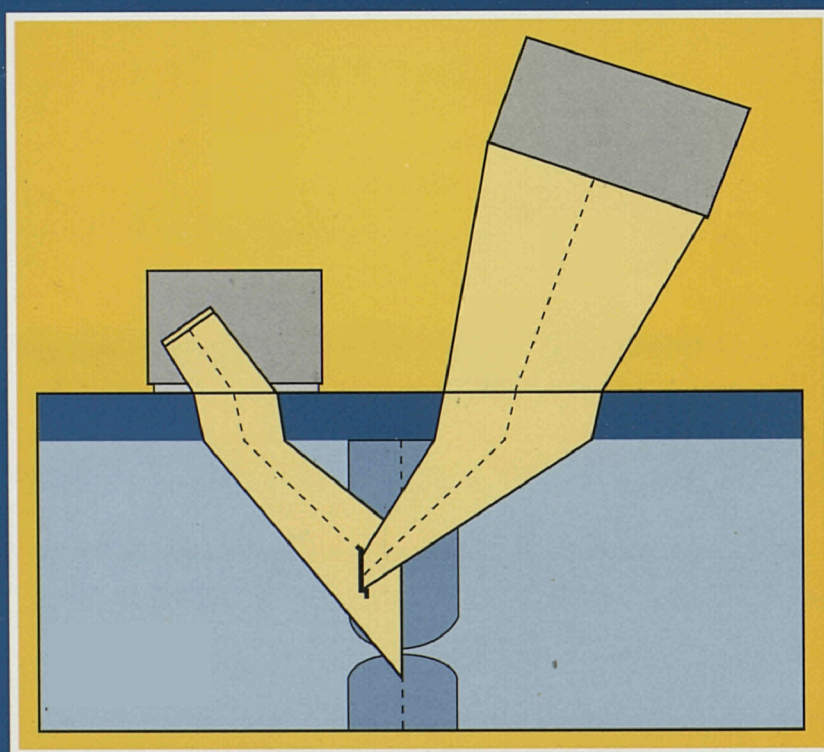

THE INTERNATIONAL INSTITUTE OF WELDING

HANDBOOK ON THE ULTRASONIC EXAMINATION OF AUSTENITIC CLAD STEEL COMPONENTS



1994



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HANDBOOK ON THE ULTRASONIC EXAMINATION OF AUSTENITIC CLAD STEEL COMPONENTS

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CONTENTS

List of working group members	4
Foreword	5
General remarks	5
1. INTRODUCTION	7
2. CLADDING PROCEDURES AND RESULTING METALLURGICAL STRUCTURES.....	8
2.1 Purpose of Cladding	8
2.2 Types of Cladding	8
2.3 Surface Finish and Repairs	11
2.4 Cladding Defects	12
3. INFLUENCE OF CLADDING ON PROPAGATION OF ULTRASONIC WAVES.....	14
3.1 Introductory remarks.....	14
3.2 The Physics of Wave Propagation in Cladding Due to Its Macrostructure	14
3.3 Practical Implications	21
4. GUIDELINES FOR THE INSPECTION PROCEDURE.....	29
4.1 General Remarks	29
4.2 Information on the Cladding Required Prior to Establishing the Inspection Procedure	29
4.3 Overview of Inspection Techniques.....	30
4.4 Equipment	33
4.5 Calibration Blocks	36
4.6 Methods for Calibration	37
4.7 Recording Level and Desirable Signal-to-Noise Ratio	38
4.8 Reporting and Evaluation	38
4.9 Performance Demonstration	40
5. RECOMMENDATIONS AND CONCLUSIONS.....	41
6. GLOSSARY OF TERMS	42
APPENDICES.....	45
A1 Standards and Specifications	47
A2 Effect of Cladding Macrostructure on Ultrasound	48
A3 Reflection and Refraction	54
A4 Angled EMUS-SH-wave Probes	60

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* TRIBUTE TO WIM VAN LEEUWEN

During the course of the preparation of this handbook Wim van Leeuwen died. Wim made a large contribution to the handbook since he had a strong technical grasp of the subject and a gift for languages. Wim was also a good friend to all of us and his departure from this world filled us with sadness.

Editing work was provided in the framework of the PISC-III Programme Action 8 "Support to Code and Standard Organisations" sponsored by CEC, JRC and OECD, NEA. (PISC = Programme for the Inspection of Steel Components)

The working group wishes to acknowledge valuable contributions by other members of the companies mentioned.

The Handbook represents the agreed view of the working group experts but has not necessarily been endorsed by the individual organisations represented.

For further background information on the subject of this handbook readers are referred to the existing IIW publications listed below:

- List of terms in ultrasonic testing, IIW 1967.
- Handbook on the ultrasonic examination of welds IIW 1977.
- Handbook on the ultrasonic examination of austenitic welds IIW 1986.

FOREWORD

This cladding handbook has been produced by the Working Group Ultrasonic Testing of Austenitic Welds of the IIW Sub-Commission VC Ultrasonics. The members of this group are engineers and scientists from a wide range of organisations who have responsibilities for implementing and improving ultrasonic techniques used by industry for testing materials. The cladding handbook follows on from a handbook on the ultrasonic examination of austenitic welds which was compiled by the same working group and published by the IIW in 1986. Existing codes and standards do not address the technical difficulties encountered when testing austenitic clad components or austenitic welded components. These handbooks contain recommendations and guidelines, but they are not intended to replace any existing codes and standards. Therefore the primary objective of both handbooks is to provide guidance and advice on how to prepare ultrasonic procedures for the inspection of austenitic clad materials and austenitic welds. The generic problems involved with both applications of ultrasonics are similar. A second objective of the handbook is to explain and apply acoustic theory in a way that can be understood by practitioners of ultrasonics, since this will lead to an improved standard of inspection for welded components.

General remarks

Austenitic cladding is often used to provide corrosion protection for important components which must be volumetrically inspected during manufacture, and possibly also inservice. The main practical implications of volumetrically testing austenitic clad components are:

- The rough surface of fusion welded cladding will have a detrimental effect on coupling the ultrasonic probe to the surface
- The physical properties of the cladding will result in:
 - restrictions on the range of beam angles which can be applied to the shear wave inspection of base material.
 - inaccuracies in locating and therefore sizing reflectors below cladding.
 - high levels of noise, compared to those encountered when testing ferritic components, which arise from the scatter of ultrasound in the cladding, or at the clad/base metal interface.
 - the attenuation of ultrasound as a function of frequency by passage through cladding can be significantly higher than that which would be expected for unclad components.
 - the possibility that unexpected beam directions will be generated by the passage of shear waves through cladding.

The degree to which the above effects occur depends on how the cladding was deposited. Austenitic cladding will not prevent a component from being volumetrically examined, but it will impose limitations which must be understood by ultrasonic practitioners.

1. INTRODUCTION

Austenitic cladding is commonly applied to ferritic base materials for corrosion protection. The fitness for service of the component depends on the quality, integrity, and thickness of the cladding. The cladding structure strongly influences ultrasonic examination of the cladding itself as well as the examination of the underlying base material and welds. Special procedures, therefore, are required to ensure effective examination of and through clad material.

The problems of ultrasonic examination of clad materials are illustrated by the following effects:

- An increase in sensitivity is required to achieve the same sensitivity as for unclad material due to attenuation in the cladding (the mean attenuation in cladding increases with test frequency). Some types of cladding have a higher attenuation than others, e.g. manual metal arc cladding is generally more attenuative than strip cladding or rolled cladding.
- Large variations have been observed in the amplitude of shear wave beams transmitted through cladding (generally the amplitude variations increase with beam angle and test frequency). Amplitude variations are large at the juncture between two cladding strips.
- Small flaws below the cladding may be difficult to detect and accurately locate using shear wave probes.
- 0° shear wave beams have been observed when the ultrasonic beam is penetrating the cladding. These spurious beams usually give rise to backwall signals which are easily identified.
- A rough cladding surface can cause loss of coupling efficiency, noise, and supplementary distortions of the ultrasonic beam. This can have a severe effect on an inspection and it is usually necessary to improve the surface.
- A high level of ultrasonic noise can be detected from austenitic cladding. Some types of cladding are more noisy than others (when examination is performed, from the unclad side, the noise from fusion welded cladding is approximately equivalent to the signal from a 3 mm Ø flat bottomed hole).

This handbook describes the problem and gives recommendations for examining austenitic clad materials. Common cladding processes, possible irregularities and defects and propagation of ultrasound are discussed. Simplified descriptions of wave propagation are included as a bridge between theory and practical examination procedures.

The information in this handbook can be used to develop examination procedures. Examination extent and defect acceptance criteria are not addressed. The handbook is intended for ultrasonic examination practitioners, procedure developers, and personnel interpreting examination results.

2 CLADDING PROCEDURES AND RESULTING METALLURGICAL STRUCTURES

2.1 Purpose of Cladding

Austenitic cladding is frequently applied to carbon steel pressure vessels and piping to reduce or prevent corrosion. Clad vessels and piping have been used in the nuclear industry for many years and their application in the petrochemical industry is increasing.

2.2 Types of Cladding

Cladding is usually applied by a manual, or an automatic welding process, or by an explosive or rolling process and it is identified by that process. Each process produces a characteristic metallurgical grain structure which influences the passage of ultrasound.

It should be realized that more than one type of cladding may be present on a component. For instance a large vessel with a regular shape may be clad by fusion or explosive welding, or by a rolling process. The cladding may be applied by a manual or an automatic process.

Manual metal arc cladding is normally used to join up the cladding on the different parts, because it can be deposited in any position. Manual metal arc cladding is also used to make the cladding continuous where there is a change in section, such as between a vessel shell and a nozzle.

The grain structure of all fusion welded austenitic cladding is coarse and anisotropic. The anisotropy is due to the austenitic weld metal solidifying with the $\langle 100 \rangle$ crystallographic axis along the direction of the maximum thermal gradient, which is approximately perpendicular to the surface (with a slight tilt towards the welding direction). Therefore columnar grains grow in this direction as can be clearly seen in Figs. 2.1 and 2.2. Since no phase transition occurs in austenitic weld metal upon cooling there is no grain refinement as in ferritic weld metal and large grains result.

Usually more than one cladding layer is deposited and the columnar grains grow epitaxially through both layers as can be seen in Figs. 2.1 and 2.2.

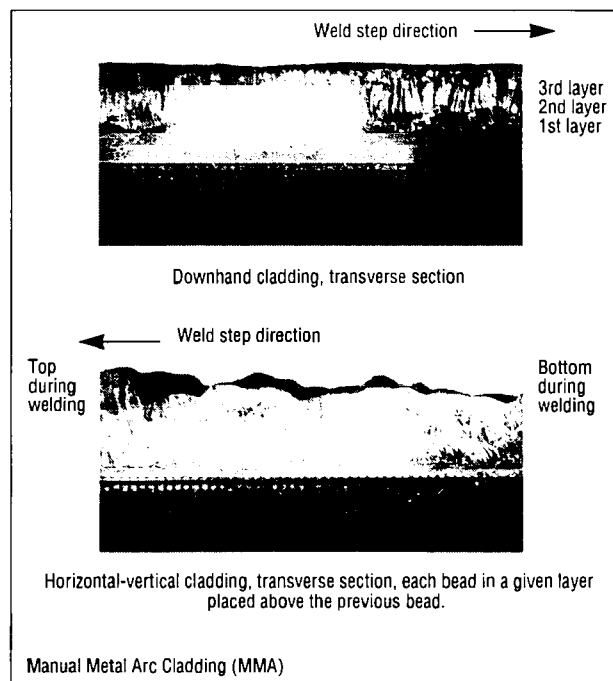


Fig. 2.1: Macrographs of downhand and horizontal-vertical cladding

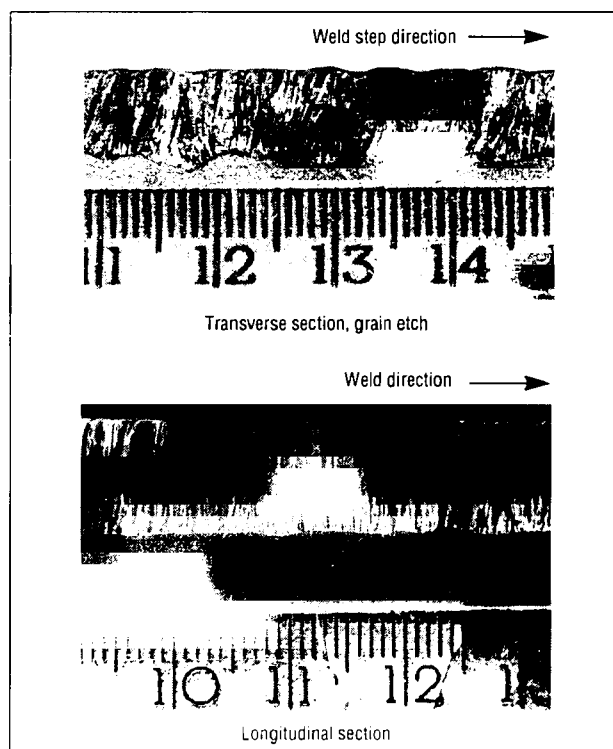


Fig. 2.2: Macrographs showing transverse and longitudinal sections of manual metal arc cladding

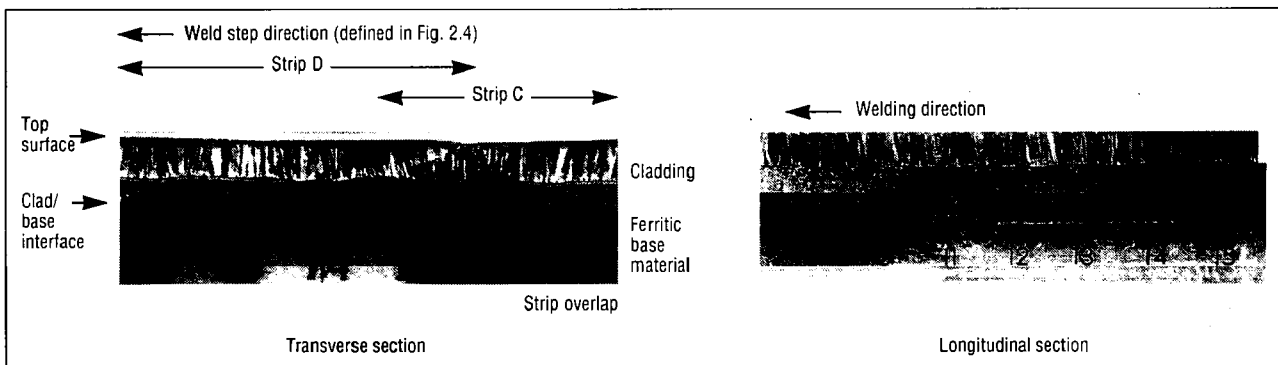


Fig. 2.3: Macrographs showing transverse and longitudinal sections of strip cladding

In the following subsections the most important cladding types are described. In particular attention is paid to:

- grain structure;
- surface condition;
- condition of interface between cladding and base metal.

2.2.1 Manual Metal Arc Cladding

The columnar structure of Manual Metal Arc (MMA) cladding is rather variable. In general there is a periodicity determined by the width of each weld bead. Grain tilt in the direction of the welding sequence occurs, but it is not very regular.

Both the surface and the interface of MMA cladding show undulations. The amplitude of the undulations is of the order of 0.5 mm and the width approximately 5 mm. Typical grain diameters are 100-200 μm but grain sizes up to 400 μm , are also found. MMA claddings may consist of one, two, three or more layers. Most MMA cladding consists of at least three layers, since the weld metal is diluted by the base metal and the nickel and chromium content of a single layer is insufficient to provide reliable corrosion protection.

2.2.2 Strip Cladding

Strip cladding is applied by means of an automated welding process and it is used for cladding large surfaces. The width of a strip can vary from 30 mm to 150 mm. Dilution of weld metal by base metal is

generally lower than for MMA cladding. The grain structure is columnar, see Fig. 2.3.

The dimensions of the grains in strip cladding are similar to those for MMA cladding and they may also be tilted slightly in the direction of welding, depending on the welding speed.

At the overlap of two strips there is a variable grain tilt in the transverse direction (see Figs. 2.3 and 2.4).

Both the surface and the interface of strip cladding are flatter than that of MMA cladding. Dips or cusps with a width of approx. 10 mm and a maximum depth of about 0.5 mm occur at strip overlaps and also at other random locations. Surface dips and interface cusps may be asymmetric (see Fig. 2.5).

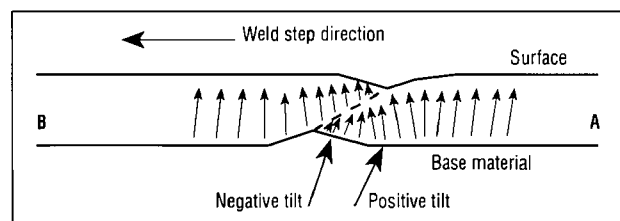


Fig. 2.4: Grain tilt variation at the overlap between cladding - strips

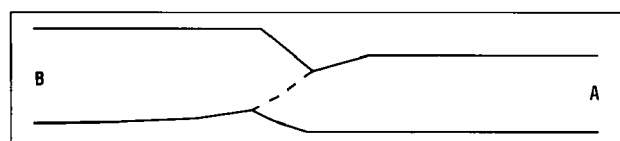


Fig. 2.5: Surface dip and cusp in strip cladding exaggerated for illustration

Single layer strip cladding is used but double layer cladding is more common to reduce the risk of reheat cracking in the base metal beneath the cladding and also to provide improved corrosion protection than is provided by one layer.

2.2.3 Explosively Bonded Cladding

Explosive cladding is a cold pressure welding process. The principle is illustrated in Fig. 2.6. During the high velocity collision of the two metals, which follows the shock-wave of the explosion, a gas jet is formed between the two parts which clears the metal surfaces of oxides and other contaminants that would be detrimental to the formation of a metallurgical bond. Parameters such as pre-welding stand off and explosion detonation velocity have to be carefully selected to obtain a good weld.

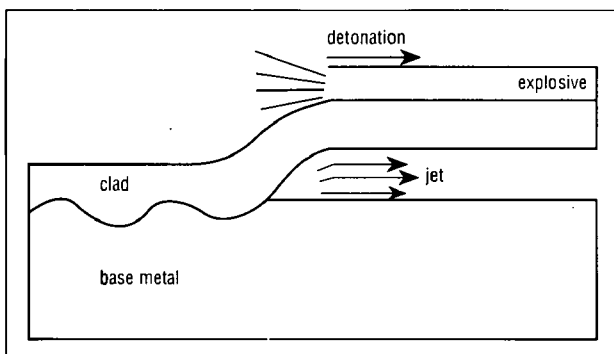


Fig. 2.6: Principle of explosion cladding

When the parameters are correctly set no melting takes place during explosion welding, the surface of the cladding remains smooth and the microstructure of the clad and base metal is only modified very close to the interface.

The pressures in the collision region exceed the dynamic yield strength of the metals and plastic flow occurs. This causes the interface to be wavy (see Fig. 2.7) with an amplitude and wavelength of typically 0.1 and 5 mm respectively. Two types of flaw which can occur in explosive welds are shown in Fig. 2.7.

Because of the high pressure and the local deformation in the bonding zone, the hardness becomes high and a stress relieving heat treatment is recommended.

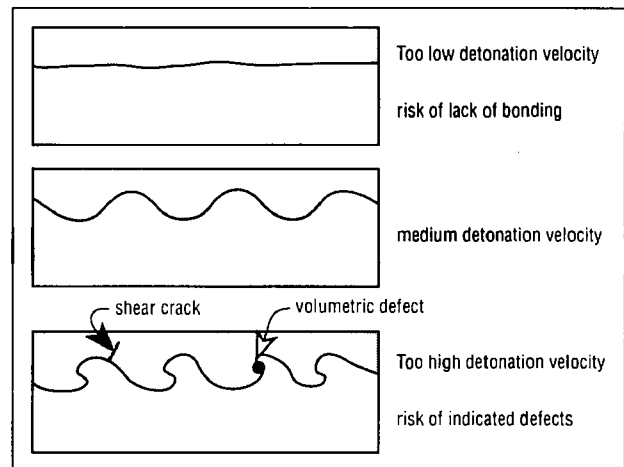


Fig. 2.7: Interface ripple and the type of flaws that may be introduced by explosive cladding

Explosive cladding is mainly used for flat plates and pipes. Sometimes more than one layer is welded by a single explosion.

Virtually all combinations of metals can be explosively welded, the main requirement is that they have a high ductility.

Explosively bonded cladding will have a fine grain structure which will not present any problems for ultrasonic testing.

2.2.4 Rolled Cladding

Rolled cladding is applied under high pressure and temperature. Providing the process parameters are correctly set considerable deformation occurs to the cladding resulting in a fine and homogeneous grain structure. However, if the rolling temperature is too high grain growth may occur and this can complicate ultrasonic testing. Both the clad surface and the interface are always flat and smooth.

There are two main processes for roll-bonding, both of which begin by laying sheets of cladding on slabs of base metal and welding them together round the edges or alternatively, by sandwiching two layers of cladding, with a separating agent, between two slabs of base metal and welding these together. (See fig. 2.8). The two processes are:

- Vacuum process where air between the cladding and the base metal is evacuated prior to rolling.

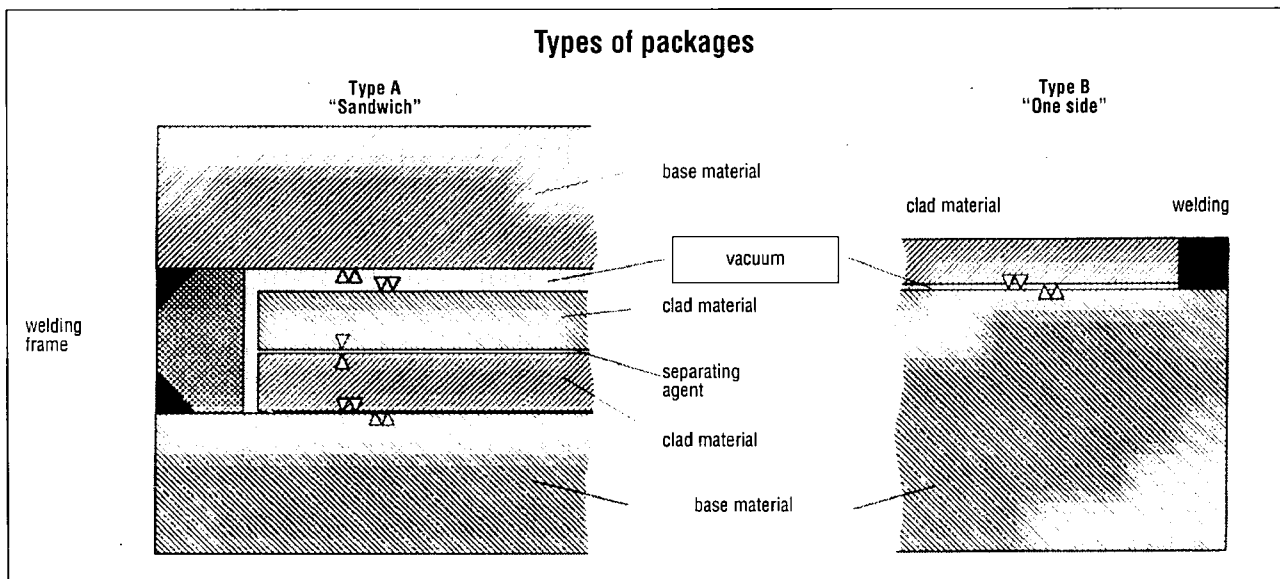


Fig. 2.8: Fabrication techniques used for the vacuum process

The contacting surfaces must be free of dust and oxide.

- The Lukens process where galvanized nickel is deposited on the cladding surface prior to making the sandwich.

The welded sandwich is then heated (Temperature: 1080 to 1200 °C) and rolled to the required thickness.

The production process follows the schematic diagrams in Fig. 2.9. It is essential to heat treat the clad plate after roll bonding to achieve the following conditions:

- the desired mechanical properties of the base material
- to improve the corrosion resistance of the cladding metal
- stress relief.

The advantages of roll bonded clad plates for inspection purposes is that both the base metal and the cladding have a fine grain structure, 16 to 32 μm (ASTM 7-9) and this enables high frequency shear waves to be used for the inspection of both materials. However precautions regarding refraction at the clad/base metal interface may be necessary.

2.3 Surface Finish and Repairs

It is often necessary to grind clad surfaces smooth to enable ultrasonic inspection to be performed. This is particularly important for MMA cladding.

Traditionally the grinding is performed manually, leaving a smooth but wavy surface, but the use of automatic grinding methods is increasing.

Grinding is often used to remove a defect in the cladding, or in the base metal. For shallow excavations the cladding may be ground smooth leaving a dip in the surface. If deeper excavations are necessary the cladding is usually repaired by welding. When the same weld metal as that used for cladding is also used for repairs it is referred to as a homogeneous repair. When a dissimilar weld metal is used for repair it is referred to as a heterogeneous repair.

Generally weld repairs are performed manually and result in a disturbance to the grain structure of the cladding. Inconel weld metal is often used to perform heterogeneous repairs of for example reheat cracking, since it remains fully austenitic even after dilution with the base metal. Fig. 2.10 shows a macrograph of a real repair.

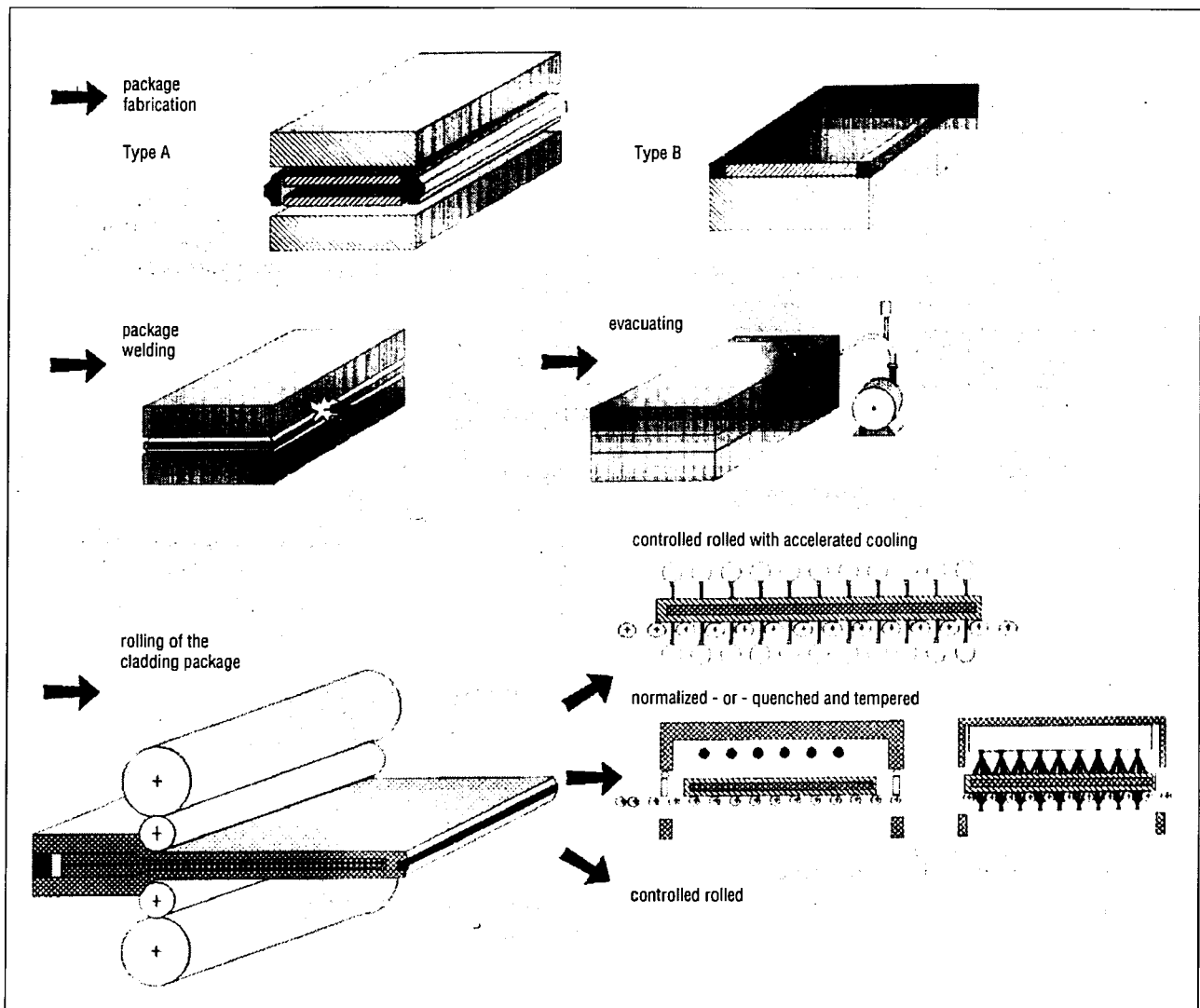


Fig. 2.9: Principal stages in the roll bonding process

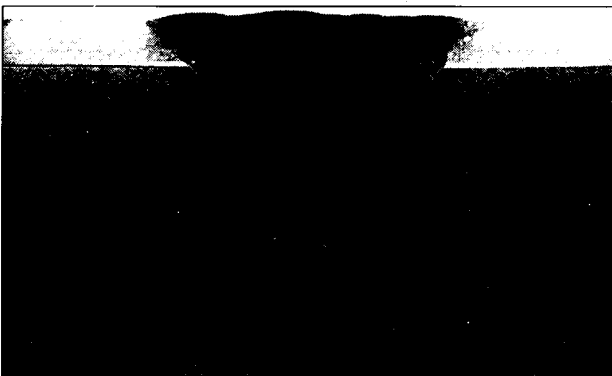


Fig. 2.10: Example of a repair of under cladding cracks

2.4 Cladding Defects

Table 1 lists the main manufacturing defects which can occur and Table 2 lists service induced defects. The acceptability will depend on the specification. Standards and specifications on the inspection of cladding and clad components are listed in Appendix 1.

Table 1: Manufacturing defects associated with cladding

Defect type	Possible causes	Location of defect
FUSION WELDING		
Lack of bond/fusion	- Inadequate heat input to melt parent plate, or a layer of cladding. Possibly also contamination by scale or rust preventing fusion.	Clad-base metal interface, or between cladding layers.
Inclusions - slag or oxide	- Poor welding control.	Occurs between strips in strip cladding. Usually widely dispersed in MMA cladding. Long lines of trapped slag can occur in strip cladding.
Porosity cluster chimney pin hole	- Not very common usually occurs due to damp flux, or contamination.	Anywhere
Cracks in cladding	- Solidification cracking, mainly due to high dilution with the parent plate. A higher alloy is often used for the first layer compared to the second to offset dilution. Cracking usually branched and may be very fine. - Hydrogen cracking due to depositing the second layer cold, combined with no heat treatment.	Usually in the first layer of cladding.
Cracks in ferritic base metal	- Hydrogen cracking due to damp consumables. - Hydrogen cracking caused by hydrogen charged segregations combined with a fast cooling rate. - Reheat cracking. This only occurs in susceptible steels which depends on composition. Alloying elements Cr, Mo and Ti precipitate in grain boundaries making them very strong and unable to yield during stress relief. - Liquation cracking. Caused by "films" of low melting point constituents along the grain boundaries. Generally only occurs in materials with a large grain size	Heat affected zone in ferritic steel. Parallel to the cladding interface. Also heat affected zone. Cracks are small and intergranular.
Cracks in repairs	- IGSCC possibly caused by primary water in contact with Inconel repairs	Surface breaking defects
EXPLOSIVE WELDING		
Lack of bond	- Detonation velocity too low, see Fig. 2.7.	Clad-base metal interface.
Cracking	- Detonation velocity too high, see also Fig. 2.7.	May be either in the cladding or base metal. Thin sections are vulnerable to cracking.
Volumetric flaws	- Damaged surfaces. Or detonation velocity too high.	Clad-base metal interface.
ROLL-BOND CLAD PLATES		
Lack of bond	- Improper surface conditioning - Surface defects before rolling	- Clad-base metal interface - Cladding
Inclusions	- Inclusions in clad material	- Cladding

Table 2: Service induced defects

Environment	Type of flaw
Erosion or aggressive corrosive species	Loss of cladding thickness or pitting Penetration of the cladding will result in rapid corrosion of the base metal and spalling of the cladding.
High stresses due to mechanical or thermal loads	Surface breaking transgranular cracking.
High stresses combined with corrosive species.	Surface breaking intergranular stress corrosion cracks.

3. INFLUENCE OF CLADDING ON PROPAGATION OF ULTRASONIC WAVES

3.1 Introductory remarks

The presence of a welded cladding layer on a component can seriously affect the ultrasonic inspection of the component for the following reasons:

- the surface of the cladding is not as even as that of the surface of the unclad base metal;
- there is an additional boundary between the cladding and the component;
- fusion welded austenitic cladding has a coarse grained, anisotropic macrostructure, see Chapter 2.

The reader will come across several phenomena which do not exist in "normal" (isotropic) materials and which are unfamiliar to most ultrasonic operators, such as:

- *Anisotropy*: An anisotropic material is one in which the properties of the material, e.g. ultrasonic sound velocity, vary with the direction in which they are measured.
- *Beam skewing*: Beam skewing is said to occur when an ultrasonic beam propagates in a direction which is not perpendicular to the wave front. This phenomenon can cause unexpected changes in beam direction and shape. (The term beam skewing as used here should not be confused with the squint or skew angle of twin crystal probes.)
- *Scattering*: The scattering of ultrasonic beams is not usually a problem when examining ferritic materials, except at high test frequencies, e.g. 10 MHz and above. Fusion welded austenitic cladding has a coarse but regular polycrystalline macrostructure which causes significant scattering of ultrasonic beams at relatively low test frequencies, e.g. 2 MHz. This can lead to very low signal-to-noise ratios for some ultrasonic examinations.

The extent to which the above phenomena affect ultrasonic testing depends on many factors such as:

- beam direction relative to the columnar grains
- wave mode
- test frequency as mentioned in the "Scattering" section.

Section 3.2 explains the physics of ultrasonic wave propagation in cladding due to its macrostructure as simply as possible. In particular it is assumed that

the columnar grains are contained in the plane of sound propagation, this being a fairly good approximation to the problem of wave propagation in claddings. If the columnar grains do not lie in the plane of sound propagation the character of the wave modes will be changed. This will be discussed in Appendix A2.

Section 3.3 deals with the practical implications of the properties of claddings on ultrasonic beams.

3.2 The Physics of Wave Propagation in Cladding Due to Its Macrostructure

3.2.1 Wave Mode and Polarization

It is well known that in the bulk of isotropic materials two different wave modes can occur, namely compression waves and shear waves. The difference between the two is in the direction of particle motion or polarization: parallel to the wave normal direction for compression waves and perpendicular to it for shear waves. The orientation of particle motion for shear waves can occur in any plane, therefore the number of shear wave modes is theoretically unlimited.

As is explained in figure 3.1, for shear waves two types of polarization are in use during ultrasonic testing;

- For the shear waves which are transmitted by a conventional piezoelectric shear wave transducer, particle motion is in the plane of incidence, (or sound propagation) which is a

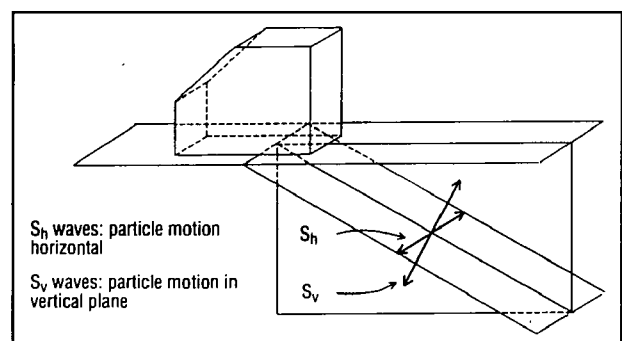


Fig. 3.1: Directions of particle motion for shear waves showing horizontal and vertical polarization

“vertical” plane, i.e. a plane perpendicular to the metal surface. Therefore such a wave is called a vertically polarized shear wave or S_v wave.

- Shear waves with the particle motion perpendicular to the plane of incidence, which is “horizontal” and tangential to the metal surface, are called horizontally polarized shear waves or S_h waves. For some practical applications S_h waves may have certain advantages, which are discussed later. They can be generated by electromagnetic acoustic transducers (EMAT; see Appendix A4).

In isotropic materials like ferritic steel the velocity of S_h and S_v waves is the same, therefore they are indistinguishable.

Whereas in anisotropic materials like cladding three and only three different wave modes may occur, namely one compression wave mode and two shear wave modes. The directions of particle motion, the polarizations, are always mutually perpendicular, but in general they are not parallel to the wave normal direction for compression waves and not perpendicular to it for shear waves; so they are generally not pure waves. This is discussed in Appendix A2.

In anisotropic materials not only the polarizations of both shear waves modes are different, but their velocities are generally different too.

3.2.2 The velocity of ultrasonic waves

The velocity of compression and shear waves in ferritic steel are different, but will be independent of beam angle. Ferritic steel is therefore said to be acoustically isotropic. Fig. 3.2(a) shows the propagation of compression waves in ferritic steel from a hypothetical point source. In three dimensions the wave front will be spherical.

Fig. 3.2(b) shows the formation of a plane wave in ferritic steel by Huygens’ principle for a large number of point sources across the width of an ultrasonic 0° probe. The wave front will propagate in a direction at right angles to the surface and its velocity will not vary with direction. The velocity of a point of constant phase on the wave front in fig.3.2(b) is called the *phase velocity* V_p . The direction of V_p is perpendicular to the wave front.

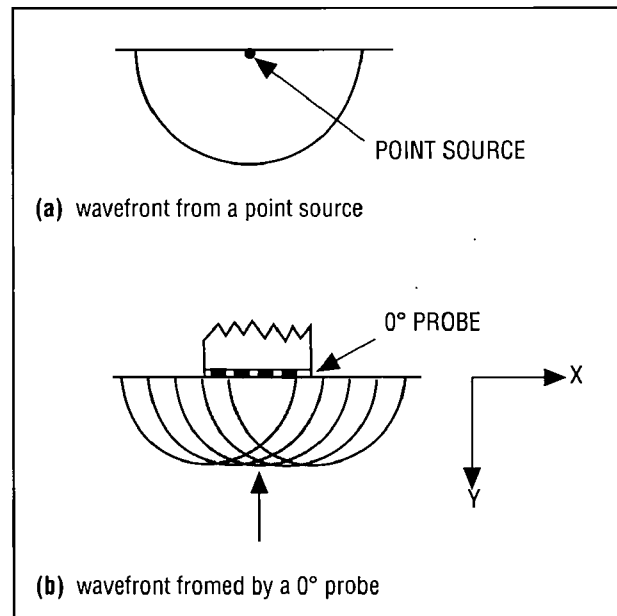


Fig. 3.2: Wave fronts generated in ferritic steel by compression wave sources

Plotting the size of phase velocity versus its direction in a polar graph one obtains the *phase velocity surface*, which is three-dimensional. The wave front in Fig. 3.2(a) can be interpreted as a phase velocity surface which is of spherical shape.

The energy of the wave in ferritic steel will propagate in the same direction as the wave fronts and have the same velocity. So the energy or *group velocity* V_g of the wave equals V_p and the group velocity surface also has a spherical shape.

The phase velocity V_p of compression waves in cladding on the other hand is a function of the angle between the wave normal direction and the long axis of the columnar grains. Therefore in general the group velocity V_g does not have the same direction and magnitude. So neither the wave fronts of a point source (or phase velocity surface), nor the group velocity surface will have a spherical shape.

The phase velocity V_p in cladding can be calculated from time-of-flight measurements on parallel sided blocks machined from pads of weld metal as shown in Fig. 3.3(a).

Fig. 3.4' shows two and three-dimensional sections of the phase velocity surface for all three wave

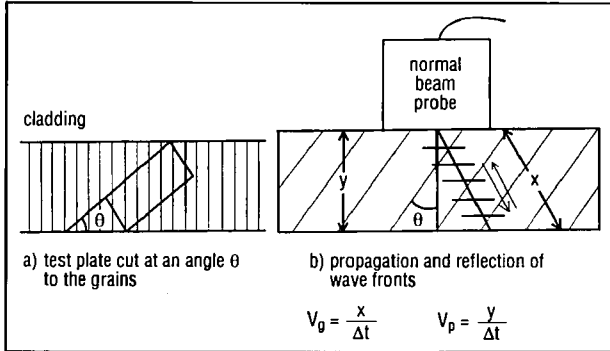


Fig. 3.3: Measurement of the phase velocity at an angle θ to the grains

modes in cladding. Since in anisotropic material one compression (C) and two shear (S_v and S_h) wave modes may propagate, the phase velocity surface consists of three sheets. The direction of phase velocity is given as the angle θ between the wave normal and the columnar grain direction.

Fig. 3.5¹ shows the group velocity V_g for compression waves in cladding. The group velocity for shear waves is more complex and is discussed in Appendix 2.

In anisotropic material now the group velocity surface is the appropriate surface for Huygens' construction of wave propagation. Each portion of the group velocity surface corresponds to the phase front for a plane wave with energy travelling in that direction. Fig. 3.6(a) illustrates this qualitatively for a point source of compression waves in a cladding layer with tilted grains.

Fig. 3.6(b) shows a plane wave front generated by a 0° probe in cladding with tilted grains constructed by Huygens' principle (for further explanation see App. A.2.). The similarities between fig. 3.2(b) for an isotropic material and fig. 3.6(b) for an anisotropic material are:

- the wave front is parallel with the surface

¹ In figs. 3.4, 3.5 and similar figures to follow, velocity is expressed in $[\text{mm}/\mu\text{s}]$ because the numbers are convenient: $V[\text{m/s}] = V \times 10^{-3} [\text{mm}/\mu\text{s}]$

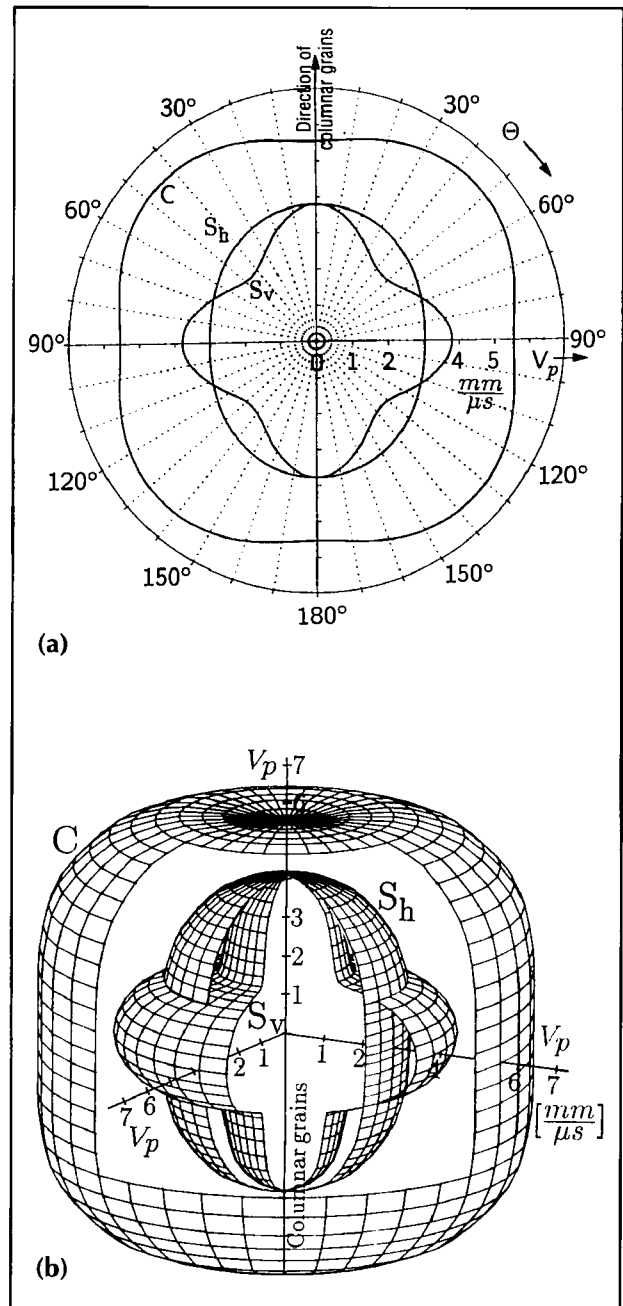


Fig. 3.4: Phase velocity surface in cladding (a): two dimensional section, (b): three dimensional view

- the directions of the phase velocity V_p are the same, namely perpendicular to the wave front

The differences between figs. 3.2(b) and 3.6(b) are:

- the magnitudes of phase velocities V_p and group velocities V_g will be different

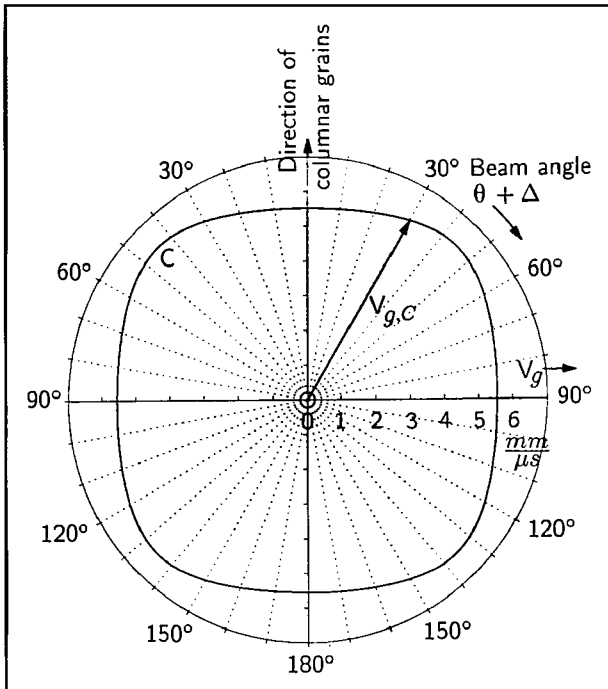


Fig. 3.5: Section of the group velocity surface for compression waves in cladding.

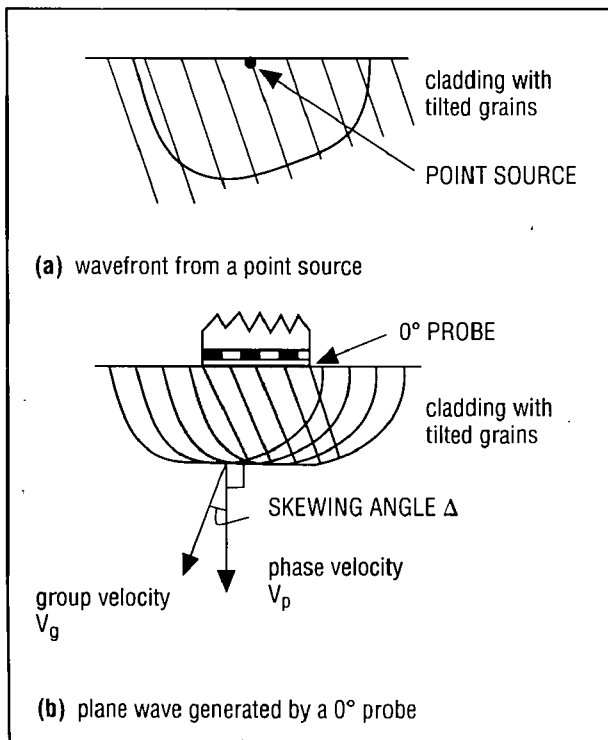


Fig. 3.6: Wave fronts generated by compression wave sources in cladding with tilted grains

- in the anisotropic case obviously the wave's energy flow is travelling at an angle Δ to the phase velocity V_p with group velocity V_g . Both velocities are related by:

$$\cos \Delta = \frac{V_p}{V_g}$$

The ultrasonic beam in fig.3.6(b) is said to be skewed and acoustic energy flows in the direction V_g .

In isotropic materials there is no difference between V_p and V_g , they are one and the same, while in anisotropic material they are generally different.

3.2.3 Beam Skewing and Focusing / Defocusing Effects

As mentioned before the following statements are based on the assumption that the columnar grains are contained in the plane of sound propagation. A tilt of the columnar grains from the plane of sound propagation changes the character of the wave modes and especially the character of the shear waves being "vertically" or "horizontally" polarized is not maintained, see Appendix A2.

The phase velocity surface for S_v waves is less circular than that for compression or S_h waves in Fig. 3.4. This means that S_v waves are more strongly affected by material anisotropy than are S_h or compression waves. One of the practical consequences of this is that S_v waves are more strongly skewed by cladding than the other two wave modes.

The beam skewing angle Δ depends on the angle θ between the wave normal and the columnar grain direction. In fig. 3.7 the beam skewing angle Δ is plotted against θ for compression waves and both shear wave modes. Fig. 3.7 was calculated from measurements of phase velocity on X 6 CrNi 1811 type stainless steel specimens according to Fig. 3.3. If we look at the compression wave curve in Fig. 3.7, we see that the skewing angle Δ is zero for a wave normal-to-grain angle of 48° . The gradient of the curve at this angle results in a focusing effect producing narrow beam widths. However, at wave normal to grain angles of 0° and 90° the sign of the gradient changes and compression wave beams are defocused, resulting in wide beam widths and poor test sensitivities.

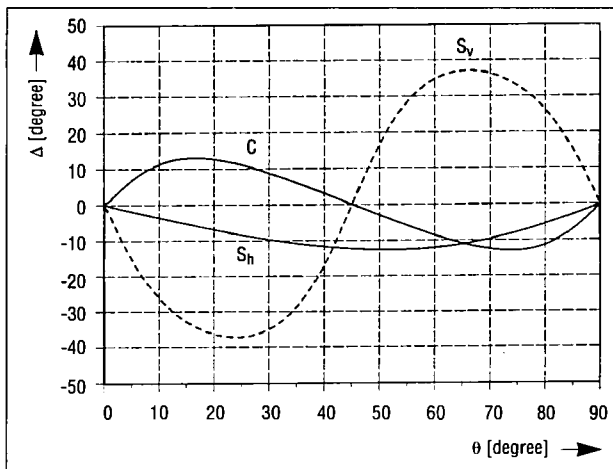


Fig. 3.7: Computed beam skewing Δ versus the angle θ between the direction of the phase velocity and the long axis of the columnar grains

The skewing angle for S_v waves is zero at a wave normal to grain angle of 45° , but the sign of the gradient of the curve in Fig. 3.7 is the opposite of that for compression waves, resulting in wide defocused beams. The skewing effect for S_v waves is much larger than that for compression waves, however S_h waves are less affected by anisotropy than compression waves.

Fig. 3.8 shows the results of applying a ray tracing computer programme to a 45° and a 0° compression wave probe placed on cladding. A beam divergence of 12° either side of the axis has been assumed and the programme shows the ray in an 8 mm thick cladding layer with vertical grains on ferritic steel. The divergence of the 45° beam is reduced in cladding, while the divergence of the 0° beam is increased because of the focusing / defocusing effects described above.

3.2.4 Snell's Law

Snell's law is widely used in ultrasonic testing to calculate the beam angle of refracted or mode converted beams. The equation:

$$\frac{\sin \theta_1}{V_1} = \frac{\sin \theta_2}{V_2} = \frac{\sin \theta_3}{V_3}$$

can be applied to isotropic materials with few complications. It is valid for anisotropic materials as

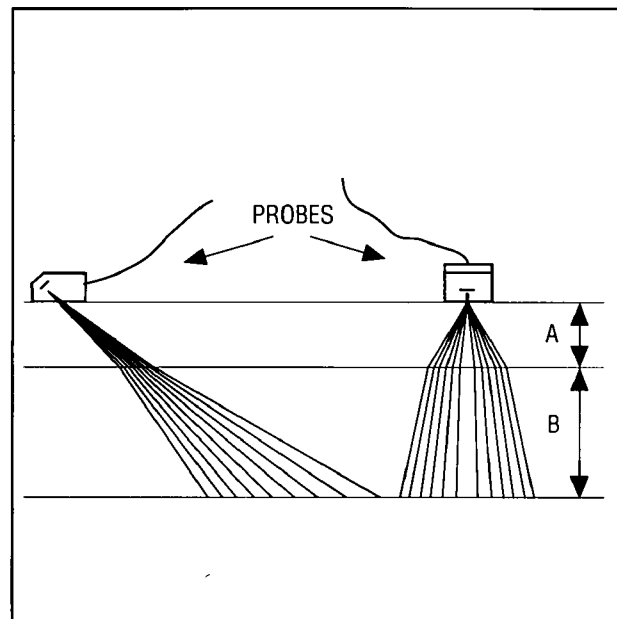


Fig. 3.8: Ray tracing computer programme results obtained for 45° and 0° compression wave probes
A = 8mm clad layer (vertical grains)
B = 17mm Ferritic base material

well, provided the phase velocities in the anisotropic material, which are dependent on propagation direction, are taken into consideration. This section shows how to apply Snell's law to anisotropic materials. (Snell's law is also dealt with in Appendix A3 where the amplitude of reflected and refracted beams is also calculated.)

Snell's law can be handled most elegantly by introducing the concept of the slowness surface, which gives the inverse of the phase velocity $1/V_p$ as a function of the wave normal direction.

In isotropic material the slowness surface is a two-sheeted surface of spherical shape. For ferritic steel, e. g., it consists of two spheres with radii of $1/5.92 \mu\text{s/mm}$ for compression waves and $1/3.23 \mu\text{s/mm}$ for shear waves, see fig. 3.9.

In anisotropic material the slowness surface is a three-sheeted surface of non-spherical shape, corresponding to one compression and two shear wave modes. Fig. 3.10 shows the slowness surfaces for compression (C), S_v and S_h waves in columnar grained austenitic steel. While by definition the direction of the phase velocity is given by a line

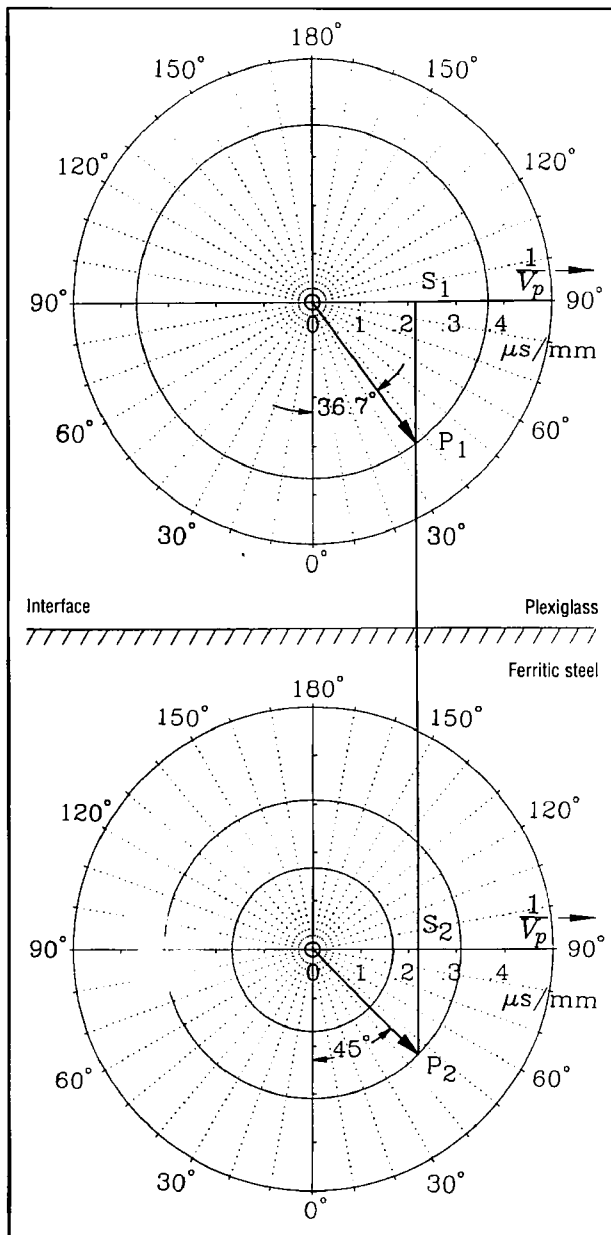


Fig. 3.9: Slowness surfaces for ferritic steel and plexiglass to determine the refraction angle at the interface

through the origin, the direction of the group velocity is given by a line at right angles to a tangent to the curve. Both these directions are marked on Fig. 3.10. The angle between the group and phase velocity direction is the skewing angle Δ .

Snell's law states:

- The incident, reflected and refracted waves all lie in the same plane

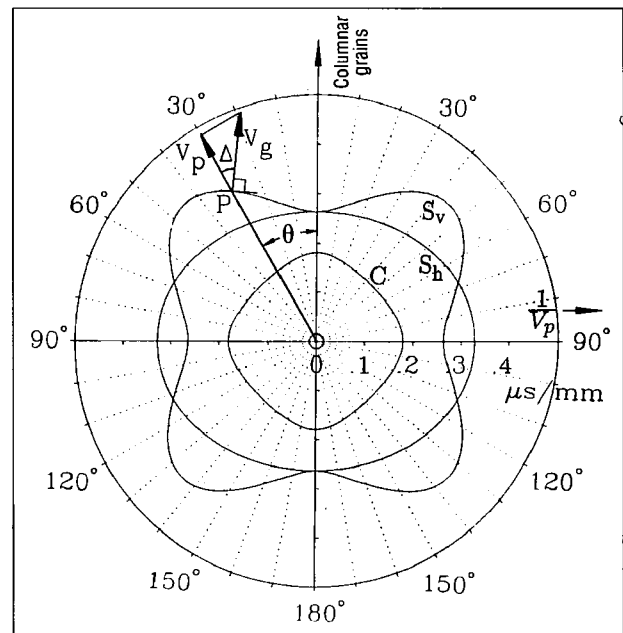


Fig. 3.10: Slowness surface for both shear waves and compression waves in austenitic cladding

- For plane waves the incident, reflected and refracted beams must all have the same component of the slowness $1/V_p$ tangential to the interface.

Thus reflection and refraction of the wave are determined by the phase velocity V_p and its direction, rather than by the group velocity and the direction of propagation of the wave's energy flow. Fig. 3.3(b) shows an example for the strange reflection property of skewed beams.

But it is the direction of the energy flow (group velocity) which decides whether a sound beam really exists in the clad material or not. The rule is, that the group velocity of incident beams must be oriented towards the interface, the group velocity of refracted and reflected beams must be oriented away from the interface, see Appendix A3.3.

To illustrate how the constructions are made, an example for the boundary between different isotropic materials is shown below.

A 45° shear wave probe for the examination of ferritic steel will have a perspex wedge angle of 36.7° as given by Snell's law:

$$\frac{\sin 45^\circ}{3.23} = \frac{\sin 36.7^\circ}{2.73}$$

where the shear wave velocity in steel is 3.23 mm/ μ s and the compression wave velocity in perspex is 2.73 mm/ μ s.

The slowness surface for compression waves in perspex is a circle with a radius of 1/2.73 μ s/mm which is shown in the top half of fig. 3.9. (Strictly speaking the slowness surface is a sphere and fig. 3.9 only shows its section in the plane of incidence.) The corresponding sections of the slowness surface for compression waves ($1/V_p=1/5.92$ μ s/mm) and shear waves ($1/V_p=1/3.23$ μ s/mm) in steel are shown in the lower half of fig. 3.9.

The point P1 is on the slowness surface for perspex, therefore

$$P_1O = \frac{1}{V_c}$$

$$S_1O = P_1O \cdot \sin 36.7^\circ = \frac{\sin 36.7^\circ}{V_c}$$

and this represents one side of Snell's law. Similarly the length of S_2O equals the other side of Snell's law. Snell's law thus states that $S_1O = S_2O$, which is equivalent to equalising the tangential component of the slowness $1/V_p$ in perspex and steel.

Fig. 3.11 shows how to determine the beam direction of a 45° shear wave beam in ferritic steel after refraction at a ferritic / cladding interface. The top figure represents the slowness surface of the shear wave for ferritic steel and the bottom figure the slowness surface of the vertically polarized shear wave (S_v) for cladding with vertical grains. The angle between the direction of phase velocity and the long axis of the grains in cladding is 34°. By constructing a tangent to the slowness surface for cladding at P2 the group velocity direction is estimated to be approximately 7°. Therefore the beam in cladding is heavily skewed.

The above theory provides a means to calculate beam angles in anisotropic material, but it does not provide any information on the amplitude of refracted waves.

3.2.5 Attenuation due to Grain Boundary Scattering

The ultrasonic examination of polycrystalline materials like austenitic weld metal produces low signal amplitudes and high noise levels when compared to the examination of fine grained ferritic

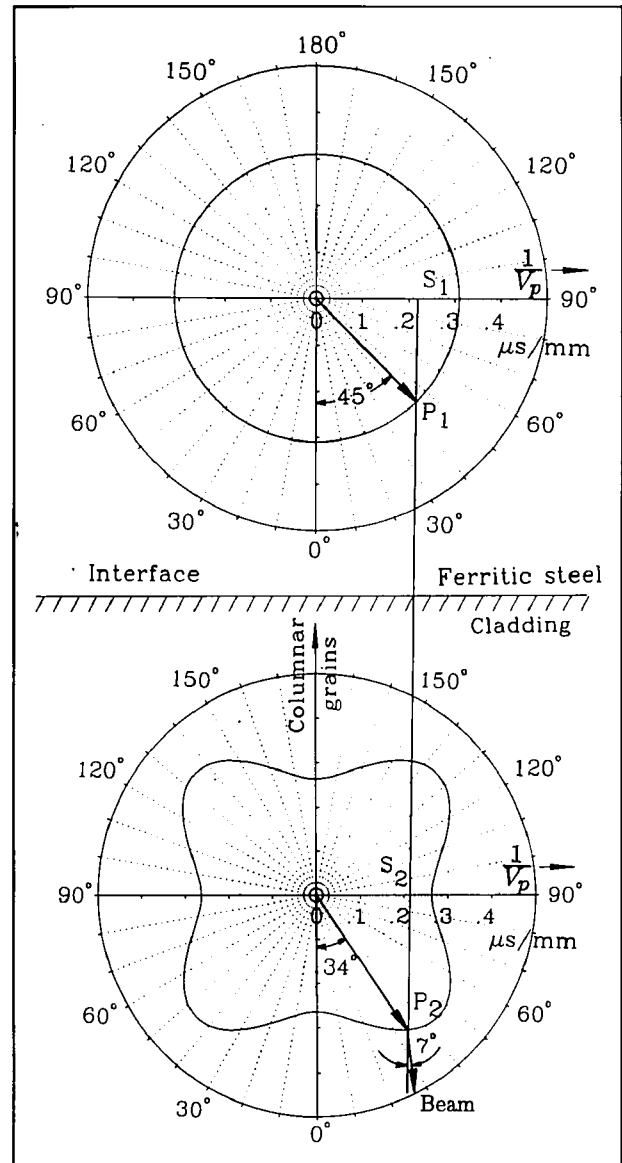


Fig. 3.11: Slowness surfaces for ferritic steel and cladding to determine the refraction at the interface

steel. If a closer comparison is made between the ultrasonic examination of ferritic and austenitic welds it is apparent for the latter that:

- a higher and variable level of attenuation occurs due to the focusing / defocusing effects discussed in the earlier part of this chapter.
- a much higher level of backscatter from grain boundaries occurs.

Apparent attenuation due to focusing / defocusing depends on the wave mode, the shape of the beam

and the beam to grain angle. It is not however frequency dependent.

In a textured structure, such as cladding, attenuation due to grain boundary scattering depends on polarisation, direction of sound propagation, and frequency, similar to what is observed for ultrasound velocity.

It is very difficult to separate the above effects practically and measure the attenuation of austenitic weld metal.

Grain boundary scattering arises because neighbouring grains will in general have different crystallographic orientations as indicated in Fig. 3.12 and a sound beam crossing the boundary between grains will undergo a change in phase velocity. This change in velocity will result in a change in acoustic impedance between the grains, producing a partial reflection at the boundary.

It has not been possible up to now to theoretically model grain boundary scattering in textured structures, as austenitic weld metal, consistently with measurement results. Therefore we are confined to an empirical description of the observed phenomena.

In the frequency range between 2 and 4 MHz the attenuation due to scattering ranges between 0.2 and 1.0 dB/mm for all three wave modes, however this does not include other factors such as beam divergence for example.

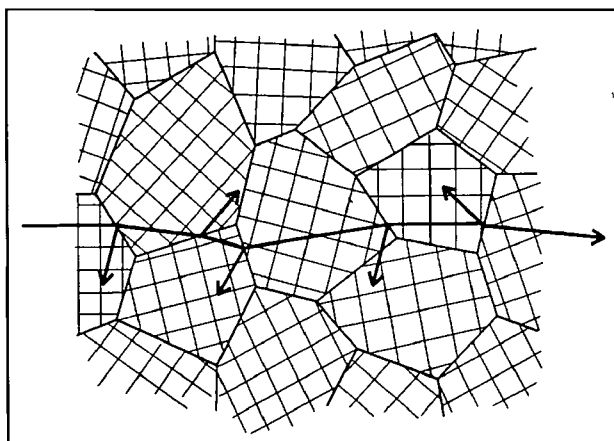


Fig. 3.12: A cross-section through columnar grains showing the scattering which occurs at the boundaries of the grains.

For practical use the following is a summary:

- For compression waves attenuation is relatively high for the direction along the columnar grains or across the grains. It is relatively low at 45-50° to the grains.
- For S_H waves high attenuation occurs for directions across the grains.
- For S_V waves the maximum attenuation occurs at 45° to the grains.

An ultrasonic beam propagating through a cladding layer will be partially reflected by the change in the acoustic impedance which occurs at the clad/ferritic interface. The reflected beams will also be subjected to back scattering, leading to noise on the flaw detector screen for a range which exceeds the beam path length through the cladding.

A very important source of noise especially for S_V waves is the specular reflection which occurs at the corners formed by the columnar grains and the free surface and the columnar grains and the clad/ferritic interface. This results in a high level of noise being detected at full skip and possibly also half skip.

Fig. 3.13 illustrates the above sources of noise. Additional sources of noise may arise if surface or creep waves are generated at the free surface of the cladding.

3.3 Practical Implications

In this section some of the practical implications of inspection resulting from the presence of austenitic cladding are described. Section 3.3.1 describes some of the consequences related to the anisotropic nature of the cladding whilst Section 3.3.2 addresses the effect of the surface finish.

Grain boundary scattering in cladding results in an overall loss of ultrasonic energy compared to that which is available when testing unclad ferritic steel. The scattering losses increase sharply at the junction between clad strips. Figure 3.22 shows the large range of ultrasonic attenuation which can occur in different thicknesses of cladding compared to that which occurs when the cladding is machined away.

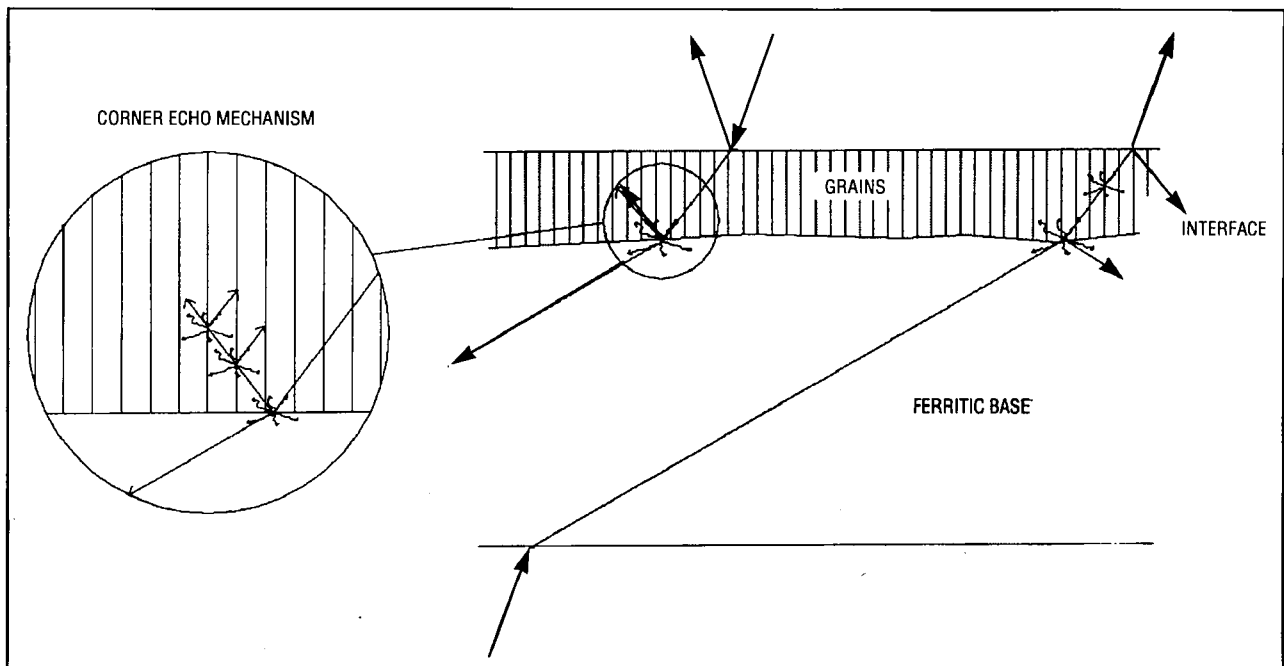


Fig. 3.13: Reflection and scattering of a beam transmitted through cladding

3.3.1 Effects of Anisotropy

The underlying theory for the effects of anisotropy is discussed in Section 3.2 and, in more detail, in Appendix 2.

(i) Flaw Location

As explained above, when sound beams propagate through austenitic cladding the propagation direction may not be the same as that of the incident beam, the precise direction being dependent upon the local grain orientation and the angle of incidence. This variation of the sound path, caused by the anisotropy of the cladding, can lead to errors in locating defects.

(ii) Effect of Grain Tilt

As explained in Chapter 2 the columnar grains in cladding may be tilted by up to 15° at the junction between two cladding strips, see fig. 2.4. In Fig. 2.5 strip A was deposited first, therefore the "weld step" direction is from right to left. The effect of a 15° grain tilt on shear wave beams generated in a cladding layer can be determined from the slowness surfaces in Fig. 3.14. If a 60° probe is placed on the cladding so that the beam travels against the weld

step the beam angle in cladding will be 19° . If the probe is rotated through 180° , so that the beam travels with the weld step, the beam angle will be 60° .

Measurements of the attenuation of 60° shear wave beams in MMA cladding are presented in Fig. 3.15. The attenuation of beams travelling with the step direction is significantly higher than that of beams travelling against the step. The reason for the higher attenuation when the ultrasonic beam is in the weld step direction is that the beam angle is much higher than when it is directed against the weld step. The higher attenuation is therefore due simply to the larger beam path in the cladding in the weld step direction.

The demonstrated phenomena must be expected for all other wave modes and may lead to sensitivity changes according to the probe orientation.

(iii) Generation of Multiple Beams

For certain angles of incidence in cladding it can be shown by consideration of the slowness surface that multiple beams may occur, see fig. 3.16. In practice, this means that in addition to the main beam, one or more additional beams may propagate

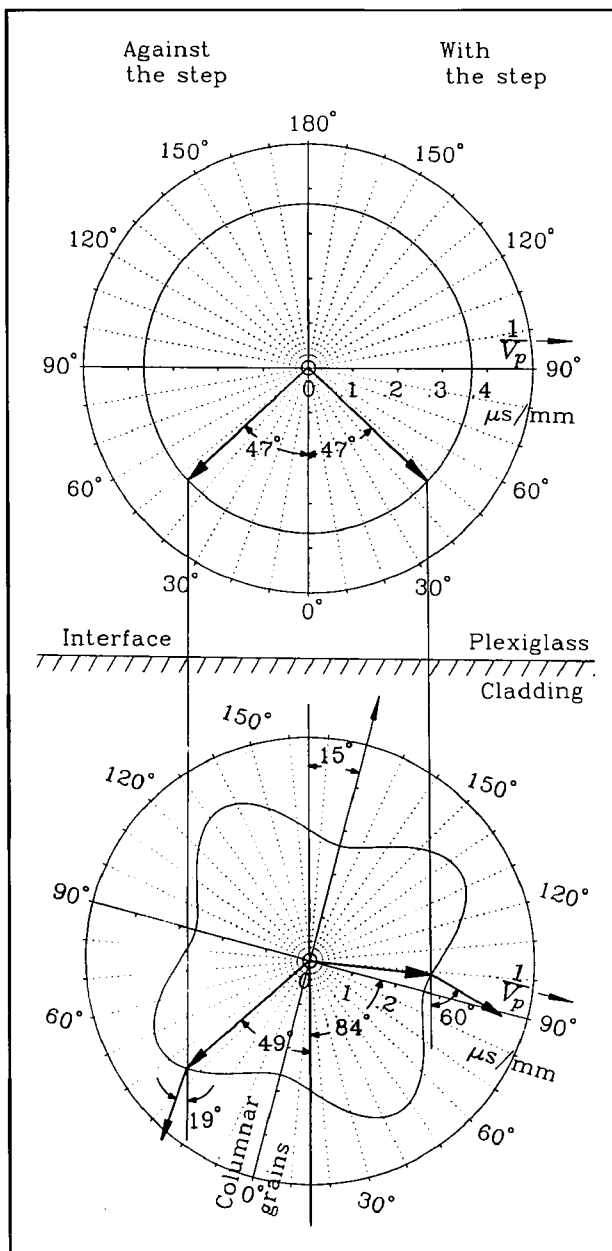


Fig 3.14: Sections of the slowness surface for plexiglass and cladding showing the direction of shear wave beams propagating in a cladding layer with a 15° grain tilt for a 60° probe

within the cladding. The effect of these additional beams is to lower the amplitude of the main beam and give rise to spurious indications.

The occurrence of multiple beams cannot be readily eliminated, their presence depends upon the precise grain tilt and angle of incidence of the sound beam.

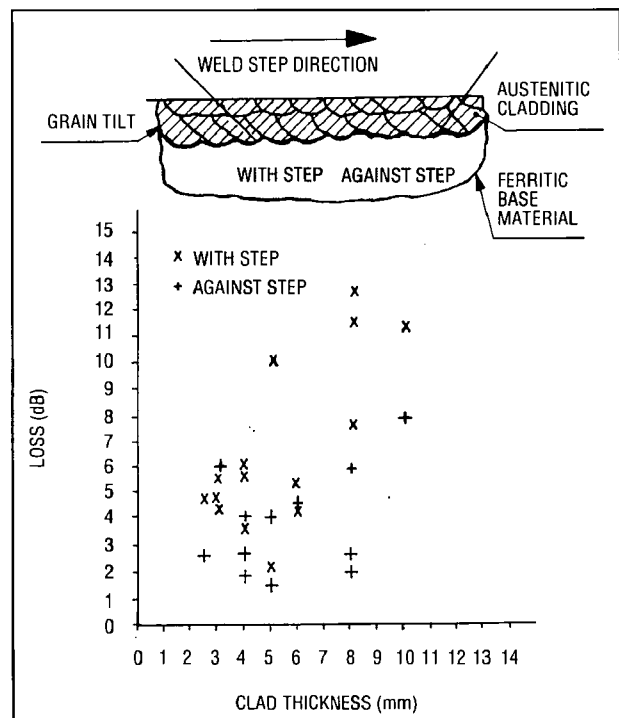


Fig. 3.15: 60° shear wave losses in test blocks clad using various MMA welding procedures

They are more likely to occur for beam angles greater than 60°. As mentioned, it is a general rule that only those beams whose group velocity direction is pointing away from the interface will propagate. In Fig. 3.16 both the 54° and the 73° beam will propagate, since both beams are pointing away from the interface. The relative intensity of the two beams can not be predicted from Snell's law, but this can be determined from Fig's. A3.15 and A3.16 of Appendix 3. These indicate that the intensity of the 73° beam is 40 dB below that of the 54° beam.

(iv) Beam Angle Limitations

Generally it is difficult to generate S_V waves in cladding with probe angles much greater than 60°, but this is not the case for compression waves. Slowness surfaces are drawn in Fig. 3.17 for S_V and compression waves in cladding material with vertical grains.

The group velocity directions are also shown for high angles θ between the columnar grains and the phase velocity directions. For S_V waves these point towards the interface for angles θ greater than 60°,

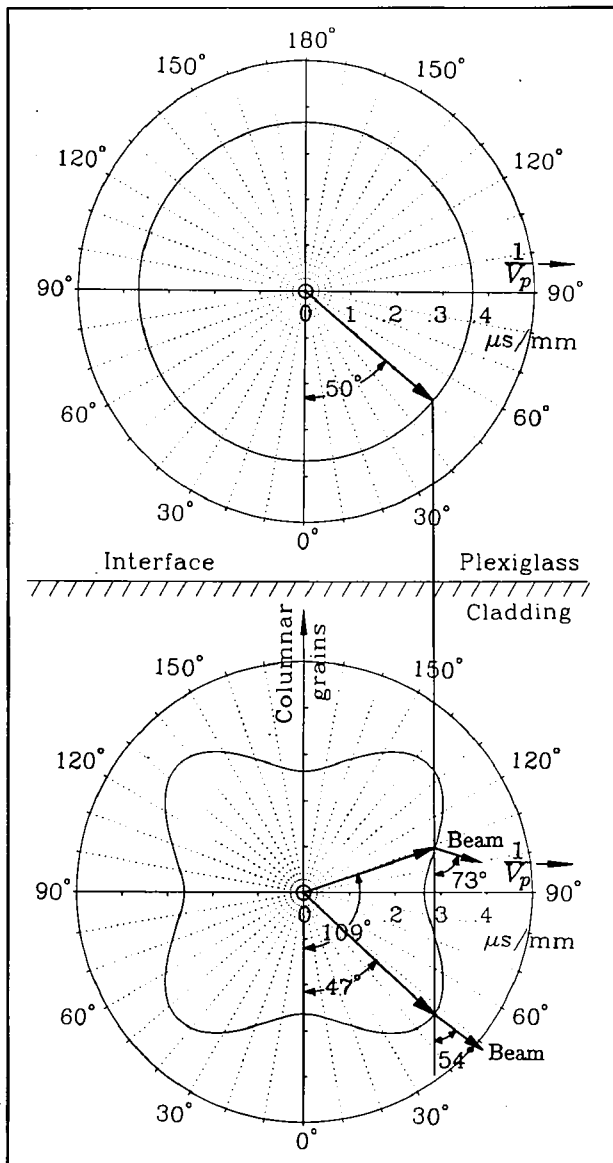


Fig. 3.16: Generation of multiple beams in cladding

indicating that they will not propagate. However there is the possibility of generating low intensity S_v waves, see the preceding paragraph (iii). Furthermore, there is also the possibility of generating surface waves and total internal reflection may occur as shown in Fig.3.18. The behaviour of compression wave beams is much more predictable than that of S_v beams.

Thus inspection of austenitic cladding using high angle (70°) beams can only be undertaken using compression waves or Sh -waves, see Section 4.

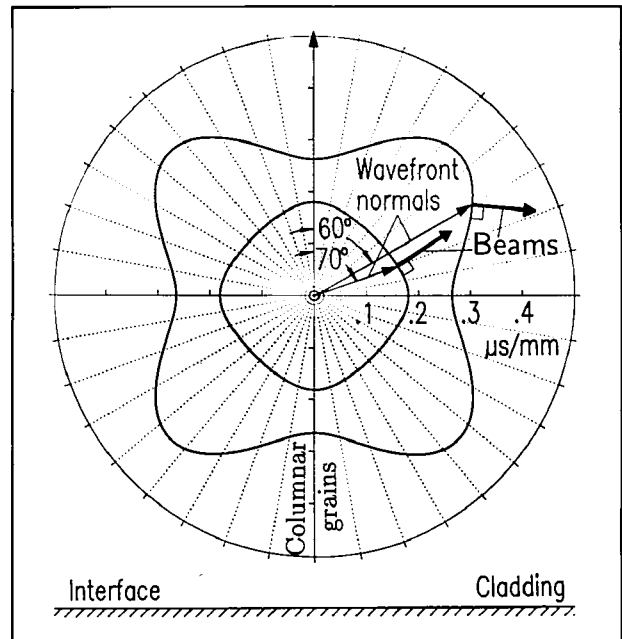


Fig. 3.17: Slowness surface for compression and S_v waves in cladding with group velocity (V_g) directions marked

(v) Noise Levels (Grain Boundary Scattering)

As discussed in Section 3.2.5, grain boundary scattering in anisotropic materials gives rise to noise (grass) on the flaw detector screen and reduces the signal to noise ratio of any indication.

In the case of ferritic components clad with austenitic steel there is a large acoustic mismatch at the boundary between the macroscopically isotropic ferritic base material and the highly anisotropic columnar grained cladding. (A similar acoustic mismatch may also occur at the interface between the buttering layer and the cladding if dissimilar metal welds are present). In both cases, the mismatch in acoustic impedance gives rise to an increased noise level, the magnitude of which increases with the acoustic frequency.

The use of a low frequency probes (1 to 2 MHz) with a pulse length of only a few cycles is recommended to minimise the background noise level. Short pulsed probes are more useful than long pulsed ones to allow discrimination between flaws and noise.

(vi) The Effect of Irregularities in the Metallurgical Grain Structure of Cladding

The angle of the columnar grains in strip cladding typically varies between 0° and 15° to the surface normal at the junction between cladding strips.

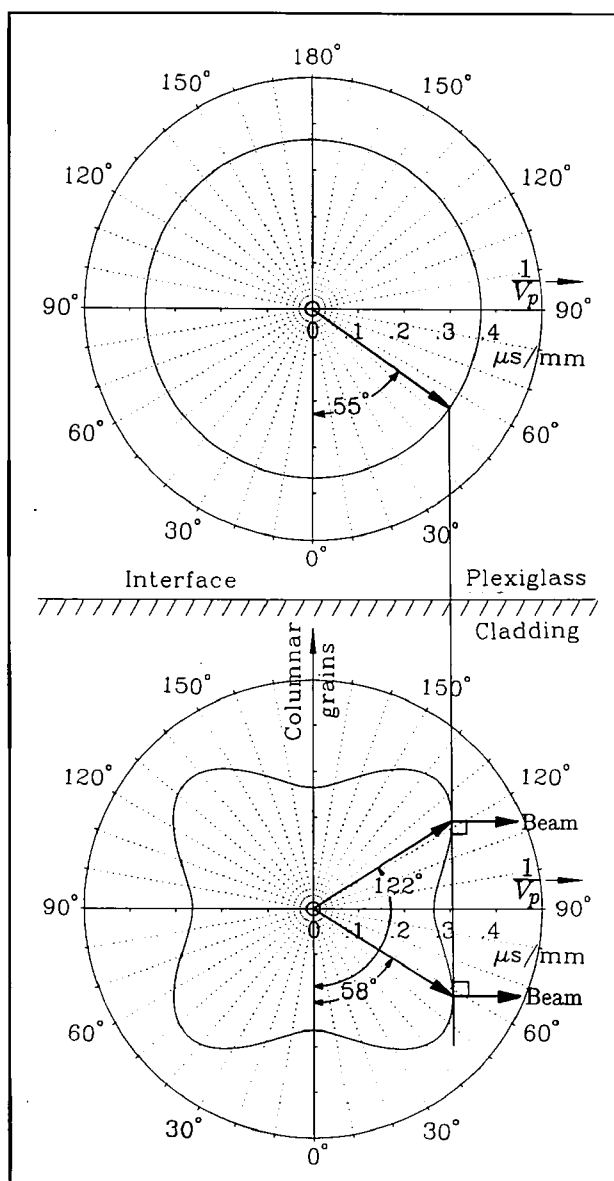


Fig. 3.18: Slowness surfaces for a 76° (i.e. 55° in the plexiglass shoe) shear wave probe on cladding which results in total internal reflection of the refracted shear wave

Much larger variations than this can be observed in MMA cladding. These variations in tilt make all cladding layers inhomogeneous and cause phase distortions of the ultrasonic wave fronts as illustrated in Fig. 3.19. This figure was produced by tracing rays from an immersion probe into a layer of cladding, then into steel. The grain tilts that occur at the junction between cladding strips have been simulated in the ray tracing and result in distortion of the rays that pass through the overlap region resulting in a loss of sensitivity.

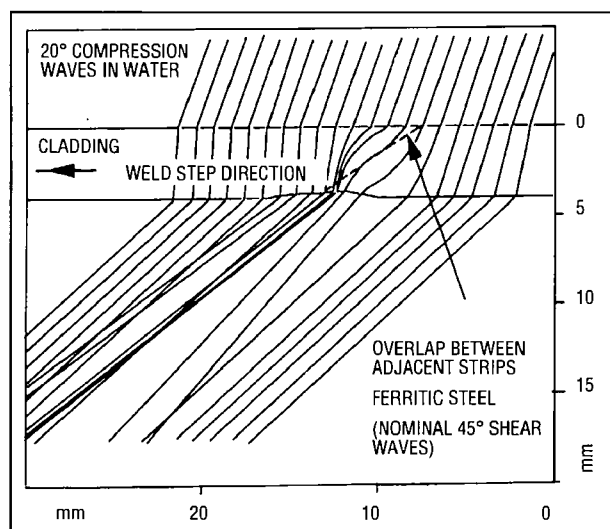


Fig. 3.19: Computer ray-tracing illustrating distortion of the sound beam at the overlap between adjacent strips of cladding for 45° shear waves

As for the previous examples probes with high test frequencies are more badly affected than probes with low test frequencies and S_V waves are more affected than compression waves. In addition to this ultrasonic beams with a high angle are more badly affected than low beam angles.

Grain tilt at the overlap between cladding strips has very little effect on the ultrasonic beams generated by large focused immersion probes, since the large aperture smears the distortion out.

3.3.2 The Effects of Surface Finish and Grain Tilt Variations

It is invariably necessary to grind fusion welded clad surfaces prior to ultrasonic examination and if the grinding is performed manually, the result is usually an undulating surface. When using contact probes on an undulating surface thick couplants are generally necessary to maintain coupling. Thick couplant layers are always undesirable since they result in distorted beams if the couplant thickness varies across the contact area of the probe.

(i) Beam Shape

The properties of cladding also have a large effect on beam shape. Fig. 3.20 is a contour map of the ultrasonic signals detected with a 1 MHz, 60°, shear

wave probe of a flat bottomed hole in a clad ferritic block. Referring to fig. 3.20 which shows the signals:

- (a): before the block was clad,
- (b): after cladding the block with two layers and dressing the surface by hand grinding,
- (c): after machining away part of the second layer of cladding to produce a perfect surface for scanning,
- (d): after machining away all the second layer of the cladding.

It is apparent in figures 3.20(b) and (c) that the beam has split in two or three components and this is not due to surface finish. Local variations in grain tilt can also produce similar distortions to this.

Focused immersion probes with diameters of at least 100mm are routinely used to examine clad nuclear components such as LWR pressure vessels. Fig. 3.21 shows a set of beam contours for a 1 MHz immersion probe with a focal length of 150mm generating a 60° shear wave beam in the same test block with the same flat bottomed hole reflectors as that from the contact probe. Therefore pictures a,b,c and d are directly comparable in the two figures.

It is apparent from Fig. 3.21 that the focused immersion probe is much less affected by the cladding than the contact probe described

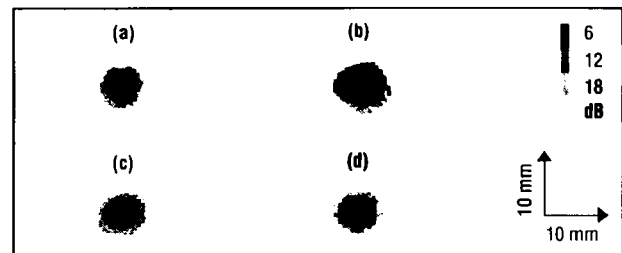


Fig. 3.21: The effect of surface finish on the beam shape of a focused 60° shear wave immersion probe after reflection on a flat bottom hole

previously. This is due to the large diameter of the focused probe which results in averaging of the signals.

(ii) Effects of Surface Finish on the Relative Attenuation of Cladding

Figs. 3.22 and 3.23 show the effect of the surface finishes detailed below on the amplitude of back wall signals detected with 45° shear wave probes:

Surface finish

- as clad surface, no dressing,
- after machining away 1 mm,
- after machining away 4 mm,
- after machining away all the cladding leaving only the heat affected zone.

(The original thickness of the cladding was 6 mm.)

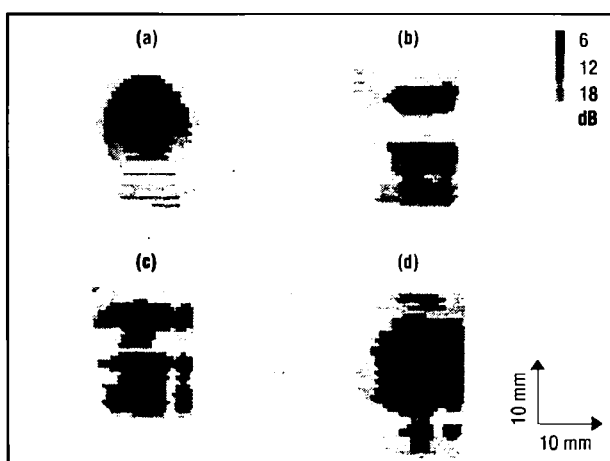


Fig. 3.20: The effect of surface finish on the beam shape of a 60° shear wave contact probe after reflection on a flat bottom hole

- (a) = without clad
- (b) = hand ground finish
- (c) = machined finish
- (d) = second layer removed

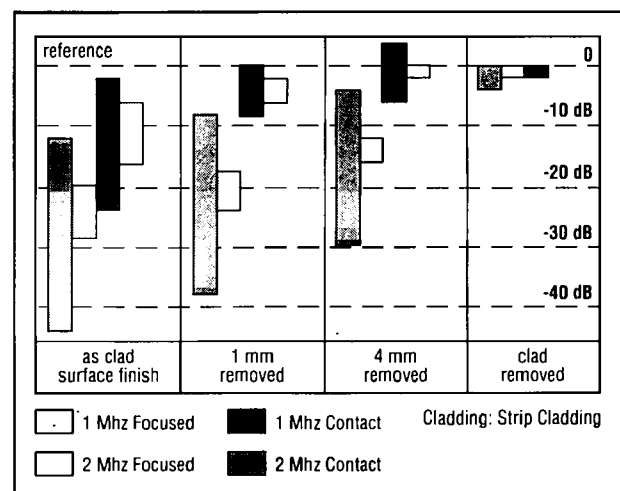


Fig. 3.22: The effect of cladding surface finish on the amplitude of a backwall signal measured with 45° shear wave probes

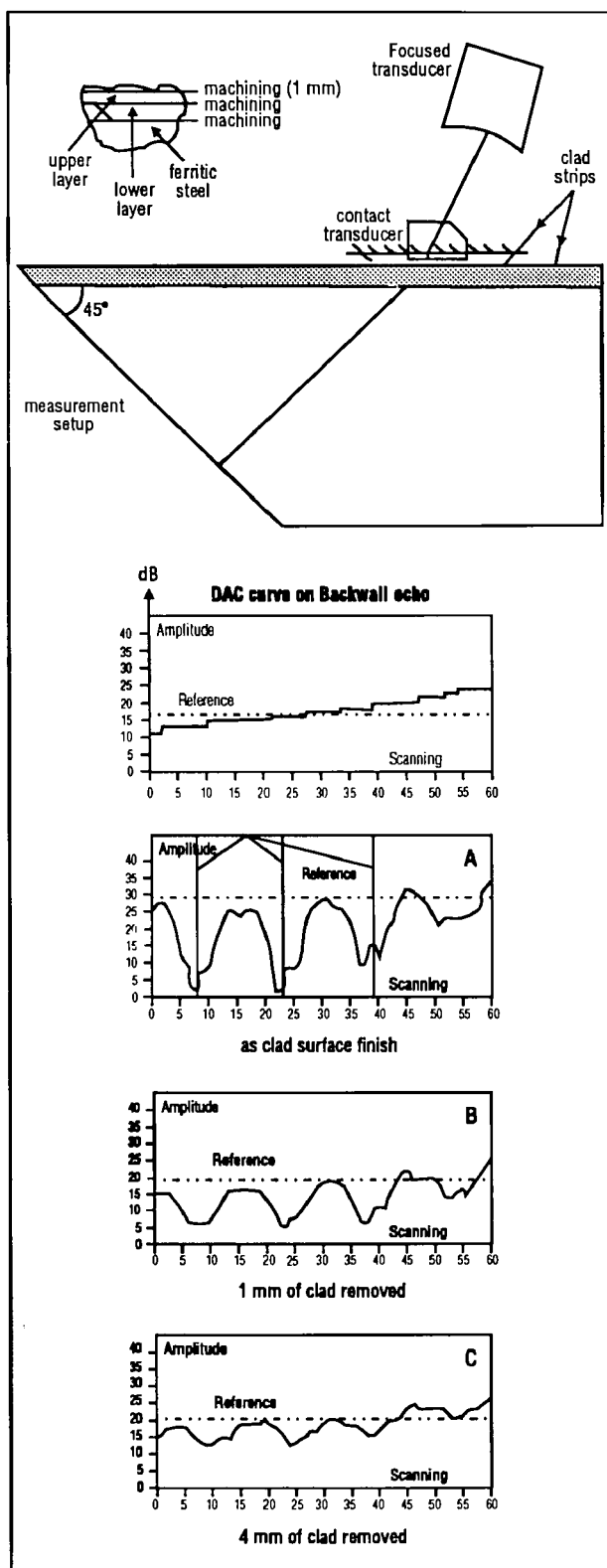


Fig. 3.23: Attenuation measurements on clad blocks using 1 MHz 45° shear wave contact probes

Figure 3.22 is a condensed presentation of many data sets like Fig. 3.23. In Fig. 3.22 results are presented for 1 MHz and 2 MHz unfocused contact probes and focused immersion probes. The experimental arrangement is illustrated at the top of Fig. 3.23. The following conclusions can be deduced from these results:

- Variations in the amplitude of the back wall signal of 20 to 30 dB are apparent for 2 MHz unfocused probes, and this is not substantially improved by machining the surface of the cladding smooth. This can only be due to the highly anisotropic properties of the cladding and also to grain tilt at the junction between cladding strips.
- The amplitude of the back wall signal measured for the 1 MHz probes was higher than that measured for the 2 MHz probes. Therefore the attenuation was lower for the 1 MHz probes than for the 2 MHz probes.
- The variation in the amplitude of the back wall signal was lower for the 1 MHz probes than for the 2 MHz probes.
- The amplitude of the back wall signal varied less for focused probes than unfocused probes.
- The heat affected zone had little, or no effect on the amplitude of the back wall signal.

(iii) 0° Shear Wave Beams

When examining clad components with shear wave probes a spurious subsidiary beam is sometimes observed propagating at approximately 0° as shown in Fig. 3.24. The amplitude of this beam is weaker than the main beam, but it causes distortion of the latter. The subsidiary beam can cause spurious back wall reflections. The origin of the 0° shear wave beam is hard to explain.

3.3.3 Comparison of MMA and Strip Cladding

Two of the most common types of cladding used today are Strip and Manual Metal Arc (MMA) Cladding (see Section 2.2). In this section we discuss the differences in acoustic behaviour between these two types of cladding.

Strip Cladding

As mentioned in Section 3.3.1 the grain tilt of the cladding has a large effect on the propagation

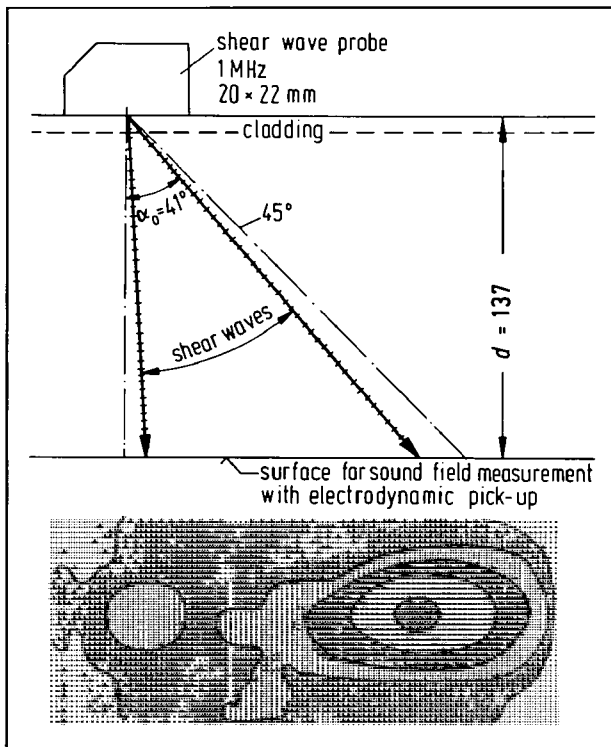


Fig. 3.24: Spurious lobe at nearly normal incidence detected at the back wall and caused by beam distortion in the cladding; single pass strip cladding, amplitude dynamic range -9 dB to -32 dB, amplitude of the spurious lobe -20 dB.

direction of ultrasound. For strip cladding, the grain tilt is uniform across most of the width of a strip, see Section 2.2.2, Fig. 2.3, but changes occur at the strip overlaps. As a result the acoustic behaviour at these overlaps is complex and an increase in the attenuation occurs. Fig 3.19 shows the distortion which occurs to a parallel ultrasonic beam at the overlap. The typical losses measured for 45° shear waves in 10 mm thick strip cladding is 4 dB to 6 dB for 1 MHz to 1.5 MHz, rising to 10 dB to 14 dB at 2 MHz. Thus, inspection frequencies of 1 MHz to 1.5 MHz are recommended for shear wave inspections.

Manual Metal Arc (MMA) Cladding

For MMA cladding, each individual weld bead, typically less than 10 mm wide, can be regarded as "strip". Hence, the overall grain structure is complex and large variations in the attenuation occur across the whole clad surface.

The magnitude of the variation of attenuation is dependent upon the precise welding procedure, e.g. weaving the electrodes during welding may produce a more uniform attenuation. Also the lower the frequency the more uniform the attenuation, see Fig. 3.25. In figs. 3.4, 3.5 and similar figures to follow, velocity is expressed in (mm/μs) because the numbers are convenient: $V(\text{m/s}) = V \times 10^{-3} (\text{mm}/\mu\text{s})$

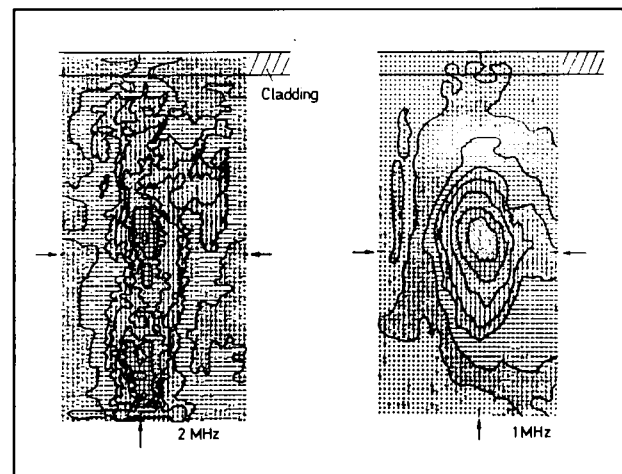


Fig. 3.25: Cross section of the sound fields of SV-wave probes after propagation of the ultrasonic beam through a double pass strip clad layer. Measurement setup as in fig. 3.23, SV-wave probes with 45° incidence angle, 2 MHz (left) and 1 MHz (right), as clad surface finish, amplitude dynamic range -4 dB to -32 dB (left) and -2 dB to -32 dB (right)

4. GUIDELINES FOR THE INSPECTION PROCEDURE

4.1 General Remarks

Since the ultrasonic inspection of cladding layers, or of ferritic base material through cladding layers, presents greater difficulties than for inspection of ferritic materials, the preparation of ultrasonic procedures requires detailed attention. In general it is important that operators are informed of the relevant details of cladding deposition, as this is likely to affect the inspection capability. The objectives of the inspection must be considered and optimised techniques chosen to meet these objectives. To deploy these techniques, detailed procedures involving the use of specialised equipment must be produced.

4.2 Information on the Cladding Required Prior to Establishing the Inspection Procedure

4.2.1 Cladding Type

Section 3.3.3 describes the effects of different cladding procedures on inspection capability.

The knowledge of cladding process parameters could thus help the inspector to optimise the inspection plan and to understand results.

4.2.2 Cladding Thickness

Section 3 describes how in general the losses associated with the cladding layer are related to the thickness of that layer. Section 3.3.1 also explains the effect of cladding thickness on the location of flaws (see Fig. 4.1). Table 3 summarises the typical corrections to be applied for flaw location assuming:

- Stainless steel cladding material.
- Ferritic base material.

- Columnar grains in the cladding are oriented approximately normal to the surface.
- A flat clad to ferritic interface.

NOTE: "The beam angles and corrections given in Table 3 have been derived from the elastic constants given in Figures A2.5, A3.2, and A3.3 (nominally 304 stainless steel) and hence are representative for a particular cladding material. Materials with different elastic constants will generate beam angles in the cladding that differ from those given in Table 3. It is recommended that for any given cladding material the actual beam angle is measured using a suitable test sample containing the material of interest."

It can be seen that cladding thickness controls the magnitude of these corrections. Therefore it is important to establish the thickness of the cladding prior to an inspection using a technique outlined in Section 4.3.

If the above conditions are not satisfied it is important to note that the simple corrections specified in Table 3 will generally no longer apply because of complications such as beam splitting as described in Section 3.

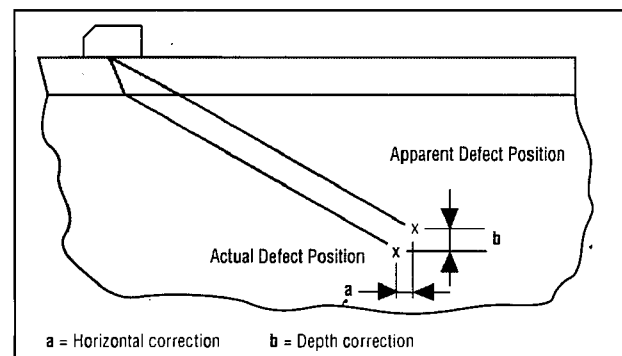


Fig. 4.1: Definition of horizontal and depth correction

Table 3: Example corrections to be applied for flaw location

Beam angle in ferritic base material	Shear(S_V)			Compression		
	45°	60°	70°	45°	60°	70°
Approximate angle in cladding	0°	27°	48°	49°	57°	60°
Horizontal correction	0.7T	0.5T	0.3T	0.1T	0.1T	0.1T
Depth correction	0.3T	0.4T	0.5T	0	0.1T	0.3T

T = cladding thickness.

Horizontal and Depth Corrections as defined in fig. 4.1

For a correct understanding of inspection results, the cladding thickness should be measured at the following locations:

- Where deviations in the cladding procedure may have occurred.
- Where an important defect has been found.

4.2.3 Surface Finish

Section 3.3.2 describes the effects of surface finish on ultrasonic inspection. Poor surface finish or error of form will adversely affect the inspection.

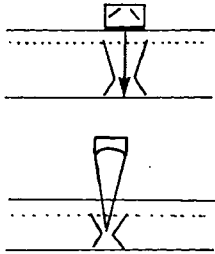
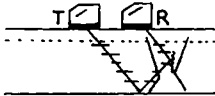
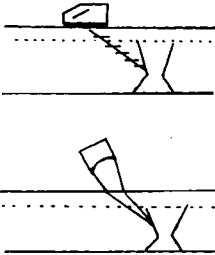
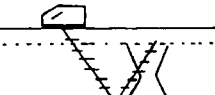
The surface finish requirements should be as defined in the inspection code or contract being used and should be referenced in the inspection procedure. The surface finish of the actual component being inspected should be checked against these requirements prior to inspection.

For optimum inspection capability the cladding surfaces must allow free movement of the probe(s) and provide satisfactory conditions for the transmission of ultrasonic waves. As a minimum requirement the surface must be free of visible flaws, undercut, weld spatter, loose scale, machining and grinding particles and any other foreign matter. The surface roughness should not exceed a centreline average of 20 μm and the waviness should not exceed ± 0.5 mm over any 50x50 mm area, except at the boundaries between two adjacent strips of cladding. These requirements are important to minimise attenuation and distortion of the ultrasonic beam.

4.3 Overview of Inspection Techniques

The techniques to be used depend on the objectives of the inspection is of primary importance. The location and type of defects being sought. Tables 4

Table 4: Techniques for the examination of the weld from the clad surface. Techniques also applicable for the inspection of the base material

Application	Configuration	Transducers	Remarks
- Defects parallel to surface - Laminations in base-material - Slag and pores in weld		Single or twin-crystal probe, 0°, compression wave, 1-5 MHz Focused probes, 0° compression wave 1-2 MHz	
- Lack of fusion - Defects perpendicular to surface		2 single probes in tandem array 45°, shear wave, 1-2 MHz	- Capability depends on local influence of the cladding - Correction for attenuation advisable
- Defects in weld and HAZ - Lack of fusion		Single or twin-crystal probe, 35°-60°, shear wave, 1-2 MHz, half skip 45°-70° compression wave 1-2 MHz, half skip Focused probe 45°-60° shear wave 1-2 MHz 40°-60° compression wave 1.5-2 MHz	- Capability depends on local influence of the cladding - Correction for attenuation advisable
- Lack of fusion - Defects in near surface		Single probe, 35°-60°, shear wave, 1-2 MHz, full skip	- Capability depends on the cladding - Correction for attenuation advisable

- Attenuation (cladding-influence) - Detection of defects large enough to cause significant beam obscuration		2 single probes in T-R arrangement (V-path), 45°, shear wave, 1-2 MHz	- Used to establish correction factor for the influence of the cladding
- Defects in weld and HAZ		2 single probes in T-R arrangement 35°-60°, compression wave, 2-5 MHz	- Time-of-flight diffraction technique (TOFD) - Special equipment needed

Table 5: Techniques for examination of cladding from clad surface

Application	Configuration	Transducers	Remarks
- Thickness measurement - Defects in cladding - Bonding defects in cladding and interface		Twin-crystal probe, 0°, compression wave, 2-5 MHz Focused probe compression wave 2-6 MHz	
- Surface breaking cracks		Twin-crystal probe, creeping-wave, 2-5 MHz Focused probe compression wave 2 MHz, 60°, 70°	- Shear wave component also present (spurious indications from interface possible)
- Deeper surface breaking cracks - Defects in cladding - Subcladding cracks		Twin-crystal probe, 70° compression wave, 2 MHz Focused probe 60° compression wave, 2 MHz	- Shear wave component also present (spurious indications from interface possible)
- Attenuation (cladding influence)		2 single probes in T-R arrangement (V-path), 45° shear wave, 1-2 MHz	- Used to establish correction factor for cladding influence
- Defects in cladding - Surface breaking cracks in cladding - Subcladding cracks		Single probe 45°, shear wave 1-2 MHz	- Due to shear waves the performance depends on the influence of the cladding - Correction for attenuation is advisable
- Surface defects - Subcladding cracks - Inclusions		2 single probes in T-R arrangement 35°-70°, compression wave, 2-5 MHz	- Time-of-flight diffraction technique (TOFD) - Special equipment needed

Key: = shear wave; = compression wave

Table 6: Techniques for the examination of the cladding from the unclad surface

Application	Configuration	Transducers	Remarks
- Thickness measurement - Bonding defects at the interface		Single probe, 0°, compression wave, 2-5 MHz Focused probe, 0° compression wave 1-2 MHz	- Resolution from backwall echo required
- Defects in cladding - Surface breaking in cladding - Subcladding cracks		Single or twin-crystal probe, 35°-60°, shear wave, 1-2 MHz Focused probe 45° shear wave 1-2 MHz	- Because of shear waves the performance depends on the influence of the cladding - Correction for attenuation is advisable
- Attenuation measurement (cladding influence)		2 single probes in T-R arrangement (V-path), 45° shear wave, 1-2 MHz	- Used to establish correction factor for cladding influence
- Thickness - Subcladding crack		2 single probes in T-R arrangement, 35°-70°, compression wave, 2-5 MHz	- Time-of-flight diffraction technique (TOFD) - Special equipment needed

Table 7: Techniques for examination of weld from unclad surface. Techniques also applicable to inspection of base material

Application	Configuration	Transducers	Remarks
- Defects being perpendicular to the surface		2 single probes in tandem arrangement, 45°, shear wave, 1-2 MHz	- Capability depends on the local influence of the cladding - Correction for attenuation advisable
- Defects in weld and HAZ - Lack of sidewall fusion		Single probe, 35°-60°, shear wave 1-2 MHz	- Capability depends on the local influence of the cladding for full ship examination
- Attenuation (cladding influence) - Detection of defects large enough to cause significant beam obscuration		2 single probes in T-R arrangement (V-path), 45° shear wave, 1-2 MHz	- Used to establish factor for cladding influence
- Defects in weld and HAZ		2 single probes in T-R arrangement, 35°-70°, compression wave, 2-10 MHz	- Time-of-flight diffraction technique (TOFD) - Special equipment needed

Key: = shear wave; = compression wave

to 7 consider some of the more common inspection requirements and provide general guidance on the optimum techniques which should be used in each case.

4.4 Equipment

There are no general rules which can be used to select the best apparatus and probes for a specific application. In many cases, the choice is guided by previous experience. The paragraphs below describe the various types of equipment and probes commonly used for austenitic cladding and weld inspection.

It is important to point out that the probes may be different from those commonly used for ferritic weld material.

4.4.1 Flaw Detector, Cable and Matching

Conventional flaw detectors used for ferritic weld inspection are usually satisfactory. However, for austenitic cladding inspection, it is often necessary to pay special attention to the correct matching of the ultrasonic equipment used, particularly when low frequency probes are chosen.

Once the best setting for the equipment has been established, it is important to maintain this setting throughout the inspection and to avoid changing any part of the equipment.

4.4.2 Probes

Introduction

Various possibilities exist for the selection of probe types for a particular examination of clad components. Particular attention must be paid to the damping of the probes. In many cases, highly damped probes give better results.

Shear Wave Probes

The general properties of conventional shear waves probes are well understood and are not described here. For inspections through cladding, frequencies between 1 and 2 MHz and beam angles between 35° and 60° should be used.

Compression Wave Probes

A wide range of compression wave probes is used for the examination of cladding and clad components because of the acoustic properties of cladding.

An important point to note is that angled compression wave probes also generate an associated shear wave beam at approximately one half the beam angle of the compression wave. The presence of this additional beam, which can have an intensity comparable to that of the compression wave beam, should always be considered because it can cause spurious echoes and consequently give rise to misinterpretation of the results, see Fig. 4.2.

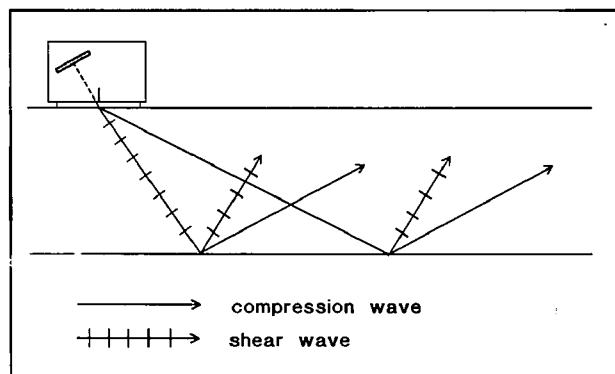


Fig. 4.2: 60° compression angle beam probe with shear wave part and mode conversion

Although the additional shear wave beam can cause confusion during the examination (because any indication could be located by either beam), careful consideration of range, angle and probe position relative to the weld often helps to decide which alternative is most likely. In particular, consideration of the echodynamic is useful for this purpose. The echodynamic of an indication arising from the compression wave beam is generally much wider than that for the shear wave beam, because the compression wave has both a larger beam angle and a larger beam width; see Fig. 4.3

As there is a division of acoustic energy between the two wave modes generated by angled compression wave probes, they do not appear to be as sensitive as shear wave probes. The percentage of the acoustic energy converted into the unwanted shear wave increases with beam angle. Therefore the apparent deficiency in sensitivity increases with beam angle.

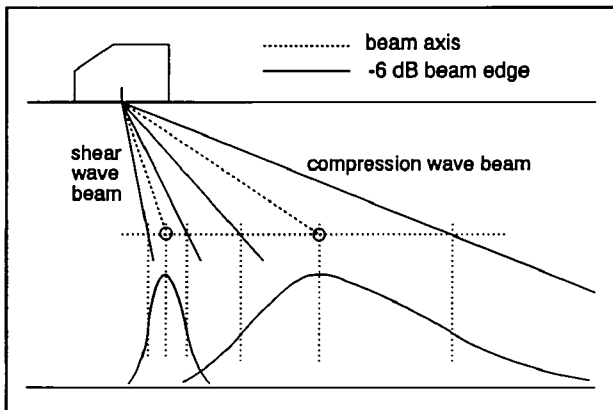


Fig. 4.3: Echodynamic with compression and shear wave beams

The other factors which affect performance are as follows:

- For a given test frequency compression wave probes have twice the wavelength of shear wave probes. Therefore the beam spread of the compression wave component is twice that of the shear wave component. Secondly the range resolution of the compression wave component is only half that of the shear wave component.
- Compression wave probes are generally only used at ranges up to the half skip distance. This is because the intensity of the reflected compression wave is reduced to a low level by mode conversion to a shear wave upon reflection.

Single Crystal Compression Probes

The basic construction of single crystal compression wave probes is similar to that of the well known single crystal shear wave probes, but the wedge angle is much smaller than for a shear wave probe with the same beam angle in steel. For this reason reverberations within the wedge are a more serious problem than for shear wave probes. Specific measures to decrease these reverberations can be taken such as increasing the wedge delay and by application of damping material to the wedge. The result of these measures is that single crystal compression probes are often relatively large in size.

Figure 4.4(a) shows a typical distance amplitude correction (DAC) curve for an unfocussed compression wave probe. They have a longer dead time and lower peak sensitivity than twin crystal probes, but they can be used to examine components at much longer ranges than twin crystal probes.

Twin Crystal Compression Probes

The crystals in a twin crystal probe are usually inclined to one another so that their ultrasonic beam axes intersect to produce a quasi focusing effect. Figure 4.4(b) shows a DAC curve for a twin crystal probe. At ranges close to the quasi focus the sensitivity and signal-to-noise ratio are higher than those for an equivalent single crystal probe, i.e. a probe with an identical crystal to the transmitter or receiver crystal in the twin crystal probe.

The disadvantage of quasi focusing is that several twin crystal probes with different focal lengths are required to examine a thick component as indicated in Fig. 4.5.

The crystals in a twin crystal probe are usually positioned side by side as shown in Fig. 4.6, but they may also be positioned one behind the other. This figure also shows the amplitude of the beam as a function of distance in two directions, one of which is the DAC curve.

The construction of the twin probe considerably reduces the effect of reverberations within the probe wedge, leading to a very short dead zone.

A complication which arises with the twin crystal compression wave probes is that the beam angle is a function of range for any material. Generally the beam angle decreases as the range increases. For

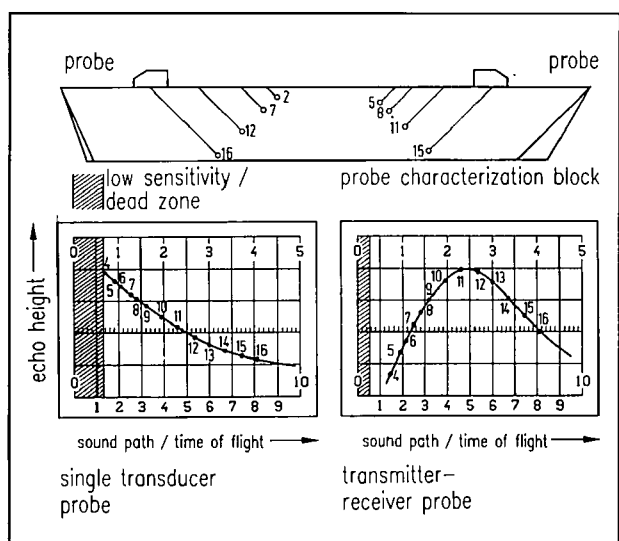


Fig. 4.4: Distance-Amplitude-Correction (DAC) curves for characterization of (a) single crystal and (b) twin crystal compression wave probes

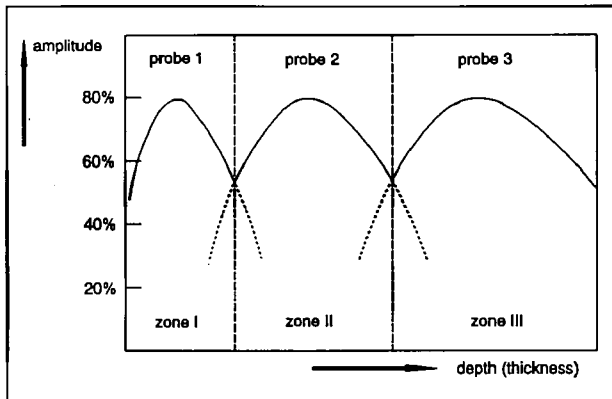


Fig. 4.5: Several probes required to maintain sensitivity over full wall thickness

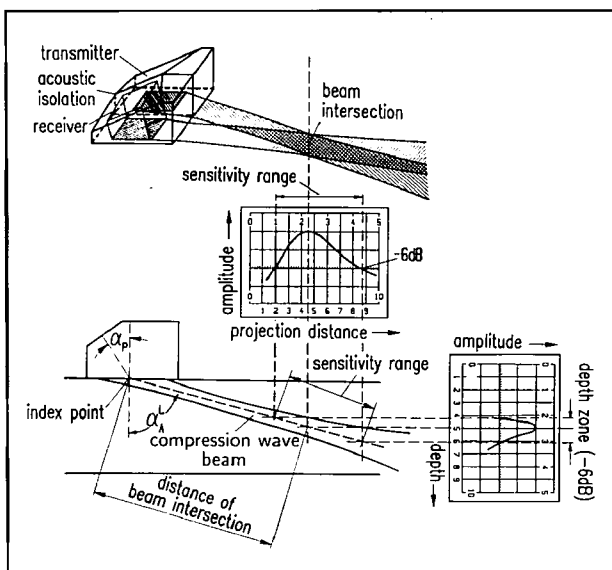


Fig. 4.6: Sensitivity diagrams of twin crystal probes for compression waves

accurate measurement of flaw location the beam angle should be measured over the useful range of the probe using side drilled holes at different depths in a test block manufactured from the material to be tested.

Creep Wave Probes

Creep wave probes are very useful for the detection of vertical flaws in cladding, since the beam angle of the compression wave component peaks at 75° , but with a significant component parallel to the surface.

Creep waves decay very strongly with range and for this reason they are usually generated by twin crystal probes with short focal length. Creep wave probes also have a very strong shear wave beam at approximately 33° .

Focused Probes

Ultrasonic beams can be focused with curved crystals or lenses in contact or immersion probes, the focusing can also be achieved with phased arrays, but these are beyond the scope of this handbook.

A contact probe which has proved very useful for the detection of cracks in cladding is a twin crystal 70° compression wave probe with a quasi focal length of 15-25 mm. True focusing is also achieved, with approximately the same focal length as the quasi focus, by using curved crystals. This combination of focusing techniques produces a sharply focused compression wave beam with a high angle which is often essential for the detection of vertical planar flaws in and under the cladding.

In principle the main advantage of using focused probes for the inspection of acoustically noisy materials is to minimize the volume of material which is sonified by the ultrasonic beam.

This minimises the scattered energy which is returned to the receiver and improves the signal-to-noise ratio compared to that which can be achieved with an equivalent unfocused probe.

There is an obvious advantage in using focused probes for sizing flaws by probe movement techniques. This may be an overriding factor in favour of using focused probes. However, a much finer scanning pitch is required for a focused probe than an unfocused one to achieve 100% coverage of a component. Furthermore, it may also be necessary to use several focused probes to examine a thick component as indicated in Fig. 4.5.

Focused ultrasonic beams can be produced by contact or immersion probes containing lenses or curved crystals; see Fig. 4.7. Generally it is possible to produce narrower beams with focused immersion probes than contact probes, since larger crystal sizes are practical for the former. Focused immersion probes must however be used as specified by the manufacturer since they are very sensitive to small changes in the beam angle in water due to the high refractive index at the water/steel interface. Furthermore their sensitivity to flaws can be strongly influenced by the beam path length in water.

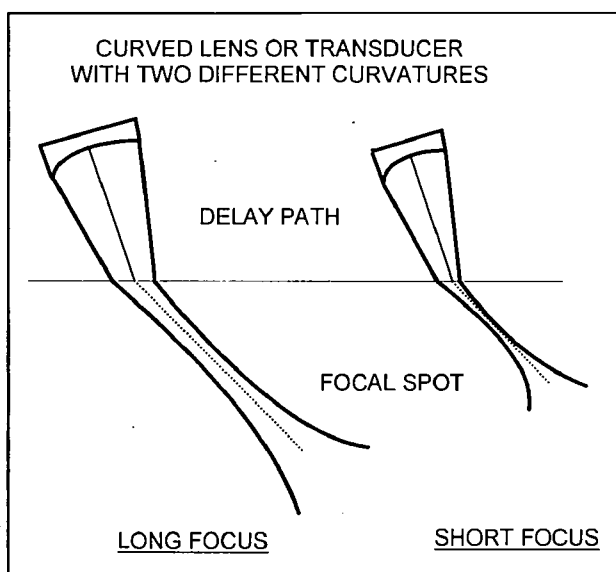


Fig. 4.7: Focused sound field due to a lens or curved crystals

On the other hand when inspecting from the clad side of a component the effect of small irregularities in the cladding layer, such as at the overlap between cladding strips, is less for large diameter focused immersion probes than for contact probes. This is due to the averaging effect of the larger beam diameter of immersion probes at the cladding surface compared to contact probes.

Electromagnetic Acoustic Transducers (EMAT's)

S_h waves, which have advantages over S_v and compression waves for certain applications, cannot be transmitted across a liquid couplant layer and hence piezoelectric transducers cannot be used for most inspections where the probe has to be scanned over the surface. Consequently, S_h waves are generated using EMATs which excite the surface of electrically conducting materials with pulsed electromagnetic fields using a combination of eddy currents and magnetic fields. Thus no liquid couplants are needed and the direction of the applied magnetic and electric fields determines the wave mode that is generated. The efficiency of the process for generating ultrasonic pulses is typically 30 to 40 dB lower than for piezoelectric devices and so special electronic hardware is required.

Although the generation of S_h waves is more complicated and the efficiency of generation is relatively poor the benefits which they offer means

the use of EMATs is desirable for certain inspection applications. In particular, S_h waves combine the good transmission (see Appendix 3) and low distortion properties of compression waves with the corner reflection properties of S_v waves. Furthermore the amplitude coefficient for the corner reflection for S_h waves is unity for all beam angles whereas this is true only for a limited range of angles for S_v waves. Thus S_h waves are particularly useful for the detection of defects that are at, or near, the far surface.

For the special case where the plane of incidence is in the meridian plane the S_h wave is not coupled to the other wave modes and hence there is no mode conversion unlike compression or S_v waves.

In deciding whether the use of EMATs is appropriate one must carefully consider the inspection situation such as the defects under investigation and the cladding macrostructure through which the beam has to propagate. Further details of the design and performance of EMATs is given in Appendix 4.

4.5 Calibration Blocks

Calibration blocks are ideal reference blocks for setting the inspection parameter such as sensitivity in a reproducible manner. The following calibration types are recommended for the inspection of cladding layers or of clad components:

4.5.1 Cladding Thickness Measurement

The calibration block should consist of ferritic base material with stepped cladding e.g: as shown in Fig. 4.8. Accurate thickness measurement depends on the representative cladding being used, both in terms of material and cladding procedure. The block may be used for the calibration of the inspection from both the clad and the unclad side.

4.5.2 Lack of Bond Detection

The calibration block should be manufactured from clad ferritic material. Flat bottomed holes are introduced from the backwall to provide suitable planar reflectors between the clad layers and at the clad to ferritic interface. The block is used for inspection from the clad side and an example is shown in Fig. 4.9.

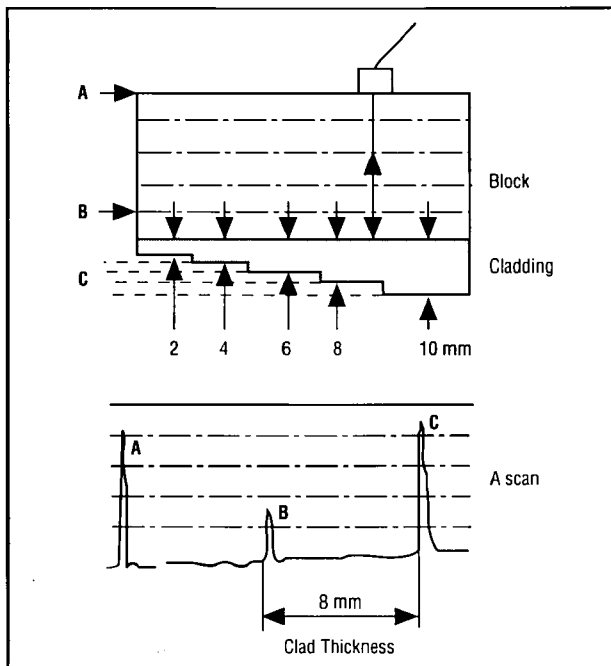


Fig. 4.8: Cladding thickness measurement from the unclad side

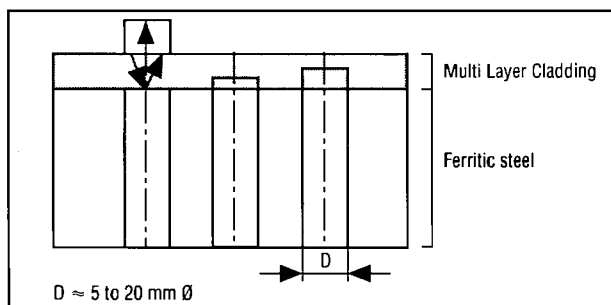


Fig. 4.9: Sensitivity setting for twin crystal compression wave probes for detection of bonding defects in the cladding area

4.5.3 Calibration Blocks for the Detection of Flaws in Cladding Layers and Clad Components

Unclad Blocks

Significant signal amplitude variations can occur when angle beams propagate through cladding as described in Section 3. Unclad calibration blocks are therefore recommended to set inspection parameters. They should be made from material representative of the base material being inspected and contain a number of 1.5 to 3 mm diameter side drilled holes and notches to allow a DAC to be established over the inspection range.

For the examination of cladding layers the calibration block should contain side drilled holes at depths of $t/2$, t and $2t$ where t is the thickness of the cladding layer. This will enable a DAC curve to be constructed for ultrasonic probes with short focal lengths for the inspection of cladding.

Similarly, for the examination of base material and welds below cladding the calibration block should contain artificial flaws such as e.g. side drilled holes at depths of $T/4$, $T/2$ and $3T/4$, where T is the thickness of the clad component.

Notches may also be included in the calibration block if required.

Clad Blocks

Clad blocks may also be used for calibration purposes, but the cladding must be representative of that on the component to be examined. The acoustic properties of the cladding will cause calibration anomalies.

4.5.4 Sweep Range Calibration Blocks

Conventional ferritic sweep range calibration blocks are recommended for all probe types, apart from range calibration for clad thickness measurement, for which a block of the type shown in Fig. 4.8 should be used.

It must be recognised however that beam velocity in austenitic cladding is variable. Section 3 describes the variations that occur between beams propagating through austenitic cladding and ferritic base material.

4.6 Methods for Calibration

4.6.1 Sweep Range Calibration

Sweep range calibration for shear wave probes and 0° compression probes is established using conventional methods and need not be discussed here.

For angle compression probes, sweep range calibration is established using either of the following methods:

- By setting velocity using a 0° compression wave probe in the conventional manner, then using the time delay control to compensate for the shoe

delay using a radius echo once the angle compression probe is connected.

- Calibrate by using a minimum of two reflectors at different but known ranges, e.g. 50 mm and 100 mm radiused calibration blocks.

4.6.2 Sensitivity Calibration

A DAC curve should be established using reference reflectors in the appropriate calibration block. If the block is clad, the gain at which the DAC curve is constructed becomes the reference sensitivity. Anomalies in the DAC curve should be averaged out.

If the calibration block is unclad a transfer correction must be applied in order to compensate for the effects of cladding. The reference sensitivity then becomes the gain at which the DAC curve was constructed, plus the transfer correction.

To calculate the transfer correction for a probe used in the procedure the loss in signal amplitude by transmission through the cladding must be measured. Since this can vary from place to place on the cladding many measurements have to be made and it is recommended that an amplitude distribution curve is constructed for each probe included in the procedure. For angled probes this usually involves V path attenuation measurements.

It will then be necessary to choose a value for the transfer correction, which is always a compromise. As an example in Fig. 4.10, a transfer correction has been chosen which results in an inspection sensitivity that is too high for 85% of the cladding and too low for the remainder. Obviously the low percentage figure should be minimised, but the incidence of false indications must also be minimised. If the transfer correction is too high it may be necessary to change the inspection procedure.

The above procedure of producing a transfer correction takes much longer than using a clad calibration block, however it is a statistical approach which is defensible. Measurements based on clad calibration blocks containing a few side drilled holes may give an inspection sensitivity which is too high, or too low, and for this reason it is difficult to defend.

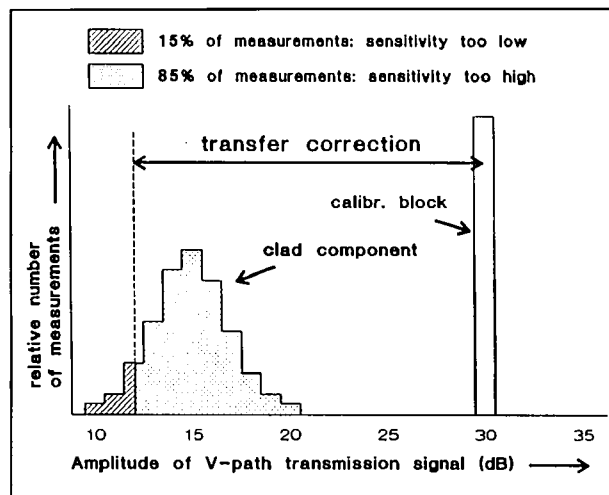


Fig. 4.10: Transfer correction (unclad calibration block)

4.7 Recording Level and Desirable Signal-to-Noise Ratio

The recording level is established by adjusting the reference sensitivity, incorporating the transfer correction as applicable, to a level at which recordable indications exceed the marked DAC curve. For instance, if the required recording level is 10% DAC, the gain is increased by 20 dB.

In some cases the prescribed sensitivity setting may lead to a high level of noise due to grain scattering which results in an unacceptable number of false calls. If this occurs attempts should be made to optimize the inspection technique e.g. by using alternative probes. If this is not possible the recording level must be changed, thus accepting a reduction in the sensitivity of the inspection. As a rule of thumb the signal-to-noise ratio should be at least 8-10 dB.

4.8 Reporting and Evaluation

4.8.1 Reporting

The results of an ultrasonic examination should be given in a report which includes all the necessary information required to

- make decisions on the acceptance of the defects revealed;
- facilitate repairs of non-acceptable defects;

– permit the examination to be repeated by the same or another operator;

As a minimum, the following data shall be reported:

- Date of examination.
- Names and levels of examination personnel.
- Examination procedure, including revision.
- Identification of the calibration block
- Identification and location of the component examined, including, if necessary, marked up drawings or sketches. The report shall include observations of any geometrical feature which has limited access compared to the reference block or in other ways reduced the effectiveness of the examination.
- Surface from which examination is conducted, scanning direction, orientation of the probe(s). Nonconformity of surface condition with regard to specification should be included.
- Identification of the apparatus, the probe(s) brand name, type, serial number, fabrication or identification number.
- Attenuation correction
- If applicable, a record of reportable indication(s) including:
 - peak amplitude, in dB or percent of DAC, range to reflector, search unit position, and sound beam path direction;
 - defect length or locations of the reflector end points where the amplitude crosses the recording level or –6 dB points;
 - plot of reflector location on a cross section sketch showing OD profile and ID geometry, such as root and counterbore, in the case of pipe welds;
 - the location of any subsidiary peaks in the amplitude response as the probe is moved towards or away from the reflector, if they are pronounced.

4.8.2 Evaluation

It is not the purpose of this handbook to define acceptance criteria for cladding inspections, since these should be established between the relevant authorities, purchaser and the manufacturer(s).

Nevertheless, it is recommended that important facts such as signal-to-noise ratio, etc. be taken into account before defining acceptance criteria.

Acceptance criteria are usually specified in terms of signal amplitude relative to the recording level, the length of the indication and possibly also the through wall dimension and the position of the indication in the component. The cladding can perturb the ultrasonic beam as discussed in Section 3.3 and false indications do occur and the operator should be aware of this. Questionable indications should be examined and their position located with a variety of probes with different beam angles before making a final judgement on acceptance.

4.8.3 Additional Investigations

For each probe used, indications detected at the specified testing sensitivity shall be examined by probe movement in two mutually perpendicular directions. Angle beam scans shall be made in directions towards and away from the reflector, and at right angles to these directions. The response of each defect shall be noted, and the defect shall be classified in terms of Patterns 1 to 3, as detailed below.

The properties of the cladding will influence the echo dynamic response detected from flaws, but it is very difficult to determine quantitatively what the effect will be, and care must be taken when discriminating between echodynamic patterns. However it is still appropriate to proceed with the investigations described below:

Pattern 1

A single sharp signal rising smoothly in height to a maximum then falling smoothly to zero (see Fig. 4.11).

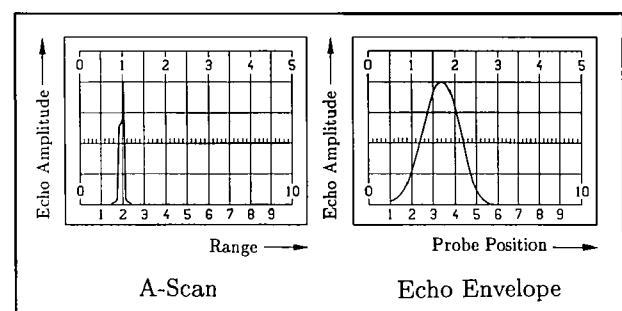


Fig. 4.11: Pattern 1 for echo envelope evaluation

Pattern 2

A single sharp signal rising smoothly in height to a maximum which is held with or without minor amplitude fluctuations with probe movement and falling smoothly to zero (see Fig. 4.12).

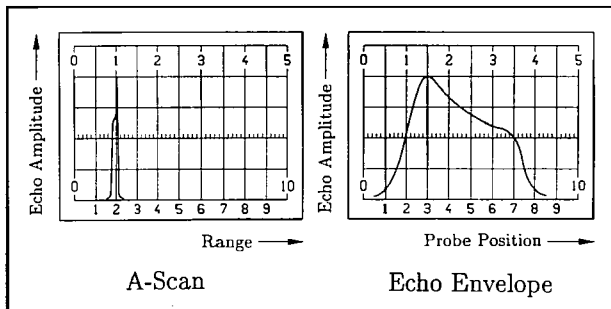


Fig. 4.12: Pattern 2 for echo envelope evaluation

Pattern 3

A signal, or group of signals, which may be fully or partially resolved, fluctuating in height as it/they rise to and fall from one or more principal maxima (see Fig. 4.13).

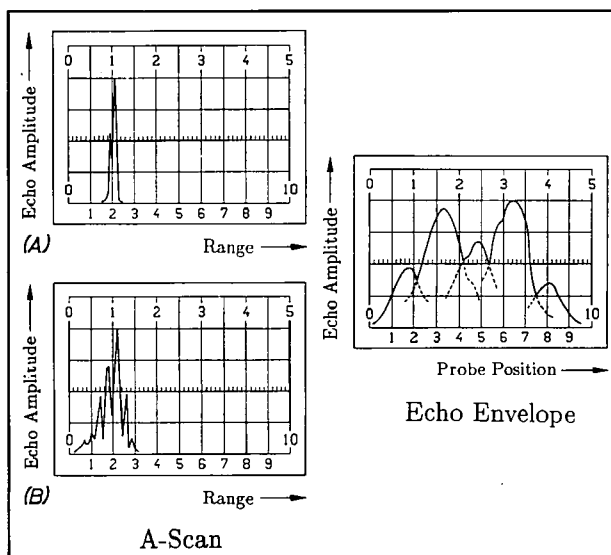


Fig. 4.13: Pattern 3 for echo envelope evaluation

For Pattern 1 behaviour, it is not possible to estimate the defect size. Such indications are often associated with volumetric defects, but it is recommended that indications of this type be assessed by other angles of probe to confirm their volumetric character.

Pattern 2 and Pattern 3 behaviour in the through wall direction are likely to indicate the presence of a planar defect. A rough estimate of defect height can be obtained by plotting the positions of the last maxima in the echo response (for Pattern 2 this involves plotting the positions corresponding to the extremes of the "plateau" in the echo response).

These techniques should only be applied when the operator has a clear understanding of the principles involved.

4.9 Performance Demonstration

The capability of a procedure to detect and size flaws and the capability of an operator to implement it can be tested with validation or performance demonstration blocks. Performance demonstration blocks must be made using the same manufacturing procedure as used for the component to be inspected and the flaws must be as realistic as possible and acoustically simulate those that can occur in the component. Furthermore, the dimensions of the flaws must be known to an acceptable degree of accuracy. Every stage of manufacture of a performance demonstration block should be controlled by a quality assurance programme.

5. RECOMMENDATIONS AND CONCLUSIONS

- The ultrasonic inspection of clad components is possible, although the capability which can be achieved is usually inferior to that of unclad components.
- The key parameters affecting the ultrasonic inspectability of clad components are the surface finish and the cladding macrostructure.
- The macrostructure of the cladding is dependent upon the cladding process. In all cases of fusion deposited cladding, however, a coarse anisotropic grain structure results which gives rise to an increased ultrasonic attenuation and skewing of the beam.
- The presence of cladding can result in the propagation of 0° shear wave beams which may give rise to false indications arising from the backwall. This is most pronounced when using 45° shear wave beams.
- The acoustic properties of strip cladding are relatively uniform except at the strip overlaps where increased attenuation and beam skewing occurs. In contrast, MMA cladding results in a variable attenuation, across the width of the cladding.
- The propagation direction of ultrasound through clad material can be predicted using the slowness surface. Hence, simple corrections can be made for positioning and sizing of defects. Alternatively, such corrections can be obtained from measurements on clad reference blocks.
- High angle (60°) shear waves can in many cases not be propagated in austenitic cladding because total internal reflection occurs at the boundary.
- The use of large focussing probes improves the signal to noise ratio for the examination from the clad surface.
- There are many advantages to using S_h waves for the inspection of cladding since it is the wave mode which is least affected by the properties of cladding. S_h waves can be generated with electromagnetic acoustic transducers (EMAT's).
- Special precautions are necessary to achieve a correct sensitivity setting for the examination of clad components. This involves either the use of unclad calibration blocks and measurements of the loss in signal amplitude caused by the cladding, or the use of representative clad reference blocks.
- Operators who are to perform the inspections should receive specialized training and have a good understanding of the problems associated with inspecting austenitic materials.
- For inspections, performance demonstration may be required to prove inspection capability.

6 - GLOSSARY OF TERMS

Acoustic impedance

This is the product of the sound velocity and density of a material.

Acoustic mismatch

Discontinuity of acoustic impedance across the boundary.

Anisotropy

An anisotropic material is one in which the elastic properties vary with direction. (see chapter 3)

Back-scattering

These are ultrasonic waves randomly reflected by a coarse grained material, which return back towards the transducer, resulting in a high noise level which is present for several milliseconds after a transmitter pulse.

Buttering layer

These are layers of weld metal deposited on fusion faces before welding between materials with different physical or chemical properties, i.e. dissimilar welds. The properties of the buttering should be intermediate between those of the two dissimilar materials involved.

Columnar grains (dendrites)

These are the long grains which grow through austenitic weld metal along thermal gradients during solidification

Coupling

- coupling a probe to a metal surface.
- when one wave mode couples to another boundary.

Crystallographic axis

On an atomic scale all metals have a crystallographic structure which has a particular type of symmetry, such as body centred cubic (bcc) for ferritic steel, or face centred cubic (fcc) for austenitic steel (see phase transition).

The crystallographic structure is defined by its system of crystallographic axes, such as the cube edges (100), (010), and (001) are the axes for the cubic structure. The symmetry of the elastic properties follows from the symmetry of the structure.

Dendrites

See columnar grains.

Dissimilar metal welds

These are welds where two dissimilar metals have been joined together by fusion welding. Often buttering layers are used in these welds.

Elastic constants

Elastic constants are those parameters which describe the elastic properties of materials. Materials with a cubic structure require three whereas textured materials such as austenitic weld metal require five

EMAT

This is an acronym for Electromagnetic Acoustic Transducer.

Epitaxial growth

This is the property of a crystal structure to maintain a certain growth pattern across boundaries, such as weld runs.

Delta (δ) ferrite content of cladding

This is the delta ferrite iron present in cladding which is added to reduce the incidence of solidification cracking.

Fibre texture

Some materials are said to have a fibre texture when they possess a crystal structure which is elongated due to mechanical work, or the solidification of columnar grains in austenitic welds.

Group velocity

See velocity.

Heat affected zone

This is the zone in the parent plate adjacent to welds (HAZ) which has been heated to a high temperature by the welding process but has not been melted.

Isotropic properties

Materials with isotropic properties have uniform properties in all directions.

Lorentz force

This is the force exerted on a conducting material by the combination of a magnetic field and an electric field and the force is the vector product.

Macrostructure

The macrostructure of a metal is that which is seen when it is polished and etched and viewed at low magnifications, i.e. x1 to x3.

Particle displacement (polarisation)

In the context of wave motion this refers to the direction of vibration of particles caused by a wave.

- In isotropic materials for compression waves the particle displacement is parallel to the direction of wave motion and for shear waves it is transverse to the direction of wave motion.
- In anisotropic materials this no longer holds, see Appendix 2, section A2.3

Phase transition

Some metals when they cool pass through phase transitions from one crystallographic symmetry to another. For example iron changes from body centred cubic to face centred cubic at 1400 °C and back to body centred cubic at 900 °C. Austenitic steels however freeze as face centred cubic and do not change.

Phase velocity

See velocity.

**Plane of wave incidence
(plane of sound propagation)**

This plane contains the normal of the interface, and the phase velocity direction.

Polarisation

Direction of particle displacement

Polycrystalline

Metals have a polycrystalline structure which means they are made up of a large number of crystallites or grains.

Pure wave

If the particle displacement is in the direction of the phase velocity for compression waves and perpendicular to the direction for shear waves, the wave mode is said to be pure. If this is not the case the waves are referred to as quasi waves.

Rotational symmetry

See transversely isotropic.

Sheeted surfaces

This expression refers to the surfaces created by plotting the velocity of elastic waves in three dimensions.

Skewing (beam skewing)

Beam skewing occurs where the phase and the group velocity of a wave are not in the same direction.

Slowness surface

This is a polar plot of the inverse of the velocity as a function of its direction. It is a special property of the slowness surface, that the group velocity is always at right angles to it. (see section 3.2.4 and Appendix 3, section A3.2).

Specular reflection

This refers to the reflection of ultrasonic beams by flaws like light reflected by a mirror.

Stiffness constants

See elastic constants

Textured structure

See fibre texture

Total internal reflection

This is where an acoustic wave is incident on a boundary at an angle which exceeds the critical angle and it is internally reflected.

Transversely isotropic

A transversely isotropic material is one which has isotropic properties in a plane at right angles to a singular crystallographic direction, which is the axis of rotational symmetry.

Velocity

phase velocity the phase velocity of an acoustic wave is the velocity of the wavefront and is measured at right angles to the wavefront.

group velocity the group velocity of an acoustic wave is the velocity of the energy flow and is measured in the direction of the sound beam.

velocity surface a velocity surface is a three dimensional polar plot of velocity versus velocity direction in the material.

Appendices

A1: Standards and Specifications

A2: Effect of Cladding Macrostructure on
Ultrasound.

A3: Reflection and Refraction

A4: Ultrasonic examination of clad components
using horizontal polarized shear waves.

APPENDIX A1

Standards and Specifications

The following are references of some of the existing standards, Codes or Specifications dealing with welding and testing of clad materials.

ASTM A 578/A 578M-85 = ASME SA-578

Standard Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications

ASTM/B-432-76a (Reapproved 1989)

Standard Specification for Copper and Copper Alloy Clad Steel Plate

SIS 21 91 30

Svensk Standard

Komponentplåt - Tekniska leveransbestämmelser
Clad steel plate - Technical delivery requirements

BS 5996: 1980

Methods for Ultrasonic testing and specifying quality grades of ferritic steel plate

ASTM A 435/A 435M - 82 (Reapproved 1987)

Standard Specification for Straight-Beam Ultrasonic Examination of Steel Plates

ASTM A 264-89a

Standard Specification for Stainless Chromium-Nickel Steel-Clad Plate, Sheet, and Strip

ASTM A 263-89

Standard Specification for Corrosion-Resisting Chromium Steel-Clad Plate, Sheet and Strip

ASTM A 20/A 20M-89a

Standard Specification for General Requirements for Steel Plates for Pressure Vessels

ASME Sect. V, Art. 5

Ultrasonic examination methods for materials and fabrication

NORSKE VERITAS (STEEL SHIPS Pt.2 Ch.1 Sec.4)

Section 4

Clad Steel Plates

BUREAU VERITAS (8-28) 1985 Edification

Rules and Regulations

For the Classification of Steel Ships and Offshore units - Materials - 1985

Amendments and Additions to the Rules and Regulations

For the Construction and Classification of Steel Ships and Offshore units Materials

No. 1 - November 1988

DIN 54123 Okt. 1980

Zerstörungsfreie Prüfung von Schweiß-, Walz- und Sprengplattierungen

Non-destructive testing; ultrasonic method of testing claddings produced by welding, rolling and explosion

AD-Merkblatt: WS Ausgabe Juli 1987

Plattierte Stähle

Werkstoffe für Druckbehälter

SEL 075

Stahl-Eisen-Lieferbedingungen 075 2. Ausgabe

Plattierte Erzeugnisse

NF-A 36-250 Juni 1987

Norme Française

Produits sidérurgiques

Tôles plaquées (Iron and steel - Plated sheet)

CODAP 85-M/65 (M5)

Regles Applicables Aux Aciers Plaqués

RCC-MR

Tome III-Méthodes de Contrôle, 1988

RCC-MR

Tome IV - Soudage, 1988

APPENDIX A2

Effect of Cladding Macrostructure on Ultrasound

Chapter 3 gives a brief explanation of some of the effects encountered by ultrasonic beams passing through anisotropic austenitic weld metal. This appendix provides more theoretical detail of these effects for those readers interested in the subject.

A2.1 Features of columnar grained cladding

This section defines the features of austenitic cladding that are important to understand the behaviour of ultrasound in this material. It also defines the necessary assumptions that are made to quantify the effects of grain structure on ultrasound propagation.

Acoustic anisotropy of austenitic weld metal or cladding is caused by the fact that the grains with cubic single crystal symmetry form an ordered columnar structure, similar to a fibre texture. One of the three crystallographic axes of the cubic crystal system has approximately the same direction for all grains, whereas both other crystallographic axes are randomly distributed, see Section 2.2. The unidirectional fibre texture is said to be transversely isotropic and therefore rotationally symmetrical.

The ultrasonic properties of the material are defined by the elastic constants.

For a single cubic crystal such as a single grain of austenitic weld metal there are only three independent elastic constants, c_{11} , c_{12} , and c_{44} .

For transversely isotropic materials such as the bulk of austenitic weld metal there are five elastic constants c_{11} , c_{12} , c_{13} , c_{33} , c_{44} , all of which can be derived from the single crystal elastic constants using the texture coefficients of the orientation distribution function for the columnar grains in the clad metal. Alternatively they can be calculated from the phase velocity surface measured on austenitic weld metal as shown in Fig. 3.3. Throughout this handbook the following elastic stiffness constants derived from phase velocity measurements on pads of X 6 CrNi 18 11 weld metal are used:

$$\begin{aligned}c_{11} &= 2.4110 \times 10^{11} \text{ N/m}^2 \\c_{12} &= 9.6916 \times 10^{10} \text{ N/m}^2 \\c_{13} &= 1.3803 \times 10^{11} \text{ N/m}^2 \\c_{33} &= 2.4012 \times 10^{11} \text{ N/m}^2 \\c_{44} &= 1.1229 \times 10^{11} \text{ N/m}^2\end{aligned}$$

The precise value of each of the constants depends upon the chemical composition of the material.

For many cases predictions of ultrasonic propagation through austenitic weld metal, such as ray tracing, are only mildly sensitive to small changes in the elastic constants. There are cases however, for instance the propagation of high angle beams in cladding, where the predictions can be very sensitive to small changes in the constants.

To theoretically model the propagation of ultrasound in cladding it is assumed that

- the ultrasound is a plane, monofrequent wave. This assumption is a fairly good model, since the ultrasonic transducer generally has large dimensions as compared with the ultrasonic wavelength. Of course, effects of diffraction and mode conversion at the aperture edges of the ultrasonic transducer, e.g. generation of surface waves, or creeping waves, are excluded by this assumption.
- the columnar grains are normal to the surface, therefore they always lie in the plane of wave incidence. There are obviously exceptions to this, such as at the overlap between cladding strips where the grain tilt may be 15° , see Section 2.2. Or, for positional manual metal arc cladding where the grain tilt may be much larger.

Two types of columnar grain tilt may occur:

- The columnar grains may be tilted in the plane of sound incidence. This would change the sound velocity, see section A2.2.
- The columnar grains may be tilted from the plane of sound incidence. This would change the character of the wave modes (namely both sound velocity and polarisation) and their energy flow would be no longer in the plane of sound propagation, see section A2.3.

For strip cladding sound propagation is modelled to take place in the meridian plane of the columnar grain texture, i.e. the plane containing the columnar grains and the incident ultrasonic beam, see Fig. A2.1. Since the transversely isotropic structure is rotationally symmetrical about the columnar grain axis, the meridian plane is any section through the material containing the columnar grain axis.

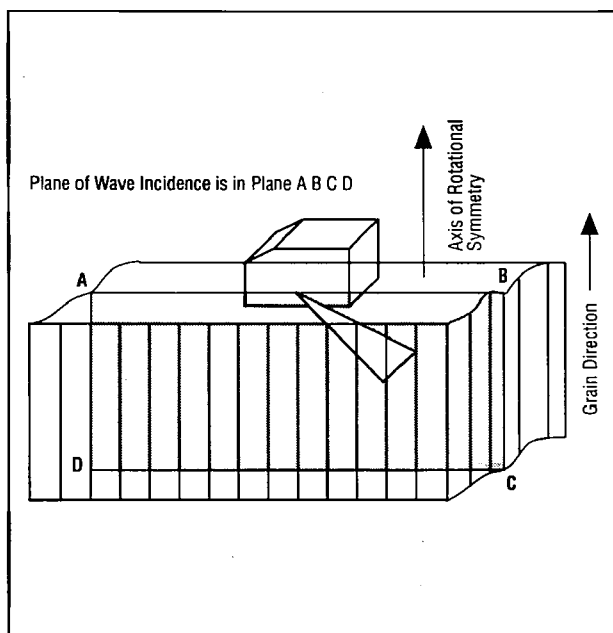


Fig. A2.1: Grain direction, plane of incidence, and axis of rotational symmetry

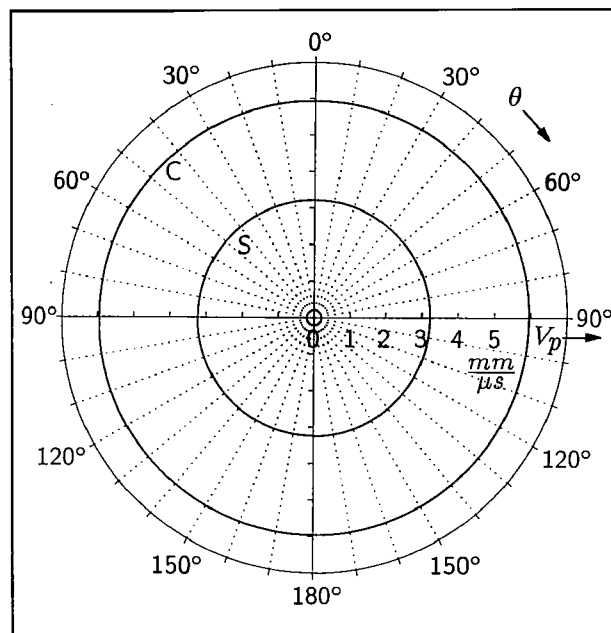


Fig. A2.2: Section of the two sheeted spherical phase velocity surface for ferritic steel

A2.2 The velocity surfaces

This section defines the group velocity and phase velocity surfaces in a more formal manner than the treatment given in chapter 3.

Imagine a small, randomly polarized acoustic source located within acoustically isotropic material, e. g. ferritic material, then the ultrasonic pulse emanating from this source would form a two sheeted spherical wave surface, e. g. Fig. A2.2. The outer sphere represents the compression (C) wave and the inner sphere the shear (S) wave. These spheres are the loci of the phase velocities and they are sometimes referred to as normal surfaces, or phase velocity surfaces.

There is an additional parameter, the group velocity (V_g), that needs to be defined in order to understand the propagation of ultrasound through anisotropic materials. The group velocity is the velocity at which the energy propagates through a material and the direction of the group velocity is often referred to as the ray or beam direction. In isotropic materials such as ferritic steel the distinction between the phase velocity and the group velocity is not normally made, since the two velocities are

the same numerically and in direction. However, as we shall see later on, this is not the case for anisotropic materials.

In acoustically anisotropic material, e.g. cladding, the propagation behaviour of ultrasound is quite different. Generally in such a material there are three and only three wave modes, one compression and two shear wave modes which propagate. They are in general non-coplanar, i.e. V_g is not in the plane of propagation.

Imagine again a small, randomly polarized acoustic source now located within the acoustically anisotropic material. The ultrasonic pulse, emanating from this source, would form the group velocity surface consisting of three sheets, e.g. Fig. A2.3. The three sheets correspond to the three wave modes with different polarisations. The group velocity surface is a plot of the group velocity V_g versus the energy flux direction. The group velocity surface, which is generally non-spherical, represents the propagation of acoustic energy. It is the appropriate surface for Huygens' construction of wave propagation. The phase velocity surface shown in Fig. A2.4, which is also non-spherical in acoustically anisotropic material, is a plot of the phase velocity V_p versus the

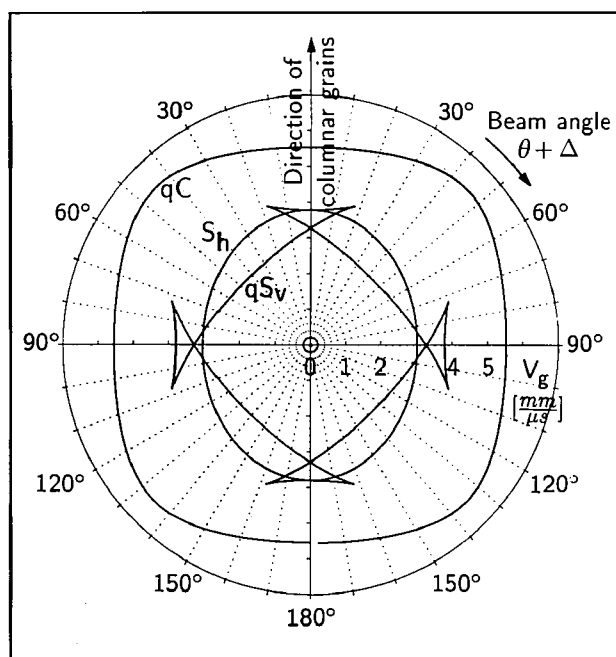


Fig. A2.3: Meridian section of the three sheeted group velocity surface in transverse isotropic austenitic cladding.

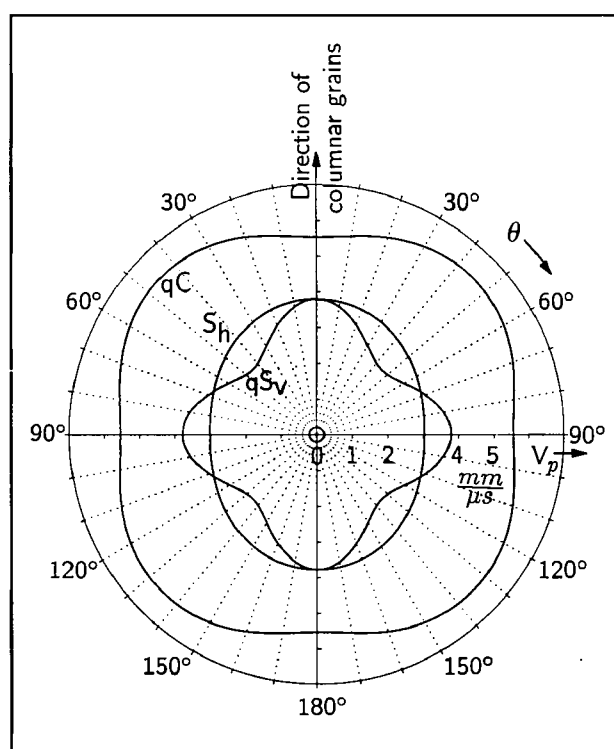


Fig. A2.4: Meridian section of the three sheeted phase velocity surface in transverse isotropic austenitic cladding.

wave vector direction. The phase velocity surface is not identical to the group velocity surface, since the velocities of acoustic energy and wave fronts are different in size and in direction. The energy flow direction is therefore skewed at an angle to the wave vector.

Because of the rotational symmetry of columnar grained austenitic cladding, the phase- and group-velocities of all three wave modes, during propagation in the meridian plane, are independent of the polar angle. Their magnitude and direction depend only on the angle θ between the columnar grain axis and the wave vector and also on the polarisations. In the case of austenitic cladding shown in Fig. A2.4, the phase velocity of quasi-compression (qC), horizontally polarized shear (Sh), and vertically polarized quasi-shear (qSv) waves could vary up to 20%, 30% and 50%, respectively.

During sound propagation in the meridian plane of transversely isotropic austenitic weld metal the energy flow of the three wave types is confined to the meridian plane. The waves are therefore said to be coplanar. If the columnar grains are tilted from the plane of sound propagation the energy flow of the three wave types is no longer in the plane of sound propagation, it is generally skewed from it: the sound propagation is said to be non-coplanar.

A2.3 Polarisation

The particle displacement polarisation of acoustic waves in acoustically isotropic material, e. g. ferritic material, is known to be in the direction of propagation, i.e. in the direction of the wave vector, for the compression wave mode and transverse to the direction of propagation for the shear wave mode. This means that the shear wave mode can be arbitrarily polarized in so far as for its particle displacement polarisation all directions transverse to the direction of propagation are possible.

In acoustically anisotropic materials particle displacement polarisations are always mutually orthogonal, but in general they deviate from the direction of the wave vector for compression waves and the direction transverse to the wave vector for shear waves. The wave modes are mixed in the sense that each mode contains components of particle displacement, which are characteristic for the other wave modes. Therefore, these wave modes are no longer pure compression or pure shear modes.

If the displacements have predominantly compression or shear wave character, they are called quasi-compression or quasi-shear, respectively.

During sound propagation in the meridian plane of austenitic cladding, a pure shear (S_h), a quasi-shear (qS_v), and a quasi-compression (qC) wave mode exist, see Fig. A2.5. The pure shear wave is polarized perpendicular to the plane of wave incidence and therefore always polarized perpendicular to the columnar grain axis. This polarisation is designated "horizontally polarized shear" (S_h). The polarisation directions of both quasi waves, qC and qS_v , are in the plane of the columnar grains, i.e. in the meridian plane, which is also the plane of propagation. In that plane, the direction of polarisation is dependent on the angle θ between the columnar grain axis and the wave vector, see Fig. A2.6. The particle displacement polarisation deviates by up to 10° from the direction of the pure wave polarisation. Only in the directions $\theta = 0^\circ$, 45° , and 90° are the wave modes pure. During propagation along the columnar grain axis ($\theta = 0^\circ$) the shear waves have the same velocity and can be arbitrarily polarized as in the isotropic ferritic material.

If the columnar grains do not lie in the plane of sound propagation, as for example at the overlap between cladding strips, the characteristics of the wave modes will be changed. In the case the particle displacement polarizations for each of the waves are uniquely determined by the direction of the wave propagation with respect to the crystallographic axes.

Even in the case where the columnar grains are tilted from the plane of sound propagation there is always a pure shear wave with polarisation perpendicular to the wave vector, while the other wave modes have the "quasi"-character discussed above. But the particle displacement polarisations of all three wave modes then are neither in the plane of sound propagation, nor are they in a plane perpendicular to it. Therefore the character of the shear waves being "vertically" or "horizontally" polarized during sound propagation in the meridian plane, is not maintained. This is the reason why generally all three wave modes couple at boundaries. All wave modes are subject to mode conversion in polycrystalline material, except where the propagation takes place in the meridian plane.

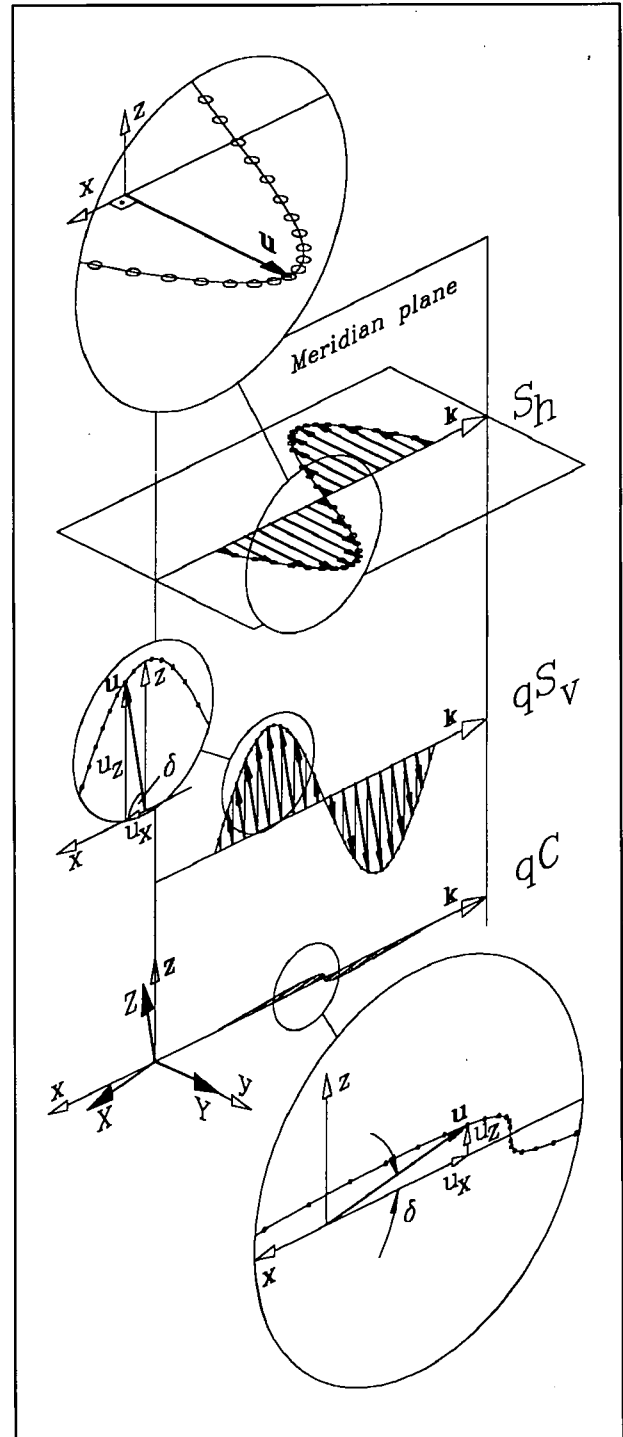


Fig.A2.5: Schematic illustration of polarization (represented by particle displacement u) and deviation δ of polarization during sound propagation in the meridian plane of clad metal. The deviation δ of polarization makes up the quasi character of the waves; Z : columnar grain direction, XYZ : crystallographic co-ordinate system, sound propagation along the direction of the rotated co-ordinate axis x in the meridian plane XZ

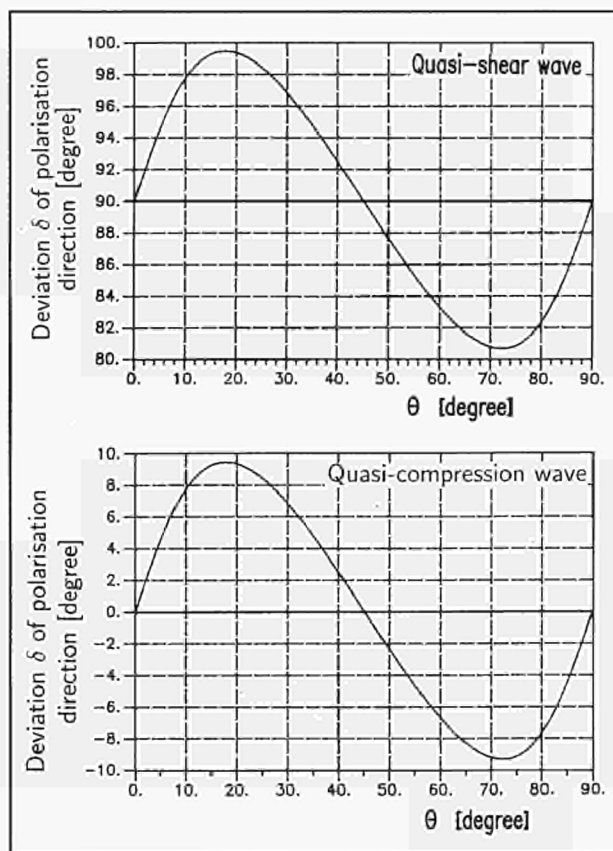


Fig. A2.6: Deviation of polarization of quasi-compression waves and quasi-shear waves (qS_V) versus the incidence angle θ during propagation in the meridian plane of austenitic cladding

A2.4 Beam skewing

Fig. A2.7 indicates the effects to be expected when a source of arbitrary polarisation and having dimensions large compared with the wave length, such as an ultrasonic probe, is applied to the surface of an anisotropic medium. The wave vector k is normal to the surface. The arbitrary oscillatory displacement of the ultrasonic source will be resolved into three mutually orthogonal polarized acoustic beams, or acoustic energy fluxes. Each beam has an energy flux, propagating with group velocity V_g , which is skewed at an angle Δ to the wave vector k . The wave fronts travel along the direction of the wave vector k with phase velocities V_p . The same effects - with adequate changes - are

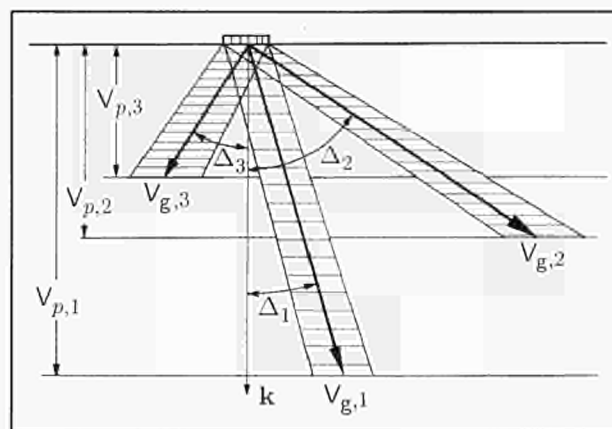


Fig. A2.7: Ultrasonic beams in an anisotropic medium when radiated from a finite arbitrarily polarized source. The lines parallel to the excited surface represent the planes which each type of vibration reaches per unit of time; the distances between source and these lines correspond to the three phase velocities V_p 1, V_p 2, V_p 3 respectively, for wave vector k

to be observed if the incidence of the wave fronts is tilted.

Phase velocity, V_p , and group velocity, V_g , are related by:

$$V_p = V_g \cos \Delta$$

Since the wave fronts are perpendicular to V_p and the end of the V_g vector is a point on the group velocity surface, Fig. A2.8 shows how the above relationship implies that the wave vector is always perpendicular to the group velocity surface. This in turn means that each portion of the group velocity surface corresponds to the wave front for a plane wave with energy travelling in that direction. From the above arguments it can be seen that the group velocity surface can be constructed from the envelope of the planes perpendicular to V_p .

Conversely the phase velocity surface can be constructed by tracing the pedal points of the tangent planes of the group velocity surface, see Fig. A2.8. The pedal points are the geometrical positions, where a vector from the origin is perpendicular to the tangent plane. This vector is the phase velocity V_p , the end of which is a point on the phase velocity surface. So the phase velocity surface can be said to be the pedal surface of the group velocity surface. These are useful relationships since they mean that either of these surfaces may be constructed from the other without knowing the skewing angle.

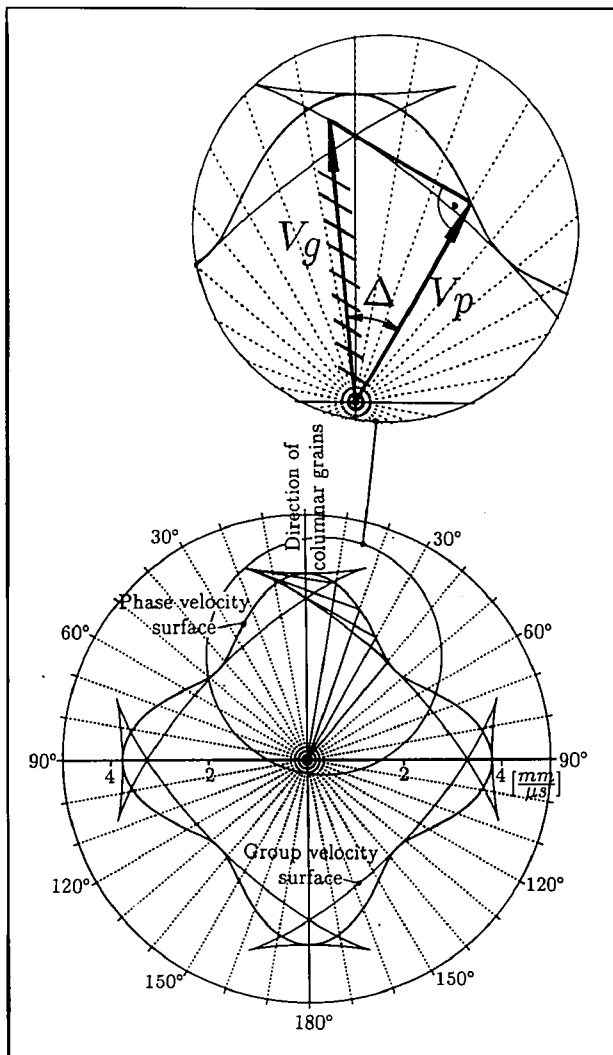


Fig.A2.8: Relationship between phase velocity surface and group velocity surface, demonstrated for the quasi-shear (qS_v) wave in the meridian plane of austenitic clad metal : Group velocity surface as envelope of the phase velocity surface; phase velocity surface as pedal surface of the group velocity surface

Fig. 3.7 summarizes the directional dependence of beam skewing Δ in austenitic cladding. The skewing angles Δ reach values up to 50° for vertically polarized quasi-shear waves and up to 20° for quasi-compression waves and horizontally polarized shear waves. In each case the beams tend to be skewed towards the direction of maximum velocity.

APPENDIX A3

Reflection and Refraction

This appendix discusses the reflection and refraction of ultrasound at boundaries between anisotropic cladding and parent material. Much of this appendix is contained within the main text of this handbook but provides a more thorough treatment for the interested reader.

Throughout this appendix it is assumed that the grains in the cladding are perpendicular to the ferritic base, so that they are in the plane of sound incidence and that the clad/ferritic interface is smooth.

A3.1 Effect of Boundaries on Wave Propagation

In the presence of cladding several boundaries may influence the propagation of ultrasound with the effect depending on whether the inspection is performed from the clad side or the unclad side of the component. The following effects are encountered:

- refraction at the clad surface,
- reflection at the free clad surface,
- refraction and reflection at the clad-ferritic interface.

The coupling layer between the ultrasonic probe and the clad surface, and the interface between the clad and the ferritic base, are boundaries between acoustically isotropic material and anisotropic material.

The three wave modes (one compression and two shear) that may propagate in acoustically anisotropic materials have their particle displacements (polarizations) in general, neither in the plane of sound incidence, nor in the plane perpendicular to it. Therefore at an interface all three wave modes may have common components of particle displacement (polarization). Consequently coupling between the separate modes may occur at an interface. The propagation directions of the reflected and refracted waves are derived from Snell's law as applied to anisotropic materials. To determine the quantity of the reflected and refracted waves it is more meaningful to consider energy, rather than pressure, reflection and refraction coefficients since the energy flow is generally in a different direction to the wave vector direction.

Appendix 2 shows that for the case where the plane of polarization is perpendicular to the plane containing the columnar grains (horizontally polarized shear waves) there is no coupling to any of the other wave modes. Consequently only reflected and refracted S_h waves are generated at a boundary for an incident S_h wave. Conversely, compression waves and S_v waves are coupled at an interface and so the following combinations may exist:

- incident compression wave;
refracted and reflected compression waves and refracted and reflected S_v waves.
- incident S_v waves;
refracted and reflected S_v waves and refracted and reflected compression waves.

In the case considered here the S_v wave has its polarization in the plane of the columnar grains, (the plane of sound incidence).

The refraction and reflection phenomena are similar to those encountered in isotropic materials except that the calculation of angles and amplitudes is complicated by the presence of the anisotropic grain structure of the cladding.

A3.2 Snell's Law

Snell's law states that:

- Incident, reflected and refracted waves all lie in the same plane and so the wave normal of all reflected and refracted waves must be in the plane containing the incident wave normal and the normal to the interface.
- Incident, reflected and refracted waves must all have the same component of the wave vector, k , tangential to the interface.

Since the slowness surface is the inverse of the phase velocity, as a function of the wave vector direction, Snell's law can be applied for both isotropic and anisotropic materials using the slowness surface and a simple geometric construction.

For the case studied in this appendix, Fig. A3.1 shows the geometrical construction of Snell's law for refraction of shear waves at a ferritic steel

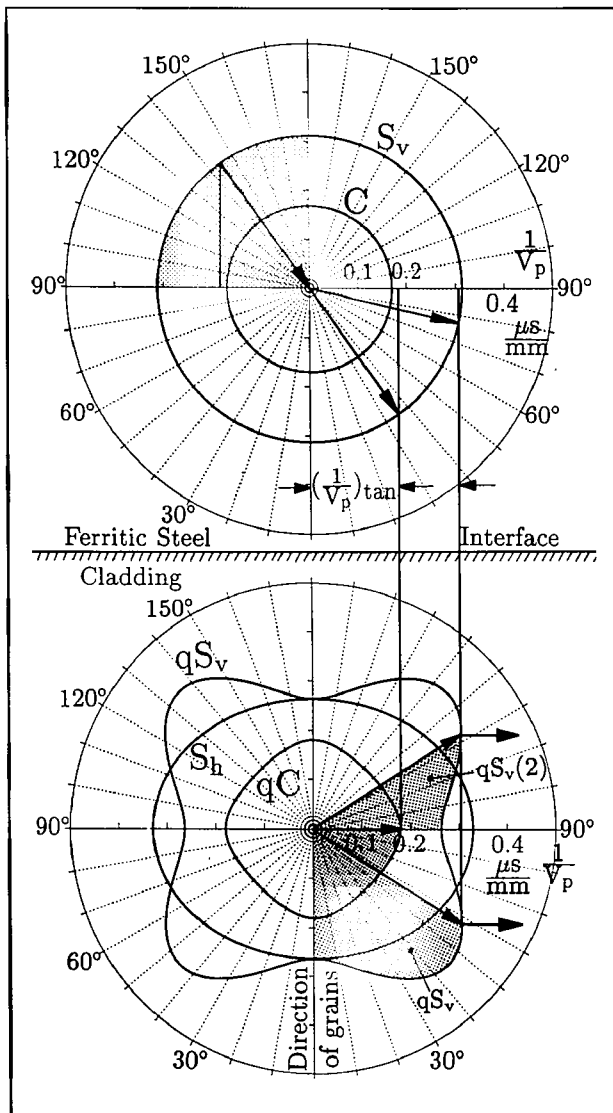


Fig. A3.1: Slowness surface construction of Snell's law for a clad-ferritic interface with the grains normal to the surface and the S_v -wave incident from the ferritic plate material. Only qC - and qS_v -waves couple into the cladding, the S_h wave does not couple. The shaded sectors show the incident and refracted wave vectors which are permitted. Wave vector angles larger than 90° are permissible for the second quasi-shear wave $qS_v(2)$. The beam directions are indicated for the critical angle of both quasi-shear waves

cladding interface for waves incident from the ferritic base metal. Since the reflected and refracted waves must have the same component of k tangential to the interface and since $k \sim 1/V_p$ then the component of slowness parallel to the interface must be the same for the reflected and refracted waves. Therefore the phase velocity of the refracted and reflected waves can be readily derived for anisotropic cases. Also the group velocity can be obtained by constructing the perpendicular to the slowness surface.

Fig.A3.2 shows how the refracted directions of phase and group velocities vary for both wave modes generated by a S_v wave incident from the ferritic base metal. As an example the left insert of Fig. A3.2 shows that for a 30° shear (S_v) wave incident from the ferritic base metal there is:

- a refracted compression wave
- a refracted shear wave with a negative angle

Note that for certain angles of incidence there are two refracted quasi-shear waves indicated by qS_v and $qS_v(2)$. These are discussed further in the following sections.

A3.3 Critical Angles

The critical angle phenomenon is significantly more complicated for the acoustic anisotropy encountered in clad materials than for the purely isotropic case.

The parameter that determines whether or not a refracted wave can propagate at an interface is the group velocity direction. Thus although the phase velocity (or wave vector k) direction may have a refracted angle of less than 90° , see right inset of Fig. A3.2, the group velocity (or beam) direction, which dictates the direction of energy flow, may be greater than 90° in which case a refracted wave cannot exist. Only in cases where the group velocity direction is less than 90° a refracted wave can exist. The special case of the group velocity direction equal to 90° corresponds to the critical angle of the quasi-shear wave qS_v .

Again using the example of a S_v wave incident from the ferritic base metal, Fig. A3.1 shows the situation where there is no longer an intersection of the

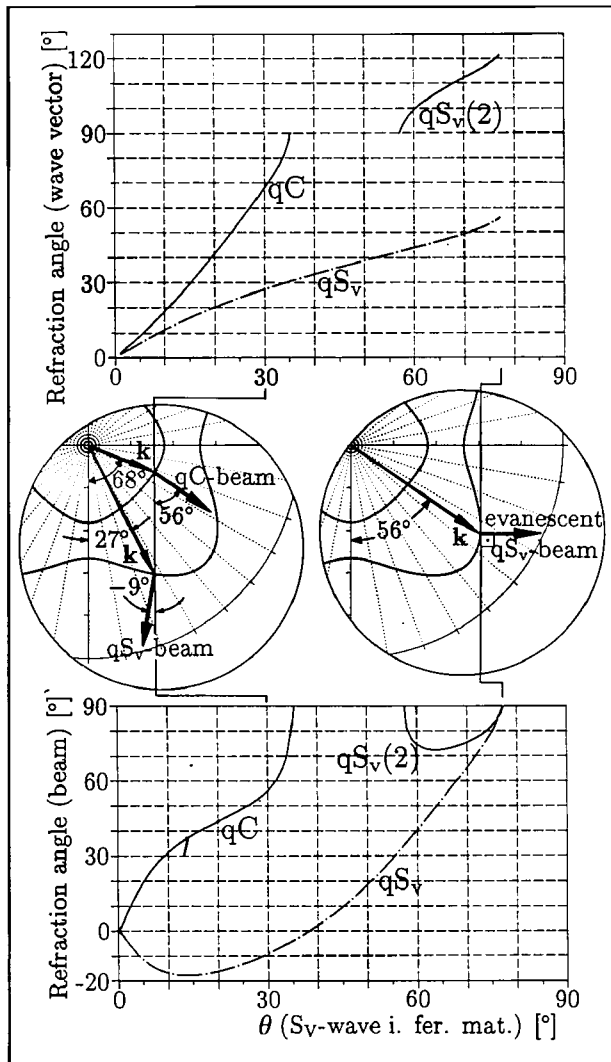


Fig. A3.2: Direction of refracted phase and group velocities in the cladding versus S_V -wave incidence angle θ in the ferritic plate material

compression wave slowness surface for the cladding. In this case, which is the critical angle for compression waves, the wave travels parallel to the interface with the particle displacement decaying exponentially away from the boundary. This is an evanescent wave. As the incident angle is increased further a second critical angle is reached, which belongs to a second quasi-shear wave referred to here as $qS_V(2)$. The angle for the phase velocity direction for this wave is greater than 90° (wavefronts pointing back into the ferritic material) but the angle of the group velocity direction is less

than 90° and so it propagates into the cladding. Fig. A3.3 shows as an example the group velocity direction and the wavefronts for the two components of the quasi-shear wave in cladding generated by a S_V wave incident from the ferritic base metal under an angle of 75° . The energy associated with this second component of the quasi-shear wave is discussed in the next section.

The vertically polarised quasi-shear wave has the peculiarity that the permissible domain of its phase velocity direction in the clad material is separated into two regions - corresponding to the two components of quasi-shear wave. This is shown in Fig. A3.1 where the shaded regions represent those parts of the slowness surface where:

- a solution exists for the geometrical construction of Snell's law
- the angle of the group velocity direction is less than 90° (condition for refraction).

Note that this phenomenon also occurs at the interface between the perspex wedge of an ultrasonic probe and the cladding, see also Fig. 3.16.

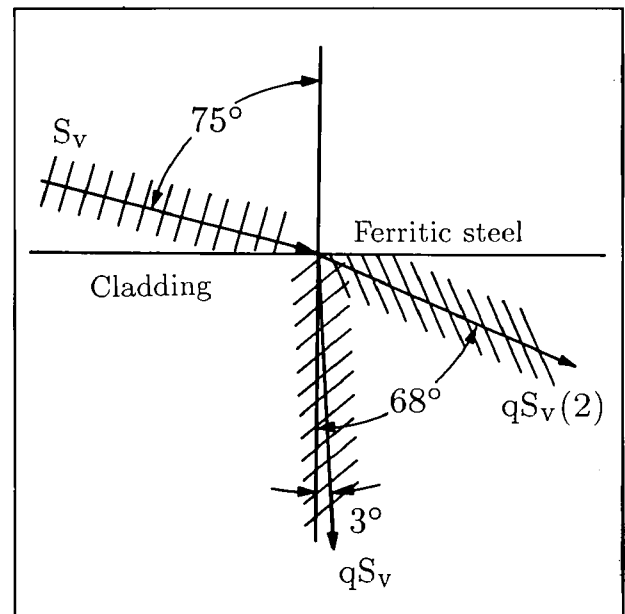


Fig. A3.3: Ultrasonic qS_V -beams and their wave fronts in the cladding for a 75° S_V -wave incidence from the ferritic plate material

A3.4 Energy Reflection and Refraction Coefficients

In addition to knowing the propagation directions it is also important to know the efficiency with which the ultrasound can be transmitted across the interface.

A3.4.1 The Clad-Ferritic Interface

The calculation of reflection and transmission coefficients at the clad-ferritic interface leads to the following conclusions:

The case of S_h waves is the most straight-forward since there is no coupling to either of the other wave mode types. Energy transmission is nearly 100% over a large range of angles of incidence for waves incident from both the ferritic and the clad side (see Figs. A3.4 & A3.5).

The compression wave, incident from both isotropic and anisotropic sides, (see Figs. A3.6-A3.9) is also found to penetrate the interface effectively over a broad range of angles. Mode converted and reflected energy is less than 5% of the incident compression wave energy for angles up to 70° therefore the problem of spurious indications from the fusion face is not significant.

Since both S_h and compression waves have good transmission properties at the clad/ferritic interface the choice of wave modes must be dictated by other

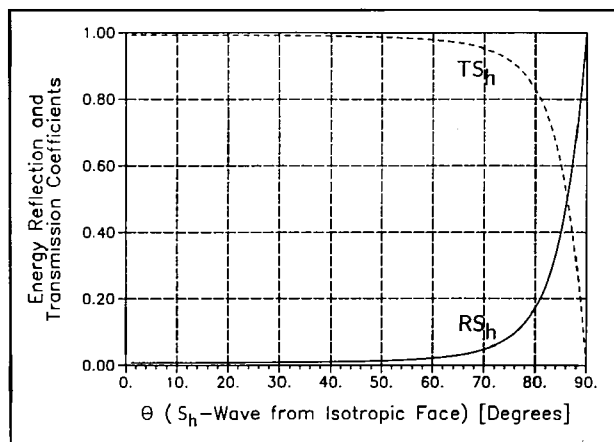


Fig. A3.4: Energy reflection and transmission coefficients for a horizontally polarized shear (S_h) wave incident at the clad-ferritic interface from ferritic base metal

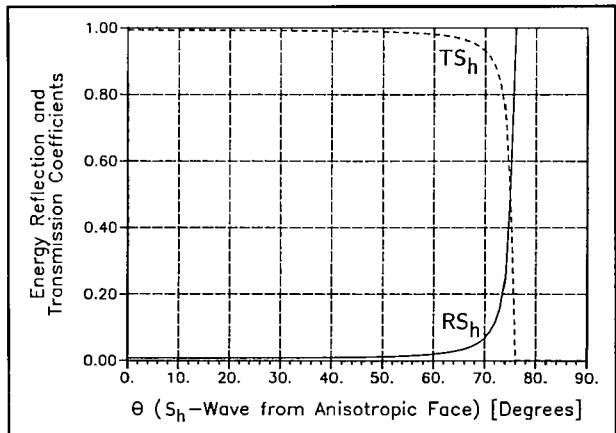


Fig. A3.5: Energy reflection and transmission coefficients for a horizontally polarized shear (S_h) wave incident at the clad-ferritic interface from the cladding

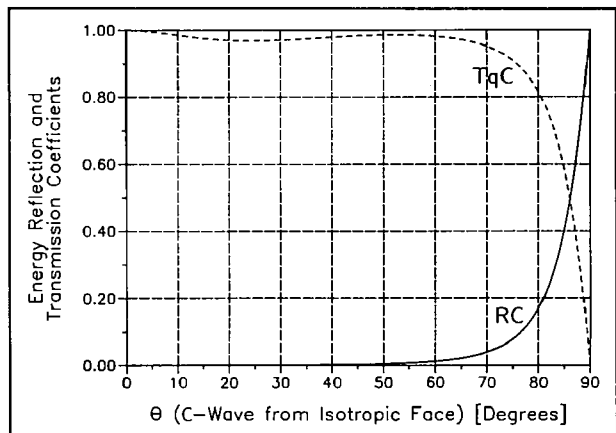


Fig. A3.6: Energy reflection and transmission coefficients for a compression (C) wave incident at the clad-ferritic interface from the ferritic base metal

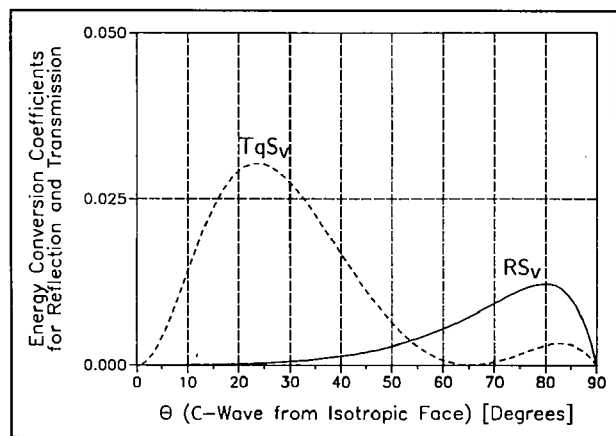


Fig. A3.7: Energy conversion coefficients for reflection and transmission for a compression (C) wave incident at the clad-ferritic interface from the ferritic base metal

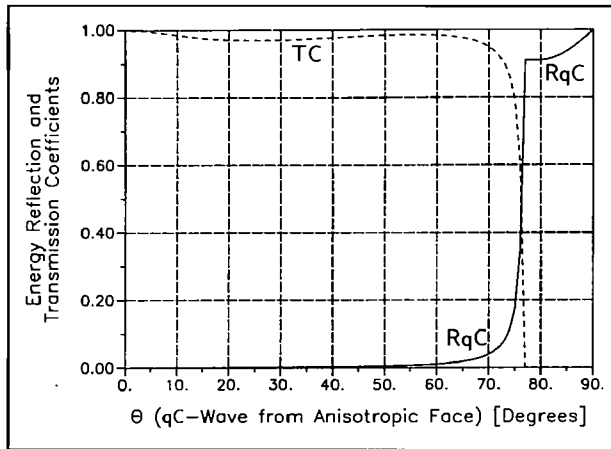


Fig. A3.8: Energy reflection and transmission coefficients for a quasi-compression (qC) wave incident at the clad-ferritic interface from the cladding

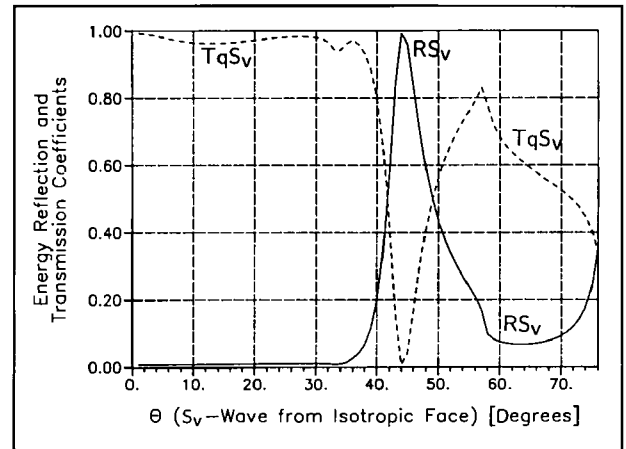


Fig. A3.10: Energy reflection and transmission coefficients for a vertically polarized shear (S_v) wave, incident at the clad-ferritic interface from the ferritic base metal

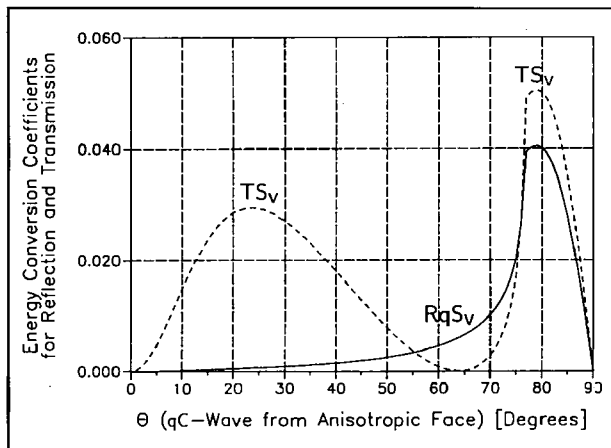


Fig. A3.9: Energy conversion coefficients for reflection and transmission for a quasi-compression (qC) wave incident at the clad-ferritic interface from the cladding

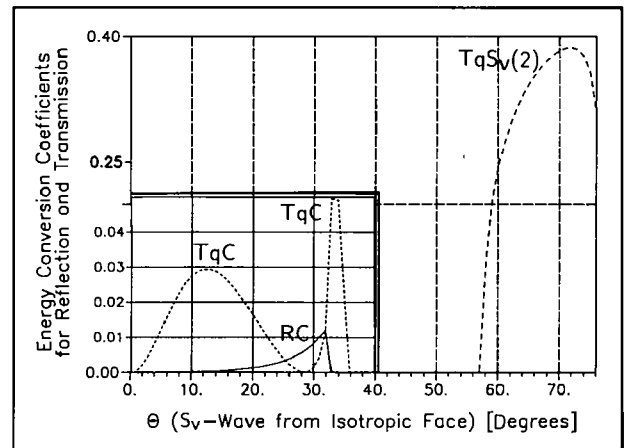


Fig. A3.11: Energy conversion coefficients for reflection and transmission of a vertically polarized shear (S_v) wave, incident at the clad-ferritic interface from ferritic base metal. (Note that the coefficients of the transmitted quasi-compression wave (T_{qC}) and the reflected compression wave (RC) are on a separate scale)

considerations. For instance, the S_h wave makes good use of the high corner reflectivity to detect defects at the far surface whereas compression waves are best utilised for defects away from the surface and, in particular, subcladding cracks.

The usefulness of vertically polarized quasi-shear (qS_v) waves is restricted to small angles of incidence. Figs. A3.10 - A3.11 and Figs A3.12 - A3.13 show the situation for S_v waves incident from the ferritic side and qS_v waves from the clad side

respectively. The critical angle for the compression wave mode occurs at approximately 35° and at higher angles the energy balance is achieved by redistribution to other reflected and refracted wave modes. At angles of incidence higher than approximately 58° it is the second quasi-shear wave mode, $qS_v(2)$, that is the dominant shear wave mode in cladding, see Fig. A3.11.

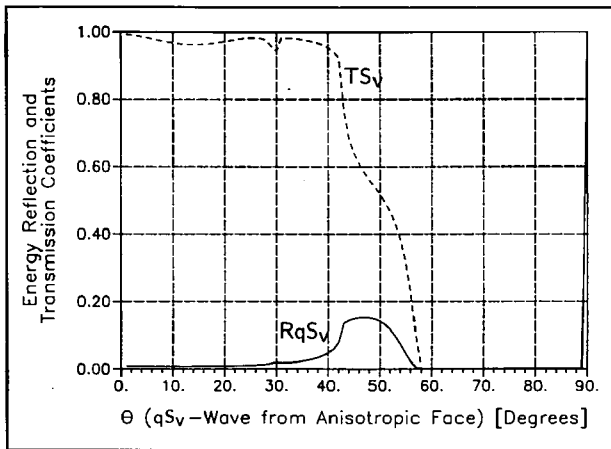


Fig. A3.12: Energy reflection and transmission coefficients for a vertically polarized quasi-shear (qS_v) wave, incident at the clad-ferritic interface from the cladding

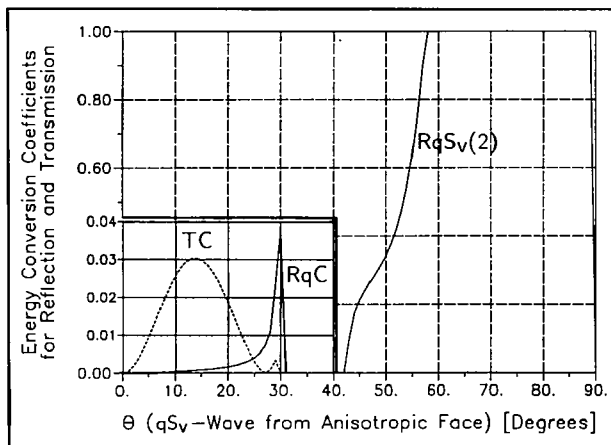


Fig. A3.13: Energy conversion coefficients for reflection and transmission of a vertically polarized quasi-shear (qS_v) wave, incident at the clad-ferritic interface from the cladding. (Note that the coefficients of the transmitted compression wave (TC) and the reflected quasi-compression wave (RqC) are on a separate scale)

A3.4.2 The Ultrasonic Probe's Coupling Layer

The special case of S_h waves is not treated here since they are not normally generated using liquid couplants and require electromagnetic techniques (see Appendix 4).

In addition to the energy transmission coefficients across the interface it is also important to know the efficiency with which energy is transmitted across the coupling layer between the perspex wedge of

the probe and the clad surface. Figs. A3.14 and A3.15 show the energy transmission coefficients for both refracted wave types which are similar to those for the case of a perspex/isotropic steel interface. Fig. A3.14 shows that the second quasi-shear wave mode $qS_v(2)$, although present, is very weak and can be ignored during ultrasonic testing.

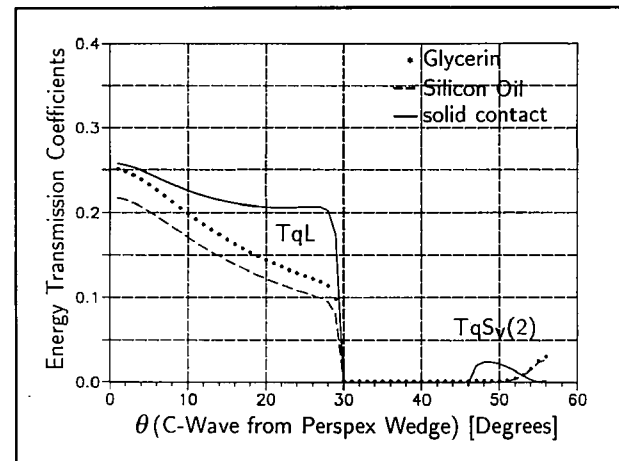


Fig. A3.14: Energy transmission coefficients of the quasi-compression (qC) wave generated in the cladding at the coupling layer between the perspex wedge of the ultrasonic probe and the cladding. Testing frequency: 2 MHz, solid contact and fluid contact. Thickness of the coupling layer in the case of fluid contact: 20 μm

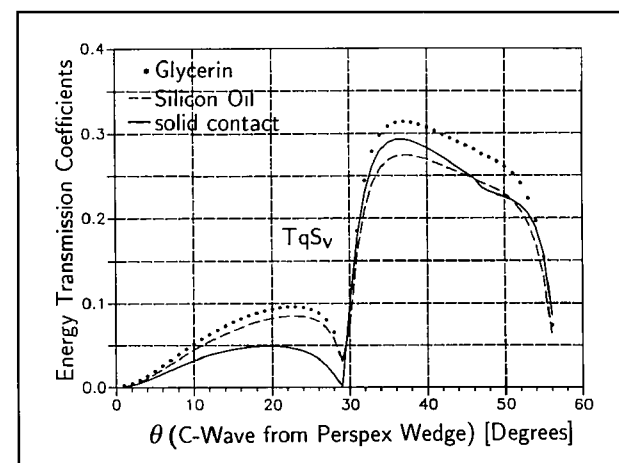


Fig. A3.15: Energy transmission coefficients of the quasi-shear (qS_v) wave generated in the cladding at the coupling layer between the perspex wedge of the ultrasonic probe and the cladding. Testing frequency: 2 MHz, solid contact and fluid contact. Thickness of the coupling layer in the case of fluid contact: 20 μm

APPENDIX A4

Angled EMUS- S_h -wave Probes

A4.1 Introduction

Section 4.4.2 briefly describes how the use of the S_h wave mode can be more beneficial than S_v or compression waves in certain inspection applications. Conventional piezoelectric transducers cannot generate S_h waves in most inspection situations and EMATs are required. At the time of writing this handbook, the use of EMATs, generating S_h waves, is beginning to see increasing use for the ultrasonic inspection of austenitic welds and cladding. This appendix summarises, for the interested reader, the physical principles by which EMATs operate and some practical aspects of EMAT design.

A4.2.1 Principles of Ultrasound Generation

EMATs generate ultrasonic waves directly in the surface of a component by either the Lorentz force or the magnetostrictive effect, depending on the magnetic properties of the component.

The Lorentz mechanism generates a force in an electrical conductor when a current flows in a direction perpendicular to an applied magnetic field with the resultant force being perpendicular to both the magnetic field and the current. In practice a pulsed current is produced in the surface of a metal by radio frequency (r.f.) coils which induce eddy currents.

Magnetic materials experience a distortion when a magnetic field is applied via the magnetostrictive effect - this is the magnetic analogy of the piezoelectric effect. To generate ultrasound an alternating magnetic field is applied through an r.f. coil in the presence of a biasing magnetic field;

To produce ultrasonic beams with a high degree of directionality and acceptable intensity with EMATs it is necessary first to generate spatially periodic forces or magnetic fields in a conducting surface as shown in Fig. A4.1

Fig. A4.1(a) shows an arrangement of permanent magnets with alternating fields which when combined with eddy currents induced in the surface by the r.f. coil generates transverse periodic forces in the surface by the Lorentz Force. By constructive interference these forces combine to produce an S_h wave with a beam angle α given by:

$$\sin \alpha = \frac{\lambda}{2d} \quad (1)$$

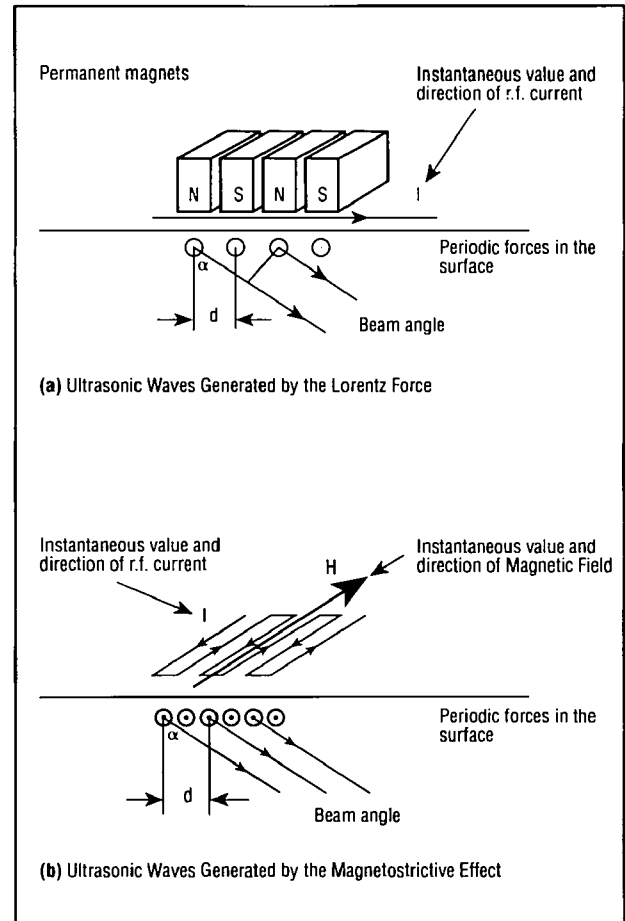


Fig. A4.1: The generation of S_h ultrasonic waves by EMATs

where λ is the wavelength and d is the spacing between the elements (magnets). For constructive interference to occur $2d$ must be equal to or larger than λ and the pulse length applied to the r.f. coil should be greater than $m/2$ cycles, where m is the number of elements. The beam angle is controlled by varying the frequency of the r.f. current pulse which is given by the simple re-arrangement of equation (1),

$$\sin \alpha = \frac{V_t}{2df} \quad (2)$$

where V_t is the velocity of S_h waves and f is the frequency of the current pulse. Fig. A4.2 gives the beam angle of an EMAT probe as a function of the frequency and spacing d , for steel where $V_t = 3.2$ mm/ μ s.

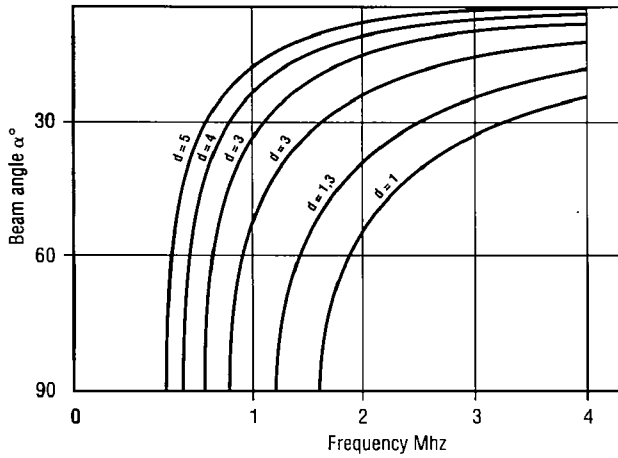


Fig. A4.2: S_h wave beam angle for an EMAT probe as shown in Fig. A4.1(a) assuming $V_t = 3.2 \text{ mm}/\mu\text{s}$, d in mm

Fig. A4.1(b) shows a meander r.f. coil in which the direction of the current in each line element alternates and the magnetic fields that are generated perturb the main bias field H . The periodic forces in the surface are produced by magnetostriction due to the superposition of the static magnetic field with the dynamic magnetic fields generated by the current in each line element. These forces combine, by constructive interference, in the same way as in Fig. A4.1(a) to produce an S_h wave with a beam angle given by equation (1).

A4.3 Practicalities of Probe Design

The precise construction of an EMAT probe must be designed to suit the application and a variety of magnet/coil configurations have been used. It is not within the scope of this appendix to describe the particular features of each design but this section presents a brief summary of the important aspects that should be appreciated.

A4.3.1 Phased Arrays

The disadvantage with probe designs based on single elements is that equal amounts of ultrasonic energy are transmitted in the backward, as well as, in the forward direction. If instead of a single transmitting element several smaller elements are used as shown in Fig. A4.3 and these are energised

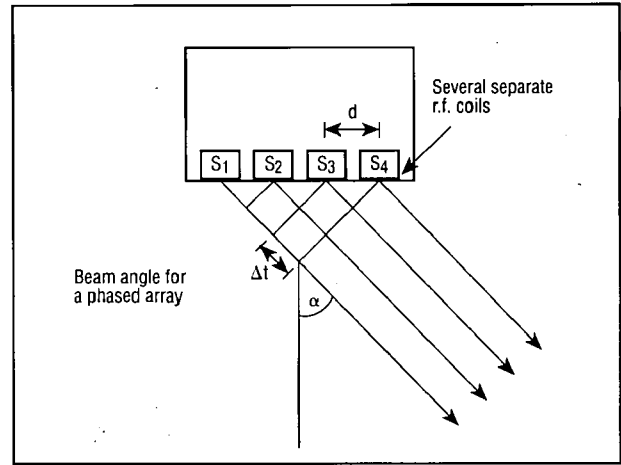


Fig. A4.3: Changing the beam angle by the time delay

sequentially as a phased array with a time delay Δt between each current pulse, a S_h wave with a plane wave front is produced with a beam angle α given by:

$$\sin \alpha = \frac{V_t \Delta t}{d} \quad (3)$$

The use of phased arrays effectively eliminates the energy transmitted in the backward direction and there are no limitations to the pulse length.

EMATs do not require any mechanical coupling between the transducer and the component under test. It is however necessary for the r.f. coils to be close to the surface of the component since eddy current losses due to lift-off can be large.

A4.3.2 Electromagnet Probes

The magnetic field necessary for the generation of S_h waves can be supplied by either permanent magnets or electromagnets. The magnetic field for magnetostrictive EMATs is most usually provided by electromagnets (see Fig. A4.4) generating either a static field or a low frequency (typically 50 Hz) alternating field. Fig. A4.4 shows how the magnetic field is provided by a U-shaped electromagnet energised by an alternating current. The alternating magnetic field, when compared with a static field, reduces the force between the probe and the surface of magnetic materials to facilitate scanning. In this

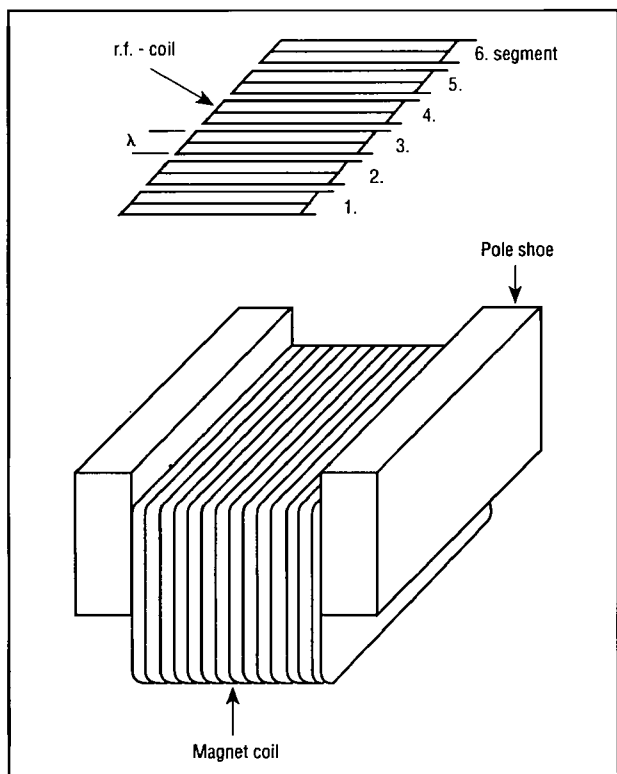


Fig. A4.4: EMAT-probe for S_h -waves with permanent magnets

example the r.f. coil is divided into several segments and these are driven as a phased array as described for Fig. A4.3 to produce a S_h wave.

A4.3.3 Permanent Magnet Probes

In non ferromagnetic or weakly magnetic materials ultrasonic waves are generated mainly by the Lorentz force. In such cases the magnetic field is usually provided by permanent magnets. Fig. A4.5 shows an arrangement of permanent magnets and coils for generating S_h waves as described earlier for Fig. A4.1. At least two rows of oppositely polarised magnets are required to generate an ultrasonic wave. The design of the meander coils is optimised to generate periodic stresses parallel to the surface and transverse to the axis of the transducer. Permanent-magnet phased arrays are generally used which are constructed of a number of elements such as that shown in Fig. A4.5

It should be noted that permanent magnet probes can be used to generate S_h waves in ferromagnetic

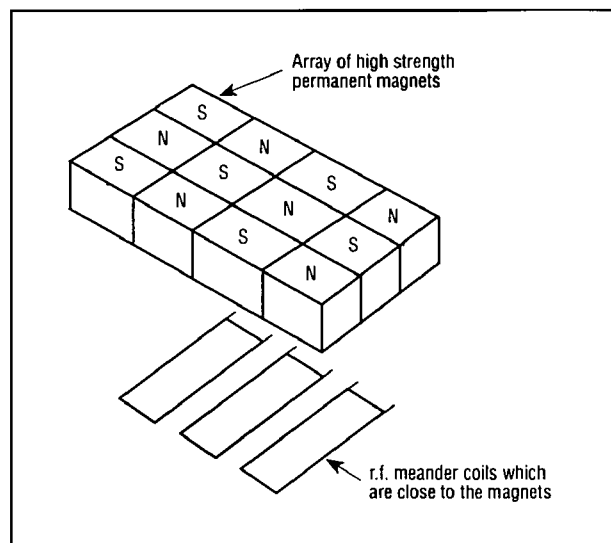


Fig. A4.5: A permanent magnet EMAT

materials, but here the practical difficulty of the force between the probe and the metal surface has to be overcome by using special probe carriers.

A4.4 Practical Features of EMAT Probes

Separate transmitter and receiver EMATs are often used due to the long dead time following the transmitter pulse.

At the time of writing this handbook the following data give typical performance parameters that are achieved in practice.

- Operating frequency range for angle beam EMATs used for inspecting austenitic welds and cladding is typically 0.5 MHz to 1.5 MHz.
- The range of beam angles which can be achieved in any type of steel is 30° to 90°.
- Beam spreads (full width at 6 dB down) of less than 10° can be achieved in the plane of incidence.
- For phased array transducers the ratio of the forward to backward radiation is typically 35 to 40 dB
- A dynamic range of typically 35 dB can usually be achieved for a probe in contact with austenitic steel. This may be significantly increased when applied to surfaces containing δ -ferrite.

European Commission

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Austenitic Clad Steel Components**

R.J. Hudgell

Luxembourg: Office for Official Publications of the European Communities

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