused by the oxidized surface of a billet flowing inward toward the center of a bar at the back end. The presence of pipe is usually characterized as a small round cavity located in the center of an end surface.

Hot Tears

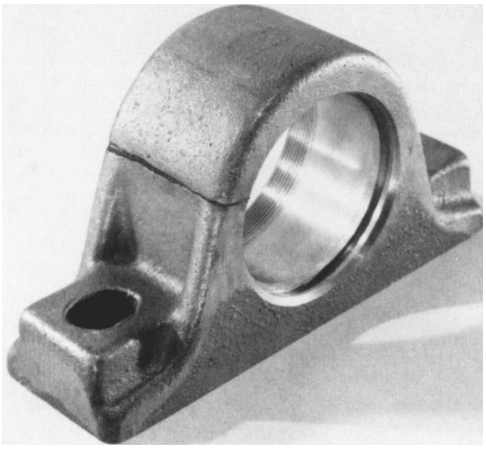
At the elevated temperature associated with solidification, cast materials are susceptible to hot tears. Segregation of low melting point impurities results in localized loss of ductility and strength. Lacking these, the cooling metal can tear and crack in the mold because of restraint from the mold. In addition, uneven cooling in thin sections or corners that adjoin heavier masses of metal can result in higher metal surface stresses that in turn produce hot tears.

Hot tears appear on the surface as a ragged line of variable width and numerous branches. In some instances, the cracks are not detectable until after machining because the tearing can be subsurface.

Blowholes and Porosity

Gas porosity or blowholes are rounded cavities (flattened, elongated or spherical) caused by the accumulation of gas bubbles in molten metal as it solidifies. A small percentage of these bubbles rise through the molten metal and escape. However, most are trapped at or near the surface of the ingot when solidification is complete (Fig. 2). During rolling or forging of the ingot, some of these gas pockets are fused shut.

FIGURE 1. Magnetic particle indication of a cold shut in casting.



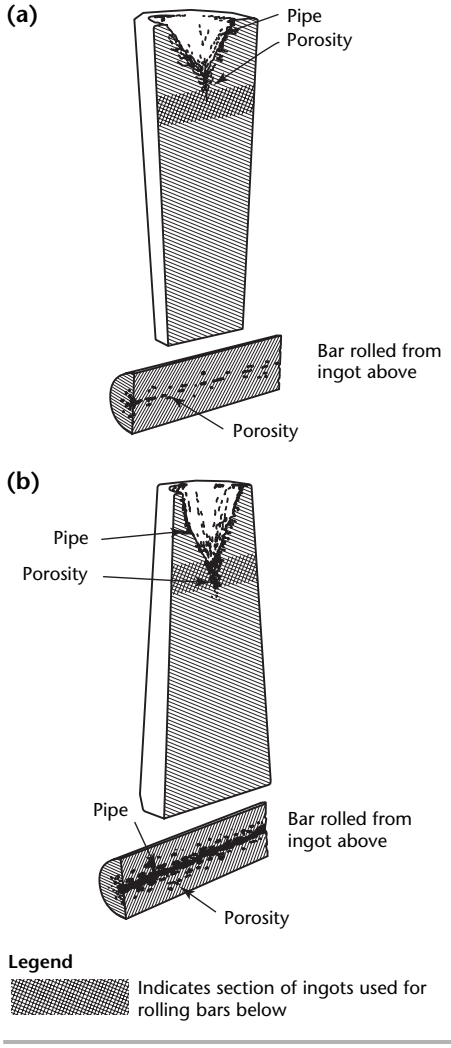
The remaining pockets may appear as seams in the rolled ingot. Deep blowholes that are not rolled shut may appear as laminations after becoming elongated in the rolling operation.

Nonmetallic Inclusions

Inclusions in ferrous alloys are usually oxides, sulfides or silicates introduced during the melting operation. Dirty remelt, crucibles or rods or poor linings may introduce nonmetallic inclusions into the molten metal. Other contributing factors are poor pouring practice and inadequate gating design that can produce turbulence within the mold.

Nonmetallic inclusions in ingots can, after forging, become stress risers because of their shape, discontinuous nature and incompatibility with the surrounding material. In many applications, it is the

FIGURE 2. Longitudinal section of two ingots, showing typical pipe and porosity: (a) detectable; (b) severe.



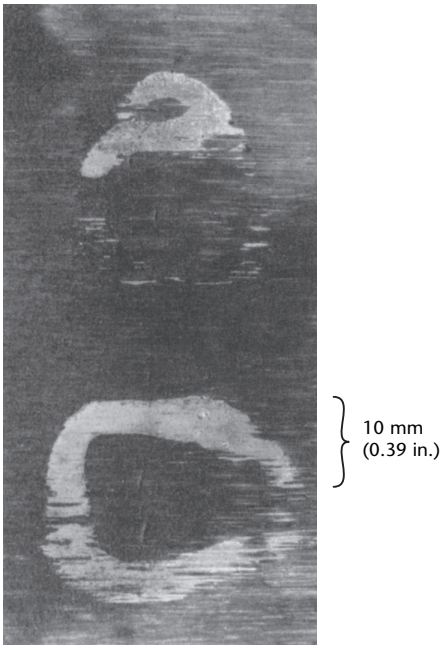
presence of these inclusions that lowers the ability of a metal to withstand high impact, static or fatigue stresses. Moreover, the effect of inclusions depends on their size and shape, their resistance to deformation, their orientation relative to applied stress and the tensile strength of the material. Many inclusions can be of a more complex intermediate composition than their host materials and each grade and type of metal has its own characteristic inclusions.

Typically, inclusions are mechanically rolled or formed, deforming plastically into elongated shapes and to appear in longitudinal sections as stringers or streaks. In transverse cross sections, the inclusion's shape is more globular or flat (Figs. 3 to 5).

Segregation

Segregation is a localized difference in a material's chemical composition. During solidification of molten metal, certain elements may concentrate in limited areas, resulting in an uneven distribution of some of the alloying elements of the steel. Equalization of the compositional differences can be achieved by hot working (forging or rolling). However, segregation is sometimes carried into the wrought product.

FIGURE 3. Inclusions in wrought product were elongated through rolling and were discovered at weld upset that joined two rails together. Magnetic particle indications are in web next to weld.



When not detected, segregation can affect corrosion resistance, forging and welding characteristics, mechanical properties, fracture toughness and fatigue resistance. Furthermore, quench cracks, hardness variations and other discontinuities are likely to result during heat treating of materials that exhibit segregation of alloying elements.

FIGURE 4. Cross section through rail sample, showing magnetic particle indications at center.

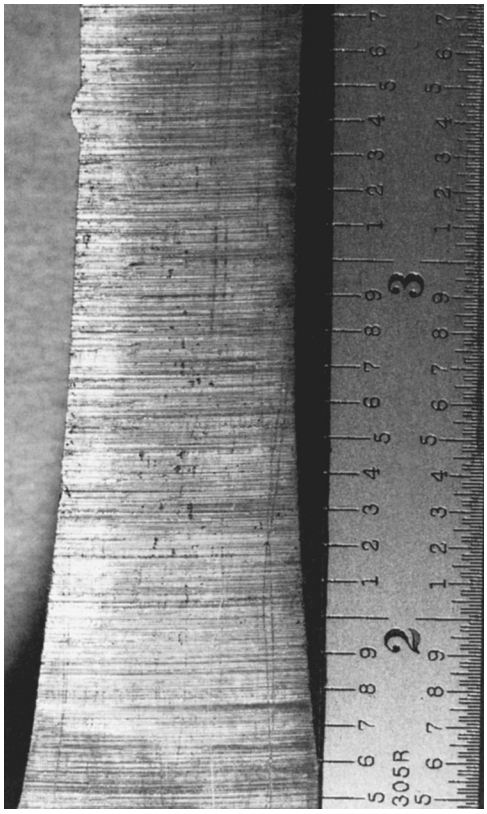


FIGURE 5. Microstructure of sections through rail sample: (a) transverse section, away from weld; (b) longitudinal section, with inclusion along length of test object.

(a)



(b)



PART 2. Forging Discontinuities

Discontinuities that originate during hot or cold forming are said to be *primary processing discontinuities*. The processing of a wrought product by rolling, forging, casting or drawing may introduce specific discontinuities into the product and inherent discontinuities that were at one time undetectable or insignificant may propagate and become detrimental.

The following is a brief description of common primary processing discontinuities that may occur in ferromagnetic materials (Table 2).

Seams

As an ingot is processed, surface discontinuities such as gas pockets, blowholes and cracks are rolled and drawn longitudinally. When these discontinuities exist, an underfill of material occurs during the rolling operation. Seams may also be initiated in the semifinishing and finishing mills because of faulty, poorly lubricated or oversized dies.

As a result of multiple passes during rolling operations, underfilled areas are rolled together to form a seam (Fig. 6). The surfaces are typically oxidized and may be intermittently welded together to form very tight, usually straight cracks that vary in depth from the surface (Figs. 7 and 8).

Laminations

Laminations are separations that are typically aligned parallel to the worked surface of a material. They may be the result of blowholes, internal fissures, pipe, inclusions, seams or segregations that are elongated and flattened during the rolling process. They can be surface or subsurface, are generally flat and extremely thin (Fig. 9).

Laminations can be detected by magnetic particle testing at an end or at a transverse cross section taken through the rolled plate.

Stringers

Stringers are predominantly found in bar stock. They originate by the flattening and lengthening of nonmetallic inclusions during rolling.

Stringers are typically subsurface, semicontinuous straight lines parallel to the length of the bar stock.

Cupping

Typically occurring during extrusion or as a result of severe cold drawing, cupping is a series of internal ruptures (chevrons) in bar or wire as shown in Fig. 10. Because the interior of a metal cannot flow as rapidly as the surface, internal stresses build, causing transverse subsurface cupping cracks.

Cooling Cracks

After bar stock is hot rolled, placed on a bed or cooling table and allowed to reach room temperature, cooling cracks may develop from uneven cooling. Such cracks are typically longitudinal and usually vary

TABLE 2. Discontinuities in ferromagnetic forgings.

Discontinuity	Location	Cause
Bursts	surface or subsurface	forming processes at excessive temperatures
Cupping	subsurface	internal stresses during cold drawing
Cooling cracks	surface	uneven cooling of cold drawn products
Hydrogen flakes	subsurface	abundance of hydrogen during forming
Laminations	subsurface	elongation and compression of inherent discontinuities during rolling
Laps	surface	material folded over and compressed
Seams	surface	elongation of unfused surface discontinuities in rolled products
Stringers	subsurface	elongation and compression of inherent discontinuities during rolling

in depth and length. Although often confused with seams, cooling cracks do not exhibit surface oxidation (Fig. 11).

Cooling cracks tend to curve around the object shape and so are not necessarily straight. The intensity of magnetic particle indications varies, heavier where the crack is deepest.

FIGURE 6. Formation of seam: (a) underfill results when there is not enough metal to fill rolls; (b) seam in finished bar occurs when underfill is squeezed tight on subsequent rolling pass.

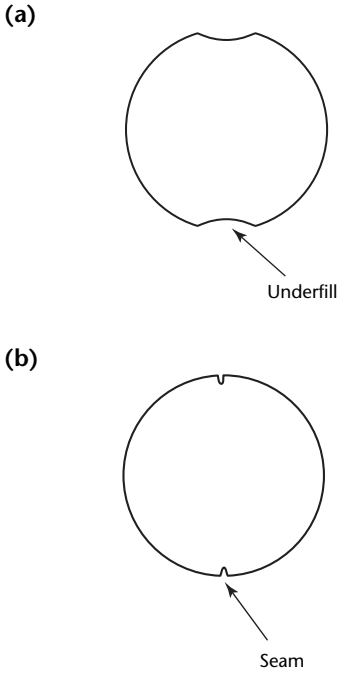
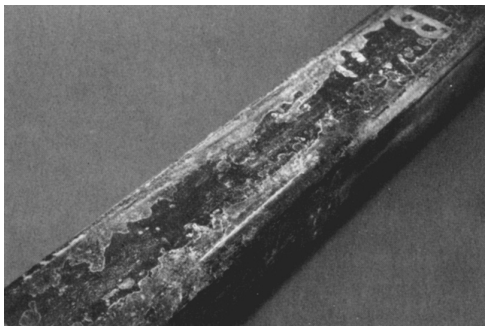


FIGURE 7. Wet fluorescent magnetic particle indication of seam in steel billet.



Forged and Rolled Laps

Forging laps are the result of metal being folded over, forming an area that is squeezed tight but not welded together (Figs. 12 and 13). They are caused by faulty dies, oversized blanks or improper handling of the metal in the die. Forging laps are usually open to the surface and are either parallel or at a small angle to the surface.

Rolled laps are a condition similar to a seam. Excessive material is squeezed out during a rolling pass, causing a sharp overfill or fin. When rotated for the following pass, the material is rolled back into the bar. Because of its heavily oxidized surface, the overfill cannot be

FIGURE 8. Photograph showing seams in bars, from left: as-received condition, sand blasted surface, pickled surface and wet fluorescent magnetic particle indication.

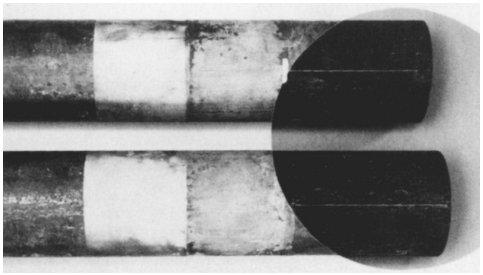


FIGURE 9. Metallographic cross section showing laminations found in resistance welded steel tube.

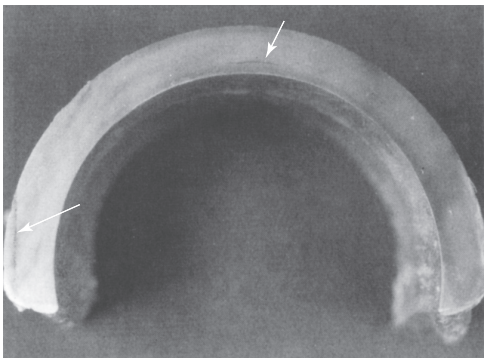
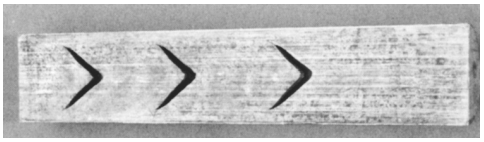


FIGURE 10. Cross section showing severe cupping in 35 mm (1.4 in.) bar.



welded together by the rolling operation. Rolling laps are usually straight or slightly curved from the longitudinal axis and are either parallel or at a small angle to the object surface (Fig. 14).

FIGURE 11. Cooling cracks indicated with fluorescent magnetic particles.

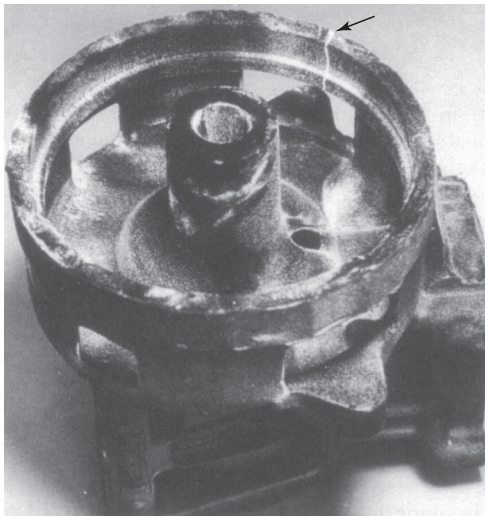


FIGURE 12. Wet fluorescent magnetic particle indication of forging lap in connecting rod.

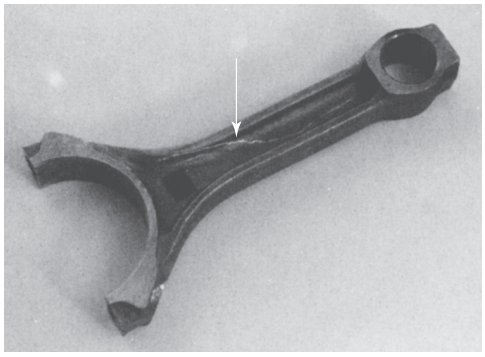
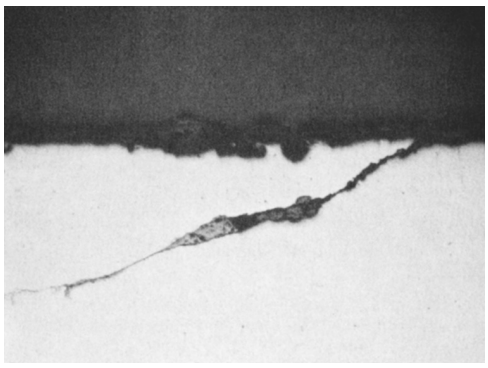


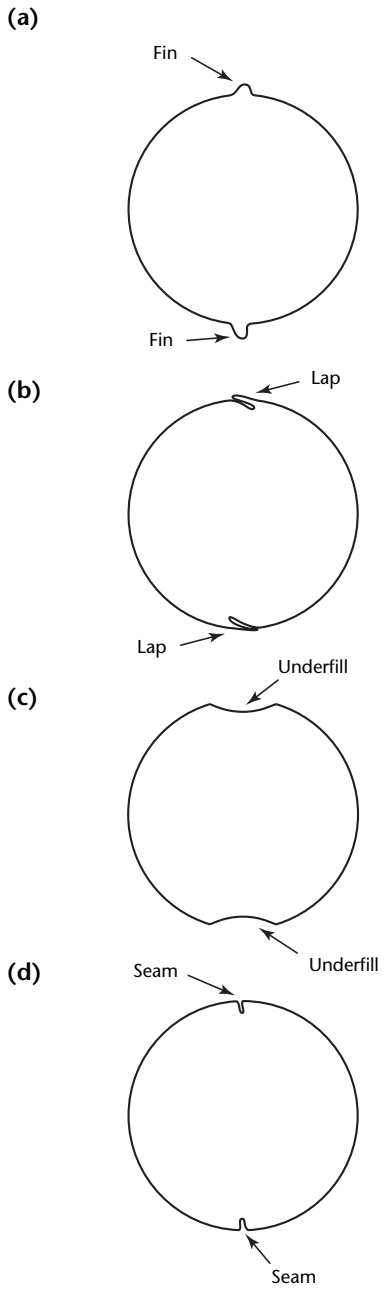
FIGURE 13. Micrograph of forging lap with included oxide in lap.



Flash Line Tears

As the dies close in the final stage of the forging process, a small amount of metal is extruded between the dies. This

FIGURE 14. Formation of seams and laps: (a) overfill produces excess metal squeezed out of rolls; (b) lap results when projection is folded over and forced back into bar's surface during subsequent pass; (c) underfill results when there is not enough metal to fill rolls; (d) seam in finished bar occurs when underfill is squeezed tight on subsequent rolling pass.



extruded metal is called *flash* and must be removed by trimming.

If the trimming is not done or not done properly, cracks or tears can occur along the flash line (Fig. 15).[2] Flash line tears are reliably detected by magnetic particle testing.

Internal and External Bursts

Internal bursts are found in bars and forgings and result from excessive hot working temperatures. Discontinuities that exist before forming (porosity, pipe, inclusions or segregation) are pulled apart because of the high tensile stresses developed during the forming operation.

Rolled and forged metals may also develop internal bursts when there is insufficient equipment capacity for working the metal throughout its cross section (Fig. 16).

External bursts typically occur when the forming section is too severe or where sections are thin. External bursts may also be formed if rolling and forging equipment is not powerful enough: the outer layers of the metal are deformed more than the internal metal and the resulting stress causes an external burst. Forming during improper temperatures may also cause external bursts.

FIGURE 15. Flash lines and laps in forgings

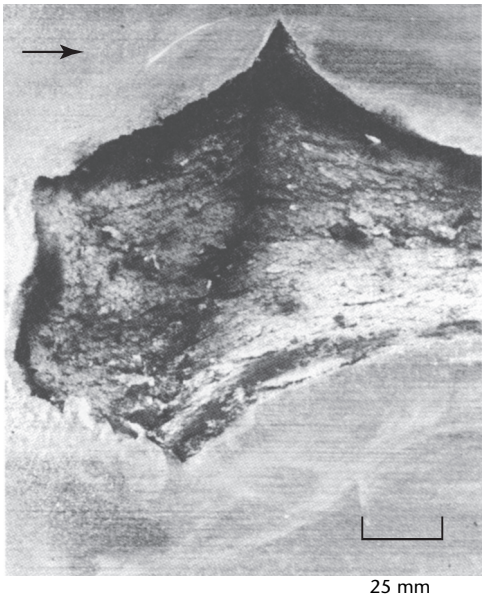


Hydrogen Flakes

Flakes are formed while cooling after the forging or rolling operations. Flakes are internal fissures attributed (1) to stresses produced by localized metallurgical transformations and (2) to hydrogen embrittlement, decreased solubility of hydrogen after rapid cooling.

Hydrogen is available in abundance during all manufacturing operations. When permitted, hydrogen dissipates freely at temperatures above 200 °C (390°F), so that the solubility of hydrogen in material proportionally increases with increasing time and temperature. Hydrogen flakes are usually found deep in heavy steel forgings, are extremely thin and are aligned parallel with the grain.

FIGURE 16. Cross section of bar showing forging burst near centerline. Arrow indicates direction of working.



PART 3. Welding Discontinuities

The discontinuities described below relate mainly to fusion welding; a few may also apply to resistance and solid state processes. The discussion covers discontinuities that lend themselves to detection by magnetic particle testing (Table 3).

Acceptance or rejection of a weldment, based on the detection of a particular discontinuity, is determined by the requirements of the designer and the applicable code. The *Structural Welding Code,* published by the American Welding Society, is specified for a great variety of projects.[3]

Cold Cracking

Cold cracking is also known as *underbead* or *delayed cracking*. It is a form of hydrogen induced cracking that appears in the heat affected zone or weld metal of low alloy and hardenable carbon steels. Cracking of this type may occur immediately on cooling or after a period of hours or even days. The principal factors contributing to cold cracking are (1) the presence of atomic hydrogen, (2) a hard martensitic microstructure in the heat affected zone and (3) high residual tensile stresses resulting from restraint.

Sources of atomic hydrogen include moisture in the electrode covering, shielding gas or base metal surface (including hydrated rust), as well as contamination of the filler or base metal by a hydrocarbon (oil or grease). Dissociation of water vapor or a hydrocarbon in the welding arc results in the rapid diffusion of atomic hydrogen into the molten weld pool and subsequently into the base metal's heat affected zone. If the zone's cooling rate is high enough and the steel is hardenable enough (a function of carbon and alloy content), a martensitic microstructure may form and the hydrogen atoms may then collect at internal discontinuities. Residual stresses caused by weld shrinkage, or externally applied tensile stresses, result in hydrogen induced cracks initiating at the hydrogen rich discontinuities.

Cold cracks produce sharply defined, heavy magnetic particle indications if they are open to the test object surface, as in the case of underbead cracks that extend to the weld toe (Fig. 17). Weld metal cracks may be oriented in any direction and are often associated with nonmetallic inclusions (Fig. 18). Subsurface indications are less pronounced or may be undetectable, depending on depth.

Hot Cracking

Hot cracking is a term applied to several varieties of weld metal and heat affected zone cracking, all of which occur at elevated temperatures. The following types are two of the most common hot cracks.

TABLE 3. Weld discontinuities.

Discontinuity	Location	Cause
Cold cracking	surface or subsurface	combination of atomic hydrogen, hardenable material and high residual stresses
Hot cracking	surface or subsurface	segregation during solidification (see *Liquation* and *Solidification*)
Inclusions, oxide	subsurface	mixing oxides on base metal surface into weld pool
Inclusions, slag	subsurface	improper cleaning of a previous weld pass
Inclusions, tungsten	subsurface	molten weld pool or filler metal comes in contact with tip of tungsten electrode
Lack of fusion	subsurface	failure of filler metal to coalesce with base metal
Lack of penetration	surface or subsurface	inadequate penetration of weld joint root by the weld metal
Lamellar tearing	surface	delamination of the base material during solidification and cooling of weld metal
Liquation	surface or subsurface	segregation in heat affected zone of material in liquid state during solidification
Porosity	surface or subsurface	vaporized constituents in molten weld metal are entrapped during solidification
Overlap	surface	insufficient amperage or travel speed
Solidification	surface or subsurface	dendritic segregation of low melting point constituents opening up during solidification
Undercut	surface	oversized weld pool (related to excessive amperage, travel speed and electrode size)

Solidification cracking occurs near the solidification temperature of the weld metal and is caused by the presence of low melting point constituents, typically iron sulfides, that segregate to the weld metal dendrite surfaces during the liquid-to-solid transformation process. The shrinkage stresses induced by cooling cause cracks to open between the dendrite surfaces (Fig. 19).

One common form of solidification cracking is called *center line hot cracking,* because it follows the longitudinal center line of the deposited weld bead (Fig. 20). During weld deposition, solidification of the progressing weld pool occurs from the outside in, beginning at both toes and meeting at the center. The low melting

FIGURE 17. Cross section of weld joint exhibiting hydrogen induced cold cracking in heat affected zone (underbead). This crack is detectable by magnetic particle testing because it extends to outside surface.

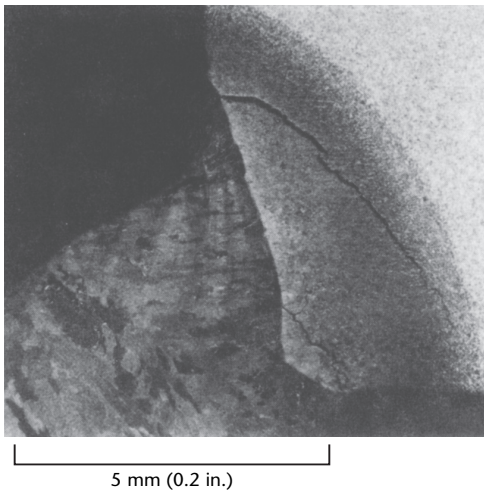


FIGURE 18. Cross section of weld joint exhibiting hydrogen induced weld metal cold cracking. This crack is oriented longitudinally but weld metal cracks may be oriented in other directions depending on joint restraint.

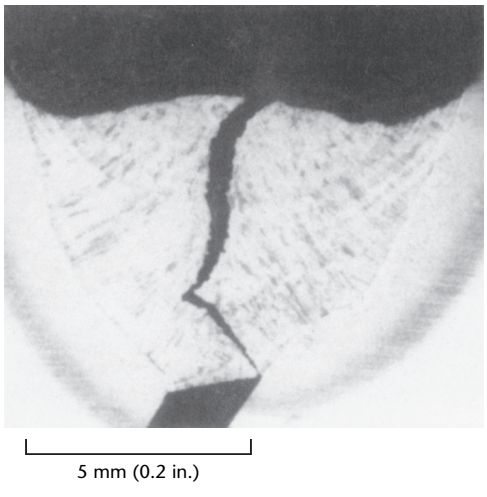


FIGURE 19. Cross section of weld joint exhibiting solidification cracking. Weld on right side contains interdendritic crack associated with slag inclusion that acted as nucleation site. Crack curves as it approaches weld center line, following dendritic solidification pattern.

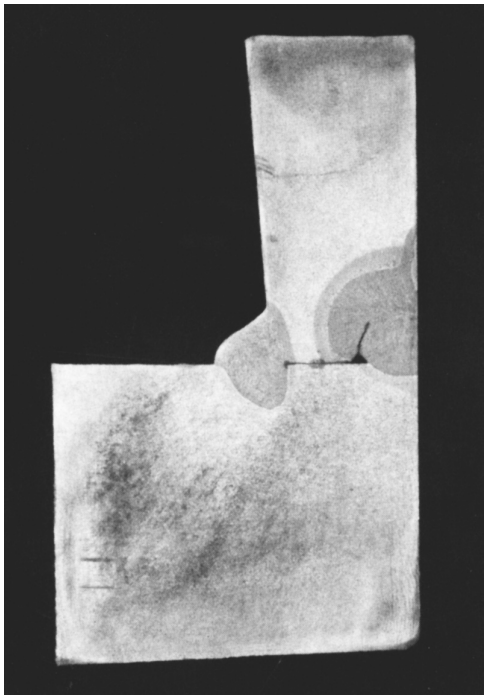
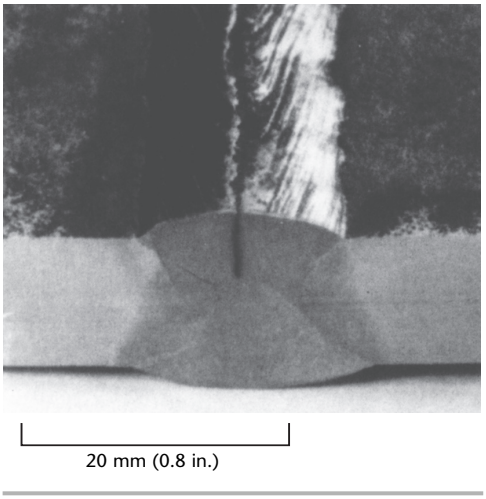


FIGURE 20. Section through weld joint exhibiting center line solidification cracking, form of hot cracking.



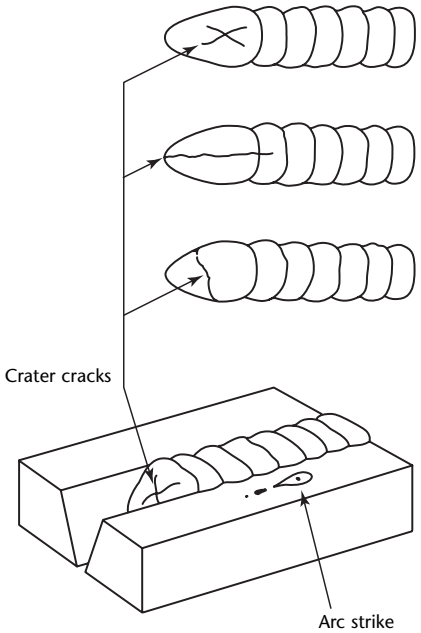
point impurities are pushed ahead of these two joining solidification fronts where they are concentrated at the center line and open up as a longitudinal hot crack under transverse solidification shrinkage stresses. The likelihood of this occurrence is increased by high travel speed, high depth-to-width ratio of the weld bead and a small weld bead, particularly in the root pass.

Another frequently observed type of solidification cracking is called *crater cracking,* which occurs in the crater formed at the termination of a weld pass (Fig. 21). Crater cracks are typically star-shaped on the surface and are the result of three-dimensional shrinkage stresses brought about by crater solidification. Sudden termination of the welding arc, rather than making the electrode linger at the end of a weld pass to fill in the crater, is a common contributor to crater cracking.

Liquation cracking or hot tearing occurs in the heat affected zone of a weld when the temperature in that region results in the liquation of low melting point constituents (inclusions or segregated alloying elements). These form a liquid grain boundary film that is unable to support the shrinkage stresses of the welding process. Such cracks are often microscopic in size but may link up under applied stresses to form a continuous surface or subsurface crack.

In general, hot cracking is associated with steels having high sulfur content and the effect is accentuated as carbon content increases. The detectability of hot cracks by magnetic particle methods is similar to that of cold cracks and depends on the hot cracks' proximity to the surface.

FIGURE 21. Location and typical appearance of crater cracks.



Lamellar Tearing

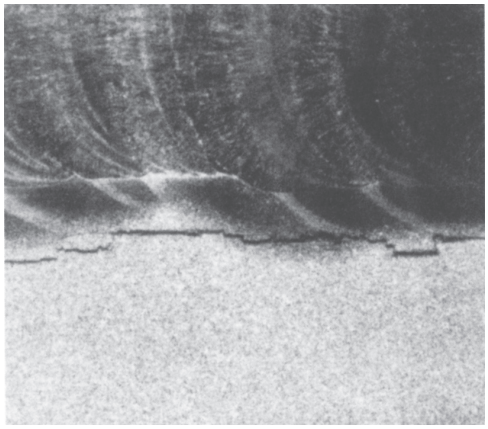
A lamellar tear is a base metal crack that occurs in plates and shapes of rolled steel exhibiting a high nonmetallic inclusion content. These inclusions are rolled flat in the steel plate manufacturing process, severely reducing strength and ductility in the through-thickness direction. When the shrinkage stresses induced by weld solidification are imposed in that direction on the base metal plate, separation of the base metal at the flattened inclusions might occur, as may shearing between those lamellar planes, resulting in a terraced fracture (Fig. 22). Lamellar tearing is readily detectable by magnetic particle techniques and is most often seen in base metal on the edge of a steel plate or structural shape, adjacent to a deposited weld bead (Fig. 23).[3]

Lack of Fusion

Lack of fusion occurs when some portion of the weld filler metal fails to coalesce with the adjacent base metal or the weld metal from a previous pass. In welding processes that use no filler metal, lack of fusion refers to incomplete coalescence between the two base metal components being joined.

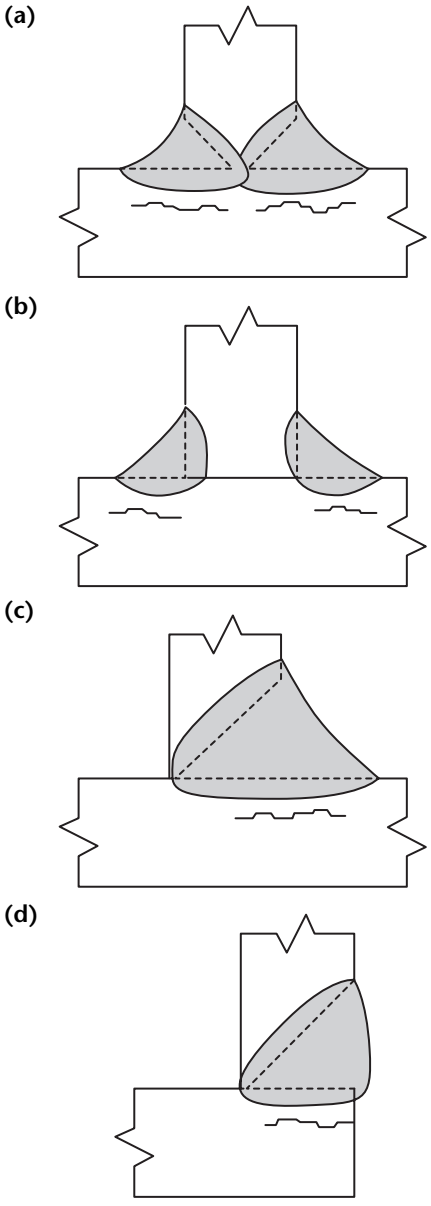
This condition is caused when the base metal surface or previous weld pass fails to reach melting temperature when the weld

FIGURE 22. Typical location and appearance of lamellar tearing. This view is parallel to rolling direction of steel plate base metal.



metal is deposited. This condition may occur when welding large components that can rapidly transfer away from the weld area because of its mass, particularly if the base material is not properly preheated before welding. In such cases, the base metal will not melt and the weld metal will not fuse into the base metal. Lack of fusion is often seen at the beginning of the first weld pass, when the base metal is at its lowest temperature during the welding process. When this condition occurs, it is commonly called a *cold start* (Fig. 24).

FIGURE 23. Locations of lamellar tears in welds of steel plate: (a) double-bevel-groove tee joints; (b) fillet welds; (c) single-bevel-groove tee joint; (d) single-7bevel-groove corner joint.[3]

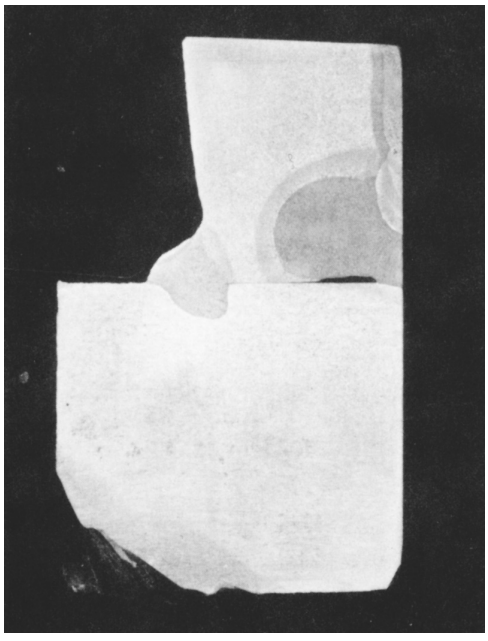


One welding process particularly susceptible to this discontinuity is gas metal arc welding (GMAW) in the short circuiting arc mode, because of its inherently low heat input. Another frequent cause of lack of fusion is attempting to weld on top of a previously deposited weld pass that has been inadequately cleaned of slag or welding on a dirty base metal surface, so that the heat of the arc is unable to reach the underlying metal.

Lack of fusion may occur at any depth in a weld, and the closer it is to the surface, the sharper the magnetic particle indication, though deeper defects may not show up in the magnetic particle process. Lack of fusion is usually oriented parallel to the direction of welding and the test indication often appears at or near the toe of the weld.

Lack of fusion in autogenous welds (welds without filler metal) may result from large inclusions in the base metal or impurities that become trapped between the surfaces of the joint before welding. Susceptible processes are those that produce a relatively shallow melted zone at the joining surfaces and then expel most of that zone by a subsequent upsetting force (high frequency resistance welding, projection welding, flash welding, friction welding). Other causes of lack of fusion in autogenous welds include inadequate heating and insufficient upsetting force. Figure 25 shows a typical discontinuity of this type.

FIGURE 24. Cross section of weld joint exhibiting lack of fusion, resulting from cold start in submerged arc weld.



Lack of Penetration

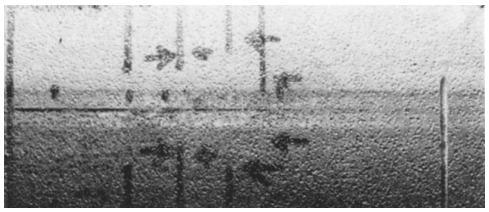
Lack of penetration is a specific type of lack of fusion that occurs only at the root of a weld when the weld metal does not fully fuse with the base metal at the root or fully penetrate the root (Fig. 26). This condition can result from any of several incorrect parameters, most related to welding technique. These include low amperage, oversized electrode, excessive travel speed, improper electrode angle, improper arc manipulation and inadequate preweld cleaning.

Often, the joint design does not facilitate good penetration because of too large a root land, too narrow a root gap or too small a bevel angle. Many procedures for double-groove welds specify back gouging of the first pass on the first side before deposition of the first pass on the second side. If back gouging is inadequate during joining, lack of penetration will likely occur.

The magnetic particle indication produced by lack of penetration has an appearance similar to a longitudinal crack and is usually found at an edge of the original root joint. On open root, single-V welds where the back side (root) of the weld is accessible, lack of penetration may be found visually. However, on double-V or single-V welds with backing bars, this condition cannot be seen.

FIGURE 25. High frequency resistance welded tube: (a) photograph of magnetic particle indication, showing lack of fusion; (b) metallographic cross section showing lack of fusion from outside surface inward.

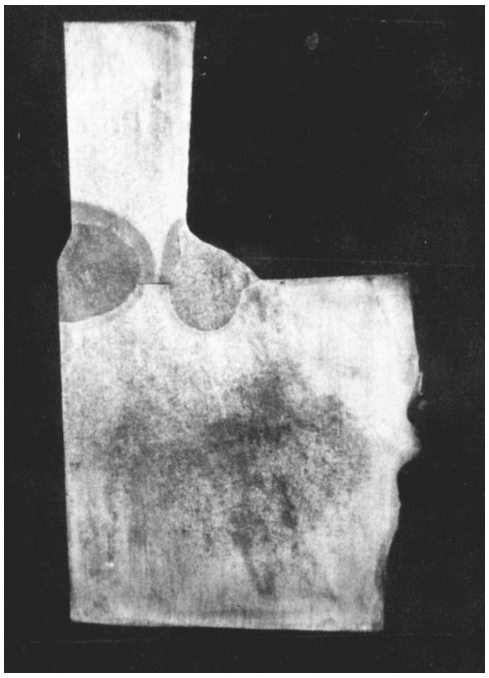
(a)



(b)



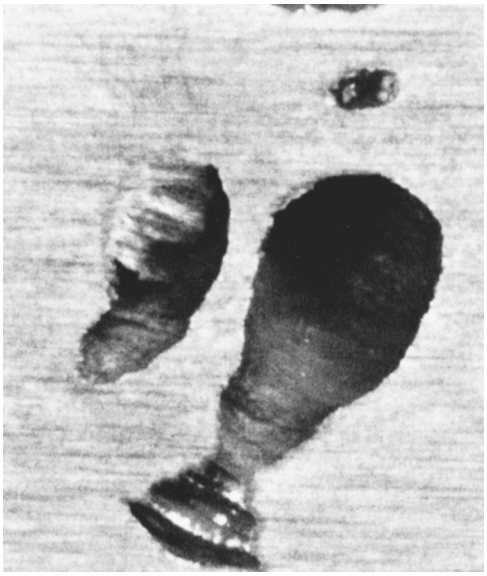
FIGURE 26. Cross section of weld joint exhibiting lack of penetration.



Porosity

Porosity is composed of cavities or pores that form when the weld metal solidifies. The pores can take a variety of shapes and sizes although they usually lack sharp edges and corners. One type of elongated pore is often called a *wormhole* (Fig. 27). The distribution of porosity within the weld metal may be clustered (usually results from improper initiation or termination of the welding arc) or linear (indicates gas evolution by welding over a contaminant confined to a linear junction such as a corner or crevice).

FIGURE 27. Longitudinal section through weld metal containing wormhole porosity.



In general, porosity is often the result of dirt, rust or moisture on the base or filler metal surface before welding and can be prevented by maintaining cleanliness and dryness. Other contributing factors include base metal composition (such as high sulfur content), high solidification rate and improper welding technique (such as excessive arc length or lack of shielding gas).

Often the surface discontinuities called *blowholes* are found where gas pockets have reached the surface of the weld pool but do not fully escape before solidification takes place. Blowholes should be removed before any subsequent weld passes are deposited because they are likely places for slag entrapment.

A magnetic particle indication of subsurface porosity is typically weak and not clearly defined. All but the smallest surface pores should be visible to the unaided eye.

Inclusions

Many weld processes use flux shielding, including shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux cored arc welding (FCAW). Welds produced by these methods are particularly susceptible to discontinuities known as *slag inclusions*. Slag can be entrapped in the weld metal during solidification if it is unable to float out while the pool is still liquid. The factors that promote slag entrapment include high solidification rate, high weld pool viscosity, use of an oversized electrode and improper joint geometry.

Slag allowed to remain on the surface of a deposited weld bead is rarely completely dissolved by subsequent passes. Therefore, it is essential to remove all slag from each pass. Joint designs that exhibit a high depth-to-width ratio and weld beads with an excessively convex profile are promoters of slag entrapment (Fig. 28). A magnetic particle indication produced by a slag inclusion is weak and poorly defined and high magnetizing field intensity is required for detection.

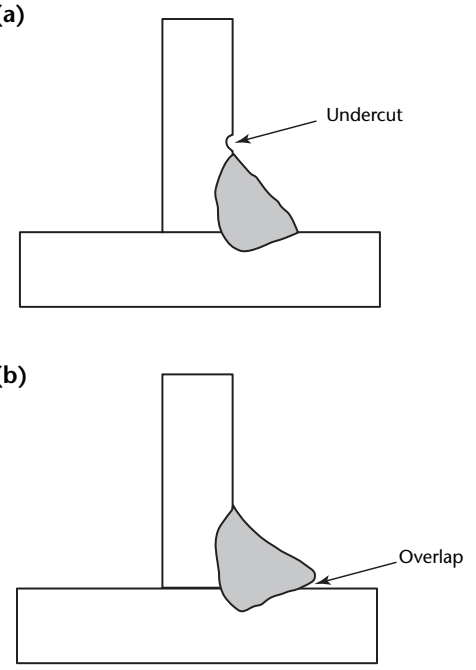
Tungsten inclusions are found in the weld metal deposited by the gas tungsten arc welding (GTAW) process and are usually the result of allowing the molten weld pool or the filler metal to come in contact with the tip of the tungsten electrode. This type of inclusion is virtually undetectable by magnetic particle methods.

Oxide inclusions are particles of high melting point oxides present on the base metal surface. During welding, these oxides are then mixed into the weld pool. The magnetic particle indications produced by oxide inclusions of significant size and quantity are similar to those produced by subsurface porosity. Small and isolated oxides are extremely difficult to detect by magnetic particle methods.

FIGURE 28. Cross section of weld joint containing slag inclusions. High depth-to-width ratio of weld on left side contributed to slag entrapment.



FIGURE 29. Diagram of weld discontinuities: (a) undercut; (b) overlap.



Undercut

Undercut occurs at the toe of a weld when the base metal thickness is reduced. Essentially, a narrow crevice is formed in the base metal, paralleling the weld toe and immediately adjacent to it (Fig. 29a). Undercut lessens joint strength in the static sense by reducing the base metal section thickness. It also creates a stress concentration that reduces the impact, fatigue and low temperature properties of the joint. Undercut is caused by an oversized molten weld pool, which is in turn related to excessive amperage, travel speed and electrode diameter.

A magnetic particle indication produced by undercut appears less pronounced than that produced by lack of fusion. Undercut is easily detected by visual testing.

Overlap

Overlap is the protrusion of weld metal over the weld toe, producing a form of lack of fusion that creates a sharp mechanical notch or stress concentration (Fig. 29b). The condition is caused by insufficient amperage or travel speed.

Overlap produces a magnetic particle indication at the weld toe similar to that produced by lack of fusion. It is often detectable by visual testing.

PART 4. Processing Discontinuities

Discontinuities that originate from grinding, heat treating, machining, plating and related finishing operations are categorized as secondary processing discontinuities (Table 4). Such discontinuities may be the most costly because all previous processing costs are lost when the test object is diverted from service.

Heat Treating and Quenching

To obtain a specific hardness and microstructure, materials are customarily heat treated. During this operation, the metal is heated and cooled under controlled conditions. However, in some cases, this process produces stresses that exceed the material's tensile strength and cause it to crack. Similarly, when an object is heated to a very high temperature and then rapidly cooled (in air, oil or water), quench cracks may develop (Fig. 30). Quench cracks serve as stress concentration sites for fatigue crack initiation and propagation. This may also serve as the initiation site for overload failures. Some quenching operations are so severe that objects break up during the process.

When an object is quenched following heat treating, an initial transformation occurs at the object's surface. During cooling and the transformation from austenite (a face centered cubic structure) to ferrite (body centered cubic) and martensite (body centered tetragonal), a volumetric expansion occurs. Immediately after the quenching process begins, a layer of body centered tetragonal or body centered cubic material is formed at the surface. When the interior cools and transforms, volumetric expansion takes place but the interior expansion is restrained by the solidified layer. If the solid layer does not expand enough or if the internal expansion is great enough, cracking through the outer layer results.

The amount of volumetric expansion is governed primarily by the chemistry of the metal, particularly carbon. As the carbon content increases, so does the amount of expansion. The severity of the quench can be lessened by using a lower carbon content material or by quenching in a less harsh medium such as oil or an elevated temperature bath.

A tempering process normally follows the quenching operation. Because of this exposure to a high temperature, the surface of quench cracks become oxidized. Identifying oxidation is one way to determine if a crack was caused by quenching.

Heat treating and quench cracks usually emanate from locations of thin cross section, corners, fillets, notches or material thickness changes because these areas cool more quickly and therefore transform first. Restricted movement of the material also influences the location of cracks during the heat treating or quenching operations. Heat treating or quench cracks are typically forked, surface indications that are randomly placed in any direction on the test object.

Straightening[2]

The uneven stresses caused by heat treating frequently result in distortion or warping and the metal forms must be straightened into their intended shape. If the distortion is too great or the objects are very hard, cracking can occur during the straightening operation.

TABLE 4. Processing discontinuities in ferromagnetic materials.

Discontinuity	Location	Cause
Grinding cracks	surface	localized overheating of material due to improper grinding procedure
Heat treating cracks	surface	stresses from uneven heating or cooling and beyond tensile strength of material
Machining tears	surface	improper machining practice
Pickling cracks	surface	residual stress being relieved
Plating cracks	surface	residual stress being relieved
Quench cracks	surface	sudden cooling from elevated temperature

Grinding[1,2]

Grinding cracks can be attributed to the use of glazed wheels, inadequate coolant, excessive feed rate or attempting to remove too much material in one pass. Grinding cracks develop where there is localized overheating of the base material.

Surface cracks in hardened objects can be caused by improper grinding operations. Thermal cracks are created by stresses from localized overheating of the surface under the grinding wheel. Overheating can be caused by using the wrong grinding wheel, a dull or glazed wheel, insufficient or poor coolant, feeding too rapidly or cutting too heavily. Grinding cracks are especially detrimental because they are perpendicular to the object surface and have sharp crack tips that propagate under repeated or cyclic loading (Fig. 31). Grinding cracks are typically at right angles to the grinding direction, are very shallow and are often forked and sharp at the root (Fig. 32).

When located in high stress areas, such cracks may result in fatigue failures caused by residual stresses. Materials that have been hardened or heat treated can be more susceptible to grinding cracks because uncracked they retain high residual stresses from quenching. During grinding, localized heating added to entrapped stresses can cause surface ruptures. The resulting cracks are usually more severe and extensive than typical grinding cracks.

FIGURE 30. Magnetic particle indications of quench cracks.

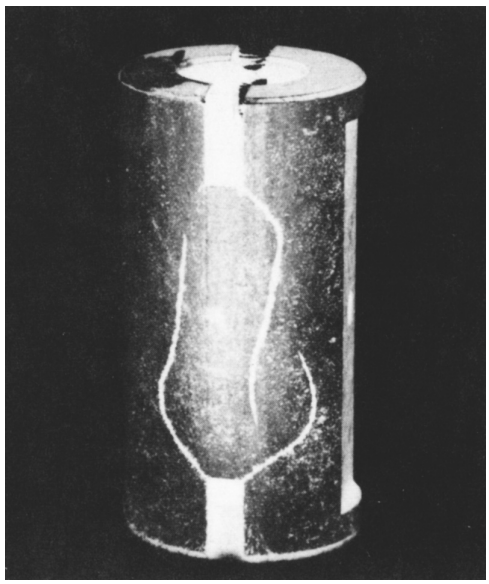
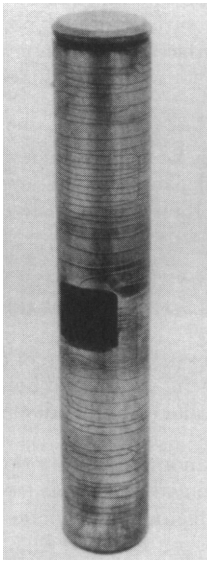


FIGURE 31. Grinding crack indications: (a) visible magnetic particles; (b) fluorescent magnetic particles.

(a)



(b)

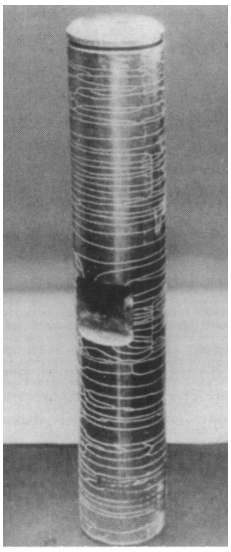
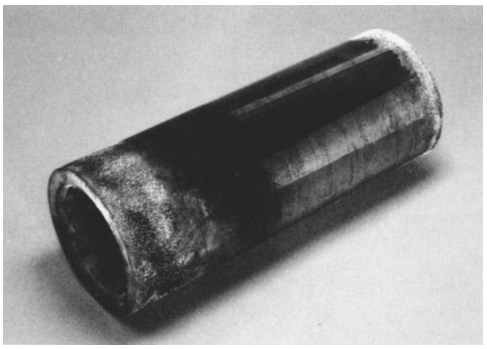


FIGURE 32 Wet fluorescent magnetic particle indication of grinding cracks in diesel engine connecting pin.



Machining Tears

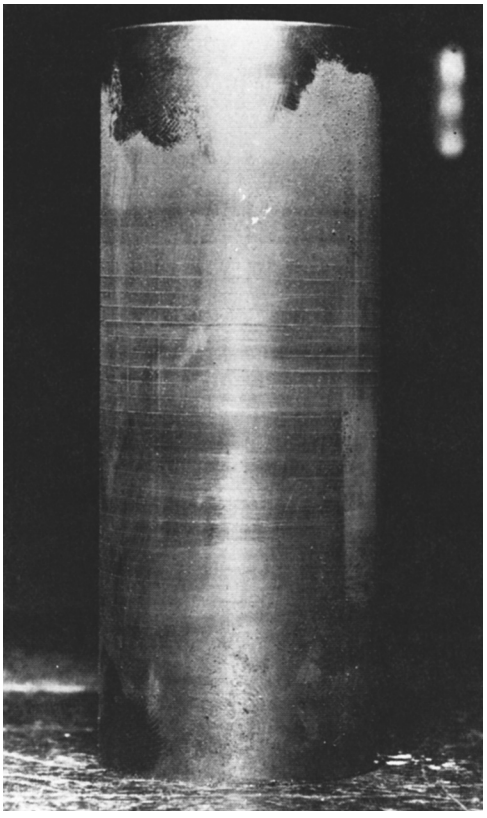
A dull machining tool shears metal off in a manner that produces rough, torn surfaces. As a result, the surface is work hardened to a degree that depends largely on the depth of cut, the type and shape of the tool and the material properties (Fig. 33).

Heavy cuts and residual tool marks from rough machining act as stress risers and can contribute to premature failure in a component. Stress risers may also occur at a change in section, such as in small fillet radii between two shaft sections of different diameters or the poor blending of fillets with shaft surfaces. Although difficult to detect, machining tears must be thoroughly and meticulously located.

Plating, Pickling and Etching[1,2]

Hardened surfaces are susceptible to cracking from electroplating, acid pickling or etching processes.

FIGURE 33 Magnetic particle indications of cracks resulting from cold working during machining.



Pickling Cracks

A pickling operation is used to remove unwanted scale for the purpose of a more thorough test of the base material. It can also be used to prepare the surface for finishing operations such as plating. Pickling cracks are predominately found in materials that have high residual stresses (hardened or cold worked metals) and in materials with voids or similar discontinuities.

Acid pickling can weaken surface structure of the metal, allowing internal stresses from the quenching operation to be relieved by crack formation (Fig. 34). During pickling, acid etching or electrodeposition, hydrogen is generated at the surface of the material. The absorption, or interstitial diffusion, of hydrogen into the metal adds to the internal stresses of the object and causes a breakdown of its molecular structure. Cracks result (Fig. 35). Internal stresses accelerate propagation of preexisting

FIGURE 34. Treating with acid weakens the surface metal, allowing release of spring's internal stresses through surface cracks.

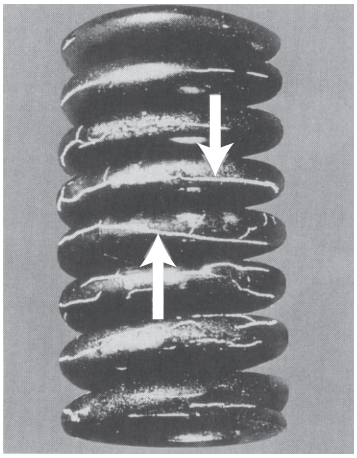


FIGURE 35. Hydrogen or pickling cracks on steel spring.



discontinuities. This mechanism, called *hydrogen embrittlement,* can result in cracking during the etching or plating operation or at some later time when additional service stresses are applied.

Plating Cracks

Plating is used for decoration, corrosion protection, wear resistance and to correct undersized dimensions for a wide variety of steel components. However, specific plating materials produce residual stresses that can be either tensile or compressive. Plating materials that develop residual tensile stresses (chromium, copper and nickel) can reduce the fatigue strength of a component.

Plating cracks may develop when there is penetration of either hydrogen or hot plating material into the base metal (Fig. 36). This action produces crack propagation or initiation. Materials high in hardness or residual stresses are more susceptible to damage from hydrogen absorption during plating or pickling operations. Furthermore, cracks that initiate exclusively in the plating material may act as stress risers and cause cracking in the base material.

FIGURE 36. Wet fluorescent magnetic particle indications of plating cracks due to hydrogen embrittlement.



PART 5. Service Induced Discontinuities

The life expectancy of a component is dependent on its service environment (both mechanical and chemical), the quality of its maintenance and the appropriateness of its design. It is essential for testing personnel to know the service conditions of a component to perform a magnetic particle test accurately. Although service induced discontinuities appear similar, the mechanisms that cause them are quite different in each case.

The following text briefly describes common service induced discontinuities (Table 5) found in ferromagnetic materials.

Fatigue Cracking

Fatigue is a fracture mechanism induced by a cyclically applied stress that is lower in magnitude than the ultimate tensile strength of the material but high enough to initiate a crack or to propagate a preexisting crack. Fatigue cracks can develop from stress risers such as sharp radii, nicks, machining or tooling marks, nonmetallic inclusions present at or near the material surface, pores, holes or notches, keyways and may even develop on a smooth surface (Figs. 37 and 38). Surface anomalies such as copper penetration (Fig. 39) contribute to fatigue cracking. Fatigue cracking typically occurs at the surface and is reliably detected by magnetic particle testing.

As a fatigue crack begins to propagate, the stress intensity at the tip of the crack starts to increase. With every incremental growth period of the crack, there is a proportional, incremental increase in the stress intensity. This process continues until the stress intensity K reaches the critical value K_{IC}, where failure occurs.

This K_{IC} factor, also known as the *fracture toughness,* is unique for each material. The variance in fracture toughness partially explains the behavior of fatigue cracks: why there is such a range of fatigue crack sizes, why some cracks may only propagate a small amount and why others propagate nearly all the way through.

Fatigue Crack Structure

From an external surface, a fatigue crack resembles any other crack, but internally a fatigue crack has certain unique characteristics. Macroscopically, features called *beach marks* or *clamshell marks* can

FIGURE 37. Helicopter rotor component: (a) no discontinuities revealed by visual testing; (b) fatigue cracks revealed by wet fluorescent magnetic particle tests.

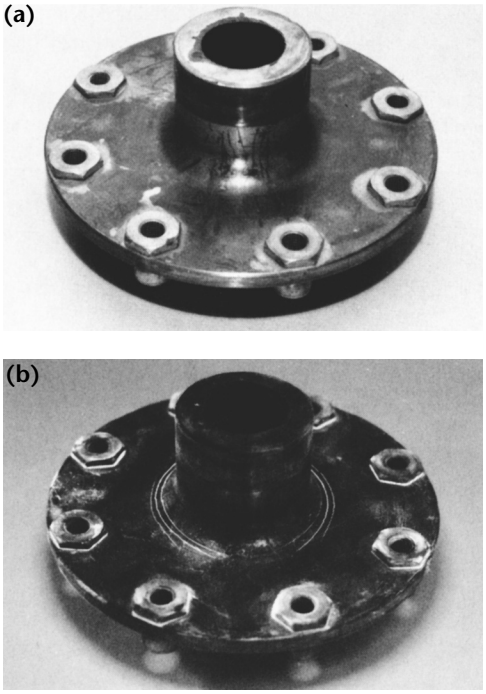


TABLE 5. Service induced discontinuities in ferromagnetic materials.

Discontinuity	Location	Cause
Creep	surface or subsurface	high temperature and stress below yield strength
Fatigue	surface	cyclically applied stress below ultimate tensile strength
Hydrogen cracking	surface or subsurface	applied tensile or residual stress in hydrogen enriched environment
Stress corrosion cracking	surface	static tensile load in corrosive environment

be found. These distinct markings are the result of variations in cyclic loading, either in frequency, environment or stress. Such marks are actually small ridges that develop on the fracture surface and they indicate the position of the advancing crack at a given time. The geometry and orientation of beach marks can help establish the location of the crack origin and the direction of propagation (Fig. 40).

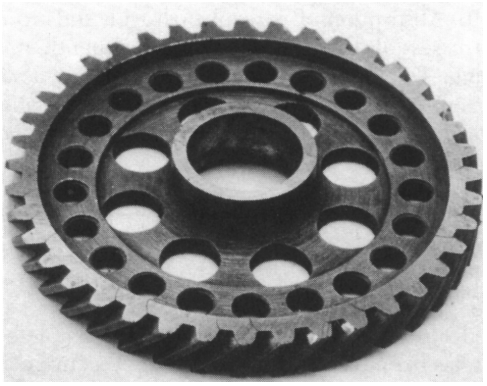
Microscopically, the fatigue fracture mechanism is characterized by features known as *striations*. Each striation represents one applied stress cycle. The distance between striations can be equated to the crack growth rate.

Striations and beach marks are not always observed on the fracture surface. Many times, loading is such that striations formed during the tensile or positive stress cycle are obliterated during compressive or negative stress. Striations appear more often in softer materials such as aluminum or low carbon steel.

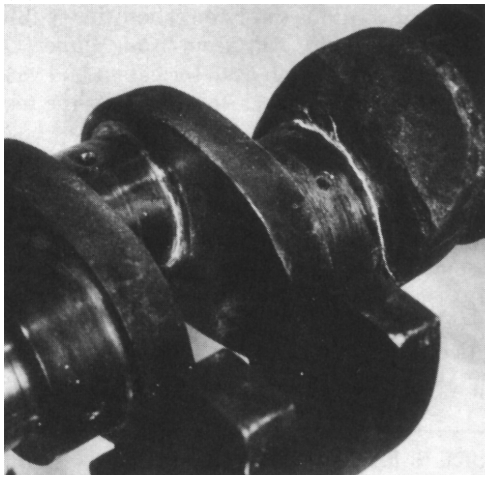
Fatigue cracks normally originate on the surface but can begin below the surface at discontinuities if the applied and residual stresses exceed the subsurface

FIGURE 38. Fatigue cracking in manufactured components: (a) gear tooth roots; (b) automobile crankshaft; (c) aircraft component.

(a)



(b)



(c)

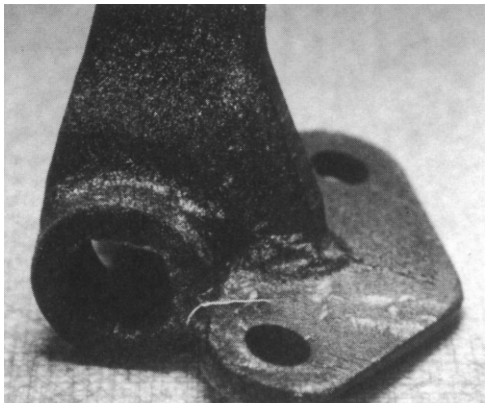


FIGURE 39. Fatigue crack from copper penetration on journal.

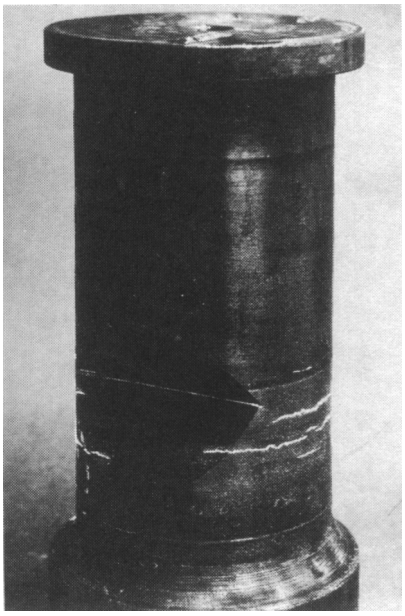


FIGURE 40. Photograph of fracture surface typical of fatigue, with initiation in upper left corner.



fatigue strength of the material. When this occurs, a circular pattern of beach marks may form around the origin, producing a bull's eye appearance.

The probability of fatigue cracking can be dramatically reduced if the designer is aware of the material's fatigue properties and designs the component accordingly. Proper care in machining is necessary to ensure that no unanticipated stress risers are introduced. Additional fatigue resistance can be gained by stress-relieving a component or by shot peening to introduce a compressive stress on the object's surface.

Creep Cracking

At temperatures greater than half the melting point in celsius and at stresses below the yield strength of the material, deformation can occur by the action of grains gradually separating over an extended period of time. This can eventually lead to cracking and finally to failure. This deformation or failure mechanism is called *creep*.

Figure 41 shows a schematic representation of creep or deformation with a constant load. The curve can be broken down into four regions. The first is the material's initial response to loading. The response is usually elastic and appears very quickly, accounting for the vertical portion of the curve. The next portion of the curve is where the material's rate of straining or creep is decreasing with time. This is called *primary creep* or *transient creep*.

The third portion is called *secondary creep* or *steady state creep*. This period accounts for the majority of a component's life and the rate of creep is nearly constant. During this stage, small voids begin to form and grow at the triple points of the grain boundaries. Because the void formation is nearly constant, the creep rate can be predicted and the remaining service life of the component can be estimated, based on the steady state creep.

Once the material moves into the region of tertiary creep, the useful life of the material is over. In the tertiary stage, the creep voids have become so large that they begin to link, forming a crack network that quickly leads to failure.

Creep can be detected and controlled. Periodic tests, particularly those involving field metallography and circumferential measurement can be used to monitor the creep process (Figs. 42 and 43). By slightly decreasing operating temperature or stress, a substantial decrease in the creep rate yields greater service life. Figure 44 shows the effect that various temperatures have on creep.

It is generally recognized that the most direct way to improve the creep properties of a metal is by adding alloying elements. Carbide forming elements, such as molybdenum, tungsten and to a lesser degree, chromium and vanadium, effectively enhance the creep resistance of steels.

Nickel additions are beneficial if sufficient quantity is added to produce an austenitic structure that is more resistant to creep. Austenitic stainless steels (particularly 18 percent chromium, 8 percent nickel types) have much better creep properties than carbon steels.

FIGURE 41. Typical curve showing three stages of creep.

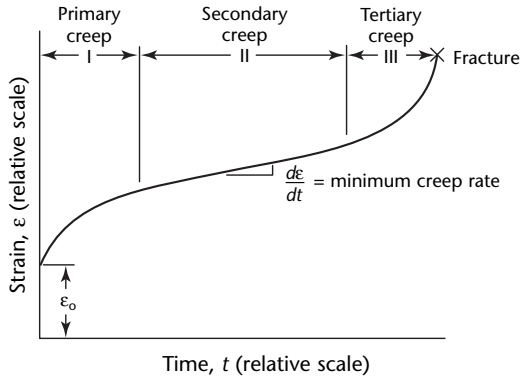


FIGURE 42. Photomicrograph of fracture and creep in various stages in heat affected zone near fusion zone interface.

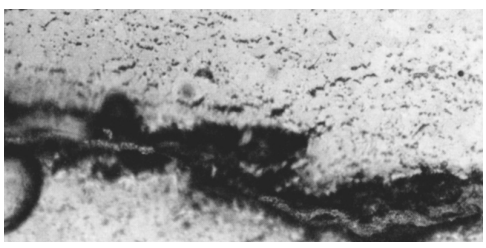
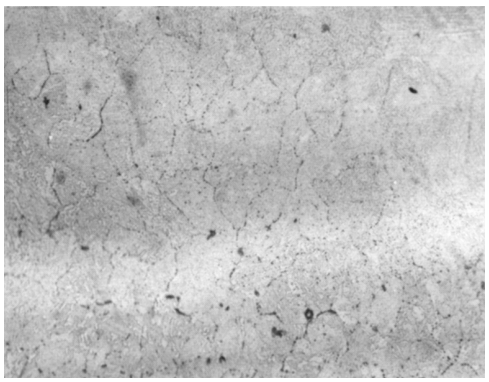


FIGURE 43. Photomicrograph of linked creep voids in weld zone.



Aside from alloying additions, heat treatment has an effect on creep properties. Heat treatment generally controls grain size and it has been found that a coarser grain at elevated temperatures has higher creep strength than a finer grain.

Because materials can be subjected to such a variety of loads and temperatures for a particular application, the type of heat treatment should be based on the degree of stability that it imparts to the component initially and throughout its service life.

Stress Corrosion Cracking

Stress corrosion cracking is a fracture mechanism that results from the combined effects of a static tensile load and a corrosive environment. The stress involved can either be from actual applied loads or from residual stresses. One of the most common causes of this residual stress is the shrinkage that occurs during cooling of weld metal.

FIGURE 44. Curves showing effect of temperature on creep over time.

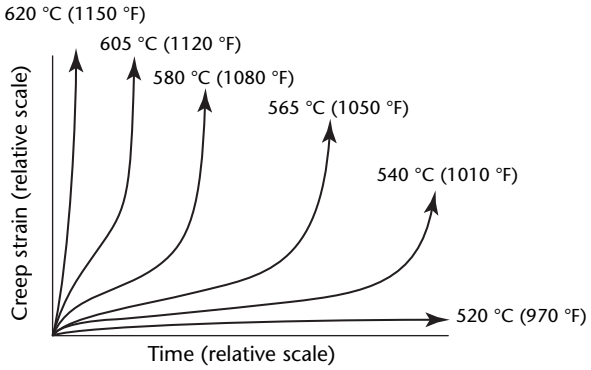
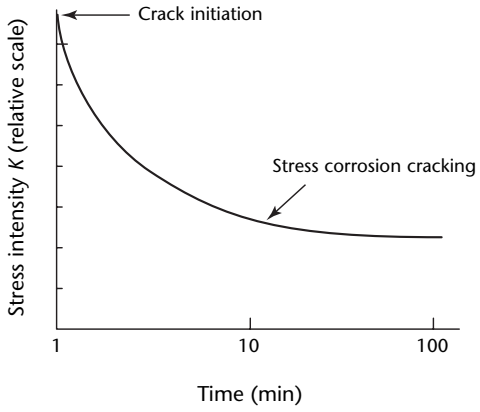


FIGURE 45. Stress intensity versus time dependence for typical stress corrosion cracking situation.

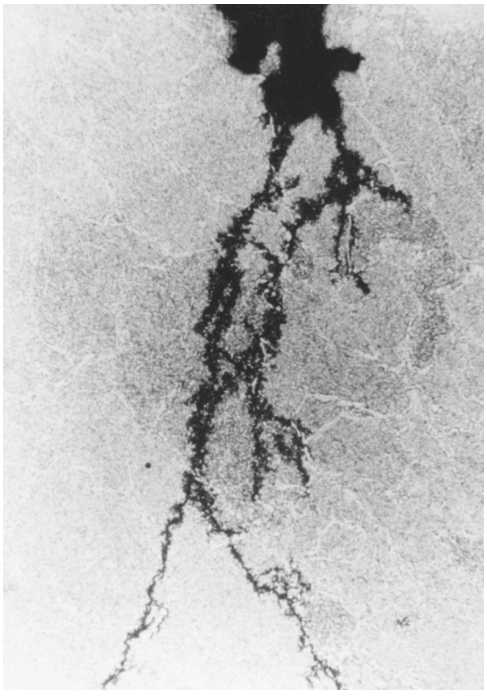


What constitutes a corrosive environment varies from material to material. Common materials and their corrosive environments include aluminum and austenitic stainless steels exposed to saltwater; copper and its alloys exposed to ammonia (NH_3); and mild steel exposed to sodium hydroxide (NaOH).

The dependence of stress intensity on time for a typical stress corrosion cracking situation is shown in Fig. 45. The basic stress-versus-time curve can be expressed in terms of the initial stress intensity level of K_I, which is based on the tensile load and a known crack length. Crack growth does not occur if the stress intensity is below its threshold value K_{ISCC}. If the initial stress intensity is above K_{ISCC}, a crack propagates. The higher the initial K_I or the closer the value gets to the critical stress intensity factor K_{IC}, the shorter the life of the component.

The initiation site of a stress corrosion crack may be a preexisting discontinuity or it may be a small pit acting as a stress riser and produced by corrosive attack on the surface. After a crack is formed, the corrosive environment penetrates the surface of the material. The tip of an advancing crack has a small radius and the attendant stress concentration is great. This stress at the crack tip ruptures the normally protective corrosion film and aids in the corrosion process (Fig. 46).

FIGURE 46. Photomicrograph showing typical stress corrosion crack. Small pit produced by corrosive attack acts as stress riser.



In addition to this, the formation of corrosion products by local attack in confined areas produces high stress levels in materials if the corrosion products occupy a larger volume than the metal from which they are formed. This wedging action of corrosion products in cracks has been measured to produce stresses over 34 MPa (5000 $lb_f \cdot in.^{-2}$), which aid in the propagation of the crack.

Stress corrosion cracking produces brittle failure, either intergranular or transgranular, depending on the type of alloy or the corrosive environment. In most cases, although fine cracks penetrate into the cross section of a component, the surface shows little evidence of corrosion.

To keep the stress intensity to a minimum, care must be taken to avoid stress concentrations, such as tooling marks, notches, arc strikes and large inclusions near the surface.

Hydrogen Cracking

Hydrogen cracking or hydrogen embrittlement is a fracture mechanism that results from the corrosive environment produced by a hydrogen medium and usually occurs with an applied tensile stress or residual stress. Hydrogen is introduced into a material by processes such as electroplating, pickling, welding in a moist atmosphere or the melting process itself. Hydrogen may also come from corrosion or the presence of hydrogen sulfides, hydrogen gas, water, methane or ammonia.

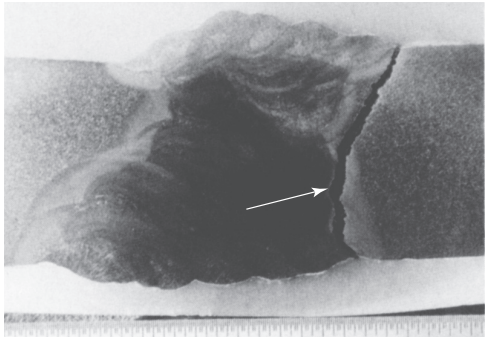
If no crack or stress riser is present on a material surface, hydrogen can diffuse into the metal and often initiates cracks at subsurface sites, where triaxial stress conditions are at maximum levels. In low strength alloys, this condition can lead to what is known as *hydrogen blistering*.

If a crack is already present, it is quite common to see hydrogen induced cracking initiated at the tips of preexisting cracks.

In many instances, hydrogen is already present internally in a metal before it is placed into service. Hydrogen is readily absorbed into molten metal during the initial solidification of the material and during welding processes. The solubility of hydrogen is quite high at elevated temperatures, and in some cases metals can become supersaturated with hydrogen during cooling.

Hydrogen cracking follows grain boundaries and rarely shows any signs of branching (Fig. 47). When such cracking results from blistering or from a static load, it always originates below the test object's surface. Hydrogen cracking from other causes can begin below the surface or at a stress riser.

FIGURE 47. Photograph of hydrogen cracking found in heat affected zone adjacent to weld.



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CHAPTER

Chemical and Petroleum Applications of Magnetic Testing

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PART 1. Chemical and Petroleum Industry

Petroleum Industry[1]

Oil refining began in the early 1850s with the production of kerosene and lamp oil. After 1890, gasoline was needed to fuel the combustion engines in automobiles. Modern refineries and petrochemical plants are highly dependent on crude oil and other fossil fuels to produce a wide range of chemicals and products.

Petrochemical plants and refineries are comprised of processing units ranging from simple distillation towers to complex fluid catalytic cracking, hydrodesulfurization units, cokers and other processing units. Process components such as vessels and piping are subject to many forms of service related material degradation. Corrosion and cracking if left unchecked could cause catastrophic failures and loss of life. The history of catastrophic failures in the refining, chemical and other industrial complexes has lead to federal regulation of process safety.[2] Part of the regulatory document covers mechanical integrity.

Nondestructive testing is vital for ensuring the mechanical integrity and serviceability of this equipment. The chemical industries use many nondestructive test methods to maintain and ensure safe operation of their production facilities. Nondestructive testing is important early, during fabrication; later, during maintenance and servicing of vessels and piping; and finally, in on-stream inspection. The goal of such testing programs is to achieve and maintain capacity production. Owner/user teams and engineering staff use nondestructive test results to plan their maintenance activities, to assess their risks and to implement risk based inspection. Risk based inspection philosophies prioritize inspections, minimize failures and maximize the performance of equipment.

Magnetic particle testing is an important NDT method for the chemical and petroleum industry. Refining and chemical plants are vital to the oil and gas industries, producing much needed resources for the world.

Test Procedures[1]

When using magnetic techniques, chemical and petroleum industry inspectors must generally ask the following questions.

1. What is the fabrication and service history of the tested parts? Has the equipment, component or material had any previous fabrication requirements or nondestructive test requirements?
2. What requirements does the customer's inspection contract specify? Are there preexisting manufacturer's or purchaser's specifications to a national or local code?
3. In what orientation are discontinuities most expected or most critical?
4. Will the surface permit adequate magnetic coupling? Does corrosion, scale, flaking or coating need to be removed? What is the surface condition before and after preparation for testing?
5. How will the test object be used?

When establishing a procedure, it can be difficult to correlate the materials with original procurement specifications. In many cases, the acceptance criteria exceed those originally specified. In the resulting confusion, high quality materials may be rejected and low quality materials could be accepted. Accurate procedures are established through reference standards with artificial discontinuities (notches or cracks) that can be used to select the orientation and intensity of magnetization. System verification, including check of particle suspensions, should also be conducted to ensure test accuracy.

Magnetic Techniques

During fabrication, visible dye and wet fluorescent magnetic particle tests are used to ensure that surface cracking is not missed. Methods such as radiographic and ultrasonic testing are often limited to subsurface discontinuities not readily seen by visual testing. Magnetic and other nondestructive methods are required to support the safety factors designed into equipment and components.

During service, induced cracking can dramatically affect the safe operation and life of components. Once vessels, piping and other components are put into service, visible dye and wet fluorescent magnetic particle tests are used again to detect service induced cracking. The effect of a failure can be catastrophic and cost refiners or chemical manufacturers millions of dollars in loss of production, loss of life, fines and litigation.

Magnetic particle testing is specified by virtually all organizations that issue nondestructive testing standards or codes. Magnetic particle techniques are easily taught and, like those for liquid penetrant testing, require the least amount of time and experience to become proficient.

Magnetic Flux Leakage Testing[3]

Magnetic flux leakage testing uses a strong magnet inside the probe to magnetize the test object. As the probe encounters a wall reduction or a sharp discontinuity, the flux distribution varies around that area and is detected either with a hall effect sensor or an inductive pickup coil.[4,5]

Magnetic flux leakage testing offers some advantages over remote field testing, an electromagnetic testing technique generally more sensitive to isolated pitting. Whereas remote field testing depends on total cross sectional area of change, magnetic flux leakage testing responses are enhanced by discontinuities such as isolated pitting. This is the result of the large flux leakage response generated.

Magnetic flux leakage testing has been used successfully on air cooled, carbon steel, finned, heat exchanger tubes. Magnetic flux leakage testing is less sensitive to the aluminum fins that are coiled around the carbon steel tubes than the remote field testing techniques are. Magnetic flux leakage testing can be performed at about the same speed as remote field tests.

Refinery Components

Heat Exchangers, Condenser Tubes and Air Cooling Tubes[3]

Tube testing is important for the refining and petrochemical industry. Heat exchangers and condensers are designed to sustain 100 percent separation between products in the tubes and products in the vessel (Fig. 1). A leaking tube can cause not only a significant effect on production but also catastrophic failure and loss of life. Tube testing techniques include magnetic flux leakage testing (Fig. 2), remote field testing, conventional eddy current testing, internal rotary ultrasonic testing and laser profilometry. Ultrasonic and laser methods complement the electromagnetic techniques and often are used in parallel.

Tube testing falls into two categories: ferrous and nonferrous. Ferrous metals include carbon steel, 400 series stainless steel and metals with similar magnetic properties; nonferrous metals are nonmagnetic and include copper, brass, nickel and most stainless steels. Table 1 lists techniques used for tubes made of different materials.

The choice of technique is mainly influenced by the type of service damage that needs to be detected but often the

FIGURE 1. Cutaway image of typical heat exchanger, showing tube bundle.

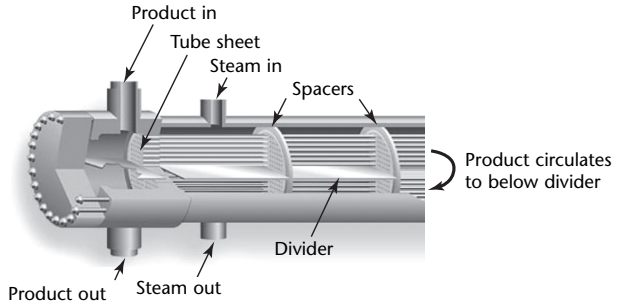
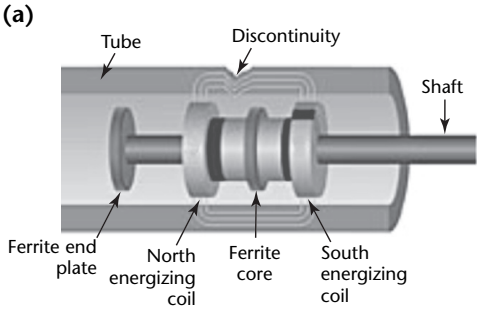


FIGURE 2. Magnetic flux leakage probe: (a) bobbin coil design; (b) probe inserted in carbon steel tube bundle of crude petroleum processing unit.

(a)



(b)



technique is dictated by tube cleanliness. For example, internal rotary ultrasonic testing and laser profilometry require very clean interior surfaces whereas electromagnetic tests do not. Often, electromagnetic techniques are used as screening tools before cleaning for ultrasonic or laser techniques.

Several damage mechanisms and discontinuities can occur, on either the inside or outside diameter surface; other discontinuities are volumetric and not connected with either surface. However, the primary discontinuities are either outside or inside surface breaking discontinuities. Table 2 lists various discontinuities that can be detected with the various techniques for both nonferrous and ferrous tubing materials.

TABLE 1. Applicability of nondestructive tests to ferrous and nonferrous metals.

Technique	Applicability to Metals	
	Ferrous	Nonferrous
Eddy current testing	no	yes
Magnetic flux leakage testing	yes	no
Remote field testing	yes	yes
Laser techniques	yes	yes
Ultrasonic testing	yes	yes

Pressure Vessels

Pressure vessels are continually subject to testing and are considered one of the most vital and volatile pieces of equipment in a petrochemical plant or refinery. Traditional preservice tests include radiographic and ultrasonic testing during fabrication. Traditional inservice tests include visual, ultrasonic, magnetic particle and more recently electromagnetic techniques such as eddy current testing and alternating current field measurement testing.

Industry practices for inservice tests of pressure vessels have involved visual, ultrasonic, electromagnetic and wet fluorescent magnetic particle testing. To perform wet fluorescent magnetic particle testing, the vessel surfaces must be prepared by sandblasting. Magnetic particle testing does not measure discontinuity depth.

TABLE 2. Discontinuity detection by nondestructive tests for ferrous and nonferrous metals in components.

Damage Mechanism	Eddy Current Testing	Magnetic Flux Leakage Testing	Remote Field Testing	Laser Profilometry	Ultrasonic Testing
Nonferrous Materials					
Pitting, inside surface	yes	no	tube and pipe	yes	yes
Pitting, outside surface	yes	no	tube and pipe	no	yes
Stress corrosion cracking, inside surface	yes	no	no	limited	no
Stress corrosion cracking, outside surface	yes	no	no	no	no
Volumetric discontinuities, embedded and other	yes	no	tube and pipe	no	limited
Wall loss, inside surface	yes	no	tube and pipe	limited	yes
Wall loss, outside surface	yes	no	tube and pipe	limited	yes
Ferrous Materials					
Pitting, inside surface	no	yes	tube and pipe	yes	yes
Pitting, outside surface	no	yes	tube and pipe	no	yes
Stress corrosion cracking, inside surface	no	limited	no	limited	no
Stress corrosion cracking, outside surface	no	limited	no	no	no
Volumetric discontinuities, embedded and other	no	limited	no	no	limited
Wall loss, inside surface	no	limited	tube and pipe	limited	yes
Wall loss, outside surface	no	limited	tube and pipe	limited	yes

PART 2. Electromagnetic Testing of Transmission and Storage Systems[6]

Pipelines

Pipelines connect field production (gas and oil extraction) with refineries and petrochemical plants where gas and crude petroleum are processed into usable products (Fig. 3). Because pipelines cross state lines in the United States, they are governed by the Department of Transportation. The construction, maintenance and testing of these pipelines are critical to the safety of the environment and the general public. Buried pipelines not only have the potential for failure but could contaminate lakes, rivers and underground water sources if leakage occurs.

Traditional preservice tests include radiographic and ultrasonic testing during fabrication to ensure the quality of the welding. Once a pipeline is in service, the pipeline companies depend largely on inservice testing to assess corrosion.

Test strategies before 1970 included leak detection systems. Since the late 1960s, flux leakage testing tools have been inserted into the pipelines and propelled by product flow. This expedient offers a test technique without significant interruption in pipeline production.

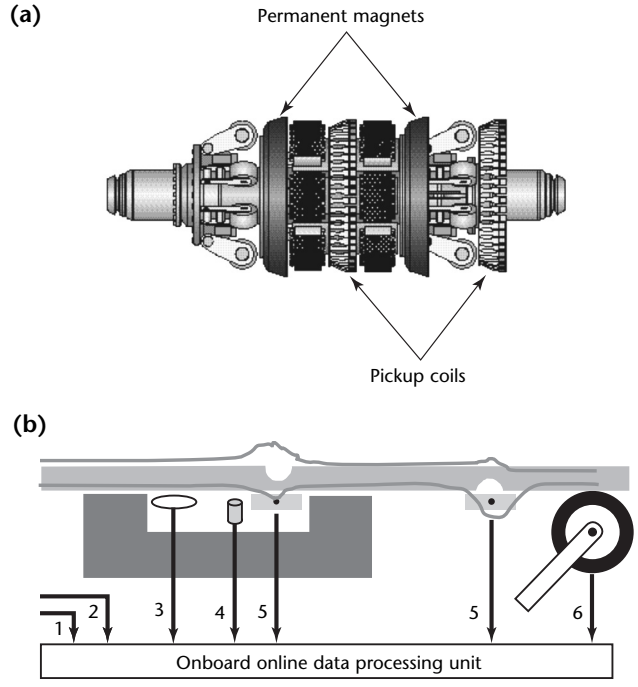
In magnetic flux leakage testing, changes in the material mass such as corrosion or pitting cause a localized flux leakage to occur at the discontinuity. These perturbations in the magnetic field are detected by the sensors within the magnetic circuit, are recorded and later are analyzed and reviewed. Much like the baffles or supports in a tube exchanger bundle, the pipeline circumferential welds provide abrupt signals and easy landmarks when the data are evaluated for discontinuity locations.[7-9]

FIGURE 3. Carbon steel, 0.75 m (30 in.) outside diameter, gas transmission pipeline.



Smart pigs are test vehicles that product flow pushes through a pipeline (Fig. 4). The technique got its name from a squealing sound from the pig moving through the pipe. At the end of the line or run, the pig is retrieved and the onboard data are then processed and analyzed. The pigs are similar to the magnetic flux leakage probes used in tube testing, but the pigs are constructed to propel themselves down pipelines and collect the required test data.

FIGURE 4. Equipment for magnetic flux leakage testing of pipes and tubes: (a) pig tool; (b) data acquisition from pig sensors.



Legend

1. Pressure.
2. Ambient temperature.
3. Magnetic field (magnetization).
4. Surrounding magnetic flux.
5. Magnetic flux leakage (stray flux).
6. Odometer (distance and speed).

Magnetic Flux Leakage Testing of Aboveground Storage Tank Floors[10]

Tank floors of aboveground storage tanks (Fig. 5) are subject to corrosion where they touch the ground. In the 1970s, ultrasonic testing was being performed on tank floors — spot ultrasonic testing using transducers on large wheels and automated ultrasonic techniques such as C-scanning. One destructive technique was to randomly cut out 300 × 300 mm (12×12 in.) square coupons, to visually test them and then either to weld them back in place or to replace them with new patch plates.

Magnetic flux leakage test techniques have been widely used in the oil field industry since the 1970s for the testing of pipe, tubing and casing, both new and used. During the 1980s, magnetic flux leakage testing for tank floor applications (Fig. 6) was introduced to the petrochemical and refining industry. Since 1990, this technique has been applied to aboveground storage tank floors to provide a reliable indication of overall floor condition within an economical time frame.[10,11]

Magnetic flux leakage floor scanners provide reliable tests at a fraction of the time and cost associated with ultrasonic thickness gaging. A tank floor test at regular intervals is required by some specifications.[12] As with other techniques, indications from magnetic flux leakage testing require verification by ultrasonic testing. Generally, the evaluation is accomplished by ultrasonic thickness gaging and sometimes by B-scan or C-scan ultrasonic testing.

For tank floor testing, a magnetic bridge is used to introduce as near a saturation of flux as is possible in the test material between the poles of the bridge. Any significant reduction in the thickness of the plate will force some of the magnetic flux into the air around the reduction area. Sensors that can detect this flux leakage are placed between the poles of the bridge (Fig. 6a).

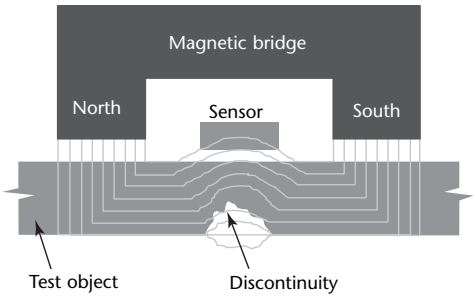
To create leakage fields from corrosion or pitting, it is necessary to achieve near saturation of the magnetic field in the material. Near saturation is accomplished with powerful rare earth permanent magnets, which offer more stability than electromagnets. The sensor can detect the magnetic flux leakage field caused by corrosion and pitting but cannot reliably determine if the flux leakage is caused by top or bottom discontinuities. For uncoated materials, the top

FIGURE 5. Aboveground storage tank for petroleum products.



FIGURE 6. Magnetic flux leakage test: (a) schematic of bridge; (b) tank floor scanner incorporating magnetic flux leakage test bridge.

(a)



(b)



discontinuities can be verified during a simple visual test. Other methods such as ultrasonic testing are performed for coated floors.

Floor scanning has problems not evident in the testing of tubular goods, where certain parameters can be closely controlled. Probably the greatest problem is that tank floors are never flat whereas tubes are always round. The unevenness of tank floors makes it hard to get reasonably consistent quantitative information. The application of rigid accept/reject criteria based on signal amplitude thresholds is also very unreliable for quantitative information. A realistic approach is required in the application of this test technique and in the design of the test equipment to ensure that fewer significant discontinuities are missed.

Test Conditions

To optimize the test, it is necessary to consider the environment and address the physical restrictions imposed by the actual conditions found when testing most tank floors.

Climate. The range of temperature and humidity conditions varies enormously during the year and around the world. The effect on both operator and equipment must be taken into consideration.

Cleanliness. Most aboveground storage tanks are dirty and sometimes dusty places to work. The conditions vary widely and depend on how much the tank operator cleans the floors in preparation for magnetic flux leakage scanning. As an absolute minimum, a good water blast is necessary and all loose debris and scale must be removed from the test surface. The surface does not have to be dry, but puddles of standing water need to be removed. The cleaner the floor, the better the test.

Surface Condition. Significant top surface corrosion and buckling of the floor plates represent serious limitations both to the achievable coverage in the areas concerned and also to the achievable sensitivity. Although very little can be done to improve this situation before testing, it must be considered in the design of the equipment. The effect of corrosion and buckling on the sensitivity of the test must be appreciated by both the tank operator and the inspector. Any physical disturbance of the scanning system as it traverses the floor will result in the generation of noise. The rougher the surface, the greater the noise and therefore the more difficult it is to detect small indications.

Equipment

It is important that magnetic flux leakage equipment produced for this particular application be designed to handle the environmental and practical problems always present. Figure 6b shows a mobile floor scanning unit.

Powerful rare earth magnets are well suited for introducing the required flux into the material under test. Electromagnets by comparison are bulky and heavy. They do have an advantage in that the magnetic flux can be easily adjusted and turned off if necessary for cleaning. Permanent magnet heights can be adjusted to alter flux levels, but the bridge requires regular cleaning to remove ferritic debris. Buildup of debris can impair system sensitivity.

It is virtually impossible for this technique to achieve 100 percent coverage because physical access is limited. The equipment should be designed so that it can scan as close as possible to the lap joint and shell. The wheel base of the scanner is an important consideration on floors that are not perfectly flat. Smaller scanning heads can be used in confined spaces to increase coverage.

Sensors

Two types of sensors are used for magnetic flux leakage of aboveground tanks: coils and hall effect sensors. Both can detect the flux leakage fields caused by corrosion on tank floors. There is a fundamental difference, however, in their response to leakage fields.

Coils are passive devices and follow Faraday's law in the presence of a magnetic field. As a coil passes through a magnetic field, a voltage is generated in the coil. The level of this voltage depends on the number of turns in the coil and the rate of change of the flux leakage. Scanning speed affects the rate of change of the magnetic flux leakage passing through the coils: scanning speed needs to be constant.

Hall effect sensors are solid state devices that form part of an electrical circuit. When passed through a magnetic field, the voltage in the circuit varies with the flux density. It is necessary to carry out some cross referencing and canceling with this type of sensor so that true signals can be separated from other causes of large variations in voltage levels generated by the test.

Hall effect sensors are more sensitive than coils and at low frequencies result in false calls when surface conditions are imperfect. For tube testing, on the other hand, coils are adequately sensitive and are more stable and reliable than hall sensors.

Interpretation of Indications

Surface Differentiation. Magnetic flux leakage testing cannot differentiate between indications from the top and bottom of the test object. Some attempt has been made to use the eddy current signals from top discontinuities for surface differentiation. Such discrimination is unreliable on real tank floors because the test surface is uneven and dirty. In most cases, visual testing is adequate. Contrary to what is expected, the flux leakage response from a top indication is significantly lower in amplitude than that from an equivalent bottom indication. To some degree, the influence of the top indications can be tuned out to assess the bottom indications.

Quantitative Assessment. Magnetic flux leakage testing is not quantitative but is a reliable, qualitative detector of corrosion on tank floors. Because of environmental and physical restrictions during tests, no reliable quantification of indications is possible. Amplitude alone does not indicate remaining wall thickness because it depends on volume loss. Discontinuities exhibiting various combinations of volume loss and through-wall dimension can give the same amplitude signal. This difficulty plus the continually changing spatial relationship of magnets, sensor and test surface makes an accurate assessment of remaining wall thickness virtually impossible. Quantitative results can be obtained by ultrasonic testing as followup.

Misuse of Signal Threshold. Expediency has sometimes motivated accept/reject criteria using a signal threshold, but signal amplitude alone is not a reliable indicator of remaining wall thickness. Significant indications can be completely missed where there is a single threshold or where the equipment does not provide a real time display to the operator during the test. To carry out a reliable test, the operator must have as much information as possible available in a real time display that is easy to interpret.

Computerized Signal Mapping. Mapping of flux leakage signals to tank floor layout is available on some systems. These maps can be used to plan further tests, for corrosion surveys and for hard copy reporting. The usefulness of this equipment must be weighed against the risk of electrical equipment inside storage tanks.

Training and Qualification. Training available to inspectors using magnetic flux leakage testing on tank floors is limited. Training must be specific to the equipment. Testing must be carried out by personnel who are adequately trained and qualified. It must be remembered that this is not just *thickness measurement* but rather corrosion evaluation and the technician must have a full understanding of the damage mechanisms and the test technique.

Conclusions

Magnetic flux leakage testing is a reliable and economical means of qualitatively assessing the condition of tank floors.

The environment and physical restrictions must be addressed in the design of the equipment. Despite the greater sensitivity of hall effect sensors, coils are more reliable for this application.

Amplitude of flux leakage signals is related to volume loss but is an unreliable indicator of remaining wall thicknesses. Quantitative information can be obtained by applying ultrasonic testing to the areas indicated by magnetic flux leakage.

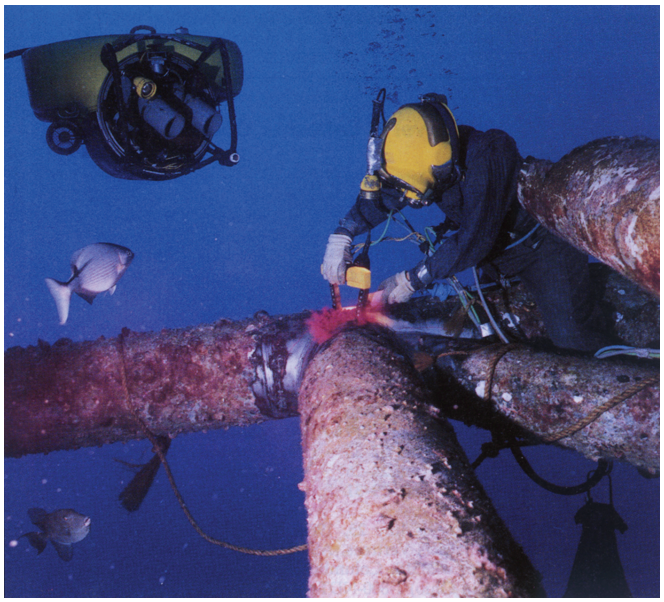
PART 3. Underwater Magnetic Particle Testing[13]

Innovative technology has been developed in the American offshore underwater nondestructive testing industry. These developments provide significant cost reductions, without reducing sensitivity, for standard magnetic particle techniques as well as underwater tests. Figure 7 shows underwater magnetic particle testing being performed as part of a damage survey.

Underwater magnetic particle weld testing is different from typical dry and wet magnetic particle testing. In practice, it resembles a hybrid form of both the dry and wet methods, more closely resembling dry fabrication and inservice testing. The main differences are that the particles are delivered in a wet slurry and that the inspector is a diver.

Magnetic particle testing can check for discontinuities after visual testing (Fig. 8). As with tests ashore, enough particles need to be applied to produce an indication; then excess particles are removed from the test surface so that indications contrast clearly with the background (Fig. 9).[14]

Figure 7. Diver performs underwater magnetic particle test for damage survey. Remotely operated vehicle provides photographic and video surveillance.



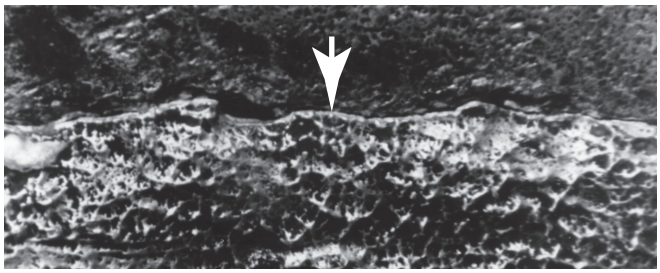
Magnetic Particle Testing through Coatings

Performing any type of underwater testing is costly because of the required peripheral diving support. The cost is increased by the need to remove marine growth before visual and magnetic particle testing. Traditionally, most oil and gas companies have required welded joints to be cleaned to bare metal, especially for magnetic particle testing (Fig. 10). Most industrial codes have limited magnetic particle testing to surfaces having less than 50 µm (0.002 in.) of thin nonconductive coating. However, research has shown that it is possible to test through thin coatings with reliable results.[15,16]

This is important because high pressure water guns operating at 138 MPa (2×10^4 $lb_f \cdot in.^{-2}$) can efficiently clean underwater structures to a thin, tightly adhering layer of black oxide having a coating thickness in the range of 75 to 125 µm (0.003 to 0.005 in.). Compared to black oxide surface finishes, the cost of

FIGURE 8. Crack about 0.3 mm (0.01 in.) wide: (a) visual indication; (b) magnetic particle indication.

(a)



(b)

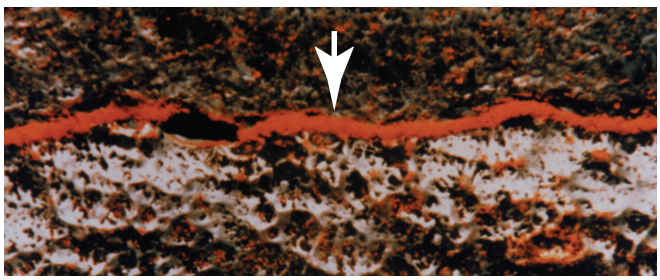


FIGURE 9. Magnetic particle application: (a) one or two applications, sufficient to cover test area; (b) removal of excess particles with enough force to leave relevant indication; (c) arrows point to false indication where excess particles on background interfere with interpretation.

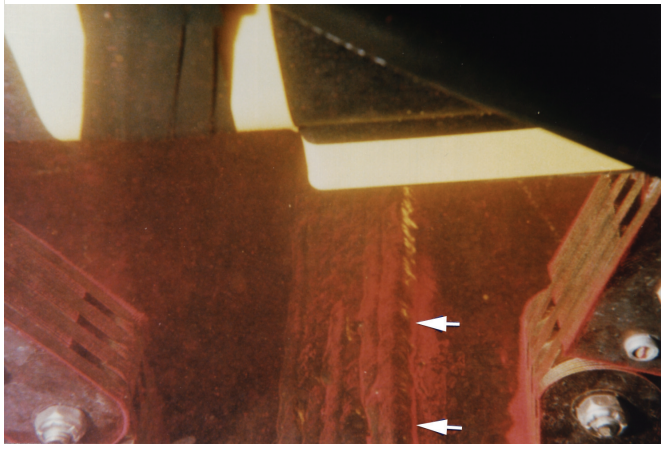
(a)



(b)



(c)



cleaning to a bare metal surface finish conservatively doubles the testing cost. It has been determined that magnetic particle testing on black oxide coatings (Figs. 11 and 12) has the same required sensitivity as testing performed on bare metal for detection of incipient fatigue cracks at joint intersections on welded offshore structures.

Underwater Tests through Coatings

A magnetic particle system sensitivity test was demonstrated to the American Bureau of Shipping (ABS) to obtain certification for using magnetic particle techniques in

FIGURE 10. Diver sandblasts structure before magnetic testing through thin coating.



FIGURE 11. Magnetic particle indication produced on black oxide using alternating current electromagnetic yoke.



the field.[17] The demonstration, performed at the ABS laboratory in Paramus, New Jersey, used painted objects having discontinuities of the type that must be located offshore. The technique was certified and subsequently found to produce the required sensitivity without costly cleaning to bare metal. The benefit to the customer is halving of inspection cost without sacrificing reliability.

Magnetic particle testing through coatings is performed with an alternating current yoke. The sensitivity of the system is based on the detection of fine inservice fatigue cracks with minimum dimensions of 13 mm (0.5 in.) length, 25 µm (0.001 in.) width and 0.75 mm (0.03 in.) depth. This sensitivity is within the range of fatigue crack sizes most oil and gas companies require for detection.

Field Tests through Coatings

After magnetic particle techniques were performed successfully underwater for several documented case studies, research was initiated to look at similar tests through coatings in air.[18,19] Research focused on defining threshold coating limits for certain discontinuity sizes. Reliable results were achieved using an alternating current yoke with dry powder on hairline indications through as much as 600 µm (0.025 in.) of paint.[19]

There were two significant findings of these studies. The most important variable for performing magnetic particle testing is not the ability to get sufficient flux density to the discontinuity site, but rather to get sufficient flux leakage from a discontinuity to form a detectable magnetic particle indication.

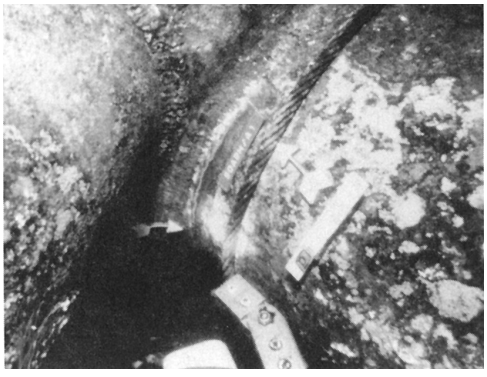
Secondly, when using the alternating current yoke (indirect magnetization), it is not always necessary to clean in the area of yoke leg contact. The alternating current provides high surface flux density as if because of the skin effect.[20] The same test results can be achieved when the area of interest is cleaned, with or without cleaning the base metal at the points of yoke contact.

For example, a crack indication of sufficient length on a coated weld can be verified by magnetic particle testing through as much as 750 µm (0.030 in.) of coatings because the break or crack in the coating provides a flux leakage path. Conversely, cracks that occur only in the paint do not produce particle indications.

Cracks occurring in offshore structural welds are almost always found in the toe of the weld. If the paint coating thickness is 500 µm (0.020 in.), one way to reduce cost is to clean the weld and 13 mm (0.5 in.) on each side of the weld and then perform the magnetic particle test.

The American Society for Mechanical Engineers' *Boiler and Pressure Vessel Code* says: "If nonmagnetic coatings are left on the part in the area being examined, it shall be demonstrated that indications can be detected through the existing maximum coating thickness applied."[21]

FIGURE 12. Magnetic particle indication produced on black oxide surface finish using single-leg alternating current electromagnet.



Single-Leg Technique

When testing T, X, K and Y tubular connections in areas of acute angle, it is often impossible to access the geometry with a typical yoke configuration. A technique that can be used successfully under these circumstances is the single-leg technique. The single-leg electromagnet produces a magnetization pattern called a *radial field,* essentially one half of the longitudinal field produced by the yoke. Because structural steel has a higher magnetic permeability than the surrounding water,[22] the magnetic field can be localized where it is needed. Figures 12 and 13 show testing with the flux leakage field produced by a single-leg electromagnet.

In some cases, the single-leg technique can provide better sensitivity than small conventional yokes. The main factors affecting test sensitivity for both yokes and single-leg electromagnets are (1) the size of the coil producing the leakage field and (2) the flux density at the area of interest.

The single-leg technique can meet specification requirements: (1) picking up a 4.5 kg (10 lb) weight, (2) producing clearly defined indications on magnetic field indicators, (3) producing greater than 2400 $A \cdot m^{-1}$ (30 Oe) in the tested area and (4) detecting discontinuities in production applications or in reference standards with known discontinuities.

Alternating current is always used with the single-leg technique because fatigue cracks typically initiate as external surface

discontinuities and then fracture through the thickness of the test object. Direct current magnetization and permanent magnets are not recommended for detection of inservice weld cracks. Figure 13 shows an example of the single-leg technique used in an area of tight access. Figure 12 shows a magnetic particle indication produced on black oxide with single-leg magnetization.

Single-leg technology also offers some unique advantages for robotic test systems. Its geometry is universal, and it is a low profile package. Because robotic arms can maneuver heavy components, coil size is not a restriction. Layering alternating current with pulsed direct current by stacking or winding one coil over the other can provide the skin effect and particle mobility of alternating current with the field penetration of direct current.[23]

FIGURE 13. Diver performs magnetic particle test using single-leg electromagnet to access tight areas of interest.



Anticipation of Discontinuity Location and Orientation

Underwater magnetic particle testing can also be used to define the types of discontinuities that occur, their frequency and the probability of detection. A discontinuity database for fixed offshore platforms[16] found that, of all the discontinuities detected, the majority was confined to the toe of the weld. This trend applies to fixed offshore platforms (T, K and Y connections, built primarily of mild strength steels) and may not apply to other marine structures, such as mobile offshore drilling units made of high strength steels.

The significance of the trend is that both fracture mechanics models and documented empirical data for fixed offshore structures indicate a low probability of occurrence for transverse discontinuities. Yoke manipulation and scanning efficiency can be maximized by restricting testing procedures to those that detect longitudinal discontinuities.

The yoke should straddle the welded joint so that the lines of flux cross discontinuities at the most nearly perpendicular angle. Techniques that use criss cross (45 degree) pole placement are less sensitive for detecting longitudinal cracks and should not be used. Figure 14 shows the proper yoke setup for testing in the longitudinal direction.

FIGURE 14. Optimum orientation of electromagnetic yoke for detection of weld toe cracks on offshore structures.



Part 4. Magnetic Testing of Oil Field Tubes[24]

In the United States, there are more than 660 000 oil and gas wells containing an enormous amount of steel tubular material down the wells, in wellhead fittings and in cross country flow lines. Below are outlines for some of the magnetic particle testing applications routinely performed in oil fields, including (1) aspects of magnetization from the oil field inspector's viewpoint, (2) specifications used for oil field tests and (3) some misconceptions about oil field applications of magnetic particle tests.

Magnetic particle testing is applicable only to ferromagnetic materials and should be studied as a specialized branch of electromagnetic testing. It is impossible to test all tubes for imperfections, both inside and out, using magnetic particle tests alone. Other magnetic flux leakage techniques are more cost effective and have been used on oil field tubes for many years. These tests often make use of hall element, magnetodiode and coil pickup methods for sensing the magnetic flux leakage from material discontinuities.

Longitudinal Magnetization

When a tube 10 to 15 m (33 to 50 ft) in length is longitudinally magnetized, discontinuities transverse to the tube axis can be detected by their magnetic flux leakage. In this circumstance, two distinct test object geometries must be considered: (1) the ends of the tube and (2) the larger region away from the ends. The axial component of the magnetic flux density (after the material has passed through a magnetizing coil) is shown in Fig. 15. In the central region and for much of the tube, the steel is magnetically saturated and holds a flux density close to the remanent value for the material. At the ends, the flux lines begin to emerge and the axial magnetic component falls as the normal component rises.

When testing tubes for longitudinally and transversely oriented discontinuities in the end regions, magnetic particle testing is preferred over other flux leakage techniques. If the normal component is greater than five times the tangential, then indications will be obscured.[25]

Because of bearding effects, wet particles are preferred, just as they are when any short object is being tested for transversely oriented discontinuities. Wet particles do not fur along external field lines because surface tension dominates the magnetic field intensity. In other words, liquid makes the particles lie flat.

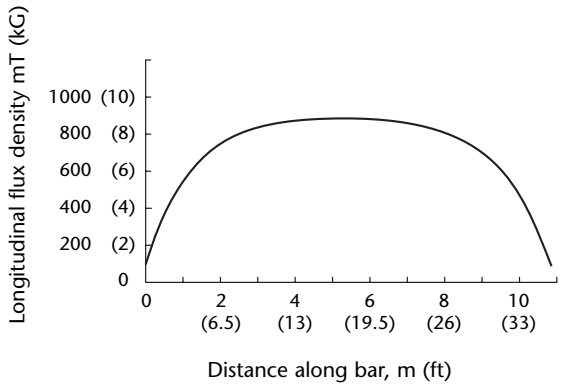
Using wet particles at the ends of tubes and bars, despite the emergent normal fields, also lets the applied coil field be raised to levels higher than those used for testing body walls.

Coil Field Criteria

When magnetizing the end of an elongated object, it is critical to ensure that the magnetization levels produce flux leakage from surface discontinuities sufficient to hold particles and give a discontinuity indication. With solid bars, this may be one magnetization level; with tubes, it may be another. Sometimes, the appropriate magnetization level is determined by the ease with which indications can be seen.

For the magnetization of tube ends, two very different types of coil are used. One is the traditional wound wire magnetization coil, excited by alternating current or direct current. The other is a coil made from a few turns of copper cable with a cross section over 100 mm^2 (0000 American Wire Gage) and pulsed from a capacitor discharge system.

Figure 15. Axial component of flux density in an 11 m (36 ft) steel bar; the value in central region is close to ring sample value (remanence or B_r); emergent fields at ends are about 0.03 T (300 G).



Direct Current Coil (Residual Induction Tests)

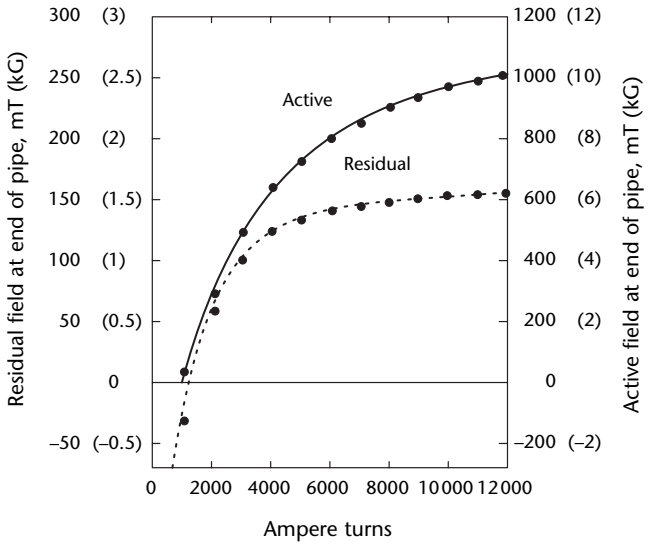
One way to magnetize the ends of long test objects is to apply the magnetizing field from a direct current coil. In view of the high field intensities used, such coils should be supported either from the floor or the roof of the testing facility so that the test object can be centered in the bore of the coil. Under such conditions, a simple test may ensure the magnetization of the ends.

The test object is saturated in one direction; then the coil is turned and placed with roughly 300 mm (12 in.) protruding beyond the coil. A hall element tesla meter is positioned to detect the field intensity that emerges from the end of the material.[26] The current in the coil is raised and turned off in increments until the tesla meter reading saturates. Figure 16 illustrates typical data for just such a test, although it must be realized that coil sizes, material diameters and material wall thicknesses all contribute to the applied field intensity at which the material saturates.

Using this technique, the ends of tubes are shown to be adequately magnetized if the following equation is applied. The equation is written for tubes with outside diameters less than 200 mm (8 in.). For tube diameter D_1 measured in millimeters and field intensity measured in millitesla:

(1a) $B = 20 + 12\,D_1$

FIGURE 16. Hall element data taken at end of tube to ensure saturation before particle application; coil positioned 300 mm (12 in.) from end of tube with 90 mm (3.5 in.) outside diameter.



or, for outer diameter D_2 in inches and field intensity in gauss:

(1b) $B = 200 + 30\,D_2$

The field intensity is over 40 mT (400 G) when the tube's outside diameter is greater than 200 mm (8 in.).[26]

This equation covers the worst situations and explains the general increase in tube wall thickness with increased outside diameter found in American Petroleum Institute (API) tubular materials. It is a relatively simple matter to determine the field intensity at the center of such a coil using a tesla meter. This eliminates the misuse of older equations that state only the number of ampere turns on coils.

Alternating Current Coil

When testing with alternating current coils, two points are important to remember. The first is that the magnetic field roughly obeys the typical eddy current skin depth relation, so that at 50/60 Hz, the skin depth in steels is on the order of 1 mm (0.04 in.). A peak surface field of 2400 $A \cdot m^{-1}$ (30 Oe) gives good discontinuity indications from outside diameter surface breaking discontinuities.

The second point is that there is little penetration to the inside diameter for tube wall thicknesses in excess of 4 mm (0.16 in.) unless a direct current field is also applied to lower the effective relative permeability of the material. Such fields can easily be measured with a tesla meter.

Capacitor Discharge Coil Field

A common means for magnetization of tube ends is to wrap a 0000 American Wire Gage (cross section greater than 100 mm^2) welding cable around the end of the test object and to apply several shots from a capacitor discharge system.

This is typically a bank of capacitors charged to a voltage limited by safety requirements (limit may differ depending on local regulations). The bank is designed to produce a single spike of unidirectional current. Ideally, the current pulse has a long decay time so that its field intensity can penetrate the material despite eddy current effects created during the initial rapid rise of the current.

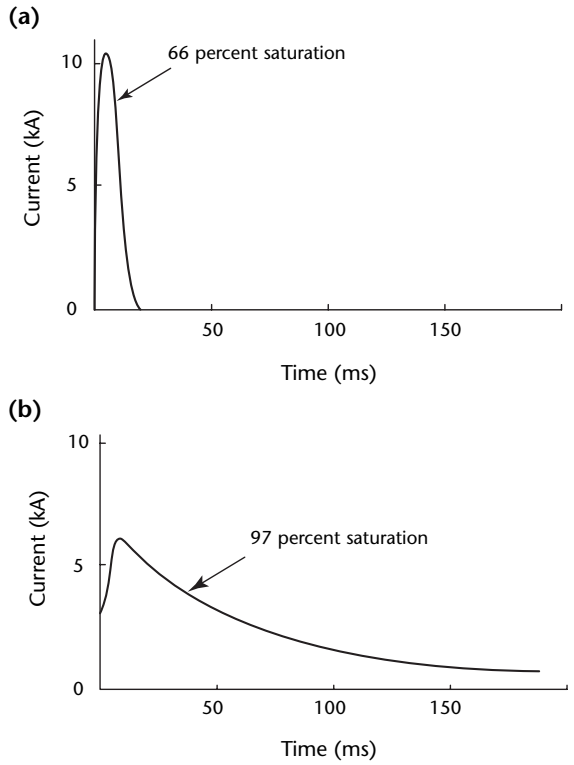
The theory of capacitor discharge magnetization includes considerations of the inductance L, capacitance C and resistance R of the entire system, including the object being magnetized. Because many different types of capacitor discharge systems exist, it is not possible to make sufficiently general statements about the measurable parameters of a

pulse and the resulting flux density in the test object.

Magnetization of the material can be ascertained by any of three means. The first is simply to hold a tesla meter near the end of the material and require that it is close to saturation. The second method is to use a portable surface discontinuity. The third is to use a flux meter.[27] The shape of the current pulse is shown in Fig. 17. Shorter pulses that are not effective for magnetizing deeper portions of an object are shown in Fig. 17a. More elongated and effective pulses[28] are shown in Fig. 17b.

As the number of coil turns increases around the test object, the inductance in the *LCR* circuit increases as the square of the number of turns. This elongates the pulse and can easily cause a capacitor discharge box (normally operating in the curve of Fig. 17a) to begin operating in the curve of Fig. 17b. The problem is that pulse systems generally operate with a rectifier that shuts down the current the instant the pulse turns to a negative direction (Fig. 17a). If the pulse is similar to that in Fig. 17b, then the rectifier never closes and circuitry must be included to close off the pulse from the capacitor charging circuitry.

FIGURE 17. Typical pulses from capacitor discharge systems: (a) short pulse effective for deeper magnetization; (b) long pulse more effective for magnetizing of tube.



Magnetization Requirements

In many cases, the number of ampere turns supplied by coils can be specified. This magnetomotive force in turn provides a flux density in the material that produces residual induction indications from surface breaking discontinuities. When a coil field is applied as shown in Fig. 18, the magnetization field at the outer layers of the material is caused by coil turns very close to the test object. This situation is different from that described in residual induction with direct current. When the tube's outer diameter is less than 200 mm (8 in.):

$$\textbf{(2)} \quad NI_m = \left(50 + 0.33\,D_1\right) D_1 = \left(1300 + 200\,D_2\right) D_2$$

and when the diameter is greater than 200 mm (8 in.):

$$\textbf{(3)} \quad NI_m = 115\,D_1 = 2900\,D_2$$

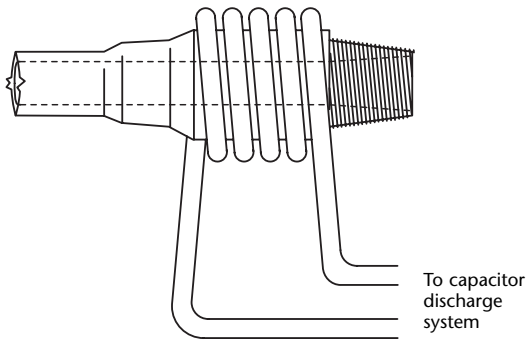
For drill collars and tool joints:

$$\textbf{(4)} \quad NI_m = 230\,D_1 = 5800\,D_2$$

where D_1 is the outside diameter of the coil (millimeters), D_2 is the outside diameter of the coil (inches), I_m is the maximum current from the capacitor discharge system (amperes) and N is the number of coil turns.[26–28]

For magnetizing the end of a 200 mm (8 in.) outside diameter drill collar, the diameter of the coil is about 225 mm (9 in.). The number of ampere turns is 230× 225 or 5800 ×9 or about 52 000. Should the capacitor discharge system produce a peak current of 9000 A, then

FIGURE 18. Longitudinal magnetization of drill pipe tool joint with capacitor discharge system and several turns of 100 mm² cross section (0000 American Wire Gage) cable.



six turns are required. Alternatively, two or three pulses should be fired and the resulting residual induction checked with a field indicator.

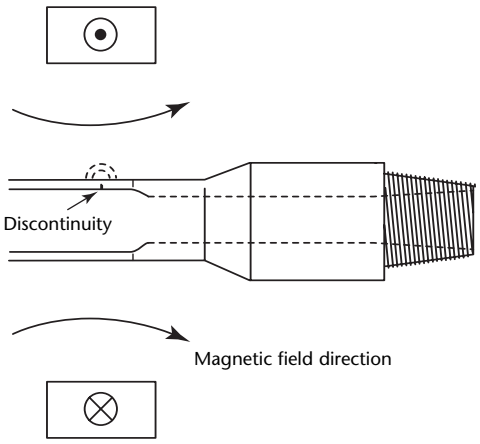
Oil Field Applications for Longitudinal Magnetization

The ends of drill pipe and drill collars are magnetized longitudinally so that cracks may be detected in their threaded regions. If the connections are not made tight enough (torque values are listed in API RP 7G recommended practice),[29] the threaded regions may first elongate and then cracks may form at the roots of the threads. The most common place for such cracking is in the last engaged thread.

To perform good magnetic particle testing, threads must be cleaned and burrs removed. The particle suspension should be more dilute than normal (1 to 3 mL per liter of solution), to make the false indications fewer. Surface ultraviolet irradiation should be around 20 $\mu W \cdot mm^{-2}$.

For internal fatigue cracking in drill pipe, the leakage field must be strong enough at the outside surface of the tube to hold dry particles (Fig. 19) or the inside must be inspected with a borescope. The presence of one fatigue crack is sufficient for rejecting the tube. The field intensity used for the test in Fig. 19 is around 40 mT (400 G). The coil is passed back and forth over the suspect region to obtain a crack indication in the presence of furring. When a borescope is used, appropriate crack indications can generally be produced with longitudinal residual induction techniques.

FIGURE 19. Direct current magnetization of drill pipe for internal fatigue crack detection. Coil field must produce sufficient flux leakage at outside surface for dry particles to bridge discontinuity.



Circumferential Magnetization

Two distinct techniques[27] are used for circumferential magnetization of tubes up to 14 m (45 ft) long (Fig. 20). Both methods use an insulated rod typically made from aluminum and designed to pass through the bore of the tube. In Fig. 20a, the rod is reasonably well centered in the bore and carries some form of direct current. In mill installations, this might be full-wave or half-wave rectified alternating current for wet fluorescent magnetic particle testing. In field operations, banks of batteries have been extensively used to provide magnetizing current.

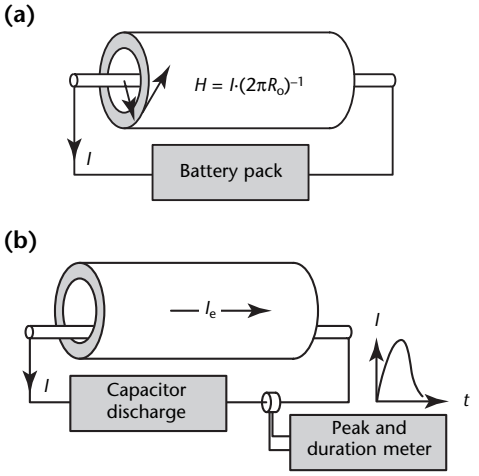
Central Conductor Magnetization

When the magnetizing current is pure direct current and the conductor is centered within the bore, the magnetic field intensity H (in ampere per meter) at the outer surface of the tube is given by:

$$\textbf{(5)} \qquad H = \frac{I}{2\pi R_o}$$

where I is the magnetizing current (amperes) and R_o is the outer radius of the tube (meters).

FIGURE 20. Two methods for establishing circumferential magnetization in long tubes: (a) central conductor method with battery pack to provide high current; (b) internal conductor method with capacitor discharge system. Peak and duration meter is often used to measure pulse amplitude and time.



Legend

H = magnetic field intensity ($A \cdot m^{-1}$)
I = rod electric current (A)
I_e = eddy current (A)
R = tube radius (m)
t = time (s)

In Eq. 5, the field intensity is given in amperes per meter because R_o is expressed in meters (Fig. 21). Field intensity can also be measured with a hall element tesla meter and, because 1 G is equal to 1 Oe in air, conversion to CGS units gives:

$$\textbf{(6)} \quad H = \frac{2I}{10R_o}$$

where I is the magnetizing current (amperes) and R_o is the outer radius of the tube (centimeters). This equation should be used with hall element meters that have scales or digital readouts in gauss.

Full-Wave and Half-Wave Rectified Alternating Current

Rectified alternating current is often used with central conductor magnetization. It is important to remember that such current waveforms induce eddy currents in the test object. The field intensity waveform at the outer surface can be seen by positioning a hall element to detect the field and then feeding the output of the meter to an oscilloscope.

Capacitor Discharge Magnetization

In another circumferential magnetization method (Fig. 20b), the electromotive force is provided by a capacitor discharge unit.[28] There is no need for precise rod centering with this magnetization technique, providing a distinct advantage for field testing. Unfortunately, magnetization by capacitor discharge obeys no simple rules. The rapid rise of the rod current causes the induction of an eddy current in the tube and detrimentally affects penetration of the magnetizing field intensity into the material.

The direction of the induced eddy current I_e with respect to the rod current I is shown in Fig. 20 for a centered rod. By Lenz's law, the eddy current induced on the inner surface of the tube must create within the material a magnetic field that opposes the field produced by the rod current I. The field intensity at radius r (in meters), at some instant while the rod and eddy current fields are finite, is given by:

$$\textbf{(7)} \quad H = \frac{I}{2\pi r} + H_e$$

where H_e is the magnetic field intensity ($A \cdot m^{-1}$) created by the eddy current itself.

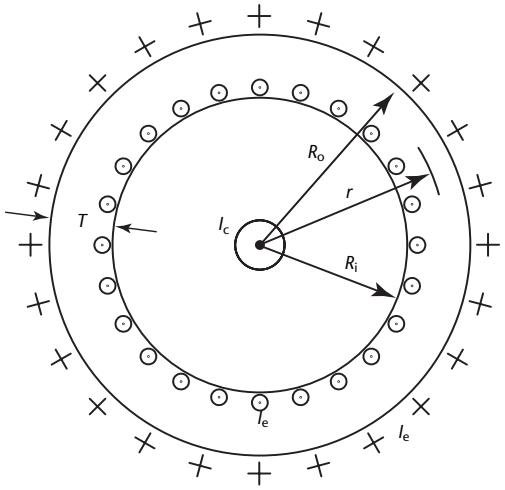
Eddy Current Effect

Ampere's law indicates that the magnetic field at the radius r is caused by the currents inside that radius, the rod current and the inner wall eddy current (Fig. 21). The outer wall eddy current is the return loop for the inner wall eddy current and plays no role in the theory as outlined so far.

However, because the outer wall eddy current does represent an unwanted current flowing in the tube, its presence leads to the very practical consideration that pipes being magnetized before testing should be insulated from each other by an air gap. If this insulation does not occur, then the outer surface eddy current can jump from protrusions in the pipe being magnetized to the next pipe in the string. The resulting arc can cause burns on both tubes and can in turn cause hardening and locations that can corrode. It is particularly important to avoid arc burns on API 5CT Group 2 materials,[30] some of which require a hardness less than 22 on the rockwell C scale for longevity in corrosive environments.

Magnetized material should also be insulated from the metal racks that carry it. If pipe racks are not insulated with a layer of electrically nonconductive material (rubber or wood), then the outer wall eddy current can flow to ground through the rack and there is a finite possibility of arc burn at the point of contact with the rack.

FIGURE 21. Eddy current I_e created in steel tube at beginning of pulse I in rod centered within bore of tube. Direction of I_e on inner surface opposes that of I. Outer surface provides return path.



Legend

I_c = center current (A)
I_e = eddy current (A)
r = tube radius (m)
R_i = tube inside radius (m)
R_o = tube outside radius (m)
T = tube thickness (m)

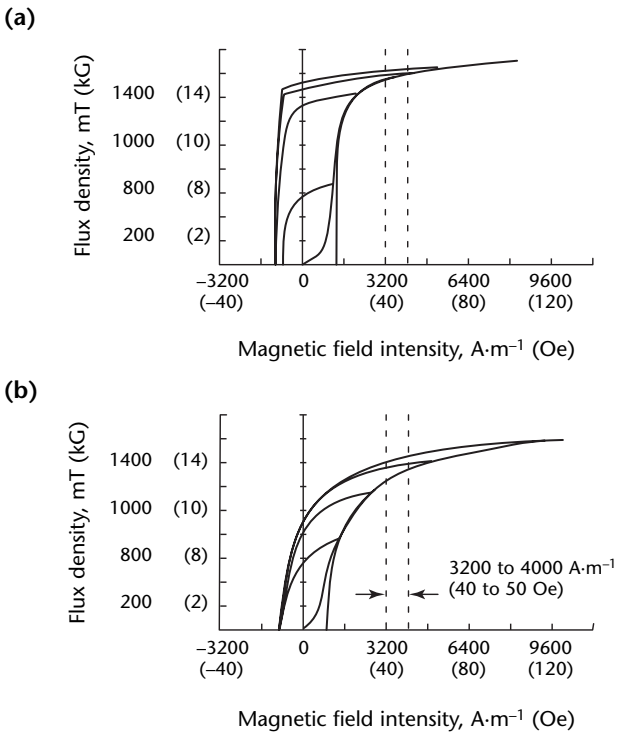
BH Curves for Setting Specifications

When test objects are magnetized with the capacitor discharge internal conductor technique, a tool steel ring hysteresis (*BH*) curve governs the flux density value in the material. In effect, knowing the *BH* properties of the material from a ring standard investigation allows field intensity levels to be set. Figure 22 shows the *BH* properties of two typical oil field tubular materials: a 620 MPa (90 000 $lb_f \cdot in.^{-2}$) proprietary material and a 380 MPa (55 000 $lb_f \cdot in.^{-2}$) casing material.[28]

After application of about 3200 $A \cdot m^{-1}$ (40 Oe), these materials are effectively saturated. It is generally true of oil field tubular materials that 3200 to 4000 $A \cdot m^{-1}$ (40 to 50 Oe) is required within the material to provide enough magnetization for residual induction testing.

This magnetic field intensity level is required at each point in the tube wall, despite the demagnetizing effect of the eddy current. Unfortunately, this requirement does not lead to a current equation that can be simply executed in the field. Experimental specifications discussed later have been found effective for saturating tubes.

FIGURE 22. Magnetization curves for oil field tubular materials. Dashed vertical lines indicate that materials are magnetized almost to saturation by application of 3200 to 4000 $A \cdot m^{-1}$ (40 to 50 Oe) magnetic field intensity: (a) high strength tube material; (b) low strength casing material.



Typical Requirements for Direct Current Magnetization

If the central conductor method is used for magnetizing tubes, then the values given in Table 3 reflect the magnetizing field at the outside diameter for typical pipe sizes. The wall thickness, the mass per meter (weight per foot) and the tube grade all affect the magnetic and electrical properties of the material, but because the magnetization technique is direct current, these parameters do not affect the magnetic field intensity. The actual field intensity value is often stated by specifications agreed on by the material's manufacturer and its user. A typical specification is given by Eq. 8:

$$\textbf{(8)} \quad I = 12\,D_1 = 300\,D_2$$

where D_1 is the diameter of the tube in millimeters and D_2 is its diameter in inches.[27] The specified equations give the equivalent of 3760 $A \cdot m^{-1}$ (47 Oe) at the tube surface. It can be seen from Fig. 22 that such a field intensity raises the value of the flux density in the tube to a high level so that, after the field has fallen to zero, the flux density in the material is at a value close to remanence B_r.

Pulsed Current Magnetization

Internal conductor magnetization using single pulses of current differs from direct

Table 3. Current requirements for magnetization of tubes by direct current or long pulse (more than 0.5 s) only. Not valid for capacitor discharge magnetization.

Diameter		Current *I* at outside surface	
mm	(in.)	at 3.2 kA·m⁻¹ (at 40 Oe)	at 4.8 kA·m⁻¹ (at 60 Oe)
60	(2.375)	600	910
73	(2.875)	730	1100
89	(3.50)	890	1340
102	(4.0)	1020	1530
114	(4.50)	1150	1720
127	(5.0)	1280	1910
140	(5.5)	1400	2100
168	(6.625)	1690	2530
178	(7.0)	1790	2680
194	(7.625)	1940	2920
219	(8.625)	2200	3300
245	(9.625)	2450	3680
273	(10.75)	2740	4110
299	(11.75)	3000	4500
340	(13.375)	3410	5120

current (and from continuous magnetization by the central conductor technique) because the induced eddy current may not have time to dissipate before the field intensity from the conductor current dies away.

Time Variations

Figure 17 shows two variations measurable for single current pulses such as those provided by capacitor discharge units. The first variation is that of the magnetizing current versus time (*I* versus *t*): a relatively rapid rise of current to its maximum value I_{max} is followed by a much slower fall to zero. The entire pulse length is about 200 ms.

This time variation is a response to the discharge of a capacitor *C* initially charged to potential V_0 (in volts) through a resistor *R* in a circuit having inductance *L* (an *LCR* circuit).

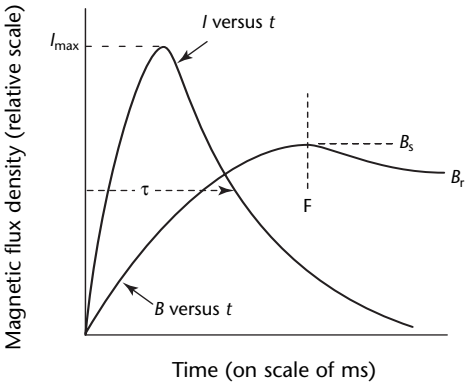
Flux Density Variations

A second variation is that of the average bulk flux density within the material (*B* versus *t*). This quantity rises at a much lower rate than *I*(*t*) due to the shielding effect of the eddy current I_e. A high level of magnetization is reached when the flux density at the point F is close to the saturation value B_s for the material. As shown in Fig. 23, deep magnetization of the tube occurs only when the effect of the eddy current is overcome by elongating the pulse in time. In this way, the magnetizing current is still effective as the eddy current is dissipating.

The fall in induction from F to B_r is expected when the magnetizing field intensity falls to zero, as it does after the passage of a pulse. This is determined by the *BH* curve for the material undergoing magnetization. Should the point F not represent saturation B_s, then the material reaches some average bulk flux density lower than B_r.

Although the surfaces are magnetized enough to form indications of longitudinal discontinuities, access to the inside surface is not necessary. However, when relatively thin elongated tubes can be inspected from the outside diameter surface only, saturation of the material is necessary for inside diameter discontinuities to produce magnetic flux leakage at the outside surface.

FIGURE 23. Plots of capacitor discharge internal conductor current (*I* versus *t*) and average flux density (*B* versus *t*) induced in tube. I_{max} and τ are measured with peak and duration meter. Flux density peaks well after current.



Legend

B = magnetic flux density (T)
B_r = flux remanence (T)
B_s = flux saturation (T)
F = saturation point
I = electric current (A)
I_{max} = maximum current (A)
t = time (ms)
τ = pulse interval (s)

Common Pulsed Current Application

A new material's magnetic condition is often unknown to the inspector who must generally assume the worst possibility: magnetic saturation in a direction directly opposite that of the operator's equipment. Stated another way, the worst possible case is that of taking a material from an unknown value of remanence in one direction to remanence in the other direction. This is shown in the *BH* curve in Fig. 24.

The material might arrive with an induction between O and $-B_r$, with testing to be performed at $+B_r$. During magnetization, the material should take the path $-B_rH_cPB_sB_r$, through saturation B_s to remanence B_r.

For materials at zero induction, the tube is at O on the *BH* curve in Fig. 24 and takes the path OPB_sB_r during magnetization. Materials not saturated by a pulse may follow a magnetization path such as $-B_rH_cPQ$ or OPQ. It is essential to then fire additional pulses. A possible magnetization path during a second pulse is QB_sB_r. The final net induction is raised as shown.

Analysis of Pulse Current Magnetization

Generalized analysis of the pulse current internal conductor technique for magnetizing long tubes is presented below. Simplified equations are given for the types of current pulses used for magnetization. The theory of current pulse time dependence (*I* versus *t* of Fig. 23) is discussed and equations are presented for the inductance experienced by the magnetizing circuit.

The equations illustrate (1) the dependence of inductances on the average value of the differential permeability $dB \cdot (dH)^{-1}$ of the test object and (2) the dependence of the field intensity and flux density limits (imposed by the exciting current) and the *BH* properties of the test object.

Current Pulse Time Dependence

For *LCR* circuits, the time variation of the current pulse obeys the equation:

$$\textbf{(9)} \qquad \frac{d(LI)}{dt} + IR + \int I\frac{dt}{C} = 0$$

The three terms on the left of Eq. 9 represent the instantaneous voltages across the inductance, the resistance and the capacitance in the circuit (Fig. 20b).

The inductance in the circuit is mainly that of the rod and tube system because by careful design the presence of additional inductance between cables and ground can be minimized. Because the inductance is time dependent, it is included in the derivative term.

The resistance is the combined resistance of the rod, cables and their connection and resistance within the capacitor discharge box. The internal resistance of the capacitor discharge box could be from the forward resistance of a silicon controlled rectifier included to eliminate the possibility of current oscillation. The capacitance of the system is generally in the region of 2 to 8 F.

There are three solutions for Eq. 9, if the time dependence of *L* is ignored. These solutions depend on the relative values of *L*, *C* and *R*:

$$\textbf{(10)} \qquad I = \frac{2V_0}{\sqrt{\frac{4L}{C} - R^2}} e^{-\beta t} \sin\sqrt{\frac{4L}{C} - R^2 t}$$

$$\textbf{(11)} \qquad I = V_0 C\left(\beta^2 t\right) e^{-\beta t}$$

$$\textbf{(12)} \qquad I = \frac{2V_0}{\sqrt{R^2 - \frac{4L}{C}}} e^{-\beta t} \sinh\sqrt{R^2 - \frac{4L}{C} t}$$

where I is current (ampere) and V_0 is the charged voltage of the capacitor bank and $b = R \cdot (2L)^{-1}$.

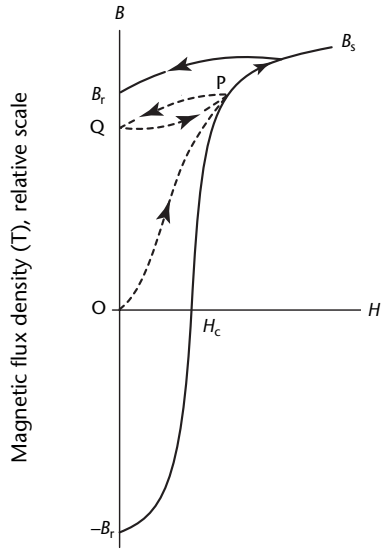
Equation 10 is an oscillatory solution, but the presence of the silicon controlled rectifier limits the pulse to the first positive-going peak (Fig. 17). In this particular example, the pulse has a length of 17 ms and reaches 10.5 kA. Such pulses are ideal for magnetizing objects of low electrical conductivity (ferrite magnets). However, with highly conducting materials such as steel tubes, the initial rapid current rise (may be millions of amperes per second) induces shielding eddy currents I_e that do not permit field penetration into the bulk of the material. The net effect of this is magnetization at the outer layer only.

The exponential Eq. 11 is known in its mechanical analog as *critical damping*. It is difficult to achieve in this magnetic particle application because it depends on a known value of *L* that in turn depends on the physical and magnetic parameters of the test object.

The sinh solution in Eq. 12 leads to the longest pulses because there is no oscillation. Pulses up to 160 ms are commonly used in oil tube testing.

It has become common to define the length of such pulses as the time taken for the pulse to reach 0.5 I_{max} during decay *t*. Both I_{max} and *t* are measurable with an inductive ammeter or a peak and duration

FIGURE 24. Possible paths taken by circumferentially magnetized material from initial magnetization conditions to saturation B_s and then remanence B_r in known direction.



Legend

B = magnetic flux density (T)
$-B_i$ = initial flux density (T)
B_r = remanent flux density (T)
B_s = flux density saturation (T)
H = magnetic field intensity (A·m^{-1})
H_c = magnetic field intensity (A·m^{-1}) when $B = 0$
O = origin at zero induction
P = point of weak pulse followed by second pulse
Q = point of remanence, zero intensity
—— = material at remanence in opposite direction
- - - = material at zero induction

meter. These pulses are effective for magnetizing tubes because the field intensity from the rod current is still high as the eddy current in the test object dissipates (there is penetration of the field into the bulk of the test material).

Because the inductance is a function of time, a full solution for the variation of the pulse current $I(t)$ can only be obtained by modeling the effect that the induced eddy current has on the instantaneous value of L. Experimental evidence indicates that, for long tubes, the physics of the magnetization process can be illustrated by a study of the constant L case.

Resistance, Capacitance and Inductance

When designing a capacitor discharge pulsing system, it is essential to provide a pulse length sufficient for deeply magnetizing the material. There are two reasons for this. First, the tested material may arrive in a longitudinally magnetized condition, and it may be necessary to remagnetize it circumferentially before magnetic particle testing. Secondly, some specifications call for relatively low emergent longitudinal field intensities at the ends of long test objects, and rotation of the bulk flux density into the circumferential direction may be the simplest way to meet the specification.

An additional consideration, unrelated to the physics of test object magnetization, is the safety of the system in permanent and field testing situations (the National Electric Code[29] should be consulted for details). In the field, it is essential to limit the charging voltage of the capacitor bank to 50 V. The tendency of meeting this limit is to add capacitance to the system.

Resistance

The resistance of the magnetization system is an important factor in permitting high currents to flow. Resistance is minimized for field tests by using parallel strands of 100 mm^2 cross section (0000 American Wire Gage) copper welding cable for connections between the rod and the capacitor discharge box.

The rod is made of aluminum, mainly because of its handling advantages, but any highly conductive material works equally well. The requirement of elongating the pulse length to ensure the presence of its field after eddy currents have dissipated far outweighs the requirement of minimizing the overall resistance of the magnetizing circuit. Typical resistance values for 50 m (165 ft) of cable and 15 m (50 ft) of rod are 1 to 5 mΩ.

Capacitance

The capacitance in a capacitor discharge supply is generally between 2 and 8 F. This relatively large value is provided for two reasons: (1) because of the need to maintain relatively low voltages around the circuit and (2) to elongate the pulse.

Although the values of resistance R and capacitance C can be controlled by the capacitor manufacturer, the value of inductance L (henries) cannot.

Inductance

Inductance depends on characteristics of the test object. In the case of a tube, inductance is given by:

$$\textbf{(13)}\quad L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{R_o}{R_i} = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{r+\frac{T}{2}}{r-\frac{T}{2}} \cong \left(\ell\frac{T}{2\pi r}\right)\frac{dB}{dH}$$

where $dB\cdot(dH)^{-1}$ is the differential permeability, ℓ is the length of the tube (meters), R_i is the inner radius of the tube (meters) and R_o is the outer radius of the tube (meters). See Fig. 21 for a diagram of these dimensions. Tube wall thickness T is often much smaller than the average radius of the tube.

In CGS units, Eq. 13 becomes:

$$\textbf{(14)}\quad L \cong 2\times10^{-7}\left(\ell\frac{T}{r}\right)\frac{dB}{dH}$$

where r is 0.5 (R_o + R_i). All lengths are in meters, and $dB\cdot(dH)^{-1}$ is dimensionless.

The inductance of thin walled tubes is seen from Eq. 13 to be proportional to the tube length ℓ and wall thickness T and inversely proportional to its radius or diameter. Neither of these physical parameters nor the value of $dB\cdot(dH)^{-1}$ can be controlled by the designer of the magnetizing equipment. However, for much of the tubular products used in oil fields, the value of $T\cdot R^{-1}$ varies slightly, perhaps by a factor of two.

The average magnitude of $dB\cdot(dH)^{-1}$ encountered during magnetization can be seen from Fig. 22 to vary widely. The value is dependent (1) on the point reached by the material on the BH curve during magnetization; (2) on the starting point for magnetization (anywhere from $-B_r$ to Q on the vertical axis of Fig. 24).

As an example of a typical inductance calculation, consider a pipe magnetized to saturation following the path $-B_rH_cPQ$ and having B_r = 1.2 T (12 kG), H = 2400 A·m^{-1} (30 Oe), ℓ = 10 m (30 ft), P = 1.2 T (12 kG), R = 136.5 mm (5.25 in.) and T = 12.6 mm (0.5 in.). Here, dB is 2.3 T (23 kG), so that $dB\cdot(dH)^{-1}$ is 0.001 in SI (800 in CGS units) and L in SI units is:

$$\textbf{(15)}\quad L = 10\text{ m}\,\frac{12\text{ mm}}{2\pi\cdot 136.5\text{ mm}}\,0.001 = 139.9\ \mu\text{H}$$

or in CGS units:

$$\textbf{(16)}\quad L = 2\times10^{-7}(10\text{ m})(12\text{ mm})\frac{800}{136\text{ mm}} = 141\,\mu\text{H}$$

Using the same tube as above, a path is taken from Q through P and B_s to B_r by a second pulse, with B_s = 1.5 T (15 kG), dH = 4000 A·m^{-1} (50 Oe) and Q = 1.0 T (10 kG).

The average value of $dB\cdot(dH)^{-1}$ is then only 1 ÷ 8000, 1.25 × 10^{-4}, in the SI system or 100 in the CGS system. Dividing the original inductance value by 8 (the ratio of the two $dB\cdot(dH)^{-1}$ values exhibited by the steel) yields L = 18.5 µH.

As another example, consider an unmagnetized pipe that follows a path O,P,B_s,B_r, where B_s = 1.5 T (15 kG); dH = 3200 A·m^{-1} (40 Oe); ℓ = 28 mm (1.1 in.); P = 9.1 m (30 ft); T = 4.8 mm (0.2 in.).

The inductance value is calculated in the SI system as:

$$\textbf{(17)}\quad L = 9.1\text{m}\left(\frac{4.8\text{ mm}}{2\pi\cdot 28\text{mm}}\right)\frac{1.5\text{ mm}}{3200} = 116\,\mu\text{H}$$

or in CGS as:

$$\textbf{(18)}\quad L = 2\times10^{-7}(9.1\text{m})(4.8\text{mm})\frac{\frac{15\,000}{40}}{28\text{mm}} = 119\,\mu\text{H}$$

The relatively large change in inductance exhibited by the tube in the two examples affects the shape of the pulse waveform, notably the easily measurable parameters of peak current I_{max} and pulse duration (Fig. 17).

Design Considerations

Good equipment design must consider the material being magnetized. The worst internal and external resistances of the magnetizing system should be known to the manufacturer and corresponding inductance values should be investigated. Under no circumstances should peak currents be stated for magnetization without an electrical and magnetic load for system evaluation.

Depending on the use of the equipment, regulations should be consulted with regard to insulation, isolation, explosion proofing, intrinsic safety and purging. Such regulations are available from many sources, depending on the use of the product. Notable among these, in the United States, are the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH). Various international standards are considerably more stringent than those in the United States. Equipment designers should particularly note the requirements of the United Kingdom, Norway and Germany when designing for North Sea applications. The Canadian Standards Administration should be consulted when designing for applications in Canada.

Magnetization Recommendations

Tubular products vary between such wide limits of diameter and wall thickness that it is difficult to provide a universal specification for the measurable parameters of current pulses for high residual induction. However, the values in Table 4 are based on research with a variety of tubes and can serve as broad guidelines to ensure adequate magnetization.[26]

As tabulated, the pulses are classified into long, moderate and short duration. Long duration pulses are those in excess of 100 ms (Fig. 23). For such pulses, the induced eddy current is assumed to have dissipated while the magnetizing field intensity is still high enough to cause saturation.

Moderate pulses are those with durations between 40 and 100 ms (Fig. 23). For magnetization, the longevity of the induced eddy current is

TABLE 4. Generalized current duration requirements for adequate magnetization of tubes.

Pulse	Duration (µs)	Current Requirement	
		SI units[a]	CGS units[b]
Long pulse	>100	$I = 11.8\cdot D_1$	$I = 300\cdot D_2$
Moderate pulse	40 to 100	$I = 74\cdot W_1$	$I = 110\cdot W_2$
Single short pulse	0 to 40	$I = 161\cdot W_1$	$I = 240\cdot W_2$
Double short pulse	0 to 40	$I = 121\cdot W_1$	$I = 180\cdot W_2$
Triple short pulse	0 to 40	$I = 97\cdot W_1$	$I = 145\cdot W_2$

a. D_1 is outside diameter (mm); W_1 is tube weight (kg·m^{-1}).
b. D_2 is outside diameter (in.); W_2 is tube weight (lb·ft^{-1}).

acknowledged by its effect on the tube, shown in calculations by the use of the tube's linear mass rather than its outer diameter.

Short pulses are defined as those with durations below 40 ms. By comparing the requirement for the single short pulse with that for the single moderate pulse, it can be seen that the maximum current requirement is higher for the same lineal tube mass. In effect, higher current causes a larger magnetizing field intensity, in an attempt to overcome the eddy current.

Should it be necessary to use two such pulses, the peak current requirement falls because the material is partially magnetized. If the peak current can only reach an I_{max} value of $180 \cdot W$, where W is tube weight in $kg \cdot m^{-1}$ (where $1\,kg \cdot m^{-1} = 0.67\ lb \cdot ft^{-1}$), then two such pulses are required. Finally, if the pulse be too small to magnetize the tube with two pulses, a third pulse is necessary. The three pulse sequence should be such that max is equal to $145 \cdot W$.

The requirements summarized in Table 4 are designed to ensure that the bulk induction following the magnetization pulse is at least 90 percent of the remanence value. In many cases, it is higher.

Evaluating Current Pulse Effectiveness

There are two techniques for evaluating the effectiveness of a magnetizing current pulse. The first is a variation on a ring technique for the evaluation of magnetic flux. The second technique is an indirect technique that uses an inductive ammeter (peak and duration meter). A third technique, using simulated contact discontinuities (flux indicators), is valuable for evaluating surface fields only.

Flux Meter Techniques

Flux meters measure the total magnetic flux threading an area defined by a search coil. When circumferentially magnetizing a hollow object by the internal conductor, the search coil can be considered a one-turn coil through the test object. Flux changes are given by:

$$\textbf{(19)} \quad \Delta\Phi = A\Delta B$$

where A is the area of the test object ($A = T\ell$) perpendicular to the search coil (square meter), ΔB is the change in the test object's flux density induced during magnetization and $\Delta\Phi$ is changes in magnetic flux density (tesla).

Commercially available flux meters often compensate for the area A so that the device reads the average flux density directly. The problem with this approach for measuring the final flux density is that the initial flux density (with respect to the vector direction of the search coil) must be zero. When flux changes are measured, the initial value must be known. However, if the tube shown in Fig. 25 is unmagnetized or if prior magnetization is longitudinal, then the flux meter reads the average density of induced circumferential magnetization.

The output of the flux meter can be presented on an oscilloscope. Flux values intermediately between the beginning and the end of the magnetization process represent the flux linked by the one-turn coil. These intermediate values contain the effect of the flux in the air between the terminals of the flux meter.

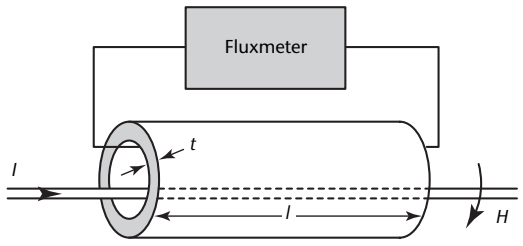
During the pulse, the air field (caused by current I in the rod) and eddy currents (I_e in the test object) affect the instantaneous flux meter reading. When these currents have died away, only the test object flux perpendicular to the one-turn coil affects the final reading. If the operator has time to wind more than one turn around the test object, the error in final bulk flux density can be reduced. However, this procedure is not necessary for establishing the presence of residual induction in the test object for magnetic flux leakage from discontinuities.

Inductive Ammeter Techniques

As shown in Fig. 20b, the pickup coil of the device is threaded onto a convenient part of the magnetizing circuit. When the pulse is fired, the meter reads the peak current (I_{max} of Fig. 23) and the duration of the pulse (τ of Fig. 23).[32]

Saturation of the material has occurred when successive readings on the ammeter are identical. This can be explained as follows. When the first pulse is fired, the material exhibits its highest $dB \cdot (dH)^{-1}$ value (the steep slope of the BH curve is included in the value of L). The average

FIGURE 25. A technique for measuring flux density induced in circumferential direction.



Legend
H = magnetic field intensity ($A \cdot m^{-1}$)
I = electric current (A)
l = tube length (m)
t = tube wall thickness (m)

value of $dB \cdot (dH)^{-1}$ is effective for determining the value of the inductance in Eqs. 9 to 13. This value is relatively large in comparison with the value exhibited during a second pulse. Figure 24 indicates high values of $dB \cdot (dH)^{-1}$ for a first pulse (about 0.0008 in SI and 800 in CGS) and much lower values during the second pulse (around 1.25×10^{-4} in SI or 100 in CGS). In effect, the second pulse experiences a lower inductance than the first pulse.

The second pulse's lowered inductance permits peak current I_{max} to reach a higher value than it reached on the first pulse. In effect, the material is different. The system response is also to lower the duration t. By monitoring I_{max} and t, it is possible for inspectors to determine the test object's relative magnetization.

Using Inductive Ammeters

When materials are magnetized with pulses, the values of field intensity H and flux density B change with time as shown in Fig. 26. The horizontal axes show the percent distance from the inner surface to the outer surface. The vertical axes show either the fraction of H required to saturate the material or the flux density B. The lowest lines show time from the start of the pulse. The uppermost lines show the field intensity and flux density levels at later time increments.

Figure 26 indicates three phenomena during pulse magnetization: (1) inner and outer surfaces are rapidly magnetized; (2) the midwall region is the last part of the material to be magnetized; (3) the midwall region can be left with a low state of magnetization if the pulse field intensity is insufficient to saturate the material.

This last phenomenon contributes to magnetic fields from discontinuities at one surface but produces no leakage field at the other surface when the material is not saturated. The leakage field into the midwall section of the material merely raises the local magnetization.

When sections of the test object are not maintained at field intensity levels sufficient for saturation (point P in Fig. 24), then the ensuing bulk residual flux density is low and the material requires additional pulses to saturate it. The magnetization process calls for the highest value of inductance L in Eqs. 9 to 13 during the first pulse and lower values during subsequent pulses. The general effect of a high inductance is to lower the value of I_{max} and extend the value of τ.

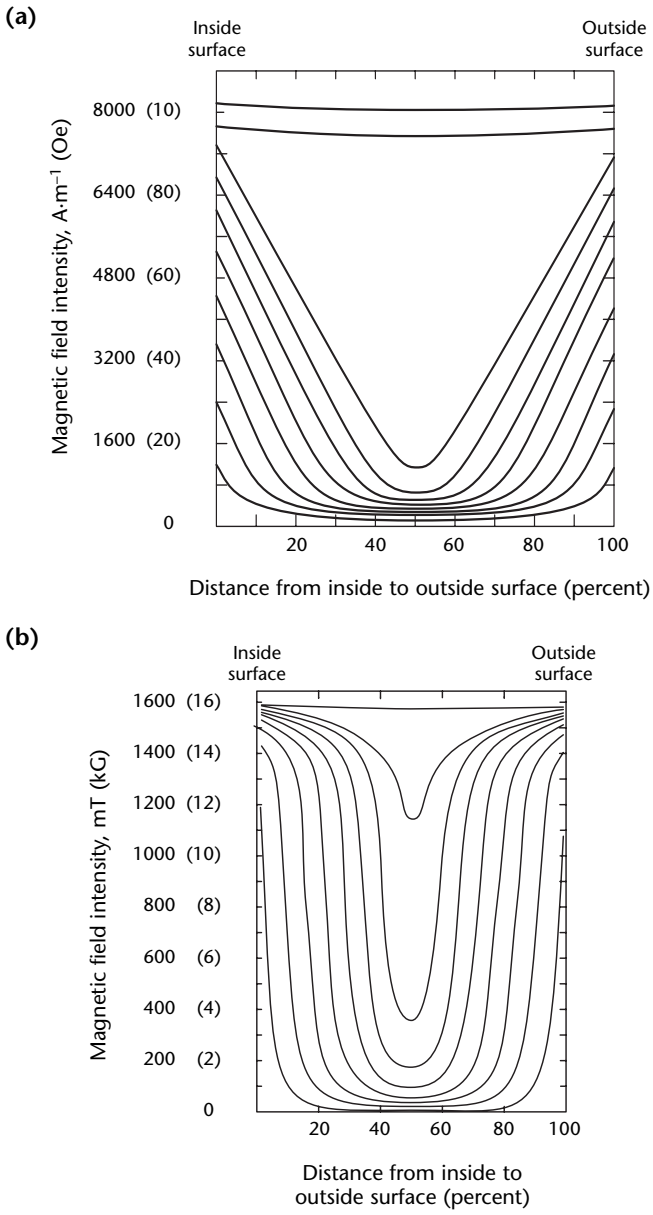
To verify this and to limit the necessary mathematical computation, Eq. 11 was selected and from it the closed form results for I_{max} and τ were found below. First, the time τ (seconds) at which I_{max} occurs is found by differentiation of Eq. 11:

$$\textbf{(20)} \quad t = \frac{2L}{R}$$

When this value is used in Eq. 11, the result for I_{max} is:

$$\textbf{(21)} \quad I_{max} = V_0 \frac{CR}{2L_e}$$

FIGURE 26. Plots against elapsed time and wall thickness of tube: (a) magnetic field intensity; (b) magnetic flux density. Lower curves represent magnetic field and induction at beginning of pulse; time proceeds from bottom to top. Central regions are last to be magnetized.



This result indicates that the value of I_{max} is inversely proportional to that of L (greater L gives lower I_{max}).

To find τ, $I(t)$ is set at $0.5\,I_{max}$:

$$\textbf{(22)} \quad \tau = 5.36\,\frac{L}{R}$$

In this case, the pulse duration (seconds) defined by τ is proportional to the value of inductance L. That is, larger values of L, such as those for the initial pulse, lead to larger τ values (the longest pulse durations).

The *BH* curve indicates that the lowest value of inductance that can occur under these magnetization conditions is exhibited by saturated material, when the value of $dB\cdot(dH)^{-1}$ is at its lowest (Eq. 13). If two identical readings are obtained from an inductive ammeter, the material must be exhibiting its lowest inductance to the magnetizing circuit and must therefore be at remanence B_r.

Operating Principles of Inductive Ammeters

The inductive ammeter is a microprocessor with an inductive pickup coil. The toroid coil contains a large number of turns wound onto a nonconducting nonmagnetic ring core. The ring is threaded onto cables from a capacitor discharge system or onto a central rod. When a pulse is fired, the flux caused by the current surge links with the windings on the ring and the voltage induced in the coil is given by:

$$\textbf{(23)} \quad E = 2\times10^{-7}\,Nd\,\frac{dI}{dt}\ln\frac{b}{a}$$

where a is the inner radius (meter) of the ring, b is the outer radius (meter) of the ring, d is the axial length (meter) of the ring, $dI\cdot(dt)^{-1}$ is the rate of change of current and N is the number of turns in the ring. This equation is derived from Faraday's law of induction. To provide a signal related to the current itself, Eq. 23 must be integrated. The result is:

$$\textbf{(24)} \quad e = \int E\cdot dt = \left[2\times10^{-7}\,Nd\ln\frac{b}{a}\right]I$$

where e is the output of the integration circuit.

In effect, because all the terms in the brackets are known, the output of the integration of induced voltage is proportional to the instantaneous current and the instrument can be calibrated to read current directly. Electronic circuits are used to measure the peak current I_{max} and the pulse duration τ.

Field Indicators and Simulated Discontinuities

Typical Configurations of Field Indicators

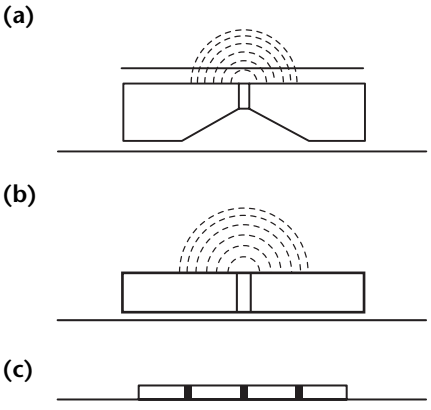
Occasionally, a magnetic particle test operator needs to verify the orientation of induction after tubes have been magnetized by the capacitor discharge internal conductor technique. In the case of perfectly concentric tubes with constant metallurgical properties throughout, there should be no external leakage field. This fact obviates berthold gages (elevated discontinuities surrounded by high permeability material) in this application.

Figure 27 illustrates three kinds of field indicators (erroneously called *penetrameters*) widely used in magnetic particle tests of tubes.

Pie Gage

The pie gage is put on the tube surface to determine the direction of induction. The pie gage comprises six 60 degree sections of high permeability steel without a nonmagnetic cap and gaps up to 0.75 mm (0.03 in.). The width of the nonconductive gaps determines the sensitivity, which is the device's ability to produce a particle indication in an ambient magnetic surface field. In leakage field theory, the particle holding ability depends on the product $(H_gL_g)^2$, where H_g

FIGURE 27. Typical portable magnetic field indicators: (a) raised cross with nonmagnetic cap; (b) pie gage; (c) strip device. Widths of air gaps or slots made from nonmagnetic materials differ between types.



is the magnetic field intensity in the gap and L_g is the gap width.[33]

Strip Indicators

The field indicator preferred for tube tests are strip indicators (Fig. 27c). Such strips typically contain three discontinuities encapsulated for support in high permeability material (often brass). The strip is placed in intimate contact with the test object after magnetization so that the liftoff is limited to the thickness of the brass carrier. Under such circumstances, the magnetized test object shares flux with the strip.

The encapsulation is necessary because strips contain discontinuities that are very small in comparison to the other types of indicators. In effect, the gaps in the high permeability base material are activated by the same surface fields that activate magnetic flux leakage from similarly sized discontinuities in the test object.

Principles of Operation[34]

The principle of operation for all field indicators relies on the ability of the device to turn a relatively constant surface field into a highly curved field (it is well known that magnetic particles are attracted to highly curved fields). The surface field of the test object is converted by an air gap or slot into a curved field. The magnetic force on a particle in such a field is given by:

$$\textbf{(25)} \quad \bar{F}_m \propto \mu_0 V\left(\bar{H}\cdot\nabla\right)\bar{H}$$

where V is the particle volume, μ_0 is the permeability of free space ($4\pi\times10^{-7}$ H·m^{-1}), the *varies as* symbol $\propto$ expresses the demagnetization factor of the particle (dependent on particle shape) and ∇ is the vector calculus gradient operator.[35] For a two-dimensional discontinuity (Fig. 28) placed at right angles to the surface field, the vector operation reduces:

$$\textbf{(26)} \quad \bar{F}_m \propto \mu_0 V\left(H_x\frac{\partial}{\partial_x}+H_y\frac{\partial}{\partial_y}\right)\left(\hat{i}H_x+\hat{j}H_y\right)$$

where H_x and H_y are the leakage field components in the region above the slot. Calculations beyond this point require equations for the leakage field components. The simplest relation for a crack leakage field is given by:

$$\textbf{(27)} \quad H_x = \frac{H_g L_g y}{\pi\left(x^2+y^2\right)}$$

and:

$$\textbf{(28)} \quad H_y = \frac{H_g L_g x}{\pi\left(x^2+y^2\right)}$$

These equations work reasonably well as long as the particle is farther than L_g from the mouth of the slot, as when the slot has a thin nonmagnetic cover. The result of combining Eqs. 26 to 28 gives:

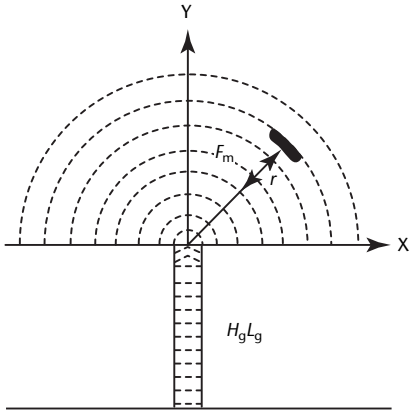
$$\textbf{(29)} \quad F_m \propto \frac{\mu_0 V\left(H_g L_g\right)^2}{\pi^2 r^3}$$

where r is the distance (meters) of the magnetic particle from the mouth of the slot. In this simple approximation, Eq. 29 indicates that the magnetic force holding a particle is (1) proportional to the gap parameter $(H_gL_g)^2$ and various particle dimensions and (2) proportional to the inverse cube of its distance from the mouth of the slot. It is necessary then to determine the cause of H_g.

Fortunately, when seamless tubes are made by mandrel piercing, there is generally some eccentricity (Fig. 29). If the material is magnetized to remanence by the capacitor discharge internal conductor technique, then the conservation of magnetic flux indicates that the flux present in the material at point A must equal the total of that at C plus the leakage flux. Consideration of the tube's cross section areas at A and C yields:

$$\textbf{(30)} \quad \Phi_{leakage} = \left(A_A - A_C\right)B_r$$

FIGURE 28. Magnetic force on isolated particle in flux leakage field from slot. Semicylindrical magnetic flux leakage approximation is according to Eq. 26.



Legend
F_m = magnetic force (N)
H_g = gap field intensity (A·m^{-1})
L_g = gap width (m)
r = distance from particle to gap (m)

where *A*a marks the cross section area at A, *A*c marks the cross section area at C and B_r is the remanence value for the test material. If the leakage field falls off in an inverse manner with distance, then the strongest surface leakage flux B_0 is approximated by:

$$\textbf{(31)} \quad B_0 = B_r \frac{\Delta R}{R}$$

where ΔR is the amount of eccentricity present in a tube of radius R. Equation 31 indicates the following.

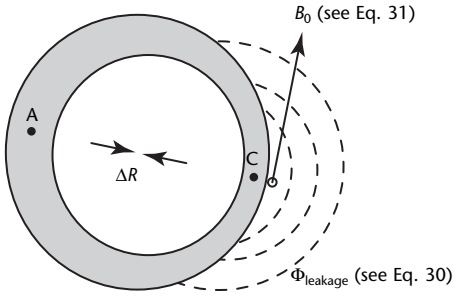
1. The higher the remanence B_r, the stronger the leakage field.
2. Larger eccentricities give larger leakage fields for the same radius and remanence.
3. For the same B_r and ΔR, the leakage field falls off as the tube diameter increases (leakage fields are stronger on the smaller tubes).

At low induction values, the flux at A and C can be equal without the presence of a leakage field. Figure 29 shows that the flux density at C (the thin wall) must be the remanence value for the material if there is to be any leakage field. When this occurs, the flux density B_A at A obeys the relation:

$$\textbf{(32)} \quad B_A A_A = B_r A_C$$

Before this occurs, it may be possible to obtain a magnetic particle indication with a strip indicator. Because there may be no external fields, it is not possible to obtain an indication with the pie gage or other field indicator. It must then be recognized that metallurgical variations within the tube affect B_r and cause some external leakage flux.

FIGURE 29. Broad magnetic flux leakage field from eccentric circumferentially magnetized tube with points A and C at remanence B_r; such leakage fields can activate magnetic field indicators (portable discontinuities).



Documents for Magnetic Particle Testing of Tubes

The references include American Petroleum Institute specifications and recommended practices, several of which refer to magnetic testing of tubular materials.[12,29,30,36-41] Of these, API RP 5A5[36] addresses the most commonly used magnetization methods, plus wet and dry magnetic particle testing procedures. Many oil and gas companies now produce their own specifications, including those for magnetic particle tests.

In most documents, particular attention is given to the following parameters: (1) wet particle concentration, (2) dry particle bulk permeability, (3) dry particle visual contrast with the inspected surface, (4) dry particle filler content, (5) verification of saturation for circular magnetism, (6) intensity of ultraviolet radiation at the test surface, (7) time intervals between ultraviolet intensity checks, (8) relation between field intensity at the center of a coil and the current through the coil and (9) time intervals between magnetizing coil current calibration.

Although not always specified, the test object surface condition plays a critical role in determining which kinds of magnetic particles are acceptable for specific applications.[42]

High contrast is required for visibility and accurate interpretation. High permeability is required so that the particles are magnetized by relatively low leakage fields from tight cracks. High bulk permeability can be verified by a test performed on bulk powders placed in a chemical test tube.

Magnetic Testing of Drill Pipe

The application of magnetic flux leakage testing to the inspection of drill and coil pipe is discussed in another volume of the *Nondestructive Testing Handbook*.[43]

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CHAPTER 14

Electric Power Applications of Magnetic Particle Testing

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PART 1. Introduction

Magnetic particle testing is extensively used in power plants because a large number of components are made out of ferritic steels. Ferromagnetic materials allow application of magnetic particle techniques, including wet fluorescent, wet visible and dry powder. The most used of these because of its high sensitivity is the wet fluorescent magnetic particle technique.

Flux leakage testing is important for quality control of tubular steel during manufacture and is discussed elsewhere.

Test Procedure

The test procedure is the most important document for any nondestructive examination. The test procedure for magnetic particle testing in a power plant must be written in accordance with ASME Section V, Article 7.[1] The procedure must address the essential variables and the nonessential variables whenever they are required. Power plants consist of a range of components; wherever possible, individual procedures should be written for each the major components. The major components of a power plant are the boiler; headers and steam lines; steam and gas turbines; feedwater heaters, tanks and condensers; auxiliary equipment (pumps, valves and fans); and structural steel.

The test procedures must describe how the magnetization and magnetic media are applied. The visible magnetic particle medium is viewed under ambient light whereas the fluorescent medium is viewed under ultraviolet radiation. When performing visible particle testing, best results are obtained when the light intensity is at least 1000 lx (100 ftc). Small and tight discontinuities may be missed at lower light intensities. Ultraviolet radiation intensity shall be at least 1000 $\mu W \cdot cm^{-2}$ with background lighting of at least 20 lx (2 ftc). Magnetic fields are applied using yokes, coils, prods or leaches.

All the equipment must be calibrated in accordance with the requirements of Article 7. This equipment calibration includes lift tests of yokes; calibration of ammeters and light meters; and checks of ultraviolet radiation intensity. When the magnetic medium is prepared, each test shall include verifying concentration and strength of particles according to Article 7. Particle concentration and strength are also discussed in ASTM 1444,[2] but that standard is not cited in the *Code*.

Inspector Training

Personnel performing magnetic particle testing are certified according to ASNT SNT-TC-1A[3] or applicable codes. Specific training course material should include discussion of the power plant equipment and the type of tests to be performed. When new magnetic particle testing inspectors are hired with no power plant experience, they must work with experienced power plant inspectors to become familiar with the many facets of this application. The inspectors must be introduced to the components they will be inspecting as well as damage mechanisms and the expected discontinuity types. This specific training shall be detailed in the written practice. The certification process normally includes general, specific and practical tests. Specific test questions must focus on power plant components and the types of tests to be carried out.

Magnetic particle testing procedures used in the power plant should also be included in the specific test. Individual specific tests can be administered for each major component. As a minimum, testing of turbine components should include a separate specific test. Inspectors with no power plant experience can miss discontinuities in turbine components if no additional training is provided.

Just as in specific tests, the practical test must include discontinuities representative of power plant damage mechanisms. When possible, practical tests must include tests on actual components with cracks, such as turbine blades, boiler tubes and pipe weld samples. Cracks in turbine components can be very tight, and an inspector with inadequate training could miss such cracks. A Level II certificate in magnetic particle testing does not ensure that the inspector can conduct the power plant examinations reliably without additional specific training.

The magnetic particle testing training for power plant components should include a description of the power plant components with their basic functions, general information on materials and operating parameters (such as temperature and pressure). Also, damage mechanisms in components, likely location and type of expected discontinuities and the smallest relevant discontinuity size for detection should be covered.

PART 2. Magnetic Particle Testing of Power Generation Equipment

Boiler

The function of the boiler is to convert water into superheated steam. Components in the boiler include waterwall tubes, superheater tubes, reheater tubes, economizer tubes, headers and drums.

Boiler Tubes

A variety of steel alloys — including carbon steels, carbon molybdenum, chromium molybdenum and stainless steels — are used in boiler tubes. A single boiler could consist of multiple grades of steel, depending on tube temperature. Common tube materials include SA-203 nickel alloy steel, temper 12; SA-209 carbon molybdenum steel, temper 1; SA-210 medium carbon steel; UNS S30815 (SA 213) austenitic steel, tempers 11 and 22; and austenitic stainless steels. (SA numbers are indexed in Section IIA of the *ASME Boiler Code*.[4] UNS numbers refer to the Unified Numbering System.[5]) Most of these grades are ferritic, but austenitic stainless steel tubes are used only in the superheater and reheater sections. The normal pressure in the tubes is 16.6 MPa (2400 $lb_f \cdot in.^{-2}$) for subcritical boilers and 24 MPa (3500 $lb_f \cdot in.^{-2}$) for supercritical boilers. The temperature in the boiler increases from the waterwall tubes to a maximum in the superheater tubes. Tube metal temperatures can be as high as 538 °C (1000 °F). Because of high temperatures, superheater tubes are made out of chromium molybdenum and austenitic stainless steels.

Boiler tubes are generally inspected through magnetic particle testing on a need-to-inspect basis. The test usually follows a failure related to surface cracking. Magnetic particle testing is then used to determine the extent of such damage for repair and then to perform a root cause analysis for avoiding future failures. One example could be a followup test after a tube failure caused by quench cracking. Magnetic particle testing is then used to survey the entire area to ensure that all affected areas are identified and repaired. Because this is an unusual type of failure that should not be expected under normal operating conditions, a root cause analysis ensures that the cause of the damage is corrected.

Another type of discontinuity is cracking between boiler tubes and the membrane, caused by corrosion fatigue. Again, magnetic particle testing is used for crack detection and for root cause analysis.

As in the examples above, there are several other types of damage mechanisms possible in the boiler. Cracks in boiler tubes are most commonly caused by mechanical fatigue, corrosion fatigue or thermal fatigue. The preferred technique for boiler tubes is wet fluorescent magnetic particle testing. Dry powder and wet visible techniques should be avoided because of low sensitivity. An alternating current yoke is used for magnetization because the area of interest is the surface. Another potential area of outside surface cracking is at the dissimilar metal welds between ferritic and austenitic tubes. False magnetic particle indications will result at the dissimilar metal welds between the ferritic tubes and the austenitic tubes. Magnetic particle testing should not be used for dissimilar metal welds, where an inexperienced inspector could make a mistake and make calls where there are no flaws. Liquid penetrant testing is used for such tests.

Headers and Drums

Headers and drums are inspected for surface cracks on the inside and outside surfaces. Inside surface examination of the headers is usually limited because of internals that have to be removed for testing. Header testing is mostly limited to the outside surface. The most important test area for headers is the circumferential (girth) welds. These welds should be thoroughly inspected through wet fluorescent magnetic particle testing. Cracking is also common at the boiler tube stub welds on the headers (Fig. 1). Depending on the header design, this area can be congested by a large number of tubes welded to the header and can have limited access. The inspector will have to maneuver the yoke in several positions to get complete testing coverage. it is recommended that, before testing, the header be sandblasted to remove rust and scale.

Steam drums are also inspected in the same manner as the headers. All the nozzle penetration welds and

circumferential welds are to be inspected through wet fluorescent magnetic particle testing. Before testing, the inspector is to ensure proper cleaning of the surface so that it is free of loose scale and oxides.

Steam Lines

Creep and fatigue are the primary causes of cracking in steam lines.

Creep crack growth is mostly limited to longitudinal seam welds (when present) where it initiates at mid wall. This type of cracking can only be detected by ultrasonic testing.

Cracking in the circumferential welds initiates from the outside surface because of bending stress. Bending stress can be especially high at the bends and elbows. Wet fluorescent magnetic particle testing is the best technique for circumferential welds. This test is always performed with an alternating current yoke and wet fluorescent particles. Figure 2 shows failure of a main steam line at the circumferential weld. The crack initiated from the outside surface and grew inwards to the inside surface.

In addition to circumferential welds, wet fluorescent magnetic particle testing is performed at the hanger support welds, thermocouple connections, penetration welds and any other branch connections.

Turbine

Steam turbines in power plants have multiple stages and can include up to three stages: high pressure, intermediate and low pressure. In some systems, the high pressure and intermediate stages are combined into a single turbine rotor. The main components in the turbine are the rotor, disks, blades, shroud, inner casing and stationary blades. Most of the components are made of steels alloyed with nickel, chromium, molybdenum and vanadium.

Creep and fatigue are the main damage mechanisms in the high pressure stages where they operate at temperatures close to 540 °C (1000 °F). Past the wilson line, in the low pressure stages, the steam is wet and the main damage mechanism is stress corrosion cracking with water impact erosion.

Periodic tests of turbines are usually outlined in great detail in the technical specifications provided by the equipment manufacturers. These documents provide details of the equipment to be inspected, testing schedules in operating hours, recommended test techniques and procedures for final disposition of test data. Periodic tests can be provided by equipment manufacturers or by plant owners or operators.

All materials used in steam turbines are ferromagnetic, so the preferred method of surface testing is magnetic particle testing.

Rotors are inspected for cracking in the outer packing groove, center bore and blade tip groove shoulder.[6] Surface cracking can occur in the heat grooves of high pressure rotors and is generally caused by thermal fatigue from cycling. Cracks generally occur in the packing grooves at the small radii of the labyrinth seal areas along the rotor. Groove cracking is usually shallow and can be removed by local grinding. There have also been incidences of transverse cracking in the low pressure rotors. Although rare, transverse cracking in low pressure rotors initiates from corrosion pits and can grow during service by corrosion fatigue. When

Figure 1. Header in fossil fuel power plant. Both circumferential welds and tube stub welds are inspected for outside surface cracking.



Figure 2. Failure of main steam line at circumferential weld. Circumferential welds must be thoroughly inspected by wet fluorescent magnetic particle testing during regular inspections. Bending stresses on outside surface initiate cracking at circumferential welds.



such cracking grows, it is usually detected by vibration monitors that can shut off the turbine. Magnetic particle testing is used on the rotor to check for initiation sites for such cracks. Rotor surfaces are commonly magnetized with coils; head shots are also used. Coils are wrapped to produce magnetization transverse to the expected cracking. Shims should be used to verify direction of magnetization and its sensitivity. A common mistake is when the inspector places the coils on the test object so that magnetization is parallel to the expected cracks. Another common mistake is insufficient magnetization. Magnetization levels should be verified with shims.

The preferred method for rotor bore testing is a combination of ultrasonic and eddy current testing. Eddy current testing is sensitive to surface cracks whereas ultrasonic testing is also sensitive to subsurface cracks. In some instances, the owners have allowed bore testing by magnetic particle testing. In such a case, the test is done by the central conductor technique and with wet fluorescent particles. Magnetic particle testing will provide an acceptable surface inspection of low pressure rotors. However, for high pressure rotors, magnetic particle testing is not a good approach because the critical crack sizes are very small and magnetic particle testing with optical devices can miss tight and small cracks.

Turbine disks can either be integral to the rotor body or connected to the rotor via a key. Keyway cracking can occur in low pressure turbines from stress corrosion cracking. The preferred methods for inspection of keyway cracking are ultrasonic and magnetic particle testing. Magnetic particle testing is, however, limited to the accessible surface on the disks. When any cracking is detected by magnetic particle testing, a thorough ultrasonic inspection must be performed to determine the extent of cracking in the keyway.

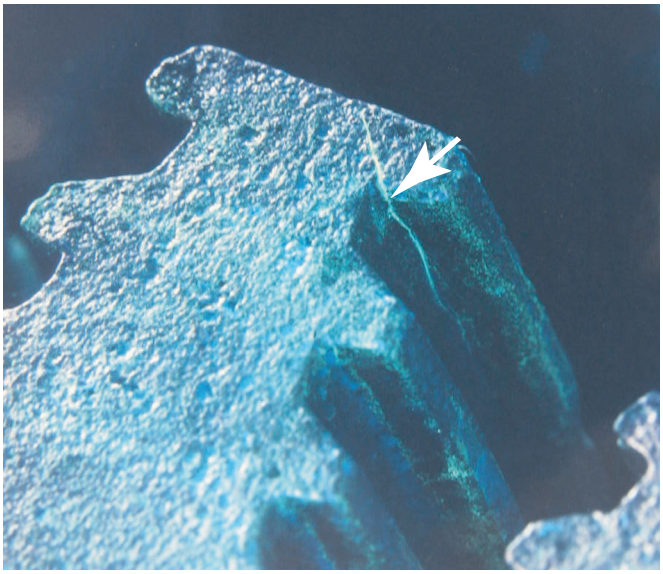
The blade attachment areas of the disk and the blades themselves are critical areas for testing. There are two types of designs of the blade attachment areas: axial entry and radial entry. Only the axial entry attachment can be inspected with wet fluorescent magnetic particle testing to detect cracks in the high stress root areas. Testing is done both at the attachment areas of the disk and the blades, where cracks are very tight and can be missed by an unsuspecting inspector. Once the crack is detected, the blade must be removed to find the extent of cracking. When this step is taken, the grooves of the attachment must be thoroughly cleaned for wet fluorescent magnetic particle testing. Figure 3 shows a crack detected with wet fluorescent magnetic particle testing in the blade attachment area of the disk. The attachment areas on the blades are also inspected with wet fluorescent magnetic particle testing, but eddy current testing is also commonly used for this inspection. Cracks in the blade attachment areas are very tight and may sometimes only produce a faint magnetic particle indication. Eddy current testing will produce a well defined signal even if the crack is very tight.

Blades in turbine and stationary diaphragms also are inspected for cracking. Coils are used for magnetization of the blades and inspection is done with fluorescent particles. Figure 4 shows testing of turbine blades. The coils are wrapped around the blade for magnetization. Wet fluorescent particles are sprayed for detection of cracks. Figure 5 shows testing of stationary blades in a diaphragm. Once the blades are removed, they are individually inspected with wet fluorescent magnetic particle testing using coils or a yoke. Again, it is very important to check the direction and intensity of magnetization using shims.

The shroud of the turbine blade is also inspected with wet fluorescent magnetic particle testing. Cracking can also occur in the tenon roots under the shroud. This area is not accessible for magnetic particle testing, so tenons are tested ultrasonically.

Cracks are commonly found in the inner casing and steam chests. These cracks caused by creep fatigue or thermal fatigue are generally open and easily detectable with visual testing.

FIGURE 3. Cracking detected by wet fluorescent magnetic particle testing in blade attachment area of turbine. This cracking can be easily missed if blade attachment is not thoroughly cleaned before inspection.



High temperature bolts hold the steam chest to the base. Cracking in the threads can occur because of metallurgical causes, poor design or poor tightening procedures. The two most common modes of failure are creep fatigue and brittle fracture. Ultrasonic testing is the most common method of testing, done by placing a straight beam probe on top of the bolt. Once a suspect indication is detected, a followup wet fluorescent magnetic particle test is performed on the threads.

All rotary components of the turbine must be demagnetized after magnetic particle testing.

Industrial gas turbines are different in construction from steam turbines. Firing temperatures in the industrial gas turbines are significantly higher than the steam turbines and approach 870° C (1600° F). Because of high temperatures, there is wide usage of cobalt based and nickel based super alloys.[6] Most of the components of the gas turbine are therefore nonferromagnetic and do not allow application of magnetic particle testing. Fluorescent liquid penetrant testing is the primary test method for gas turbines.

FIGURE 4. Wet fluorescent magnetic particle testing of turbine blades. Magnetization is performed by coils. (Inspection was done with ultraviolet irradiation, but this picture was taken in visible light.)



Feedwater Heaters, Tanks and Condensers

Certain areas of the feedwater heater are prone to cracking, especially the welds between the divider plate and the shell. Cracks can also be found between the tube sheet and the shell. These cracks are caused by fatigue and will be more common in units that have higher use cycles. Wet fluorescent magnetic particle testing can be used for such tests; however, because of space restriction liquid penetrant is also used.

Deaerator tanks are inspected regularly, preferably with wet fluorescent magnetic particle testing. Testing is done from inside the tank with alternating current yokes. The areas to inspect are the welds around the manhole, nozzle penetration welds, circumferential welds and longitudinal seam welds. Surfaces must be thoroughly cleaned before testing.

Condensers operate at almost no stress from the process; the only stress is from structural loads. There is, therefore, minimal magnetic particle testing of condensers performed on a regular basis. Testing is only done if there is a structural failure in the condenser. This testing is done to assess the damage and inspect the surrounding area for similar damage.

Auxiliary Equipment

Auxiliary equipment generally includes pumps, valves and fans. Cracking can occur in the impellers, stationary vanes and pump shafts. Pump shafts must be

FIGURE 5. Wet fluorescent magnetic particle testing of stationary vanes of steam turbine. Prepared fluorescent magnetic medium is sprayed while magnetic field is applied by coils. Inspector uses coils for magnetization. (Inspection is done with ultraviolet irradiation, and this picture was taken in visible light.)



inspected at the keyways, at the diameter transitions and at the thread. Liquid penetrant testing is used when pump shafts are made out of stainless steel. Wet fluorescent magnetic particle testing is performed on the pump casing. Large, swiftly rotating, circulation fans are inspected by wet fluorescent magnetic particle testing to detect high cycle, fatigue cracking.

Other methods, such as eddy current testing and vibration monitoring, are important but not discussed here.

Structural Steel

Extensive tests of structural steel are performed during power plant construction. Almost all of the structure is steel, so there is extensive magnetic particle testing of the welds. Structural steel is inspected by either dry powder or visible magnetic particle testing. Both tests are done using an alternating current yoke. Prior to testing, the surface must be cleaned of loose scale and dirt. White contrast paint should be used for wet visible magnetic particle testing. Magnetic particle testing of the structure is also performed during modifications of the plant. Structural steel tests are performed in accordance with AWS D1.1.[7] While structural steel tests sound simple, inspectors must be trained to detect cracks within the weld ripples. Also, if not applied correctly, excess dry powder can cover the cracks.

PART 3. Requirements for Nuclear Power Plants

Rules for inservice tests of nuclear power plants are governed directly by ASME Section XI.[8] Section XI provides detailed and specific requirements for testing of components. Section XI opens with a chapter that clearly defines two terms: *examination* and *inspection*. *Examination* is defined as performance of all nondestructive testing methods. *Inspection* denotes verifying the performance of examination by an authorized nuclear inservice inspector representing an authorized inspection agency or a state or municipality having jurisdiction over the nuclear power plant. Section XI, Division 1, consists of subsections covering the following aspects of rules: IWA, "General Requirements"; IWB, "Class 1 Components"; IWC, "Class 2 Components"; and other sections for other components

The rules identify components for examination in the inservice inspection plan. These components include power plant items such as vessels, containments, piping systems, pumps, valves, core support structures and storage tanks, including their support structures. Section XI does not ask for a specific test method but divides examination methods into three types: visual, surface and volumetric. When a surface method is specified, the examination may be carried out by either magnetic particle or a liquid penetrant method. The selection and application of a specific method is the responsibility of the owner. The owner is responsible for preparation of written instructions and procedures for examination. When a surface test is specified for nonmagnetic or dissimilar metal components, the only choice is liquid penetrant testing. However, either magnetic particle or liquid penetrant testing can be selected by the owner for application on ferromagnetic materials. Magnetic particle tests in a nuclear plant are conducted in accordance with Section V, Article 7, of the *Boiler and Pressure Vessel Code*.[1]

Subsections IWB and IWC of Section XI identify components for surface examination. IWB covers reactor vessel nozzle-safe-end welds and reactor vessel nozzle-safe-end welds, piping, pumps and valves. IWC covers nozzles, nozzle-to-shell welds, reinforcing plate welds to nozzle and vessel, pump casing welds, valve body welds, piping circumferential welds and piping longitudinal welds.

For each of the components identified for testing, Section XI also includes the first and successive examinations in ten-year intervals.

When indications are detected, detailed information is included in the *Code*[8] on the acceptance criteria. Discontinuities detected through Section XI surface examinations are treated as cracks or linear discontinuities. When linear discontinuities are detected by magnetic particle or liquid penetrant testing, the specific allowable indication length is included, which depends on nominal wall thickness. Acceptance criteria differ for preservice and inservice examinations.

The above discussion on nuclear plant examination shows that the rules for testing of nuclear plant components are very specific. Inspection personnel in nuclear plants must therefore be very familiar with the procedures and must follow written instructions.

Many systems outside of containment are similar to those in fossil plants, so the discussion of fossil plant tests pertains to them too.

Conclusions

Power plants consist of a variety of components that must be inspected reliably. Tests in power plants cover a wide range of test sensitivity, from testing of welds in structural steel to tight cracking in turbines. Inspectors working in the power plants must familiar with damage mechanisms and types of discontinuities that can be expected in various plant components. Training is necessary in addition to the basic magnetic particle testing training according to ASNT Recommended Practice No. SNT-TC-1A or ASNT CP-189.[3,9]

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15

CHAPTER

Infrastructure and Aerospace Applications of Magnetic Testing

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PART 1. Infrastructure Applications of Magnetic Testing

The most conspicuous magnetic testing of infrastructure is magnetic particle testing for buildings and bridges. The testing of steel welds is important in many industries and is discussed elsewhere in this volume, too. The present discussion focuses on surface preparation.

Wire cables are used in suspension bridges and ski lifts, and their inspection with flux leakage is mentioned below.

Field Tests of Structural Welds[1]

Magnetic particle testing is performed on a variety of welds used in bridges, buildings and other structures. The American Welding Society Structural Welding Code with its nondestructive testing requirements is often incorporated into construction contracts.

Inspectors typically must work under less than ideal conditions, particularly when existing structures are tested. Field welds made to connect fabricated subassemblies can also present significant problems.

Effect of Weld Surface

Most weld surfaces are left in the as-welded condition for service or for testing. It is up to the inspector to decide whether a particular surface is good enough for magnetic particle testing. Dry magnetic particles and either half-wave rectified current or alternating current are typically used with electromagnetic yokes.

The mobility of dry powder with the pulsed magnetic fields produced by yokes is essential for effective testing of irregular surfaces. Testing with yokes and fluorescent suspensions is increasingly required for welds that are ground smooth, such as those in vessels fabricated to Section VIII of the ASME *Boiler and Pressure Vessel Code*.[2]

On rough surfaces, particle suspension can be trapped in depressions, creating unwanted background fluorescence. The geometry of the test surface, particularly where fillet welds are used, often requires a yoke with articulating legs. The distance between the yoke poles may have to be changed frequently to fit the available contact areas. Some yokes have adjustable magnetizing current when used in the half-wave rectified mode.

Field Intensity Adjustments for Tests of Welds

The magnetic field intensity is adjusted to correspond to the required pole spacing and the test material. This is done by observing the test surface for nonrelevant indications and excessive buildup of particles around the poles. With rectified current electromagnetic yokes, the current is usually increased to the point where these things occur and is then reduced slightly for the actual test.

Alternating current and switchable yokes do not have a means for adjusting the magnetizing current. However, some alternating current yokes do have removable pole extensions to compensate for variations in pole spacing on the surface. These are available in more than one length and are sometimes articulating. Depending on their length and design, the addition of pole pieces can reduce the tangential magnetic field intensity midway between the poles by a factor of 25 to 50 percent. It is possible to determine the reduction of field intensity caused by incomplete contact of the poles with rough surfaces using a hall element tesla meter.

Partial penetration in structural welds is common, as are welds joining sections with substantial differences in thickness. These conditions are common causes of nonrelevant indications with half-wave rectified magnetization. This problem may be eliminated by changing to alternating current — because of its skin effect, variations in magnetic field intensity with section thickness are minimized.

Although rectified current is sometimes specified because of its deeper penetration and its increased ability to detect subsurface discontinuities, alternating current is becoming more widely accepted in the United States. Empirical data have shown that alternating current yokes are capable of detecting discontinuities that are not open to the surface, to a depth of at least 1 or 2 mm (0.04 to 0.08 in.). With any type of yoke, it is difficult to predict the maximum depth at which a subsurface discontinuity will be detected.

Lighting for Weld Inspection

It is important to have adequate illumination of the test surface. Even when working outdoors in bright daylight, some welds are covered by shadows. Some specifications leave determination of adequate visible light intensity to the discretion of the inspector[3] whereas others specify a minimum intensity (for example, 2200 lx [200 ftc]) at the test interface.[4] An ordinary flashlight is inadequate.

Electric power is required at the test site for the electromagnetic yoke and it can also be used with a portable high intensity lamp. Instruments such as borescopes and fiber optic borescopes can be used to inspect areas where direct visual access is limited.

When dry fluorescent powders are used outdoors, it is important to have shielding for minimizing visible light. This precaution is at least as critical as providing ultraviolet radiation of sufficient intensity.

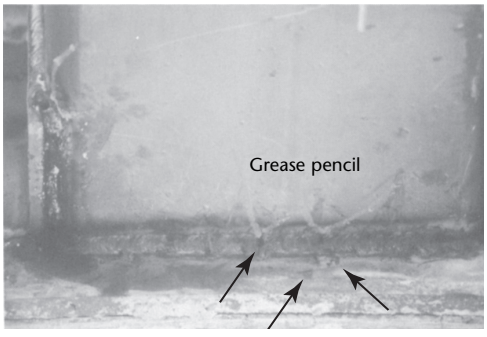
Relationship with Welder

The magnetic particle inspector often works closely with the welder, who is called on to clean surfaces that are too rough and to follow up on discontinuity indications. The welder is often the best source of information about what types of discontinuities are probable and where they are likely to be.

Developing good communication with the welding contractor can result in more effective and reliable testing. A good start is to explain the magnetic particle procedure and the need for particular surface conditions. It is equally helpful if the inspector is informed of the welding process used.

Figure 1 shows a fillet weld presented as ready for testing. The inspector has marked three deep crater pits to be reworked before magnetic particle testing. In Fig. 2, a short overhead fillet weld is tested for transverse discontinuities. In Fig. 3, a longitudinal indication of a discontinuity goes around the corner of a weld.

FIGURE 1. Fillet weld with three deep crater pits to be reworked before magnetic particle testing. The inspector has marked the area of concern with two grease pencil marks.



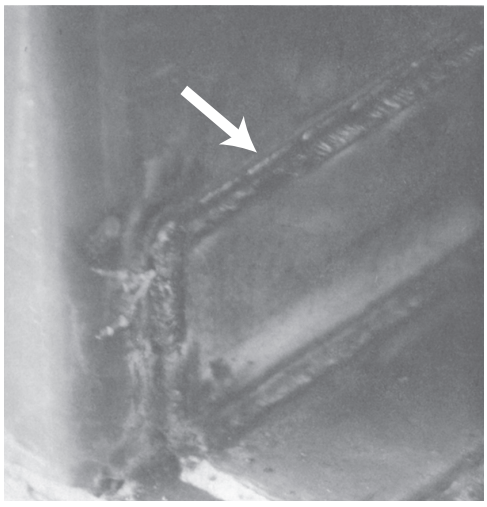
Testing of Welds through Paint

When welds in existing structures are being tested, they are often coated with paint or rust. Studies have shown that paint's reduction of discontinuity detection depends on the coating material, its thickness and the weld surface profile.[5,6] Because the type and thickness of coatings on an existing structure are generally unknown, the safe

FIGURE 2. Yoke is oriented parallel to fillet weld to find transverse discontinuities.



FIGURE 3. Magnetic particle indication of linear weld discontinuity.



thing to do is to remove them in the areas of interest. Although it is possible to make measurements of paint thickness with a portable magnetic induction coating gage, this does not provide information about the relative magnetic effects of different coatings.

Dry Powder Magnetic Particle Tests of Painted Welds[2]

Opinion is mixed about alternating current yoke magnetic particle tests of painted welds. There are reports of both successful and unsuccessful magnetic particle tests of welds through paint.

Comparing the length of two types of small fatigue cracks in fillet welds, one study[7] evaluated various nondestructive tests: visual, liquid penetrant, eddy current, ultrasonic and magnetic particle tests. The limits of detection were compared and a relationship was established between crack size and estimated size. Finally, the effect of paint on superficial fatigue crack detectability was studied. The optimal process conditions are equally defined for control techniques.

Yoke Break Test

A yoke break test was devised to help evaluate the effect of coating type and thickness on the introduction of flux to a ferromagnetic substrate. This simple test relies on the contention that the flux intensity produced in a ferromagnetic material may be gaged by the amount of pull produced by the yoke on that material. The test uses a dynamometer to pull an energized yoke from a bare test plate. The plate is then coated with progressively increasing thicknesses of paint. After the application of each paint layer, the force required to pull (or break) the yoke from the plate is measured along with the coating thickness. During this test, the poles of the yoke are maintained at a constant spacing.

Some variation in reported feasibility is expected. Thousands of different paints exist and are applied in a wide range of thicknesses and in a nearly infinite number of primer and topcoat combinations. Each paint or coating system has a characteristic magnetic permeability that influences the degree to which magnetic flux may be introduced to a ferromagnetic substrate.

Such a test was performed using ASTM A 36 steel plates[8] as a substrate. Four separate coating types were evaluated, including inorganic zinc, zinc chromate, enamel and phenolic epoxy. Yoke break test data obtained for each coating are presented graphically by Fig. 4, where pull is plotted against applied coating thickness.

Weld Bead Crack Reference Standards

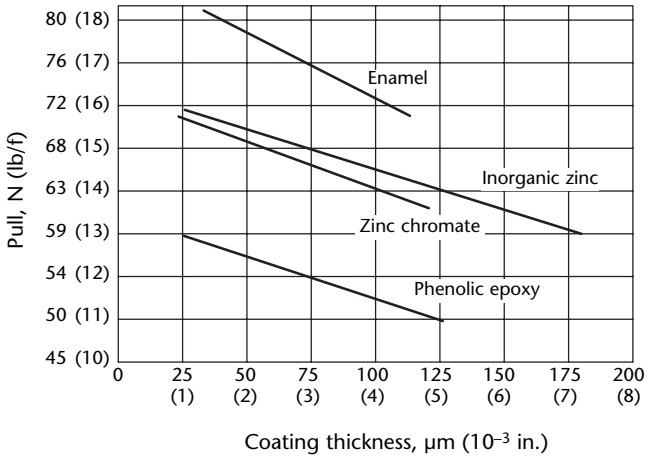
In an attempt to quantify the thickness of the coating at which sensitivity is diminished, four ASTM A 36 plates were prepared,[8] each containing a single shielded metal arc weld bead in which copper ferrite dilution cracking had been induced. Copper ferrite cracks are very fine and barely visible to the unaided eye. Each plate was tested with yoke magnetization and a record of the particle indications was made for each direction of magnetization.

Each plate was then coated with inorganic zinc, zinc chromate, enamel or phenolic epoxy. Coating thicknesses were measured and recorded and the plates were then retested with a yoke technique. Particle indications were recorded and the indications were compared to those obtained during magnetic particle tests of the bare metal. This process was repeated until each plate reached the point at which coating thickness diminished the indication detectability. Table 1 summarizes the results of this study and lists the critical thickness of each coating.

Reference Standards for Weld Cracking

To confirm that bead crack test data would be valid when applied to actual welds, three additional plates were prepared to contain multiple-pass groove butt welds with multiple bead weld caps.

Figure 4. Decrease in pull with increase in coating thickness. Yoke produces pull of 85.3 N (19.3 lb_f) on bare test plate. Yoke center-to-center pole spacing maintained at 110 mm (4.25 in.) during all tests.



Each weld cap was approximately 25 mm (1 in.) wide. These welds contained undercuts of varying severity as well as copper ferrite dilution cracks. Except for the cracking, the welds were typical of those commonly encountered during industrial magnetic particle tests.

An initial test was performed and records of particle indications were made. Each plate was then coated with inorganic zinc, zinc chromate or enamel. The paints were allowed to dry, coating thicknesses were measured and recorded and each plate was retested with yoke magnetization.

Records of the particle indications were made and test results were compared to those obtained from the unpainted plates. Even though each of the applied coating thicknesses was less than 80 µm (0.003 in.), all of the test objects revealed a dramatic loss of indication detectability.

Effect of Coating Thickness on Test Results

The data in Fig. 4 show that the introduction of magnetic flux to a ferromagnetic substrate with an alternating current yoke is affected by interposing thicknesses of paint. The extent of this effect may be significant, depending on the type of paint and its thickness.

There is a surprisingly large difference in the data obtained from single bead test welds and from multiple bead test welds, especially as it relates to the coating thicknesses that permit yoke magnetization. It is believed that this difference may be the result of concurrent leakage fields (Fig. 5) that existed in the multiple bead weld cap but not in the single bead weld. This could have produced decreased flux density in leakage fields at the crack sites and in turn could have reduced the ability to attract and hold particles through the coatings.

TABLE 1. Copper ferrite dilution cracking detectability for various applied coating thicknesses.

Coating Type	Critical Thickness[a] µm	(in.)
Enamel	300	(0.012)
Inorganic zinc	225	(0.009)
Zinc chromate	200	(0.008)
Phenolic epoxy	175	(0.007)

a. Maximum thickness of applied coating at which no loss of indication detectability was observed.

Concurrent Leakage

The concept of concurrent leakage was investigated further. A single shielded metal arc weld bead containing copper ferrite dilution cracking was deposited on a carbon steel plate. The bead was tested with magnetic particle yoke techniques and the discontinuity indications were recorded.

An additional bead was then deposited on each side of the original weld and the new weld was retested. After seven beads had been deposited (three on each side of the original weld bead), a distinct decrease in indication detectability was observed.

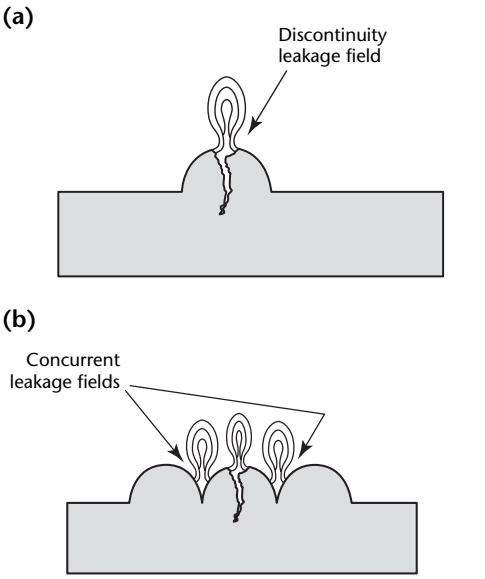
This indicates that magnetic particle testing of painted welds depends not only on coating type and thickness but also on the weld profile.

Mechanical Paint Removal and Crack Detectability[9]

Studies have also shown that mechanical removal of paint, such as by power wire brushing with solvents, does not significantly reduce the reliability of magnetic particle testing.[10]

To assess the effect that mechanical paint removal might have on weld discontinuity detection, a comparison was made of the detectability of copper ferrite dilution cracking in welded test plates before and after a paint removal procedure. Copper ferrite dilution cracking is characteristically very fine and

FIGURE 5. Leakage fields in weld caps: (a) single weld bead; (b) multiple weld beads. Cross sectional change at weld toe redistributes flux and reduces leakage in adjacent discontinuity.



difficult to detect visually. Its small size makes it representative of the sort of weld discontinuity that could be affected by surface working during paint removal.

Object Preparation

Five ASTM A 36 steel plates were prepared,[8] each about 300 mm (12 in.) long by 150 mm (6 in.) wide by 13 mm (0.5 in.) thick. A single V groove butt weld was produced in the center of each plate by the shielded metal arc welding process, using E-7018 electrodes.[11] Each weld was divided into segments 50 mm (2 in.) long and two of these segments in each weld were selected for crack implantation.

Copper ferrite dilution cracking was induced in each of the two selected segments. Each plate was assigned a sample identification number and each was tested using an alternating current yoke and dry magnetic particles.

A transparent tape transfer record was made of all discontinuity indications for each direction of magnetization. Because liquid dye penetrant materials are difficult to remove from capillary voids such as the cracks produced in the sample plates and because these materials could interfere with subsequent coating application, an initial liquid penetrant test was not performed.

Visual Test Results

Copper ferrite dilution cracks tend to form fine, branched indications that vary significantly in length and width. Depending on orientation and their reflective characteristics, many such cracks are not consistently detectable during visual testing. To ensure that crack detection comparisons were based on a reliable and consistent frame of reference, an effort was made to determine which of the sample weld crack indications could be repeatedly and consistently detected.

Fifteen welding inspectors certified by the American Welding Society visually inspected each of the five test plates and produced a detailed sketch of crack locations and orientations. Each inspector's sketch was compared to the previously obtained magnetic particle tape transfer record for the appropriate sample segment.

Those cracks that were most consistently reported by all fifteen inspectors were selected for use as reference cracks in comparing detectability before and after paint removal.

Coating Application

The five plates were sandblasted in preparation for coating application. Five commonly used paint systems were applied by brushing or spraying in strict accordance with the manufacturers' recommendations. The applied paint systems and the average applied coating thicknesses are detailed in Table 2.

Each plate was given fourteen days to dry and cure. After curing, the welds were visually inspected to determine if cracking was visible through the paint and none was detected.

Visual Retesting

The coatings were removed by applying surface conditioners (solvents) in combination with manual and power wire brushing. Five certified welding inspectors then performed visual examinations of the plates. Each inspector produced a detailed sketch of the location and orientation of detected cracks.

A redetection frequency was determined for each of the reference cracks by comparing the sketches to the original magnetic particle transfer record and to the sketches of crack locations before coating. In all cases, the reference cracks were redetected and recorded without significant change. A reduction in the cracks' reflective characteristics was noted.

Magnetic Particle Test Results

An alternating current yoke, dry powder magnetic particle test was performed on each sample segment. Transparent tape transfers of all discontinuity indications were obtained for each direction of

Table 2. Coatings and thicknesses in paint removal study.

Sample	Primer	Thickness		Top Coat	Thickness	
		µm	(10^{-3} in.)		µm	(10^{-3} in.)
1	zinc chromate	35	(1.4)	enamel	98	(3.9)
2	plastic based	48	(1.9)	enamel	88	(3.5)
3	plastic based	45	(1.8)	diethylenetriamine	130	(5.2)
4	zinc rich	110	(4.4)	diethylenetriamine	275	(11.0)
5	zinc rich	85	(3.4)	none	0	(0)

magnetization. Comparisons were made of tape transfers taken before and after coating removal and the discontinuity indications were found to be identical.

A liquid penetrant test was then applied to each test plate using a solvent removable visible dye penetrant and nonaqueous wet developer. A dwell time of twenty minutes was observed before penetrant removal and developer application. Eighty percent of the reference cracks were not revealed by this method.

Cross Sections

The welds were then cross sectioned through various crack locations. Cross sectioning was used to determine physical characteristics such as crack width; to determine if smearing or working of the metal surrounding the crack openings had occurred; and to determine the extent to which the coating may have entered and occluded the reference cracks.

On the basis of laboratory reports and a subsequent test of the samples, crack widths were determined to be in the range of 25 μm to 0.25 mm (0.001 to 0.01 in.) at the plate surface. After paint removal, a layer of disturbed metal was observed to partially seal the crack openings. Laboratory tests indicate that this layer was on the order of one or two metal grains in thickness. No paint was detected in any of the crack voids.

Conclusions

Magnetic particle tests of welds produce reliable results after coating removal operations. No significant degradation in crack detectability was noted (all reference cracks detected by magnetic particle methods were also detected by visual tests).

Test results suggest that, compared to magnetic particle techniques, the liquid penetrant testing method is not reliable for detecting discontinuities after paint removal. It is suspected that this is primarily the result of a partial smearing of the weld surface metal across discontinuity openings.

In a further investigation, a test weld containing copper ferrite dilution cracking was liquid penetrant tested both before and after sandblasting. Before sandblasting, the cracks were readily detected. After sandblasting, crack detectability was significantly reduced. This suggests that surface preparation also contributes to smearing and again points to the advantages of magnetic particle test methods.

Magnetic Flux Leakage Testing of Wire Ropes[12]

Wire rope is an elongated steel product tested by the magnetic flux leakage technique. Such ropes are used in the construction, marine and oil production industries, in mining and elevator shafts and for overhead cables for personnel and raw material transportation. Testing is performed to detect general wall loss caused by wear and elongation and the breakage of internal strands. The type of flux loop used (electromagnet or permanent magnet) can depend on the accessibility of the rope. Permanent magnets might be used where taking power to an electromagnet might cause logistic or safety problems.

By making suitable estimates of the parameters involved, a reasonably good estimate of the flux in the rope can be made. Because discontinuities can occur deep inside the rope material, it is essential to maintain the rope at a high value of flux density 1.6 to 1.8 T (16 to 18 kG). Under these conditions, breaks in the inner regions of the rope will produce magnetic flux leakage at the surface of the rope.

The problem of detecting magnetic flux leakage from inner discontinuities is compounded by the need to maintain the probes far enough from the rope for splices in the rope to pass through the test head. Common probes include hall elements and encircling coils.

The cross sectional area of the rope can be measured by sensing changes in the flux loop that occur when the rope gets thinner. The air gap becomes larger and so the value of the field intensity falls. This change can easily be sensed by placing hall effect probes anywhere within the magnetic circuit.

The discussion above treats magnetic particle testing of structural steel welds, but magnetic testing finds other applications in the inspection of infrastructure. In particular, the wire rope in suspension bridges and other civil structures needs inspection when manufactured and periodically during its service life. Magnetic flux leakage is a preferred technique for this application and is discussed at length in the *Nondestructive Testing Handbook* volume on electromagnetic testing.[13]

PART 2. Aerospace Applications of Magnetic Particle Testing

Magnetic particle testing is used in the aerospace industry for the detection of both manufacturing and inservice discontinuities. This method of nondestructive testing is important in maintaining safe aircraft, engines and components.

Technique and Processes

The techniques of magnetic particle testing in aerospace are much like those in other industries in the general application of the process. However, there is notable emphasis to certain process variables.

Fluorescent particles are the major particles used because of their increased sensitivity in detecting surface defects. The particles are applied primarily by the continuous method for increased sensitivity because of higher flux leakage during magnetization. The residual application technique is used but usually to verify indication. Alternating current is the primary magnetizing force because the skin effect increases the magnetic force induced at the part surface.

Stationary, mobile and portable equipment are applied. To prevent burn marks or arcing damage to surfaces, prods are not used on aerospace products.

Application

Magnetic particle testing of ferrous parts is critical to maintain a safe aerospace product. Aircraft and engine parts are inspected to determine the serviceability of the part for continuity airworthiness of the component. Examples of parts inspected are aircraft wheel bolt and brake key parts, aircraft brake components, engine internal parts, engine mounting parts, landing gear applications and hydraulic component applications.

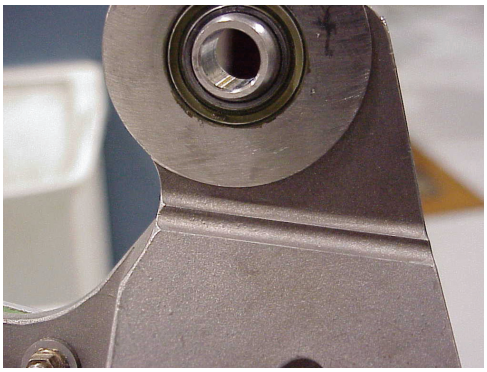
Although inservice inspections are important, it is necessary to understand why a crack developed. Some reasons can be attributed to structure overload, corrosion, fatigue life or manufacturing. The first three are not difficult to understand. However, a manufacturing induced discontinuity is related to a manufacturing operation. Undetected during manufacture, the discontinuity later contributes to or causes an inservice discontinuity.

An example of a manufacture induced cause is the cracking developed in steel mounting brackets. Figure 6a shows an inservice mounting bracket with proper machining. A machine operation was performed on the cast bracket to smooth out the area around the mounting bore. In some cases, the operation cuts into a section of reinforcing cast metal. Figure 6b shows an inservice mounting bracket with improper machining. The added loss of material in this area caused a stress riser. During operation of the component, cracks developed. Magnetic particle testing was used to detect the cracking (Fig. 7).

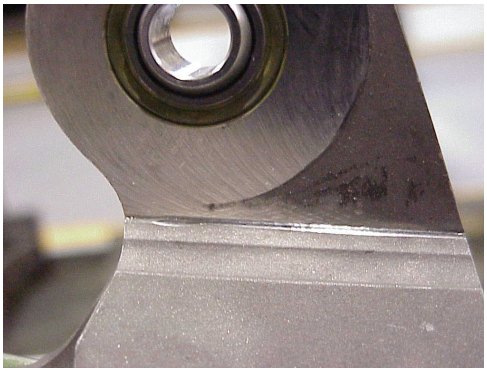
It is important that the inspectors involved in the manufacturing and

FIGURE 6. Machined mounting brackets: (a) satisfactory machining; (b) excess machining and weakening of mount (bevel is nearly flush with neck).

(a)



(b)



inservice stages understand the consequences of machining operations. Inspectors at the manufacturing stage can catch and identify potential issues that could affect use of the part. The inservice inspectors must understand the process used to create parts, the discontinuities that can result and how during service these parts might fail.

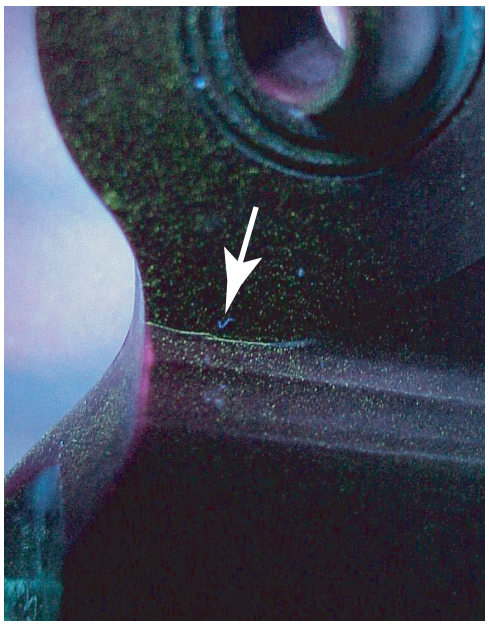
Regulatory Requirements

Regulatory requirements are an everyday part of the aerospace industry. Personnel performing magnetic particle testing on aerospace equipment must be trained, qualified and certified to do the testing. Inspection personnel should ensure that equipment, materials and processes are according to approved procedures. It is the inspector's responsibility to ensure that he or she is performing the testing within the guidelines of the regulatory authorities. Dozens of standards have been published, and only a few examples are referenced here, their topics ranging from personnel qualification[14,15] to discontinuity evaluation[16] and particle baths.[17] The published standards followed for each component should be specified in the contract.

Procedure Requirements

Procedures are required to perform magnetic particle tests. Most but not all test requirements are contained in the manuals for the product. In some cases, the procedure must be written. There are minimum information requirements for procedures. Procedures should at least include information on the following: (1) procedure number and date written, (2) part identification including material and alloy, (3) sequence of magnetic particle test, (4) identification of reference standards for system performance verification, (5) areas of the part to be examined, (6) part preparation, (7) positioning of the part with respect to magnetizing equipment, (8) type of magnetizing current and equipment, (9) current level or the number of ampere turns and the duration of current, (10) type of magnetic particle material to be used and the method and equipment for its application, (11) directions of magnetization, (12) acceptance requirements, (13) demagnetization and post cleaning instructions, (14) rust prevention treatments and (15) documentation, recordkeeping and means of marking parts after testing. Procedures should be carefully developed, written and verified by Level III personnel certified in magnetic particle testing.

FIGURE 7. Fluorescent magnetic particle indication of stress crack in mounting bracket at machined interface.



Process Controls and Human Reliability

While magnetic particle testing is valuable for the detection of cracks, it is only as good as the process controls used. When a process is used incorrectly, the result is a degradation of the inspection and the possible release of nonairworthy parts. There are several industrial documents that provide guidelines for process control. Processes should be controlled and monitored constantly. Documentation of the monitoring process is important to provide objective evidence that the process was under control during an inspection.

Although process control is normally thought to deal with the equipment and the materials used for the inspection, an important part of process control is the inspector. Inspectors should be trained, qualified and certified to do the magnetic particle testing. Human reliability factors must also be taken into consideration. Human reliability factors can be viewed as internal and external. Internal factors deal with the inspector's mental and physical state. An inspector who has worked a full 12 h shift can experience fatigue. The fatigue can lead the inspector to not apply the degree of focus and attention to detail needed to perform an inspection. An external factor can be an inspector working in an extremely hot environment or in an awkward position. Both factors will by human nature affect the ability of the inspector to remain focused on the inspection. Management and inspectors

must be aware of the human reliability factors and take measures to minimize their impact on inspection results.

Magnetic Particle Tests of Maintenance Induced Cracking[18]

Grinding Cracks

There are many operations designed or intended to repair material discontinuities in manufactured components. Magnetic particle tests often reveal the need for such operations by providing visible indications of the discontinuities. Because repair procedures typically introduce thermal or mechanical stresses, attempts to restore a component or remove discontinuities can often create new problems.

Grinding is an operation used to remove surface or near surface discontinuities or to provide a specified surface finish. Grinding operations can also produce thermal cracks from localized overheating. These cracks are typically perpendicular to the grinding direction. Figure 8 shows the grinding cracks present in a section removed from a steel landing gear. Also visible in the figure are the legs of an electromagnetic yoke used to magnetize the component for magnetic particle tests. Figure 9 shows grinding cracks around the flanges of two steel fittings.

Figure 10 shows cracks in a twist drill bit caused by straightening the bit with a peening hammer. Figure 11 shows cracks in a steel test fixture caused by using a rivet gun to loosen fasteners.

These illustrations represent an important application of magnetic particle testing. The technique may be used to locate discontinuities in an object, but it must also be used in retesting after operations intended to repair the original problem. Such retesting is especially important subsequent to control operations such as sharpening cutting wheels and straightening drill bits.

FIGURE 8. Fluorescent magnetic particle indications of cracks in section removed from steel landing gear component.

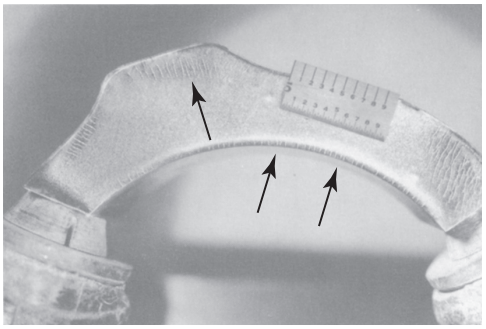
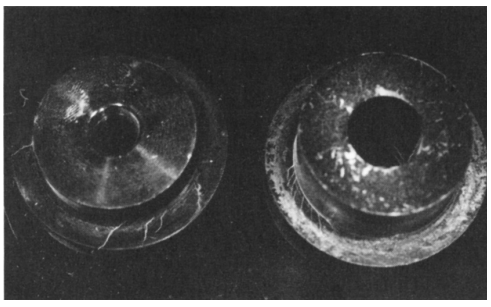


FIGURE 9. Fluorescent magnetic particle indications of grinding cracks.



Repair of Hydroplane Blades

Unlimited class hydroplanes use aircraft engines developing 3000 or more horsepower and may reach speeds over $90\,m{\cdot}s^{-1}$ ($200\ mi{\cdot}h^{-1}$). Highly stressed components that require magnetic particle tests include propellers, propeller

FIGURE 10. Fluorescent magnetic particle indications of cracks caused by straightening of drill bit with peening hammer.

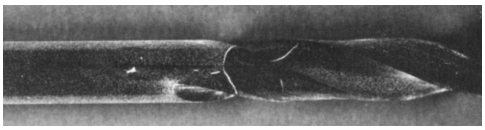
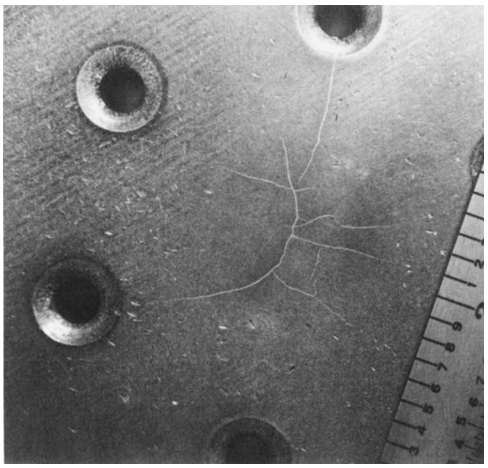


FIGURE 11. Fluorescent magnetic particle indications of cracks caused by using a rivet gun to loosen fasteners from steel fixture.



shafts, gears and turbocharger components.

Hydroplane propellers rotate more than 10 000 times per minute. In service, such rotation rates alone can cause stress cracking. In addition, under racing conditions, propellers can leave and return to the water very quickly. This causes rapid and dramatic changes in the density of the blades' operating medium, which in turn produces sudden flexing and very high stresses.

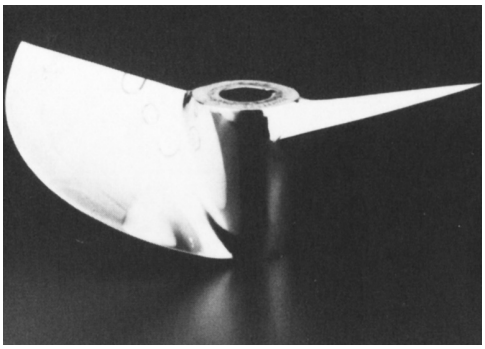
A propeller blade is originally shaped for thrust by machining, grinding and polishing. For purposes of operating efficiency, the blade tip is very thin, sometimes tapering to a sharp edge that serves as a stress riser during use.

After magnetic particle or visual tests locate damaged areas, propeller blades are often repair welded. This may initiate new problems in the heat affected zone and can introduce any of the discontinuities associated with welding procedures. Retesting after weld repair is a critical magnetic particle application.

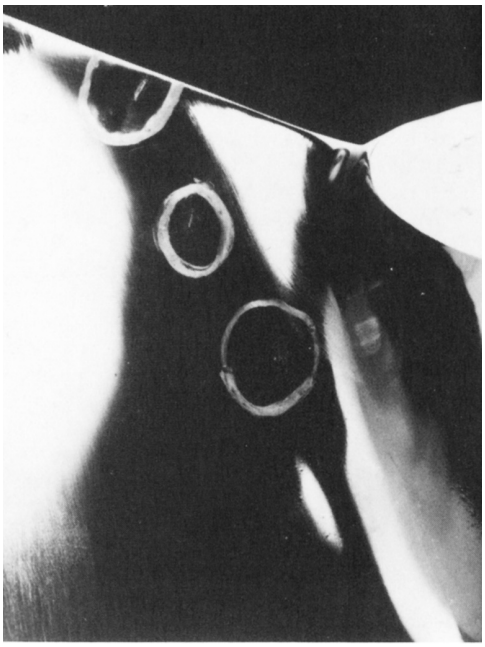
Figure 12 shows three magnetic particle indications of cracks in a propeller blade. These cracks were found using coil magnetization and a fluorescent magnetic particle water suspension.

FIGURE 12. Magnetic particle indications of cracks in racing hydroplane propeller blade: (a) photograph of blade; (b) close-up with indications circled in grease pencil.

(a)



(b)



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CHAPTER

Magnetic Testing Glossary

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PART 1. Terms

Introduction

Purpose

Standards writing bodies take great pains to ensure that their standards are definitive in wording and technical accuracy. People working to written contracts or procedures should consult definitions referenced in standards when appropriate. For example, persons who work in accordance with standards published by ASTM International are required to refer to definitions in the *ASTM Book of Standards*.[1]

The definitions in this *Nondestructive Testing Handbook* volume should not be referenced for tests performed according to standards or specifications or in fulfillment of contracts. This glossary is provided for instructional purposes. No other use is intended.

On References

Many definitions in this glossary are adapted from other volumes of the *Nondestructive Testing Handbook* series. Many definitions from the second edition's *Magnetic Particle Testing* (1989)[2] are reprinted but not referenced below. Definitions from three volumes of the third edition are referenced.[3-5]

Some terms apply generally to nondestructive testing and are not specific to magnetic techniques — terms on subjects such as metallurgy, quality control and personnel qualification. Most of these definitions come from the second edition volume *Nondestructive Testing Overview* (1996),[6] and some are rephrased in the most recent volume, the third edition's *Ultrasonic Testing* (2007).[4]

All definitions in this glossary have been modified to satisfy peer review and editorial style. For these reasons, references in this glossary should be considered not attributions but rather acknowledgments and suggestions for further reading.

Definitions

A

acceptance criterion: Benchmark against which test results are to be compared for purposes of establishing the functional acceptability of a part or system being examined.[4]

acceptance level: Measured value or values above or below which test objects are acceptable in contrast to *rejection level*.[4]

acceptance limit: Test signal value used in electromagnetic testing, establishing the group to which a material under test belongs.[4]

acceptance standard: (1) Specimen, similar to the product to be tested, containing natural or artificial discontinuities that are well defined and similar in size or extent to the maximum acceptable in the product.[4] (2) Document defining acceptable discontinuity size limits.[5] See also *standard*.

accommodation: Of the eye, adjustment of the lens' focusing power by changing the thickness and curvature of the lens through the movement of tiny muscles.[3]

ACGIH: American Conference of Governmental Industrial Hygienists.

agglomeration: Clustering where smaller particles collide and adhere as groups.

alternating current: Electric waveform that changes cyclically in magnitude and direction.[7]

alternating current magnetization: Inducing of a magnetic state by a cyclically reversing waveform, a state generally characterized by its form following ability and by shallow penetration.

ampere (A): SI unit of electric current.[4]

ampere per meter ($A \cdot m^{-1}$): SI derived unit of magnetic field intensity. The measurement 1 $A \cdot m^{-1}$, for example, describes a current of 1 A flowing through a coil of 1 m diameter.[4]

ampere turn: Unit for expressing the magnetomotive force required for magnetization using a coil in terms of the product of the number of coil turns and the current in amperes flowing through the coil.

angstrom (Å): Disused unit of length. 1 Å = 0.1 nm.

anomaly: In nondestructive testing, an unintentional or undesired material condition that may qualify as a defect. Compare *defect; discontinuity*. Some anomalies, such as inadequate case hardening or rough surface finish, may be defects but, because there is no interruption in the material structure, are not discontinuities.

apposing field: See *bucking field*.

arc: Current flow across a gap, producing intense heat and light.

arc strikes: Localized heat damage to an object sometimes caused by poor arc weld initiation technique or by poor coupling between a test object and contact pads or prods.

arc welding: See *electric arc welding*.

articulated pole pieces: Independently adjustable legs of an electromagnetic yoke enabling satisfactory contact on irregular test object profiles.

ASNT: American Society for Nondestructive Testing.

***ASNT Recommended Practice No.-SNT-TC-1A*:** See *Recommended Practice No. SNT-TC-1A*.

automated system: Acting mechanism that performs required tasks at a determined time and in a fixed sequence in response to certain conditions.[4]

axial: Of or pertaining to a direction along the length of an oblong object and perpendicular to its radius — for example, down the length of a cylinder. Compare *radial; tangential*.

B

background: (1) In magnetic particle testing, the appearance or brightness of the surrounding area acting to reduce the contrast of an indication. (2) Nonrelevant signal that tends to interfere with the normal reception or interpretation of the target being sought.

bath: Combination of well agitated water based or oil based carrier fluid with a controlled concentration of suspended magnetic particles.

bearding: See *furring*.

berthold penetrameter: Shared flux indicator of magnetic field orientation, for use during continuous magnetization. Similar to a pie gage but containing an cover plate with height adjustable to vary the magnetic flux density required to form an indication. See also *shared flux indicator*.

black light: Disfavored term for *ultraviolet radiation*. The term is misleading because the phenomenon is not black and is not light and has also been applied to the lamp.

blind spot: Portion of the retina where the optic nerve enters the eye and no photoreceptors (rods and cones) are present.

blister: Discontinuity in metal, on or near the surface, resulting from the expansion of gas in a subsurface zone. Very small blisters are called *pinheads* or *pepper blisters*.[4]

blowhole: Hole in a casting or a weld caused by gas entrapped during solidification.[4]

blue light hazard: Danger posed to the eye due to long term exposure to high intensity visible light.

borescope: Industrial endoscope; electronic and/or optical device that allows the inspector to view normally inaccessible interior surfaces.

borescope, fiber optic: Industrial endoscope, or fiber optic borescope, that uses glass or quartz fibers to transmit light and the optical path to and from the test object.

bucking field: Magnetic flow technique configuration where poles of like polarity are induced on the ends of a test object to force magnetization into extremities that are normally field free.

butt weld: Weld that joins the edges of work pieces in the same plane.

C

calibration: (1) Determination of the correlation between a known input value and an output value from a measurement device. (2) Act of returning an instrument to the condition of the original equipment manufacturer.

candela (cd): Base SI unit of luminous intensity, in a given direction, of a monochromatic radiation source that has a frequency of 5.4×10^{14} Hz and that has a radiant intensity in that direction of 1.464 $mW \cdot sr^{-1}$.

capacitor discharge technique: Magnetization technique generally characterized by a short duration, high intensity electrical pulse, often performed on oil field components.

carrier fluid: Water based or oil based component of the bath, the agitation of which holds magnetic particles in suspension.

central conductor: See *internal conductor*.

centrifuge tube: Vial that holds liquids and has graduations to indicate the concentration of solids that settle out of a known suspension volume.

certification: With respect to nondestructive test personnel, the process of providing written testimony that an individual has met the requirements of a specific practice or standard. See also *certified* and *qualified*.[5]

certified: With respect to nondestructive test personnel, having written testimony of qualification. See also *certification* and *qualification*.[5]

CGS system: Obsolete measurement system based on the centimeter, gram and second. Compare *SI*.

checks: See *grinding crack*.

circular magnetic field: Active or residual magnetization oriented along the circumference. See also *circular magnetization*, *current flow technique* and *right hand rule*.

circular magnetization: Result of current flow or internal conductor techniques where flux lines are oriented along the circumference of the test object.

circumferential magnetization: See *circular magnetization*.

coercive force: Reverse external magnetic field intensity required to reduce the test object's bulk magnetism to zero.

coercivity: See *coercive force*.

code: Standard enacted or enforced as a law.[3]

coil technique: Magnetization technique using an encircling current carrying solenoid that imparts a longitudinal magnetic field in ferromagnetic components with a length-to-diameter ratio greater than 3. See also $L \cdot D^{-1}$ *ratio* and *self-demagnetizing factor*.

coil shot: See *coil technique*. One instance of the coil technique; one pulse of current in the coil technique.

color: Visual sensation by means of which humans distinguish light of differing hue (predominant wavelengths), saturation (degree to which those radiations predominate over others) and lightness.[3]

color blindness: Deficiency in ability to perceive or distinguish hues.[3]

conditioning agent: Additive to water based carrier fluid aiding with defoaming, surface wetting, particle dispersion, pH or corrosivity, or antifungal properties.

conductance (*G*): Transmission of electric current through material. Measured in siemens (S). Inversely related to electrical *resistance* (*R*):[4]

$$\textbf{(1)} \qquad G = \frac{1}{R}$$

conductivity (σ): Ability of material to transmit electric current, measured in siemens per meter. Reciprocal or inverse of *resistivity* ρ:[4]

$$\textbf{(2)} \qquad \sigma = \frac{1}{\rho}$$

cone cells: Common name for three color sensitive photoreceptors concentrated at the inner region of the retina. Cones assist with mesopic vision and are responsible for photopic vision. Compare *rod cells*.

confidence level: Level of assurance for detecting a specified discontinuity size with a specified probability.[3] See also *probability of detection*.

contact technique: See *current flow technique*.

contact pad: Replaceable metal pad, usually made of braided copper and/or lead, that prevents electrical arcing between the headstock and test object during a head shot.

continuous technique: Technique of magnetic particle testing, a test sequence where the particles flow over the test object only during active magnetization.

contour probe: In magnetic particle testing, yoke with legs adjustable for test objects of various shapes.

contrast: Difference in color or brightness between indication and background.

cosine law: Physical law stating that the illumination of a surface varies as the cosine of the incidence angle. Maximum illumination is obtained when the source is perpendicular to the surface.

coupling: Percentage of magnetic flux from a primary circuit that links a secondary circuit; effectiveness of a coil in inducing eddy currents in the test object.[4]

crack: (1) Break, fissure or rupture, sometimes V shaped in cross section and relatively narrow. By convention, a discontinuity is called a *crack* if it is at least three times longer than it is wide. (2) Propagating discontinuity caused by fatigue, corrosion or stresses such as heat treating or grinding. May be difficult to detect unaided because of fineness of line and pattern (may have a radial or latticed appearance).[5,6]

curie point (T_c): Temperature at which a phase transformation causes ferromagnetic materials to lose their magnetic properties.

current flow technique: Circular magnetization of a test object within a short period of time by passing electric power through the test object with prods, or the headstock and tailstock of a stationary unit. See also *circular magnetization* and *right hand rule*. Compare *magnetic flow technique*.

current induction technique: See *toroidal magnetization*.

cycle: Single period of a waveform or other variable.[4]

D

dark adaptation: Time required for the pupils to dilate and for the two types of photoreceptors in the retina to change chemical balance. After a finite amount of time, an inspector will transition from photopic vision to mesopic or scotopic low illumination vision.

defect: Discontinuity whose size, shape, orientation or location (1) makes it detrimental to the useful service of its host object or (2) exceeds an accept/reject criterion of an applicable specification. Some discontinuities do not exceed an accept/reject criterion and are therefore not defects. Compare *crack; discontinuity; indication*.[5,6]

demagnetization: Reduction of residual magnetism to an acceptable level, generally less than 0.2 to 1.0 mT (2 to 10 G). See also *demagnetizing coil* and *direct current downcycle demagnetization*.

demagnetizing coil: Solenoid or coil carrying the current to be used for demagnetization. Current waveform may be alternating for pass-through solenoids, or a rectified current when a multiple-step downcycle demagnetization process is used. Some residual magnetization may remain in large parts magnetized with direct current or rectified current, but subsequently demagnetized with alternating current. See also *direct current downcycle demagnetization*.

demagnetizing factor: See *self-demagnetizing factor*.

density: Mass per unit volume, measured in kilograms per cubic meter ($kg \cdot m^{-3}$).

depth of penetration: See *skin effect*.

diamagnetic material: Substance with a magnetic permeability less than 1 that weakly repels an external magnetic field.

diffuse indication: Particle cluster not clearly defined — for example, indication from a subsurface discontinuity.

direct current: Electricity that flows continuously in one direction through a conductor. The only true source of direct current is a battery, although some rectified power waveforms may resemble direct current. See also *full-wave current* and *half-wave current*.

direct current downcycle demagnetization: Massaging the magnetism of a component down to an acceptable level through a 25-step to 30-step process, where the persistence of one polarity is overcome in decreasing steps by a field reversing at each step.

discontinuity: Interruption in the physical structure or configuration of a test object. After nondestructive testing, a discontinuity indication can be interpreted to be a *flaw* or a *defect*.[10] Compare *defect*; *indication*.[5,6]

discontinuity, artificial: Reference discontinuity such as hole, indentation, crack, groove, or notch introduced into a reference standard to provide accurately reproducible indications for determining sensitivity levels.[4]

domain: Macroscopic dipole substructure within a ferromagnetic material permanently magnetically saturated. Domains are randomly oriented in a demagnetized material, but their orientation may be preferentially rotated through the application of an external field.

downcycle: See *direct current downcycle demagnetization*.

dry powder: Ferromagnetic particles, larger than those used in wet suspensions, introduced to the test object surface by dusting or puffing.

dry technique: Magnetic particle test technique, generally used with portable equipment, where the ferromagnetic particles are applied as powder.

dual-use particle: Magnetic particle coated with pigment that provides contrast when viewed under controlled levels of ambient white light but that also fluoresces under ultraviolet radiation. Testing with fluorescent particles is performed under low ambient lighting and controlled ultraviolet radiation. Compare *dual-use particle*; *visible particle*.

E

eddy current: Electrical current induced in a conductor by a time varying magnetic field.[4]

electric arc welding: Joining of metals by heating with electric arc. Also called *arc welding*.[3]

electromagnet: Ferromagnetic core surrounded by a coil of wire that temporarily becomes a magnet when an electric current flows through the wire.[4]

encircling coil: See *coil technique*.

endoscope: See *borescope*.

equivalent 20/20 near vision acuity: Vision acuity with remote viewing or other nondirect viewing that approximates 20/20 direct viewing closely enough to be considered the same for visual testing purposes.[3]

equivalent sphere illumination: Level of perfectly diffuse (spherical) illuminance that makes the visual task as photometrically visible within a comparison test sphere as it is in the real lighting environment.[3]

evaluation: Process of deciding the severity of a condition after an indication has been interpreted. Evaluation determines if the test object should be rejected or accepted. See also *indication* and *interpretation*.[5]

eye sensitivity curve: See *photopic vision*.

F

false indication: Test indication that could be interpreted as originating from a discontinuity but that actually originates where no discontinuity exists in the test object. Distinct from a *nonrelevant indication*. Compare also *defect*.[4]

farsightedness: Vision acuity functionally adequate for viewing objects at a distance, generally at or farther than an arm's length. Also called hyperopia.[3] Compare *nearsightedness*.

ferromagnetic material: Material such as iron, nickel or cobalt whose relative permeability is considerably greater than unity, depends on the magnetizing force and often exhibits hysteresis. Materials that are most strongly affected by magnetism are called *ferromagnetic*.[4]

field flow technique: See *magnetic flow technique*.

fill factor: Convenient quantity for characterizing how closely the outside diameter of a specimen matches the inside diameter of the magnetizing coil. With a high fill factor, the ratio of the cross sectional area of the coil divided by the cross sectional area of the specimen is less than 2; intermediate, 2 to 10; low, greater than 10.

fillet weld: Weld that joins the edges of workpieces at right angles.

flash magnetization: See *capacitor discharge technique*.

flash point: Lowest temperature at which a substance will form an ignitable mixture in air. The value varies with circumstances.

flaw: Rejectable or unintentional anomaly.[4] See also *defect* and *discontinuity*.[4]

fluorescence: Luminescent phenomenon exhibited by some substances where higher energy electromagnetic waves are absorbed and reemitted as lower energy waves. The emission ceases as soon as the exciting energy is removed. Different from phosphorescence, which will continue to emit after the exciting energy is removed. In magnetic particle testing, pigments coating the magnetic particles are excited by invisible UV-A radiation and emit visible light.

fluorescent particle: Magnetic particle coated with pigment that fluoresces when excited with UV-A radiation. Testing with fluorescent particles is performed under low ambient lighting and controlled ultraviolet radiation. Compare *dual-use particle*; *visible particle*.

flux: Convenient concept for visualizing the vector field of magnetic induction that comprises a magnetic field. Flux lines form closed loops that do not cross. Magnetic flux is governed by the density of flux lines. The number of flux lines is expressed in weber (Wb), where 1 Wb = 10^8 maxwell (Mx). The density of flux lines is expressed in tesla (T), where 1 T = 10^4 gauss (G).

flux density: See *magnetic flux density*.

flux indicator: See *shared flux indicator*.

flux leakage field: Magnetic field that leaves or enters the surface of an object.[4]

flux leakage technique: Electromagnetic test technique for the detection and analysis of a surface discontinuity or near-surface discontinuity using the flux that leaves a magnetically saturated, or nearly saturated, test object at a discontinuity.[4]

flux meter: Device that measures total change in magnetic flux density by monitoring the voltage induced in a coil.[8] See also *tesla meter*.

footcandle (ftc): Non-SI unit of illuminance, where $1\,ftc = 1\,lm \cdot ft^{-2} = 10.76\,lx$.

footlambert (ftl): Non-SI unit of luminance, where 1 ftl = 3.426 $cd \cdot m^{-2}$.

fracture mechanics: Field of solid mechanics that deals with behavior of cracked bodies subjected to stress and strain.

frequency: Number of times per second that a cyclical waveform repeats. The unit of frequency is hertz (Hz).

full-wave current: Single-phase or three-phase alternating current converted to produce unidirectional current. Rectified current contains more amplitude variation, or ripple, than direct current from a battery.

furring: Buildup of dry magnetic particles at magnetic poles resulting from overmagnetization of the test object.

G

gas metal arc welding: Inert gas shielded metal joining process that uses a continuous and consumable wire electrode. Also called MIG (metal inert gas) welding. Compare *gas tungsten arc welding* and *shielded metal arc welding*.

gas tungsten arc welding: Inert gas shielded metal joining process that uses a nonconsumable tungsten electrode. Filler material, when needed, is manually fed into the molten weld puddle. Also called *tungsten inert gas welding*. Compare *gas metal arc welding; shielded metal arc welding*.

gauss (G): Old CGS unit of magnetic flux density denoting one flux line, or maxwell, passing through one square centimeter. The preferred unit of flux density is the tesla (T), where $1\,T = 10^4\,G$.

gauss meter: See *tesla meter*.

general examination: In personnel qualification, a test or examination of a person's knowledge, typically (in the case of nondestructive testing personnel qualification) a written test on the basic principles of a nondestructive test method and general knowledge of basic equipment used in the method. (According to ASNT's guidelines, the general examination should not address knowledge of specific equipment, codes, standards and procedures pertaining to a particular application.)[4]

glare: Excessive brightness (or brightness varying by more than 10:1 within the field of view) that interferes with observation or interpretation of a test response. Glare may be caused by reflection, whether specular (smooth surface) or diffuse (rough surface), of light or radiation sources.

grinding crack: Shallow crack formed in the surface of relatively hard materials because of excessive grinding heat or the high sensitivity of the material. Grinding cracks typically are oriented 90 degrees to the direction of grinding.[4]

H

half-wave current: Power waveform rectified from single-phase alternating current to produce a pulsating unidirectional field.

hall effect: Potential difference developed across a conductor at right angles to the direction of both the magnetic field and the electric current. Produced when current flows along a rectangular conductor subjected to a transverse magnetic field.[4]

hall effect detector: Semiconductor element that produces an output electromotive force proportional to the product of the magnetic field intensity and a biasing current.[4]

headstock: One of two points on a wet horizontal unit, often equipped with a pneumatic ram, which contacts and supports the test object during application of the current flow technique.

head shot: See *current flow technique*.

heat affected zone: Base metal that was not melted during brazing, cutting or welding but whose microstructure and physical properties were altered by the heat.[4]

heat treatment: Heating and cooling a metal or alloy in such a way as to obtain desired conditions or properties. Heating for the sole purpose of working is excluded from this definition.[3]

hertz (Hz): Measurement unit of frequency, equivalent to one cycle per second.[4]

horseshoe magnet: U shaped bar magnet. See also *keeper*.

human factors: Factors in the overall test sensitivity based upon mental and physical condition of the inspector, training, experience level and the physical conditions under which the inspector must work.

hyperopia: See *farsightedness*.

hysteresis: Lagging of a ferromagnetic test object's magnetization under the influence of a changing external magnetic field intensity; phenomenon exhibited by a magnetic system wherein its state is influenced by its previous history.[4]

hysteresis loop: Curve showing flux density *B* plotted as a function of magnetizing force *H* as *H* is increased to the saturation point in both negative and positive directions sequentially. The curve forms a characteristic loop.[4]

I

IACS: International Annealed Copper Standard.

illuminance: Intensity of radiant energy in the visible light spectrum. Illuminance is measured in footcandles or lux.

incremental permeability: Ratio of the change in magnetic induction to the corresponding change in magnetizing force.[4]

indication: Nondestructive test equipment response to a discontinuity that requires interpretation to determine its relevance.[4] In magnetic particle testing, a visible accumulation of magnetic particles that serves as evidence of a magnetic leakage field. See also *defect*, *discontinuity*, *false indication* and *nonrelevant indication*.

induced current magnetization: Noncontact means for testing delicate ring shaped objects for circumferential discontinuities. The technique is based on the fact that a time varying current passing through an internal conductor, often a soft iron or laminated core, self-induces an encircling magnetic field. This time varying magnetic field will induce a secondary current circling through the ring. This secondary current then self-induces the toroidal magnetic field used for testing. See also *right hand rule*.

inductance: Property of electric circuit, by which current in it or in a nearby circuit creates magnetic flux in the other circuit. Inductance is measured in henries, where one henry equals one weber per ampere (1 H = 1 $Wb \cdot A^{-1}$). See also *self-inductance*.

initial permeability: Slope of the induction curve at zero magnetizing force as a test object begins to be magnetized from a demagnetized condition (slope at the origin of the *BH* curve before hysteresis is observed).[4]

internal conductor: Rod of conductive material threaded through a hole in a cylindrical test object to induce circular magnetic flux. An internal conductor may be centered in the hole (a central conductor) or be offset near or touching one side of the cylinder's inside surface.

intergranular stress corrosion crack: Anomaly caused by intergranular corrosion as a result of sensitized material, stress and corrosive environment (typical in the heat affected zone of stainless steel welds).[4]

International Annealed Copper Standard (IACS): Conductivity measurement system in which the conductivity of annealed, unalloyed copper is arbitrarily rated at 100 percent and in which the conductivities of other materials are expressed as percentages of this standard.[4]

interpretation: Determination of the source, significance and relevance of test indications.[5,6]

inverse square law: Physical law for a point source of energy. The quantity or strength is inversely proportional to the square of the distance from the origin.

iris: Ring of variable area around the pupil and in front of the lens of the eye. The surface area of the iris adjusts spontaneously to change the amount of light entering the eye.[3]

irradiance: Radiant power falling upon a known surface area at a given angle. In nondestructive testing, the unit for irradiance of a UV-A source is microwatt per centimeter squared ($\mu W \cdot cm^{-2}$) and maximum irradiance occurs when the source and surface are perpendicular. See also *radiometer*.

J

jaeger eye chart: Eye chart used for near vision acuity examinations.[3]

K

keeper: Ferromagnetic material placed across the pole faces of a permanent horseshoe magnet to reduce the reluctance of the gap and to prevent loss of magnetism.

ketos ring: See *test ring*.

kinematic viscosity: Ratio of absolute viscosity divided by the liquid's density. Kinematic viscosity is often reported in centistokes.

L

$L \cdot D^{-1}$ ratio: Convenient means for expressing the shape of a test object in terms of length *L* divided by diameter *D*. In magnetic particle testing, ratio used to judge whether a test object is appropriate for coil magnetization or demagnetization alone or whether pole extensions or stacking is required. See also *self-demagnetizing factor*.

lambert cosine law: See *cosine law*.

laminated pole pieces: See *articulated pole pieces*.

leach: See *leech*.

leaked visible light: Unwanted electromagnetic radiation that has a wavelength between 400 and 800 nm that is generated by the UV-A source but not filtered out of the emission spectrum. Leaked visible light is generally perceived as purple or dark blue light and will not be accurately measured using a photometric sensor. See also *light contamination*, *photometer*, *radiometer*, *UV-A*, *UV-A filter* and *visible light*.

leakage field: See *flux leakage field*.

leech: Permanent magnetic or electromagnetic accessory used to ensure adequate electrical contact during current flow magnetization. Sometimes spelled *leach*.

lifting power: In magnetic particle testing, the mass of a ferromagnetic bar that a yoke can suspend through attraction. Often this mass is provided as a minimum that the yoke must meet or exceed.

light: Electromagnetic radiation that falls within the human eye's response range. See also *photopic vision*.

light contamination: Unwanted visible light present in darkened test area. Sources may include gaps in curtains, leaked visible light from the UV-A source or fluorescence from the inspector's clothing.

light meter: See *photometer*. Compare *radiometer*.

limited certification: Individuals certified only for specific operations; usually called *limited Level* (I, II *or* III) or designated as having *limited certification* because they are not qualified to perform the full range of activities expected of personnel at that level of qualification.[3]

lines of force: See *flux*.

longitudinal magnetic field: Active or residual magnetization oriented along the longest axis of the part. See also *longitudinal magnetization* and *magnetic flow technique*.

longitudinal magnetization: Result of magnetic flow technique where induced flux lines flow between the poles of an electromagnet or pair of permanent magnets.

lumen (lm): SI photometric unit of luminous flux, weighted according to the photopic vision response. One lumen equals the light emitted by one candela (cd) point source into one steradian (sr) solid angle ($1\,lm = 1\,cd \cdot sr^{-1}$).

luminance: Photometric brightness of a light source as defined by the density of its luminous intensity. Luminance is a measure of the luminous flux per unit solid angle per unit area in a given direction and is reported in candela per square meter ($cd \cdot m^{-2}$).

luminous intensity: Measure of a light source's power output per unit solid angle emitted or reflected from a point, when weighted by the photopic spectral luminous efficiency response curve. Luminous intensity is measured in candela. Compare *luminance*.

lux (lx): SI unit of illuminance, equal to one lumen per square meter ($1\,lx = 1\,lm \cdot m^{-2}$).

M

magnetic circuit: Path followed by flux lines that may include the test object, any air gaps and an electromagnetic or permanent magnet yoke.

magnetic field: Energy vector field surrounding a magnet or electric circuit.

magnetic field indicator: See *pocket field indicator*.

magnetic field intensity (*H*): Magnitude of the vector field surrounding a magnetic dipole,[9] in ampere per meter. Sometimes called *magnetic field strength*.

magnetic flow technique: Longitudinal magnetization technique where at least part of the test object completes a magnetic circuit. See also *longitudinal magnetization* and *yoke*.

magnetic flux: See *flux lines*.

magnetic flux density (*B*): Amount of magnetic induction passing perpendicularly through a given area, measured in tesla.

magnetic flux leakage testing: Nondestructive test technique where induced magnetism in a ferromagnetic sample forms localized poles at surface. Near-surface discontinuities are indicated by a signal in an induction coil or hall element; if they are indicated by magnetic particles, the technique is called *magnetic particle testing*.

magnetic gradient: Change in magnetic field intensity ($A \cdot m^{-2}$).

magnetic particle testing: Nondestructive test technique where induced magnetism in a ferromagnetic sample forms localized poles at surface and near-surface discontinuities indicated by a finely divided iron based powder. Compare *magnetic flux leakage testing*.

magnetic particles: Finely divided ferromagnetic powder of proper size, shape, relative permeability, visibility and retentivity for use in a test.

magnetic pole: One of two opposite ends of a dipole where flux enters or leaves a magnetized object. Any location where flux enters or leaves the test object.

magnetic rubber: Replica casting medium containing magnetic particles, which when cured and removed from a properly magnetized recess, provides a permanent mold with visible indications.

magnetic saturation: Result of complete domain alignment where an increase in the coercive field H produces no change in flux density B.

magnetic stripe card: In magnetic particle testing, a credit card sized device with encoded magnetic reversals of varying strength for regular evaluation of bath sensitivity. See also *particle concentration*. Compare *settling test*.

magnetic writing: Nonrelevant indication that may be caused when two magnetized objects come into contact.

magnetization: (1) Induced dipole moment per unit volume of a solid. (2) Act of inducing a magnetic field in a ferromagnetic object.

magnetizing force: Magnetomotive force per unit length of a magnetic circuit. Measured in ampere turns per meter ($At \cdot m^{-1}$).

magnetomotive force: Magnetic field intensity, measured in air or vacuum in ampere turns.

magnetometer: See *pocket field indicator*.

magnitude: Absolute value of a complex quantity (number) without reference to the phase of the quantity.[4]

material safety data sheet (MSDS): Document that contains information on safety and health in storage, handling, use, cleanup and disposal of substances. Manufacturers of testing materials are required to provide material safety data sheets to users in accordance with the *OSHA Hazard Communication Standard*.

Maxwell's equations: Fundamental equations of electromagnetic field theory:

$$\textbf{(3)} \quad \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\textbf{(4)} \quad \nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}$$

$$\textbf{(5)} \quad \nabla \cdot \boldsymbol{B} = 0$$

$$\textbf{(6)} \quad \nabla \cdot \boldsymbol{D} = \rho$$

where $\boldsymbol{B}$ is magnetic flux density, $\boldsymbol{D}$ is electric flux density, $\boldsymbol{E}$ is electric field intensity, $\boldsymbol{H}$ is magnetic field intensity, $\boldsymbol{J}$ is current density, t is time, ρ is volume charge density and ∇ is the del operator.[4]

mesopic vision: Intermediate state of dark adaptation where retinal cones and rods work together in semidark conditions. This state would be expected in typical fluorescent nondestructive evaluation applications. See also *photopic vision* and *scotopic vision*.

MIG welding: See *gas metal arc welding*.

model, analytical: Mathematical representation of a process or phenomenon.[4]

multidirectional magnetization: Two or more magnetic fields in different directions imposed on a test object sequentially and in rapid succession through phase control of the supplied current. See also *phase* and *swinging field magnetization*.

myopia: See *nearsightedness*.

N

NDE: (1) Nondestructive examination. (2) Nondestructive evaluation. See *nondestructive testing*.

NDI: Nondestructive inspection. See *nondestructive testing*.

NDT: See *nondestructive testing*.

nearsightedness: Vision acuity functionally adequate for viewing objects nearby, generally within an arm's length. Also called myopia.[3] Compare *farsightedness*.

near-surface discontinuity: Subsurface interruption in the physical structure or configuration of a test object that is close to, but not breaking, the test object's surface. (This sense of *near surface* differs from that in methods that distinguish a test object's near surface from its far surface, a distinction rarely made in magnetic particle testing.)

noise: Component of physical quantity, such as voltage, that provides nonrelevant information. Compare *signal*.

nondestructive testing (NDT): Determination of the physical condition of an object without affecting that object's ability to fulfill its intended function. Nondestructive test methods typically use an appropriate form of energy to determine material properties or to indicate the presence of material discontinuities (surface, internal or concealed).[5,6] Sometimes called *nondestructive evaluation, nondestructive examination* or *nondestructive inspection*.

nonferromagnetic material: Material not magnetizable and essentially not affected by magnetic fields.[4]

nonrelevant indication: Test response caused by sample geometry or by a physical condition that is not a discontinuity.

numerical analysis: Technique to generate numbers as the solution to a mathematical model of a physical system; used in place of a closed form analytic expression; usually requires digital computation.[4]

O

oersted (Oe): Obsolete CGS measurement unit of magnetizing force, or magnetic field intensity. Replaced in SI by ampere per meter, or ampere turns per meter: $1\,\text{Oe} = 79.57747\ \text{A}\cdot\text{m}^{-1}$.

ohm (Ω): Measurement unit of electrical resistance.[4]

oil country tubular goods (OCTGs): Hollow cylindrical components, such as pipes, used to convey petroleum and related products.[4]

P

parallel magnetization: Dubious practice of imparting circular magnetization in a sample near a current carrying conductor. Compare *internal conductor*.

paramagnetic material: In electromagnetic testing, a material that has a relative permeability slightly greater than unity and is practically independent of the magnetizing force.[4]

particle concentration: Amount of powder suspended within a known sample volume of bath. Typically measured using a settling test, or through evaporation and weighing. See also *centrifuge tube*.

percent International Annealed Copper Standard (%IACS): Traditional measurement of *conductivity* σ as a percentage of the conductivity of pure copper, arbitrarily rated at 100 percent.[4] In SI, conductivity is measured in siemens per meter ($\text{S}\cdot\text{m}^{-1}$). See also *conductivity; International Annealed Copper Standard*.

period: Absolute value of the minimum interval after which the same characteristics of a periodic waveform or a periodic feature repeat.[4]

permanent magnet: Material with high retentivity, which maintains magnetization after a coercive field has been removed. In magnetic particle testing, permanent magnet yokes must also have a high coercivity.

permeability (μ): (1) Ability of a material to be magnetized, measured as increase in flux density. (2) Ratio of magnetic induction *B* over magnetizing force *H*. Absolute permeability in SI units is measured in henries per meter ($\text{H}\cdot\text{m}^{-1}$). See also *relative permeability* and *permeability of free space*.

permeability of free space (μ_0): Calculation constant describing the ratio of magnetic induction *B* to magnetizing force *H* within a vacuum. $1\ \mu_0 = 4 \times 10^{-7}\ \text{H}\cdot\text{m}^{-1}$. See also *permeability* and *relative permeability*.

pH: A measure of the acidity or alkalinity of a solution. Negative of log *C*, where *C* is the concentration of hydrogen ions. Values lower than 7.0 are acidic; values equal to 7.0 are neutral; values higher than 7.0 are alkaline.

phase: (1) A circuit conductor carrying alternating current of a given frequency, as in one-phase or three-phase power. (2) Point on a 360-degree harmonic power waveform (thyristors, for example, vary total power output through phase control).

photochromic lens: Eyeglass material that automatically darkens to reduce light transmission when exposed to ultraviolet radiation.

photometer: Device used to measure illuminance. The sensor is filtered such that its response closely matches the spectral responsivity curve of the human eye. In nondestructive testing, photometers measure lux. Compare *radiometer*.

photometry: Study and measurement of electromagnetic radiation with wavelengths between 400 and 800 nm, within the human eye's spectral responsivity. See also *photometer* and *photopic vision*. Compare *radiometry*.

photopic vision: Average spectral responsivity curve of the human eye when adapted to well lit conditions (greater than 0.034 $cd \cdot m^{-2}$). The photopic spectral luminous efficiency response curve is governed by an averaged retinal cone response with sensitivity peaks centered at about 555 nm.

pie gage: One type of shared flux indicator in the form of a handle mounted disk comprised of ferromagnetic wedges surrounded by a copper matrix. When properly demagnetized before use the space between wedges provides artificial discontinuities at 0, 45 and 90 degrees and provides a measure of magnetic flux direction during dry powder testing.

pocket field indicator: Small, hand held device used to display the intensity of uniform external magnetic flux as angular deflection of a display needle. The device contains a permanent reference magnet coupled to a movable, field sensing magnet, and some units may be calibrated.

pole: See *magnetic pole*.

powder blower: Compressed air device used to deliver a cloud of dry magnetic particles to the surface of a test object.

powder bulb: Container compressed by hand to deliver a cloud of dry magnetic particles to the surface of a test object.

practical examination: In certification of nondestructive testing personnel, a hands-on examination using test equipment and sample test objects.[3] Compare *general examination* and *specific examination*.

probability of detection (PoD): Statistical analysis of a specific test procedure indicating how likely a given discontinuity length may be reliably found.

probe: See *transducer.*

prod magnetization: See *current flow technique*.

prods: Handheld electrodes for transmitting magnetizing current from a portable power source to the test object. See also *leech*.

pseudoisochromatic plates: Testing device used for color vision examinations. Each plate bears an image that would be difficult for the examinee to see if their color vision was impaired.[3]

pulse magnetization: See *capacitor discharge technique*.

pupil: Aperture in the center of an eye's iris, through which light focused by the lens passes.[3]

Q

qualification: Process of demonstrating that an individual has the required amount and the required type of training, experience, knowledge and abilities.[5,6] See also *certification* and *qualified*.

qualified: Having demonstrated the required amount and the required type of training, experience, knowledge and abilities.[5,6] See also *certified* and *qualification*.

quality: Ability of a process or product to meet specifications or to meet the expectations of its users in terms of efficiency, appearance, reliability and ergonomics.[5,6]

quality assurance: Administrative actions that specify, enforce and verify quality.[5,6]

quality control: Physical and administrative actions required to ensure compliance with a quality assurance program. Quality control may include nondestructive testing in the manufacturing cycle.[5,6]

quantitative quality indicator (QQI): Shim that has an artificial discontinuity and is held in intimate contact with a test object's surface during active magnetization to indicate that proper magnitude and direction of magnetic induction have been obtained for testing. The artificial discontinuity may be circular or linear and is defined in terms of percent of total shim thickness.

quick break: Sudden cessation of magnetizing current. A quick break is needed when using three-phase full-wave rectified alternating current during coil or induced current magnetization. The rapid change in current produces strong magnetic induction during toroidal magnetization and reduces the disturbing flux near poles for sensitive testing of the test object's ends in coil magnetization.

R

radial: Of or pertaining to direction from center of a sphere or cross section of a cylindrical object to its surface, and perpendicular to its axis. Compare *axial* and *tangential*.

radiometer: Device used to measure irradiance. In nondestructive testing, radiometers are used to measure UV-A output, or leaked visible light, in microwatt per square centimeter ($\mu W \cdot cm^{-2}$). See also *irradiance*. Compare *photometer*.

radiometry: Study and measurement of electromagnetic radiation emitted by a source or falling upon a surface.

recommended practice: Set of guidelines or recommendations.[4]

Recommended Practice No. SNT-TC-1A: Set of guidelines published by the American Society for Nondestructive Testing, for employers to establish and conduct a nondestructive testing personnel qualification and certification program.[4]

recommended practice: Set of guidelines or recommendations.[5,6]

Recommended Practice No. SNT-TC-1A: Set of guidelines published by the American Society for Nondestructive Testing, for employers to establish and conduct a qualification and certification program for nondestructive testing personnel.[5,6]

rectified alternating current: See *half-wave current* and *full-wave current*.

reference standard: (1) Test object containing known discontinuities representing accept or reject criteria. (2) Sample test object selected for reference.[5]

relative permeability (μ_r): Unitless ratio of a material's permeability to the permeability of free space.

relevant indication: In nondestructive testing, an indication from a discontinuity or condition and requiring evaluation.[5]

reluctance: Resistance of a material to changes in magnetization. Reciprocal of permeability.

rejection level: Value established for a test signal above or below which test objects are rejectable or otherwise distinguished from the remaining objects. This level is different from the *rejection level* as defined for ultrasonic and other test systems.[4]

remanent magnetism: See *residual magnetic field*.

residual magnetic field: Magnetization remaining in a ferromagnetic material after magnetizing force H is reduced to zero.

residual technique: Testing procedure used only with highly retentive materials where a remnant magnetic field is relied on to attract magnetic particles. Compare *continuous technique*.

resistance, electrical (R): Opposition to flow of electric current through material; ratio of voltage to current. Measured in ohms (Ω). Inversely related to *conductance:*

$$\textbf{(7)} \quad R = \frac{1}{G} = \frac{\rho L}{A}$$

where A is the conductor's cross sectional area (square meter), G is conductance (siemens), L is the length of the conductor (meter) and ρ is resistivity (ohm meter).[4]

resistivity (ρ): Ability of material to resist electric current. Measured in ohm meter (Ω·m), which is the resistance of a cube made of the material whose dimensions are 1 m on each side. Inversely related to *conductivity* σ (siemens per meter):[4]

$$\textbf{(8)} \quad \rho = \frac{1}{\sigma}$$

resolution: An aspect of image quality pertaining to a system's ability to reproduce objects, often measured by resolving a pair of adjacent objects or parallel lines.[6]

retentivity: Material's ability to maintain remnant magnetism in the absence of a coercive field.

retina: Rear portion of the eyeball, opposite the pupil, where light sensitive rods and cones are present.

right hand rule: Technique for visualizing the relationship between a flowing current and its induced magnetic field. When the right hand is closed in a fist with the thumb extended and when current flows out along the thumb, the fingers represent the self-induced magnetic field.

rise time: Amount of time for a current source to reach its set point.

rod cells: Low light photoreceptors concentrated toward the outer region of the retina. Rods assist with mesopic vision and are responsible for scotopic night vision. Compare *cone cells*.

root mean square (rms): Statistical measure of the magnitude of a varying quantity, such as current. Square root of the mean square of a set of measures, usually a time series.

S

saturation: See *magnetic saturation*.

scalar: Quantity completely specified by a single number and unit.[4]

scotopic vision: Average spectral responsivity curve of the human eye when adapted to very dark conditions (less than 3×10^{-5} cd·m^{-2}). Illumination levels for scotopic vision are below the sensitivity of retinal cones, so no color perception is possible.

self-demagnetizing factor: Estimate of the resistance of a test object to magnetization due to the proximity of magnetic poles of opposite polarity. For coil magnetization, the internal magnetization within a low $L{\cdot}D^{-1}$ ratio test object is opposite of the coil's magnetic field and a lower distance between poles results in a greater internal resistance.

self-inductance: Ratio of magnetic flux formed around a conductor to the amount of current passing through a straight or coiled conductor. Self-inductance is measured in henries, where one henry equals one weber per ampere (1 H = 1 Wb·A^{-1}). See also *inductance*.

sensitivity: See *probability of detection*.

sensor: Device that detects a material property or mechanical behavior (such as radiation or displacement) and converts it to an electrical signal. *Probe; transducer*.[5]

settling test: One procedure used to determine the concentration of magnetic particles in a new bath or to check for contamination or other bath problems. See also *centrifuge tube* and *particle concentration*. Compare *magnetic stripe card*.

shared flux indicator: Device held in intimate contact with test object during active magnetization to show the direction of magnetic induction. Examples include the berthold penetrameter, magnetic flux indicator strip and pie gage.

shielded metal arc welding: Metal joining process that uses a consumable flux coated electrode. The flux both covers the molten weld pool and forms the protective shielding gas. Also called stick welding. Compare *gas metal arc welding* and *tungsten metal arc welding*.

shim: Indicator of magnetic field orientation, consisting of thin foil of high permeability material having artificial notch discontinuities.

shot: In magnetic particle testing, the period of time when current is flowing through the test object. Shot duration and the number of shots required for testing may be varied. See also *current flow technique*.

SI (International System of Units): Measurement system in which the following seven units are basic: meter, mole, kilogram, second, ampere, kelvin and candela.[5,6]

siemens per meter (S·m^{-1}): SI unit of conductivity.

signal: Physical quantity, such as voltage, that contains relevant information.[4]

signal-to-noise ratio: Ratio of signal values (responses that contain relevant information) to baseline noise values (responses that contain nonrelevant information).[4]

silicon controlled rectifier: Solid state electronic component used to vary power output in an arcless manner. The power waveform from a silicon controlled rectifier will contain spikes and conversion between peak, root mean square and average is not straightforward across the output range.

skin depth: In electromagnetic testing, the depth at which the magnetic field intensity or intensity of induced eddy currents has decreased to 37 percent of its surface value. The square of the depth of penetration is inversely proportional to the frequency of the signal, the conductivity of the material and the permeability of the material.[4] See also *skin effect*.

skin effect: Term used to describe the penetration ability of cyclical current or magnetization as a function of frequency, conductivity and relative permeability. In magnetic particle testing, skin effect refers to alternating current's inability to penetrate deeper than 1 to 3 mm (0.04 to 0.12 in.) with typical testing variables.[10] See also *skin depth*.

slurry: See *bath*.

SNT-TC-1A: See *Recommended Practice No. SNT-TC-1A*.

specific examination: In certification of nondestructive testing personnel, a written examination that addresses the specifications and products pertinent to the application.[3] Compare *general examination* and *practical examination*.

specific gravity: Unitless ratio of the density of a material divided by the density of water. Water has a density of about 1 g·cm^{-3}, or 1000 kg·m^{-3}.

specification: Set of instructions or standards invoked to govern the results or performance of a specific set of tasks or products.[5,6]

spectral irradiance: Measure of energy emitted by a radiation source as function of wavelength. Units of spectral irradiance are in watts per meter squared and are often plotted versus wavelength.

spectral luminous efficiency: See *spectral responsivity*.

spectral responsivity: Measure of a photometric or radiometric sensor's sensitivity over a wavelength range of interest, often presented as percent versus wavelength. Photometric sensors should exhibit a bell shaped spectral responsivity curve over the visible light range, whereas radiometric sensors may exhibit a flat or other response curve.

standard: (1) Reference object used as a basis for comparison or calibration. (2) Concept established by authority, custom or agreement to serve as a model or rule in the measurement of quantity or the establishment of a practice or procedure.[5,11]

standard depth of penetration: See *skin depth*.

standardization, instrument: Adjustment of instrument readout before use to a specified reference value.[4]

stick welding: See *shielded metal arc welding*.

stress concentration: Region where force per unit area is elevated, often because of geometric factors or cracks. Also known as a *stress raiser.*

stringer: In wrought materials, an elongated configuration of microconstituents or foreign material aligned in the direction of working. Commonly, the term is associated with elongated oxide or sulfide inclusions in steel.[3]

subsurface discontinuity: Discontinuity not open to the surface. See also *near-surface discontinuity.*

susceptibility: Dimensionless property describing a material's response to an external magnetic field.

suspension: See *bath.*

suspension vehicle: See *carrier fluid*.

swinging field magnetization: One form of multidirectional magnetization where two time varying magnetic fields are combined such that the resultant vector magnetization rapidly rotates through an angle. See also *multidirectional magnetization.*

T

tangential: Of or pertaining to a direction impinging on a curved surface of an object and perpendicular to the radius at the point where it impinges. Compare *axial* and *radial*.

tesla (T): SI derived unit of measure for magnetic flux density. $1\,T = 1\,Wb \cdot m^{-2} = 10^4$ G.

tesla meter: Magnetometer used to measure active or residual magnetic induction in the location and direction of interest. See also *flux meter, hall effect*.

test object: Hollow, ring shaped specimen, typically made of 01 tool steel, containing artificial subsurface drilled through-hole discontinuities. The ring is used to compare the daily performance of a wet horizontal test unit or to evaluate the sensitivity of dry powders when magnetized using three-phase full-wave rectified current.

test object: Physical part or specimen subject to nondestructive testing.

threshold level: Setting of an instrument that causes it to register only those changes in response greater or less than a specified magnitude.[4]

thyristor: See *silicon controlled rectifier*.

TIG welding: See *gas tungsten arc welding*.

toroidal magnetization: See *induced current magnetization*.

transducer: Device by means of which energy can flow from one or more transmission systems or media to one or more other transmission systems or media; sensor or probe.[4]

tubing string: Pipe with which oil or gas has contact as it is brought to the earth's surface.[4]

U

ultraviolet radiation: Electromagnetic radiation with wavelengths between 100 and 400 nm. See also *irradiance* and *UV-A*. Fluorescent nondestructive testing uses UV-A and safe exposure limits for ultraviolet radiation and blue light hazard are available through the American Conference of Governmental Industrial Hygienists.

ultraviolet source: Term for the device providing excitation energy for fluorescent materials. See *UV-A radiation source*.

Unified Numbering System: Alphanumeric system for identifying alloys according to a registry maintained by ASTM International and SAE International.[4]

UV-A: Electromagnetic radiation with wavelengths between 315 and 400 nm. Fluorescent nondestructive testing has historically used ultraviolet energy centered at 365 nm. See also *irradiance* and *radiometer*.

UV-A filter: Device that is used to modify the emission spectrum from a radiation source to eliminate visible light and higher energy ultraviolet energy, while allowing the desired long wavelength ultraviolet radiation to pass through.

UV-A radiation source: Preferred term for the device providing excitation energy for fluorescent materials.

V

vector quantity: Any physical quantity whose specification involves both magnitude and direction and that obeys the parallelogram law of addition.[4]

viscosity: Measure of the resistance of liquid to deform under shear stress. See also *kinematic viscosity*.

visible light: Radiant energy with a wavelength between 400 and 800 nm as measured in photometric units of lux.

visible particle: Common term describing finely divided powder for use in nonfluorescent magnetic particle tests. The particles may be their natural color or may be coated to enhance contrast. Testing using visible particles is performed under a controlled level of ambient lighting and typically does not need any ultraviolet light.

vision acuity: Quantitative measure of the acuteness of vision.

visual efficiency: Reliability of a visual system. The term *visual efficiency* uses 20/20 near vision acuity as a baseline in the United States for 100 percent visual efficiency.[3]

visual field: Locus of objects or points in space that can be perceived when head and eyes are kept fixed. The field may be monocular or binocular.[3]

visual perception: Interpretation of impressions transmitted from the retina to the brain in terms of information about a physical world displayed before the eye. Visual perception involves any one or more of the following: recognition of the presence of something (object, aperture or medium); identifying it; locating it in space; noting its relation to other things; identifying its movement, color, brightness or form.[3]

visual performance: Quantitative assessment of the performance of a visual test, taking into consideration speed and accuracy.[3]

visual task: Appearance and immediate background of those details and objects that must be seen for the performance of a given activity. The term *visual task* is a misnomer because it refers to the visual display itself and not the task of extracting information from it.[3]

volt (V): Measurement unit of electric potential.[4]

W

water, break free: Rinse water, having the ability to cover an entire surface in an unbroken film.[3]

wavelength: Distance between repeating units of a wave. For example, the distance from one peak to the next peak.

wet horizontal unit: Stationary equipment that provides a measured amount of electric current to a headstock and tailstock, allows bath application and may be equipped with a rigid multiple-turn magnetizing coil.

wet technique: Testing procedure in which the suspended magnetic particles are applied as a well agitated bath.

wetting action: Action of liquid in spontaneously spreading over and adhering to solid surfaces.[3]

white light: Light combining all frequencies in the visible spectrum and in equal proportions.[3]

working standard: Work piece or energy source calibrated and used in place of expensive reference standards. In calibrating of photometers, the standard would be a light source.[3]

Y

yoke: Portable U shaped electromagnet or permanent magnet that induces longitudinal magnetization in the region of the test object between its magnetic poles. See also *articulated pole pieces* and *magnetic flow technique*.

PART 2. Symbols

TABLE 1. Symbols and units used in electromagnetics.

Symbol	Property	SI Unit	SI Symbol
A	magnetic vector potential	weber per meter	$Wb \cdot m^{-1}$
A_x, A_y, A_z, A_R, A_r, A_θ, A_ϕ	components of vector		
At	(unit)	ampere turn	At
B	magnetic flux density	tesla	T
D	electric flux density	coulomb per square meter	$C \cdot m^{-2}$
$\boldsymbol{ds}$	differential area (vector)	square meter	m^2
$\boldsymbol{d\ell}$	differential length (vector)	meter	m
E	electric field intensity	volt per meter	$V \cdot m^{-1}$
F	force	newton	N
f	frequency	cycles per second	Hz
G	conductance	siemens	S
H	magnetic field intensity	ampere per meter	$A \cdot m^{-1}$
I	(electric) current	ampere	A
J	current density	ampere per square meter	$A \cdot m^{-2}$
J_s	surface current density	ampere per square meter	$A \cdot m^{-2}$
L	inductance	henry	H
ℓ	length, distance	meter	m
$\boldsymbol{M}$	magnetization	ampere per meter	$A \cdot m^{-1}$
$\boldsymbol{m}$	magnetic moment	ampere per meter	$A \cdot m^{-2}$
$\hat{\boldsymbol{n}}$	normal (component of vector)		
$\hat{\boldsymbol{n}}$, $\hat{\boldsymbol{Q}}$, $\hat{\boldsymbol{R}}$, $\hat{\boldsymbol{r}}$, $\hat{\boldsymbol{x}}$, $\hat{\boldsymbol{y}}$, $\hat{\boldsymbol{z}}$, $\hat{\boldsymbol{\theta}}$, $\hat{\boldsymbol{\phi}}$	unit vectors	meter	m
P	power	watt	W
P_d	dissipated power	watt	W
$\boldsymbol{P}$	poynting vector	watt per cubic meter	$W \cdot m^{-3}$
q	electric charge	coulomb	C
R	resistance	ohm	Ω
$\boldsymbol{R}$	position vector	meter	m
S	area	square meter	m^2
t	time	second	s
V	(electric) potential, voltage	volt	V
V_m	electromotive force	ampere turn	At
v	velocity, speed	meter per second	$m \cdot s^{-1}$
W	work	joule	J
w	energy density	joule per cubic meter	$J \cdot m^{-3}$
W_e	electric stored energy	joule	J
W_m	magnetic stored energy	joule	J
δ	skin depth	meter	m
ϵ, ϵ_0, ϵ_r	(electric) permittivity	farad per meter	$F \cdot m^{-1}$
Λ	flux linkage		
μ, μ_0, μ_r	(magnetic) permeability	henry per meter	$H \cdot m^{-1}$
ρ	resistivity	ohm meter	$\Omega \cdot m$
ρ	charge density	coulomb per square meter	$C \cdot m^{-2}$
ρ_s	surface charge density	coulomb per square meter	$C \cdot m^{-2}$
σ	conductivity	siemens per meter	$S \cdot m^{-1}$
τ	tangential component of vector		
X [chi]	magnetic susceptibility		
ω	angular frequency	radian per second	$rad \cdot s^{-1}$

Tables 1 and 2 list physical quantities for electromagnetics.

By convention, symbols for constants and variables from the Roman alphabet are printed in italic; vectors representing four-dimensional information are printed in bold.

For physical quantities and properties in materials science, the reader is served by reference books such as the *CRC Handbook of Chemistry and Physics*[12] and Leonard Mordfin's *Handbook of Reference Data for Nondestructive Testing*.[13]

Measurement units and their symbols are covered in the introduction to this volume.

TABLE 2. Physical constants for electromagnetism.

Symbol	Property	Value
ϵ_0	permittivity of free space	8.8542×10^{-12} F·m^{-1}
μ_0	permeability of free space	$4\pi \times 10^{-7}$ H·m^{-1}
e	charge on one electron	-1.602×10^{-19} C
c	speed of light (vacuum)	2.99792×10^{8} m·s^{-1}

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Chapter 4

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Figures 10, 11, 17-21 — Karl Deutsch + Company, GmbH, Wuppertal, Germany.

Chapter 5

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Figure 4 — Baker-Hughes Tubular Services, Houston, TX.
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Figures 12-13 — LDJ Electronics, Troy, MI.

Chapter 6

Figure 1 — Magnaflux Division of ITL, Glenview, IL.
Figure 2a — Parker Research Corporation, Clearwater, FL.

Chapter 8

Figure 5 — Academic Press, Burlington, MA.
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Chapter 9

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Chapter 12

Figures 1, 7, 8, 10, 30, 32, 33, 36 — Magnaflux Division of ITL, Glenview, IL.
Figures 2, 16, 21, 27 — ASM International, Materials Park, OH.
Figures 17-20 — The Welding Institute (formerly British Welding Institute), Abingdon, United Kingdom.
Figure 23 — American Welding Society, Miami, FL.

Chapter 15

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