

COATING AND DRYING DEFECTS

COATING AND DRYING DEFECTS

Troubleshooting Operating Problems

Second Edition

EDGAR B. GUTOFF
EDWARD D. COHEN

Chapter 11 authored by

GERALD I. KHEBOIAN

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To the memory of Luiza Cohen and Grace Kheboian

and

To Hinda Gutoff, for her constant support and encouragement

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PREFACE

There is an ongoing need to troubleshoot and to reduce the occurrence of defects in web coating. The quality requirements have increased and the means of reducing defects has become more complicated. In addition, there have been advances in technology. This second edition of *Coating and Drying Defects* was prepared to fill these needs.

The sections from the first edition have been updated to discuss the significant advances that have been made in on-line defect detection, in coating weight control, and in improved analytical methods for defect analysis. These are now important in all coating lines. Advances in process technology and an understanding of defect mechanisms in process technology have resulted in reduction in defects and the ability to successfully coat defect-free thinner layers. In addition, technically sophisticated and low-cost process computer monitoring capability has been developed, which can provide the extensive data needed to troubleshoot problems. Statistical techniques are available to analyze this data.

The second edition has expanded the range of defects covered. The first edition focused only on defect reduction and the major process unit operations—coating, drying web handling, and mixing. This edition covers the secondary process operations, since they too can affect defects and are often overlooked as defect sources and a method to improve defects.

Another added topic is the prevention of defects. Technologies and procedures that can be used to prevent defect formation and improve operating procedures are presented.

There are new sections on coating machine alignment using optical tooling and laser technology and on the influence of surface roughness on the limits of coatability.

EDGAR B. GUTOFF
EDWARD D. COHEN

December 2005

PREFACE TO THE FIRST EDITION

This book is intended to serve as a guide to help solve the various types of problems that occur in the coating and drying of films on continuous sheets or webs. It is intended for manufacturing and quality control personnel, the operators and supervisors who are directly involved in the production of coated products, and for the engineers and scientists who are involved in the design and production of coated products. The material presented is nonmathematical and should, we hope, be easy to understand. The main focus is on eliminating the many types of coating defects that, unfortunately, do occur in a coater. These defects must be eliminated to produce a satisfactory high-quality product at a competitive price. The difference between a successful and an unsuccessful process can be how rapidly defects are eliminated, how rapidly problems are solved, and how permanent is the cure. Other types of problems that coating personnel typically encounter in running a coater, such as controlling the drying, are also discussed.

Coated products are pervasive in our economy. They cover a wide range of stand-alone products as well as being key components in many others. Coated products vary from the painted metal in automobiles and appliances, to the photographic films for color and for medical x-rays, to the coatings used to produce electronic printed circuits, to the magnetic coatings that store information in computers and in music and video recorders, and to the coated catalysts in the converters used to reduce pollution in automobiles. These coatings all have a common basis, which is the replacement of air on a substrate with a liquid to give the final product having the desired properties. The goal of all these processes is to produce the desired coating at a competitive cost and yield.

The rapid advances in coating technology coupled with rapid development of product formulation technology have led to many new products that are more uniform and have a low defect level, resulting in higher yields and lower costs. Quality levels that were acceptable only a few years ago are no longer acceptable and in future will be even more demanding. Environmental needs and the resulting economic considerations will also become more stringent and will require that a much higher fraction of the starting materials end up as usable product, not scrap to be disposed of by burial in landfill or by incineration.

Although painted surfaces suffer from many of the same defects that occur in coated continuous webs and substrates, this book does not cover paint film defects as such. It also does not cover defects in the very thin films produced by vacuum deposition techniques. It does cover defects in most coated webs. For all coated products, standards are established that specify the characteristics of the coating solutions, the coating process operating conditions, and the final chemical and physical properties of the coating. Unfortunately, the reality of the coating process is that these standards are often not achieved and product is often produced which is, therefore, defective. There are many process steps where defects and nonuniformities can be introduced into the coating process. These defects can have a variety of causes, and many defects that appear different can have similar origins. Conversely, many defects that seem to be similar can have different causes. Ongoing diligence and effort are required to minimize these defects. Troubleshooting to eliminate defects, nonuniformities, and waste is an ongoing function of all personnel, from the operators to the research and development scientists and engineers who design the products and processes.

In our previous book, *Modern Coating and Drying Technology* (VCH Publishers, New York, 1992), we described the basics of the coating processes. It was intended as an introduction to the coating process. Its purpose was to answer the question that we had encountered: How do we learn about the coating process? This book is intended to answer the question: How do I eliminate typical operating problems that occur in a coater, such as a specific defect in the product I am now making, and how do I ensure that defects do not return? This book is intended to be a troubleshooting guide. It provides a description of the troubleshooting process and problem-solving techniques, and descriptions of common problems and typical solutions. Our approach is to present in one volume all the tools needed to troubleshoot defects and the means to eliminate defects, as well as brief descriptions of the major coating processes. A methodology is presented to guide one from the start of the troubleshooting process, when the defect is first detected, to the end of the process, where the mechanism for the formation of the defect is defined and the defect is eliminated.

The ideal state in any coating process is to run the process so that defects are never formed and problems are never encountered. Therefore, some guidelines for defect prevention will be given. Where possible, specific information on the major defect categories is also presented. We focus on the use of instruments and statistical tools, not on the mathematical derivations and the theory of their operation. Some references are given to the supporting theory for those who want to go to the literature for greater detail.

The web coating process consists of several major unit operations:

- Compounding, mixing, and dispersing the coating formulations, including binder components, solvents, coating aids, dyes, matte agents, and active ingredients, such as silver halides, iron oxides, and so on
- Obtaining the support to be coated on, such as polyester film or paper
- Coating the formulation on the support
- Transporting the coated support
- Drying the coating
- Converting the coated web into the final size and form for use by customers
- Shipping the product to customers or to storage

We focus on the steps of the process up to the final slitting operation. Although it is recognized that defects may be introduced there, this book does not cover that operation.

While all coated products are different in terms of their formulation and many different coating processes are used, the underlying science is similar. Many defects in different products have similar causes and similar cures. The principles developed from the elimination of bubbles in a low-viscosity barrier layer apply also to the coating of a low-viscosity photographic layer.

A wide variety of different coating application methods can apply a coating to a web; however, the successful processes are those that are defect-free over a wide range of operating conditions. In industrial environments, coating personnel spend a significant amount of their time in eliminating defects and trying to make the process defect-free. We have observed that while coating personnel may be trained in the basic sciences, there is very little formal training in troubleshooting or problem solving, even though it is one of the main functions of industrial personnel. The basic procedures and tools used to troubleshoot or to problem-solve are similar for a wide variety of different defects and problems.

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October 1994

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Edgar B. Gutoff (194 Clark Rd., Brookline, MA 02445, phone/fax 617-734-7081, e-mail ebgutof@coe.neu.edu, website www.coe.neu.edu/~ebgutof/) is a consulting engineer specializing in the coating and drying of continuous webs. He conducts semiannual Coating and Drying Technology Seminars in the Boston area and also gives on-site seminars. He received his B.Ch.E. from City College of New York and his M.S. and Sc.D. in Chemical Engineering from MIT. In 1988 he became a consultant after 28 years at Polaroid. Since 1981 he has been a part-time Lecturer or an Adjunct Professor at Northeastern University, and in 1994 was an Adjunct Professor at Tufts University. He organized the first biennial AIChE Coating Symposium in 1982, organized a Coating Course in 1990 given at these symposia and now given at the University of Minnesota, and organized a course in Coating and Drying Defects at the 1994 Coating Symposium. Ed was founding Secretary of the International Society of Coating Science and Technology that now conducts these International Coating Symposia and serves on the Board of Directors. He is a Fellow of the AIChE and in 1994 received the John A. Tallmadge Award for contributions in coating technology from the AIChE and the Fellow Award from the Society for Imaging Science and Technology for long-term contributions to the engineering aspect of photographic coatings. Ed is a member of the AIMCAL Technical Advisory Panel. With Ed Cohen he edited *Modern Coating and Drying Technology*, and with Paul Frost he coauthored *The Application of Statistical Process Control to Roll Products*. Ed has authored or coauthored over 50 papers, of which over 30 are related to coating and drying.

Edward D. Cohen (15638 N. Cerro Alto Dr., Fountain Hills, AZ 85268, phone 480-836-9452, e-mail Cohened146@aol.com, website edcohenconsulting.com) is a technical consultant in all aspects of the web coating process. He received a Ph.D. from the University of Delaware and a B.S.Ch.E. from Tufts University. His expertise is in the coating and drying of thin films, coating process development and scale-up, polyester base development, film defect mechanisms, and defect characterization techniques. He has over 40 years experience in coating research and manufacturing technology.

He recently retired from DuPont Central Research and Development as a DuPont Fellow. Ed is coeditor of *Modern Coating and Drying Technology*, coauthor of *Coating and Drying Defects: Troubleshooting Operating Problems*, and coauthor of *AIMCAL Defects Lexicon*. In addition, he has many other publications and teaches continuing education courses. He is Technical Consultant for AIMCAL (The Association of Industrial Metallizers, Coaters and Laminators), Treasurer of the International Society of Coating Science and Technology, and is a contributing author for *Paper Film & Foil Converter*. He received the John Tallmadge Award for Contributions to Coating Technology and the AIMCAL President's award in recognition of meritorious service to AIMCAL and the Converting Industry.

Gerald I. Kheboian (24 Fiske St., Worcester, MA 01602, phone 508-799-6038, e-mail gikheboian@aol.com), author of Chapter 11, holds an Associate E.E. degree from Wentworth Institute and B.S.B.A. from Clark University. Jerry consults in the field of web handling machinery, drives, and tension controls that are applied to the transport of web in the paper, plastics, textile, metals, and wire industries. He gives presentations and seminars on these subjects. His professional career began with 15 years at Rice Barton Corporation of Worcester, MA, where he was responsible for roll coaters, flying splicer unwinds, color kitchens, and drives and controls. He then joined Polaroid Corporation as a Production Engineer and rose to become Technical Manager of Electrical Engineering and Control Systems for Process Machinery and Chemical Systems. He had been the chairman of the TAPPI short course for paper making machinery and winders and was chairman of the national TAPPI Electrical Engineering Committee. Jerry has written a number of papers concerning the horsepower selection and control of coaters and the service factors for gear reducers used in the paper industry. As a member of the TAPPI drive requirements committee, he contributed to the determination of horsepower constants and mechanical factors of drive component selection. His extensive experience as a design engineer, startup engineer, and problem solver has led him to become a consultant for applications in the field of web processing machinery and industrial drives.

1

INTRODUCTION

The occurrence of defects in the coating process is an ongoing concern to all who operate a coating line. A low defect level and high quality level are essential to meet the needs of the customer and to ensure a profitable business. Defects have become a particular current concern as product quality standards are continually increasing. In many instances, a product defect level that was considered to be of salable quality in the recent past (five years or more ago) would not be acceptable in the current marketplace. In addition, a wide range of new technically complex products, such as fuel cell membranes, thin film batteries, solar cells, and RFID (radiofrequency identification) chips, are being developed and manufactured and have very high quality and reproducibility specifications. They require an improvement in coating line performance and technology to obtain a defect-free product. Additional examples of difficult or complex products are thin coatings applied to thin substrates, high-speed coatings, and multilayer coatings.

One result of this increased need to reduce defects is that the knowledge to troubleshoot and eliminate defects on a coating line is an essential skill that all personnel must have to ensure success in eliminating the many different defects that can and do occur. The intent of this book is to provide the technology, procedures, and skills that are necessary for all personnel to effectively troubleshoot coating defects. The focus is on practical useable technology and procedures.

The definition of defects is a very important starting place for the discussions on troubleshooting defects that are in the following chapters. It is essential that all have the same understanding of what constitutes a coating and drying defect. The dictionary definitions of a defect are:

- The lack of something necessary or desirable, a deficiency
- An imperfection that impairs worth or utility
- A deficiency

However, for our purpose the best definition is: “anything in the coating and drying process that results in customer dissatisfaction.” Typically, the common usage of a coating and drying defect refers only to a physical imperfection in the coating or substrate such as spots, repellents, chatter, or streaks. However, this new definition gives a more accurate view of defects and quality concerns that can arise in the web coating process. It also gives a better indication of the improvement opportunities in the coating and drying process. This new definition is used in this book.

This definition of coating and drying defects encompasses a wide variety of faults in the film and is not necessarily limited to the physical defects that were the focus of the first edition of this book. The range of defects covered by this definition are:

- Physical defects in the coated layer and in the substrate. Examples are bubbles, streaks, ribbing, air entrainment, contamination defects, chatter, wrinkles, comets, curl, condensation spots, and repeat marks.
- Deficiencies in the coating weights or thicknesses of the applied layer. There are several types of deficiencies affected by the coating process. The average coating weight must be at the required value for all of the rolls in a production run. The coating weight must also meet uniformity standards across the width of the web—the transverse direction or TD profile—and also along the length of the roll—the machine direction or MD profile. Transverse or machine direction variations can range from 1% to 10%, and a coating line designed for 10% will produce a defective product if 2% is needed.
- Deficiencies in product performance properties. These can be affected by variations in the coating and drying conditions. An example is the background density in silver halide films that is influenced by the drying conditions, which must be closely controlled to achieve desired levels. Adhesion of the coating to the substrate is influenced by the wetting of the coating on the substrate in the coating line. Haze and clarity of a coating can also be influenced by the process conditions. Many formulations are cured or cross-linked using either heat or ultraviolet radiation that will be influenced by the process.
- The inability to consistently obtain specified process conditions. If the location of the dry point, where the coating appears dry to the eye, is not maintained, then the product can be overdried, leading to poor product performance, or it can be underdried, leading to the product being wound with wet spots that will keep the wound roll stuck together and unable to be unwound. The latter can lead to reduced line speeds, resulting in higher costs and perhaps insufficient product to meet customer needs.

The elimination of defects is technically complex for several reasons. The current web coating line has many different process hardware elements and is technically sophisticated. Any of these process elements, starting with mixing the coating solutions, coating the substrate, drying the wet coating, unwinding and tracking the web, and winding the coated product, can introduce defects into the final product. Every raw material used can introduce defects.

Support equipment consists of the equipment and subsystems that are needed to sustain the effective operation of the major coater elements—the coating applicator, dryer, roll unwind, roll rewind, and web tracking. These secondary support systems can either lead to defects or can be used to eliminate them. In addition to the direct effect of a process element leading to defects, interactions between the different process elements can also lead to defects.

Another complication is that the defect does not necessarily appear in the same process step where it is created. Often the defect is observed several operations after it was created. A coating streak can be seen at the applicator. However, a mixing or contamination defect may not be seen until the product is coated and dried. A substrate defect may not be detected until the final product is wound or until it is slit into narrow widths to meet customer needs.

Additional complexities are that defects can and will occur at any stage in the product development cycle, starting with laboratory coatings and proceeding through the pilot plant for development coatings and finally through routine manufacture. There may be different defects at each stage, and eliminating them in the initial stage does not guarantee defect-free product in the next stage. A variety of different defects can be created that occur sporadically. A further complication is that similar appearing defects can have many causes and the cause may be different for each occurrence. Bubbles are a good example, since they can have a variety of causes, from air in the coating lines to boiling of solvents in the dryer. The defect cause can be simple, such as repeats from a dirt spot on a roll, or sophisticated, such as ribbing in roll coating or air entrainment in premetered coating.

Another source of defects can be in the inherent design of the coater and the capability of various hardware elements that make up the coating line. The coater may have been acceptable for the initial products for which it was designed. Changes in product composition and economic requirements can make the coater inadequate for current needs. In addition, the initial design is often a compromise and can have been built with some rate-limiting steps that become apparent as new products are produced and production rates are increased.

As a result of this complexity, a formal troubleshooting protocol or *modus operandi* is required to characterize the defect, identify its cause, and eliminate it. A random empirical approach will not be as effective, since it requires more time and resources than a formal approach and may not completely eradicate the defect or determine the true cause. This troubleshooting protocol includes several technologies to achieve a rapid, accurate, and cost-efficient solution. The components of this troubleshooting protocol are:

- A structured troubleshooting or problem-solving procedure.
- Analytical techniques to characterize the defect and the process elements in the coating line.
- The use of statistical methods to design necessary experiments and to analyze the data.
- A computer database to store all data and past experiences, which can be accessed by all personnel in the company.
- An understanding of how each of the process elements functions and what parameters in each system can lead to defects. Both a practical knowledge of the unit operation and a fundamental understanding of basic process mechanisms are needed to determine the causes of defect and to eliminate them.

The above protocol is a reactive program that is followed when defects are detected and need to be eliminated. The information gained from carrying out a successful troubleshooting procedure can also be used to prevent defects before they result in significant losses. Thus a similar structured but proactive protocol can be used to prevent defects and upgrade the process. It complements the reactive approach.

This book is organized to present a detailed discussion of each of the above steps of the protocol. Specific chapters are:

1. Introduction
2. Troubleshooting or Problem-Solving Procedure
3. Coater and Defect Analytical Tools
4. Problems Associated with Feed Preparation
5. Problems Associated with Roll Coating and Related Processes
6. Problems in Slot, Extrusion, Slide, and Curtain Coating
7. Coating Problems Associated with Coating Die Design
8. Surface Tension Driven Defects
9. Problems Associated with Static Electricity
10. Problems Associated with Drying
11. Problems Associated with Web Handling
12. The Role of Process Support Equipment
13. Coating Defects Databases
14. Defect Prevention

2

TROUBLESHOOTING OR PROBLEM-SOLVING PROCEDURE

This chapter discusses the problem-solving methodology and procedures that are needed to effectively troubleshoot coating process defects. Guidelines are presented for a systematic approach for identifying and defining the defect, for determining its cause, and for eliminating it. The basic assumption is that there is a defect or problem in a coated product on a specific coater and it must be removed. The problem can be a physical defect, such as chatter, ribbing, or streaks, or it can be an operational problem, such as the web not tracking properly in the coater and causing creases, or wet film exiting the dryer. The problem can also include production needs such as increasing the coater line speed, reducing solvent emissions from the film, or improving the performance properties of the product. The advantage to this approach is that some of the standard problem-solving techniques and principles can be used and adapted to the specific needs of the coating or drying process (Kepner and Tregoe, 1965; Rubinstein, 1975; Brown and Walter, 1983; Kane, 1989; Pokras, 1989).

A basic assumption is that a structured process is the most effective method of solving the particular problem encountered. An unstructured approach has several disadvantages. It can result in duplication of effort from the lack of a clear focus. The problem can take a long time to solve if the problem solver jumps to conclusions as to the cause without the necessary supporting data. The first thought is often assumed to be correct, and then experiments are run that do not solve the problem. Then the next suggested cause is assumed to be correct, and it too may fail. Many possible causes can be tested before the correct answer is found. It also frequently occurs that the problem is never truly solved and the factors that cause it may go away on their own or by an accidental change. The problem will then probably reoccur at a later date, and the entire procedure will have to be repeated. In addition, most coating processes are sophisticated and involve many parameters. Some of these are known and understood and can be treated scientifically.

Some are unknown or are less well understood, and these cause coating to be part art. The defects are often subtle and may result from small process variations or from interactions among several variables. It is essential to have a set procedure to follow to obtain and analyze all the data needed. The use of a formal procedure is more efficient and cost effective than a random shotgun approach.

A systematic troubleshooting procedure may appear to be long and expensive, may strain available resources, and may not appear to be warranted for all situations. However, it is our belief that a formal methodology is effective and should be followed consistently. When necessary it can be adapted to meet specific needs. The size of the team assigned to the current task can vary depending on the particular problem. A major problem for an important customer who is on the just-in-time system and needs product immediately may require a large team that will follow all the steps. On the other hand, a small defect on one side of a web may require a part-time person who will skip some of the steps while still using the basic concepts. Our belief is that we should try to eliminate all defects and to determine the underlying cause of all problems, starting with those of highest priority. Even minor defects with a low loss should be studied. Far too often, when the history of a major loss is assembled, it is seen that the defect started with a low loss frequency that was not treated promptly and eventually built up in severity over a period of time. If the defect had been studied at the first occurrence, subsequent major losses could have been avoided.

The problem-solving process consists of an orderly series of steps. First one defines the problem, then gathers the needed information about the product or process, develops hypotheses as to possible causes, tests the hypotheses, and uses the correct hypothesis to solve the problem. If this sounds very much like the scientific method, well it is. Since physical processes are responsible for the defects, the scientific method is the most efficient for solving problems.

The primary focus of this effort is on defects, since they are a major problem in a coater. Table 2-1 lists the steps in this process, and these steps form the general outline for this chapter. The same procedure can be used for all coating machines, in the laboratory, in the pilot plant, or in the manufacturing unit. The same steps also apply to any type of problem.

BASIC TROUBLESHOOTING PRINCIPLES

A basic principle of this troubleshooting protocol is that there are only two basic causes of problems or defects in a coater. The specific problems being studied can be based on either of two mechanisms: (1) something in the process or formulation has changed, or (2) an underlying physical principle is being violated.

The authors believe that the majority of the problems typically encountered in production are in the first category. The product has been in several production runs made without the defect being observed and something has changed, causing the undesired effect. By the time a product is in normal production, all of the problems due to underlying science and physical principles have been eliminated. Thus the goal of the analysis procedure is to focus initially on what has changed in the process that could have led to the defect, or to what has changed between the defect-free part of the coating and the defect area.

The second mechanism primarily occurs when a new product is being introduced or the capabilities of an existing coating line are being increased. In these cases it is possible to have limitations because physical principles are being violated. Suppose the dryer requirements are to evaporate 1000 pounds of solvent per hour and the new product

TABLE 2-1 Problem-Solving Procedure

1. <i>Defect detected, problem recognized</i>
• By on-line real-time inspection system • By visual examination in coater • By visual examination in converting area • By customer complaint • By analysis of yield data
2. <i>Define the defect or the problem</i>
• Collect representative samples • Describe the defect but do not name • List and record the characteristic attributes of the defect • Formulate the problem statement
3. <i>Collect and analyze additional data</i>
• Collect general process information • Collect analytical data on the defect • Collect analytical data on the raw materials • Statistically analyze the process data • Check the standard operating procedures
4. <i>Analyze the data and identify potential causes of the problem</i>
• Brainstorming sessions • Problem-solving techniques • Collect specialized data on process • Conduct statistically designed laboratory experiments • Run computer simulations
5. <i>Eliminate the Problem</i>
• Run production coater trials to test hypothesis • This may take several trials, with returns to step 4
6. <i>Document the results</i>
• Collect all data, charts from working sessions, and analytical results • Prepare report and issue
7. <i>Use results to prevent reoccurrence</i>

requires 1300 pounds of solvent per hour to be evaporated. Higher dryer temperatures than the equipment can supply may be needed. The use of a new thin substrate may require lower web tensions and better web transport control than can be attained. This class of defects may require hardware upgrades.

Even with defects resulting from a change in the process or formulation, the basic physical principles are important to the coating and cannot be ignored. An understanding of these principles is needed as a guide in looking for the changes and to determine whether the changes identified can possibly have the effect that has been observed. Both of these mechanisms work together to guide you to a rapid solution.

DETECT THE DEFECT

There are several conditions that can lead one to start the troubleshooting procedure. It can be when a defect is first detected, or when a problem is encountered on the coater that results in the termination of the current manufacturing campaign. Detection can occur through visual examination of the coating by operating personnel or by automatic defect inspection instrumentation. It can also occur in several locations, such as at the coating applicator, in the dryer, in the windup area of the coater, or upon visual inspection of the coated product. A customer report of a defect in the product can start the procedure. In addition, analysis of defect losses can identify profit opportunities if a defect is eliminated. Research and development can also identify a problem that needs to be solved in order for a new product line to be manufactured.

The use of real-time automatic inspection based on a variety of optical techniques is in widespread use on many coating lines. These inspection systems detect many different defects as the product is coated. The systems give the exact location on the web and can give information about the size, shape, and frequency of the defect. They are particularly effective in coaters where the web is difficult to view either because of subdued light, as in the case of photographic films, or because the coating machine and the dryers are enclosed. Also, at high coating speeds any nonuniformities can be hard to see. In addition, it is both stressful and boring to continuously examine the coated web throughout a shift. Coating machines run continuously, and operating personnel have other functions to perform. A more detailed discussion of on-line inspection systems is given in Chapter 3.

Defects originating in the coater can also be detected in the finishing or converting area, where the product is cut to size and packaged. Both automatic laser inspection and human observation can be used. Typically, representative samples of the product are taken to check the quality of the final product as it is being packaged. The product may also be given use tests to verify the quality. In the case of photographic films, the product is exposed and processed to give the same type of image the customer will see. This can pick up subtle coating defects that are not detected otherwise. The worst possible location for the detection of defects is when the customer uses the product. Although the customer should not receive any poor quality material, realistically this will occur at some level. A key point to remember is that the location of detection and the location where defect occurs may not be related at all. A spot first seen in the converting area can be caused by problems in the support manufacturing process.

Interestingly, one of the issues that may arise at this point is the lack of agreement by all functional personnel in manufacturing, quality control, research and development, marketing, and management that there is a problem that needs to be acted on. In fact, some may deny that there is a problem. It cannot be assumed that everyone will recognize that there is indeed a problem. Often, comments such as the following are heard in the coater area:

“We have always seen this.”

“There has always been chatter with this product.”

“We always get bubbles for the first 2 to 10 rolls.”

“We never could get the desired conditions in that zone.”

“We get these and always add some surfactant to fix it.”

“It will go away in an hour.”

“We need to ship product to meet an order.”

“The customer will never see this.”

Thus, the first important step in the troubleshooting process is to ensure that there is agreement that there actually is a problem and that it needs to be solved. This is essential to obtaining the resources in terms of the people, testing, and experimental time that is needed to conduct the investigation. The key is communication among all concerned. Use the historical files or check the product and process specifications to see whether the product or process is indeed within specs. The use of statistical quality control, ISO standards, and zero-defect goals all should help eliminate the denial phase and ensure agreement on all problems. However, denial is an inherent human reaction and will not go away easily.

Care should be taken at this step to avoid treating the problem and the cause as one step. They are very different steps, and treating them as one will lengthen the troubleshooting procedure and complicate the analysis. It is essential to define the problem rapidly and clearly and to get all to agree that there is a problem to be solved. A particular reason for doing this is that as the problem is being defined it will often turn out that there are several problems that require a solution, not just one. If you pass too quickly to the subsequent steps, this may not become apparent. Also, the initial guess as to the cause of the problem can lead to wasted effort.

Another factor in obscuring a problem is that often gradual changes in a process may occur over a long period. When examined over a short time period, these long-time changes can make the process appear to be stable. An example of this occurred in photographic film. One of the causes of photographic fog, or high background density, is the drying conditions. Thus conditions in the dryer must be optimized and closely controlled to maintain optimum film performance. Figure 2-1 shows typical levels of fog as measured on individual rolls of a product for 3 days. On this time scale the process does not appear to have a problem. However, Figure 2-2 shows the performance over 10 weeks; the gradual drift becomes apparent and the problem becomes obvious.

DEFINE THE DEFECT OR PROBLEM

The goal of this step is to further define the defect and to develop a statement, which clearly defines the problem to be solved and the results that are to be achieved from the troubleshooting effort. This involves gaining a better understanding of all the attributes of the defect. The following questions need to be asked and answered:

- What is the defect?
- Is the defect a functional defect that affects performance or is it esthetic?
- Where is the defect located?
- When is the defect observed—what is the time of day, the season, the temperature, and the relative humidity?
- How is the defect observed—by the naked eye or using a microscope or analytical instruments—and under what light conditions?

To answer the above questions, representative samples of the defect should be obtained from a variety of locations and over different times in the process, or else from varying

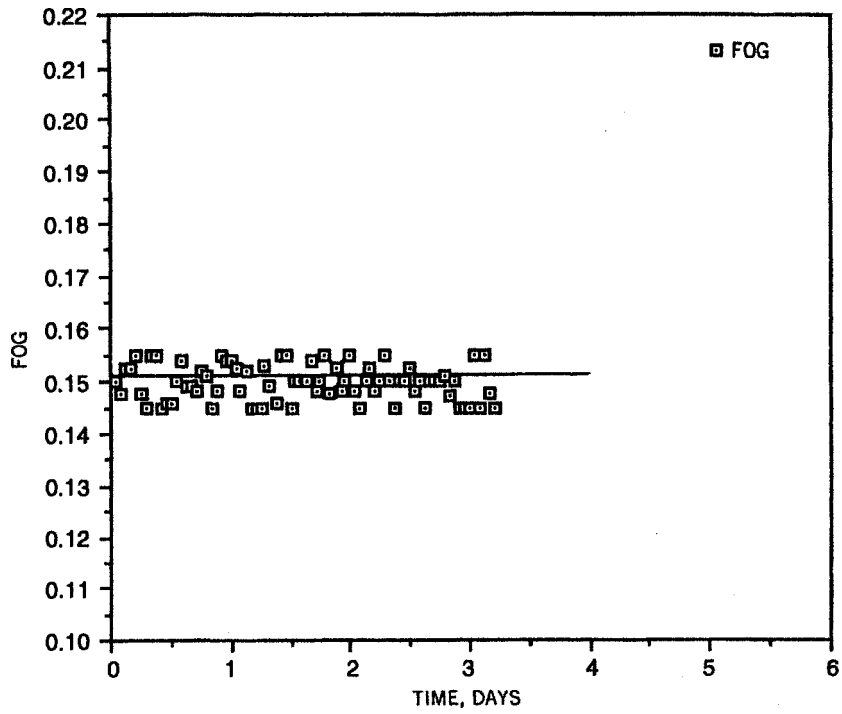
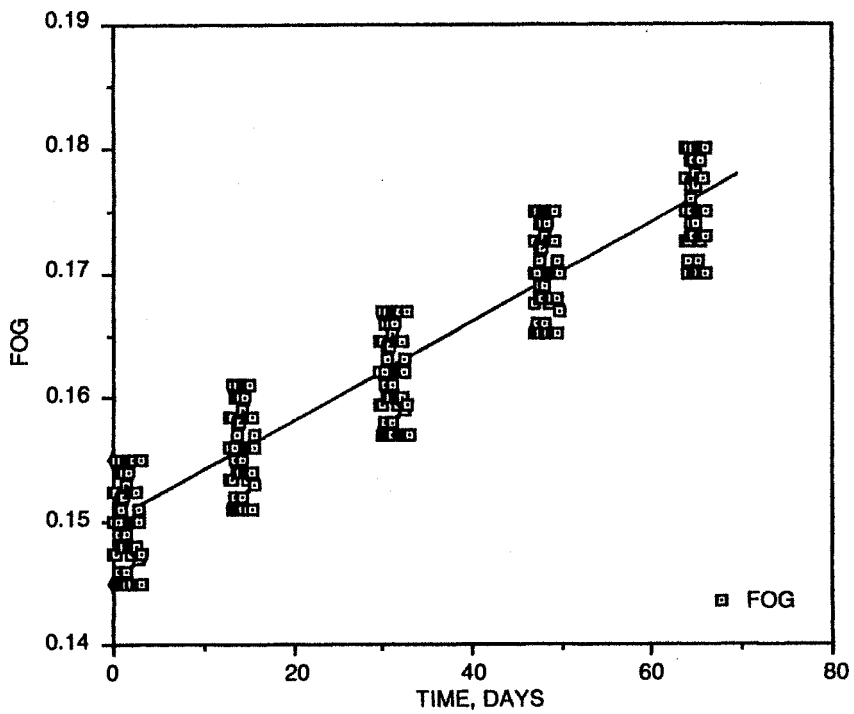


Figure 2-1. Fog levels over 3 days.



positions within the coated roll. When taking these samples the entire section of the web should be removed and the orientation of the web marked to a reference side of the coater. A large sample normally should be taken, as it is easier to discard an extra few feet of a sample than it is to try and retrieve more material from the scrap system. The samples should be clearly labeled with complete product identification, the time, and the machine being used. The large sample size will ensure that the true defect is seen and that a statistically valid sample is characterized. It is common to have several different defects in a coating, and time can be wasted in analyzing a defect that is not the most frequent or the most critical.

A technique that is particularly useful in the later stages of the troubleshooting process is to stop the coater and dry the coating in place. The distance from the coating applicator of the start of the section of web should be noted. Once dried, the coated web can be laid out and analyzed to determine where the defect first appeared. If it is present in the coating solution, it will be visible immediately after the coating applicator. If it is caused by dirt in the dryer air system, the first occurrence will be in the dryer. If it is due to contamination on a roll after the dryer, it will not be visible until after that roll. Samples of the uncoated web can be very useful in the troubleshooting procedure and should be taken. Some defects in the final coated product are caused by defects in the support material. A web contaminated with grease will cause defects in the coating due to wettability problems. Similarly, dirt on the support surface can cause defects. These effects may not be uniform from roll to roll. A sample of the base can help give insight into the problem. Also, it may not be possible to get a sample of the base later when it might be needed.

NAME THE DEFECT

After the sample is obtained, the next step is to name the defect. This is a unique feature of the troubleshooting methodology and is critical for its successful implementation. The name may be given to the defect when it is first seen, but whenever it is done it is a key step. While giving a name to a problem is an obvious starting point for any troubleshooting procedure, it is a particularly important consideration for coating and drying defects because these defects often have rather nebulous, hard-to-define characteristics. There can be a wide variety of names for the same defect, and defects that appear similar can have a wide variety of causes. As a result, defects can easily be misnamed and this can have serious consequences. Typically, at the start of the troubleshooting procedure, after the defect is detected, the first observer gives it a name that is descriptive of the defect. A round defect with a clear center that looks as though it had a bubble in its center is a *bubble*, a spot with a center is called *dirt*, transverse direction marks are called *chatter*, a soft nonuniformity in the coating is *mottle*, and so on. In the spray coating of automotive finishes, *pinholes* and *microfoam* both describe the same defect, even though the names imply that the defects are very different. In coating and drying defects there are few tests to quantitatively define a physical nonuniformity such as a bubble or a streak, and there are no universally agreed on naming conventions or standards as there are with performance properties, such as color, hardness, coating weight, or coverage, and sensitometry of photographic coatings. This leads to a wide variety of names for defects. It also leads to a variety of defects from many sources having the same name; examples are chatter and streaks, both of which refer to a wide variety of defects from many different causes. This can be seen more easily in Table 2-2, which summarizes some of the widely used common

TABLE 2-2 Some Names of Physical Defects

<i>Continuous Defects</i>	
Ribbing	Chatter
Chatter marks	Waves
Streaks	Bands
Transverse waves	Barring
Rib pattern	Drier bands
Wine tears	Bead breaks
Tailing streak defects	Weeping
Herringbone	Rivulets
Snake air	Cascade
<i>Discrete Defects</i>	
Bubbles	Craters
Thin spots	Blotchiness
Pinholes	Fisheyes
Blisters	Mottle
Bénard cells	Convection cells
Orange peel	Fat edges
Picture framing	Cracking
Starry night	Galaxies
Fleets	Crinkling
Cavities	Inclusions
Cracks	Buckling
Cockle	Air entrainment
Volcanoes	Bubbles with tails
Gel slugs	Dirt
Cell pattern	Hooks
Chicken tracks	Bar marks
Agglomerates	Shear
Bands	Randoms
Sea gulls	Snerts

names of defects. These names have been obtained from papers presented at various symposia, from the patent literature, from general publications, and from discussions with many practitioners of the art of coating and drying.

It is our belief that many defects are initially defined incorrectly and that the initial assignment of a name often implies an incorrect cause. This hampers the subsequent troubleshooting process significantly. This is a more important effect than is generally realized. The phenomenon has been called the *initial name syndrome* in order to point out clearly the importance in the troubleshooting process of correctly identifying a defect before naming it (Cohen, 1993). The initial name syndrome quickly and incorrectly gives a defect a descriptive name that implies both a cause and a specific course of action to eliminate the defect. An incorrect name shifts the focus from the true cause of the defect and results in an ineffective troubleshooting process.

Bubbles are a good example. Once the defect is called a bubble, it implies that air entered the coating solution from a source such as a feed line leak, a poor seal on a pump, too high a mixing speed in the preparation kettle, or air entrainment at the coating stand.

Then the initial effort will be focused on examining all these possible causes. If, however, the defect is caused not by an air bubble but by dirt falling onto the wet coating, much effort will be wasted in tracking down possible problems that could not possibly cause the defect.

Another reason for the initial name syndrome is that while defects on a modern high-speed coater should be eliminated rapidly by the operating personnel, the tools needed to analyze defects rapidly are often not readily available. A cursory visual examination, possibly using microscopy, and reference books of typical defects are widely used to aid in identifying defects, but they are not that accurate and can lead to incorrect names. This is particularly true if the operating personnel have other functions that may be of higher priority, such as keeping the coater running. Good preliminary characterizations can go a long way to avoid the initial name syndrome. However, conventional microscopy can be a time-consuming and tedious process, and it requires a skilled person to get good results on a microscope. In addition, manual searching of the past history to correctly identify a defect can also be tedious and often is not very useful. Scanning electron microscopy, EDX (energy dispersive x-ray), and ESCA (electron spectroscopy for chemical analysis) give accurate information but are time consuming. Note also that there is an inherent human tendency, when looking at a defect, to associate the defect with a name that implies a cause.

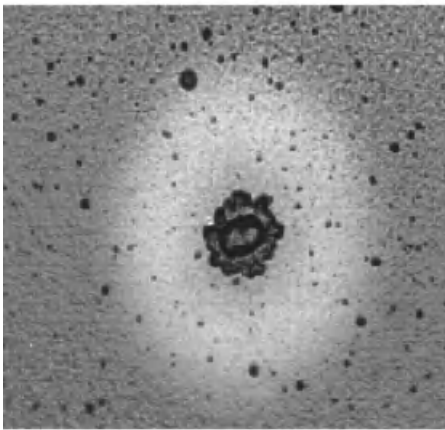
The importance of the initial name syndrome became apparent to us as a result of an ongoing effort in the laboratory to develop improved photographic film test methods based on a low-cost modular digital image analysis system (Cohen and Grotovsky, 1993). This digital image system consists of a microscope with resolution capability of $25\text{--}750\times$ to magnify the defect, a television camera and frame grabber to digitize the image, a computer with software to analyze the image and to calculate quantitative parameters, a high-capacity storage device, and a database to store and retrieve the images.

This equipment was used to improve defect characterization. A motivating factor was the desire by the troubleshooting and product development teams for better and more rapid evaluation technology. They submitted samples and we found that defects could be analyzed rapidly, resulting in much useful data to help in the troubleshooting procedure. As more samples from a variety of sources were analyzed, several observations were made:

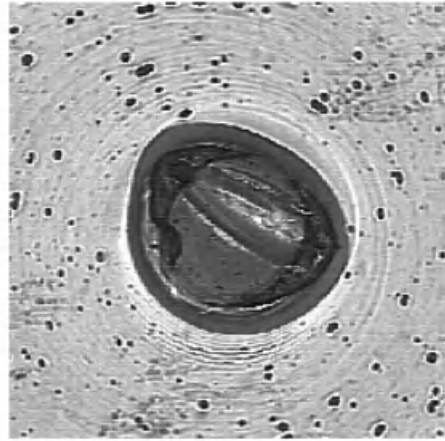
1. The vast majority of the defects were submitted with a name already assigned by the first observer.
2. Approximately 50% of these initial names did not accurately or correctly describe the defect.
3. When the digital image analysis results were discussed with the persons submitting the sample, they consistently agreed with our conclusions.

The correct identification after the digital image analysis step significantly improved the troubleshooting process. The causes were more rapidly found, there was less wasted effort, and, more importantly, problems were solved more rapidly. Figure 2-3 shows several examples of defects, all of which were submitted originally as bubbles. These defects are all different, as seen from this analysis, and were not caused by bubbles. The information provided by the digital image analysis led to more rapid discovery of the true causes and elimination of the defects.

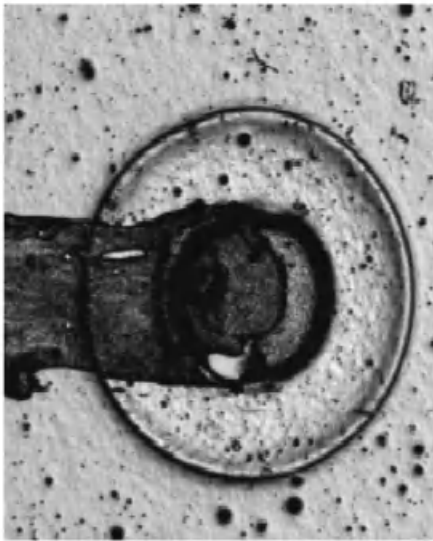
The best method of avoiding the initial name syndrome is to avoid giving the defect a poetic or descriptive name that implies a cause at the initial observation. While giving an initial name is a normal tendency for all of us, the temptation should be resisted. Instead,



DIRT SPECK



SURFACE CONTAMINANT



BACTERIA



PICK-OFF

Figure 2-3. Defects initially named as bubbles.

use general terms to describe the defect and its attributes. Instead of calling it a bubble, describe it as a series of round areas with no coating in the center. If the defect appears to be chatter, describe it as a series of coating nonuniformities running across the web. Add, for example, that the nonuniformities are light in the center, are $\frac{1}{8}$ in. wide, and are spaced at 2-in. intervals. At least several representative defects should be checked to ensure that the attributes are correct. After that, an innocuous name can be given, but care must be taken that the name does not imply a mechanism.

Although we have no desire to create documents and impose an additional burden on the operating personnel, at this point it is worthwhile to generate a form to record information gathered so far. This is very helpful for the analytical personnel and for the technical personnel who will become involved in the subsequent steps. Table 2-3 is a

TABLE 2-3 Initial Data Description of Defect**PRODUCT COATED**

The product being coated was a B-210a vinylidene chloride barrier layer, Formulation S-20, lot 45623, on a 1-mil polyethylene terphthalate substrate, S-400. The gravure coater applicator was being used at 400 fpm.

DEFECT DESCRIPTION (attributes: size, shape, frequency, appearance, general description, etc.)

Round clusters of spots with no apparent coating in center. They appear to be $\frac{1}{16}$ in. in diameter and occur in clusters.

WHEN AND WHERE OBSERVED

They were first observed on machine # 5, at 10 pm. They were first seen at the end of the coater. The initial indications are that they are only on the left side of the web, 2 ft 6 in. in from the left side of the coater. They were occurring about every 20 feet. After the second roll they were continuous. Subsequent examination showed they were occurring at the end of the applicator.

SAMPLES TAKEN

Samples were taken at start, middle, and end of three rolls, Id #050293-2, 050293-5, 050293-9. [We suggest using the date and month as part of the Id. Thus Id #050293-2 means May 2, 1993, roll number 2. The location can also be included.]

Operator _____ Date _____

filled-in form, which contains the essential information that should be available at this stage. This defect is a possible bubble problem.

This discussion was focused on the initial stages of the problem-solving process and its specific application to defects. These same principles should also be applied to the initial stages of any other problems that are encountered in the coater. The problem should be defined as generally as possible and should not be given a name that defines a cause and a cure. At this stage of the process, the problem solver should expand consideration of the problem and be very inclusive. No possible sources of the defect or problem should be ruled out.

If the coating, for example, is coming out of the coater wet, define the problem as wet coating from the coater. Do not define the problem as being that the coating does not dry. The latter description will focus your efforts on the dryer, whereas the problem may in fact be a heavier coating weight or too high a solvent loading in the coating formulation. If a nonuniform density pattern is seen down the web, define the problem as nonuniform coating density. Do not define it as coating chatter, which will cause you to focus on the coating applicator. A broader definition will allow you to look for other causes, such as web vibration, building vibration, substrate quality, and dryer effects.

Problem Statement

The last step in this part of the troubleshooting procedure is to develop a problem or mission statement. This statement defines the goal of the current effort and the anticipated result. The statement should be agreement by all involved. It should be kept readily available to ensure the correct focus of the effort as the team proceeds with the subsequent steps. It can also be modified as the effort proceeds. The statement does not have to be elaborate and can be short and concise. For example:

- Eliminate bubbles in product CDA-12 at 500 ft/min in coater #1. Reduce frequency to 1 in 10,000 ft². Manufacturing unit experiment needed no later than 2 weeks. Final recommendation needed in 4 weeks and report in 6 weeks.
- Reduce high coating weight spike at 10 inches from gear side of substrate in product TBC-1 from high of 10 g/m² to 9.0 g/m². Identify causes no later than 3 weeks. Plant test needed in 5 weeks. Final recommendation needed in 6 weeks and recommendations for hardware modification in 8 weeks.

COLLECT AND ANALYZE ADDITIONAL DATA

A major requirement for successful problem solving and troubleshooting of defects is to obtain the necessary information about the problem or defect and about the coating process used. Typically, there are many separate sources of information and all the information has to be analyzed and integrated to understand the cause of the defect and how to eliminate it permanently. Although all coating processes have some unique characteristics, there is certain basic information that applies to a wide variety of coating techniques and is the basic building block of the data collection process. The next chapter discusses the detailed analytical procedures needed to obtain specific defect information.

Process Information

There is some general information needed for the initial analysis that is discussed in this section. There are many types and sources for this information, and all need to be searched to determine if there is relevant data for the current problem. The specialized data for certain types of defects are covered in the specific process sections. In addition, the next chapter gives more details of some of the special instruments and tools that are needed for this effort.

First one should obtain the information and measurements needed to characterize the process both during normal operation and when defects are observed. It is assumed that the coating process is basically as shown in Table 2-4. The process starts with the incoming web and the raw materials for the coating liquids. The next step in the process is

TABLE 2-4 Coating Process Unit Operations

-
1. Receive raw materials
 - Active ingredients
 - Solvents
 - Coating aids
 - Substrate
 2. Test raw materials
 3. Compound and formulate coating solution
 4. Purify coating solution
 5. Test coating solution
 6. Coat on substrate
 7. Dry to remove solvent
 8. Cure coating
 9. Inspect for defects
 10. Convert into final form and package
-

compounding or formulating the coating solutions, purifying them, coating them, drying the coating, and then converting the material to the final shape and form. The process does not have to use a continuous web, such as rolls of sheet metal or of polyester. The coating can also be applied to discrete parts, as in spray-painting cars, dip coating individual parts, or curtain coating cut sheets of glass.

Each of these unit operation or process steps influences the final coating quality and can cause the eventual formation of defects. Thus process information and data are needed from each step. The data and measurements needed should be made both while the process is running without defects and while defects are occurring. In most instances a change in a specific parameter, such as viscosity or surface tension, may be more important than the actual level. It is difficult to interpret measurements and data obtained only when defects are occurring because then there is no idea of what the normal state should be. An understanding of the performance and characteristics of the process while it is making good product is as important as while it is making unacceptable material.

One question that could be asked at this point is why the terms *information* and *measurements* are both used. By *information* we include subjective observations by the people running the process and by those doing the testing, and these observations may not be in the form of numerical data such as pH, surface tension, or coating weight. A key effect in running a coating process is to observe all of the process, not just those parts that lead to conventional measurements and data. Subjective observations can and should be used in the troubleshooting procedure. They are often a key part because the cause of the defect may be a result of a change in a property or combination of properties. These observations then lead to a new measurement technique to quantify the property.

A basic rule of troubleshooting is that one can never have too much data. It is better to have more data and determine the cause of the defect than to have too little data and miss an observation that can lead to defect elimination. It is important to observe the process and record the key information. There is, however, also a danger of recording too much data and filling many file cabinets with never-used data. This balance needs to be determined, and the safest procedure is to err on the side of too much data. It is not possible to go back in time and get lost information. Murphy's law applies here, in that the time when you do not record key information will be the time of poorest quality and highest yield loss. The converse is not true, unfortunately, in that taking too much data will not prevent defects.

One of the best ways to avoid defects is to detect the potential problems before they occur. It is much more efficient to scrap a batch of contaminated coating solution than to scrap the finished coating. The focus should be on properties, information, and characteristics that bear directly on coating quality and on defects. A main incentive for following the procedure is to arrive at a cause of the defect, and then modify the coating process so that if the same circumstances are again present, they are detected before the product is coated. The earlier in the process that the conditions leading to a defect are eliminated, the better the process will be.

General Process Information

Both quantitative and qualitative data can be obtained from the process. Quantitative measurements are obtained from process instrumentation, from measurements with portable diagnostic instruments, and from the quality control and analytical measurements that are taken at each step in the process. With the widespread availability of computers and low-cost data storage, these data are stored digitally. Typically the majority of measurements are obtained automatically and stored in digital format on magnetic tape

TABLE 2-5 Typical Quantitative Measurements

• Raw Materials
• Formulating and Compounding
Mixing conditions: time, temperature profile, agitation rate, agitator motor amperage, filter type, pressure buildup, milling conditions, etc.
Coating solutions: viscosity, surface tension, temperature, density, % solids, % active ingredients, viscoelastic properties
• Coating
Premetered coating applicator: pump rpm, pump size, pressure if pressurized feed, flow rate, applicator temperature, gap between coating roll and applicator, bead vacuum level (if used)
Roll applicator: roll speeds, gaps, roll speed ratios, roll diameter, roll surface
Dried coating weight, dry coverage of active ingredients
• Dryer
For each drying zone: total air volume flow rate, velocity in representative nozzle slots or plenum pressures, air temperature, solvent level delivered to nozzles, pressure drop across filters, solvent removal unit conditions, return air temperature and solvent level, make-up air conditions, air balance
Location of end of falling rate period, and uniformity across web
• Unwinding, web transport, and rewinding
Coater line speed, web tension in each zone, drive roll conditions
• Miscellaneous
Air conditions: temperature, relative humidity, and balance in coating room and in the unwind and rewind area

or on disk for later recall and analysis. As a result, the subsequent analysis is considerably easier since the data can be retrieved from a data analysis program and analyzed. Also, the same computer program that records the data can also recall and plot the data for the time period desired. If automatic data collection is not available, the data can also be recorded by hand on log sheets or log books and then entered into a data analysis program from which graphs can be prepared. Graphs make the identification of trends much easier. Table 2-5 is a summary of some of the quantitative measurements that can and should be made on a process, and which will be useful to analyze when defects occur.

Not all of the important process variables are recorded by instruments. Qualitative observations made by operating personnel are also essential for the troubleshooting process. The state of the shipping container needs to be checked to ensure that it is intact and has not been damaged in transit. The outside of the container should be checked to see if there is anything unusual on it. Dirt from a container top can inadvertently be added to a formulation kettle, leading to defects. The appearance of all raw materials needs to be observed and anything unusual noted as part of the data collection process.

The substrate for the coating should be checked to ensure that it is the right material and it should be tested occasionally to ensure that the correct side is coated. It is our experience that almost all coating operators and coating engineers have inadvertently coated on the wrong side of the base or on the wrong support at one time or another. If a precoated support is used, the coating quality should be checked as the roll is being mounted on the unwind stand and any unusual conditions noted. The quality of the roll as it is unwinding is all important. An unbalanced roll can send vibrations throughout the web and this can lead to coating chatter.

The overall condition of the whole coating complex is important. Is the coater/drying room unusually dirty? If so, that can lead to dirt contamination in the dryer and dirt can be wound up in the coated roll, leading to pressure defects. Is the coater unusually warm or cold? A cold stream of air blowing on a roll can lead to condensation and defects. Are there drafts of air in the coating room that have not previously been present? This can change the air balance in the coating applicator room and blow dirt on the coating instead of protecting it. Are there unusual vibrations felt in the building or coming from motors and bearings? This can lead to chatter. Has any maintenance been done in the building recently?

Analytical Data

Analytical data on the apparently defective material, on the raw materials used to manufacture them, and on the normal defect-free material is necessary and is a major part of the troubleshooting procedure. Once samples of the defects have been collected, a complete physical analysis, and if warranted a chemical analysis, should be conducted to determine the exact nature of the defect and how it differs from normal material. The objective is to collect information on the defect in order to determine the cause. If spot defects are present, the chemical analysis is needed to determine if there are any foreign materials present and what they are. These tests should include both defective and standard material. Often, the cause of a defect may be differences in the level of a normal component of the coating. If the product is exiting the coater wet, the coverage should be measured to ensure that it is within limits. In the next chapter we discuss the different analytical methods in more detail.

Testing of the raw materials used for the coated product is a key step in preventing and troubleshooting defects. The major materials are tested to ensure product performance. However, it is worthwhile to check that they are indeed the correct material at the time of use. If a surfactant typically is a clear liquid and today it has white strands, something has changed. This should be recorded and consideration given to using a new batch. There are many raw materials that go into the final product. All should be tested. Coating formulations include polymers, binders, surfactants, cross-linking agents, pigments, and solvents. They and the coating support are the obvious raw materials. Testing of the raw materials used for the coated product is a key step in preventing and troubleshooting defects. Materials need to be tested to ensure that they are, indeed, the material indicated on the label and that the chemical composition, activity, and impurity level are all within specifications.

Standard Operating Procedures

Standard operating procedures and the ongoing data logs that result from them are another source of information. The procedures and actual operating conditions that were used for the product and process under investigation should be compared to ensure that all of the correct conditions were used.

ANALYZE THE DATA AND IDENTIFY POTENTIAL CAUSES OF PROBLEM

The next step in the problem-solving and troubleshooting process is the analysis of the data collected to determine the cause of the defect. One must integrate all the information

that has been obtained. This is the most difficult step in the process. If the previous steps have been followed, the answer should be available. All the information suggested in the section *Collect and Analyze Additional Data* should be available for analysis. The difficulty is to find and isolate the relevant important information from the useless and false leads. It is very important at this step to ensure that the process used and the logic and the thinking encompass all possible solutions and do not focus too rapidly on the most obvious solution, which may not be correct.

A team approach is recommended to identify the causes, to formulate hypotheses, and to test these hypotheses. This will bring a wide perspective and will help to ensure that all possible causes are identified. There is a definite synergy from having several people participate. The team can be small or large depending on the size of the problem and the available resources. For a large, high-value problem, the data are collected by a number of people, all of whom should obviously participate in the analysis process. Representatives from manufacturing, engineering, quality control, and research and development should all participate. The team for a smaller problem can be two or three people discussing the problem over coffee.

For a large team of four or more people, a structured process should be used and a brainstorming technique is recommended. Give the group the statement of the problem that had been developed earlier and have the group develop a list of questions that need to be answered or are suggested by the problem statement. This list of questions will then be the basis for the analysis step. As an aid, Table 2-6 is a general-purpose list of questions to start the problem-solving process and to stimulate thinking. This list contains both general questions and specific questions on coating defects. The list of questions should be

TABLE 2-6 List of Questions on the Defect

When was the problem first observed?
Has it been seen previously?
Is it present for all products on coater?
Is it seen more or less frequently on a particular shift?
Is it seen more or less frequently at any time period?
Is it seen more or less frequently with a season of the year?
Does the outside weather have an influence?
Is it seen more at a particular point in the process?
How does the problem change with time?
Is anything else going on in the facility at the same time as the problem?
Is there anything different in the coater or storage area?
Is the area cleaner or dirtier than usual?
Is the temperature and humidity in the coater different than usual?
Is it more prevalent with a particular applicator?
Is the defect more prevalent with a particular product?
Are all the defects really the same?
How are they distributed?
Are there any new constraints that have been imposed on the coater?
Are the standards the same now as previously?
Is a different person interpreting the standards?
Are there any new sources of raw materials? What is the age of the raw materials?
Are there any changes that have occurred in the coater or converting area?
Has there been a recent shutdown?

expanded to incorporate the specifics of the particular problem. The next step is to answer the questions with the data that have been accumulated.

At this point there are some analytical techniques that can be used to develop defect mechanisms from the raw data. One of these is defect mapping, which is a technique to identify the specific location on a web where defects are occurring. It uses measurements, graphs, and statistics to determine the frequency and exact location of defects in both the machine and transverse directions. The method does not require expensive tools and will give process insight. It ensures that you analyze the right defect and points to best areas for characterization.

The map is a graph that shows the location and frequency of defects in both the machine and transverse directions. This defect map is easy to prepare and can rapidly suggest some causes. If repeating spots are observed, then a defect map that shows locations and spacing between spots is needed. This spacing between spots can then be related to the circumference of rolls in the coater and perhaps identify the source of the spots.

Another example is shown in Figure 2-4. The defect studied was a spot defect, which was believed to be slivers of base from the edge trim in the slitting operation being deposited onto the coated substrate. A long sample of the original coated web was obtained and the location of each spot determined. The defect map shown in Figure 2-4 was prepared. The map showed a high frequency of defects in a lane 18–24 inches from the gear side. This ruled out the edge trimmers, because spots would be along the edges. Investigation of the web path of the edge trim revealed a direction change device in the location of the spots, which was scraping off the coating.

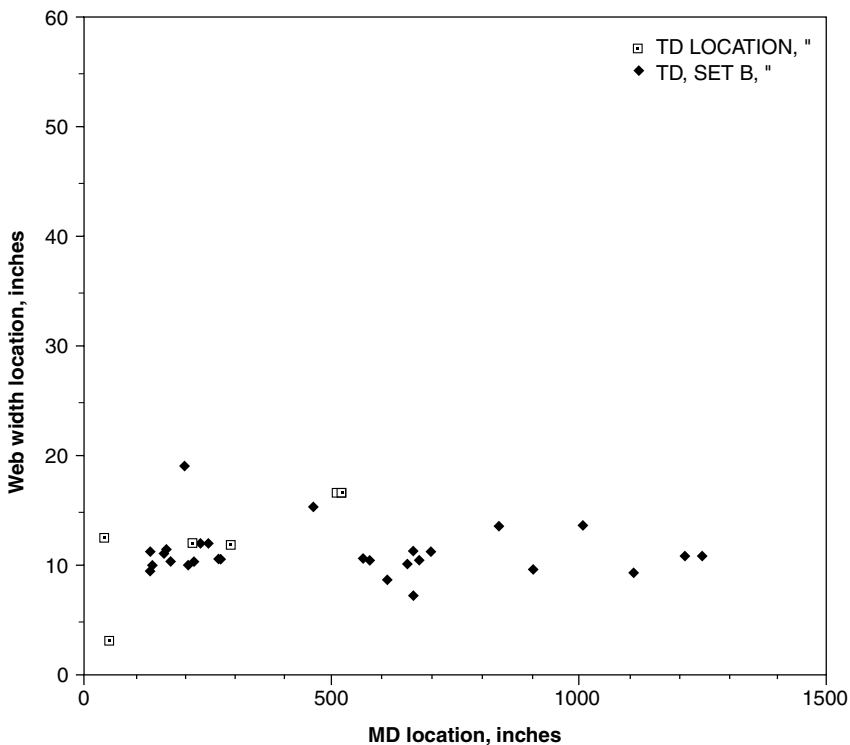


Figure 2-4. Defect map.

Causes of Defects Initially Classified as Gels

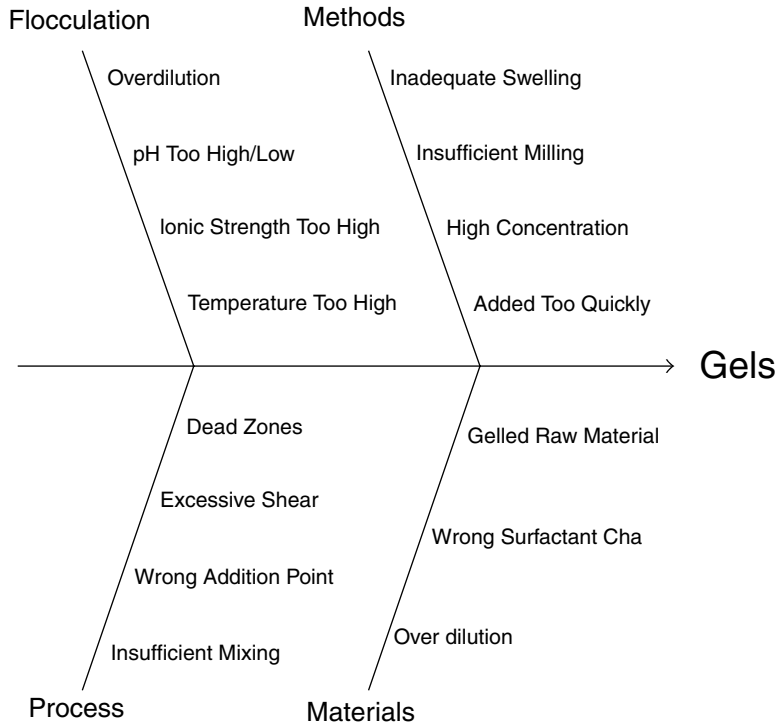


Figure 2-5. Fishbone diagram.

Another technique that is useful in establishing potential causes of defect is the fishbone diagram. It is also called a cause-and-effect diagram or Ishikawa diagram, named after the inventor Kaoru Ishikawa. It is a graphical tool that, for a specific problem or quality characteristic, helps identify the possible causes that can influence it. This diagram helps determine all possible causes of the defect under study. It has four base characteristics: *machinery*, *people*, *methods*, and *material*. Subcategories are developed under each class. Figure 2-5 shows a typical diagram for a gel spot defect that needed to be eliminated. It shows the several variables that can influence the gel spots. These are then studied to confirm an effect or lack of it.

After the questions have been answered, the possible mechanisms or causes of the problem are developed. One of the many brainstorming techniques should also be used for this as well as for developing the questions. A good way to record all the comments is to use Post-it notepads or index cards and affix them to a wall in the room. A basic rule is to be positive and not reject any idea. Record everything and encourage all to contribute anything that they think is reasonable. After every comment is recorded, they can be combined and priorities assigned for testing the hypotheses.

A very useful methodology for the analysis phase of the procedure is the worksheet used by Kepner and Tregoe (1965). It provides for a sequential procedure to focus the information that has been collected and to help identify the changes that have led to the current problems.

TABLE 2-7 Kepner–Tregoe Problem Analysis Worksheet

	Defect Is	Defect Is Not	What Is Distinctive in This
What	Bars across web Non uniform density chatter bars	Spot defects Streaks	Vibrations will induce hydrodynamic instabilities and cause chatter
Where	Across web	At edges only At center only	Uniform source of vibrations Uniform transmittal to web
When	At start of coating roll	During balance of roll End only	Vibrations only at coating start Vibrations disappear
Extent	Severe at start Decreasing severity to 200 feet	Not uniform Same intensity	Coating start hardware active in this time

Possible Suggested Causes

Coating start hardware malfunctioning
 Coating start hardware conditions set wrong
 Coating roll bearings defective
 Vacuum initiation source

There are four key elements to this worksheet, illustrated in Table 2-7. In the columns, one puts down these four basic attributes of the problem or defect:

1. What is the deviation?
2. Where did it occur?
3. When was it seen?
4. To what extent is it present?

The top row gives the heading for the columns. The first column is for what is true about the attribute, and the second is for what is not true. This information is drawn from what has been collected in the initial part of the troubleshooting procedure. The third and last column, which is sometimes omitted, is to identify what is distinctive about the information, based on the first two columns. Finally, at the bottom of the worksheet, possible causes of the defect are listed.

For example, if there is a spot that occurs on the right side of the web, under *Where*, you indicate that it is on the right side and is not on the center or left side. This then leads to consideration of the process and to what is distinctive about the right side. It could be air ducts, or spargers, or web aligners, and then these have to be checked.

Variations of this form can be used. For a large group working on a complex problem, each point can occupy several pages. The troubleshooter working alone can use a simple one-page form, as in Table 2-7. The format is flexible and can be modified as needed. Several examples are shown in Kepner and Tregoe (1965).

Table 2-7 is based on a chatter problem in a coated photographic film product. Chatter was found on an increasing number of rolls, and a small team was assigned to identify the cause and eliminate it. Table 2-7 is the worksheet as filled out after the data on the problem were assembled. It was used to organize the information that was obtained. The *What* was chatter or variable-density bars, which were uniform across the web. The *Where* was across the entire web, and not random, or only at the edges or at the center. *When* was only at the start of coating. The extent of the chatter was severe at the start and then fell off

rapidly in intensity. The uniformity of the chatter suggested mechanical vibrations as the source, not hydrodynamic instabilities. Since it occurred only at the start, this suggests possible malfunctions of the coating start hardware. This hardware was checked and it was found that a part was misaligned when initially activated. This caused the vibrations until the part finally aligned itself into the correct position. Other causes were also suggested and are listed at the bottom of the worksheet, and these would have been checked if the first, most likely, cause was shown not to be the problem.

Typically, the analysis will lead to several possible causes, which have to be pursued either by obtaining more data or by running experiments in a laboratory coater or even in the production facility. This can be time consuming and inefficient. It is easy to obtain an enormous amount of data very quickly and spend many hours in generating plots. You can end up more confused than before and can drown in the mass of data. The availability of personal computers and easy-to-use computer software programs can help the analysis, or, on the other hand, they can complicate the analysis and hinder the solution. Computers definitely make the job easier by providing more sophisticated analysis tools and reducing the time to prepare plots and calculate statistical parameters. Computer plots are faster to make and are more accurate than hand plots. However, if you are not careful, more plots can be prepared than can possibly be analyzed. This can and will slow down the troubleshooting process. All the computer does is simplify the mechanics; it does not analyze and formulate possible defect-causing mechanisms. It is not a replacement for creative thinking.

As discussed in Chapter 1, identifying the change in the process that could lead to the defect is one of the goals of the data analysis. Identifying these changes and pursuing them is a good starting place in the defect reduction process. This concept can be illustrated in several typical problems, which are often encountered in a coating process.

When coating chatter is observed, the possible changes that can lead to this are (1) changes in vibrations at the coating applicator and web, (2) changes in the coating solution rheology, and (3) changes in the coating applicator conditions. Therefore data collection and analysis should focus on vibrations in the web, the building, at the coating applicator, and in the roll bearings and the feed systems. In addition, data on viscosity and preferably on viscoelasticity, on coating weight data, and on changes in the applicator conditions, such as vacuum level, tilt of a slot die, and die-to-web gap in slot or slide coating, need to be obtained.

When bubbles are detected, the solution preparation kettles, pumps, and feed lines should be analyzed to determine if changes have occurred that lead to air leakage into the coating solution. If the film is leaving the dryer wet instead of dry, changes have occurred in the solvent load into the dryer or the solvent removal capability.

Correct identification of the defect or problem is a key step in this process, as described previously. It determines the possible changes to look for in the process and should be the first step in the analysis process. The defect should not be named until after it is characterized. In some cases it is possible to name the defect, such as chatter or bubbles, rapidly and correctly. For other defects, particularly spot defects, extensive analyses may be needed to identify them correctly. There are a wide variety of causes for spots, and many are due to contamination. Thus analytical identification of the contaminant is needed to determine possible sources and where to look for the changes.

Once the team has established the potential causes, laboratory or plant experiments are needed to verify the mechanism. This can be done by using different lots of raw materials, a different base, changing bearings, adjusting airflow to the dryer, adjusting solution

viscosity, and so on. In all these cases, the initial goal is to prove the hypothesis either correct or incorrect, that is, that the factor can lead to the defect or that it cannot lead to the defect. These experiments should be designed to gain a solid base of information about the defect. Several rounds of experiments may be needed. Statistically designed experiments are highly recommended to improve the quality of the results and the efficiency. The differences between good and bad product are often subtle, and the precision and accuracy of statistics are needed. Well-designed experiments are far more cost effective than nonstatistical experiments, such as one-variable-at-a-time studies.

A major error in tactics at this point is to try and make one good coating and resume production by combining all of the identified changes in one “Eureka” cure. Occasionally the defect is eliminated by this approach and everyone is satisfied that the task is apparently concluded successfully. Then there is no more effort. It could be that the changes have solved the problem; it is also equally probable that they did not and the cure was a result of an unknown fortuitous change. Since the cause of the problem is unknown, it will usually reemerge and then the entire process must be repeated at considerable expense.

The two basic mechanisms for causing defects also apply to the laboratory coater. However, in the development of new products and new processes, it is important to define the basic physical principles involved and then operate without violating them. Once this has been done, any changes become the prime factor to be considered.

Computer simulations can also play a key role in analyzing problems and identifying solutions. Programs are available that can simulate coating flows for several coating processes. These can be used for problems such as chatter, ribbing, streaks, and unstable coating beads (Grald and Subbiah, 1993; Subbiah et al., 1993). It may be more effective to simulate the process change and gain an understanding of the underlying principles using a computer model as opposed to extensive coatings. The role of these programs is a prescreening tool. It will not replace some level of laboratory and plant experiments.

ELIMINATE THE PROBLEM

To summarize, at this point the problem or defect has been defined, the data collected, possible causes identified, and statistical laboratory experiments run to verify the hypotheses that have been developed. In addition, computer simulations may have been run to help define the mechanisms. The next step, then, is to select a preferred solution and take it into the production coater and implement it. Again, the use of a statistically based experiment is recommended to verify the laboratory results and to determine the optimum solution. When this experiment is run, extensive data should be obtained in the event that the problem is not completely solved. It may be necessary to go back to the preceding step and reanalyze the problem with the latest data.

DOCUMENT THE RESULTS

After the problem has been solved, it is important that a closing report to document the results be completed. Our experience in troubleshooting defects has shown that a significant percentage of defects will reoccur at some time in the future and their causes will be similar. In addition, we have observed that coaters and products on these coaters

tend to have certain patterns of characteristic defects. Some products are prone to streaks and others are prone to agglomeration and spot defects. Some machines tend to give chatter while others tend to give similar types of winding problems. If complete information is easily available from previous problem-solving exercises at the start of the current problem, then when problems do reoccur, this historical information can simplify the current procedure. Also, at this point in the problem-solving procedure, a great deal of time, effort, and money have been expended to obtain a wide variety of diagnostic information about the coater and the defect. It is cost efficient to record the information so that it has ongoing value. This documentation will also help in the future operation of the coater and can also be a very useful training tool for new personnel.

There may also be preliminary progress reports presented as the problem-solving procedure is occurring. These reports can be in the form of weekly or monthly reports or of team reviews for management. It is a common practice in oral presentations to provide copies of the visual aids used, which then become a circulated record. Often preliminary data and possible mechanisms are presented in these preliminary reports, which turn out not to be true when the problem is solved. However, the early report may be found later and the reader will not be aware of the subsequent change. One final official report will prevent this and will be of ongoing value.

Documentation is often not considered as part of the problem-solving procedure for many reasons. The personnel involved have put in extra hours and effort in solving the problem and are expected to get back to their regular assignments or to solve the next problem. Also, many scientists and operating personnel are not comfortable with report writing and do not believe that it is as valuable as running a coater or doing experiments. Reports are often viewed as a research-type function and do not have a role in manufacturing operations. The mechanics of report writing can be a chore and very time consuming, particularly if the report is handwritten and then has to be retyped for legibility. There may not be the personnel to do the retyping, duplication, and distributing of the report. Typically, several people did the work, and writing a report in which many people contribute can lengthen the process to the point where the report never issues.

The final closing report is an important part of the problem-solving process and we recommend that it be an official part of the process. The report preparation does not have to be a major task and can be accomplished very easily by using the following guidelines:

1. Issue the report within 30 days after the problem is solved.
2. The preparation and issuing of the report is the responsibility of the team leader and is his/her last official function on the team.
3. A report with 80% of the information issued on time is much better than a report with 95% of the information that never issues.
4. Prepare progress reports and summaries as the work is evolving. These can then be easily edited and modified for the final report.
5. The final report should be simple and easy to follow. A good format is to have an overall summary at the beginning. A couple of paragraphs on each problem-solving step will provide the reader with a good overview of the problem and its solution. Subsequent sections can be the details from each of the team members, analytical reports, defect samples, and so on.
6. The report can include copies of appropriate material and does not have to be all original writing.

7. Include the names of all team members and participants so that they can be contacted to discuss results.
8. The report should be in digital format so that it can be stored in a computer database and easily retrieved.

As an incentive, the team leader should not move onto a new assignment until the report is submitted. This will help guarantee completion.

USE RESULTS TO PREVENT REOCCURRENCE

The last step in the troubleshooting process is use the accumulated knowledge from previous troubleshooting incidents to prevent their reoccurrence. A good approach is to review the technical and operating results with a goal of developing action items that, if implemented, would improve the process and help reduce defects. If there have been more than one defect episode, they should be discussed together to determine any common solutions that exist.

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3

COATER AND DEFECT ANALYTICAL TOOLS

One of the requirements to conduct a successful troubleshooting program is to be able to effectively characterize the defective product and the coater variables when the product was coated. As a result, a working knowledge of a wide variety of diagnostic techniques is needed by the troubleshooter to provide the necessary information about the coater and the defects being studied. This information must be accurate so that when used in the problem-solving procedure it will help eliminate the defect. This chapter reviews some of these specialized methods and shows how they are used to provide information about the unique problems that arise in a coating operation. Each of the methods or tools described is well known and has been described extensively in the general literature and in formal courses. Our intent in this chapter is to describe the methods that are particularly useful for coating problems and to focus on the specific type of information that they provide on coating defects. The troubleshooter needs to understand the capability of a wide variety of analytical techniques so that only those analytical techniques are used that provide useable relevant information.

Problem solving is a discipline in the same way as chemical engineering, physical chemistry, or physics and requires its own tools to meet its objectives. A physician, in order to treat a sick patient, requires specialized tools to obtain measurements on the patient's condition and to diagnosis the illness. A stethoscope is used to listen to the heart, a sphygmomanometer to check the blood pressure, an ophthalmoscope to check the eyes. X-rays, CAT scans, MRI, and ultrasound are used to see inside the patient's body, and a thermometer is used to check the temperature of the patient. These tools provide the physician with the measurements and data that are needed to correctly diagnose and treat a disease. The effective coater problem solver also needs specialized measurement tools to assess the status of the coater and the coating, to determine the cause of the problem. Over the years, the authors have developed a working knowledge of a variety of diagnostic tools to diagnose and correct coating problems. In fact, one of the authors has a collection of

portable instruments in his lab used to diagnose problems, which are available for loan to other problem solvers. These are engraved with the author's name so they can be returned, when inadvertently left in the dryer or in a corner of the coating line.

OVERVIEW OF ANALYTICAL TOOLS

The four basic categories of analytical tools that are needed for effective characterization are:

- Analytical methods to characterize the coating defects area and the nondefect area
- Instruments to obtain more information about the overall coater behavior
- On-line instrumentation
- Statistical techniques to analyze the data and extract useful information

The following sections describe them in more detail. The basis for the selection of these tools is our own experience in problem solving and troubleshooting defects in film coaters. These are the tools we have used and have found to be consistently helpful over many years. There are a wide variety of analytical tools, computer programs, statistical methods, and instruments that are available from a variety of manufacturers. All of these can be used and will provide needed information. It is not our intent to rate these instruments as to effectiveness or to endorse specific vendors and equipment. We cite specific instruments so that readers are aware of how they function and of the information they provide, to help problem solvers build their own collections of tools. Much of the selection is individual preference due to familiarity gained by using the tools over a period of years. If an analytical method or instrument is easier to use or gives better information, then use it. A limited amount of data taken with a usable instrument is much better than no data at all. An inexpensive instrument that is used is better than an expensive, sophisticated instrument that is never used. Also, the technology in this area is advancing rapidly and more powerful instruments at lower costs are becoming available. The troubleshooter should keep current on these advances and use them when necessary.

Analytical Methods to Characterize Defects

In order to eliminate a defect in a coating, it is necessary to analyze the defect to determine its cause and source. The goal of this analysis is to rapidly determine the uniqueness of the defect as compared to the main body of the coating. A complete and thorough analysis using a wide variety of techniques is the ideal state; however, there are practical factors that dictate a more selective approach to the analysis. Although there are many useful and expensive surface analytical methods available, it is neither possible nor economically feasible to run all of these tests even when the equipment is available. There are many occasions when a rapid answer is needed to meet the needs of production and to get the coater running again. The test methods should be selected for the best overall value at the lowest cost. A partial analysis obtained quickly may be far more helpful than a detailed and elaborate analysis that takes several weeks. The analysis is only part of the overall procedure, and a partial analysis coupled with the other observations will often lead to a solution.

For this analysis there are four basic categories of analytical instruments that can be used to rapidly provide characterization data:

- Optical video microscopy with digital image analysis (i.e., video enhanced microscopy)
- Infrared microscopy
- Scanning electron microscopy (SEM) and energy dispersive x-ray (EDX)
- Electron spectroscopy for chemical analysis (ESCA)

In addition, there are some supplementary techniques that can be used if more information is needed than was obtained from the above:

- Fourier transform infrared spectroscopy (FTIR) to identify organic and some inorganic compounds
- Atomic absorption (AA) to measure elements in a sample
- Gas chromatography and mass spectrometry (GC-MS) for elemental analysis
- Atomic force microscopy (AFM) to measure surface topography
- Contact angle measurements using goniometry

Defect Test Procedures

The first step in the defect characterization procedure is to obtain samples that have the desired defect in them. The defect mapping procedure and techniques in Chapter 2 will help to ensure that the appropriate samples are tested and that the dominant defect is identified. It is a good practice to retain a sample from each coated roll and of the uncoated substrate, so that if a defect is found after the roll has been converted, original samples can be studied.

We recommend that the analysis be done in two stages: a preliminary analysis to gain some rapid characterization data followed by a more detailed analysis. The first step can be done in the quality control laboratory of the production facility or in R&D laboratories, with only limited instrumentation. It may give the operating personnel enough data to solve the problem without the expense of additional testing. This first stage also helps determine the types of tests, if any, that are needed in the second stage. A more selective approach to the second stage in running only needed tests will be far more efficient than running all of the tests simultaneously.

Video Enhanced Microscopy

For the first stage of analysis, a good light microscope is the basic tool. The unaided eye is a poor analytical instrument, but the eye aided by the magnification of a microscope is excellent in determining the characteristics of a defect. Table 3-1 summarizes a wide variety of different types of microscopic methods and gives some of the characteristics of each. The light microscope has several advantages. It is rapid, is reasonably priced, and has a good magnification range for the defects usually encountered in coating. It is easy to use with some training. There are also many publications available that have micrographs

TABLE 3-1 Microscope Capabilities^a

Type	Acronym	Magnification	Resolution	Analysis Time ^b (seconds)	Environment
		Range	Nanometers		
Light microscope	LM	5–2,000	200	10	Ambient
Scanning electron microscope	SEM	10,000–250,000	5	60	Vacuum
Scanning electron microscope field emitter	SEM/FE	10,000–40,000	1.0	90	Vacuum
Transmission electron microscope	TEM	1,000–1,000,000	0.5	300	Vacuum
Scanning TEM with selective area diffraction	STEM/SAD	1,000–1,000,000	0.15	30	Vacuum
Scanning laser acoustic microscope	SLAM	10–500	1,000	60	Ambient
Confocal scanning microscope	CSM	100–10,000	0.1	20	Ambient
Scanning tunneling microscope	STM	5,000–10,000,000	0.0001	300	Vacuum
Atomic force microscope	AFM	5,000–2,000,000	0.0005	600	Ambient

^aBased on Studt (1990).^bTime to acquire image.

of standard particles and basic information on techniques (McCrone et al., 1993, 1999). The advent of video enhanced microscopy in the late 1980s greatly advanced the utility of this technique. In video microscopy, the eyepiece of the microscope is replaced with a television camera and monitor (Maranda, 1987). Instead of viewing through an eyepiece, the image is viewed on a high-resolution monitor. This considerably reduces the eye strain involved in looking at many samples. Magnifications up to several hundred times can be obtained from instruments available at reasonable prices. Microscopes with a variety of viewing modes (transmitted, reflected, or incident) are available. These systems are relatively low in cost and are rugged enough to be installed in a coater and used by operating personnel. An additional advantage is that hard copies of these images can be made either from the monitor screen or by a special attachment on the microscope. Good quality printed images can be obtained by using high-resolution inkjet or laser printers.

A widely used enhancement of the microscopy technique is to integrate the microscope into a computer-based digital image analysis system. These systems provide a quantitative analysis capability and electronic storage for the images being studied. In these systems the image from the TV camera is digitized and stored in a computer, and then quantitative characteristics of the defects are calculated using specialized software programs (Cohen and Grotovsky, 1993). There are a wide range of systems that can be assembled for this use, depending on the need and the funds available. A variety of handheld microscopes are available. A microscope that can be attached to a laptop is available with a magnification capability of 1×, 50×, or 200×. A portable handheld digital camera and portable

microscope are also available, which is useful for analyzing samples in the coating line area. In addition, completely assembled digital video microscopy systems with software are available.

A further advantage of this technique is that since these images are stored in computer-readable format, they can easily be recalled for study and comparison with previous samples. Since the images are in digital format, they can be widely distributed throughout the company. An advantage of all the microscope techniques is that they can be run rapidly and provide a fast result.

Microscope techniques are very useful for discrete coating defects and those with moderately sharp boundaries such as spots, streaks, ribbing, chatter, scratches, bubbles, contamination, and a wide variety of defects with poetic descriptive names such as fleets. Microscopy is not very useful for subtle defects that have vague boundaries such as mottle. However, microscopy is useful in selecting representative defects for the second stage analysis. Often when discrete defects are seen in a web, there are many of them and they may not all be the same type. It is more efficient to screen the defects with a conventional microscope and select those defects that are the most representative for further analysis. With conventional microscopy, an individual defect can be studied and characterized in 5–10 minutes. The second stage techniques require about an hour per sample and are more expensive to run. This prescreening will ensure that the proper defects are characterized while reducing the costs and the time involved.

Examples of defects that have been analyzed are shown in Figures 3-1 and 3-2. These show some of the range of magnifications and the quantitative properties of the defects that can be calculated.

The infrared microscope is a standard microscope that is equipped with infrared transmitting optics that measures the infrared absorption of minute samples with the aid of photoelectric cells. In these techniques the sample is optically analyzed and, if any areas of interest are found, then the infrared spectra can be obtained and plotted with the same microscope. These spectra can then be compared with standard reference spectra to determine the composition. In the defect mapping example, specks were found on the surface of the product in a lane. The infrared microscope was used to analyze them. The expectation was that these were particles of polyethylene terephthalate (PET) from the edge. However, the spectra showed that it was product backing that was being abraded and deposited on the web. A check of the web path of the edge trim then revealed the source of the specks.

Surface Characterization Techniques

The second stage of the analysis uses a wide variety of surface characterization techniques to chemically and physically characterize the surface. Tables 3-1 and 3-2 show some of the more sophisticated analytical methods that are available for a detailed characterization of the surface. Of these, the scanning electron microscope (SEM) is the most useful for a wide variety of typical coating defects. The SEM provides very high magnification and resolution and gives a three-dimensional view of the image. All the needed detail can be seen. An additional advantage of this method is that an analyzer (EDX) can easily be integrated into the system and used to measure the chemical composition, both qualitatively and quantitatively, of the defect and the normal sample area. The optical image in a SEM is developed by irradiating the surface to be studied with an electron beam in a vacuum, collecting the scattered electrons and developing an image on a television

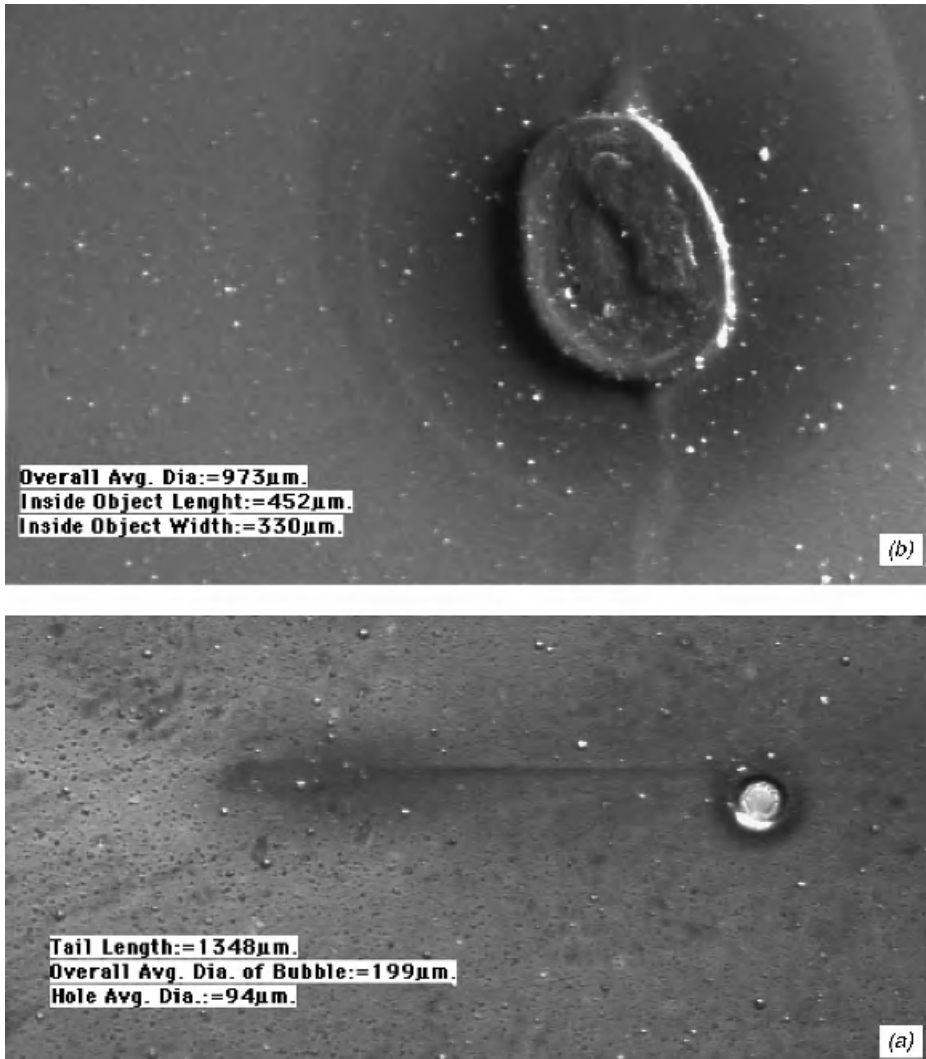


Figure 3-1. Defects as seen by digital image analysis: (a) particle contamination and (b) bubble with streak.

monitor. These electrons also create x-ray emissions, which can be analyzed to determine which elements are present along with an estimate of their quantity. The limitation is that only the elements heavier than sodium can be determined. Organic compounds cannot be detected. However, there are other readily available methods to characterize organic compounds.

In SEM/EDX the visual image and the x-ray images can be combined and presented in a variety of formats. An image of a particular element can be obtained and its composition displayed throughout the sample. Another format is to scan the beam in a single line both across the defect and through a normal coating sample. This will show how the element distribution varies from the standard material to the defective material. This combined image will show the physical appearance of the defect and which elements are associated

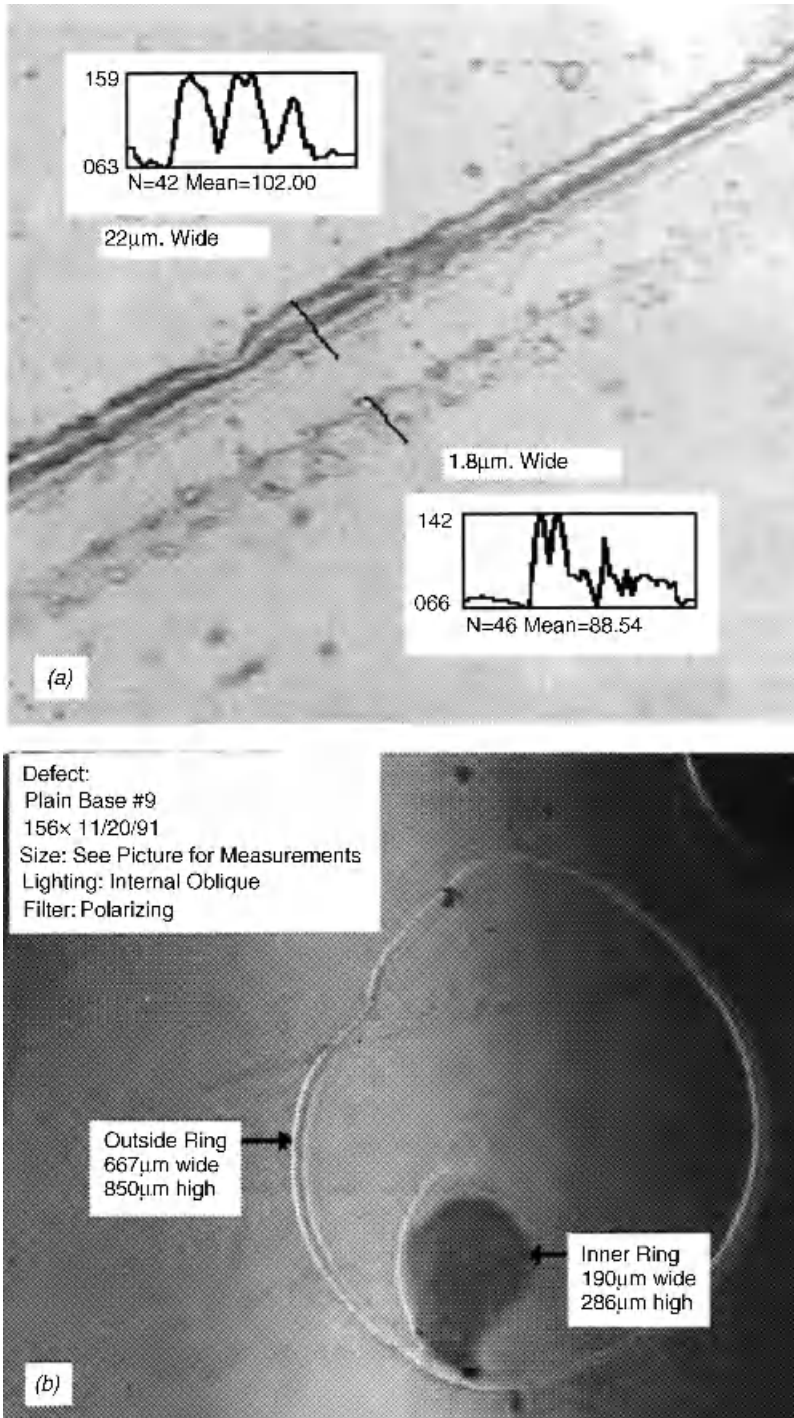


Figure 3-2. Defects as seen by digital image analysis: (a) scratch and (b) bacterial contamination on base.

TABLE 3-2 Surface Chemical Analysis Instruments^a

Type	Acronym	Detectable Elements	Sample Size (cm)	Analysis Time ^b (s)	Depth of Resolution (Å)
Scanning Auger microscopy spectroscopy	SAM	Lithium to uranium	20	10–100	50
Electron spectroscopy for chemical analysis	ESCA	Lithium to uranium	20	10–100	50
Secondary ion mass spectroscopy	SIMS	Hydrogen to uranium	20	100	40
Energy dispersive x-ray	EDX	Sodium to uranium	2	100	50,000
Fourier transform infrared spectroscopy	FTIR	Organic functional groups	7	10–500	10,000
X-ray fluorescence spectroscopy	XRF	Magnesium to uranium	20	500	2×10^8
Laser ionization mass spectroscopy	LIMS	Hydrogen to uranium	20	10	20,000
Surface analysis by laser ionization	SALI	Hydrogen to uranium	2	50	20,000

^aBased on Karesek and Laub (1974), Willard et al. (1974), Karasek (1975), and Studt (1990).

^bTime to acquire image.

with specific features of the defect. Also, if there are contaminants or particles present, the SEM and EDX can be combined into one image. The images obtained from these techniques can be stored digitally and can be added into the defects catalog that is described in the Chapter 13.

The SEM/EDX technique is powerful since it combines both the physical and chemical elemental analyses into one measurement. It is very useful for defects with discrete boundaries, such as spots, and defects that are suspected to be from foreign contaminants. Once the chemical elemental composition of the defect is known, the source can be determined and eliminated. To help in the identification process, the composition of potential contaminants from the coater can be characterized and then compared with the defect to give a definite identification. In addition, samples can be made in the laboratory, which have the suspected contaminants deliberately added to the coating composition. These can then be analyzed by SEM/EDX. There is also some utility in analyzing diffuse defects if the areas can be identified and are in the size range of the SEM. It can also be used to study surface effects, such as surface haze, orange peel, and reticulation.

A good example of the utility of this method is in the identification of metallic contaminants that get into a coating. The metals used in the bearings, idler and coating

rolls, pumps, and ducts are all different and have unique compositions of iron, nickel, chromium, carbon, molybdenum, and titanium. The following are some specific examples of the composition of stainless steels that are typically found in coaters (Perry, 1963):

Alloy	Composition, Nonferrous (%) (Balance Is Iron)				
Stainless, 17-7 PH	Cr 17	Ni 7	Al 1		C 0.09
Stainless, 17-4 PH	Cr 17	Ni 4	Cu 4	Co 0.354	C 0.07
Stainless, 316	Cr 18	Ni 11	Mo 2.5		C 0.10
Stainless, 304	Cr 19	Ni 9			C 0.08

If metal is found in a defect, its composition can be compared with known sources to aid in determining its source.

The samples in SEM/EDX must be run under vacuum so that the high-voltage electron beam can be directed to the sample and then to the analyzer. At normal pressures the electron beam is scattered by the air and does not have enough energy to eject electrons from the sample. Also, the sample must be coated with a conductive coating, such as gold, so that current does not build up on the surface. This can limit the type of samples that can be used. The environmental scanning microscope, a recent development, can be used on samples without the conductive coating and this extends the range of samples that can be studied.

The other methods referred to in Table 3-2 are very powerful tools for surface analysis. They are really research tools and are not for routine plant tests. However, they should be considered if some of the specific characteristics are particularly needed. If there is a suspected support coatability problem, atomic force microscopy (AFM) or the scanning tunneling microscope (STM) should be considered. These will give a good deal of information about the submicroscopic surface characteristics that cannot be seen with conventional microscopy. If there is a reason to suspect a difference in the properties in the depth of the sample, a confocal scanning microscope (CFM), which generates three-dimensional (3-D) images, should be considered. This microscope can focus in varying planes in the depth of the defect and create a 3-D image.

In addition to the EDX, there are several surface characterization techniques that can be used to determine the chemical nature of the surface and to indicate the compounds present. Of these, electron spectroscopy for chemical analysis (ESCA) and Fourier transform infrared spectroscopy (FTIR) are the most widely used for defect analysis. ESCA will detect the elements heavier than lithium and also organic compounds, and it can indicate the type of bonding that is present. This can be used to identify specific compounds. A drawback is that it requires a larger sample size than EDX and it is a surface measurement that only penetrates 50 angstroms. It is useful for detecting contaminants in large spot coating defects and for analyzing the base or support. Infrared spectroscopy is widely used to identify organic compounds. There are several sources of standard spectra that can be used for comparison and identification. FTIR is particularly useful for providing the infrared spectra of a surface. Both normal and suspect surfaces can be characterized to indicate the difference in organic composition. A limitation of this technique is the thickness of the layer. A thin layer may not give a strong enough signal for analyzable spectra. These instruments are available in most analytical laboratories and should be considered for use if organic compounds are suspected, or SEM/EDX does not give any chemical composition data.

A practical example of the concept that running simple basic tests can lead to defects elimination occurred in an adhesive coating problem that one of the authors was involved with early in his career. An adhesive layer was being coated on a metal support for a photopolymer printing plate. In the early stages of production, spot defects were found all over the web. Simultaneously, the filter pressure climbed to the point where the filters were plugged. Production was stopped, the filters were changed, a new batch of adhesive was prepared, and production resumed. Again the defect was seen after a short time. At that point technical assistance was requested by manufacturing and a small team was assembled. The problem was defined as agglomerates in the coating solution. Possible causes were incomplete dissolution of the adhesive, coagulation of the adhesive during pumping and holding, or contamination.

The first steps to gain information were to obtain the used filters to determine why the pressure was increasing, and to obtain samples of the coated defect for analysis. The filters were found to contain a white polymeric-appearing contaminant with the colored adhesive. The defects in the coating were also found to have the same contaminant in them. None of the adhesive normally contained any white components, which indicated a foreign contaminant. The major component of the adhesive was obtained from an outside vendor who had indicated that the equipment was used for many other syntheses. We had a list of these, and one that stood out as having similar properties to the white component was a cellulose nitrate based lacquer. At that point more samples were in the process of being obtained and were to be taken back to the lab to be characterized by infrared spectroscopy. However, a quicker test was found. The contamination was collected and placed in an ashtray and touched by the flame from a match. The material exploded. This was good evidence that it was indeed cellulose nitrate, a known explosive. Infrared spectroscopy verified that the compound was cellulose nitrate. The hypothesis was that the batch we were using had been contaminated in the manufacturing process. A call to the vendor confirmed that the batch previous to the one we were using was indeed made with cellulose nitrate. An earlier lot was used next for the solution preparation, and it coated without any problems. The corrective action taken was to change procedure so that there was thorough cleaning of lines and kettles before manufacturing of this adhesive.

This is an example of the problem-solving procedure and how it can lead to a successful solution to a defect problem. Complex sophisticated analytical methods are not always needed. The microscope coupled with a simple analytical test often can lead to a successful solution in a very short time.

COATER CHARACTERIZATION INSTRUMENTS

Specialized instruments are also needed to measure coater properties and provide information for the questions that have been posed in the initial part of the problem-solving procedure. Even though most modern coaters have extensive control and measurement systems, it is not economically feasible to measure all possible variables in a coater and to measure all properties in all locations. In addition, it is possible that instruments are not functioning or are out of calibration, and additional measurements are needed to verify the data. Also, more frequent observations may be needed than obtained by the standard data collection procedures. As a result, additional measurements are often needed.

All of these specialized tools have been greatly improved by the electronics revolution of the last ten to fifteen years. The rapid advances in miniaturization and the advent of new

TABLE 3-3 Coater Characterization Tool Kit

<i>Portable infrared pyrometer:</i>	To measure temperature of substrate coating and rolls in coater substrates.
<i>Strobe tachometer:</i>	To measure film and roll speeds in coating line.
<i>Cameras:</i>	To record events during coating and on the coating line. Equipment includes digital camera, video camera, and tripod to support camera.
<i>Portable data loggers:</i>	To measure process conditions at specific locations.
<i>Microcassette tape recorder:</i>	To record observations when it is not possible to write comments.
<i>Tape rule and straight rule:</i>	To measure locations on coating line.
<i>Velocimeter or hot wire anemometer:</i>	To measure air velocity and static pressure in ducts and nozzles.
<i>Temperature meter and selection of probes:</i>	To measure temperature and humidity of ambient and dryer air, coating solutions.
<i>Rheometers:</i>	To measure rheological properties of coating solutions.

electronic devices have resulted in a wide variety of powerful, low-cost devices that are readily available and easy to use. Also, powerful low-cost computers are now available that can process data orders of magnitude faster than the computers of the 1970s. Analog strip chart data loggers have been replaced by multichannel devices, which store the data in digital format for direct processing by the computers.

In addition to the instruments required to characterize the product, there are several additional characterization instruments needed to characterize the coating process and provide essential data. These instruments are summarized in Table 3-3. The selection of which instruments to use is up to the individual troubleshooter and depends on the available funds to purchase them.

Temperature is an important parameter in coating solution preparation, coating application, drying, roll and raw material storage areas, and in the varying process rooms that contain the mixing kettles, the applicator, the unwinder, and the rewinder. In most coaters the key temperatures are recorded and controlled. However, there are many times when the problem solver needs to check locations that are not recorded, or to check whether the recorded readings are correct. As a result, temperature measurement should be considered a necessary diagnostic tool. There are several basic measurement techniques that are available to measure temperature:

- Liquid-based thermometers, which use the expansion of a fluid as an indication of temperature
- Bimetallic dial thermometers in which a strip formed from two metals bends with temperature because of differences in thermal expansion
- Thermocouples in which an electrical potential arises in the junction of two dissimilar metals as a function of temperature
- Resistance temperature devices (RTD) in which the resistance of a platinum or other metal sensor is a function of the temperature
- Thermistors, which use the change in the electrical resistance of a semiconductor as a function of temperature
- Infrared thermometry in which the energy emitted from the surface is an indication of the temperature

Each of these has its advantages and fills different needs. Thermocouples are used when many measurements are needed at the same time. The thermocouples can be placed in a variety of locations and the data recorded in a central data logger. The wires that form the thermocouples are inexpensive and can be run over long distances without a loss of signal strength. Thermocouples can also be used to give an indication of the web temperature in a dryer. In single-sided dryers, where rolls are used to transport a web and drying air is not blown against the rolls, there is usually a large wrap of the web on at least some rolls. That roll surface will reach temperature equilibrium at or near the web temperature, and a thermocouple placed inside the roll, close to the surface, will then sense the temperature of the web. This is inexpensive and can be used to obtain data on the web temperatures in the different dryer zones.

Resistance temperature devices are the most accurate and are used when precision measurements are needed, such as in the basic dryer air control system. They are too expensive to use for many measurement points in a coater. They are ideal for a handheld meter and can be obtained from laboratory supply houses.

If the temperature of a moving web, a coating bead, or any hard to reach location is needed, infrared thermometry is an excellent method to use, especially for remote measurements. Portable IR thermometers are available with a wide range of precision and accuracy. These are aimed at the remote object and the temperature is measured. They are good for characterizing moving webs in the dryer and determining the temperature profile of a coating throughout the dryer. They can be more accurate than using a thermocouple in the roll. However, they are more expensive and may require calibration, as they depend on the emissivity of the surface. They are particularly useful in floaters dryers that have no rolls in the dryer. In addition to the single-point IR thermometers, there are also thermal imaging devices, which can give an overall temperature scan of a wide area. The measured temperatures are converted to a color and then used to form the image of the part being measured. The image viewed on the monitor will be one uniform color if the temperature is constant over the viewing area, and will be many colored if there are temperature variations. These devices are useful for locating leaks in heating and ventilating systems or heat losses in the dryer.

The portable data loggers discussed in the next section meet many of the needs for temperature measurements. They have their own sensors or they can be hooked up to thermocouples. They are compact and can be placed in any location where a temperature reading is needed.

The need for temperature and air velocity measurements can be met by having a handheld velocity meter or hot wire anemometer that combines temperature and air velocity measurements in one long probe. These can be used to check the dryer airflow in plenums or the airflow from the dryer nozzles.

A tachometer is recommended to check the speed of the many rolls in a coater, the dryer fan speed, the coating pump speed, and, by using a roll that rotates without slipping, the web speed. The commercially available models have accuracies and resolution on the order of 1% or better. They come in a variety of speed ranges, such as 5–10, 10–100, 100–1000, and 1000–10,000 revolutions per minute.

Tachometers are available in both mechanical or contacting models and strobe or noncontacting models. The noncontacting tachometer is preferred because it can get readings on hard-to-access rolls, and it is safer to use than a contacting tachometer. The contacting units require the measuring head to be held against the web or roll for which the speed is needed. A variety of heads are available to get the best contact. Noncontacting

stroboscopic devices should be used where the speed is very high or access is difficult. These devices need some form of indicating marker on the rotating wheel for the light to reflect from. Special reflective liquids and tapes are available from laboratory supply companies such as Cole-Palmer, Fisher, or Edmund Scientific. Care must be taken in using the stroboscopic tachometer in order not to be misled by multiples of the true speed. Thus half the true speed will also give the same stationary appearance.

The microcassette recorder is used to record both data read aloud from instruments and spoken observations, while one is in the coating area taking measurements or observing the operation. The tape recorder is preferred to writing because data can be recorded rapidly and recalled very easily. It provides flexibility in recording data while still performing other duties. The coater is a high-speed operation with many functions going on simultaneously. It is easier to speak into a recorder than to write on a clipboard or in a notebook. Also, it may be hard to read the notes at a later time, and written notes are more likely to be incomplete. A small voice-activated microcassette is preferred because it is lightweight and can easily be stored in a pocket. The voice-activated feature permits the recording of data hands-free while setting an applicator roll speed, adjusting a damper, and so on. These are relatively inexpensive and reliable machines and can be purchased in any commercial electronics store.

Two-way radios are very useful for communicating during an experiment when several people need to coordinate actions or observations. Typically, a damper may be located far from the gauge that measures flow, or the tension control device is located away from the web where wrinkles are occurring. Two people are needed to set the conditions at the desired value and the two-way radios simplify communications while reducing the time needed. It is always possible for one person to do this, but, in a production unit with expensive raw materials, the time saved can be an appreciable cost factor. Careful coordination by radio can help to optimize a process condition without obtaining an adverse effect in the coater. When setting a tension in a coater, the observer can instantly see when the web goes unstable and communicate that fact to a colleague who can adjust it. The time interval for one person to set the condition and walk to see the result could lead to web wrap and coater shutdown. Two-way radios are also relatively inexpensive and can be purchased at commercial electronics stores.

A visual recording device is also an important part of the tool kit. There are a wide range of digital cameras and video recorders that can provide both still and continuous images which can be transferred into computers for storage. A visual recording device can make a permanent visual record of any point in the process where there is a problem. A recording of the coating bead or applicator roll can help define a quality problem. If there are creases formed in winding, a visual recording can help define the cause. The recording can then be played back for further analysis at a later time and can be played at lower speeds for slow-motion analysis. For additional analysis, key frames from the recording can be captured and analyzed in an image analysis system. This can be used to calculate properties such as the size of bubbles, the deflection of a web, or the motion of a bead. Some additional equipment such as lights and a tripod to hold the camera should be used.

When taking measurements in the coater area, there is another important factor that needs to be considered and that is personal safety. The taking of the temperature and pressure measurements on a catwalk, checking the process for problem areas, inspecting a moving web, installing thermocouples, and so on all have the potential for causing an accident with injury to the troubleshooter and personnel in the vicinity. The troubleshooter may be in an unfamiliar situation because this is the first visit to the coater, or because

modifications have been made since the last visit. While concentrating on the measurement and not on the surroundings, it is possible to have an injury, by inadvertently tripping and falling over a loose wire or cord that is on the floor, by getting a hand caught between a roll and the moving web, and so on. To minimize the dangers, one should be aware of the area safety rules. One should wear the proper protective equipment and should consider all actions before doing them. Make sure that the coater operating crew is aware of your presence and knows what you are doing and where you will be. Consider the safety aspects when you run wires or set up specialized equipment. If there are many thermocouple wires, bundle them with tape and use a route to get them to the recording device that is not a walkway. If need be, tape them to the floor or wall with bright tape and make a sign to mark them. Be aware of the equipment and how it operates, and consider the possible interactions with the coater environment. In a solvent environment explosion-proof equipment is needed.

Data Loggers

The sensors described in the first part of the chapter can generate a significant amount of process data and measurements, all of which need to be recorded for further analysis. This section describes some of the various data logging devices that are available to record the data from these sensors. Most modern coater control systems have some form of data logging systems that preserve the measurements in electronic format for further analysis. These will give the troubleshooter much of the needed data. However, we have found many occasions where additional measurements must be taken. Data loggers will automatically record these measurements without requiring a person to be present.

Both analog and digital devices are available. The analog strip charts provide a continuous record of the process variable versus time and have been in widespread use for many decades. They have several advantages: qualitative information is easily obtained by visual examination, time trends stand out clearly, and strip charts are inexpensive. However, quantitative information is hard to obtain for detailed statistical calculations because the troubleshooter must transcribe each point to a digital format for statistical analysis. In addition, practical experience has shown that the pen may clog or run out of ink at the most critical point in the data set and much data may be lost because of this.

The preferred devices are portable digital data logging devices that can record the desired sensor measurements in digital format, that will add the time of the measurement to the record, and that will store both in some form of a magnetic or solid state memory. These units have several advantages. They are small, about the size of a package of cigarettes. They can be inserted into any part of the process and left there to continuously record data. When the memory is full it starts again at the beginning of the memory. This allows the monitoring of potential trouble spots in the process. Thus when a defect is detected, the data logger can be removed and data analyzed. Since the data is in digital format, it can be transferred directly to a computer for analysis and plotting. The time for analysis will be greatly reduced, leading to a faster solution to the problem. The data loggers are inexpensive. The units are flexible and the same equipment can monitor pressure, temperature, or viscosity, depending on the sensor to which it is attached. Most of the hardware is light and portable and can easily be transported into the coater. The functions these data loggers perform is to take the input sensor signal, which is usually in either milliamperes or millivolts, convert this signal to the desired units through the use of an appropriate algorithm, and then record the results. A central program is required to

convert the signal, provide the time base, and control the recording function. These devices are all basically digital computers and vary in the range of functions that they can perform. Within this category there are many types of devices to record a variety of signals and to store data on a wide variety of recording media. These data loggers can record all of the sensor information described previously, along with the time and date of the reading. Temperature data is a frequent need in the coater and specialized temperature measurement data loggers are available. They can record up to 1000 channels per second and can be used with either thermocouples or resistance temperature devices. All of the conversion algorithms are provided and the reading is directly in °F or °C.

Personal computers, both IBM PC and the Macintosh, can also be used to perform data logging functions. Both desktop and laptop models can be used. Special boards are made to be placed in the expansion slot of the computers, which will attach the sensors in the field to the computer. Typically these boards also come with the necessary computer software programs. These programs are easy to use and allow the user to specify the data storage, the conversion of signals to desired units, the time sequence, and any other calculations that are needed. Once the data is recorded through these boards and programs, it can be analyzed in the same computer, and this saves time. It is much easier to prepare reports and analyze data by using this method than with analog devices.

Portable data loggers are now available from several companies and laboratory catalogs. When originally introduced, there were a limited number of models to cover the basic temperature, relative humidity, pressure, current, and voltage measurements. There are now a wide variety of specific instruments that can measure:

- Temperature: Thermistors, -60 to 255°C (-76 to 491°F)
- Temperature: Thermocouple Types J, K, T, E, R, S, B, and N, -40 to 70°C (-40 to 158°F) or much higher
- Relative humidity: 0–100% R H from -40 to 70°C (-40 to 158°F)
- The ac current or voltage: 5–500 A, 0–5 V or 120 V or 480 V
- Pressure: 0–5, 30, 100, and 150 psi
- Process signals: 0–2.5 V, 0–5 V, 0–10 V, 4–20 mA, 0–200 mV

Other parameters are memory capacity of 32 kB to 1.5 MB, 8- or 12-bit resolution, measurement frequency, and several measurement channels per logger. The exact capacity, precision, battery life, and number of channels depend on the vendor and the price of the data logger.

All the data logging functions, recording functions, battery, and sensors are contained in small, self-contained units that are lightweight. They are designed to be easily attached to ducts, dryers, or almost any location where a reading is needed. The memory can contain up to 1.5 MB and measurements can be recorded over an extended period, depending on the frequency of the measurements. The units record continuously and the recording memory is of the wraparound type. Thus it will record over the first readings when the memory is full. With this feature, the logger can be left in place and removed when a problem occurs. Because of the small size and low cost, these units can be carried in the tool kit and used whenever needed. Just record the time in and the time out of the process so that the correct data is identified for analysis. The loggers function with a personal computer and special software that is used to set the timing of the desired measurements and to move the data from the data logger to the computer for subsequent

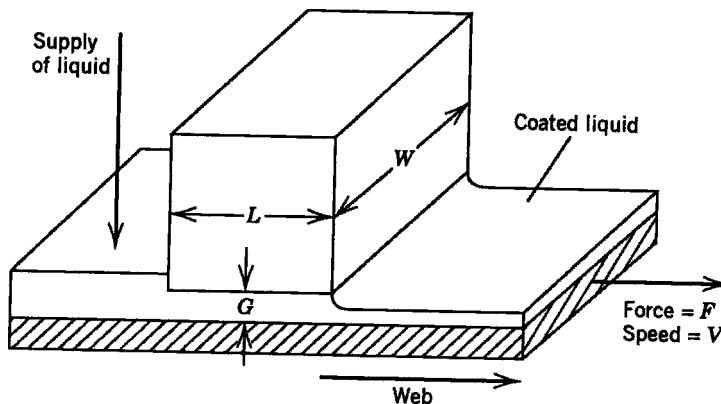
analysis. An example of data obtained from a data logger is given in Figure 10-6 in Chapter 10, where it was used to diagnose a drying problem.

Rheological Measurements

The properties of the coating solution are obviously important to the ongoing performance of a coating process. Changes in these properties can be a source of problems in a coater and optimization of these properties is an important part of developing new products. As a result, measurement of the coating fluid properties is an important aspect of the coater troubleshooting process. Fluids are complex and some of the properties are difficult to measure. Before the measurement techniques are discussed, some of the basics of fluid flow properties are reviewed.

By definition, a fluid is a substance that undergoes irreversible deformation when subject to a steady-state shear or tensile stress. Viscosity is a key parameter to characterize this deformation and is a measure of the resistance of the solution to flow under mechanical stress. High-viscosity solutions require a high level of stress to flow rapidly, while a low-viscosity solution will deform and flow rapidly with a minimum of force. For example, water has a low viscosity and will flow readily out of a glass under normal gravity forces, whereas molasses, a high-viscosity material, will take a long time to flow from a glass.

Viscosity, often represented by the Greek letter eta (η) or mu (μ), is defined as the ratio of the shear stress to the shear rate. The shear rate, $\dot{\gamma}$ (Greek gamma with a dot over it), is the rate of change of the velocity with distance perpendicular to the direction of flow. In Figure 3-3 the shear rate is the velocity of the bottom plate divided by the gap, or V/G . As the units of velocity are distance per unit time, the units of shear rate are 1/time. As time is



$$\text{Shear rate: } \dot{\gamma} = \frac{V}{G}$$

$$\text{Shear stress: } \tau = \frac{F}{LW}$$

$$\text{Viscosity: } \eta = \frac{\tau}{\dot{\gamma}} = \frac{F}{LW} \cdot \frac{G}{V}$$

Figure 3-3. Illustration of the terms in the definitions of shear stress, shear rate, and viscosity.

measured in seconds, shear rates are measured in reciprocal seconds, or s^{-1} . The shear stress, τ (Greek tau), is the force per unit area parallel to fluid flow. In Figure 3-3 it is the force to pull the bottom plate divided by the area of the upper block, or $F/(LW)$. The units of shear stress are force per unit area. In English units this is pounds per square inch. In SI units this is newtons per square meter, or pascals, and in the cgs system it is dynes per square centimeter. As viscosity is shear stress divided by the shear rate,

$$\begin{aligned}\text{viscosity} &= \frac{\text{shear stress}}{\text{shear rate}} \\ &= \frac{\text{force/area}}{1/\text{time}} = \frac{\text{force} \times \text{time}}{\text{area}} \\ &= \frac{\text{dyne} \cdot \text{s}}{\text{cm}^2} = \text{poise} \quad (\text{in cgs units}) \\ &= \frac{\text{N} \cdot \text{s}}{\text{m}^2} = \text{Pa} \cdot \text{s} \quad (\text{in SI units})\end{aligned}$$

The usual units of viscosity are centipoise, cP. One cP is equal to one millipascal second, mPa·s. Typically, to measure viscosity, the shear stress versus shear rate curves, at a given temperature or over a range of temperatures, are measured with one of a variety of viscometers, and the slope of a line from the origin to a point on the curve is the viscosity. When the curve is a straight line, as in Figure 3-4, the slope is constant and the viscosity is independent of the shear rate.

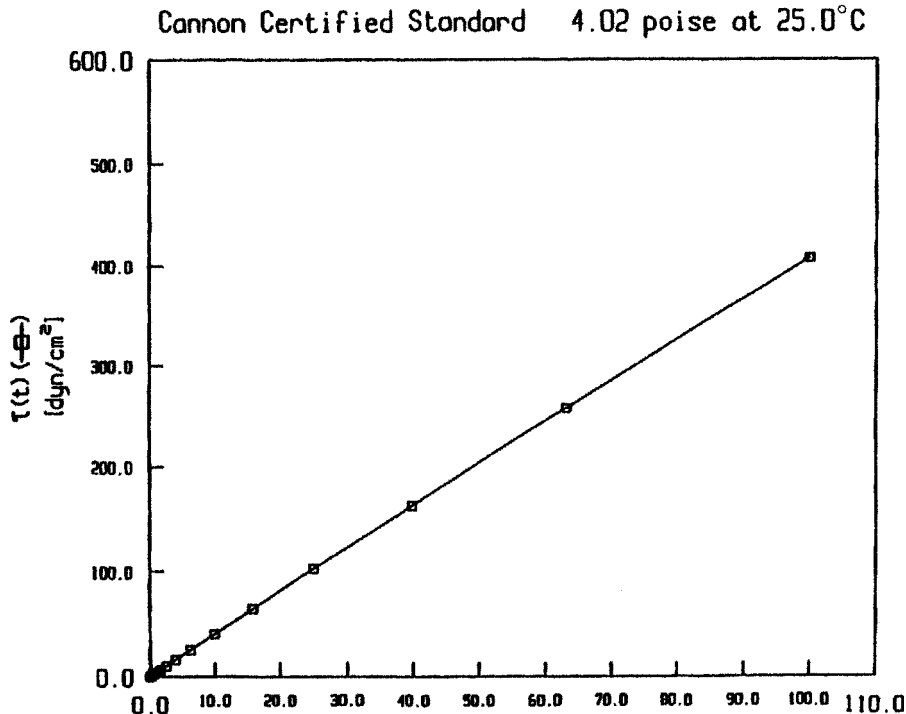


Figure 3-4. Shear stress versus rate of shear curve for a Newtonian liquid with a viscosity of 402 cP.

The kinematic viscosity of solutions is usually measured with a capillary, pipette, or cup type viscometer and is equal to the viscosity (the shear viscosity) divided by the density. If one uses Newton's second law of motion (force equals mass times acceleration) to convert between force and mass, it is easy to show that the units of kinematic viscosity are distance squared divided by time. In the cgs system, this is cm^2/s and is called a stoke, written St. The more common unit is the centistokes, cSt. If the viscosity is 1 cP, and the density is 1 g/cm^3 , then the kinematic viscosity is 1 cSt.

In general, the viscosity of fluids depends on the shear rate at which it is measured.

- A Newtonian fluid has a constant viscosity independent of shear rate. The shear stress is a linear function of shear rate and the stress is zero at zero shear rate. Common, low molecular weight fluids are Newtonian.
- Pseudoplastic or shear-thinning behavior occurs when the viscosity decreases with increasing shear rate. This is typical of polymer solutions. The curve of shear stress versus shear rate bends toward the shear rate axis, as in Figure 3-5.
- Dilatant or shear-thickening behavior occurs when the viscosity increases with increasing shear rate. In the shear stress–shear rate plot, the curve bends toward the shear stress axis, as in Figure 3-6.
- A Bingham solid with yield–stress behavior occurs when the stress has to exceed some finite value before the fluid flows.

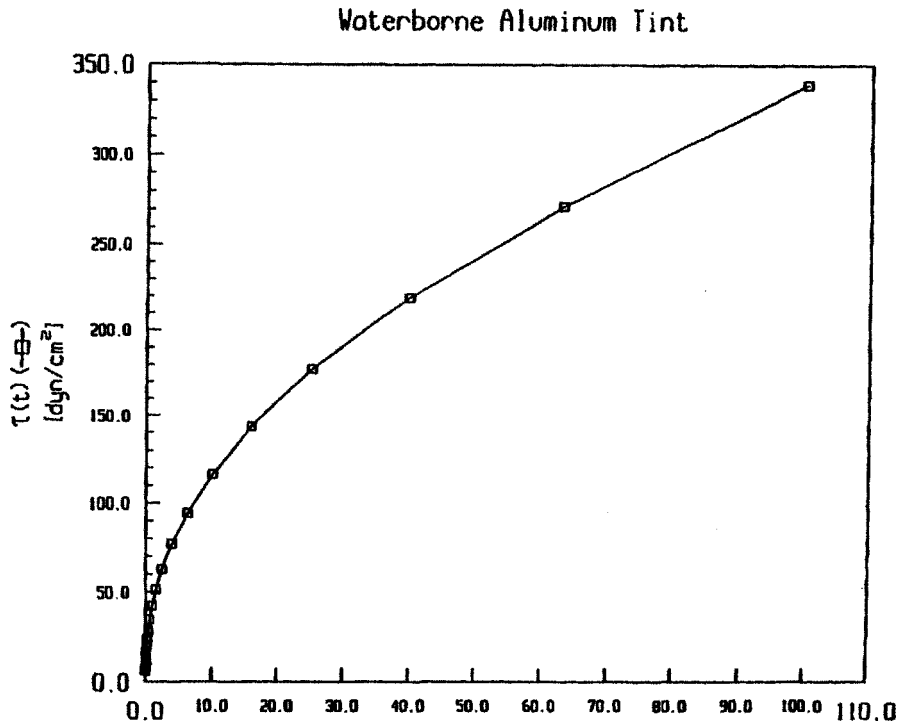


Figure 3-5. Shear stress versus rate of shear curve for a pigmented shear-thinning liquid.

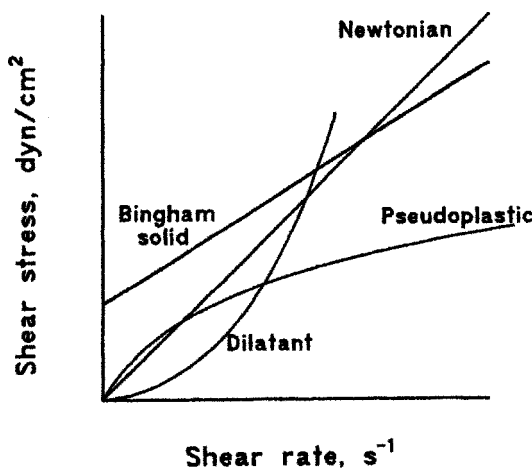


Figure 3-6. Shear stress versus rate of shear curves for a Newtonian liquid, a pseudoplastic or shear-thinning liquid, a dilatant or shear-thickening liquid, and a Bingham solid.

Figure 3-6 gives example of these different flow behaviors. In some liquids the viscosity can also depend on how long the liquid has been flowing, giving rise to:

- Thixotropic liquids, in which the viscosity decreases with time while undergoing shear. This behavior is common in latex paints, where the thick paint flows easily while being brushed.
- Rheopectic liquids, in which the viscosity increases with time while undergoing shear.

Routine measurements of viscosity prior to coating should be part of the normal quality control system for the coater. Often a problem is detected after the solutions are all consumed in the production process. If rheological data are not available, then it may be very difficult to determine the source of the problem. It is possible to save samples and characterize them latter. However, the viscosity of some liquids changes with time. If rheological data are not now being taken, they should be.

There are a great variety of commercial instruments available to measure all of these properties in a wide range of prices and complexity. For viscosity measurement there are two basic types: those with constant shear rate and those with variable shear rate. The constant shear rate instruments provide a single-point viscosity measurement, although some may cover a limited range of shear rates. They are convenient to use and inexpensive and may be adequate for routine quality control. A disadvantage is that the inherent shear rate of these instruments is very low (usually well under 300 s^{-1}), and the shear rates in coating processes (Table 3-4) is normally very high. Thus for shear-thinning liquids the data can be misleading. The variable shear rate viscometers can provide data over a wide range of shear rates. In some viscometers the shear rate is programmed to change automatically and a curve of viscosity versus shear rate is printed out; in others the shear rates have to be set manually. The advantage of the variable shear rate is that they may be able to provide viscosities at the shear rates of interest in the coating applicator. Also, they provide data on solution changes that are not seen in a single-point measurement. The disadvantages are the cost and the complexity of operation.

TABLE 3-4 Shear Rate Ranges for Web Coating Process

Operation	Shear Rate (s^{-1})
Coating	
Dip	10–100
Roll, reverse	1,000–100,000
Roll, forward	10–1,000
Spray	1,000–10,000
Slide	3,000–120,000
Gravure, reverse	40,000–1,000,000
Gravure, forward	10–1,000
Slot die	3,000–100,000
Curtain	10,000–1,000,000
Blade	20–40,000
Ancillary operations	
Simple mixing	10–100
High shear mixer	1,000–100,000
Measurement	
Brookfield	1–300
ICI	10,000
Haake	1–20,000
Fenske-Cannon	1–100

Examples of essentially constant shear rate viscometers are:

- Glass capillary viscometers
- Cup viscometers
- Pipette viscometers
- Falling ball viscometers
- Electromagnetic viscometers

The constant shear rate viscometers are very useful for routine plant quality control measurements and are an excellent starting point if no routine measurements are now being taken. They are easy to use and inexpensive. When coupled with a quality control chart, they can be very useful. The glass capillary viscometers, such as the Cannon-Fenske type, are an excellent research tool and are also good for routine measurements. They require only a small sample, on the order of 10 mL. They are used with a constant temperature bath and give accurate and repeatable results. However, they are fragile and must be handled with care. With such care they can be recommended for use in a quality control laboratory.

The cup viscometers measure the time for the solution to drain from a cup. This time can then be converted to a kinematic viscosity if the cup has been calibrated and then, by multiplying by the density, to the normal shear viscosity. The individual cups have a limited viscosity range, and thus a series of these is needed. They are very easy to use in a plant situation and are widely used for spray applications because of their low cost and simplicity of use. Another advantage to the cups is that, if used with a large volume of solution, the solution mass can provide a constant temperature and no additional temperature control is needed.

The many types of rotational viscometers can give variable shear rates. A good basic unit is one in which a spindle rotates in a solution and the torque required to keep constant speed is measured and converted to viscosity. An example is the Brookfield viscometer. One instrument with a variety of spindles can cover a very wide range of viscosities. It also has some limited ability to vary the rotational speed, and some simple low shear rate–viscosity data can also be obtained.

The variable shear rate rotational viscometers, such as by Haake, Anton Paar, or Rheometrics, give a wide range of shear rates, $1\text{--}20,000\text{ s}^{-1}$, over a wide range of temperatures. Fluids can be characterized extensively to determine their viscosity–shear rate behavior and also the time-dependent behavior. These are particularly useful for optimizing a formulation in the preproduction process.

A single-point low shear rate viscometer is not adequate for the coating process because the varying coating processes components have a wide range of shear rates. Therefore, the coating solutions must be characterized at the shear rate that they will be subjected to in the process. The viscosity behavior can be much different at the higher shear rates. Table 3-4 summarizes the shear rate of varying coating application processes; the dip coating shear rate is only $10\text{--}100\text{ s}^{-1}$, whereas reverse gravure is $40,000\text{--}1,000,000\text{ s}^{-1}$. Brookfield viscometer measurements can be adequate for dip coating at its low shear range, but they are not adequate for reverse gravure. In terms of optimizing the process, it is better to characterize the solution at low shear rate than to not characterize it.

Surface Properties

The surface tension of coating liquids is important in relation to wetting the coating support. Because coating involves spreading a liquid out into a thin film with a very large surface area, surface forces play a large role. The terms surface tension and surface energy may be used interchangeably. Surface tension is expressed as force per unit length, such as dynes/cm or mN/m (millinewtons per meter). Surface energy is expressed as energy per unit area, such as ergs/cm² or mJ/m² (millijoules per square meter). Numerically, all four terms are identical.

When we speak of liquids we usually refer to surface tension. We may find it difficult to visualize an undisturbed solid surface as being in a state of tension and may find it easier to conceive the surface of a solid as possessing surface energy. It is a matter of personal preference which term we use.

In a freshly created liquid surface, the surface tension may change with time as dissolved materials diffuse to the surface to accumulate there, as surfactants do. This changing surface tension is called the dynamic surface tension.

When a drop of liquid is placed on a surface, it may wet the surface and flow out or it may remain as a stationary drop. Figure 3-7 shows a drop on a surface when the forces are in equilibrium. The contact angle, θ , is a measure of the wettability of the surface by the liquid. With a liquid that spreads over the surface, the contact angle is zero. The contact angle formed on a support by a pure liquid, such as water, is a useful measure of the wettability of the support.

Surface tension is commonly found by the Wilhelmy plate method, where the force necessary to withdraw a thin platinum plate from the solution is measured, or the duNuoy ring method, where a ring made out of platinum wire is substituted. See, for example, Adamson (1982). These instruments are available from a variety of sources. These methods are static in that the surfaces have reached equilibrium and do not change with

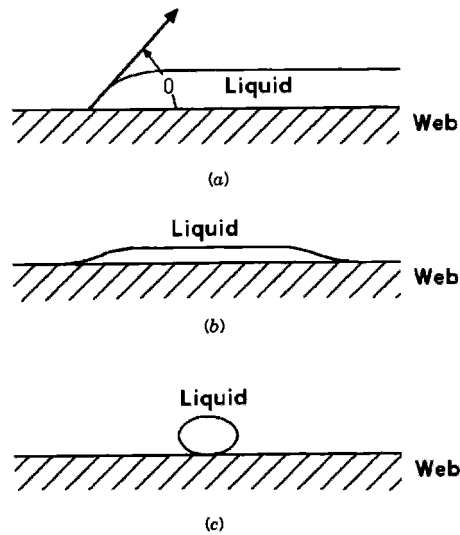


Figure 3-7. The contact angle between a liquid and a solid: (a) the contact angle is measured through the liquid; (b) when the contact angle is zero, a drop spreads out over the surface; (c) with complete nonwetting, the liquid balls up and the contact angle is zero.

time. However, the coating process is dynamic in that the surface changes rapidly over a small time scale. Results from static surface tension measurements may not be representative of the coating process, but they are useful in ensuring that a solution has not changed between batches and has not changed with time. Dynamic surface tension measurements are considered to be a research tool only. To study the surface wettability of the support, goniometers that measure the contact angle of a drop of a solution on a support are available. A drop of liquid is placed on the surface and viewed through a microscope to measure the contact angle. It is also possible to use a series of calibrated and variable surface tension liquids for a qualitative test of the wettability of the surface. The drops are placed on the support and if they bead up, surface tension of the support is numerically below that of the liquids. If they flow out, the surface tension of the support is numerically higher than the liquids. With a series of liquids an estimate of the support surface energy or tension can be obtained. Such a series of liquids is available in felt tip pens, colloquially called *dyne pens*.

ON-LINE CHARACTERIZATION SYSTEMS

On-Line Inspection Systems

The recent development of on-line defect inspection systems, also called surface vision systems, has significantly changed the technology for inspecting coatings for physical defects. Typically, the standard method for inspection was to take a sample at the start or end of a roll and take it to a light table that had both transmitted and reflected light. The coating was then inspected visually by trained operators to detect and count defects. The inspection process was time consuming and required highly trained operators to reproducibly detect defects, and often some defects were missed. There were some custom

systems that were developed for high-quality requirement products such as photographic film. However, they were too expensive for routine use in all coating operations.

Starting in the late 1980s there were significant developments in improved technologies, lasers, optics, computer processing speed, data storage, and software, which led to the start of development of high-quality, low-cost inspection systems. Starting in the mid-1990s, commercial systems were available and started to gain widespread acceptance (Thome, 1995; Mykytiuk, 1996).

There are currently wide ranges of available inspection systems that inspect the web for defects and indicate their locations, so that areas of the web that are unacceptable to the customer can be identified. Use of these systems will indicate defects in the coated product much earlier than the off-line inspection. This will lead to less waste, increased efficiencies, and improved costs. These systems will also permit on-line experiments to allow troubleshooters to understand and reduce defects. The result of changes made in the process can rapidly be detected, and optimum process conditions can quickly be determined. In addition, the data stored in the system can be analyzed for more detailed process correlations.

The technical components of an inspection system depend on the defect detection requirements:

- A laser detection system or a camera-based, area line scan system
- Type of lighting, such as aperture fluorescent, light-emitting diode (LED), fiber optic cable, infrared, gas vapor, or special colors
- Observations by transmitted or reflected light
- Scanning system
- Software program to run inspection system
- Display system
- Data storage and analysis

Such systems are capable of detecting a wide range of defects in the coatings. Figures 3-8 to 3-13 show several different types of defects that were detected in a moving web.

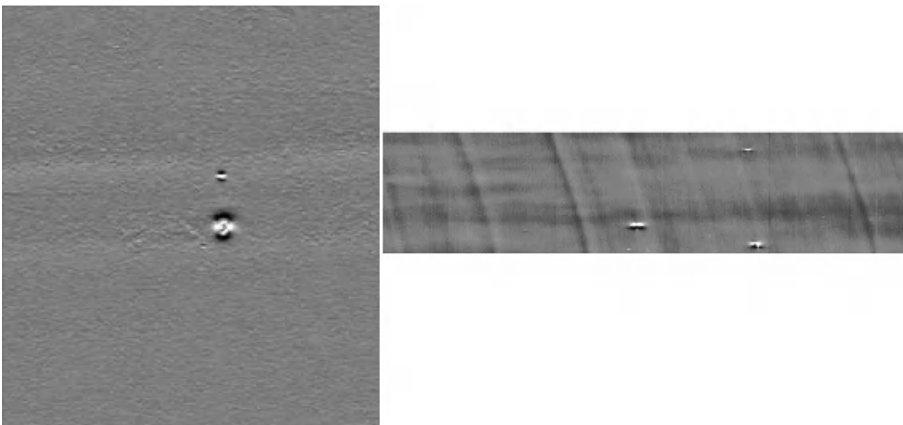


Figure 3-8. Inspection system image—gel. Images courtesy of ISRA Surface Vision.

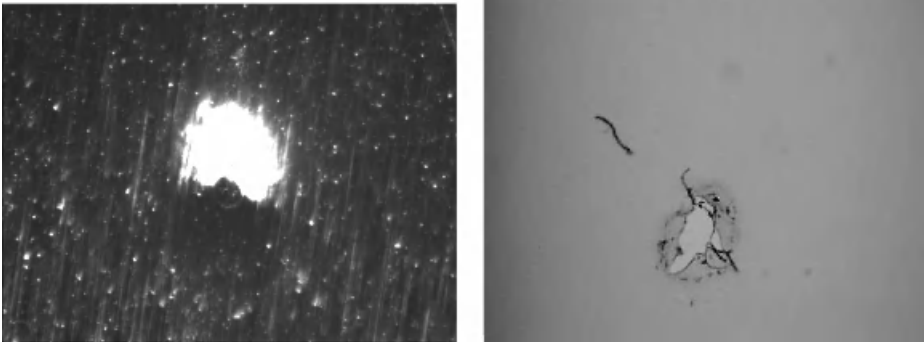


Figure 3-9. Inspection system image—hole. Images courtesy of ISRA Surface Vision.

On-Line Coating Weight Measurement

On-line coating weight gauging systems are essential characterization tools that help ensure that all necessary parameters are within specification. These systems provide rapid and accurate measurements of several coating weight parameters including the transverse direction profile, the machine direction profile, the roll average, and roll to roll variability.

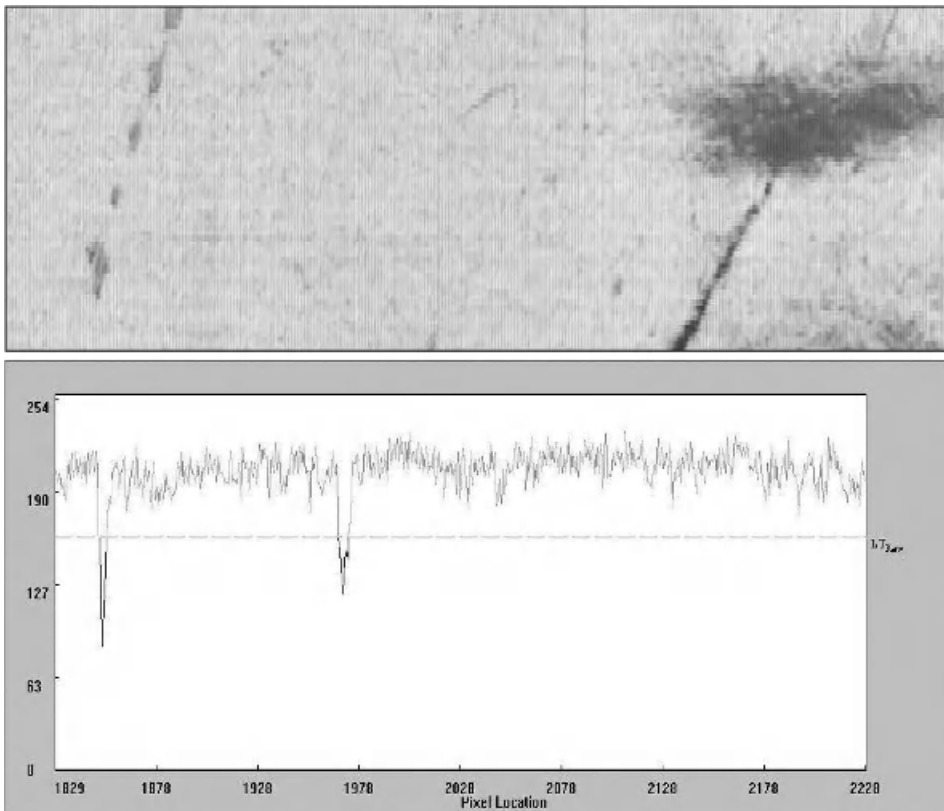


Figure 3-10. Inspection system image—crease and wrinkle. Image courtesy of ISRA Surface Vision.

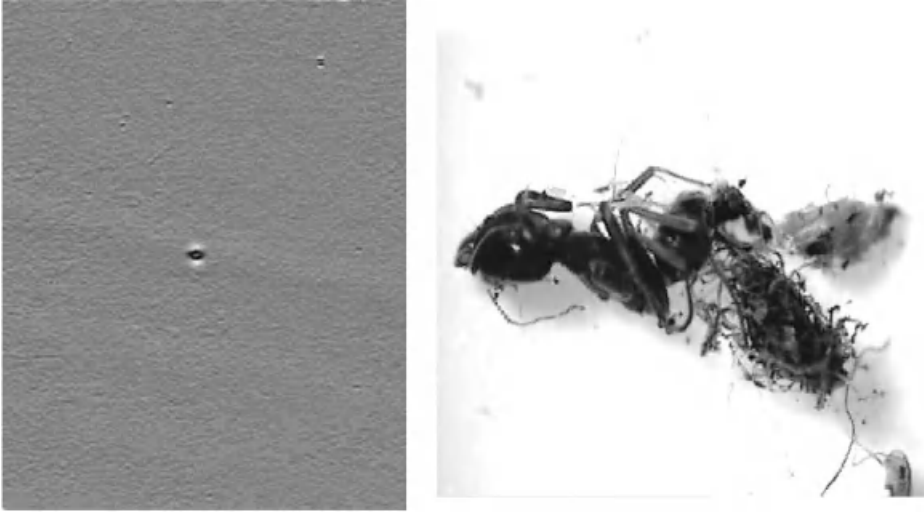


Figure 3-11. Inspection system image—contamination. Images courtesy of ISRA Surface Vision.

Control of the coating weight in all coated products is critical and it is one of the more frequent defects encountered in the web coating process. Therefore accurate characterization systems are needed to rapidly identify defective material.

These systems are far superior to the off-line system characterizing coating weight by thickness or gravimetric techniques. Advances in technology have resulted in several different techniques that are used for a wide range of samples. The system can scan the web and measure transverse direction and machine direction profiles. Data can be stored and displayed in several different ways. In addition, measurements can be made shortly after start-up and problems identified quickly with a minimum loss of material. Experiments

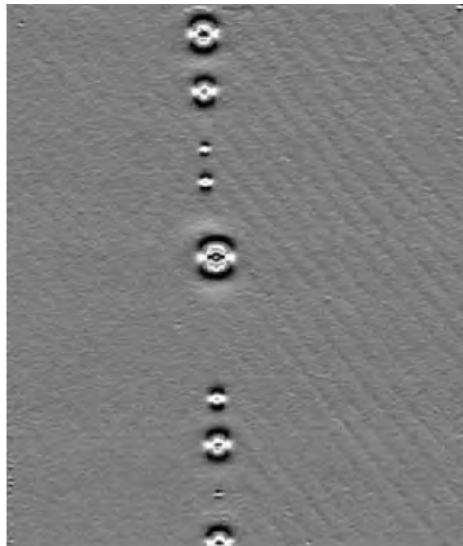


Figure 3-12. Inspection system image—air bubbles. Image courtesy of ISRA Surface Vision.

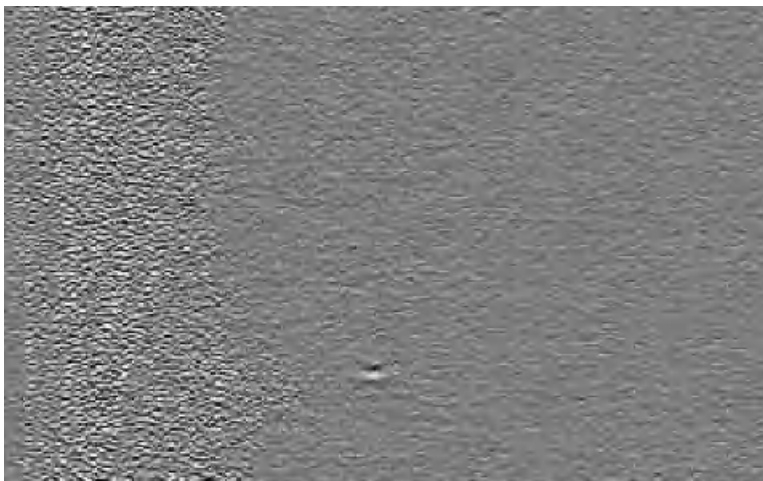


Figure 3-13. Inspection system image—orange peel. Image courtesy of ISRA Surface Vision.

can easily be run and the results can rapidly be obtained. The data generated can also be used in a control loop to optimize process efficiency.

There are a variety of sensors that can be used. The selection depends on the installed location of the sensor and whether the coating is wet or dry at the measurement location. Other factors are the material composition, the thickness and coating weight value, the accuracy desired, and the web speed. There are two basic types of gauges: sensors that measure the total weight of the product including substrate, and sensors that measure the coating only.

In the total weight system the uncoated and coated substrates are both measured; then the subtraction of uncoated weight from the coated gives the desired coating weight. Total weight gauges are based on beta ray, gamma ray, or x-ray transmission. The other type of gauge measures the coating weight directly. Some direct coating weight gauges make use of infrared transmission, beta ray backscatter, or x-ray fluorescence. The x-ray fluorescence gauge is particularly useful in coatings that generate a strong x-ray response, such as those products that use zinc stearate as a lubricant. The zinc level is easily detected by its fluorescence when stimulated by an x-ray source.

On-Line Viscosity

The viscosity of the coating solution is a key variable in controlling the coating weight and quality of coated products. Viscosity variations from temperature variations, evaporation of solvent, air inclusion as bubbles or foam, batch-to-batch variations, and agglomeration of particulates can result in defective product during a coating campaign. Historically, these variations have gone unnoticed because the viscosity is not constantly monitored. Readings are taken at the end of the preparation cycle and occasionally during the coating. As a result, some defects may not be detected. Viscosity variations can be especially hard to detect in non-Newtonian solutions.

The use of in-line viscometers can help to avoid this problem by providing a constant measurement of viscosity. This data can be analyzed and correlated with defect levels or with variations in coating weight. They can also be used as part of a control loop to

maintain the viscosity constant at a set temperature. An in-line system can add solvent as needed to compensate for evaporation losses and can maintain the temperature constant.

There are several commercial on-line viscometers manufactured by companies that specialize in rheological equipment, such as Brookfield, Anton Paar, Biode, and Cambridge Applied Systems, that can be used. The Cambridge Applied Systems viscometer is very useful as it simultaneously measures both the viscosity and temperature. It has the advantage that it can be used continuously in a flow line or even directly in a kettle or off-line with samples (Wright and Gould, 1986; Wright and Gogolin, 1992; Krause, 2003). As with most modern instruments it can be interfaced directly to a data logging system.

DATA ANALYSIS TECHNIQUES

Modern analytical and characterization methods in conjunction with computer-based data logging tend to generate a vast quantity of data. This data then needs to be analyzed to determine trends and conclusions that will support or disprove the various hypotheses that have been developed. It is often easier to generate the data than it is to analyze it. Most organizations have statisticians to help the troubleshooter with the analysis and to guide him/her in the formulation of statistically designed experiments for the action step. However, we believe it essential that the troubleshooters have a basic working knowledge of data analysis techniques in order to be able to do a portion of the statistical analysis themselves. There are many occasions when a preliminary analysis of the data by operating personnel is needed to help solve a problem. A good rapid analysis of a small data set is better than no analysis of a larger data set. Also, there may not always be a statistician available to help, and then there is no other choice than for the troubleshooter to do it. In addition, operating personnel can bring a valuable essential reality check to the conclusions that are reached from the data. It is easy in statistics and data analysis to develop correlations that are mathematically valid but have no relation to the reality of the process and to the science behind it.

A summary of the steps needed for statistical analysis of the data once it has been assembled is as follows:

- Develop a set of questions that analysis of the data can either answer or suggest possible trends or correlations to be further explored. Typically one question is to determine which of the process variables have changed significantly and how this change influences the defects or problem under analysis.
- Assemble the specific data set that covers the time period under investigation. It should include time periods surrounding the regions of interest, where the process is believed to have been producing good product.
- Select the appropriate statistical parameters to be calculated. For an initial screening, plotting data and correlation matrices can be used to obtain preliminary trends and correlations. Also, for a preliminary analysis lower confidence limits can be used.
- Calculate the selected statistical parameters.
- Interpret the parameters to decide which relations are valid and how they answer the questions that were originally posed.
- Perform additional analysis using advanced parameters and additional data sets, if available.

In the past, the bottleneck or rate-limiting step in the statistical analysis was the calculation of the selected parameters. The appropriate parameters for an analysis could be determined quickly through consultation with a statistician, discussion with a colleague who has a background in statistics, or by referring to one of the many references in statistics or statistical process control (Davies, 1958; Natrella, 1966; Brooks et al., 1979; Frost and Guttoff, 1994). It is relatively easy in most problem-solving situations to get recommendations on what to calculate or to plot, and to get assistance in interpreting the data once the calculations are performed. It is, however, much more difficult to get someone to do the actual calculation, particularly if there is a large data set to be processed.

In the last decade the widespread availability of personal computers has revolutionized the calculation procedure and has eliminated this as the bottleneck in the statistical analysis procedure. The next section focuses on the calculation steps and discusses some of the basic parameters and computer tools that we have found helpful in our own troubleshooting efforts. These computer-based tools are readily available, are inexpensive, and can very quickly generate the parameters needed to characterize and analyze the data. A basic assumption is that everyone has access to personal computers either by the coater or in the office. For a more detailed discussion of the statistical parameters to calculate, refer to the previously cited references on statistics.

There are a wide variety of readily available, easy-to-use computer software statistical analysis programs, all of which are effective and have the ability to calculate a wide variety of statistical parameters. Some have sections on experimental design and 3-D plotting. The exact program selection depends on the ease of use by the scientist and the availability of funds.

Another alternative is the use of a spreadsheet program, such as Microsoft Excel. It contains functions that can do a wide range of statistical calculations and can produce many different types of plots. There are 82 functions available in Excel, and of these Table 3-5 lists a number of the statistical functions often used to analyze data. There are also sets of data analysis routines in Excel, which can perform a range of calculations on the data set. These are shown in Table 3-6.

An example of a typical analysis using a spreadsheet is shown in Table 3-7. The data of viscosity, temperature, time, and date were obtained for a coating solution using an in-line viscometer and a data logger. The data was extracted in spreadsheet format with one row (horizontal data) giving a complete reading. The complete data set is not shown, only the first 3 hours of the data. For this data set, the average, standard deviation, and range were felt to be adequate to characterize the measurements. However, the use of the descriptive statistics routine in Table 3-6 calculates and outputs the 13 statistical parameters shown in Table 3-8, for the data in Table 3-7.

Graphing of data is a very powerful analytical tool and should be used when possible. The eye and the human brain are an excellent combination for spotting trends and determining relations. Often, the trends reveal clues and general answers to some questions. A plot will rapidly determine if there is a justification for pursuing an analysis or not. The spreadsheets can plot data in many formats and are an excellent tool for preliminary analysis.

KEEPING CURRENT

The analytical technology for the coating process and for coated products is continually advancing and the prices are dropping. Both new tools and new and improved versions of

TABLE 3-5 Excel Statistical Functions

AVEDEV	Returns the average of the absolute deviations of data points from their mean
AVERAGE	Returns the average of its arguments
AVERAGEA	Returns the average of its arguments, including numbers, text, and logical values
BETADIST	Returns the cumulative beta probability density function
BETAINV	Returns the inverse of the cumulative beta probability density function
BINOMDIST	Returns the individual term binomial distribution probability
CHIDIST	Returns the one-tailed probability of the chi-squared distribution
CHIINV	Returns the inverse of the one-tailed probability of the chi-squared distribution
CORREL	Returns the correlation coefficient between two data sets
COUNT	Counts how many numbers are in the list of arguments
COUNTA	Counts how many values are in the list of arguments
COUNTIF	Counts the number of cells within a range that meet the given condition
COVAR	Returns covariance, the average of the products of paired deviations
DEVSQ	Returns the sum of squares of deviations
EXPONDIST	Returns the exponential distribution
FDIST	Returns the F probability distribution
FINV	Returns the inverse of the F probability distribution
FORECAST	Returns a value along a linear trend
FREQUENCY	Returns a frequency distribution as a vertical array
FTEST	Returns the result of an F -test
GEOMEAN	Returns the geometric mean
GROWTH	Returns values along an exponential trend
HARMEAN	Returns the harmonic mean
INTERCEPT	Returns the intercept of the linear regression line
KURT	Returns the kurtosis of a data set
LARGE	Returns the k th largest value in a data set
LINEST	Returns the parameters of a linear trend
LOGEST	Returns the parameters of an exponential trend
LOGINV	Returns the inverse of the lognormal distribution
LOGNORMDIST	Returns the cumulative lognormal distribution
MAX	Returns the maximum value in a list of arguments
MEDIAN	Returns the median of the given numbers
MIN	Returns the minimum value in a list of arguments
MODE	Returns the most common value in a data set
NORMDIST	Returns the normal cumulative distribution
NORMINV	Returns the inverse of the normal cumulative distribution
NORMSDIST	Returns the standard normal cumulative distribution
NORMSINV	Returns the inverse of the standard normal cumulative distribution
PEARSON	Returns the Pearson product moment correlation coefficient
PERCENTILE	Returns the k th percentile of values in a range
PERCENTRANK	Returns the percentage rank of a value in a data set
PERMUT	Returns the number of permutations for a given number of objects
POISSON	Returns the Poisson distribution
PROB	Returns the probability that values in a range are between two limits
QUARTILE	Returns the quartile of a data set
RANK	Returns the rank of a number in a list of numbers
RSQ	Returns the square of the Pearson product moment correlation coefficient
SKEW	Returns the skewness of a distribution
SLOPE	Returns the slope of the linear regression line

(continued)

TABLE 3-5 (Continued)

SMALL	Returns the <i>kth</i> smallest value in a data set
STANDARDIZE	Returns a normalized value
STDEV	Estimates standard deviation based on a sample
STDEVA	Estimates standard deviation based on a sample, including numbers, text, and logical values
STDEVP	Calculates standard deviation based on the entire population
STDEVPA	Calculates standard deviation based on the entire population, including numbers, text, and logical values
STEYX	Returns the standard error of the predicted <i>y</i> -value for each <i>x</i> in the regression
TDIST	Returns the Student's <i>t</i> -distribution
TINV	Returns the inverse of the Student's <i>t</i> -distribution
TREND	Returns values along a linear trend
TRIMMEAN	Returns the mean of the interior of a data set
TTEST	Returns the probability associated with a Student's <i>t</i> -test
VAR	Estimates variance based on a sample
VARA	Estimates variance based on a sample, including numbers, text, and logical values
VARP	Calculates variance based on the entire population
ZTEST	Returns the two-tailed <i>P</i> -value of a <i>z</i> -test

old tools are being introduced all the time. They have improved measurement performance and can often provide a new technical capability. The troubleshooter needs to be aware of these because the new tools can help to improve the efficiency of troubleshooting. In addition, tools often get damaged and need to be replaced when they wear out, get broken, or are lost.

There are several methods to keep current in this area of troubleshooting coater defects. A convenient method of staying current is to get on the subscriber list for monthly

TABLE 3-6 Excel Data Analysis Routines

ANOVA	Single factor
ANOVA	Single factor with replication
ANOVA	Single factor without replication
CORRELATION	
COVARIANCE	
DESCRIPTIVE STATISTICS	
EXPONENTIAL SMOOTHING	
F-TEST	Two-sample for variance
FOURIER ANALYSIS	
HISTOGRAM	
MOVING AVERAGE	
RANDOM NUMBER GENERATION	
RANK & PERCENTILE	
REGRESSION	
SAMPLING	
T-TEST	Paired two sample for means
T-TEST	Two-sample assuming equal variances
T-TEST	Two-sample assuming unequal variances
Z-TEST	Two-sample for means

TABLE 3-7 Example of Statistical Analysis with Spreadsheet

Summary	Temperature (°F)	Viscosity (cP)
Average	97.43	9.97
Standard deviation	1.53	1.17
High	98.53	18.50
Low	91.18	9.19
Number of points	58	58
Coeff. of variation	1.57%	11.75%

Data Obtained from In-line Viscometer in Plant Coating Using Smart Reader Elapsed Time (Hours)

Time	Date	Temperature (°F)	Viscosity (cP)	(Calculated)
0:36	11-Feb	91.18	18.5	0.00
0:41	11-Feb	93.63	10.36	0.08
0:46	11-Feb	96.08	10.36	0.17
0:51	11-Feb	96.08	9.77	0.25
0:56	11-Feb	96.08	9.77	0.33
1:01	11-Feb	96.08	9.77	0.42
1:06	11-Feb	98.53	9.77	0.50
1:11	11-Feb	96.08	9.77	0.58
1:16	11-Feb	96.08	9.77	0.67
1:21	11-Feb	96.08	9.77	0.75
1:26	11-Feb	96.08	9.77	0.83
1:30	11-Feb	96.08	9.77	0.92
1:35	11-Feb	96.08	9.77	1.00
1:40	11-Feb	96.08	9.77	1.08
1:45	11-Feb	96.08	9.77	1.17
1:50	11-Feb	96.08	10.36	1.25
1:55	11-Feb	96.08	10.36	1.33
2:00	11-Feb	96.08	10.36	1.42
2:05	11-Feb	98.53	10.36	1.50
2:10	11-Feb	96.08	10.36	1.58
2:15	11-Feb	98.53	10.36	1.67
2:20	11-Feb	96.08	10.36	1.75
2:25	11-Feb	96.08	9.77	1.83
2:30	11-Feb	96.08	9.77	1.92
2:35	11-Feb	96.08	9.77	2.00
2:40	11-Feb	96.08	9.77	2.08
2:44	11-Feb	98.53	9.77	2.17
2:49	11-Feb	98.53	9.77	2.25
2:54	11-Feb	98.53	9.19	2.33
2:59	11-Feb	98.53	9.77	2.42
3:04	11-Feb	98.53	9.77	2.50
3:09	11-Feb	98.53	9.77	2.58
3:14	11-Feb	98.53	9.77	2.67
3:19	11-Feb	98.53	9.77	2.75
3:24	11-Feb	98.53	9.77	2.83
3:29	11-Feb	98.53	9.77	2.92
3:34	11-Feb	98.53	9.77	3.00
3:39	11-Feb	98.53	9.77	3.08
3:44	11-Feb	98.53	9.77	3.17

(continued)

TABLE 3-7 (Continued)

Time	Date	Temperature (°F)	Viscosity (cP)	(Calculated)
3:49	11-Feb	98.53	9.77	3.25
3:54	11-Feb	98.53	9.77	3.33
3:58	11-Feb	98.53	9.77	3.42
4:03	11-Feb	98.53	9.19	3.50
4:08	11-Feb	98.53	9.19	3.58
4:13	11-Feb	98.53	9.19	3.67
4:18	11-Feb	98.53	9.77	3.75
4:23	11-Feb	98.53	9.77	3.83
4:28	11-Feb	98.53	9.77	3.92
4:33	11-Feb	98.53	9.77	4.00
4:38	11-Feb	98.53	9.77	4.08
4:43	11-Feb	98.53	9.77	4.17
4:48	11-Feb	98.53	9.77	4.25
4:53	11-Feb	98.53	9.77	4.33
4:58	11-Feb	98.53	9.77	4.42
5:03	11-Feb	98.53	9.77	4.50
5:08	11-Feb	98.53	9.77	4.58

magazines specializing in equipment. These are usually free. Once you are on one of these mailing lists, more subscriptions for other magazines will follow. Manufacturers of these tools advertise in these journals and will send you information. Some useful references are:

- *Paper, Film, & Foil Converter*
- *Converting Magazine*
- *Scientific Computing and Automation*
- *Laboratory Equipment*
- *Omega Encyclopedia*

TABLE 3-8 Statistical Analysis Using Spreadsheet Statistical Tools^a

	Temperature, °F	Viscosity, cP
Mean	97.77	9.67
Standard error	0.07	0.03
Median	98.53	9.77
Mode	98.53	9.77
Standard deviation	1.24	0.61
Variance	1.55	0.37
Kurtosis	1.67	141.62
Skewness	-1.18	9.30
Range	9.80	11.64
Minimum	91.18	6.86
Maximum	100.98	18.50
Sum	31287.05	3095.28
Count	320	320

^aSame data set as in Table 3-7.

In addition, all of these magazines have web sites that contain technical articles and buyers guides.

Catalogs from equipment vendors who sell the specialized instruments used in the converting industry are another source. Their catalogs contain good technical information on the technology and the application of the instruments. While paper catalogs are issued, all of the vendors have web sites that can be searched for specific information. Some useful vendors in this are:

- Cole-Parmer
- Omega Engineering
- Paul N. Gardner
- Fisher Scientific
- Edmund Scientific
- BYK Gardner

The Thomas Register of American Manufacturers is another source of information. This is a service with a web site (www.thomasnet.com) that lists United States manufacturers of a wide range of commercially available products and services. It has information on the companies, provides links to their web sites, and can be searched for specific types of equipment. It was previously available as a large set of printed volumes, issued yearly. Another way of keeping current is by attending trade shows and technical society meeting that have expositions, such as:

- American Chemical Society (ACS)
- American Institute of Chemical Engineers (AIChE)
- Technical Association of the Pulp and Paper Industry (TAPPI)
- Association of Industrial Metallizers Coaters & Laminators (AIMCAL)
- International Society of Coating Science and Technology (ISCST)
- CMM International

Searching the web using a search engine such as Google also yields information on new products.

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4

PROBLEMS ASSOCIATED WITH FEED PREPARATION

The preparation of the coating solution and the system to deliver the coating solution to the apparatus can be sources of defects and problems. Poor or improper preparation and poor control of flow to the coating stand can lead to the presence of particulates, agglomerates, or bubbles in the coating; poor cross-web uniformity due to concentration and viscosity variations across the coating stand; poor down-web uniformity due to viscosity fluctuations; plugging of filters due to colloidal instability or incomplete dispersion in the coating liquid; and down-web coverage fluctuations due to poor flow control to a coating die. If the coating liquid is not suitable a high-quality coating cannot be achieved, and if a good feed system is not available a uniform coverage cannot be achieved.

DIRT AND OTHER PARTICULATES

Filtration is needed to remove dirt and other unwanted particulates from the coating liquid. Particulates can come from almost anywhere. Dirt can be carried in with the raw materials. Dust in the air can settle onto the coating solution in an open vessel. Corrosion in the pipes leads to metal oxides in the coating. Pumps can chew up gaskets into tiny pieces. Colonies of bacteria can slough off a pipe into the flow stream. Some polymer or resin may not dissolve but only swell, and these swollen, undissolved polymer globs in the liquid, called fisheyes, then become spot defects when coated on a web. Some desired particles of active ingredients may be too large in size and could show up in the coating as defects, and others, while small in size, may agglomerate to form large clumps. However they arise, all these particulates should be removed before the coating liquid is coated. Filters are used to remove them. Filters should be used on all coating lines, even when the coating liquid, as is

often the case, contains dispersed active ingredients. The filters must permit the active ingredient, which is of small particle size, to pass through while preventing the passage of larger, unwanted particles.

Particulates may be classified into two types—hard and soft. Hard particles do not deform and are relatively easy to filter out. They comprise dirt, agglomerates, corrosion products, pieces of gaskets, and so on. Dried coating liquid may be hard or soft. Soft particles deform easily and can elongate to squeeze through pores in a filter under a high enough pressure drop, to reform their spherical shape after passing through. If soft particles are present, the pressure drop across the filter must be limited to a low value, perhaps 3–5 psi (20–35 kPa), while normally filters operate up to about 30 psi (205 kPa). This means that a larger area of filtration (more filters) may be necessary to maintain the flow rate with a low pressure drop. Swollen but undissolved polymer and bacterial colonies are the principal soft particles. It is desirable to completely prevent the formation of soft particles. Sterilization by heat or by use of bactericides should prevent any bacteria from growing. The polymers and resins should be completely soluble; if not, a better source of supply should be found. The solution preparation method and the dissolution time and temperature should be such that the polymer dissolves completely. “Fisheyes” will dissolve if held for extended times, and higher temperatures increase the rate of dissolution.

The dissolution of polymers and resins requires special care. If powdered polymer is dumped into a solvent, the outside of the mass will soak up solvent and start to swell. However, this outer layer of swollen polymer may act as a skin to greatly slow down the flow of solvent to the interior. The dissolution time may then go from minutes to many hours. It is generally recommended that polymer be added slowly to the eye of a vortex in the agitated solvent. With particular polymers and solvents, other procedures and special temperature cycles may be needed.

Filtration

Filters come in two types—surface filters and depth filters. Surface filters can be represented as a membrane with pores, as in Figure 4-1. Particles larger than the largest pore cannot pass through (assuming the particles are hard). Thus these filters can be considered absolute filters when the pore size is carefully controlled and fairly uniform. The active area for filtration is just the open surface area. Filter cloths used in filter presses are surface filters, as are the membranes used to remove yeast cells from beer in room temperature sterilization. Surface filters are used when it is imperative to remove every single large particle. When heavy solids loading is present, a filter cloth may just act as a support for a filter cake, which frequently does the actual filtration.

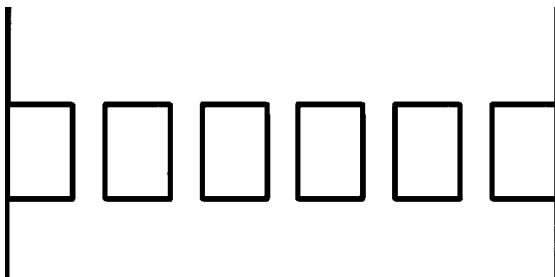


Figure 4-1. Surface filter. Hard particles larger than the largest pore cannot pass through.

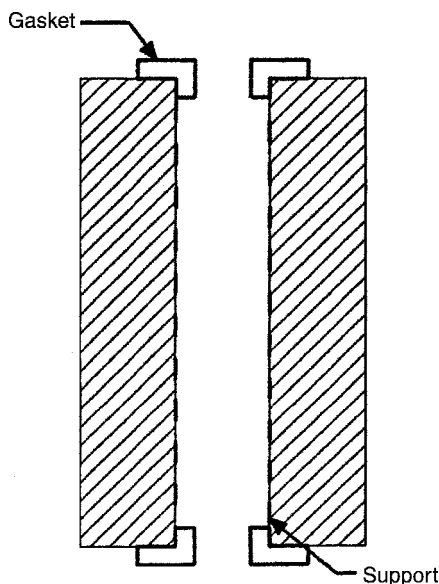


Figure 4-2. Cartridge filter made by winding a filament around a support is a typical depth filter.

Depth filters function differently. They generally consist of a filament wound around a central core in a special pattern, to give a cylindrical element perhaps an inch (2.5 cm) thick (Figure 4-2). The openings are relatively large. The particles are removed by impaction. A particle entering a pore may strike a filament before changing direction and then stick to the filament. If a particle passes through the surface openings, it still has many more opportunities to strike an interior filament and stick to it. Thus some small particles may be trapped, and some large particles may pass through. For example, if the initial material had a particle size distribution as shown in Figure 4-3, the filtrate—the filtered

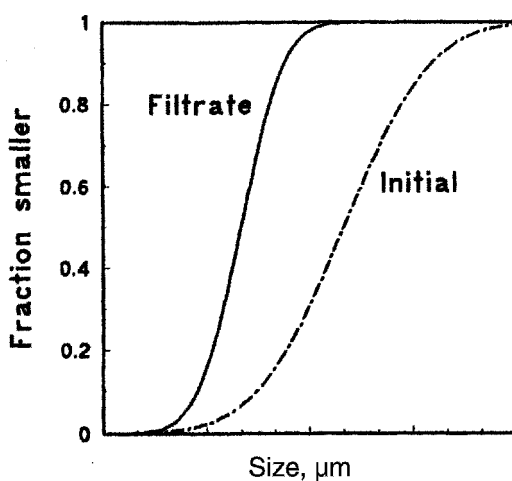


Figure 4-3. Particle size distribution of particles in a liquid, before and after filtration with a depth filter.

coating liquid—may still have particles with a broad, but narrower, particle size distribution such as shown in the same figure. Essentially all the particles larger than a certain size are removed, while most of the small particles remain. The fraction of particles retained in the filter increases with increasing size.

The size rating of depth filters is not unambiguous. The filter shown in Figure 4-3 can be rated anywhere from the largest particle size that passes through the filter to the smallest size that is retained. Different manufacturers use different rating systems. Thus you cannot compare ratings from one manufacturer to another. A 10- μm filter from one manufacturer may be larger than a 20- μm filter from another. All one knows is that a 10- μm filter from one manufacturer is smaller than a 20- μm filter from the same manufacturer.

Depth filters are used where the liquids have a relatively low loading of solids to be removed. They are commonly used in coating lines. For dirty liquids it is often desirable to use a coarse filter followed by a fine filter. Filters must be properly installed. It is possible to mount a depth filter with the gasket improperly seated, and such a filter will not filter. Liquid will bypass the filter to flow through the opening formed by the improperly seated gasket.

Depth filters are frequently made from filaments formed from staple (short) fibers. It is not uncommon for some such fibers or fibrils to slough off at first use. Also, the filters are often sealed on their ends with a potting compound, which can leach out low molecular weight species on first use. It is advisable to flush the filters before using. If material leaching out of the filter is not a concern, then recirculating the coating liquid can be used to flush out the fibers and fibrils, which will then be filtered out of the circulating liquid. Otherwise a suitable solvent should be used.

Depth filters are made from many different fibers, including cotton and many synthetics. The proper material must be chosen for chemical compatibility. The surface properties would also affect how well particles stick to the filament, and this should be checked by experiment.

Both surface and depth filters have been used for removing soft particles. Bag filters, a type of surface filter, have been recommended for this purpose.

Two sets of filters, one in operation and a spare piped in parallel, are recommended so that when the operational filter plugs (the pressure drop across the filter reaches the maximum permitted value) the spare can be quickly put into service. Also, as particulates can break off in the lines to the coating station, it is recommended that an additional, small, relatively coarse filter, such as of wire mesh, be installed just before the coating stand.

Agglomerates

Agglomerates exist in a coating liquid because of an initial poor dispersion or because the dispersed particles agglomerate due to poor colloidal stability. The initial dispersion may be easy or difficult to achieve depending on the material. With some solids that consist of weak agglomerates, gentle agitation is adequate for a good dispersion; while with others one of many mechanical mills must be used. The *Chemical Engineers' Handbook* (Perry and Chilton, 1973) gives a good summary of tumbling mills, stirrer and sand mills, vibratory mills, roller mills, disk attrition mills, colloid mills, and so on that are available.

Once a solid has been dispersed, it must be kept dispersed. Surfactants and polymers are used for this purpose. The surfactants used are called dispersing agents. Most often the dispersing agents are anionic surfactants. The surfactants adsorb onto the surface and impart a charge to the particles. With anionic surfactants the charge is negative. As like

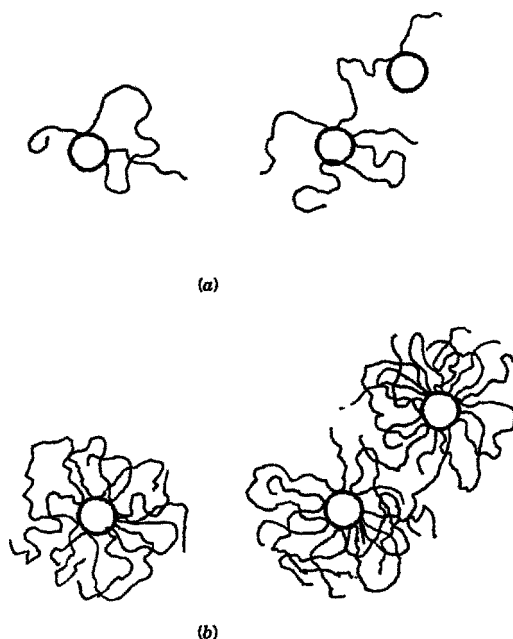


Figure 4-4. Effect of dissolved polymers on dispersed solids: (a) sensitization to agglomeration at low concentrations, where polymer bridges tie particles together; and (b) protection against agglomeration at higher concentrations.

charges repel each other, the particles have little tendency to agglomerate, and the dispersion gains stability. High concentrations of ionizable salts, especially polyvalent salts, overwhelm the charge on the particle (so to speak) and cause agglomeration. In some cases, the use of two different types of surfactants, such as an anionic surfactant with a nonionic surfactant, may give increased stability.

Polymers adsorb onto the surface of a particle, with the polymer chains dangling out around the particle, keeping away similarly coated particles. This protection against agglomeration by adsorbed polymers is called steric stabilization. On the other hand, if the polymer concentration is very low, a polymer chain dangling free from one particle can attach itself to an uncoated area on another particle, causing agglomeration. At low concentrations, a dissolved polymer sensitizes the dispersion to agglomeration. Thus a polymer at very low concentrations can be an agglomerating or coagulating agent, while at higher concentrations it can be a dispersing agent. This is illustrated in Figure 4-4.

With some dispersions the pH can be an important factor in stability, as the pH can strongly affect the ionic charge on some particles. If latices have carboxylic or sulfonic acid groups on the surface, they will become ionized as the pH is raised, thus developing a negative charge and increasing stability.

Although agitation is needed to disperse materials, too high an agitation rate can cause agglomeration. The high shear rates in the pumps used to feed the coating solution to the coating applicator have been known to agglomerate dispersions. Centrifugal pumps have high shear rates, and gear pumps, where most of the fluid sees only low shear rates, have highly localized high shear occurring where the gear teeth wipe the wall. This is of particular concern in coating processes where there is a recycle stream from the coating stand back to the feed vessels, thus subjecting particles to many cycles of this destabilizing

force. In such a system the agglomerates, if not removed by filtration, would increase with time. If agglomeration due to pumping is suspected, set up a recirculating system of a feed vessel and a pump, and monitor the solution for agglomeration with time. An in-line filter in such a system should show little increase in pressure drop once the initial particulates are removed, unless new agglomerates are formed. Agglomeration from whatever cause often shows up in rapid plugging of the filters.

BUBBLES

Bubbles form when air is introduced into a liquid or dissolved air in the liquid comes out of solution. Bubbles can form in the coating process and in the dryer, but in most cases they arise from air introduced during fluid preparation and handling. Care should be taken to ensure that air is not introduced into the system. It is usually much easier to prevent air from entering the system than it is to remove bubbles once they form. However, as one never knows when air will be introduced, it is well worthwhile to have debubbling devices in place to remove bubbles in case any do form.

Air can be introduced (1) during mixing of liquids if the agitation is too strong; (2) when a liquid stream impinging on the surface of a liquid carries entrained air into the preparation vessel; (3) when liquid is pumped into another vessel and the line, initially filled with air, enters below the surface; (4) at a pump suction, if the seal leaks and the suction pressure is below atmospheric; and (5) from air pockets in the lines. To avoid air pockets all lines should slope upwards. As this is usually impossible, it is desirable, where possible, to have all lines slope with no more than one high point and to have a bleed valve at that high point.

Bubbles can also form from air that is dissolved in the coating liquid. The air can come out of solution when the solution temperature is raised or where the pressure is low. Low pressure occurs (1) at the ends of lines, such as at the coating stand, since it takes a pressure drop for the liquid to flow; and (2) where the fluid velocity is high. It is easy to show that, neglecting friction, as the velocity is increased the pressure must be reduced. This occurs in valves and in other constrictions.

It is therefore desirable to remove bubbles and also to reduce the amount of dissolved gas, to reduce the likelihood of bubbles forming in the lines. It should be noted that if one fills a glass with clear water and lets it stand for several hours, bubbles will appear attached to the glass walls.

To reduce the amount of dissolved gas one has to reduce the solubility of the gas. The solubility of gas is less at lower pressures and higher temperatures. Normally we cannot heat the liquid above a certain temperature. Liquids are usually degassed by pulling a vacuum. One should also allow enough time for the bubbles to form and rise to the surface. The nucleation of the gas to form bubbles can be aided by ultrasonic energy. With a shallow depth of liquid the bubble needs less time to rise to the surface.

Degassing is frequently done on the coating liquid before it is pumped into the system. The vacuum should be high but insufficient to cause boiling. Mild agitation is helpful but is often not used. The length of time that should be allowed varies with the viscosity of the liquid and its depth. It can vary from minutes to hours. The amount of solvent that evaporates during this process is usually negligible.

Debubbling—the removal of bubbles that already exist—is normally done in the line from the coating liquid to the coating stand. Often the liquid is pumped downward onto a spherical dome, to flow down the sides while a vacuum is pulled. The vacuum should

be high but not enough to cause boiling. The vacuum causes the bubbles to expand and thus rise faster. This unit has to be elevated to a height sufficient to support the vacuum (up to 32 feet for water), or else a pump with a level control must be used to remove the liquid.

Another way to remove bubbles without the use of vacuum is to use a simple trap, with liquid entering below the surface near the top, and leaving at the bottom. There should be enough residence allowed for any bubbles to rise to the surface.

Ultrasonic energy is sometimes added to nucleate air coming out of solution. Centrifugal devices are also used, as are units similar to liquid cyclones that use the fluid energy to generate the centrifugal force.

Some filters will filter out bubbles, much as entrainment separators remove drops of liquid entrained in a gas stream. The wettability of the fibers in the filter is important. Here the liquid should flow downward at a velocity slow enough that the bubbles caught by the filter can agglomerate to a larger size and rise up against the flowing stream.

Other debubbling methods, such as the use of sonic energy to drive the bubbles out of the flow stream, have been under development (Hohlfeld and Cohen, 1993) but have not been marketed.

POOR CROSS-WEB UNIFORMITY

Cross-web uniformity is mainly dependent on the construction of the coating system; however, nonuniformities in the concentration in the coating liquid from the center to the wall of the line may cause nonuniformities in coverage. The liquid in the center of the line may go to one part of the coating, and the liquid near the wall may go to another part. Nonuniformities in the liquid can arise just because a dispersion flowing in a line in laminar flow will segregate to some extent, with the maximum concentration somewhere between the center and the wall. In laminar flow, a fluid flows in streamlines that do not mix, while in turbulent flow there is strong mixing in the line. The flow regime is determined by the ratio of "inertial forces" to "viscous force," and this ratio is expressed as the Reynolds number, equal to $DV\rho/\mu$ or, equivalently, equal to $4Q\rho/(\pi D\mu)$, where D is the line diameter, Q is the volumetric flow rate, V is the fluid velocity, μ is the fluid viscosity, and ρ is the fluid density. Consistent units must be used, or else conversion factors have to be introduced. When this Reynolds number is relatively low, under a critical value of 2100, viscous forces predominate and the flow is laminar.

In coating operations the flows rates are usually fairly low and the flows are almost always in the laminar regime. As there is little or no mixing in the laminar flow regime, an in-line mixer should be installed just before the coating stand.

The temperature also may vary in the feed line from the center to the wall. This will happen if the liquid is heated by flowing through a jacketed line, or if the liquid temperature is other than ambient such that the wall of the line will heat or cool the liquid. This can cause problems because the viscosity is a strong function of temperature. If liquid of one temperature goes to one part of the coating stand and liquid of a different temperature to another part, then the viscosity will vary across the coating stand. Because of resulting viscosity differences, the flows and thus the coverage will vary across the web. Both in roll coating and in die coating, the local flow is dependent on the viscosity. (In die coating the total flow depends only on the pumping rate, but the coverage at any cross-web position will vary as the viscosity varies.) For this reason, too, an in-line mixer should be installed just ahead of the coating stand.

In-Line Mixers

There are both dynamic and static in-line mixers. Dynamic mixers are essentially agitated vessels in the line. They provide excellent mixing and are high-shear units. They have a moderate holdup; the lowest holdup unit we are aware of is 600 mL. Because of the rotating mixing blades, they do introduce high-frequency pulsations. These pulsations, however, can be damped out by just a short length of plastic tubing. Many companies that make mixers and agitators also make these dynamic mixers.

Static mixers are small units with no moving parts, of the same diameter as the line, that contain internal elements that essentially cut and recombine the liquid. In one type an element cuts the fluid into two slices. With 21 elements, which is a common number, there would then be 2×10^6 slices. These units give fair to good mixing, have very low holdup, and are low-shear devices. Bubbles may be trapped in them unless there is upflow, depending on the internal construction. Kenics, Koch, and Sulzer are among the suppliers of static mixers.

Temperature Control

In roll coating the coverage is strongly dependent on the liquid viscosity, and this in turn is a strong function of temperature. In a coating die if the temperature, and therefore the viscosity, is not uniform across the full width, then the flow will not be uniform. The coating liquid and the coating die should be at the same temperature. Thus unless one coats at room temperature and room temperature does not fluctuate appreciably, and if the coating solution is also at the same room temperature, temperature control is necessary.

The container for the coating liquid can be jacketed to heat or cool the coating liquid, a heat exchanger in the line to the coating stand can be used, or jacketed lines to the coating stand can be used as a heat exchanger. If jacketed lines are used to heat the liquid, the heat transfer liquid—usually water—should be hotter than the desired temperature, with the jacket flow controlled to give the desired temperature of the coating solution. Static mixers in the jacketed line improve the rate of heat transfer and may be used as heat exchangers. If the jacket water is just at the desired coating temperature, the coating liquid will only approach that temperature but not actually reach it. Jacketed lines with the jacket water at the desired temperature should be used only to maintain the coating liquid at the desired temperature once it has already been brought to that temperature.

FLOW CONTROL FOR DOWN-WEB UNIFORMITY

In roll coating, the wet coverage depends on the geometry of the system, the liquid rheology or flow behavior, and the speeds of the various rolls at the coating stand. In slot, extrusion, slide, and curtain coating, the wet coverage depends on the pumping rate of liquid to the coating die, as well as the web speed and the coating width. It is therefore necessary to have good flow control from the feed vessel to the coating die in these systems. Control of the web speed is also important for good down-web uniformity.

Feeding the Coating Liquid

In general, there are three methods of feeding the coating liquid to a coating die, as shown in Figure 4-5. Gravity feed can be used, where excess liquid is pumped to an elevated head

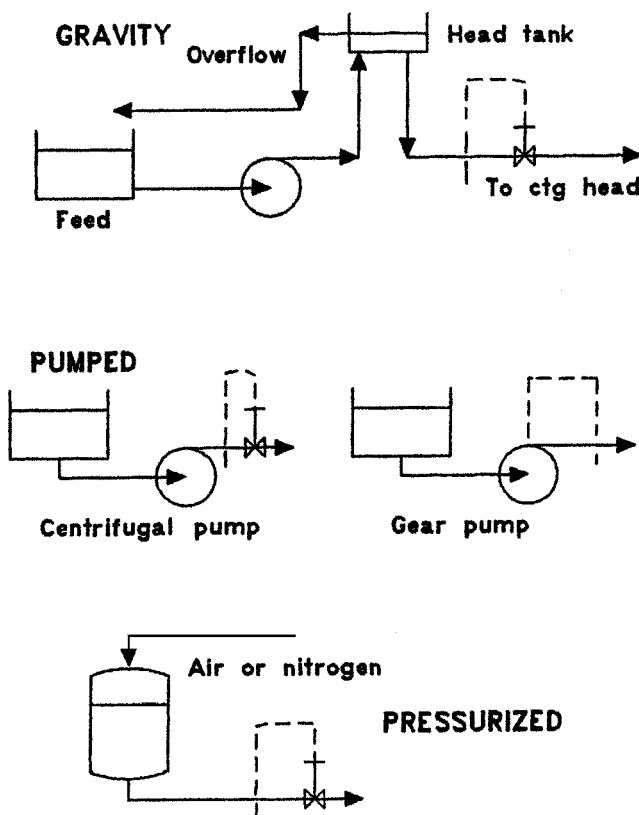


Figure 4-5. Methods of feeding coating liquid to the coating die.

tank, with the overflow returning to the feed tank. The head tank provides a completely constant head or pressure in the lines, making flow control, indicated symbolically by a flow meter connected by dashed lines to a control valve, relatively easy. The system requires little maintenance, the tank is easy to refill, and the system is pulsation-free. However, the elevated tank requires long coating lines, and the head obtainable is still relatively low. The holdup in these long lines is large, and the system is open. Several decades ago this was the recommended system; now it is no longer recommended.

Pressurized systems, shown at the bottom of Figure 4-5, are also pulsation-free. A pressure vessel is required for these systems, which are completely closed. There is the likelihood of dissolving gas in the liquid, which could lead to bubble formation later on. If the liquid is not agitated, then not very much gas will dissolve, and if the coating liquid is withdrawn from the bottom of the vessel this should not be a problem. It is difficult to refill the vessel while it is pressurized, and so two vessels might be required for long runs. It may be difficult to achieve bumpless transfer from one vessel to the other, and a few chatter bars would likely result when switching vessels. Also, it is difficult to completely empty a vessel. If one attempts to, and if air (or nitrogen) gets into the exit line, then the resistance to flow in the line will decrease because the viscosity of air is very low. The velocity in the line will therefore increase, and a slug of liquid and gas will come shooting out of the coating die and will spray everything in sight. This has to be avoided at all costs.

Pressurized systems are successfully used but are not generally recommended except for pilot runs and low-flow or short-run areas.

The pumped systems are the ones we recommend for most production coating areas. The vessels are easy to refill and can be pumped dry if desired. Pulsations may arise from both centrifugal and from gear pumps, but these pulsations are easily damped out. Usually plastic tubing (such as polyethylene tubing) after the pump provides sufficient damping to eliminate most pulsations at the coating die, even from gear pumps. Pumps do require regular maintenance, but this is a minor item. With a gear pump the flow meter would control the speed of the gear pump, rather than adjust a control valve.

For feeding a very low flow rate stream, or for low flow rates of an additive into the main stream ahead of an in-line mixer, a syringe pump is usually used. For longer runs two pumps can be used, one filling while the other is emptying, but it is difficult to achieve bumpless transfer from one to the other.

Flow Control

The flow to a coating die should be metered and controlled. One should not depend on a calibrated valve or gear pump to control the flow since good coverage control is needed. One should measure the flow and have feedback control to a valve or to the speed of a gear pump. There are many different types of flow meters available, but we recommend three: magnetic flow meters, ultrasonic meters, and Coriolis meters. All three can achieve flow accuracies of 0.5% of full scale.

Magnetic Flow Meters A conductor passing through a magnetic field generates a voltage. In the magnetic flow meter, illustrated in Figure 4-6, the fluid itself is the conductor, and the magnetic field is external to a nonconductive section of pipe. The electrodes measure the voltage generated. Permanent magnets or electromagnets may be used. The voltage to the coils of the electromagnet can be either direct current or alternating current, giving two classes of meters. These meters work very well, but the liquid in the pipe must have some conductivity, essentially limiting its use to aqueous coating liquids. In some situations the electrodes can foul and give erratic readings, but it is not difficult to clean them.

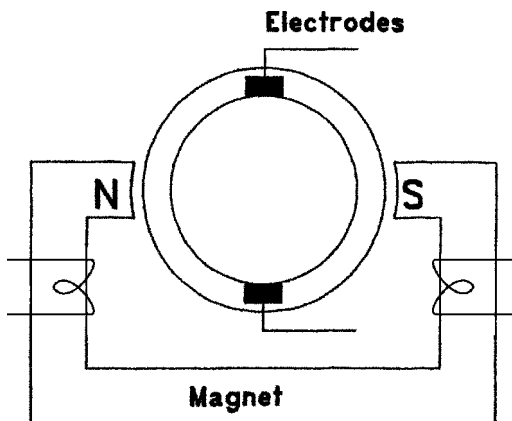


Figure 4-6. Principle of the magnetic flow meter. A conductor, the liquid, passing through a magnetic field generates a voltage that is a function of the flow rate.

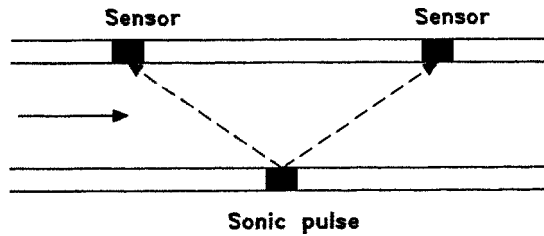


Figure 4-7. In an ultrasonic meter, the difference in transit time for an ultrasonic pulse to travel upstream or downstream is a measure of the flow rate.

Ultrasonic Meters In an ultrasonic meter (Figure 4-7) the transit time for an ultrasonic pulse to travel upstream is compared with the transit time to travel downstream. The transit time *with* the flow is less than *against* the flow, and the difference is a measure of the flow rate of the liquid.

Coriolis Meters Coriolis meters are true mass flow meters, compared to the others that measure the volumetric flow rate. They are based on Coriolis forces, which are the same forces that cause a swirl in the water draining from a bathtub. One type is shown in Figure 4-8. The liquid is pumped through a stainless steel U-tube that is vibrated at its natural frequency. As the liquid moves through the tube, it takes on the tube's motion up or down. When the tube is moving up, liquid moving into the tube resists this upward motion, effectively pushing downward on the tube. On the other hand, liquid flowing out

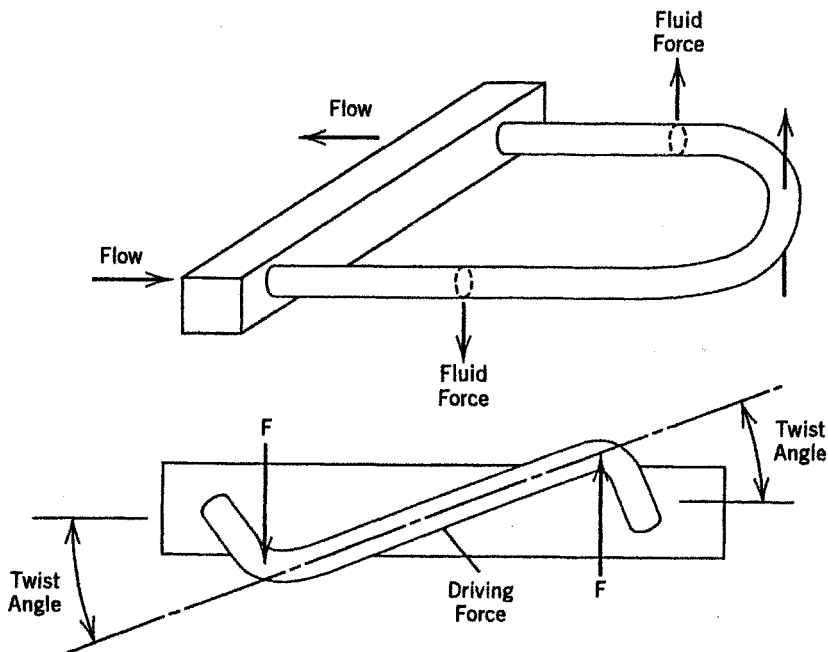


Figure 4-8. In a Coriolis meter, the twist in the tube is a measure of the mass flow rate. From a Micro Motion bulletin, with permission.

of the tube tends to keep moving upward and pushes upward against the walls of the tube. This combination of forces imparts a twist to the tube. This twist is measured and is directly proportional to the mass flow rate of the liquid.

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5

PROBLEMS ASSOCIATED WITH ROLL COATING AND RELATED PROCESSES

COATING METHODS

This chapter briefly covers coating problems in roll coating and related processes, that is, in all coating methods other than those where the wet coverage is determined solely by the flow rate to a coating die and the coating speed. Coyle (1992) gives a working definition of roll coating as *a coating method whereby the fluid flow in a nip between a pair of rotating rolls controls both the thickness and the uniformity of the coated film*. Extending this definition to include a roll of infinite radius covers flat sheets, and considering a roll of zero velocity covers knives and blades. The term *roll coating* is generally understood, and we now illustrate some specific configurations.

In forward roll coating (Figure 5-1), the web travels over a backup roll while an applicator roll, turning in the same direction as the web and with a small gap separating it from the web, applies the coating. Since the web and the applicator roll are turning in the same direction, the coating liquid carried into the nip on the applicator roll splits at the nip exit with some remaining on the applicator roll and the rest leaving as the coating on the web. The web and the applicator roll may be moving at the same speed or the speeds may differ. The coating liquid can be supplied to the applicator roll by many different methods. Figure 5-1 shows a pan-fed applicator roll where the rotating applicator roll picks up liquid from the pan in which it sits. The liquid can also be supplied by a slot die, in place of the pan, and aimed upward to give a fountain-fed system. A fountain roll can pick up the liquid from the pan and transfer it to the applicator roll to give a three-roll pan-fed forward roll coating system. In another system, a third roll butts against the applicator roll, with the liquid supplied to the nip between them and contained between end dams, to give a three-roll, nip-fed forward roll coating system. Any number of rolls can be used, and the rolls can be smooth chrome-plated steel or they can be rubber covered. Ceramic rolls are coming into use.

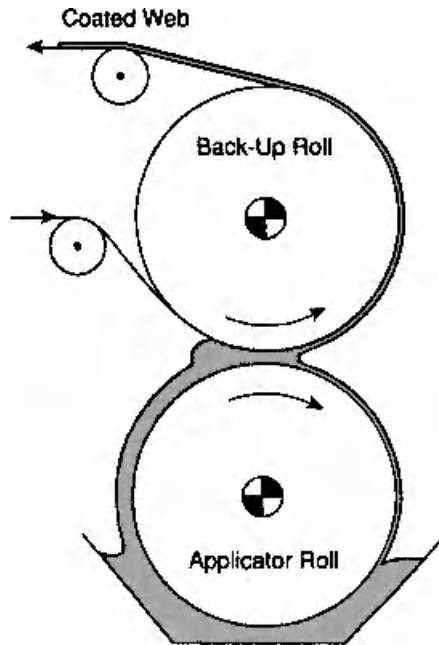


Figure 5-1. Two-roll, pan-fed, forward roll coater. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

In reverse roll coating, the backup roll is usually rubber covered, and the web travels in the opposite direction to the applicator roll, presses against it, and wipes off all of the coating from the applicator roll, as in Figure 5-2. The amount of liquid on the applicator roll is controlled by a metering roll, which rotates in the opposite sense. Figure 5-2 shows

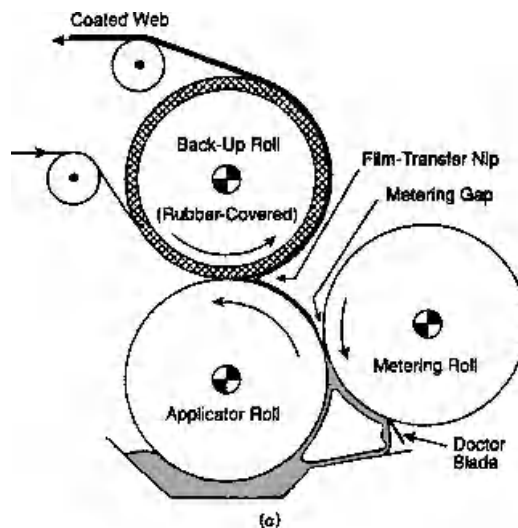


Figure 5-2. Reverse roll coating: (a) three-roll, pan-fed reverse roll coater; (b) four-roll, pan-fed reverse-roll coater; and (c) three-roll, nip-fed reverse roll coater. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

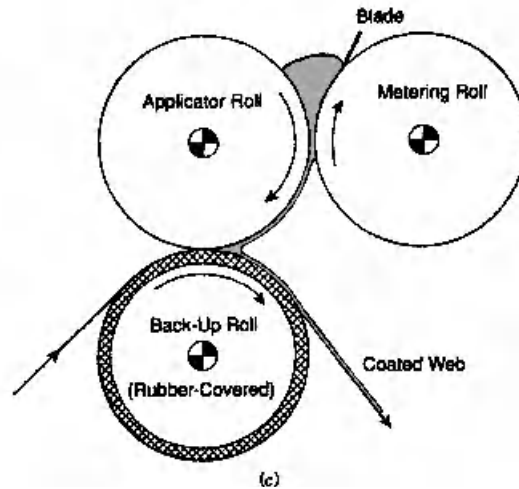
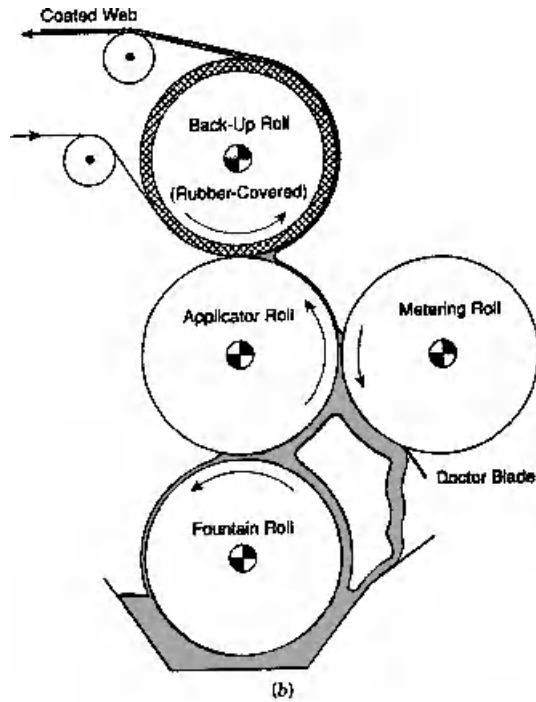


Figure 5-2. (Continued)

several different reverse roll configurations. Note that in every case a doctor blade is used to wipe off all the coating liquid from the metering roll shortly after it does its job of metering the fluid on the applicator roll.

In gravure coating, the gravure roll has indentations or cells that hold the liquid after the excess is wiped off the surface by a doctor blade. In forward direct gravure, the liquid is then transferred to the web moving in the same direction on a rubber covered backup roll,

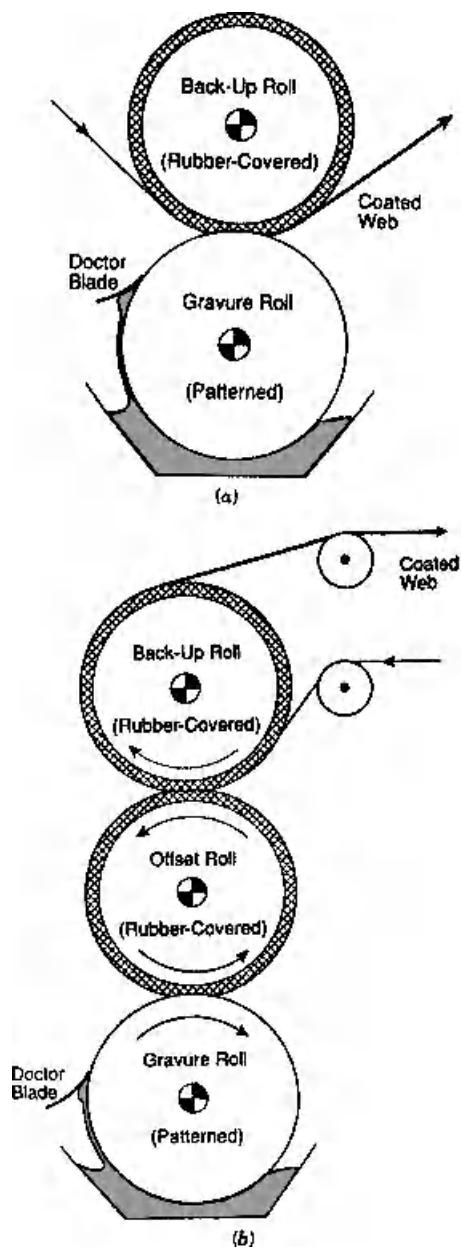


Figure 5-3. Gravure coating: (a) direct gravure and (b) offset gravure. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

as in Figure 5-3a. The web and the backup roll always move at the same speed; the gravure roll usually, but not always, also moves at that speed. If the web travels in the direction opposite to the gravure roll, we have reverse gravure. If the liquid is first transferred to an intermediate rubber-covered roll, called an offset roll, we have offset gravure. Forward offset gravure is shown in Figure 5-3b. The amount of liquid transferred is controlled by

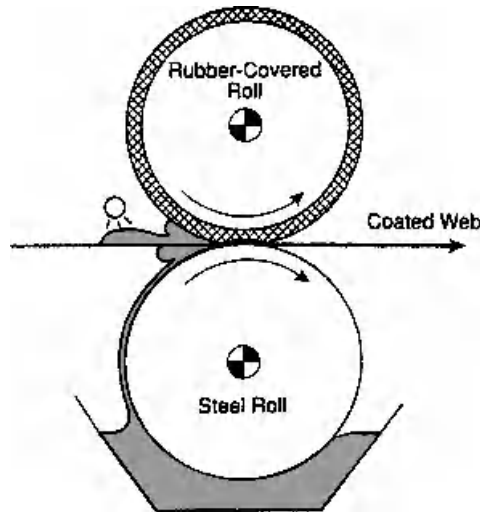


Figure 5-4. Two-roll squeeze roll coater. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Guttoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

the cell volume per unit area of the gravure roll, the volume factor, and how well the cells empty.

In forward roll coating, if a rigid roll presses the web against a rubber-covered roll we have squeeze coating (Figure 5-4). And again in forward roll coating, if the liquid thickness on the applicator roll is less than the gap between the roll and the web we have meniscus coating, as in Figure 5-5. The lower roll is not necessary; in meniscus coating the web and the backup roll can be just above the surface of a pool of liquid, as in Figure 5-5*b*. Surface tension keeps the liquid against the web. In kiss coating (Figure 5-6), the web, traveling in the same or opposite direction to the applicator roll, is held against the applicator roll only by the web tension.

In rod coating, a wire-wound rod—a Mayer rod—doctors off excess coating liquid (Figure 5-7). Excess coating liquid is applied to the web ahead of the coating rod by any

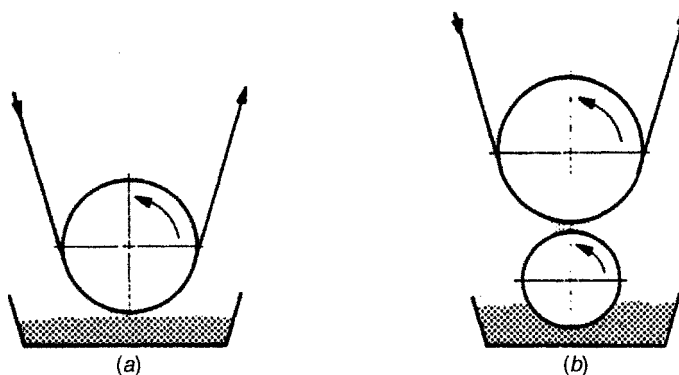


Figure 5-5. Meniscus coating. From D. Satas, Ed. (1984), *Web Processing and Converting Technology and Equipment*, Van Nostrand Reinhold, New York 1984, with permission of Saule Satas.

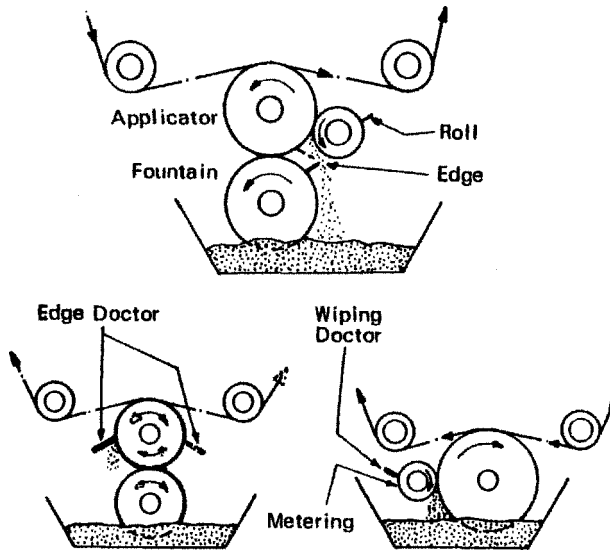


Figure 5-6. Kiss coating. From H. Weiss (1977), *Converting and Laminating Machines*, Converting Technology Co., Milwaukee, (1977), with permission of Sheila Weiss.

convenient method. The amount of liquid remaining in the coating is related to the free space between the high points of the wires. If this liquid is spread uniformly, one would expect the coating thickness to be 10.7% of the wire diameter; however, it is often less. The rod is usually slowly rotated so as to wear evenly and also to free any particles caught against the rod that would create streaks. The direction of rotation should be such as to tighten the wire.

In knife coating, a rigid blade that is held perpendicular to the web and close to or against the web doctors off excess liquid. In Figure 5-8a, a knife-over-roll coater is shown. The roll can be steel, in which case a fixed gap should be maintained; or the roll can be rubber-covered, with the knife pressing against the roll. The knife can also be held against an unsupported web as in the floating knife coater (Figure 5-8b). Here the control of web tension is very important.

In blade coating, a thin blade is pressed against the web at an angle, as in Figure 5-9a, to doctor off the excess liquid. In beveled blade coating, the blade is rigid, (Figure 5-9b). The bevel, if not originally parallel to the web, would soon become

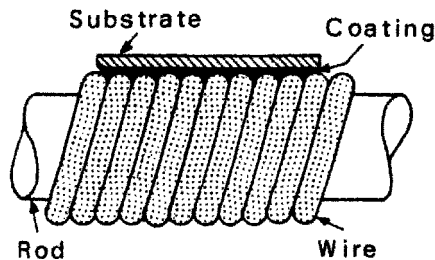


Figure 5-7. Rod coating with a wire-wound rod. From H. Weiss (1977), *Converting and Laminating Machines*, Converting Technology Co., Milwaukee, (1977), with permission of Sheila Weiss.

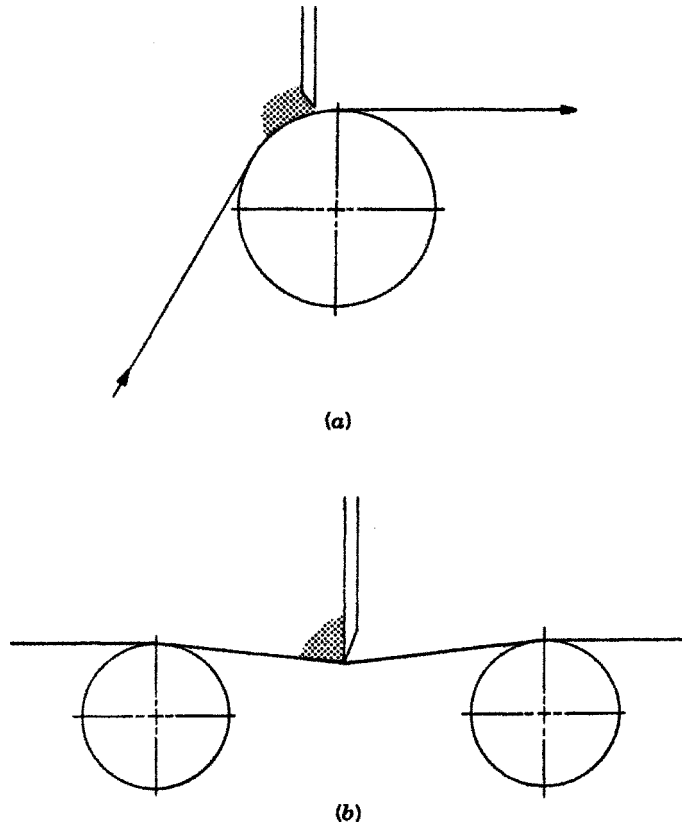


Figure 5-8. Knife coating: (a) knife-over-roll coating and (b) floating knife coating. From Grant and Satas (1984), Reprinted from D. Satas, Ed., *Web Processing and Converting Technology and Equipment*, Van Nostrand Reinhold, New York 1984, with permission of Saule Satas.

parallel due to wear. In flexible blade coating, the blade bends under the pressure, and the flat of the blade, rather than the edge, often does the doctoring, as in Figure 5-9c.

In air-knife coating, a blast of air, (Figure 5-10) doctors off the excess liquid. Air-knife coating can operate in one of two possible modes. At lower air pressures the plane jet of air acts just like a doctor blade to control coating weight, rejecting the excess fluid, which cannot pass and flows back to the coating pan. In higher pressure systems the air acts as a squeegee and blows off excess fluid from the web. The resulting spray has to be contained. Air-knife coating works very well, but containing the spray in high-pressure systems can be a problem. Air-knife coating is not often used today because of the high rate of energy consumption in compressing the needed air.

In dip coating, the web is carried into and then out of a pool of coating liquid (Figure 5-11). The web carries off whatever liquid does not drain back into the bath. The web can travel around several rolls in the tank, and one or both sides can be coated. A doctor blade may be used to reduce the coated thickness. This is one of the oldest methods of coating and is still used for coating webs, fibers, and discrete objects.

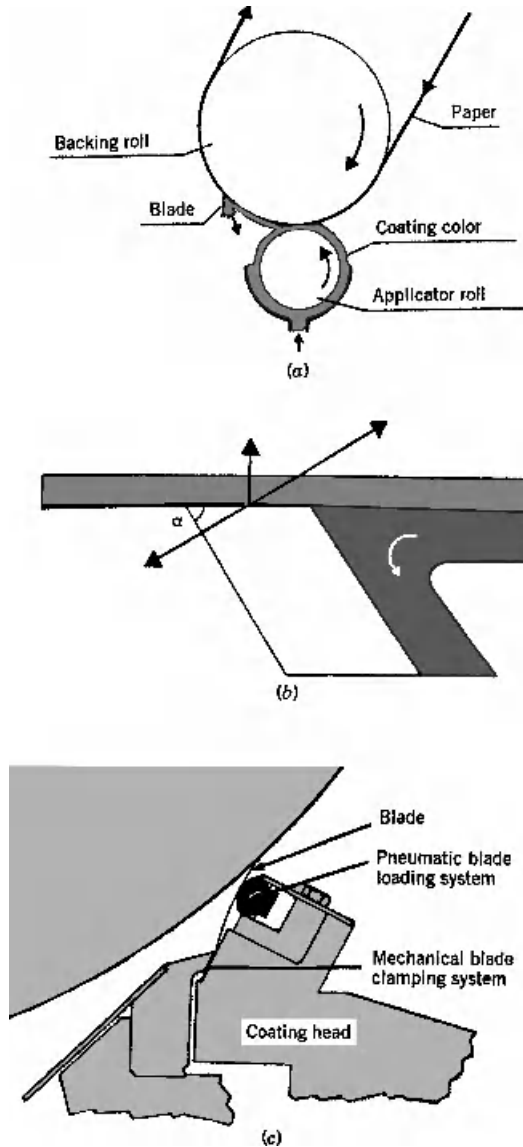


Figure 5-9. Blade coating: (a) general arrangement, (b) the beveled blade in blade coating, and (c) flexible blade coating. From Eklund (1984), Reprinted from D. Satas, Ed., *Web Processing and Converting Technology and Equipment*, Van Nostrand Reinhold, New York 1984, with permission of Saule Satas.

CONTROL OF COATING WEIGHT

The scientists who design a coating and the customers who buy the coating are primarily interested in the dry coating weight. But to the coating operators and engineers who manufacture it, the wet coating weight is most important. The wet coating is what is applied, and the wet coating coverage controls coatability. When we discuss coating weight here, we refer to the wet coating weight. As long as the coating liquid is well mixed and homogeneous, the dry coating weight will be proportional to the wet coating weight.

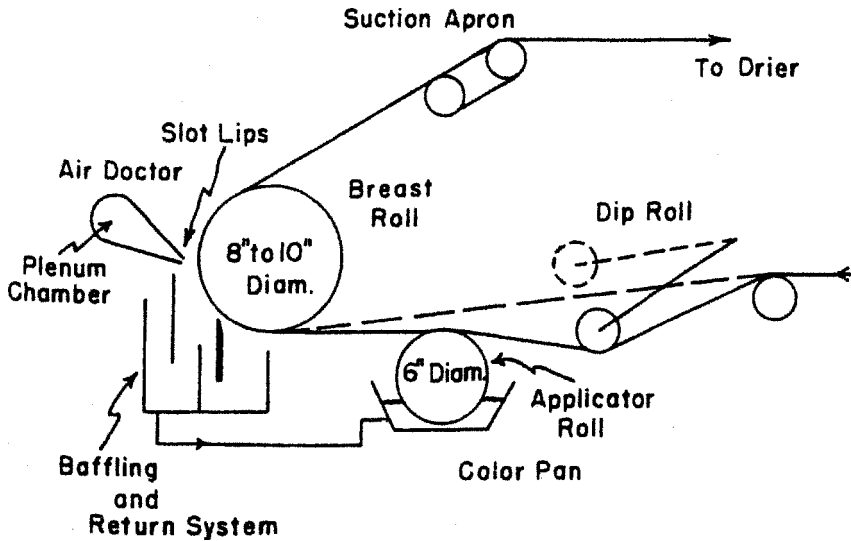


Figure 5-10. Air-knife coating. From Eklund (1984), Reprinted from D. Satas, Ed., *Web Processing and Converting Technology and Equipment*, Van Nostrand Reinhold, New York 1984, with permission of Saule Satas.

Control of wet coating weight involves three factors: control of the average coating weight, control of coating uniformity in the machine or down-web direction, and control of coating uniformity in the cross-web direction. In the machine direction, coating weight often varies cyclically, as illustrated in Figure 5-12a. Across the web the coating weight is controlled by the construction of the system. A typical cross-web coating weight profile is shown in Figure 5-12b.

In most roll coating operations, the average coating weight is controlled by the geometry of the system, the speeds of the web and of the rolls, the forces applied (as web tensions, or the forces applied to knives, blades, or rigid rolls against rubber-covered rolls), and the viscosity or rheology of the coating liquid (Coyle, 1992). In air-knife coating, the

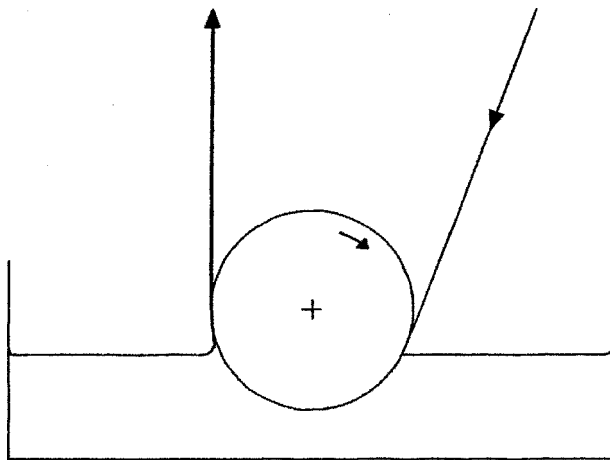


Figure 5-11. Dip coating.

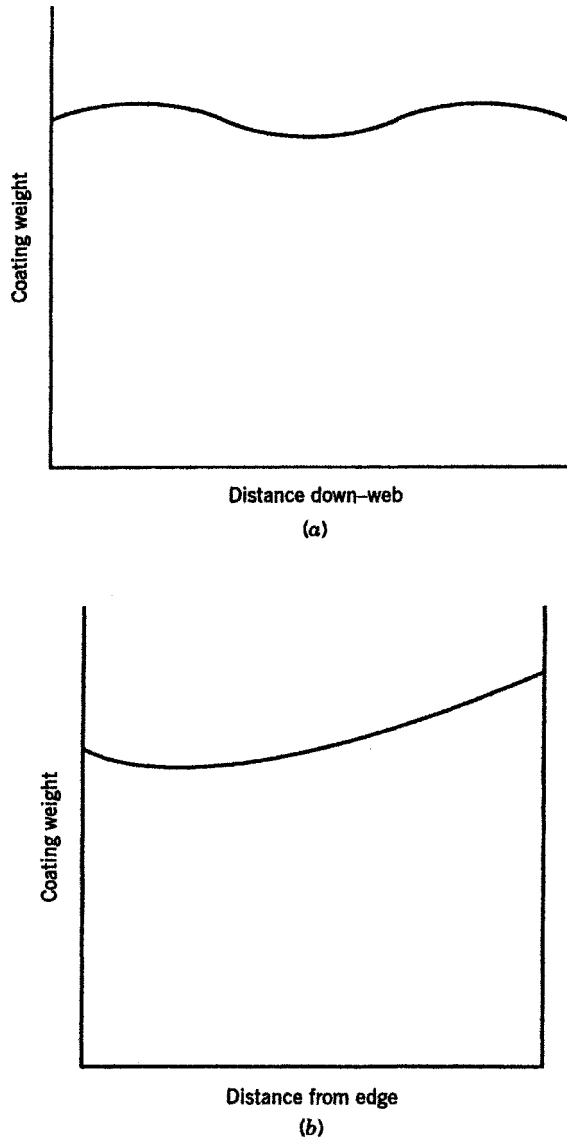


Figure 5-12. Typical coating weight profiles: (a) in the machine direction and (b) cross-web profile.

air pressure is also an important variable (Steinberg, 1992). In gravure coating, the gravure pattern on the cylinder is the major factor in coating weight control.

Good control of coating weight can only be obtained by measuring the coverage and making adjustments. Rolls are difficult and expensive to change, and so this is rarely done. Changing the rheology or concentration of a coating liquid involves making a new batch; that takes time and the ingredients may be expensive. The operator will adjust those items that are easy to adjust and that do not interfere with production. Thus the operator will rarely reduce the coating speed. But the operator will adjust roll speeds and coating gaps or applied forces until the coating weight is correct. An automatic system

with an on-line sensor, such as perhaps a beta gauge, and feedback control is desirable. This can adjust a roll speed or a coating gap to automatically control the coating weight.

In blade coating, the coating weight is controlled by the force of the blade against the web. When the angle between the blade and the web is low, under about 20° , as in bent blade coating, the coating fluid develops a pressure that opposes the force on the blade and tends to lift it. This fluid pressure depends on the geometry, with a gentle angle causing a greater pressure, and is proportional to the coating speed and the fluid viscosity.

Blade coating is often used to coat clay and other heavily loaded liquids. Those liquids that contain a high percentage of suspended solids, such as a clay, can behave strangely. Most polymer solutions will show a drop in viscosity as they are sheared or stirred faster and faster, as will be described in Chapter 6. However, liquids with high loadings of suspended solids may show the opposite behavior; their viscosity may increase at high shear or high stirring rates. Liquids that exhibit such shear-thickening behavior are called dilatant. A plot of shear thinning and shear thickening behavior was shown in Figure 3-6.

In blade coating clay suspensions, the clay loadings may be so high that the coating liquid is too dilatant, which could cause the viscosity to increase greatly in coating. This could increase the fluid pressure against the blade sufficiently to lift it away from the web, allowing excessive liquid to be coated. If the external force on the blade cannot be increased enough to bring the coated thickness down to the desired level, the blade angle should, if possible, be increased. Otherwise one would have to thin down the coating liquid to reduce its dilatancy.

The coating uniformity is limited by the inherent properties of the system. Most roll coating systems cannot do better than a 5–10% variation in coverage. However, precision reverse roll systems with very precise bearing are capable of keeping the variation within 2%.

Gravure coating, like precision reverse roll coating, can also give very uniform coverages. However, on a very small scale the uniformity may not be that good, since the coating liquid from the cells in the gravure cylinder, after transfer, has to flow together and level. Large land areas—the flats on the gravure cylinder between the cells—tend to promote printing, or the retention of the cell pattern on the web. This is undesirable for a uniform coating. Therefore for uniform coverage and for good leveling, the land areas should be as small as possible for a given cell volume. Leveling is also promoted by reverse gravure rather than forward gravure, as this tends to smear the cells together. Differential gravure, where the gravure cylinder runs at a different speed than the web or the offset cylinder, similarly should help in leveling.

Sometimes in gravure and other roll coating operations a smoothing bar—a stationary or slowly rotating smooth rod or bar—is used to aid in leveling. Since it is an additional mechanical device, it is preferable not to use a smoothing bar unless absolutely necessary.

In gravure coating, the volume factor—the total cell volume per unit area of the gravure cylinder—is the main determinant of the coating coverage. A volume divided by an area is a length. Thus the cell volume per unit area of the cylinder is the height of coating liquid that would be on the gravure cylinder if the cylinder were smooth. If all of this liquid were transferred to the web at the same speed, this would be the wet coverage. The volume factor, if expressed as cm^3/m^2 , is exactly equal to the wet thickness in micrometers if all the cell volume were transferred. But not all of this liquid does transfer to the web. Pulkrabek and Munter (1983) found that, with a number of different knurl rolls, the amount of coating liquid transferred is only about 59% of the cell volume. The wet thickness is then about 59% of the volume factor. Coyle (1992) suggests that for all

gravure rolls the amount transferred is 58–59% of the cell volume. Actually this fraction transferred varies greatly, both higher and lower, depending on the situation. It is common to buy a test cylinder to check this. If the coverage is not correct, this test cylinder can be reworked until the correct coverage is obtained.

At times the amount transferred in gravure coating is much less than this 59% or whatever of the volume factor that we would expect. The problem is usually due to too low a force between the impression or backup roll and the gravure cylinder, or, in offset gravure, the force between the gravure and offset cylinders. The minimum force needed depends on the viscosity of the coating liquid, the type of web, and the cell type and size. Obviously, in direct reverse gravure, the force between the gravure cylinder and the impression roll has to be much less than in direct forward gravure, or else the web and the gravure cylinder would not slide past each other. This lower force may then result in a more incomplete pick-out, and this may be one reason that direct reverse gravure is not often used.

RIBBING

Ribbing is the formation of lines running down the web and very uniformly spaced across the web, as if a comb were drawn down the wet coating. Ribbing has also been called comb lines, phonographing, rake lines, and corduroy. It can occur in just about every type of coating. In fact, the brush marks or lines formed in painting a wall with a bristle brush are most often ribs from the hydrodynamics of the coating process and are not, as generally thought, caused by the bristles of the brush. In coating with a wire-wound rod, where one would expect ridges or ribs to be spaced at the wire spacing (the wire diameter), Hull (1991) has found that the rib spacing is often different from the wire spacing and is related to interactions between the wire spacing and the hydrodynamic ribbing frequency. Here, too, it is the coating hydrodynamics that causes ribs.

In rigid knife coating, the geometry of the gap between the knife and the web determines whether or not ribs form and also the appearance of the ribs. When the gap is purely converging with no diverging zones beyond the narrowest clearance, as illustrated in Figure 5-13, then no ribs were observed by Hanumanthu et al. (1992). Diverging zones, which would be present if a round rod were used in Figure 5-13, seem to promote rib formation.

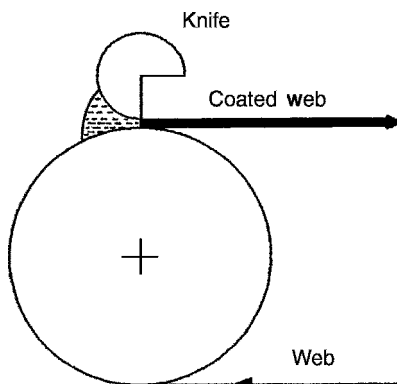


Figure 5-13. In knife coating, all diverging zones in the flow direction, as would be present if the missing quadrant were present, should be avoided to prevent ribbing.

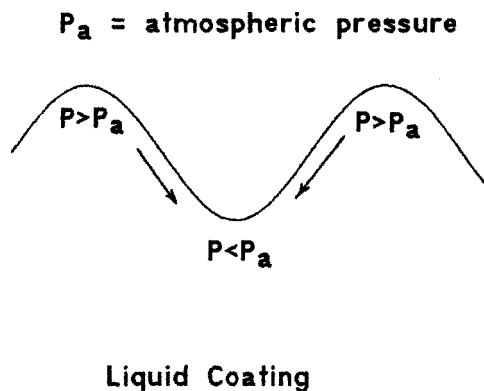


Figure 5-14. High surface tension aids leveling. Due to surface tension, the pressure on the concave, or inwardly curving, side of an interface is higher than on the convex, or outwardly curving, side. This pressure difference promotes flow from the peaks to the valleys.

When ribs form they will persist into the dried coating unless the liquid levels well—that is, unless liquid flows from the ridges into the valleys. This leveling is more likely to occur with low-viscosity liquids and will be aided by a longer time in the liquid state. High-viscosity liquids are unlikely to level when they are dried quickly or are cured very quickly by ultraviolet light or electron beam radiation. High surface tensions aid leveling. As will be described in Chapter 8 on surface tension effects in coating, when a curved interface—as between a liquid and air—exists, then there will be a pressure differential across this interface. This pressure difference is called capillary pressure and is proportional to the surface tension. The pressure will be higher on the inwardly curving, or concave, side of an interface. Thus when ribs exist, as in Figure 5-14, under the high points of the ribs the pressure in the liquid will be above atmospheric. At the low points, however, the inwardly curving side is above the interface, and the air pressure is higher than the pressure in the liquid. Since liquid will flow from regions of higher pressure to regions of lower pressure, liquid will flow from the peaks of the ribs to the valleys. This will aid in leveling. Gravity also aids in leveling.

When ribs are present in knife or blade coating, the geometry should be altered to ensure that there are no diverging zones for the liquid flow. If this is not possible, the surface tension should be as high as possible while still permitting good wetting on the support, and the viscosity should be as low as possible, to aid in leveling. Adding an additional leveling rod with no diverging zones is sometimes used, but it is better practice to avoid the initial rib formation if at all possible.

Ribbing in Forward Roll Coating

Rib formation almost always occurs in forward roll coating. The diverging geometry of the flow exiting the nip between the rolls and also the viscous forces that are always present favor rib formation. Surface tension, as we have just discussed, opposes rib formation. As a result, the ratio of viscous forces to surface forces is an important variable in determining rib formation. The ratio of viscous to surface forces is called the *capillary number* and is equal to $\mu\bar{U}/\sigma$, the product of the viscosity and the coating speed divided by the surface

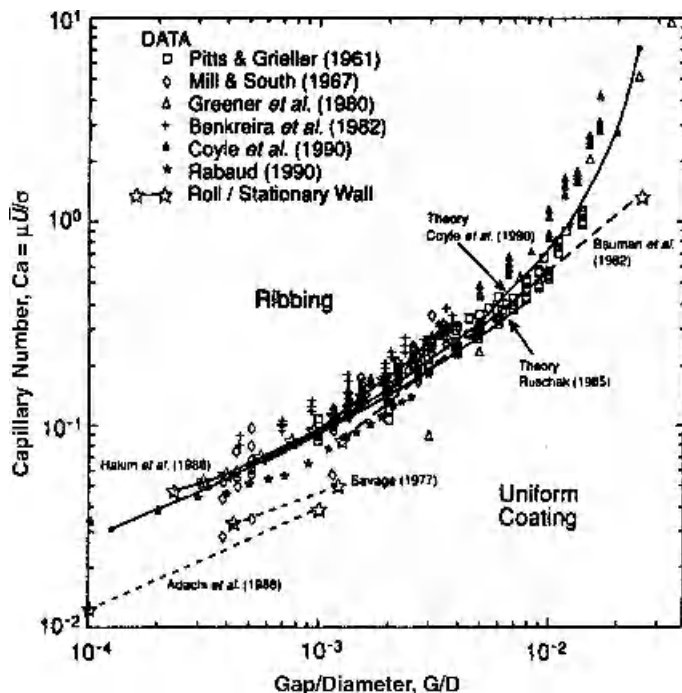


Figure 5-15. Ribbing in forward roll coating. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

tension. Here μ is the viscosity of the liquid, σ is the surface tension, and $\bar{U}$ is the average surface speed of the two rolls—the applicator roll and the backup roll.

The ratio of the gap between the web and the applicator roll to the roll diameter is also important in rib formation. If the applicator and the backing rolls are of different size, then in the gap-to-diameter ratio a special average diameter should be used, such that

$$\frac{1}{D} = \frac{1}{2} \left(\frac{1}{D_1} + \frac{1}{D_2} \right)$$

Figure 5-15 shows the operating conditions under which ribs form as a function of these two ratios, the capillary number or ratio of viscous forces to surface forces, and the gap-to-diameter ratio.

In Figure 5-15, we see that as the capillary number increases there is a greater tendency to form ribs. This means that ribs are more likely to form at higher coating speeds, higher viscosities, and lower surface tensions. Also, ribs are more likely to form at lower gap-to-diameter ratios. This means that tight gaps and also large-diameter rolls favor rib formation. Wide gaps, which would reduce the tendency to form ribs, give thicker coatings, and so the gap cannot be changed arbitrarily.

If we take a typical coating speed of 200 ft/min or 1 m/s, a typical surface tension of 40 dynes/cm or 0.040 N/m, and a typical viscosity of 100 cP or 0.1 N-s/m², then the capillary number would be (0.1 N-s/m²)(1 m/s)/(0.040 N/m) or 2.5. At this high capillary number, ribs would form except at extremely large gap-to-diameter ratios.

This demonstrates that in forward roll coating rib formation is the usual occurrence. Forward roll coating should not be used unless rib formation is not objectionable, or the liquid levels well, or ribs in the product do not affect its usability. Because of this great tendency to form ribs, forward roll coating is used much less now than it had been in the past.

Viscoelastic liquids are liquids that, while they flow like ordinary liquids, show some elastic effects. Egg white is a common viscoelastic liquid. In fact, all polymer solutions and polymer melts are viscoelastic to a greater or lesser extent. And viscoelastic liquids show ribbing at much lower critical capillary numbers than do the simple Newtonian liquids that were used for the data in Figure 5-15. Also, viscoelastic liquids can have a greater rib height than do Newtonian liquids. We may note that most coating liquids contain dissolved polymers and would therefore show viscoelastic behavior under the conditions that exist in most coating operations. Thus they would form ribs even under conditions where Figure 5-15 predicts no rib formation.

We may conclude that it is almost impossible to avoid rib formation in forward roll coating. However, rib formation is minimized by operating at low speeds (we normally want to run at as high speeds as possible) and low viscosities, and with wide gaps (which would give thick coatings).

As mentioned earlier, the use of a leveling bar with no diverging zones is sometimes helpful. A better solution appears to be the use of a fine wire or monofilament stretched across the machine and touching the liquid in the film splitting region, between the applicator roll and the web on the backup roll (Figure 5-16), as suggested by Hasegawa and Sorimachi (1993).

Ribbing and Cascade (or Herringbone or Seashore) in Reverse Roll Coating

In reverse roll coating, the most critical conditions exist in the gap between the metering roll and the applicator roll, and not where the applicator roll meets the web. After the metering operation, all of the coating on the applicator roll is transferred to the web, and any defects formed prior to that point will also transfer.

Cascade, also called herringbone or seashore, is a distinct defect that occurs at high capillary numbers (based on the applicator roll speed) and at high ratios of the metering roll speed to the applicator roll speed. As Coyle (1992) points out, cascade is a periodic cross-web disturbance with a sawtooth pattern. It is caused by air being entrained in the gap between the metering roll and the applicator roll. Thus this defect shows up as areas of low coverage. Let us see how this can occur.

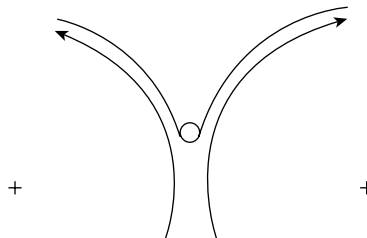


Figure 5-16. In forward roll coating, a fine wire or filament stretched across the gap exit and touching the liquid eliminates ribbing (Hasagawa and Sorimachi, 1993).

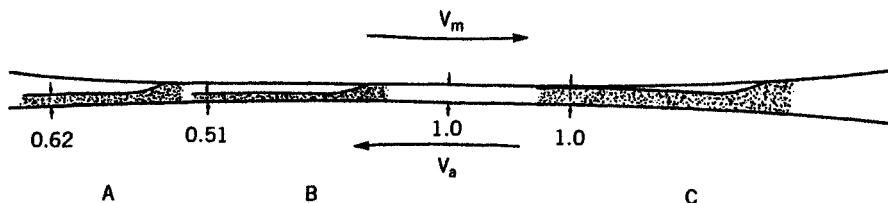


Figure 5-17. Formation of entrained air—the cascade defect—in reverse roll coating. The metering roll is above, the applicator roll below. From D. j. Coyle et al., *AIChE Journal* **36**, 61-174(1990). Reproduced with permission of the American Institute of Chemical Engineers. Copyright © 1990 AIChE. All rights reserved.

Figure 5-17 illustrates the process. At a given capillary number, meaning at a constant applicator roll speed, as the metering roll turns faster the meniscus retreats into the gap. This is as one would expect. With the higher speeds, as the meniscus approaches the center of the gap the metered film thickness gets smaller. However, once the meniscus passes through the center of the gap, the separation of the roll surface increases and the metered film gets thicker again. When the metered film thickness becomes greater than the clearance at the center of the gap, air is trapped. But this condition cannot exist at steady state. When the liquid reattaches at the minimum gap, the film again becomes thinner, the meniscus retreats back through the gap, the film then becomes thicker and again entraps air, with the cycle repeating itself. This gives the periodic cross-web disturbance called cascade.

Figure 5-18 illustrates the defect-free operating regions in reverse roll coating. At very low capillary numbers (low speeds and low viscosities), the coating is defect-free. At low ratios of the metering roll speed to the applicator roll speed, with higher values of the capillary number (higher speeds), ribbing occurs. At higher ratios of the metering roll speed to applicator roll speed, cascade occurs. But note that at high capillary numbers there is a range of speed ratios between the ribbing and the cascade regions where defect-free coatings can be made, which is not possible at lower capillary numbers. We see in Figure 5-18 that at some speed ratios one can go from ribbing to a defect-free coating by increasing the speed. This is one case where increasing the coating speed makes coating easier. This ability to get defect-free coatings at high coating speeds is one reason why reverse roll coating is so popular.

In the discussion on ribbing in forward roll coating, we used an example where a typical capillary number might be 2.5. Figure 5-18 shows that there should be no trouble getting a rib-free coating in reverse roll coating at this capillary number, if the ratio of the metering roll speed to the applicator roll speed is about 0.3. It does not matter whether the gap is wide (1000 μm or 40 mils) or tight (125 μm or 5 mils).

We also see in Figure 5-18 that at tighter gaps the defect-free operating region is narrower. In some cases it can even disappear. There is even a suggestion (Coyle et al., 1990) that ribs are always present, but in the “stable” region they are just of extremely low amplitude and almost undetectable to the naked eye, and therefore unobjectionable.

As in the case of forward roll coating, viscoelastic liquids such as polymer solutions appear to be more prone to form ribs than simple or Newtonian liquids. Thus in some cases the defect-free operating region may completely disappear. In such cases one could add a leveling bar with no divergent zones, as mentioned earlier.

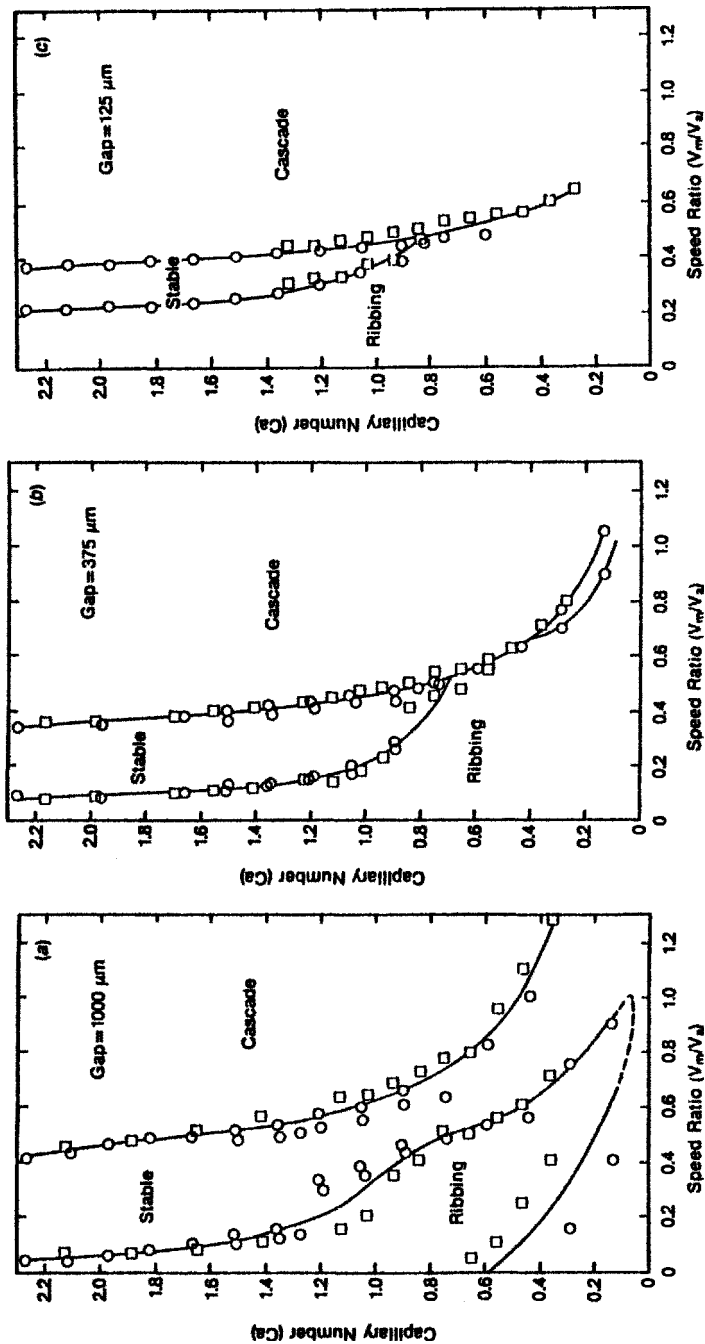


Figure 5-18. Operability diagram for reverse roll coating. The capillary number, $\mu V/\sigma$, is based on the applicator roll speed. $\square$, 200 mPa-s; $\circ$, 400 mPa-s. From D. J. Coyle et al., *AIChE J.* 36 161–74(1990). Reproduced with permission of the American Institute of Chemical Engineers. Copyright © 1990 AIChE. All rights reserved.

GRAVURE COATING

Defects in gravure coating mainly concern pick-out—the transfer of the coating liquid from the gravure cylinder to the web or to the offset roll. The three major problems that can occur are flashing, combined or multiple pick-out, and misting. Flashing occurs when the liquid in one or more grooves or rows of cells only partially transfers, leaving uncoated lines on the web. In combined or multiple pick-out, one or more adjacent grooves or cells are picked out to form a single line or a large combined cell. This large, wide line will not level well. Misting occurs when fine droplets are ejected from the coating nip in high-speed operations.

Misting is often related to *cobwebbing*. The coating liquid forms threads as the gravure cylinder separates from the web. These threads look like cobwebs. Similar thread formations are often seen when painting a wall with latex paint using a roller. It is related to the viscoelastic properties of the coating liquid. Longer polymer molecules (higher molecular weight polymers), as indicated by higher viscosity grades of the polymer, tend to show this when in solution or as a melt. Thus misting is related to the properties of the coating liquid. To a lesser extent, it is also related to the geometry and speed of the process, with higher speeds showing greater misting. When the coating liquid cannot be altered and the system has to be run at high speed, one may have to live with the misting and control it by adequate shielding and controlled air flows and ventilation. Misting should not affect the quality of the coating, although it would reduce the coverage somewhat.

The stability of pick-out depends mainly on the gravure pattern. As discussed earlier, the volume factor—the cell volume per unit area—controls the wet coverage, with perhaps 59% of the cell volume being transferred. The pitch—the number of cells per inch or per centimeter perpendicular to the pattern angle—and the cell design control the pick-out. Pulkrabek and Munter (1983) found that multiple line pick-out occurs when the natural ribbing frequency differs from the cell pitch multiplied by the sine of the helix angle. They worked with a number of knurl rolls and found that when the knurl roll line frequency, equal to the knurl roll pitch times the sine of the helix angle, equals the natural ribbing frequency of the system, then multiple line pick-out does not occur. The severity of multiple line pick-out increases with the degree of mismatch. Figure 5-19 shows the results of their work.

Larkin (1984) recommends the quadrangular pattern for direct gravure, the pyramid pattern (like the quadrangular pattern but with a pointed bottom) for offset gravure, and the trihelical pattern for heavy coatings or for easy flushing and cleaning (see Figure 5-20).

STREAKS AND BANDS IN ROLL COATING

Streaks are long narrow lines of higher or lower coverage, usually running down-web, and bands are similar lines but much, much wider. In those devices using doctor blades, knives, or bars, such as blade or knife coating and gravure coating, particles of dirt caught against the blade, knife, or bar will cause a streak. Such particles should not be present. They should be removed by filtration before the coating solution reaches the coating station. In addition, a small filter should be installed just before the coating station to remove particles that may come from the feed lines. Also, it is advisable to have the coating operation under at least partial clean room conditions, perhaps on the order of class 1000 or at least class 10,000, to reduce the incidence of particles of dirt settling out of the air onto the coating liquid.

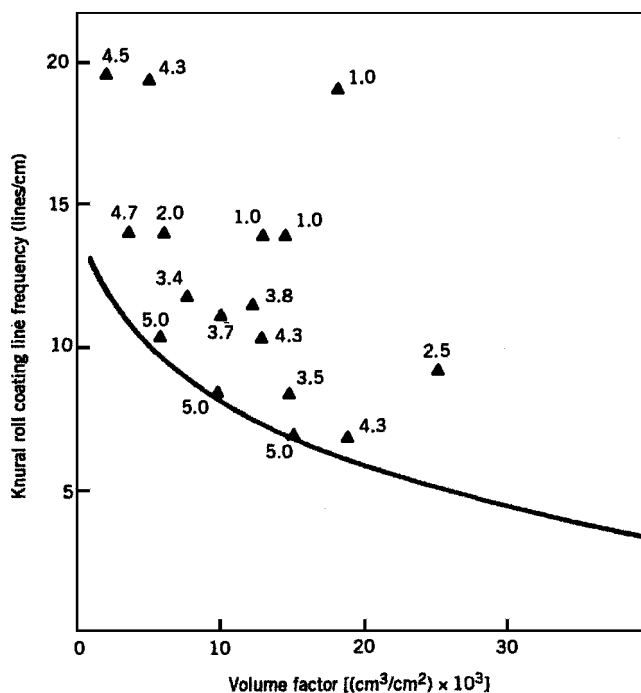


Figure 5-19. Knurl roll line frequency (equal to pitch times the sine of the helix angle) versus volume factor for stable pick-out. The solid line is the natural ribbing frequency. Quality numbers range from 1 (very poor) to 5 (very good), and each number is an average of 12 tests covering the range of coating conditions. Reprinted from *Chem. Eng. Sci.* **38**, W. W. Pulkrabek and J. D. Munter (1983). Knurl Roll Design for Stable Rotogravure Coating, pp. 1309–14. Copyright © 1983, with permission from Elsevier.

Bubbles can sometimes get stuck in a coating device, remaining there to cause streaks. The coating liquid should be thoroughly debubbled before it reaches the coating stand, and precautions should be taken to avoid bubble formation in the lines to the coating stand. Dissolved air can come out of solution to form bubbles where the pressure is low due to high velocities in constrictions, as in valves.

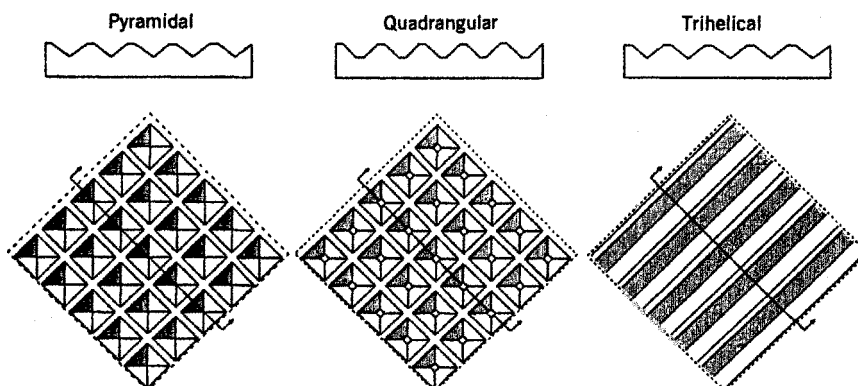


Figure 5-20. Gravure cell patterns. From Coyle (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

Nicks or any unevenness in the blade, knife, or bar will cause a streak or a band. In high-speed blade coating, coating liquid can accumulate on the downstream side of the blade to form column structures or “stalagmites,” and these can cause streaks at those locations.

Unevenness in a roll surface can cause a band. The rolls may be perfectly straight but can deflect under their own weight or under the forces present in the system. When coating or doctoring against unsupported web, any unevenness in web tension can cause bands. Unevenness in web tension is usually caused by poor quality web. Poor quality web can also be puckered, which will cause uneven coverage and perhaps bands. And a puckered web can also cause flow by gravity in the wet coating, resulting in higher coverages in the low spots and lower coverages in the high spots on the web.

CHATTER IN ROLL COATING

Chatter is the appearance of uniform cross-web bars or bands of different coverage. It may ruin the utility of the product, but sometimes it does not affect the usefulness but just ruins the appearance. Chatter in roll coating, as chatter in all coating operations, is usually caused by mechanical problems. Mechanical vibrations from the building, the air handling system, the drives, and so on are sources of chatter. Fluctuation in web speed or roll speed caused by a speed controller or a tension controller is another source. These sources will be discussed further in Chapter 11 on defects related to drives and web handling. In addition, rolls that are out of round and operate at a narrow gap, such as in forward and in reverse roll coating, and in certain knife coating operations, are a possible further source of chatter. Bearings for the shafts supporting the rolls, if they have too high a total indicated runout, will similarly cause chatter.

If all mechanical sources of chatter have been ruled out, then the chatter may be caused by the hydrodynamics of the system. This seems to be more pronounced near the limits of coatability, that is, near the maximum coating speed or the minimum coating thickness. We are unaware of any discussion of chatter in roll coating caused by system hydrodynamics.

SAGGING

The maximum thickness of a coating is often set by the maximum thickness that the web can carry away. This obviously depends on the angle the web makes with the horizontal. A web traveling vertically upward cannot carry away as thick a layer as a horizontal web coated on its upper surface. Also, the maximum thickness increases with web speed and with the viscosity of the liquid, and decreases with increasing surface tension of the liquid. A simple theory for dip coating says that the maximum thickness that a web moving vertically upward can carry away is proportional to the $2/3$ power of the viscosity, to the $2/3$ power of the coating speed, and inversely proportional to the $1/6$ power of the surface tension (Groenvelt, 1970).

When one tries to coat a layer thicker than this maximum thickness, sagging will occur, similar to the sagging we see when painting a vertical surface, such as a door, with too heavy a coat of oil-based enamel. From the discussion above, the cure for sagging is to coat thinner so that all the liquid coated will be carried away, or to carry away a thicker layer by coating faster or using a more viscous coating liquid. Of course, just increasing the coating speed or viscosity in these nonpremetered coating systems will most likely

change the coated thickness, and then adjustments to the geometry or roll speeds would also have to be made.

From the discussion on the thickness of liquid carried away, lowering the surface tension would also have a beneficial effect in reducing sagging, but because the relationship involves only the 1/6 power of surface tension, the effect would be small. Decreasing the surface tension from 40 to 30 dynes/cm (or mN/m) would only increase the thickness carried away by 5%. As we have already seen, for good leveling we want a high surface tension. We do not recommend lowering the surface tension.

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6

PROBLEMS IN SLOT, EXTRUSION, SLIDE, AND CURTAIN COATING

Slot, extrusion, slide, and curtain coating are all premetered coating systems, in that all the material metered to the coating die gets coated onto the web. Thus once we know the web speed, the coating width, and the desired wet coverage, it is a simple matter to calculate the necessary flow rate. This assumes, of course, that all the material gets coated onto the web to give a uniform, smooth coating. This does not always happen, and this chapter addresses some of the problems that can occur. But when a smooth coating is obtained, it should not be difficult to maintain coverage control to within 2% of aim in slot, slide, and curtain coating, both in the machine direction and across the web. In extrusion coating, when the slot opening is adjusted manually and not automatically, and in curtain coating when a weir or a downward-pointing slot die is used, the cross-web uniformity is poorer.

In all coating operations discussed in this book, a wet layer is laid down on the web. The wet coverage is controlled by the coating operation. Unless the coating is solidified by cooling (such as when coating hot melts) or by curing (using radiation with ultraviolet light or an electron beam), the dry coverage is much less than the wet coverage due to evaporation of the solvent. If the dissolved or dispersed solids are uniformly distributed in the coating liquid and if there is no flow of the coating after it is on the web, then the dry coverage will be as uniform as the wet coverage.

DESCRIPTION OF COATING METHODS

In *slot coating* the coating fluid is fed into the manifold of the coating die, where it spreads across the width and flows out of a slot onto the moving web, usually held against a backing roll as illustrated in Figure 6-1. In slot coating, the coating liquid wets both lips of the coating die, although if the die is tilted or the lower lip is swept back only one lip may

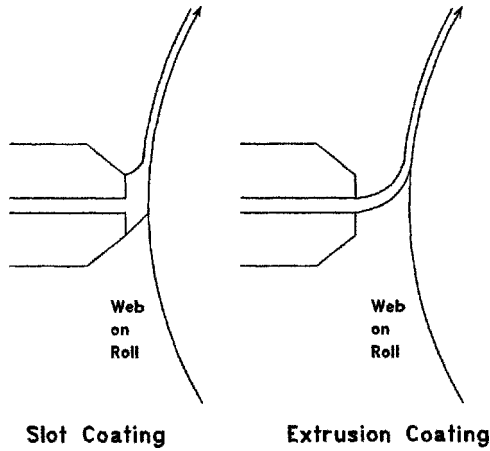


Figure 6-1. Slot coating and extrusion coating.

be wet with the coating liquid. As illustrated in Figure 6-1, we distinguish slot coating from *extrusion coating* in that in extrusion coating the coating liquid exits the slot as a ribbon and does not wet the lips of the die. However, this distinction is not universal, and some engineers use the terms slot coating and extrusion coating interchangeably. For very thin coatings the slot coating die may be used to coat against unsupported web, as in Figure 6-2. The coating die is usually aimed perpendicular to the web, but tilting the die slightly upward so that the flow between the lip and the web is slightly converging (Figure 6-3) is beneficial in thin coatings. In slot coating, the coating lips are usually in one plane, that is, one directly above the other. However, at times it is advantageous to have

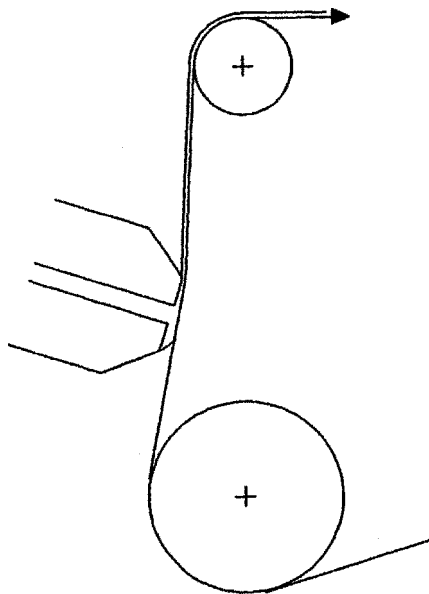


Figure 6-2. Slot coating on unsupported web.

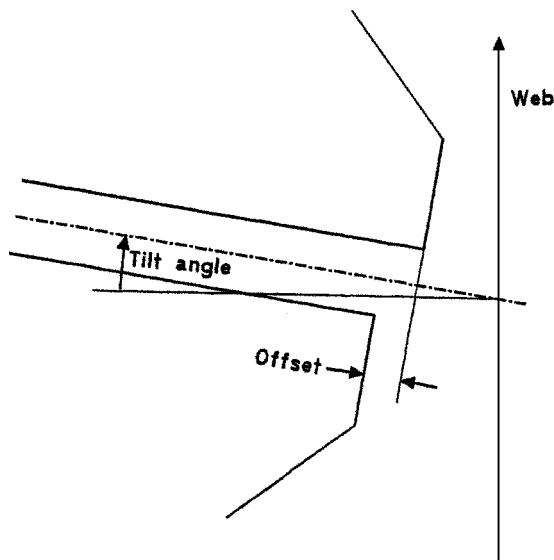


Figure 6-3. Tilt and offset in slot coating.

overbite (or offset); that is, the upper or downstream lip protrudes beyond the lower or upstream lip, as indicated in Figure 6-3. Tilt and offset (or overbite) are mainly beneficial for very thin coatings, when even with the use of bead vacuum, indicated schematically in Figure 6-4, thin enough coatings cannot be made with the standard configuration. Bead vacuums of up to 1000 Pa (4 inches of water) and even higher are often used to increase the window of coatability, that is, to allow thinner coatings to be made or to permit use of higher coating speeds.

The upper edge of the upper coating lip, where the upper meniscus is pinned, and the lower edge of the lower coating lip, where the lower meniscus is pinned, should be sharp. If it is not sharp the meniscus may not pin at any one location but may wander back and

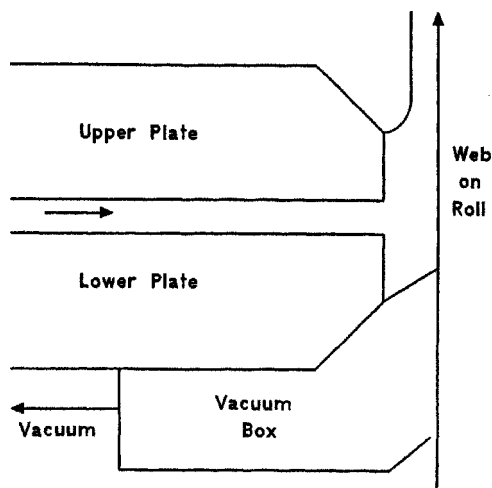


Figure 6-4. Slot coating with bead vacuum.

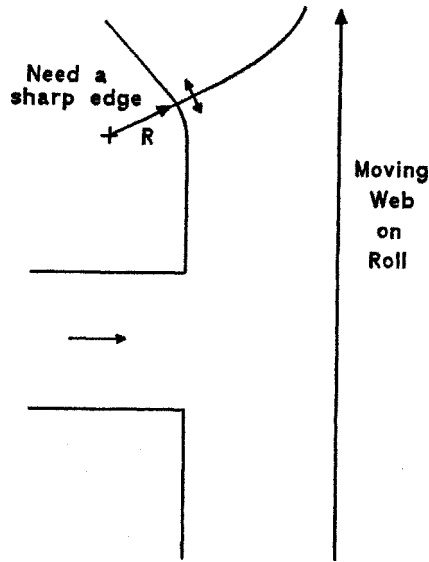


Figure 6-5. A sharp edge is needed to pin the meniscus.

forth over the curved edge, as indicated in Figure 6-5. At wider gaps this will lead to chatter. Any edge where a meniscus is pinned should be sharp. But these edges should not be too sharp, for sharp edges are easily damaged to form nicks that can cause streaks. Also, operators can easily cut themselves when handling dies with sharp edges. It is suggested that the radius of curvature where a meniscus is pinned should be $50\text{ }\mu\text{m}$ (2 mils) (Fahrni and Zimmerman, 1978), but even twice that may still be satisfactory. The radius of curvature of an edge can be measured by molding the edge with dental molding compound, cutting out a thin section with a razor blade, and making a photomicrograph of the corner of the mold at low magnification, $50\text{--}200\times$. If the magnification is not known it can be measured by including a millimeter scale in the photomicrograph. The radius of curvature of the photo can then be read by eye using a millimeter scale and dividing by the magnification. By this technique one can easily measure the radius of curvature to within 5 or $10\text{ }\mu\text{m}$ (0.25 or 0.5 mil).

3M has patented a fairly complex slot die, shown in Figure 6-6, that incorporates both tilt and overbite, has a rigid arrangement for bead vacuum, and uses an upper (downstream) plate that does not have a flat lip but is wedge-shaped with a very sharp edge (Brown and Maier, 1995). Gates (1999) confirms that a knife edge may be best for the downstream lip and found that short lips are better than larger ones. Both the lower lip and the lip of the vacuum system are machined to the same radius as the backup roll and then tilted very slightly. In the figure the angle of tilt is called the convergence.

As mentioned earlier, *slot coating against unsupported web*, also known as *slot coating against tensioned web*, *free span coating*, or *off-the-roll coating* (Figure 6-2), is a technique used for very thin coatings, under about 300 or $400\text{ }\mu\text{m}$ (10 or 15 mil) wet thickness. It is easy to show that in slot coating the coating gap is roughly proportional to the wet thickness. As we will see later in the section on *Limits of Coatability*, Lee et al. (1992) showed that in many cases the minimum wet thickness is $2/3$ of the gap, meaning the gap is 1.5 times the minimum wet thickness. Apparently this does not apply to the 3M

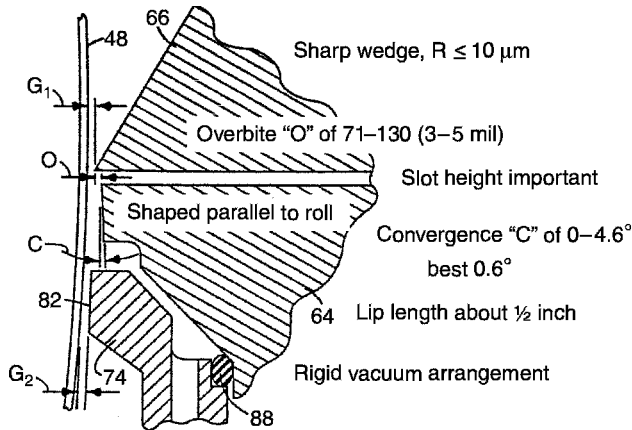


Figure 6-6. A slot coating die patented by 3M. From Brown and Maier (1995).

die shown in Figure 6-6, which, it is claimed, can coat much thinner layers at much wider gaps. But for standard die designs, it means that for very thin coatings the gap has to be very tight. However, a very tight gap, much under $75\text{--}100\text{ }\mu\text{m}$ (3–4 mil) is very difficult to maintain, and if for any reason it goes to zero then the die would cut the web. Operators do not like this. The wet web would make a mess as it is pulled through the dryer. The system would then have to be thoroughly cleaned before production can resume.

Also, for very tight gaps, the run-out of the bearings (TIR, or total indicated run-out) on the backing roll can become a significant fraction of the gap. This would mean the volume of the coating bead would fluctuate with every revolution of the backing roll, causing coverage variations and chatter marks in the coating with every revolution.

For both these reasons, it is advantageous to investigate coating against unsupported web for very thin coatings. Lee and Scriven (2002) showed in Figure 6-7 that coatings as

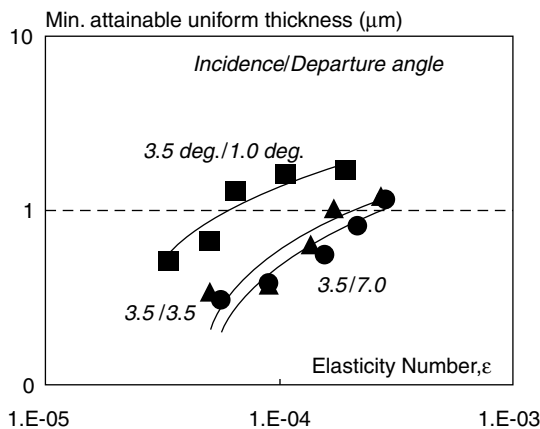


Figure 6-7. In slot coating against unsupported web, wet thicknesses of $1\text{ }\mu\text{m}$ and under can be attained. From H. Lee and L. E. Scriven (2002), Tensioned web slot coating, *Extended Abstracts of the 11th Internatl. Coating Sci. and Techn. Symposium*, Sept. 23–25, 2002, Minneapolis, pp. 164, with permission of the authors.

thin as $1\text{ }\mu\text{m}$ wet or even thinner can be made by this technique, and we had also found this. Lee and Scriven (2002) also found that the entrance and exit angles made by the web are very important. The web tension is very important, for the x -axis in Figure 6-7 is an elasticity number that is inversely proportional to the web tension. Lee and Scriven (2002) define the elasticity number, ε , as the viscosity times the web speed divided by the web tension, all multiplied by six. The angles can be controlled by the tilt and the penetration of the die into the web path and should not be controlled independently. It is easy to show that the force of the web against the coating die is approximately proportional to the penetration of the die into the web path times the web tension.

Our suggested experimental approach to optimize conditions in coating against unsupported web on a pilot or on a production machine, for a given system, coverage, and speed, is to (1) try three overbites, say, 0, 25, and $50\text{ }\mu\text{m}$; (2) at each overbite try three tilt angles, say, 0° , 1° , and 3° ; (3) at each tilt angle try 5–10 web tensions going from low to high; (4) at each condition the penetration of the die into the web path should not be prescribed as a controlled variable, but the operator should move the die in and out of the web path to get the best coating by visual appearance. The machine is then stopped and a sample taken. All the experimental data can be gathered in half a day. The optimum conditions are then found by visual examination of the samples.

We have found in one case that the tilt of the die, as shown in Figure 6-3, should be on the order of 1° , and the overbite should be on the order of $25\text{ }\mu\text{m}$ (1 mil), and the web tension should be relatively high. In the patented 3M die in Figure 6-6, a tilt of 0.6° is suggested, with an overbite of $71\text{--}130\text{ }\mu\text{m}$ (3–5 mil).

Multilayer slot coating may be used to coat two or more layers simultaneously, as illustrated in Figure 6-8. The several slots may come together internally, as in Figure 6-8a,

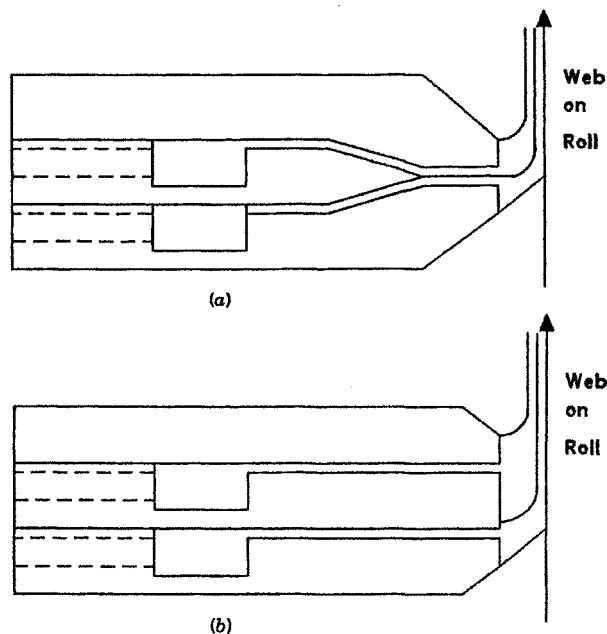


Figure 6-8. Two-layer slot coaters: (a) with a multiple manifold and one exit and (b) with multiple slots.

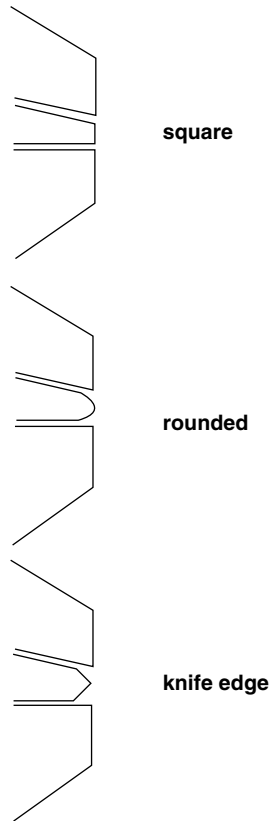


Figure 6-9. The preferred shape of the central section in a two-layer slot coating die is rounded, according to Taylor and Hrymak (1999).

or they may form a single layer in the coating bead, as in Figure 6-8*b*. Joining the layers in the bead as in Figure 6-8*b* is always used, as joining the layers internally is likely to cause instabilities unless the several layer viscosities are very close.

The shape of the lip of the middle plate affects the stability of flow. Taylor and Hrymak (1999) showed that a rounded middle plate, as shown in Figure 6.9, is most stable and causes the fewest flow oscillations.

For multilayer slot coating, many shapes of dies have been proposed. One of the many that were patented for coating thin magnetic layers against unsupported web is shown in Figure 6-10.

Extrusion coating is similar to slot coating and is sometimes not distinguished from it. In extrusion coating, the coating fluids are of much higher viscosity, often a polymer melt, and the stream exiting the slot does not spread against the lips of the die but remains as a ribbon between the die and the web, as mentioned earlier and shown in Figure 6-1. Because of the high viscosities, the pressures within the extrusion die may be very high. The extruded material is often molten plastic fed by a screw feeder, and temperature control is important. To obtain a uniform coating, bolts are positioned every few inches across the slot width to adjust the slot opening or an internal choker bar. These adjusting bolts are sometimes under computer control, based on a scanning sensor that measures the cross-web coverage.

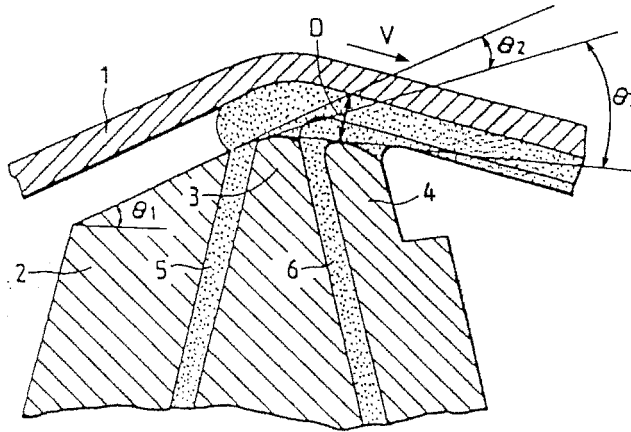


Figure 6-10. One of many patented two-layer slot coating dies. This is for coating against unsupported web. From Chino, N., N. Shibata, and H. Cai Kamas (1991). Process for producing multi-layered magnetic recording media, (to Fuji), US Pat. 5,069,934 Dec. 3.

Because of the high pressures, the adjusting bolts, and the temperature control, these extrusion dies tend to be both complex and massive, as illustrated in Figure 6-11.

Multilayer extrusion or *coextrusion* is a very common technique for obtaining the barrier or the surface properties of an expensive polymer while still having a thick enough combined layer for coating or for mechanical strength, or for obtaining the desirable properties of several polymers in one multilayer coating. Several exit slots can be used in a multiple slot die, as in Figure 6-8b. However, the layers can also be joined together externally in a combining adapter or feed block, as in Figure 6-12, before entering a standard single-layer extrusion die. The layers still remain separate and distinct in this system. The only change in the die is that the entry port may be rectangular and not round. This is the simplest and most commonly used system.

With the combining adapter, when the layers have similar rheologies, each layer will be of uniform thickness across the full width of the extrusion die. When the layers differ in viscosity, the lower-viscosity layer will tend to be thicker toward the edges while the higher-viscosity layer will be thicker in the center. Mainstone (1984) states that viscosity ratios of 3 or even more between layers will still give commercially acceptable thickness

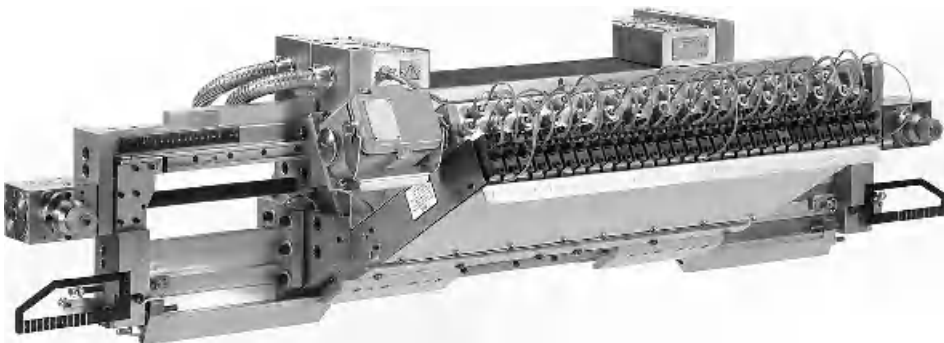


Figure 6-11. 28-in. AutoFlex VI-R H40 CL EPC extrusion die. [Courtesy of Extrusion Dies, Inc., Chippewa Falls, WI 54729].

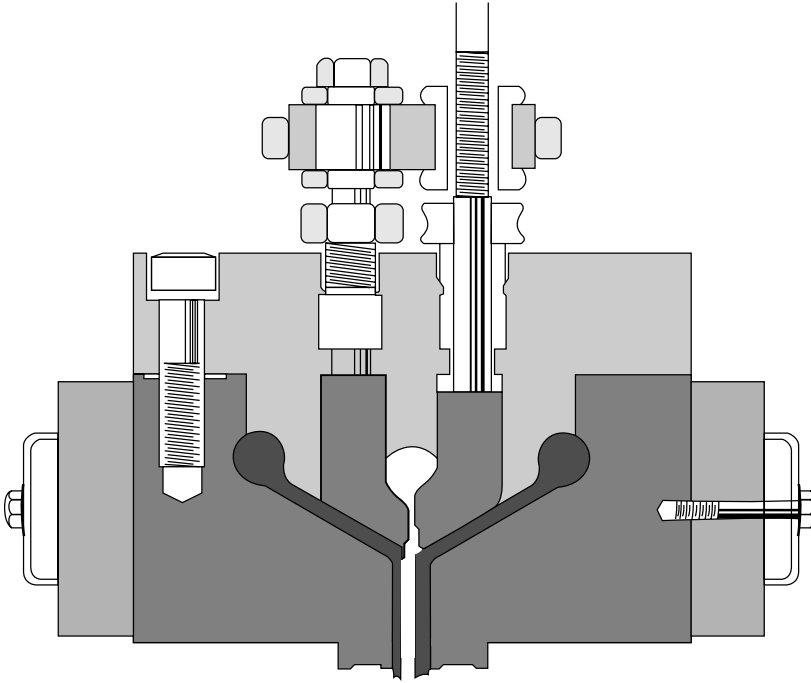


Figure 6-12. Combining adapter for three-layer coextrusion, for feeding into a single-layer extrusion die. From K. A. Mainstone (1984). Extrusion, Chapt. 8 in *Web Processing and Converting Technology and Equipment*, D. Satas, ed., Van Nostrand Rheinhold, New York, 1984, with permission of Saule Satas.

uniformity of the individual layers. The adjusting bolts are used to ensure that the total package is of uniform thickness.

In *slide coating* (Figure 6-13), multiple streams exit onto an inclined plane, flow down the plane without mixing, across a gap, and onto an upward moving web. The streams

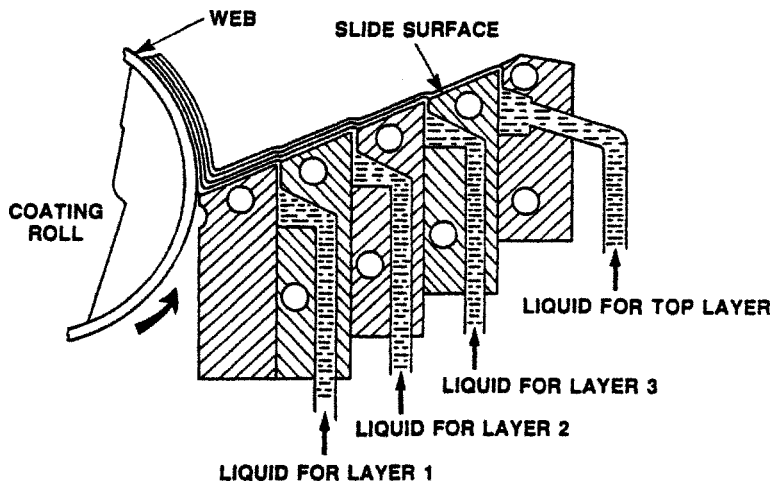


Figure 6-13. Slide coating. After Mercier et al. (1956).

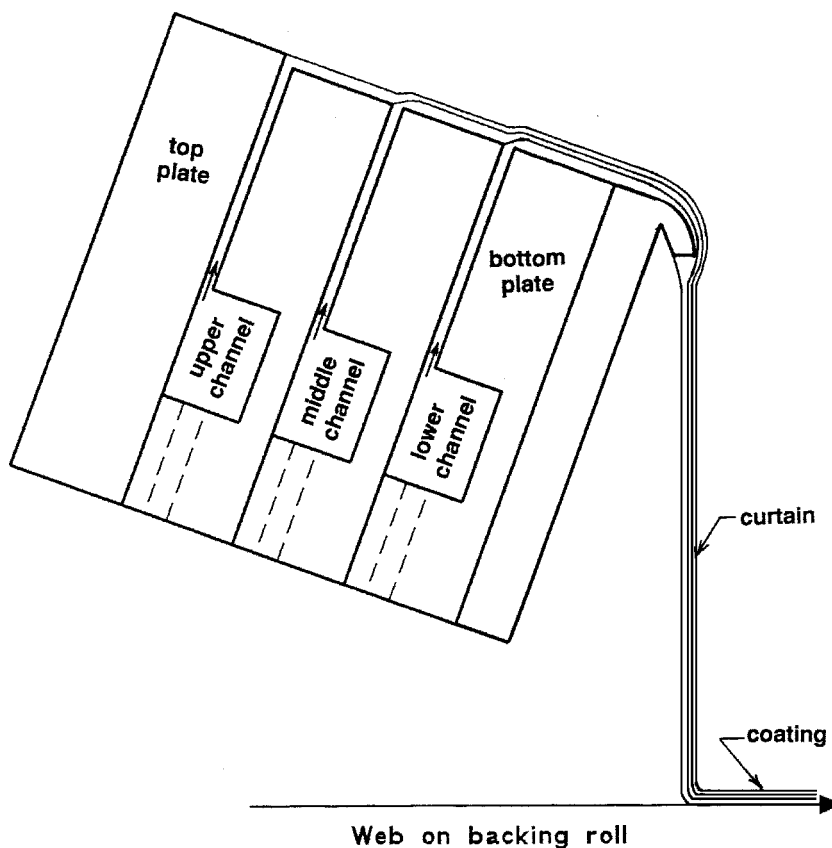


Figure 6-14. Curtain coating.

remain separate and distinct from the moment they emerge onto the slide, cross the gap, get coated on the web, and are dried in the final coating. Dies now are commonly made with rectangular plates, as shown in Figure 6-14 for a slide coater transformed into a curtain coater. Slide and curtain coating are commonly used in coating photographic films and papers, which, for color products, contain at least nine distinct layers. The wet edge of the bottom plate in slide coating should be sharp to pin the bottom meniscus, as in slot coating. Also as in slot coating, a bead vacuum is often used to extend the window of coatability.

Curtain coating is an old technique that has long been used in the converting industry for coating sheets of paperboard, with the sheet passing through a falling curtain of fluid. The curtain was often formed by liquid flowing over a weir, or by an extrusion die aimed downward. In recent years curtain coating has been used as a precision coating technique for multilayer photographic products, with the fluid flowing off the rounded edge of a slide coater and falling vertically downward onto a horizontally moving web, as in Figure 6-14. To keep the coating from necking-in, edge guides need to be used (Greiller, 1972). These can be metal or plastic rods going from the coating die to the base. The bottom of the rods can be bent and can ride on the web. The bent ends can be pointed slightly outward to spread out the edges to avoid heavy edges. The flow remains laminar at all times, and in multilayer coating the individual layers retain their identity.

Curtain coating has two significant advantages over slide coating:

1. In curtain coating, the gap is the height of the curtain and thus is very wide, allowing splices to pass without withdrawing the coating die, as sometimes must be done in slide coating.
2. In slide coating, a bubble may stay in the coating bead, floating on the surface and causing a continuous streak; while in curtain coating, a bubble would flow off the slide, down the curtain, and onto the web to give a point defect. Point defects are much less objectionable than streaks.

The rear lower edge of the curtain coating die, where the rear meniscus from the bottom layer is pinned, should have a sharp edge, just as in slot and slide coating. As before, by a sharp edge we mean one with a radius of curvature of about 50 μm (2 mil), and certainly not over 100 μm (4 mil).

In discussing the problems related to premetered coating, we first concern ourselves with the limits of coatability—that is, the limiting conditions under which coatings can still be made—and then discuss the problems that can arise when coatings are made within these limits of coatability.

LIMITS OF COATABILITY

When one coats too slowly or tries to apply too heavy a coverage on a web that is moving upward, the wet layer may run back. The web cannot carry away all of the wet liquid layer and *sagging* occurs. The appearance is similar to sagging on a door painted with too thick a coat of an oil-based enamel. The sag lines can be far apart, as on the painted door, or very close together. If sagging occurs, the cure is simple: either coat faster, coat a higher viscosity liquid, or make the web path more horizontal. All of these will allow the web to carry off more liquid. Runback or sagging occurs at the high-flow, or low-speed, limit of coatability and is rarely a problem.

On the other hand, if we are making a good coating and then try to coat faster at the same coverage, we sometimes find that we cannot do so because the coating will no longer spread uniformly across the web. And if we are making a good coating and then try to coat thinner, we sometimes find that we cannot do so for the same reason. Both of these limits are often one and the same and are called the low-flow or high-speed limits of coatability.

The Window of Coatability

The low-flow and high-flow limits of coatability lead to a window of coatability within which one can coat the desired product. Determining this window of coatability is a useful and practical technique for optimizing the coating formulation and the coating process. We recommend that the window of coatability be determined for all new products, or at least the portions of it relevant to the product. Thus if operations are near the low-flow limit, it may not be worthwhile determining the high-flow limits, and vice versa. The extent of the coatability window can be used to aid in determining the best of several alternate formulations. It can also be used in problem solving for production problems.

The coatability window can be found on the production coater or, preferably, on a pilot coater if it can coat at the production speeds and has been shown to duplicate production

conditions. While it is preferable to examine the dried coating for defects, the coatability can be determined just by looking at the coating as it leaves the coating stand while wet with no drying. A narrow pilot coater with no drying capability but able to cover the full speed range of the production machine is ideal for this purpose. Most of the coating can be doctored (squeegeed) off the web before it is wound up wet, reducing the mess at the windup.

In the case of a slide coater, there are several different types of data that can be obtained to generate the window of coatability. Ideally, the maximum and minimum wet coverages would be determined over a wide range of coating speeds, coating gaps, and bead vacuums. Practically, the following measurements are desirable:

- The maximum and/or minimum wet coverages over a range of coating speeds at several coating gaps and at several levels of bead vacuum, including no vacuum
- The range of bead vacuum that can be used to stabilize the coating bead at the desired wet coverage over a range of coating speeds and at several coating gaps
- The range of bead vacuum that can be used to stabilize the coating bead over a range of coating gaps at the desired wet coverage and coating speed

When a series of data points are obtained, repetition is not necessary; but if only a few points are obtained, then repeat measurements should be made. It is also useful to vary the direction in approaching a coatability limit, such as first increasing the speed, and then decreasing it.

It is desirable to operate near the center of the coatability window, as the operation tends to be more stable and defects are more likely to occur near the boundaries.

Making measurements on the production coater is expensive and imposes limits on the conditions that can be run. Coatings often cannot be run as fast as needed to determine the high-speed limits, and in pilot lines the dryers often cannot dry high-speed coatings. It is necessary to ensure that wet coatings do not contaminate face rolls in the dryer and in the windup, and, except in the pilot machine without a dryer (mentioned above), that wet coatings do not reach the windup. One can always run the dryer as hot as possible, but this still may not be enough to dry high-speed coatings. In this case, one should coat just a short section, then stop the coating machine and let the coated section dry in place.

When the low-flow or high-speed limits of coatability are exceeded, in slide coating one of several conditions can occur (Guttoff, 1992):

1. The coating bead completely breaks down and the coating liquid cannot get across the gap to the web.
2. Ribs are formed and, at still higher speeds, the spaces between the ribs become dry lanes and the ribs become rivulets.
3. Air is entrained in the coating to appear as bubbles in the coating.
4. Dry patches where air is entrained are interspersed with the coated areas. This has been noted with more viscous liquids.
5. One or both of the edges neck in. The neck-in can be considerable, a matter of centimeters or inches, and the remaining coating is then thicker.

We will now examine the low-flow limits of coatability for slide and for slot coating, and both the low- and high-flow limits for curtain coating.

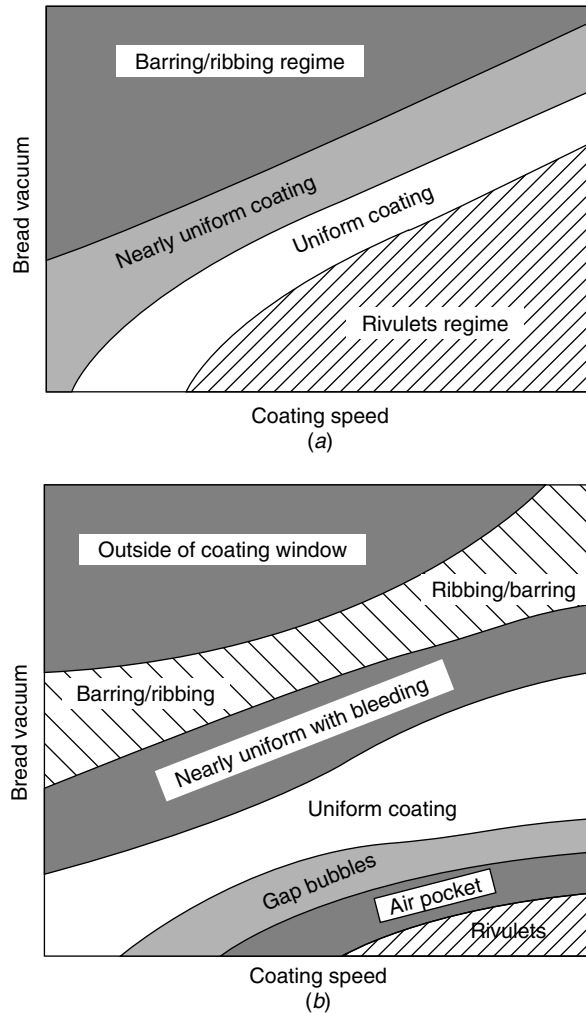


Figure 6-15. Operating diagrams in slide coating: (a) with glycerin water and (b) with an aqueous cellulosic polymer. The high-speed limit is not shown. From Chen (1992), with permission of the author.

Slide Coating

The window of coatability in slide coating can be shown in a plot of bead vacuum versus coating speed for a given coverage of a particular solution, as has been done by Chen (1992); see Figure 6-15. There is an upper coating speed above which air entrainment occurs and this is not shown, but we know it occurs in every type of coating. The regions in which various defects occur are shown. Many of these defects will be discussed later in this chapter. *Barring* is another term for chatter. *Gap bubbles* refer to entrained air, and *air pockets* refer to bubbles covering a larger area. *Rivulets* occur when the coating consists of narrow stripes of coating running down-web, separated by dry lanes. Chen (1992) found that, with the formulations he used, at too low a vacuum a good coating could not be made except at low speed, as air entrainment or rivulets would occur.

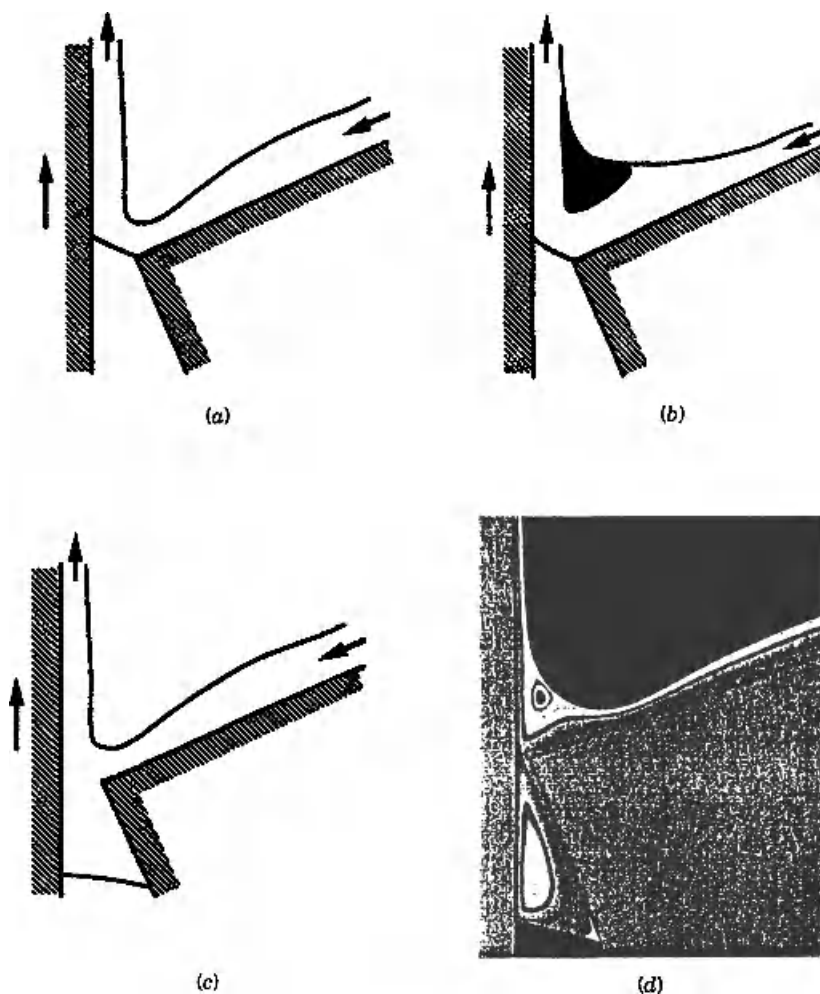


Figure 6-16. Bead profiles in slide coating: (a) the desirable condition, (b) with an upper vortex, (c) with die-face wetting, and (d) with an upper vortex, die-face wetting, and a lower vortex. From Chen (1992), with permission of the author.

On the other hand, at too high a bead vacuum ribbing or chatter would occur, and at still higher vacuums a coating could not be made. In Figure 6-15b, in the region marked *uniform coating*, there still was an oscillating cross-web wave that seemed to originate on the slide, and so in this case no completely satisfactory coating could be made. Waves are discussed later in this chapter.

Vortices and Eddies Vortices and eddies can form within the coating bead in slide coating. The bead profile in a good coating would appear as in Figure 6-16a. Vortex formation should be avoided, as the liquid in a vortex can remain for long periods to degrade with time and cause coating defects as the material slowly leaves the vortex. When the bead is too thick, perhaps because the coating speed is too low for this coverage, a vortex can form in the bead, as indicated in Figure 6-16b. When the bead vacuum is too high, the bead can be sucked below the edge of the die lip, as in Figure 6-16c. A

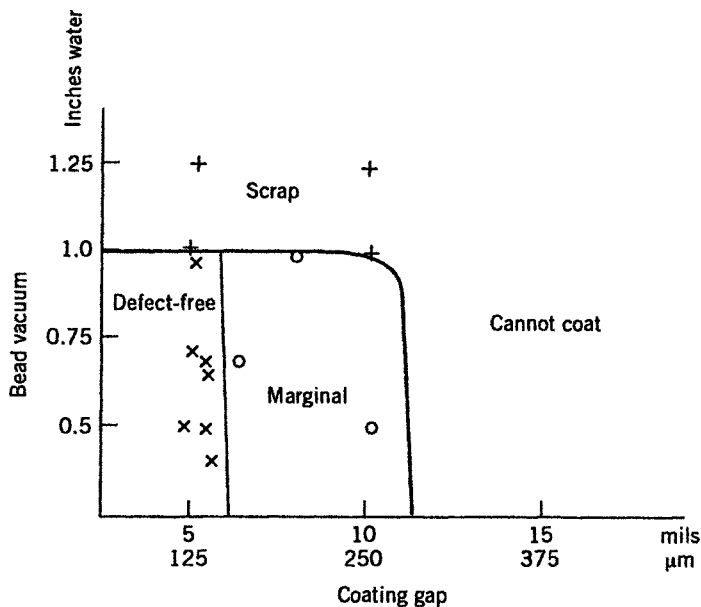


Figure 6-17. Operating window for a particular slide coating in terms of bead vacuum and coating gap.

vortex can also form in this region. Figure 6-16*d* is a computer-generated profile showing both vortices.

It is sometimes useful to look at the window of coatability in another manner. As it is often desired to coat a given coating solution to a given coating coverage at a fixed coating speed (often the maximum coating speed that the dryer can handle), a diagram of bead vacuum versus coating gap—the two controllable variables—showing the regions of operability at a given coverage and speed can be very useful to the coating operator. Such a diagram for a particular set of conditions is shown in Figure 6-17.

In slide coating the minimum wet thickness increases with coating speed, as shown in Figure 6-18. Above some maximum speed, a coating cannot be made, no matter how thick the layer. Bead vacuum lowers the minimum thickness at any speed and increases the maximum coating speed, perhaps by about 25%. The increase appears small on this plot. The data for a bead vacuum of 500 Pa (2 in. water) is not shown on this graph as it falls almost on top of the data for a bead vacuum of 1000 Pa (4 in. water). Gap has a slight effect. In Figure 6-18, tighter gaps allow slightly thinner coatings, but gap does not affect the maximum coating speed. With some other liquids, gap has an opposite effect; that is, at a wider gap one is able to coat thinner, but in almost all cases the gap effect is small. Note that with the bead vacuum of 1000 Pa (4 in. water) there is very little data at the wide gap of 300 μm . At wide gaps only a low bead vacuum can be used; otherwise the vacuum will suck the bead down. The lines of best fit for similar data for a number of simple liquids with no bead vacuum are shown in Figure 6-19, where it is seen that as the viscosity increases the minimum coating thickness increases and the maximum coating speed decreases. With a bead vacuum of 1000 Pa (4 in. water) (Figure 6-20), the minimum coating thickness decreases considerably and the maximum coating speed increases slightly. This is why bead vacuum is usually used. The increase in maximum coating speed is about 25%, which hardly shows up on these log plots.

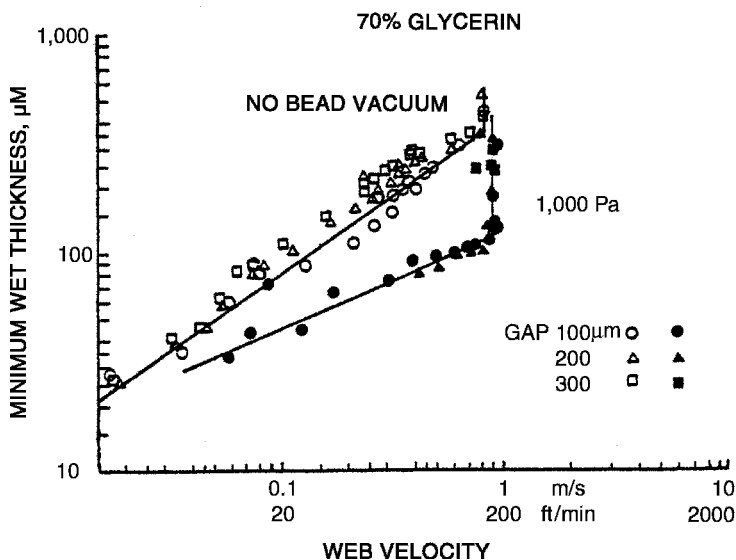


Figure 6-18. Minimum wet thickness in slide coating versus web velocity, for 70% glycerin. Reproduced from E. B. Gutoff and C. E. Kendrick, *AIChE Journal* **33**, 141–145 (1987), with permission of the American Institute of Chemical Engineers. Copyright © 1987 AIChE. All rights reserved.

Polymer solutions are easier to coat, in that one can coat thinner layers and at higher speeds than simple, Newtonian liquids, as shown in Figure 6-21. Here we see that a polyvinyl alcohol solution can be coated at about an order of magnitude ($10\times$) faster than a glycerin solution of the same viscosity.

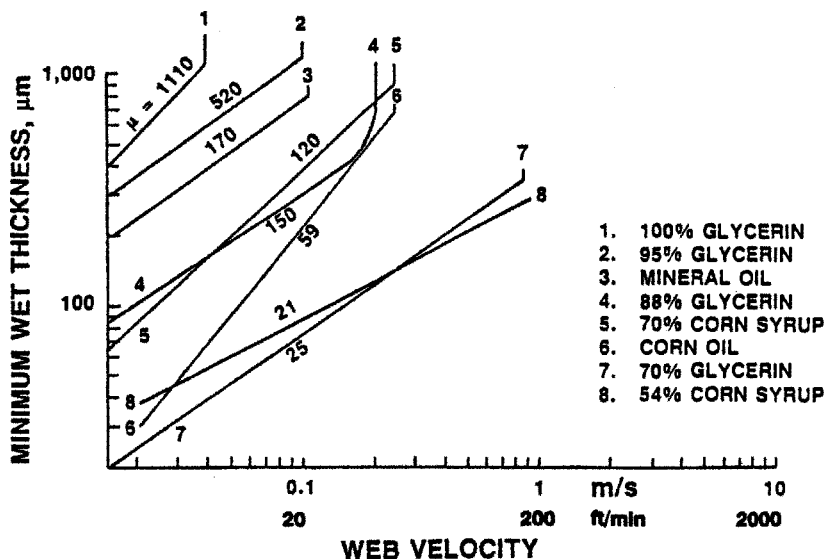


Figure 6-19. Minimum wet thickness in slide coating versus web velocity for a number of liquids. No bead vacuum was used. Reproduced from E. B. Gutoff and C. E. Kendrick, *AIChE Journal* **33**, 141–145 (1987), with permission of the American Institute of Chemical Engineers. Copyright © 1987 AIChE. All rights reserved.

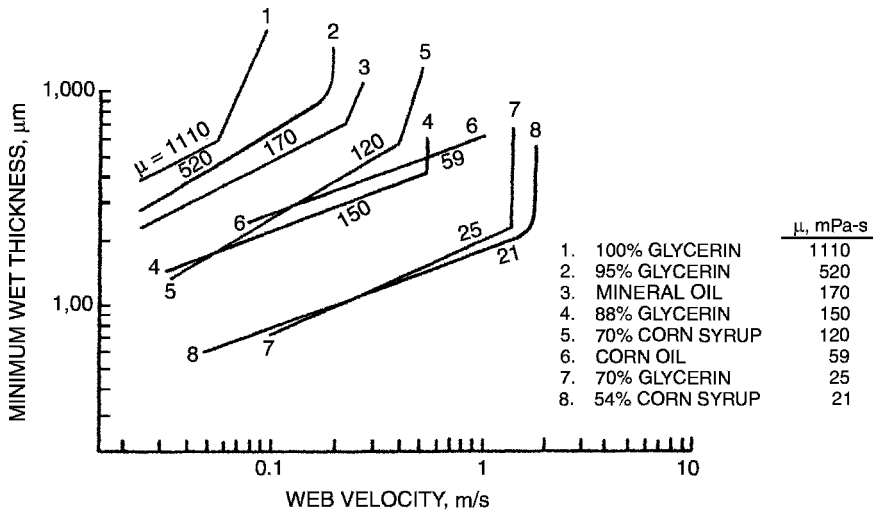


Figure 6-20. Minimum wet thickness in slide coating versus web velocity for a number of liquids, with a bead vacuum of 1000 Pa (4 in. of water). Reproduced from E. B. Gutoff and C. E. Kendrick, *AIChE Journal* 33, 141–145 (1987), with permission of the American Institute of Chemical Engineers. Copyright © 1987 AIChE. All rights reserved.

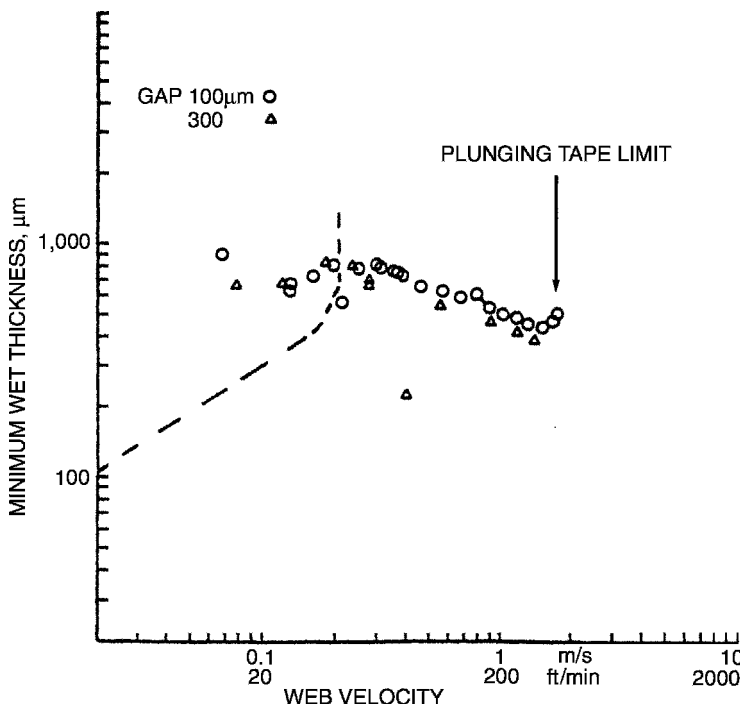


Figure 6-21. Minimum wet thickness versus web velocity for slide coating a polyvinyl alcohol solution. The viscosity is 146 mPa-s (146 cP), and no bead vacuum was used. The dashed curve is for a glycerin solution of the same viscosity from Figure 6-16. Reproduced from E. B. Gutoff and C. E. Kendrick, *AIChE Journal* 33, 141–145 (1987), with permission of the American Institute of Chemical Engineers. Copyright © 1987 AIChE. All rights reserved.

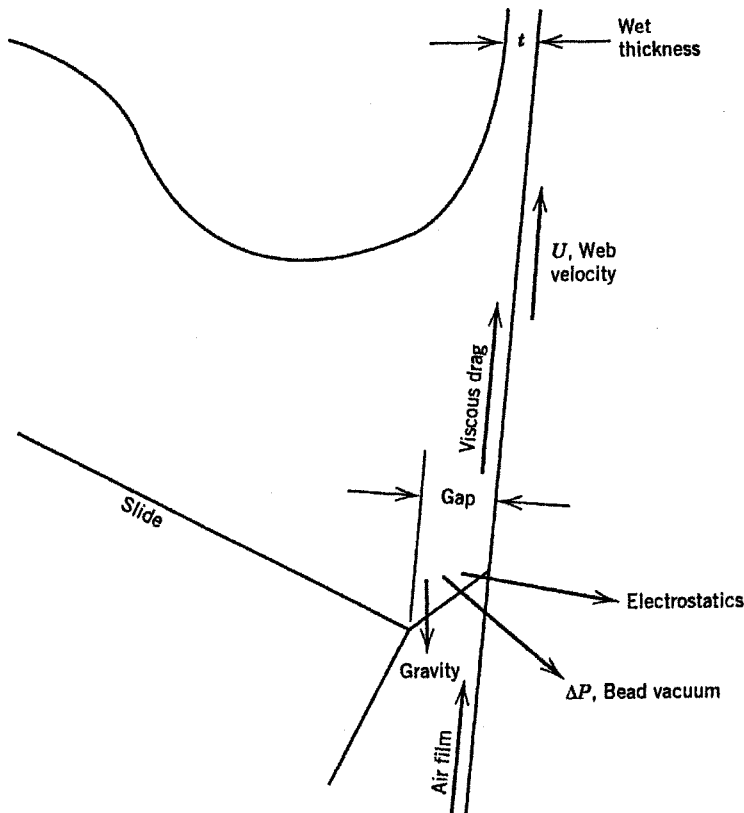


Figure 6-22. Slide coating bead, showing some of the forces acting on it. From Gutoff (1992), Reprinted from *Modern Drying and Coating Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

It is not difficult to give a qualitative explanation for all these effects (Gutoff, 1992). Let us look at the forces involved in the slide coating bead, as sketched in Figure 6-22. There are stabilizing forces, which tend to hold the bead against the web, and destabilizing forces, which tend to tear the bead apart.

The stabilizing forces are:

- *Bead vacuum.* The force per unit width is the bead vacuum times the length of the bead; thus at wider gaps less vacuum should be, and is, needed. The bead vacuum tends to push the bead against the web, and so is stabilizing.
- *Electrostatic forces.* If the backing roll is charged and the coating die is grounded, or if the web has a uniform static charge, then the coating fluid will be attracted to the web. Electrostatic assist is not commonly used. Although in cases there is evidence that it may be slightly better than bead vacuum, in most cases it appears at best to be about as good as bead vacuum, and in combination with bead vacuum is often no better than bead vacuum alone.
- *Gravity.* Gravity acts downward and so tends to keep the liquid from being pulled out from the bead. But in these thin layers, the gravitational force is very weak and has no significant effect on the system.

- *Fluid inertia.* The momentum of the fluid flowing down the slide tends to force the bead against the web, but this force, like gravity, is very weak and usually can be neglected. The destabilizing forces are:
- *Shear stress in the liquid.* This arises from the motion of the web. The web tends to pull the fluid along with it. This shear stress is proportional to the fluid viscosity times the shear rate. The shear rate is the rate of change of velocity with distance in the direction perpendicular to the direction of motion, that is, perpendicular to the surface. As a first approximation, we may take the shear rate as the web speed divided by the bead thickness, which we can say is approximately equal to the gap. Thus the shear stress is approximately equal to the viscosity times the web speed divided by the gap. It pulls the liquid along and shows up as a tensile stress in the bead, trying to pull the liquid apart.
- *Air film momentum.* The web carries along with it a very thin film of air, which has to be removed for the liquid to wet the web. This air pushes against the bead and tends to push the bead away from the web. Thus it is a destabilizing force.
- *Centrifugal force of the rotating backing roll.* This tends to throw the coating fluid off the web, but like gravity and fluid inertia, it is a very weak force.

Thus the strong destabilizing forces of the shear stress and the air film momentum act to tear the coating bead apart. If no bead vacuum or electrostatic assist are used, the remaining stabilizing forces of gravity and fluid inertia are too weak to have any appreciable effect. Then what resists the destabilizing forces? It is only the inherent properties of the coating fluid itself that can resist the destabilizing forces. It is the cohesive strength of the liquid or, if you will, the elongational viscosity of the liquid that allows a liquid in motion to sustain a tensile stress.

Now everyone knows that liquids cannot be in tension—at rest. But less well known is that liquids in motion *can* be in tension. If we dip a finger in a jar of honey and then lift our finger up, some honey will tag along. The strand of honey between the jar and the finger is in tension. If we hold the finger still, much of the honey will drop back into the jar.

The tensile stress that a liquid can sustain is equal to the elongational viscosity times the extension rate, which is the rate of change of velocity with distance in the direction of motion. Thus it is a measure of how fast the liquid is being stretched. The elongational viscosity of simple fluids is three times their normal viscosity. Thus honey, which is a thick or viscous Newtonian fluid, will sustain a greater tensile stress than water.

Polymer solutions, by their very nature, tend to have high elongational viscosities at high elongation rates. When a polymer solution is pulled slowly, the polymer molecules just slide past one another and its elongational viscosity is just about what it would be for a simple liquid of the same viscosity. But when a polymer solution is pulled quickly, the molecules do not have time to “relax,” and they remain entangled and hard to pull apart. The elongational viscosity goes way up and the solution can sustain high tensile stresses. This would occur with all polymer solutions at the high pull or elongation rates that exist in the coating bead. This is why the polyvinyl alcohol solution can be coated about ten times faster than the glycerin solution of the same viscosity, as we saw in Figure 6-21. With some polymer solutions, such as polyacrylamide, this ability to withstand tensile stresses can be demonstrated at the relatively low pull rates that exist in a tubeless syphon, shown in Figure 6-23. The vacuum tube is dipped into the polymer solution and is then pulled up above the surface, and the liquid continues to be sucked up.

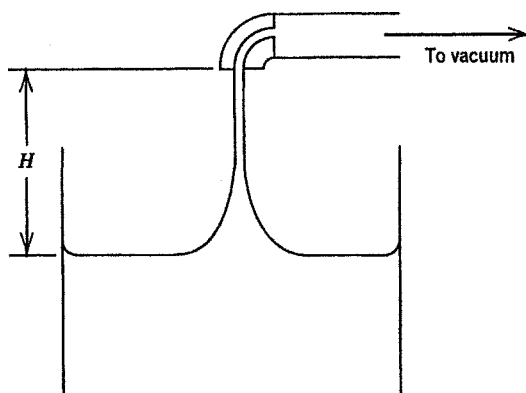


Figure 6-23. The tubeless syphon with a polymer solution such as polyacrylamide in water.

Polymer solutions also coat better than simple liquids because their viscosity tends to decrease at high shear rates. Imagine a polymer solution in a beaker, and imagine that we are stirring the beaker with a paddle. When we stir at a very slow rate, such that the polymer molecules remain undisturbed and retain their normal shape of a random coil—a sphere—then at a slightly higher stirring rate the shape remains unchanged and the resistance of these coils to flow remains unchanged, and the viscosity will not change. This is called the zero shear viscosity. But as the stirring rate increases, the spherical coils will become elongated—football shaped—and their smaller cross section in the direction of flow will present less resistance to flow. The viscosity will then drop, as sketched in Figure 6-24. At a sufficiently high stirring rate, the polymer molecules will be stretched as much as they can be, and further increases in stirring will not reduce the resistance to flow. Thus the viscosity will again be constant. This is called the infinite shear viscosity. In many cases, on a double log plot, as in Figure 6-24, there will be a straight-line region where the viscosity decreases with shear. This is called the power law region, and the fluid would be called a power law fluid. The mathematics of power law fluids are relatively simple. However, with modern computers that can numerically handle any type of shear thinning liquid, power law fluids are of less interest.

When we coat a fluid at its minimum thickness and try to coat faster, we cannot get a good coating. As we increase the coating speed the shear stress, very approximately the

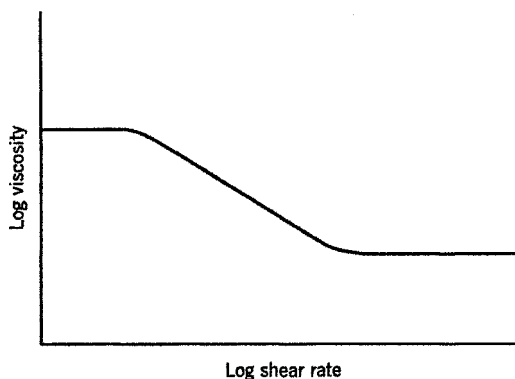


Figure 6-24. Typical curve of viscosity versus shear rate for a polymer solution.

viscosity times the coating speed divided by the gap, increases. This shearing force on the web acts as a tensile force in the bead. When the shear stress increases, the tensile stress in the bead will increase, and it will pull apart the coating bead that was already at its maximum tensile stress. What happens when we coat thicker? The tensile force remains the same. But as the flow down the slide is now greater in order to coat thicker, the bead will also be thicker. With the thicker bead the tensile stress, equal to the tensile force divided by the area of the bead, will now be less and may be within the cohesive strength of the liquid. Thus as we coat faster, we have to coat thicker.

Similarly, as we coat with higher viscosities, the shear stress and therefore the tensile forces and stresses will increase. If initially we are at the limits of coatability and then we switch to a higher viscosity liquid, we will no longer be able to coat because the higher tensile stress could exceed the cohesive strength of the liquid at that particular elongation rate. By coating thicker the tensile force will be spread over a larger area, the tensile stress will be reduced, and we may now be within the limits of coatability for this liquid.

However, we should note that the tensile stress in the liquid is greatest at the contact line where the bead meets the web. The tensile stress will be lowest at the upper surface of the bead. As the bead becomes thicker and thicker, we will reach a point where the surface of the bead is relatively unstressed. Thus increasing the thickness of the bead will no longer reduce the tensile stress in the bead. At this condition, we have reached the maximum coating speed, where increasing the wet thickness, and thus the bead thickness, no longer allows an increase in speed.

Bead vacuum and electrostatic assist, because they are stabilizing forces, significantly lower the minimum wet coverage and also slightly increase the maximum coating speed.

The ability to coat lower viscosity liquids at higher speeds and in thinner layers explains why, in multilayer slide coatings, the bottom layer is often of low viscosity. The bottom layer is most highly stressed. It had been suggested that one can use an inert, additional layer as a carrier or bottom layer, to make coating easier (Dittman and Rozzi, 1977; Choiniski, 1978; Ishizaki and Fuchigami, 1985). In fact, Ishizuka (1988) suggested using plain water as a carrier layer and showed that it works just fine.

Slot Coating

The window of coatability can be illustrated by a graph of bead vacuum versus the coating speed, as has been done by Sartor (1990) for a slot coating (Figure 6-25). We see in this figure that within a certain range of coating speeds and bead vacuums, good, defect-free coatings can be made. Outside this region, on the low-vacuum side, ribs will form. At too high a bead vacuum, the coating liquid will be sucked down to wet the lower die plate below the lower edge of the die lip, on the swept-back section. In Figure 6-25 this is called swelling of the upstream meniscus. In the liquid below the die lip, a vortex will form, within which the liquid will have a long residence time. With some materials a long residence time leads to degradation of the liquid. A vortex may also cause a streak or a band. With a slight additional increase in vacuum, the bead will be sucked down out of the gap and coating will no longer be possible.

When the coating speed is too high, air is entrained and no coating can be made. In Figure 6-25 this high-speed limit was neither measured nor calculated, but just sketched in by us to indicate that a limit does exist.

One should also emphasize two points illustrated by Figure 6-25. The first is that at very low speeds a defect-free coating may not be able to be made. Either ribbing will occur or

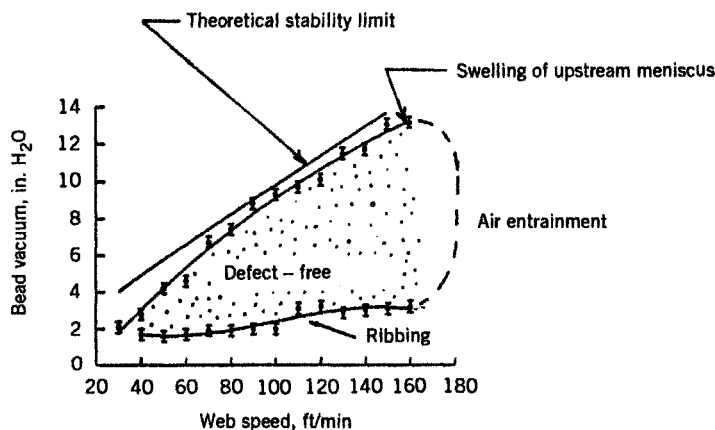


Figure 6-25. Window of coatability plot for slot coating at 25 mPa-s (25 cP) with solution 85 μm thick with a gap of 250 μm (10 mils). After Sartor (1990), with high-speed limits added, and with permission of the author.

the upstream meniscus will swell with formation of a vortex and the consequent long residence time and the possibility of streaks and bands. The second is that, in the case illustrated, some bead vacuum is needed to obtain a defect-free coating. In many cases bead vacuum is not necessary, but as the coating thickness decreases or the coating speed increases, it is more likely that bead vacuum will be needed.

Figure 6-26 indicates that below some fairly low coating speed, in a behavior similar to that of slide coating, the minimum coating thickness increases with coating speed but appears to be independent of the gap. However, at higher coating speeds, the minimum wet

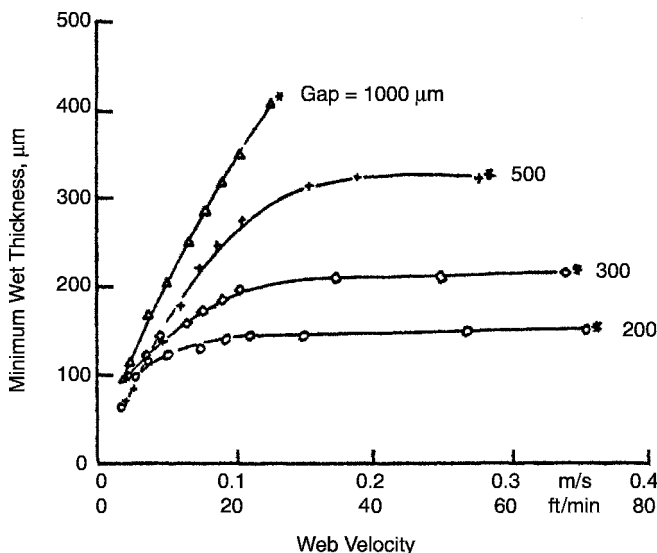


Figure 6-26. Effect of coating gap in slot coating on the minimum wet thickness, with a 50 mPa-s (50 cP) liquid. The asterisks indicate the maximum coating speeds. Reprinted with some modifications, from Chem. Eng. Sci. 47, K. Y. Lee et al. (1992). Minimum Wet Thickness in Extrusion Slot Coating, pp. 1703–1713, copyright © 1992, with permission from Elsevier.

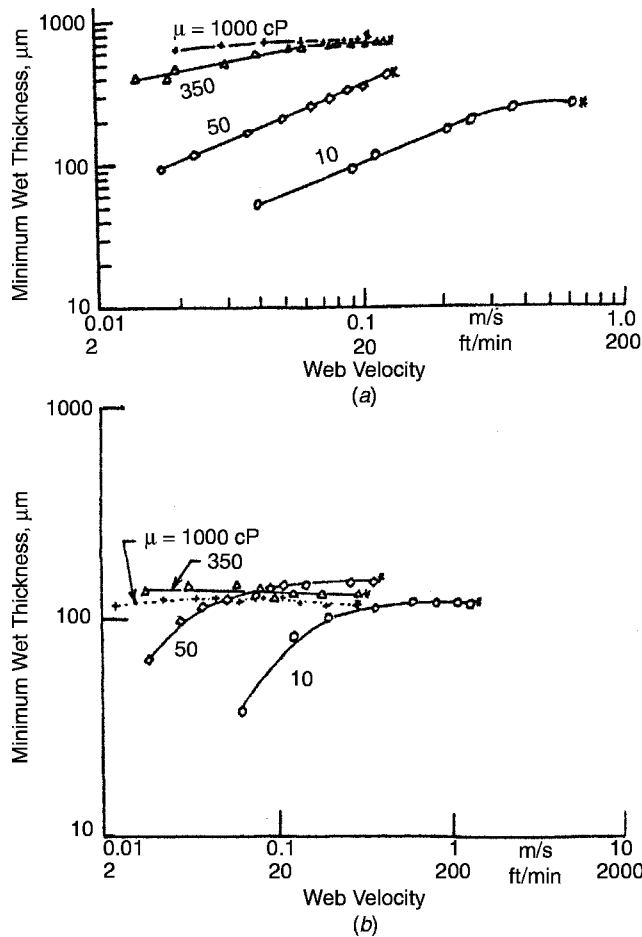


Figure 6-27. Effect of viscosity in slot coating on the minimum wet thickness, at gaps of (a) 1000 μm and (b) 200 μm . The asterisks indicate the maximum coating speeds. Reprinted with some modifications, from Chem. Eng. Sci. **47**, K. Y. Lee et al. (1992). Minimum Wet Thickness in Extrusion Slot Coating, pp. 1703–1713, copyright © 1992, with permission from Elsevier.

thickness does increase with the coating gap and at still higher speeds becomes independent of the speed. The asterisks at the high-speed ends of the curves indicate the maximum speed at which the coating can still be made—the high-speed limit of coatability. At higher speeds either air is entrained and a complete coating cannot be had or else ribbing occurs, and then at still higher speeds stripes separated by dry regions, or rivulets, would be coated.

Figure 6-27b shows that below a certain velocity that varies with gap, the minimum wet coverage, as in slide coating, increases with viscosity. But at the higher speeds, where the minimum coverage levels off, the coverage appears independent of viscosity. At the very wide gaps in Figure 6-27a, at the lower viscosities the leveling off is not reached before one can no longer coat. Much of the data is replotted in Figure 6-28 as a dimensionless minimum wet thickness—the thickness divided by the gap—versus the capillary number, which is the velocity times the viscosity divided by the surface tension. The capillary

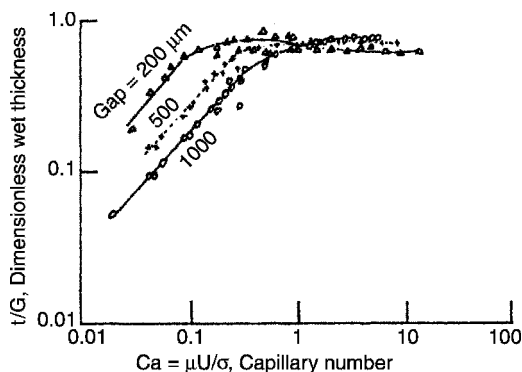


Figure 6-28. Minimum wet thickness divided by the gap in slot coating as a function of the capillary number, for various gaps. Reprinted with some modifications, from Chem. Eng. Sci. 47, K. Y. Lee et al. (1992). Minimum Wet Thickness in Extrusion Slot Coating, pp. 1703–1713, copyright © 1992, with permission from Elsevier.

number represents the viscous forces divided by the surface forces and is a dimensionless group important in many coating operations.

Figure 6-28 shows that at the lower capillary numbers—at lower speeds or viscosities—the minimum dimensionless wet thickness is a strong function of gap. This is because the thickness is independent of gap, and so thickness over gap is inversely proportional to gap. At the high capillary numbers, on the other hand, the minimum wet thickness divided by the gap is constant at a value of about 0.6–0.7. In this high capillary number region therefore, the minimum coating thickness is about 2/3 of the gap. For thin coatings in this region, one has to use tight gaps. In Figure 6-28, one can see that critical capillary number, above which the minimum wet thickness divided by the gap is constant, increases with gap. Table 6-1 summarizes some of this high capillary number data.

In slot coating, gravity normally has little effect, and the slot die, aimed at the center of the backing roll, can be pointed up, down, horizontally, or at any angle. The horizontal position is most common, but when the die is aimed upward it is easier to get rid of air that is in the system, and there is less likelihood of bubbles building up to disrupt the flow. It should be noted that there is some evidence (Liu, 1998) that rotating the slot coater from the horizontal to point vertically downward allows one to coat slightly thinner and slightly

TABLE 6-1 Dimensionless Minimum Wet Thickness, t/G , for $Ca > Ca^*$

Viscosity, μ (mPa-s)	Gap, $G(\mu\text{m})$			
	200	300	500	1000
10	0.61	0.55	0.44	Defects
50	0.70	0.70	0.65	Defects
350	0.67	0.71	0.66	0.70
1000	0.65	0.70	0.65	0.72

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Note: Ca^* is the critical capillary number.

faster. And some cases were reported where the minimum wet thickness unexpectedly decreased with increasing speed.

It was also found that in slot coating pointed downward with a wide gap of 5 mm (this perhaps should be called curtain coating with a short curtain), the use of edge guides, such as are normally used in curtain coating, may allow one to coat slightly faster and slightly thinner (Liu, 1998). This implies that perhaps edge guides should be tried in other slot coating applications.

The slot opening in the die has little effect. It controls the liquid momentum against the web, and, as we discussed in slide coating, this is normally insignificant. It does help to determine the pressure within the coating die on which there are upper and lower limits, as will be discussed in Chapter 7.

As with slide coating, in slot coating bead vacuum lowers the minimum wet thickness (Figure 6-29). Also as with slide coating, at wide gaps the bead is unstable at higher bead vacuums. Bead vacuum seems to be less effective with high viscosities, over 500 mPa-s (cP) (Lee et al., 1992). At the lower viscosities bead vacuum can easily reduce the minimum wet thickness by 20–30%.

Lee et al. (1992) found that at relatively low speeds and with low-viscosity liquids the limits of coatability are very similar to the limits in slide coating, as seen in Figure 6-30, a plot of minimum wet thickness versus the capillary number. The agreement between slot and slide coating occurs when the capillary number (equal to $\mu V/\sigma$, the product of the viscosity and the coating speed divided by the surface tension) is below a critical value. However, above the critical value of the capillary number, the slot coater can coat at higher speeds and in thinner layers than can the slide coater. As with slide coaters, at low values of the capillary number the gap has relatively little effect, and the minimum wet thickness increases with viscosity and with coating speed.

Figure 6-31 shows that, in slot coating at higher speeds, one can sometimes coat considerably thinner than indicated in the data presented earlier, as shown by Carvalho and Kheshgi (2000).

In slot coating as in slide coating, it is easier to coat polymer solutions than Newtonian liquids. Ning et al. (1996) found that with the addition of small amounts of polyacrylamide or carboxymethylcellulose to glycerin solutions:

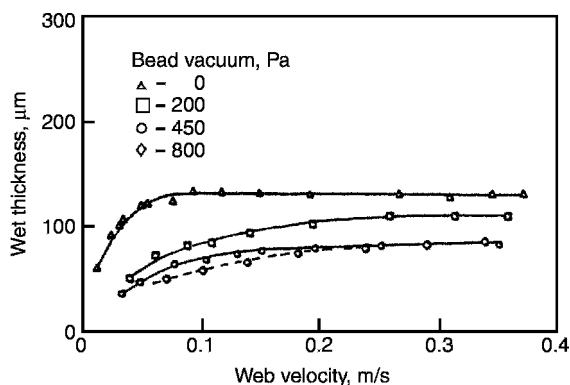


Figure 6-29. Effect of bead vacuum on the minimum wet thickness in slot coating, with a 50-mPa-s (50-cP) liquid, at a 200- μ m gap. The bead vacuum is: Δ , 0; $\square$, 200 Pa; $\circ$, 450 Pa; $\diamond$, 800 Pa (3.2 in. water). Reprinted from Chem. Eng. Sci. **47**, K. Y. Lee et al. (1992). Minimum Wet Thickness in Extrusion Slot coating, pp. 1703–1713, copyright © 1992, with permission from Elsevier.

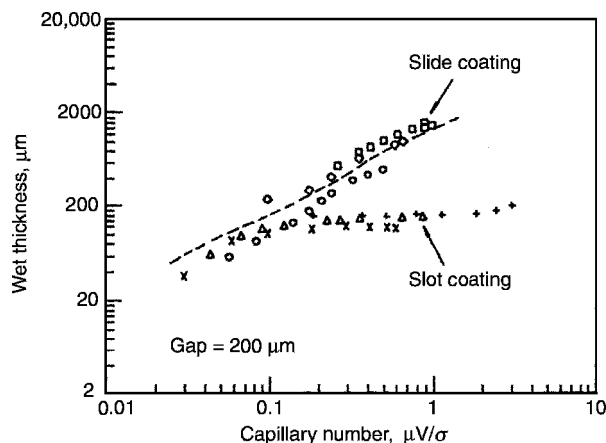


Figure 6-30. Comparison of slot coating with slide coating, with a 200- μm gap. The dashed line is from Gutoff and Kendrick (1987). Δ and $\circ$, silicone oil, 50 mPa-s (cP); +, 95% glycerin–water, 420 mPa-s (420 cP); $\times$, silicone oil, 10 mPa-s (cP); $\diamond$, 88% glycerin–water, 133 mPa-s (133 cP). Reprinted from Chem. Eng. Sci. **47**, K. Y. Lee et al. (1992). Minimum Wet Thickness in Extrusion Slot Coating, pp. 1703–1713, copyright © 1992, with permission from Elsevier.

- The maximum coating speed increases to a maximum and then decreases.
- There is little effect on the minimum wet thickness, and at high capillary numbers the minimum wet thickness remains at about 2/3 of the gap.
- When the viscoelasticity gets too high the surface becomes rough, as with melt fracture in extrusion.
- The maximum coating speed decreases slightly with gap.

Just as in slide coating, a low-viscosity carrier layer in a two-layer slot coating can make coating easier and reduce the minimum wet thickness, as shown by Yu et al. (1995).

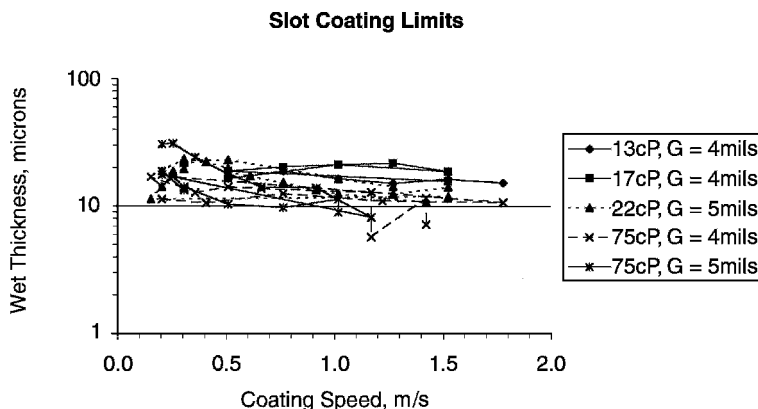


Figure 6-31. Normal slot coating limits may be exceeded at higher coating speeds. Plotted from data courtesy of Prof. Mario Carvalho, from Carvalho and Khesghi (2000).

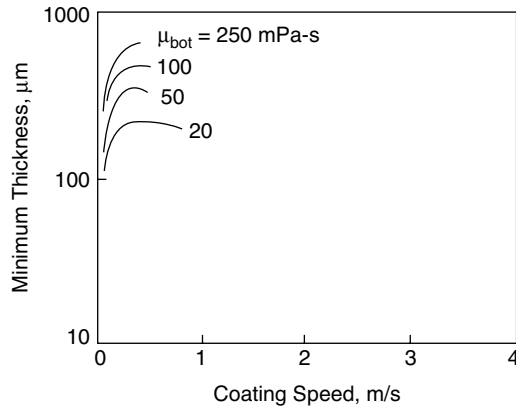


Figure 6-32. Effect of carrier layer in two-layer slot coating, with identical wet thicknesses for each layer. Viscosity of top layer is 250 mPa-s (cP). A very wide gap of 1000 μm was used. Data replotted from Yu et al. (1995).

Figure 6-32 shows the large effect when coating a low-viscosity carrier layer under a relatively high-viscosity layer. This can be explained similarly to the effect of carrier layers in slide coating. However, Yu et al. (1995) also showed (see Figure 6-33) that with a low-viscosity carrier layer, as the upper layer viscosity increases, surprisingly the minimum wet thickness decreases. Neither they nor we have an explanation for this.

A qualitative comparison of slide and slot coating can be made by referring to Figure 6-34, which is similar to one of Lee et al. (1992). The slide coater has the lower meniscus pinned to the coating die with the upper meniscus completely free, while the slot coater has both the upper and the lower menisci pinned. When the coated layer is thin compared to the gap, as it can be at low viscosities or low speeds (low capillary numbers), then the upper lip of the slot coater has little influence on the meniscus that is pinned to it, except very close to the lip. The upper menisci of both the slot and the slide coaters are then

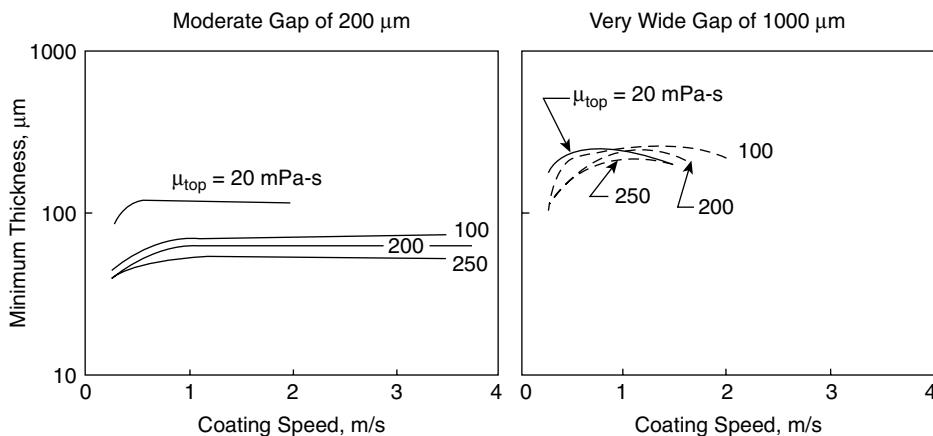


Figure 6-33. With a carrier layer of 20 mPa-s (cP), effect of upper layer viscosity on minimum wet thickness. Identical wet thicknesses in each layer. Data replotted from Yu et al. (1995).

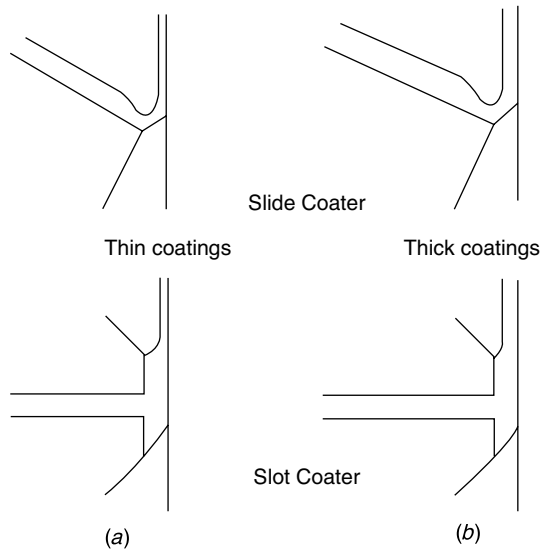


Figure 6-34. Flow behavior in the coating bead region for a slot coater and a slide coater for (a) thin coatings and (b) thick coatings. Based on Lee et al. (1992).

similar, and the limits of coatability are similar. However, at higher capillary numbers the minimum wet thickness increases up to about $2/3$ of the gap. The upper lip then acts as a doctor blade to prevent the coated layer from getting thicker (Lee et al., 1992).

Extrusion Coating

The upper speed limit in extrusion coating occurs when the extruded material is no longer smooth or uniform. There are many types of instabilities that can occur in extrusion coating, and they are generally classified under the terms melt fracture or draw resonance. *Melt fracture* occurs when the material is extruded at too high a rate and can result in haze, surface roughness—also called sharkskin—or even gross surface distortions. In extrusion coating, the extruded film is often stretched by coating at a higher speed than the speed at which the material is extruded. The ratio of the coating speed to the extrusion speed is called the draw ratio. When the coating speed is too high and a certain critical draw ratio is exceeded, the film thickness varies sinusoidally. This instability is called *draw resonance*. Melt fracture is highly dependent on the viscoelasticity of the material, and draw resonance is somewhat related to viscoelasticity.

There are a number of possible phenomena that may result in the instabilities known as melt fracture. Agassant et al. (1991) gives some as follows:

- Vortex formation in sudden contractions. As indicated in Figure 6-35a, when a simple liquid enters a contraction, all the streamlines flow toward the exit region. However, viscoelastic liquids often do not flow completely toward the outlet but form vortices in the corners as indicated in Figure 6-35b. When liquid in a vortex on either side exits into the contraction, there is a pressure pulse, and this can cause the instability. Polymer melts (usually with branched chains) such as polystyrene, polymethylmethacrylate, polyamide, and most low-density polyethylenes tend to

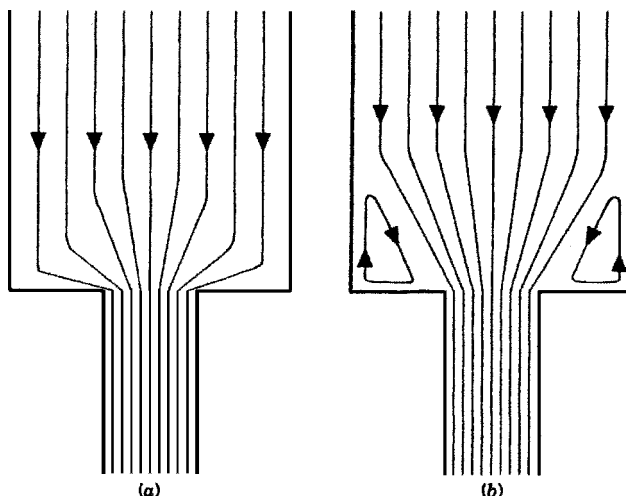


Figure 6-35. Fluid flow into a sudden contraction: (a) simple Newtonian fluid and (b) viscoelastic liquid.

form these vortices, while other polymer melts (usually linear) such as high-density polyethylene and linear low-density polyethylene tend to have all the streamlines converge into the contraction (Figure 6-35a) with no vortex formation.

- High entry pressure drops. When a liquid enters a straight pipe or a slit, the velocity profile rearranges to form the typical parabolic shape of well-developed flow. This flow rearrangement involves a higher pressure drop. There is some evidence that when this excess pressure drop becomes too high, flow instabilities occur.
- High wall shear stress. With some polymer melts, instabilities occur when the wall shear stress exceeds some critical value. In one model fluid, this appears as a pulsating flow. This may be similar to the occurrence of turbulence in pipe flow when the Reynolds number, $DV\rho/\mu$, exceeds a critical value of 2100.
- Stick-slip conditions at the wall. For a melt of high-density polyethylene flowing in a capillary, melt fracture seems to occur at high values of the length to diameter ratio. It is thought that stick-slip phenomena are occurring. Stick-slip conditions may occur when the shear stress is sufficiently high that the molecular entanglements do not have time to relax and rearrange, and molecular motion becomes restricted. When the yield stress is exceeded, melt fracture occurs; the material “gives” and the process repeats. It is also possible that the material loses adhesion to the wall above a critical shear stress and starts to slip. The wall shear stress then drops below the critical value, adhesion to the wall reoccurs, and the process repeats.
- Elastic energy stored in the deformed polymer chains. The stress increases rapidly with increasing rates of stretching. At some point the material “gives.”
- Melt fracture in simple shear flow. This has been demonstrated in a cone-and-plate viscometer, where the cone rotates and the shear rate is the same throughout the polymer. When the shear rate exceeds a critical value, the shear stress or torque decreases with time to a new, much lower value. When the rotation is stopped, the liquid melt will heal itself to its original state. The lower stress is possibly due to

disentanglement of the polymer chains along a “fracture” surface, which may be within the polymer or at the metal surface.

- Flow rearrangement at the die exit. Sharkskin has been attributed to this.

Many authors believe that a critical shear stress has to be exceeded for melt fracture to occur, and this critical value decreases with increasing molecular weight of the polymer. For a flow in the slit of a die, the shear stress increases with flow rate, with viscosity, and even more rapidly with decreasing gap. Thus if melt fracture does occur, one may be able to correct the problem by opening up the exit slot, by switching to a lower molecular weight polymer, or by operating at a lower production rate.

Other authors suggest that melt fracture occurs when a critical ratio of elastic stress to viscous stress (this ratio is called the Wiessenberg number) is exceeded. The viscous stresses are proportional to shear rate, and the elastic stresses increase much more rapidly with shear rate. Thus this ratio increases rapidly with shear rate.

The other instability in extrusion coating, draw resonance, has been analyzed mathematically. It will occur even for simple, Newtonian liquids, when the draw ratio exceeds about 20. Thus, when the final film thickness is less than one-twentieth of the film thickness at the exit of the extrusion die, we would expect draw resonance to occur. Middleman (1977) quotes one case in the casting of a polypropylene film, where, when draw resonance occurred, the film thickness varied sinusoidally between 20 and 36 μm with a wavelength of about 1 meter. The thickness variations can be even more extreme, and the width of the extruded film can also vary when there is draw resonance. The distance between the peak thicknesses increases with the stretching distance and with the draw ratio.

By comparison with draw resonance in fiber spinning, we might expect that viscoelasticity would have an effect on the critical draw ratio.

Curtain Coating

In curtain coating, there are not only the limits of coatability on the coating, but there are also limits on the curtain. A certain flow rate is needed in order to form and maintain the falling curtain. This minimum flow rate is fairly high and varies with different fluids from approximately 0.4 $\text{cm}^3/\text{s}\cdot\text{cm}$ width (24 $\text{cm}^3/\text{min}\cdot\text{cm}$ width) to approximately 1.5 $\text{cm}^3/\text{s}\cdot\text{cm}$ width (90 $\text{cm}^3/\text{min}\cdot\text{cm}$ width). The presence of surfactants appears to reduce the upper values. It is recommended that at least double the minimum should be used. With this fixed minimum flow rate for the curtain, the minimum coverage will decrease as the coating speed goes up. This means that for thin coatings high coating speeds have to be used. Curtain coating is inherently a high-speed coating operation. Thus with a desired curtain flow of at least 1.0 $\text{cm}^3/\text{s}\cdot\text{cm}$ width and for a wet coverage of 25 μm , the minimum coating speed would have to be

$$\text{Speed} = \frac{1.0 \text{ cm}^3}{\text{s cm}} \frac{1}{25 \mu\text{m}} \frac{10^4 \mu\text{m}}{\text{cm}} \frac{\text{m}}{100 \text{ cm}} = 4 \frac{\text{m}}{\text{s}}$$

or 800 ft/min.

Surfactants are needed in every layer in curtain coating. The surface tensions of all the layers should be about the same, except for the top layer, which, as always, should be slightly lower than the rest.

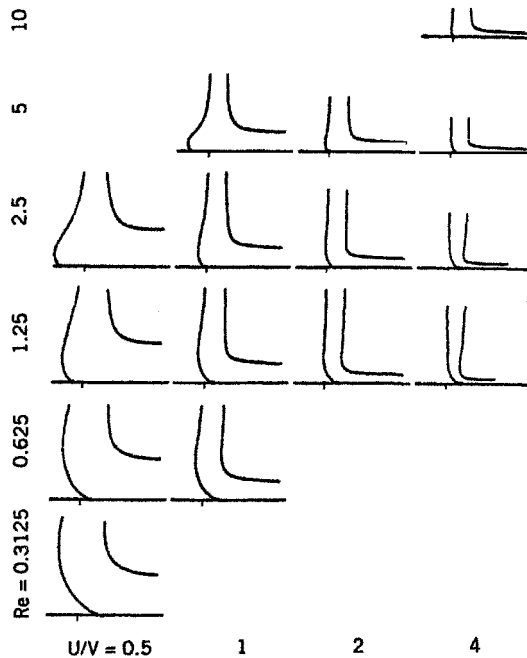


Figure 6-36. Heel formation in curtain coating. Re , the Reynolds number, equal to $q\rho/\mu$, is proportional to the flow rate. U/V is the coating speed divided by the speed of the falling curtain. From Kistler (1984), with permission of the author.

In curtain coating, the momentum of the falling curtain aids in holding the coating liquid against the web and opposing air entrainment. Thus the velocity of the falling curtain, determined by the height of the curtain and also by the velocity of the liquid film leaving the slide, helps determine the maximum coating speed. Also, as with both slide and slot coating, the flow rate itself is very important, aside from the need for a minimum flow to form the curtain. If the web is stationary, the curtain on striking the web will split into two streams, with half going in the direction of the web movement and half going in the opposite direction. As the web starts moving, more of the flow goes in the direction of the web. Above some speed, all the liquid moves in the web direction. But even when all the liquid moves in the web direction, at speeds just above the minimum, some liquid still goes backward a short distance before turning forward, to form a heel, as shown by Kistler (1984) in Figure 6-36. In this figure, the flow rate is plotted on the y-axis as a Reynolds number, $q\rho/\mu$, where q is the flow rate in $\text{cm}^3/\text{s-cm}$ of width, ρ is the density in g/cm^3 , and μ is the viscosity in poise.

On the x -axis, U/V is the ratio of the web speed to the speed of the falling curtain.

We see in Figure 6-36 that with higher flow rates or lower viscosities (higher Reynolds numbers) we tend to get more of a heel, and also with higher curtain speeds—because of a higher curtain—or with lower web speeds (lower ratio of web speed to curtain speed) we tend to get more of a heel.

The heel is objectionable because, when it is large enough, it contains a recirculating eddy, and the liquid in the eddy can remain there for a long time. The eddy can cause a streak or a band, and in many cases the coating liquid degrades with time, and this too can cause a defect.

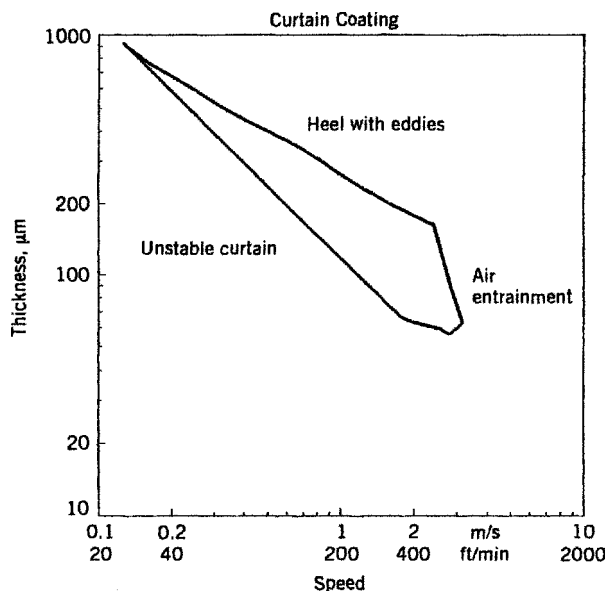


Figure 6-37. Coating window in curtain coating for a 33- mPa-s (33- cP) liquid and a 50-mm (2-in.) high curtain. Data are from Kistler (1984).

The limits of coatability for one example of slide coating, with the data taken from Kistler (1984), is presented in Figure 6-37. This can be compared with similar plots, shown earlier, for slide and for slot coating. The minimum flow rate to form a stable curtain gives a low-speed, thin-film limit that is the straight line with the 45° slope in the figure. Heel formation gives the thick-film limit on the top of the figure; air entrainment gives the high-speed limits. Curtain coating can coat about an order of magnitude faster than slide coating for the same materials. Also, as with slide and slot coating, lower viscosity liquids can be coated faster.

Figure 6-37 shows that the coating window in curtain coating is limited on all sides. The coating window may cover a wide speed range (in Figure 6-37 from about 0.1 to 3 m/s (20–600 ft/min)), but for most coating thicknesses the range is much narrower. The thickness range is more limited than in slot or in slide coating. However, with polymer solutions, we would expect the coating window to be much wider than for the glycerin–water mixture coated in Figure 6-37.

Effect of Surface Roughness on the Limits of Coatability

The paper industry has long been coating paper, which has a very rough surface, at very high-speeds, up to about 250–300 m/s (5000–6000 ft/min), while with smooth film such as for magnetic tapes, the highest coating speed is only perhaps 7.5 m/s (1500 ft/min). Scriven (1984) suggested that with rough surfaces the air carried along by the web is able to escape easier in the “valleys” between the “mountains,” and on porous surfaces, such as paper, air can also escape through the back. Buonopane et al. (1986) showed that rough surfaces with root mean square (rms) roughnesses of 1.8–5 μm are able to be coated up to 1.5–5 times faster before air entrainment occurs, than for smooth surfaces with rms roughnesses no more than 1.0 μm.

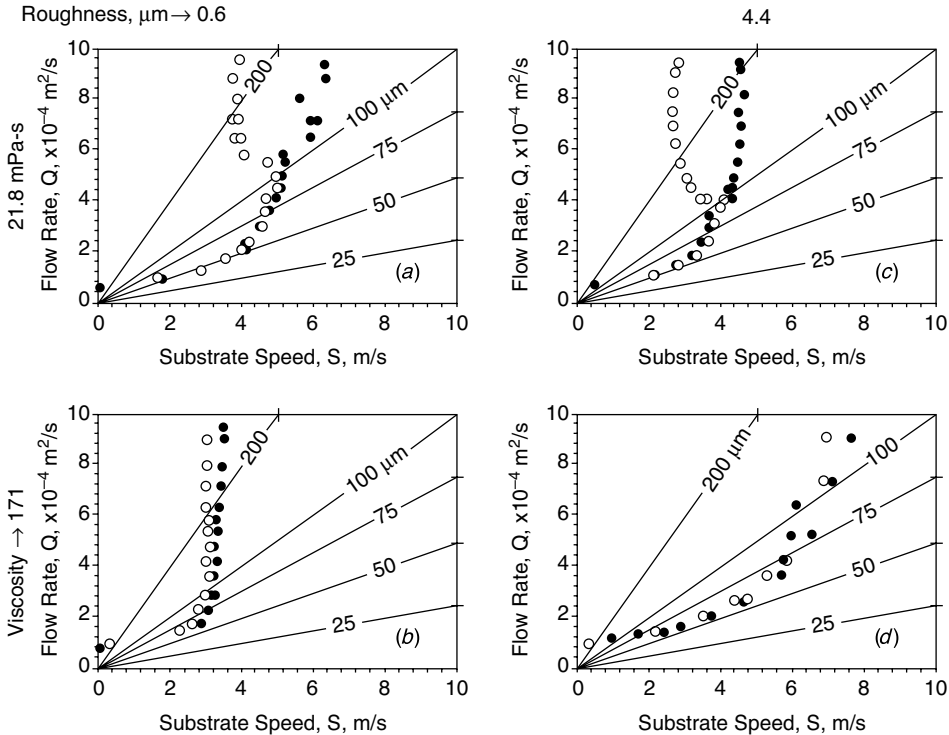


Figure 6-38. Effect of roughness and viscosity on minimum wet thickness in curtain coating with a 70-mm curtain height. The smooth surface is polyethylene terephthalate with a roughness of $0.6\mu\text{m}$; the rough surface is polyethylene coated paper with a roughness of $4.4\mu\text{m}$. The liquid coated is aqueous gelatin. The solid circles are for wetting failure with increasing speed; the open circles are for the disappearance of wetting failure on reducing speed. From A. Clarke *AIChE Journal* **48**, 2149–2156 (2002), with the lines of constant coverage added. Reproduced with permission of the American Institute of Chemical Engineers. Copyright © 2002 AIChE. All rights reserved.

Clarke (2002) showed that the effect of the surface roughness depends on the viscosity of the coating liquid. A low-viscosity liquid fully wets the web surface and, as the true wetting speed is approximately constant, with a rough surface with its larger surface area, the effective wetting speed is reduced by the area ratio. In contrast, a high-viscosity liquid will just slide over the air pockets between the “mountain peaks” on a rough surface. The air offers very little resistance to flow since it has a very low viscosity, and thus the coating speed is greatly increased. Clarke defines a rough surface as one with a 10 point average peak-to-peak height of at least $2.5\mu\text{m}$ by ISO 4287 or DIN 4786.

In Figure 6-38, Clarke (2002) shows that with a liquid with a viscosity of $21.8\text{ mPa}\cdot\text{s}$ ($1\text{ mPa}\cdot\text{s} = 1\text{ cP}$) there is not a great difference between the curves for the smooth and rough surfaces, but at a given flow rate the smooth surface has a slightly higher coating speed. In contrast, with a liquid with a high viscosity of $171\text{ mPa}\cdot\text{s}$ (or cP), on the rough surface the coating speeds are much higher. Figure 6-39 confirms this data with a higher viscosity liquid of $208\text{ mPa}\cdot\text{s}$ (or cP).

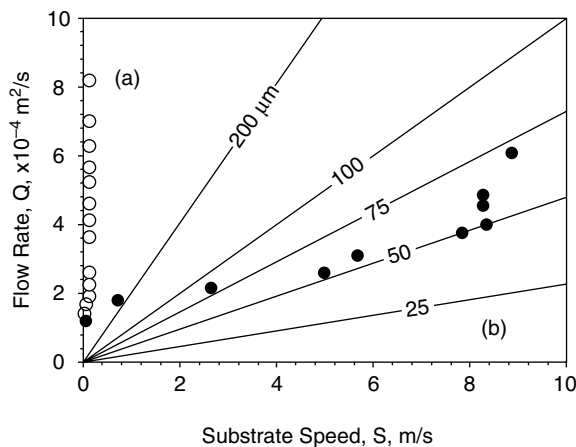


Figure 6-39. Effect of surface roughness on curtain coating a 208-mPa-s (cP) gelatin solution. ○, Onto a smooth polyethylene terephthalate film with a roughness of $0.6\text{ }\mu\text{m}$; ●, onto a rough polyethylene coated paper with a roughness of $4.4\text{ }\mu\text{m}$. From A. Clarke AICHE Journal **48**, 2149–2156 (2002), with the lines of constant coverage added. Reproduced with permission of the American Institute of Chemical Engineers. Copyright © 2002 AIChE. All rights reserved.

Figure 6-40 suggests that the viscosity effect takes place somewhere in the range of 83–100 mPa-s (cP) and shows that, with high-viscosity fluids on a rough surface, one can coat much thinner at a given speed than with low-viscosity liquids. This is much different from what we saw earlier with smooth webs, where with low-viscosity liquids one can coat thinner.

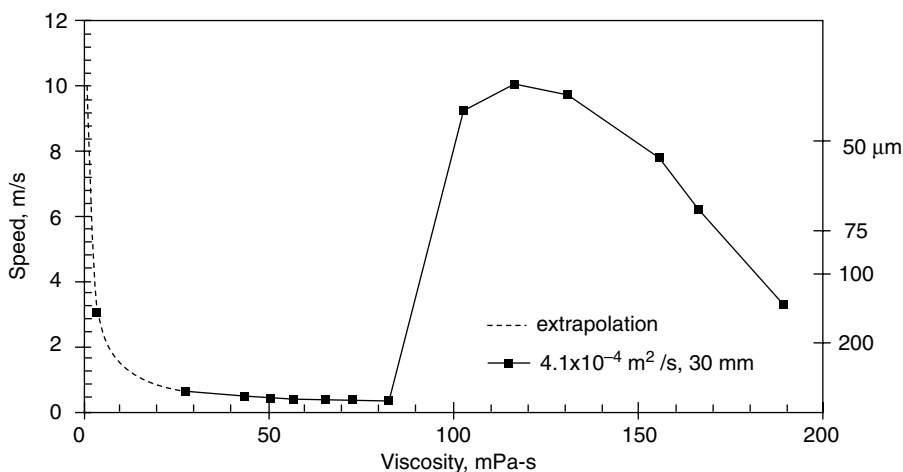


Figure 6-40. Effect of viscosity of aqueous glycerin on minimum wet thickness in curtain coating onto a rough polyethylene coated paper with a roughness of $4.4\text{ }\mu\text{m}$. The flow rate is constant at $4.2\text{ cm}^3/\text{s}$ -cm width, and the curtain height is 20 mm. From A. Clarke AICHE Journal **48**, 2149–2156 (2002), with right ordinate added. Reproduced with permission of the American Institute of Chemical Engineers. Copyright © 2002 AIChE. All rights reserved.

Rough webs consist of paper, some coated papers, and embossed plastics. The work discussed above suggests that they may be useful in coating thinner or possibly in coating faster, if the roughness itself can be tolerated.

INSTABILITIES IN PREMETERED COATING

Chatter

Chatter is the appearance of cross-web lines or bars at regular intervals down the coating, arising from periodic coverage variations. It is also referred to as barring. In a significant number of cases, these coverage variations—chatter—result from mechanical causes, such as vibrations, speed fluctuations, an eccentric backing roll or a roll with too great a total indicated run-out in the bearings, fluctuations in the flow of the coating fluid, or bead vacuum fluctuations. Some of these are discussed later in Chapter 11 on defects caused by the drive system.

Fluctuations in flow rate can occur from pump pulsations that remain undamped. Plastic lines from the pump to the coating die are usually adequate to damp the slight pulsations arising from gear pumps. Pulsations in flow have also been known to occur with jacketed plastic lines, when the jacket water experienced pressure pulsations.

One should always check whether the frequency of any of the mechanical disturbances is the same as the chatter frequency. The chatter frequency in cycles per second (or Hz) is found by dividing the coating speed (e.g., in cm/s) by the spatial frequency of the chatter (in cm). By using a vibration analyzer, the frequency of any vibrations can be determined. One should also compare the spatial frequency of the chatter with the circumference of the backing roll, as a bad bearing or an out-of-round roll can cause chatter.

The frequency of bead vacuum fluctuations can be determined with a rapid-response pressure sensor. Bead vacuum fluctuations often arise because the bead vacuum system acts as a giant wind instrument. As in a tuba, for example, the greater the airflow the greater the amplitude of the sound, equivalent to the amplitude of the pressure waves. Thus, in a bead vacuum system, the greater the air leakage into the system the more likely visible chatter will result. Therefore one should reduce the air leakage as much as possible. Bead vacuum fluctuations cause chatter mainly at wide coating gaps.

It is impossible to eliminate all air leakage into the vacuum system, because the web has to enter the vacuum chamber and rubbing contact against the web must be avoided to prevent scratching the web. However, the clearance between the vacuum seal and the web should be as small as possible, and all other seals—mainly against the face or sides of the backing roll—should be with rubbing contact. The coating liquid itself forms the seal between the web and the coating die.

If all mechanical causes of chatter have been eliminated and the problem remains, it is likely that the chatter is caused by the hydrodynamics of the system. Sartor (1990) has reported chatter occurring near the limits of coatability, and in some systems hydrodynamics-caused chatter is not uncommon.

Ribbing

Ribbing appears as evenly spaced, uniform, down-web lines in the coating, as if one ran a comb down the wet coating. Ribbing is a common defect in all coating operations. It arises from the hydrodynamics of the coating system. Even when painting a wall with a

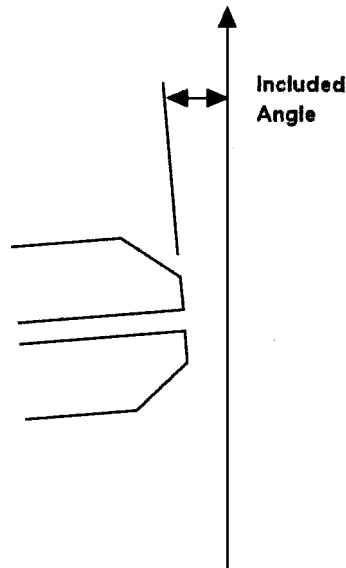


Figure 6-41. Diverging included angle between the slot coating die and the web tends to promote ribbing.

paintbrush, the lines that appear are not from the bristles on the brush but from rib formation. Bixler (1982) studied ribbing in slot coating mathematically, and from his analysis one sees that to avoid or reduce ribbing one should (1) have a low-viscosity liquid, (2) coat at low speeds, (3) have high wet coverage, and (4) operate with a tight gap.

In most coating systems, a diverging included angle, as shown in Figure 6-41, tends to promote ribbing. Either the lips should be parallel to the web or the included angle should be slightly converging. In slot coating a thin layer, ribs can also form when the upper or downstream lip of the coating die is too rounded, thus presenting a diverging included angle to the exiting flow.

Sartor (1990) showed that ribbing appears near the limits of coatability in slot coating, and Christodoulou (1990) showed mathematically that in slide coating ribbing is more severe at high bead vacuums, high coating speeds, and low flows. Earlier Tallmadge et al. (1979) showed that ribbing appears near the limits of coatability in slide coating. Valentini et al. (1991) showed that the choice and level of surfactant affects the bead vacuum in the coatability window, and thus the bead vacuum at which ribbing occurs.

Although some viscoelasticity is desirable in coating, too high a viscoelasticity promotes ribbing. In extreme cases, the ribs can be transformed into filaments or strings. If adjustments of bead vacuum, gap, or included angle cannot eliminate ribbing, then the cure may be to use a less viscoelastic (lower molecular weight) polymer. However, viscoelasticity can also be caused by some surfactants forming temporary structures at higher concentrations, above the critical micelle concentration. Thus the type and concentration of surfactant may have an effect on ribbing. Viscoelasticity may also be caused by some suspensions at high concentrations tending to develop structures.

Ribs can originate in the top or in the bottom of the coating bead. The rib spacing tends to increase in thicker coatings and with wider gaps.

Ribs can also form when a viscoelastic fluid is forced through too narrow a slot opening in the coating die. If this occurs, the slot opening in slot, slide, or curtain coating should be increased.

Neck-in

In all forms of premetered coating, whenever there is a coating gap the liquid tends to neck in. In curtain coating, this neck-in is prevented by the edge guides. In slot, slide, and extrusion coating, it can and does occur. However, with low-viscosity liquids that are commonly used in slot and slide coating, edge guides have been used effectively to prevent neck-in.

Neck-in is most severe when one approaches the limits of coatability, where it is difficult to coat unless the coverage is increased. When an edge necks in, the coverage near that edge is increased. Neck-in seems to be more severe with more viscous and also more viscoelastic liquids and is more severe at wider gaps. High surface tensions would also contribute to neck-in, especially with low-viscosity liquids. Therefore using surfactants to lower the surface tension can be tried.

In extrusion coating, the gap tends to be much greater than in slot coating, and neck-in is correspondingly more severe. In addition, the polymer melts tend to be of high viscosity and also viscoelastic. This also tends to increase neck-in. Neck-in is also more severe the more one stretches the film—that is, the higher the draw ratio. Thus to reduce neck-in, one should try to reduce the draw ratio by using a narrower slot opening in the extrusion die, thus giving a smaller initial thickness but with a higher exit velocity; and one should try to use a smaller gap or draw distance. Of course, a narrower slot opening increases the shear rate and the shear stress, and, as discussed earlier, this can cause other problems.

An edge can move in and out in a smooth, cyclic manner. This may be caused by an out-of-round backing roll or by bearings with too much run-out. The gap would then cycle between a tighter and wider opening with each revolution of the roll. At the wider gaps, neck-in would tend to be more pronounced, and this would cause a smooth cycling of the edge with a wavelength equal to the circumference of the backing roll.

Scalloped Edges

Scalloped edges are a higher-frequency defect, where the edge of the coating moves in and out with a spacing of a few centimeters or so, with pointed peaks and valleys. Scalloped edges seem to be more common at wide gaps and near the limits of coatability at low coverages and high-speeds. The origin of this cyclic condition is unknown, but it is much more common with viscoelastic liquids. The viscoelasticity is usually caused by dissolved polymers, but it can also result from some suspensions tending to form three-dimensional networks, and from some surfactants above the critical micelle concentration tending to form temporary structures.

Edge Beads and Heavy Edges

In almost all coating operations, the edges of the coating tend to be thicker than the broad central area. The heavy edges are objectionable for several reasons. First, a roll of coating with heavy edges cannot be wound properly. The web in the central portion of the roll will not be in contact with the wrap underneath it. One suggestion is to oscillate the roll from side to side, so the heavy buildup will not be in the same location throughout the roll. The heavy edges, while still wet, can be doctored off with a small rubber blade or blown off by a small jet of air. This can be messy.

Second, unless the coating is solidified by curing (e.g., by ultraviolet light or an electron beam), the heavy edges will dry slower or incompletely. If the coating encounters a face

roll before the edges are dry, the wet coating will transfer to the roll and get it dirty, and this could cause defects in the following material. Also, wet edges in a wound roll will cause it to stick together such that it might tear during unwinding.

In Chapter 8, on surface tension effects in coating, it is pointed out that surface forces may be the cause of fat edges that occur during drying. But in many cases the thick edges occur in the coating operation before the wet coating gets to the dryer. In curtain coating, it has been suggested that the edge guides be bent to ride on the web, and that the bent sections point outward to thin down the heavy edges. Air jets have been suggested to blow the heavy edges outward. It has also been suggested to dilute the edge with solvent (usually water) to reduce the viscosity and then suck it off with a vacuum tube.

In premetered coating, edge beads can be caused in the coating operation by surface tension effects, by die swell, and by stresses due to the stretching of the film (Dobroth and Erwin, 1986). These authors show that surface tension is most likely the cause of edge beads when the viscosity is low, the coating speed is low, the film thickness is low, and the gap is large. In slot and slide coating, the coating speed is usually high, the gap is small, and the viscosity is fairly low. In extrusion coating, the coating speed is high, the gap is large, and the viscosity is high. In most cases, surface tension contributes only slightly to the edge bead. When surface tension is a major contributor, the bead would normally extend no more than about 5 mm in from the edge.

Die swell can also contribute to the edge bead. Viscoelastic liquids swell when they are extruded to give an initial thickness larger than the die opening. Because of the extra wall at the edges, there can be additional stresses at the edges and this can lead to additional swelling. It is unlikely that the thickness of an edge bead due to die swell would be more than twice the thickness in the broad central area, and it is unlikely that such an edge bead would extend more than 5 mm in from the edges (Dobroth and Erwin, 1986).

The most common cause of edge beads in extrusion coating—and probably in slot and slide coating as well—is from the stresses that build up in stretching the film, with the web or coating speed being much higher than the speed at which the material exits the coating die. This ratio of coating speed to the die exit speed is the draw ratio. Dobroth and Erwin (1986) show that the ratio of the bead thickness to the thickness at the center—the bead ratio—is equal to the square root of the draw ratio irrespective of the properties of the coating liquid. It does not matter whether the material is viscoelastic or not, or what its viscosity is. It depends only on the draw ratio. The draw ratio for typical coatings is about 10 and ranges from about 2 to 14. Therefore one can expect that the bead will be thicker than the central portion by a factor ranging from about 1.4 to a little under 4.

The extent of the edge bead due to the stresses caused by stretching will vary with the gap or draw distance. In extrusion operations with gaps as large as 15 cm (6 in.), the edge bead can extend about 5 cm (2 in.) in from the edge. In slot or slide coating, with gaps of 100–400 μm (4–16 mil), the edge bead would extend well under 1 cm.

There is not much one can do to prevent the formation of this edge bead. Narrowing the slot opening of the extrusion or slot die would increase the die exit speed and thus decrease the draw ratio, but it would increase the pressure drop in the die, and the narrower opening might well require more precise machining (e.g., lapping rather than grinding) to maintain the cross-web uniformity of the coating. And the narrower slot would increase the stresses in the coating liquid, which, if viscoelastic, would increase the die swell and may also result in rib formation. Higher die swell may be undesirable as it is possible that the draw ratio should really be defined as the ratio of the maximum thickness at the exit (in the die

swell region, rather than the slot thickness) to the coated thickness, and thus this might be counterproductive and increase the draw ratio.

However, as the extent of the edge increases with gap or draw distance, decreasing the gap should help in reducing the extent of the edge. This may be possible to do in extrusion coating, but in slot or slide coating, with much smaller gaps, one usually wants a relatively wide gap of over 200–300 μm (8–12 mil) to allow splices to pass without withdrawing the coating die.

In slide coating, one could coat at a steeper angle to increase the velocity on the slide. This would reduce the draw ratio and thus the edge ratio. But this is not recommended, for with slide coating the edge extent is usually only about 5 mm, and a steeper slide is more likely to cause interfacial waves (see below).

Waves in Slide and in Curtain Coating

When a liquid flows down an inclined plane, waves can form on the surface. Many of us have seen such waves when rainwater runs down a hill on a paved street. The waves often have a wavelength of about 30 cm (1 ft). These are surface waves. Such waves can form on the slide in slide or in curtain coating. In multilayer slide or curtain coating, both surface and interfacial waves can form. Figure 6-42 gives an example of interfacial waves on a slide, with a wavelength of about 1 mm. This is a much shorter wavelength than for surface waves, which are on the order of 10 cm. The longer interfacial waves, perhaps a centimeter long, can appear as a series of jagged V's.

In pure liquids, surface waves form above some critical flow rate, which is proportional to the viscosity and to the cotangent of the angle of inclination of the slide to the horizontal. Thus with higher viscosities, the critical flow rate is higher and waves are less likely to form. Also, because of the cotangent function, at lower angles the critical flow rate is higher and waves are less likely to form. Surfactants tend to stabilize the flow, and when surfactants are present much higher flow rates are required for surface waves to form.

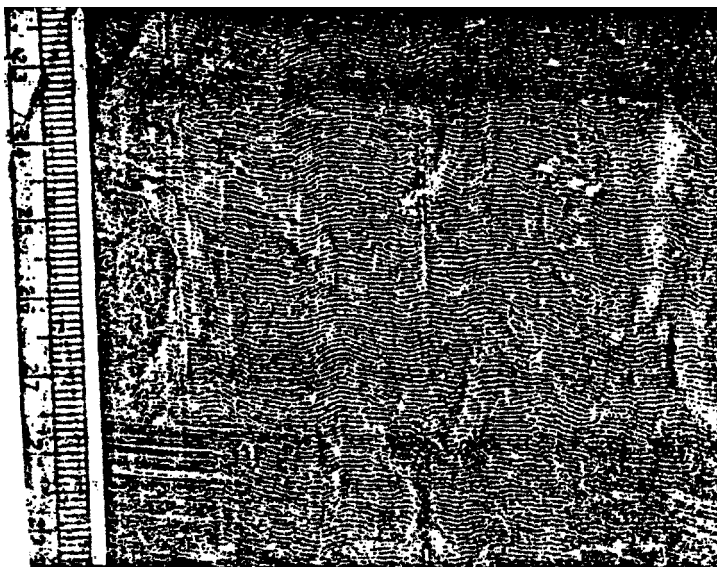


Figure 6-42. Interfacial waves in a three-layer slide coating.

The use of surfactants to dampen waves was known to the ancient Greeks. When a ship was caught on the rocks and in danger of breaking up due to the wave action, the sailors would slowly pour vegetable oil (carried in the amphora they would often transport) over the windward side to calm the waters. The oils are fatty esters of glycerin and are surface active. This is the origin of the expression “pouring oil on troubled waters.”

Because surfactants are always used in aqueous systems, and multilayer coatings are most often aqueous systems, surface waves are rarely seen in slide or curtain coating. However, in multilayer flow, there are interfaces between adjacent layers, and interfacial waves can form. But if all the layers have the same properties, the system would behave as if it were one large layer with no interfaces (as long as there are no interfacial tensions). In this case, there could be no interfacial waves. Density and viscosity are the main physical properties of concern. Densities of aqueous layers do not vary greatly from that of water, and in addition we have little control over them. Kobayashi (1992) concluded that the viscosities of adjacent layers should either be the same, or the upper layer could be more viscous by a factor of up to 1.5 or at most 2, to avoid interfacial waves. Also, one should avoid using an upper layer with a viscosity under 70% of the viscosity of the lower layer. When the upper layer is very much more viscous, well above a factor of 10, the interface again becomes stable. This explains the stability of the flow suggested by Ishizuka (1988), who uses water as a carrier layer with a second layer having a viscosity of 50 mPa-s (cP), giving a ratio of the upper layer viscosity to lower layer viscosity of about 60.

Just as with surface waves, there is greater stability at lower angles of inclination to the horizontal. At lower angles the layers are thicker, and this also gives increased stability to interfacial waves. Coating at higher speeds gives thicker layers because of the higher flow rates, and thus interfacial waves are less likely to occur at higher coating speeds.

These viscosity effects are similar to what was found in flat film coextrusion (Han and Shetty, 1978); see Figure 6-43.

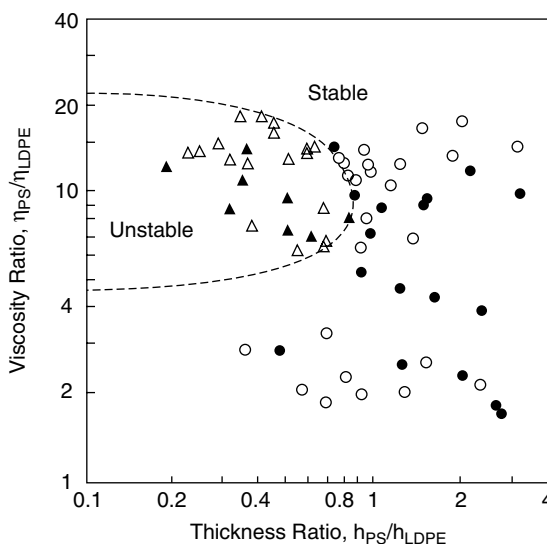


Figure 6-43. Studies on multilayer film extrusion: interfacial instabilities in flat film coextrusion. From C. D. Han and R. Shetty, *Polym. eng. Sci.* 18, 180–186 (1978), with permission of the Society of Plastics Engineers.

Interfacial tensions, where they do exist, tend to stabilize the system against interfacial waves (Kobayashi, 1990).

Although we are unaware of any reports of waves forming in the coating bead, they presumably could form there as well as on a slide. Presumably the cure would be similar as for waves forming on the slide.

Slot coaters and extrusion coaters can also be used for multilayer coatings. We are unaware of reports of waves forming in these systems.

Streaks and Bands in Premetered Coating

Streaks are lines running in the direction of the coating and appear in many forms, but they are visible because they usually have a significantly lighter or significantly heavier coverage than the average value. One example of a streak is shown in Figure 6-44. They can have a variety of widths. Bands are wider than streaks and often differ only slightly in coverage from the rest of the coating. Bands can be caused by broad fluctuations in the slot opening in the coating die, by incorrect tension in the web when coating against unsupported web, by uneven tension in the web, by poor quality web with “valleys” and “ridges” causing flow of the wet coated layer, and, perhaps, even by the system hydrodynamics. Eddies and vortices are also thought to cause streaks and bands.

Particles of dirt carried along by the web and caught in the gap between the coating die and the web can cause streaks. This is less likely to occur with a wide coating gap. If it does occur, a piece of plastic shim stock can be used to sweep the particles to the side. The web used should be clean and free of dirt, and a good web cleaner should be used just before the coating stand.

Particles of dirt and even bubbles that are carried in the coating liquid can get caught inside the coating die—usually in the slot—where they disrupt the flow and cause streaks. If this occurs, the slot should be “shimmed”; a piece of plastic shim stock is inserted into the slot and moved across the width to sweep any particles to one side. With a slot coater the die would have to be pulled back to do this. The coating liquid should be filtered before being delivered to the coating die and an additional coarse, small filter should be placed just before the coating die to remove any particles that break free from the line or from the fittings. Coating dies often have two channels, with the front slot having a greater clearance than the rear slot. Thus any particles large enough to be trapped in the die are more likely to get caught in the narrower rear slot than in the wider front slot. A flow disturbance in the rear slot, such as caused by a trapped particle, is more likely to heal itself by the time it reaches the slot exit than would a disturbance in the front slot.

Particles lighter than the coating liquid, especially bubbles, can float in the bead of a slide coater and not get carried off onto the web by the coating liquid, causing streaks. If this occurs, one should “shim” the gap and sweep the bubbles or particles to the side with a piece of plastic shim stock.

Nicks in the coating die can cause streaks. Even though the coating die may be made of stainless steel, the edge is very delicate and the die should be handled as if it were made of the finest crystal. The edges, especially, are easily damaged, and a damaged edge will cause a streak. Nicks can be “stoned” out with a whetstone (an abrasive stone), but this rounds the edge. A round edge does not pin the meniscus tightly and can cause chatter at wider gaps. When the edge gets too rounded, above about 50–100 μm (2–4 mil) in radius of curvature, the coating die has to be refinished (by grinding or lapping).

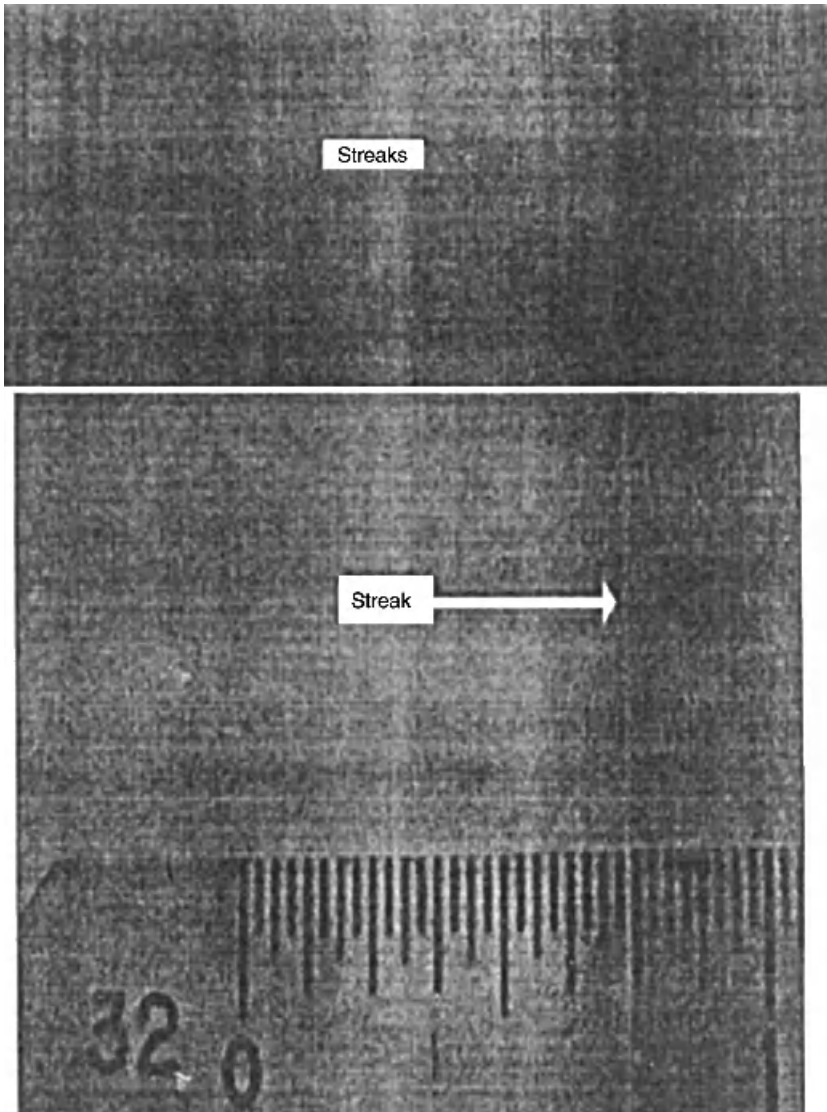


Figure 6-44. Streaks in a coating.

Coating liquid flowing under the front edge of the slide coater can cause streaks, as shown by Ishizuka (1988); see Figure 6-45. Liquid in this region is likely to form vortices or eddies. This disturbance to the flow may be the cause of streaks. Liquid will enter this region when the bead vacuum is too high or the gap is too wide for the given coating liquid and speed. Less bead vacuum must be used for low-viscosity liquids, for wide gaps, and for low coating speeds.

Streaks can also be formed in slide and in curtain coating by liquid from an upper slot flowing into an incompletely filled lower slot, as in Figure 6-46 (Ishizuka, 1988). This rarely occurs, because in order to obtain a reasonable minimum pressure drop across the slot, the slot opening would be narrow enough to prevent this from occurring. However, in

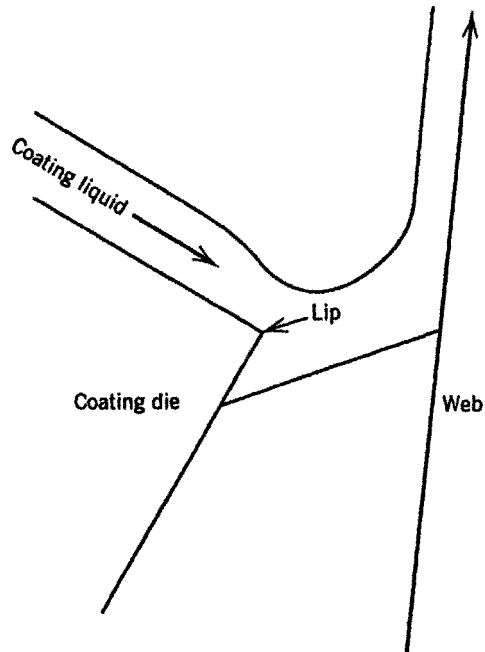


Figure 6-45. In slide coating, liquid flowing below the lip can cause streaks (Ishizuka, 1988).

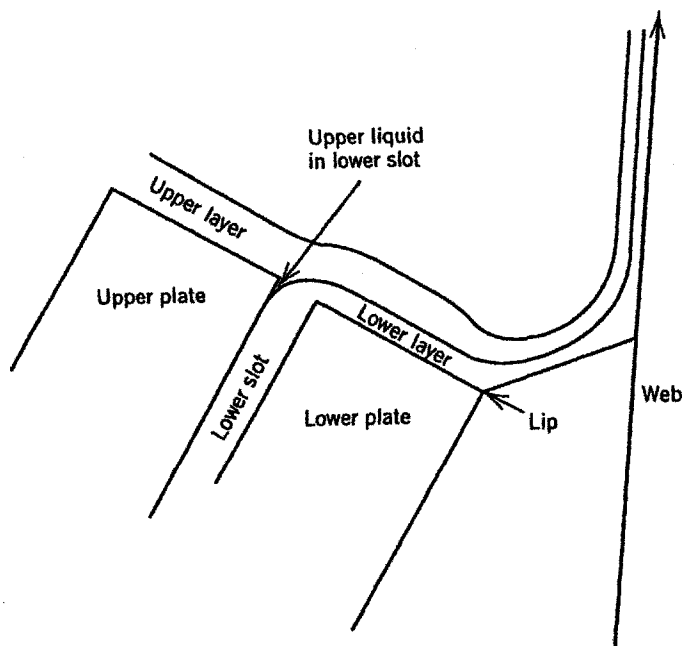


Figure 6-46. In slide and curtain coating, liquid flowing into an incompletely filled lower slot can cause streaks (Ishizuka, 1988).

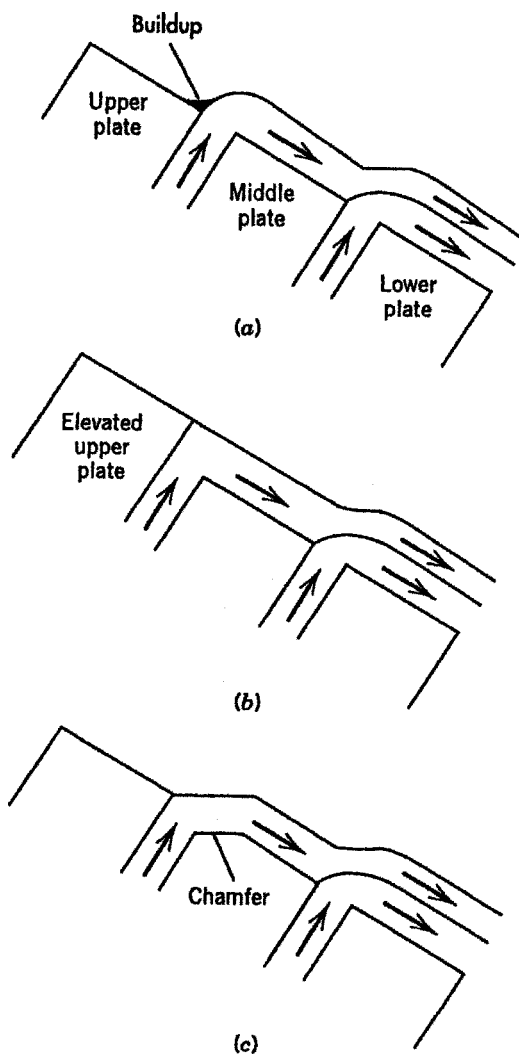


Figure 6-47. Preventing runback and buildup on the top plate of a slide or curtain coater. (a) Buildup formation. Buildup prevented by (b) elevating the top plate or (c) chamfering the lower edge of the top slot (Ade, 1978).

very thin layers of low-viscosity liquids, such as carrier layers, one could inadvertently use a wide slot designed for higher flow rates of more viscous liquids.

The coating fluid can dry up under the coating bead, and also on the top plate of a slide or curtain coater, and thus disturb the flow and cause a streak. If this occurs, the buildup has to be washed off. If the buildup is under the bead, the coating die first has to be withdrawn. Latex layers are often coated, and they are known to build up aggregates under the coating lip and cause streaks. Huang and Nandy (1993) found that latex particles that have more carboxylic acid groups on them, and therefore swell more as the pH is raised to 7.0, have a greater colloidal stability and a greatly reduced tendency to form streaks. Buildup on the top plate can be prevented by elevating the top plate to about the height of

the flowing layer, so that the liquid does not run up over the edge (Figure 6-47). Ade (1978) suggests chamfering the lower edge of the top slot (Figure 6-47c), to get the same effect.

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7

COATING PROBLEMS ASSOCIATED WITH COATING DIE DESIGN

The assumption made in all coating operations is that the coating device will lay down a wet coating that is completely uniform across the web and is free of all defects. Unfortunately, this is often not the case. This chapter explores some of the problems with coating dies; more specifically, with coating dies for slot, extrusion, slide, and curtain coating. With slot, slide, and curtain coating, a coverage variation of under $\pm 2\%$ can be achieved without too much difficulty, and we explore what is necessary to achieve this uniformity. In extrusion coating, this level of uniformity normally cannot be attained. We also explore how to achieve a more uniform residence time distribution and, when it may be desirable, how to maintain a minimum wall shear stress and why one might want to do this, how to clean the coating die, and how to change the coating width without changing the coating die. Down-web or machine direction variability is discussed in the section on *Chatter* in Chapter 6.

CROSS-WEB UNIFORMITY

The internals of slot, slide, and curtain coating dies are all relatively similar. We now refer to the internals of a slot coating die, as in Figure 7-1. In slide coating, the plates are tilted upward and the slot exits onto an inclined plane (Figure 7-2). In precision curtain coating, the coating fluid flows off the inclined plane to form a curtain that falls down onto a horizontally moving web, as in Figure 7-3. In all these systems, the die internals should be built to give a uniform flow across the width of the coating, and not with the crown in the profile shown in Figure 7-1. The die should not be adjustable because adjustable coating dies are very difficult to adjust accurately, and uniformities of $\pm 2\%$ are almost impossible to attain with them. By a $\pm 2\%$ uniformity we mean that the coefficient of variation of the coverage across the web—that is, the standard deviation of the cross-web coverage divided

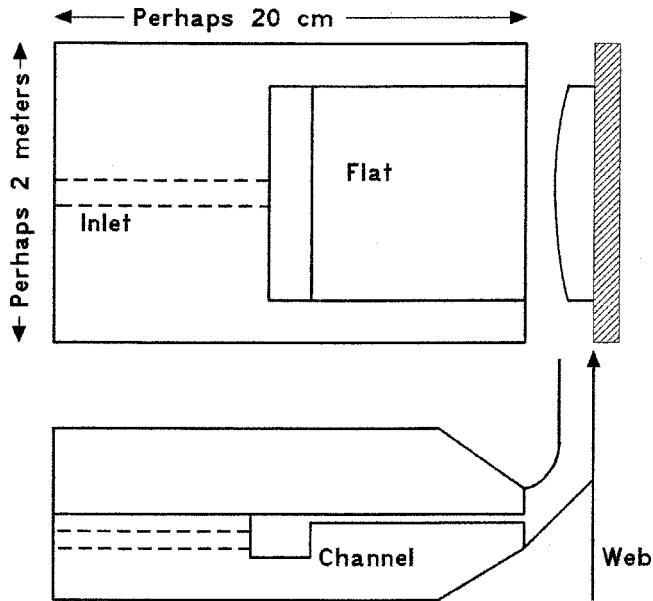


Figure 7-1. Slot coating die showing the coverage profile with uncorrected internals. Reprinted from E. B. Gutoff, *J. Imag. Sci. Techn.* 37, 615-627 (1993), with permission of IS & T, The Society of Imaging Science and Technology, sole copyright owners.

by the mean—is no greater than 2%. Nonadjustable dies are routinely used to coat low-viscosity liquids, under some thousands of mPa-s (cP). The coating dies should be made so that they can be assembled only one way, thus ensuring that they are always assembled correctly. Extrusion coating dies, because they are normally used for many different

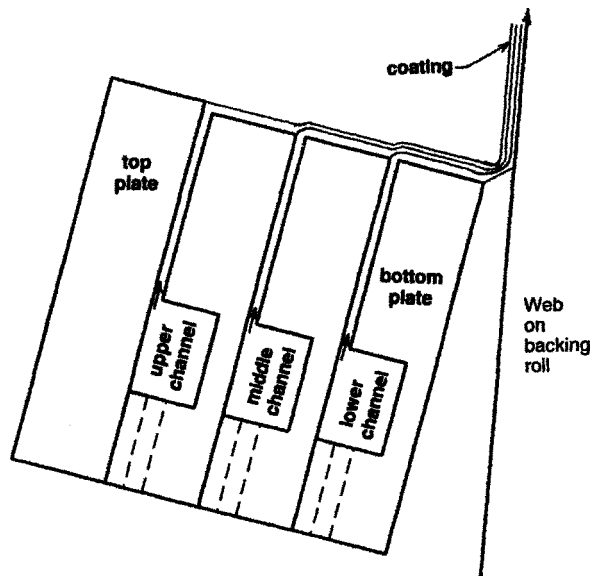


Figure 7-2. Slide coating.

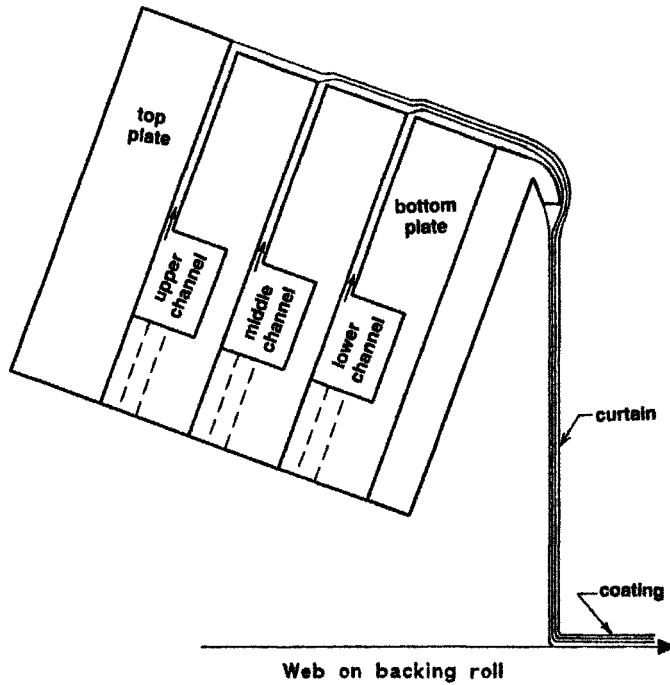


Figure 7-3. Curtain coating.

high-viscosity liquids with varying rheologies such as polymer melts, are always adjustable and these are discussed separately.

Let us examine the slot coating die in Figure 7-1. Coating liquid enters the center of the distribution channel and flows down the channel toward both edges while flowing out through the slot clearance to exit at the coating lips. If the slot length—the distance from the channel to the front lips—is constant, and if the slot clearance is everywhere constant, then the flow through the slot at any point along the width will be proportional to the pressure drop from the channel to the atmosphere. But the pressure at the feed entrance, the center of the channel, has to be higher than at the ends of the channel in order to cause flow in the channel from the center to the edges. Because of this, the flow out of the slot at the center will be greater than the flow out of the slot at the edges, and the wet coating will be thicker at the center, as shown in Figure 7-1. This crown in the profile is sometimes called a “frown” profile. The opposite situation, when the coverage is low in the center and higher near the edges, gives a “smile” profile. The die internals are usually altered or corrected to give a uniform profile, but it is important to know when an uncorrected die can be used and still give a sufficiently uniform coverage across the web—that is, to know what is the coverage variation in an uncorrected die.

Carley (1954) studied the coverage variation in an uncorrected die, and his results can be plotted as in Figure 7-4, where the percent error is the coverage variation from the center to the edge. For a simple Newtonian liquid, the error is only a function of C , a grouping of geometric parameters equal to

$$C = \frac{8H^3W^2}{3\pi LD^4}$$

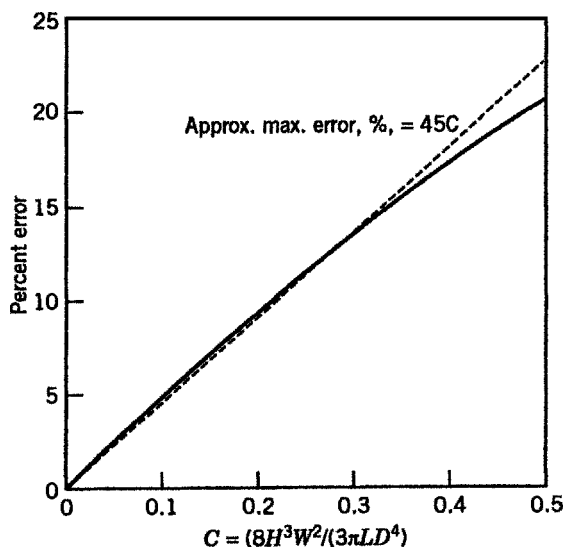


Figure 7-4. Coverage error for Newtonian liquids in an uncorrected die. See text for nomenclature. Reprinted from E. B. Gutoff, *J. Imag. Sci. Techn.* 37, 615-627 (1993), with permission of IS & T. The Society of Imaging Science and Technology, sole copyright owners.

where D is the equivalent diameter of the channel, H is clearance in the slot, L is length of the slot from the channel to the lips, and W is the width of the coating (for a side-feed die, this would be twice the width of the coating).

All these measurements have to be in the same units, such as millimeters or inches. The curve in Figure 7-4 can be accurately approximated in the region of interest by the linear relationship (Gutoff, 1993)

$$\text{Fractional error} = 0.45C$$

Thus for simple (Newtonian) liquids, it is easy to calculate whether a given uncorrected die design will give the necessary coverage uniformity. We would suggest that, if a $\pm 2\%$ uniformity is desired, the calculated uniformity should be no worse than 0.5%, or at most 1%, to allow for other sources of error.

Note that the side-to-side coverage variation for Newtonian liquids is only a function of the geometry of the coating die and is independent of the liquid viscosity and flow rate. Now obviously the flow rates and the viscosity are important to the coating die design. For a given geometry, the pressure drop across the coating die from the channel to the exit, equal to the gauge pressure in the channel, is directly proportional to the viscosity and to the flow rate. If the viscosity or the flow rate is too high, then the internal pressures will be excessive, and the die may spread apart or the feed system may not be able to supply coating liquid at the desired flow rate. A wider slot opening or clearance would be required to lower the pressure drop in the slot, and thus lower the internal pressure in the channel. As the height of the slot opening is raised to the power of 3 in the equation above for the geometric grouping C , this would greatly increase C and thus the coating nonuniformity unless the channel is also made larger.

If the viscosity or the flow is too low, the pressure in the die may be so low that gravity will become important, and the liquid will just dribble out of the slot unevenly. In this case,

a narrower slot opening or clearance should be used. Also, if the pressure is too low, inertial effects—the kinetic energy in the moving liquid—may become significant compared to the pressure in the die, and this is undesirable for the coating die to be versatile and usable with different viscosities and flows. The minimum pressure needed to ensure that the inertial effects are insignificant is discussed below.

When the pressure in the die is too low in slide and in curtain coating, liquid from an upper layer can fall into the incompletely filled slot. This can result in streaks being formed, as shown by Ishizuka (1988). This was illustrated in Figure 6-46 for slide and curtain coating.

Since the channels in coating dies are usually not round but often are rectangular in cross section, the equivalent diameter of a rectangular channel needs to be found. If the channel width and height are a and b , where a is the larger dimension, then the equivalent diameter is $D = g(b/a)a$, where the function $g(b/a)$ is tabulated in Table 7-1 (Gutoff, 1993).

For non-Newtonian liquids, where the viscosity is not constant but depends on the shear rate, the coverage errors are considerably larger and the simple relationship given above is no longer reliable. The shear rate can be thought of as the motion of a sheet of fluid relative to an adjacent sheet. It is defined as the rate of change of velocity with distance in the direction perpendicular to the motion, such as the rate of change in a channel as one moves away from the channel walls. Shear rates were discussed in Chapter 6, and a common type of shear-thinning behavior was shown in Figure 6-24. When the a plot of the logarithm of viscosity against the logarithm of shear rate is a straight line, as in the central section of Figure 6-24, then the liquid is called a power law liquid, and the viscosity can be expressed as

$$\mu = K\gamma^{n-1}$$

where K is the consistency, equal to the viscosity when the shear rate is unity; n is the power law index, γ is the shear rate, and μ is the viscosity.

TABLE 7-1 Values of $g(b/a)$ for Calculating the Equivalent Diameter of Rectangular Channels^a

b/a	$g(b/a)$
0.1	0.2375
0.2	0.3925
0.3	0.5222
0.4	0.6350
0.5	0.7346
0.6	0.8231
0.7	0.9021
0.8	0.9728
0.9	1.0364
1.0	1.0939

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Note: a is the larger dimension, normally the channel width; b is the smaller dimension, normally the channel height. The equivalent diameter is $D_e = g(b/a)a$.

The coverage error is now a function of the power law constant n , as well as the geometric factors, but is not a function of the consistency, K . The coverage errors in an uncorrected die when using a power law fluid have been reported (Gutoff, 1993, 1994).

The power law relationship had been used relatively frequently because it is the simplest relationship for non-Newtonian behavior, which can be handled mathematically relatively easily, even though it covers only a portion of the viscosity–shear rate curve and does not include viscoelasticity. Today, with powerful personal computers everywhere, it is relatively easy to find numerical solutions involving complex rheological behaviors.

TEMPERATURE CONTROL

The calculation of the coating nonuniformity in an uncorrected die assumes a constant viscosity, and the viscosity will be constant only if the temperature is constant. If the coating is made at room temperature, the coating liquid should be at room temperature. If the coating liquid is stored at a different temperature, it should be brought to room temperature before the start of coating. If coating is carried out at elevated temperatures, as may be necessary, the coating liquid and the coating die should be brought to the coating temperature before coating.

The coating liquid can be brought to the coating temperature in the feed vessel, or it can be brought to coating temperature in the line from the feed vessel to the coating die using a heat exchanger. For moderately elevated temperatures, a simple technique is to pump the liquid through jacketed lines through which hot water is flowing. The temperature of the coating liquid should be measured as it enters the coating die, and the jacket water flow or temperature should be adjusted if needed. One should not assume that because the jacket water is at the coating temperature, the coating liquid is at the coating temperature. Also, if the coating liquid is heated to the coating temperature in the feed vessel, the circulating water in the jacket should be at the coating temperature to prevent the liquid from cooling in the lines.

The coating die should also be at the coating temperature. When coating is done at other than room temperature, there are several techniques commonly used to do this. One is to circulate water or another heat transfer fluid through holes bored through the plates of the coating die. This works quite well but complicates the die and the die assembly. Another technique for moderately elevated temperatures is to enclose the coating stand in a small, temperature-controlled room. This can be used for temperatures up to about 40 or perhaps even 50 °C. The room has to be at that temperature many hours before start-up, as the die reaches the desired temperature very slowly. Also, operators are not happy working at such elevated temperatures, and this technique should be considered only when the coating die is normally unattended. Electrical heaters in and around the coating die can also be used. Uniform temperature control is more difficult with electrical heaters, but this method is commonly used for the high temperatures needed with polymer melts in extrusion dies.

The temperature of the coating liquid in the coating die should be the same everywhere in order for the viscosity to be the same. Because the flow rate is directly proportional to the viscosity, we can specify how much viscosity variation can be tolerated. We suggest that the flow variation caused by viscosity variations should be no more than 0.25%, or at most 0.5%. This can then be used to set the allowable temperature variation. But first one should determine how the viscosity varies with temperature. Figure 7-5 shows typical

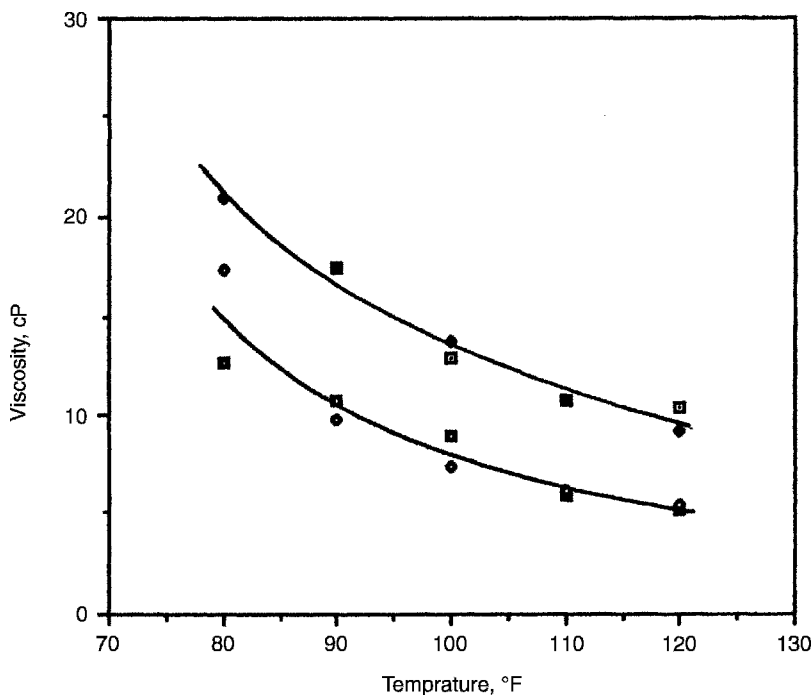


Figure 7-5. Variation of viscosity with temperature for some coating liquids containing gelatin.

curves of viscosity versus temperature for several coating liquids containing gelatin. One should measure the viscosity at the coating temperature, and then at 5 °C (or °F) above and below the coating temperature. A smooth curve can then be drawn through the three points, and from this curve viscosity variation should be found for a one degree temperature variation. It is then simple to determine the temperature variation that would cause a 0.25% or a 0.5%, or whatever, viscosity variation.

If it is found that in the vicinity of the coating temperature the viscosity varies 1% per degree Celsius temperature change (this is a reasonable value), and if we want to control the viscosity to within $\pm 0.25\%$, then we would have to control the temperature to within $\pm 0.25^\circ\text{C}$. This temperature control is about the best that can be attained with good controls and without going to extreme measures.

As the coating liquid can have a different temperature at the center of the coating line from the temperature at the wall, and as the liquid in the center may go to a different part of the coating die than the liquid at the wall, the liquid should be mixed just ahead of the coating die. Either static (motionless) mixers or dynamic mixers should be used to do this. These mixers also remove any stratification that may have occurred in the lines.

CORRECTIONS TO THE COATING DIE INTERNALS

If the error in the uncorrected die is excessive, the internal shape has to be changed so as to give a uniform flow across the width. The methods of doing this are described in texts such as the one by Tadmor and Gogos (1979). In principle, the slot length from the channel to

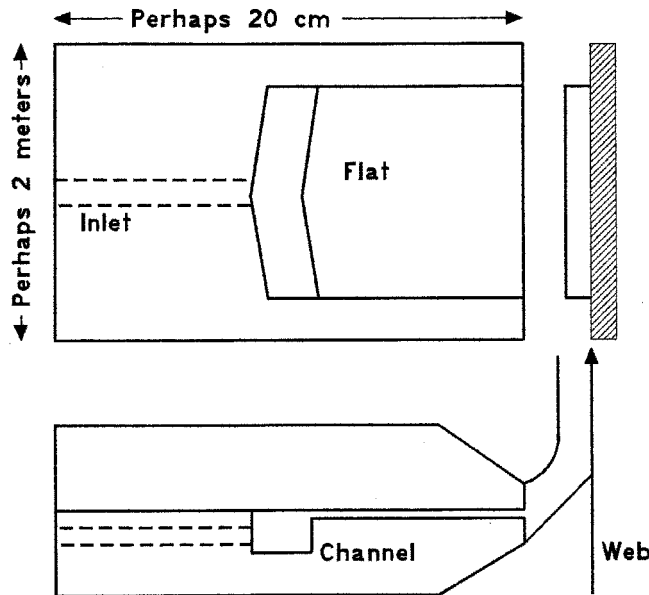


Figure 7-6. Slot coating die corrected to give a uniform flow. From E. B. Gutoff, *J. Imag. Sci. Techn.* 37, 615-627 (1993), with permission of IS & T. The Society of Imaging Science and Technology, sole copyright owners.

the die lips has to be changed so as to be shorter at the edges, schematically illustrated in Figure 7-6. When inertial effects can be neglected, one can calculate how to do this for both Newtonian and power law (shear-thinning) liquids using a relatively simple equation for the slot length given by Gutoff (1993). The fractional correction to the slot length at the edges can be used as an approximation to the error in an uncorrected die. A very accurate, finite element technique for calculating the complete flow is described by Sartor (1990) in his Ph.D. thesis under Professor Scriven at the University of Minnesota. Scriven heads up a large research group there studying coating flows, drying, and coating die design. Vrahopoulou (1991) gives a finite difference technique that appears to be simpler.

Instead of varying the shape of the channel so that the slot length is less near the edges than in the center, one die manufacturer corrects dies by varying the slot height so that it is greater near the edges than in the center.

DIE INTERNAL PRESSURES AND SPREADING

As mentioned earlier, there are both low and high limits on the pressures in the coating die. On the low-pressure side the liquid will just dribble out unevenly, and gravity will become important. Also, if inertial effects are neglected in the design, the pressure in the channel should be such that the pressure effects due to inertia are negligible. Whenever possible, the inertial effect should be neglected in the design in order that the coating die can be versatile and usable with different liquids of different viscosities and at different flow rates. Now the pressure rise due to the loss of the inertia of the fluid flowing down the channel when it makes a 90° turn into the slot may be about ρV^2 , where V is the average velocity in the channel near the feed entrance and ρ is the density. (It is easy to show that

ρV^2 has units of pressure. Thus, in SI units, and introducing Newton's second law to convert between force and mass,

$$\rho V^2 = \frac{\text{kg}}{\text{m}^3} \left(\frac{\text{m}}{\text{s}} \right)^2 \frac{\text{N} - \text{s}^2}{\text{kg} - \text{m}} = \frac{\text{N}}{\text{m}^2} = \text{Pa}$$

Pascal is the SI unit of pressure.) We may then specify that the pressure in the channel be high enough that the inertial pressure is only some small fraction of it, say, 0.0025 ($\frac{1}{4}\%$). Thus, if the inertial pressure (ρV^2) in the channel at the feed entrance is 80 Pa, then the minimum pressure in the channel should be 80 Pa/0.0025, or 32,000 Pa, or 4.6 psi.

The pressure in the channel is equal to the pressure drop in the slot, and for simple (Newtonian) liquids this is

$$\Delta P = \frac{12\eta qL}{H^3}$$

where H is the slot height or clearance (in cm) L is the length of the slot (cm), q is the flow rate per unit width ($\text{cm}^3/\text{s} - \text{cm}$ of width), and η is the viscosity (poise).

Any consistent set of units can be used; cgs units are given above, and the pressure drop will then be in dyn/cm^2 . To convert dyn/cm^2 to pascal units one should divide by 10. To convert pascals to pounds per square inch one divides pascals by 6895.

The maximum pressure is limited by the strength of the die. If the internal pressure in the channel is 1 MPa (150 psi), and the die is 1 m wide with a combined length of the slot plus channel of 10 cm, and we say the average pressure in the die is half the maximum pressure, then the spreading force will be

$$\frac{10^6 \text{Pa N}/\text{m}^2}{2} \frac{\text{Pa}}{\text{Pa}} (1 \text{ m wide})(0.1 \text{ m deep}) = 50,000 \text{ N or } 11,000 \text{ pounds}$$

A die has to be massive to resist this force. And even then, it is difficult to prevent the slot clearance from opening up in the center region of the die. Therefore the dies that are not adjustable are only suited for relatively low-viscosity liquids, where the internal pressures to force the liquid out the slot are relatively low, often under 100 kPa (15 psi).

EXTRUSION DIES

Although some engineers use the terms interchangeably, we distinguish between extrusion coating and slot coating by noting that in slot coating the coating liquid wets the lips of the die (see Figure 7-1), while in extrusion coating the lips are not wet, as shown earlier in Figure 6-1. In extrusion coating, the viscosities are high, ranging up to the millions of $\text{mPa} \cdot \text{s}$ (cP). The pressures in the die are high and the pressure drops in the channels are high. Because of these high pressure drops in the channels, the corrections have to be large, leading to the "coat-hanger" design (Figure 7-7b). Because these dies are used for fluids with differing rheologies (shear-thinning behaviors), the corrections that are good for one liquid are often not good for another. For this reason, and because the high internal pressures tend to spread open the slot clearance even with massive dies, the slot openings are made adjustable at the front edge. In addition, adjustable choker bars may be used further back. The adjustments are made with bolts at least every few inches along the width of the die (Figure 7-8). As it is very difficult and

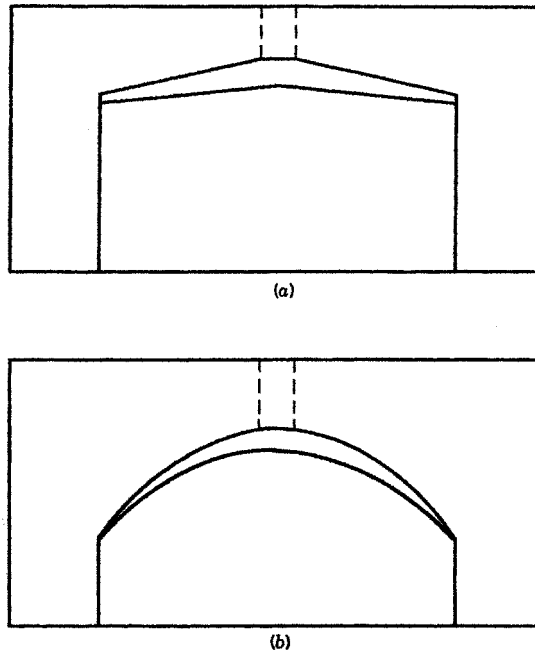


Figure 7-7. The bottom plate of dies with tapered channels: (a) slot coating die and (b) extrusion die of coat-hanger design. Part (b) is from E. b. Gutoff *J. Imag. Sci. Techn.* 37, 615-627 (1993), with permission of IS & T, The Society of Imaging Science and Technology, sole copyright owners.

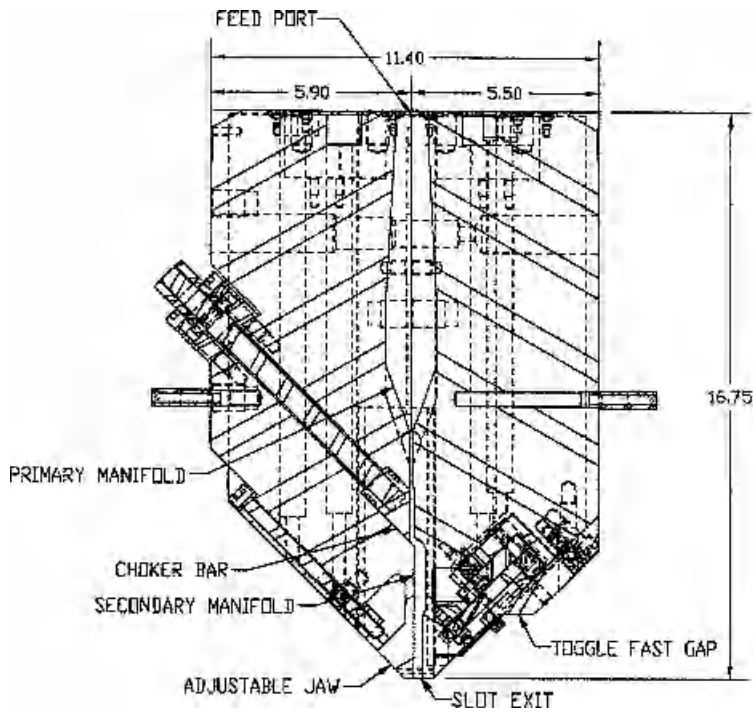


Figure 7-8. Ultraflex HRC-75 Coaterhanger Manifold, with adjustable jaw and choker bar. From Extrusion Dies Industries, LLC, with permission.

time consuming to manually adjust all of these bolts to obtain a reasonably uniform cross-web coverage, an on-line sensor can be used to measure the cross-web coverage and, using a computer, to correctly adjust the slot opening and/or the choker bars. In some cases the adjusting bolts can be heated or cooled, and thermal expansion is used to adjust the bolt lengths.

WALL SHEAR STRESS CONTROL AND RESIDENCE TIME CONTROL

By stress we mean the force per unit area of material. Most of us are familiar with tensile and compressive stresses. A tensile stress is illustrated in Figure 7-9a and is equal to the force, F , tending to pull the rectangular rod apart divided by the area, wh , perpendicular to the force. A shear stress is illustrated in the Figure 7-9b, as the force, F , pulling the box along the surface divided by the contact area, wh , which is an area parallel to the force. For shear stress in a liquid, one can imagine a slot coating die W meters wide with a slot height of H meters and slot length of L meters. If the average pressure in the channel is P pascals, then the force in newtons, equal to pressure times area, is

$$F = PHW$$

and the wall shear stress in the liquid, equal to the force divided by the area parallel to flow, is, neglecting edge effects,

$$\tau_w = \frac{PHW}{2HL} = \frac{PW}{2L}$$

In some operations one wants to be above a minimum wall shear stress in all parts of the coating die in order to prevent accumulations of material on the wall, especially if the coating liquid has a yield stress and tends to set up as a gel. Even when the liquid does not form a gel, one may want a minimum shear stress to prevent particles from settling out

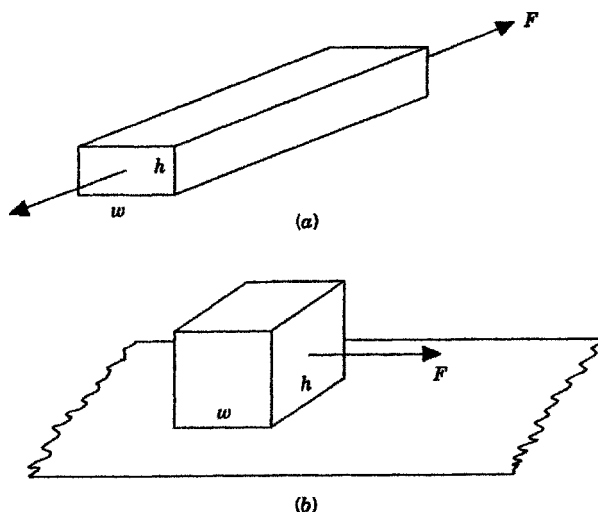


Figure 7-9. (a) Tensile stress and (b) shear stress. In each case the stress is F/wh .

onto the wall. With laminar flow—in coating dies the flow is normally laminar and not turbulent—the wall shear stress is directly proportional to the liquid viscosity and to the flow velocity, and inversely proportional to the diameter of the channel. Thus, as we move away from the feed port and down the channel toward the edges and the flow rate decreases because of the flow into the slot, the equivalent diameter of the channel will have to decrease in order to maintain a minimum wall shear stress. This will give rise to the tapered channel shown in Figure 7-7. This is sometimes used in slot coating dies and is the basis for the coat-hanger design in extrusion dies.

Residence time control can also be important. In some but not all operations, the properties of the coating liquid deteriorate with time, and thus no liquid should remain in the coating die for excessive periods of time. Especially in such cases, there should be no dead areas where fluid does not move at all; there should be no areas where vortices form and fluid moves in closed circles and is only replaced very slowly; and the fluid velocity should not drop too low to the point where the transit time down the channel is excessively long.

The first two of these three criteria apply to all good designs. There should be no dead areas in a good design, and there should be no vortex formation in a good design. The third or transit time criterion would apply only where residence time control is important.

The avoidance of dead areas is relatively simple and is accomplished by avoiding dead-ended spaces. The avoidance of vortices is more difficult and is often not obvious. Figure 7-10 gives examples of vortex formation in some flow situations. Streamlining is a general means to avoid vortices. To predict vortex formation, one usually has to use

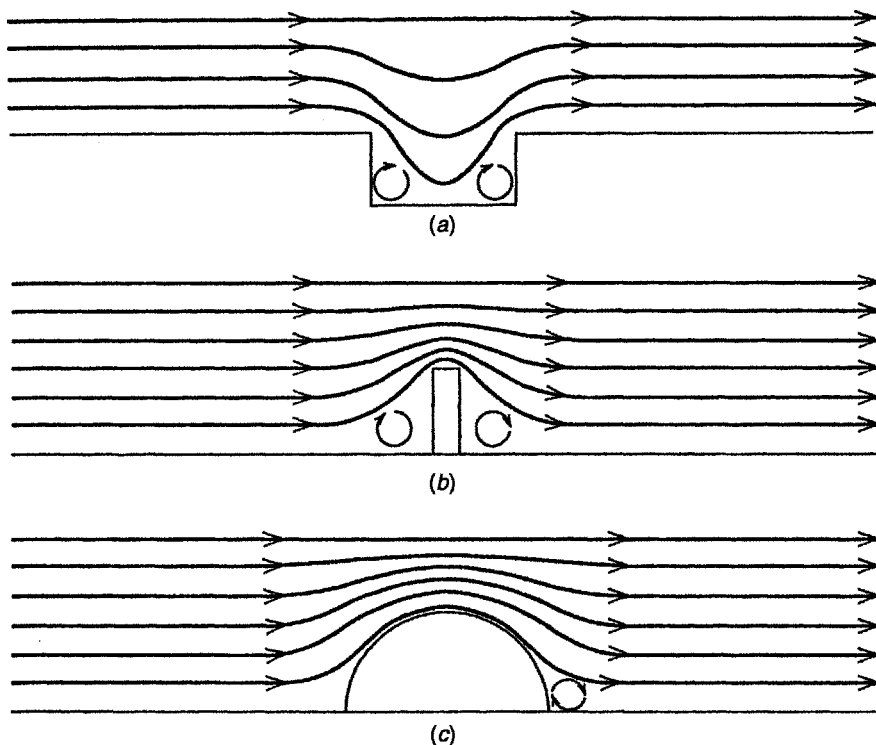


Figure 7-10. Vortex formation in some flows: (a) flow over a rectangular hole, (b) flow over a vertical plate, and (c) flow over a hemisphere.

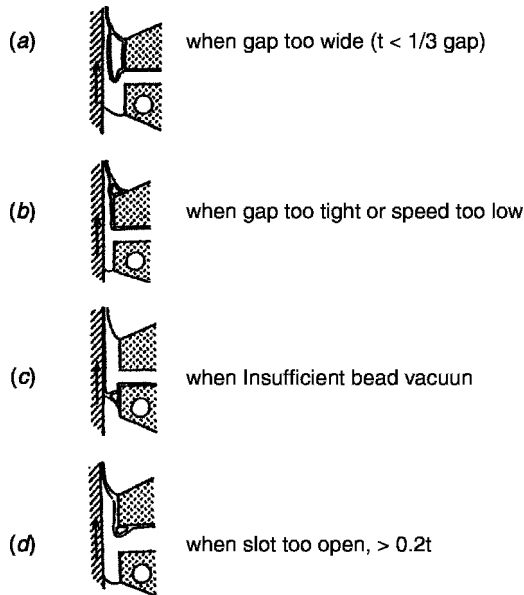


Figure 7-11. Vortex formation in slot coating dies. From Sartor (1990), with permission of the author.

involved numerical techniques such as finite element analysis. Sartor (1990) has done this for slot coating dies. Figure 7-11 shows some results of his study of vortex formation in the exit slot. The ideal situation is to have no vortices. The most common type of vortex formation is along the upper meniscus, between the upper lip and the web, shown in Figure 7-11a, which occurs when the gap is too large, more than three times the wet coated thickness. When the gap is too tight relative to the wet thickness, or the coating speed is too low, then the liquid can wet the shoulder of the upper die lip, as in Figure 7-11b, and a vortex will form there. At very low coating speeds vortices cannot be avoided; either the vortex as in Figure 7-11a, due to a wide gap, or the vortex as in Figure 7-11b, due to a tight gap, will form. Only at higher speeds can both types of vortices be avoided. If the coating liquid retreats from the lower edge into the slot, as in Figure 7-11c, then a vortex will form near the lower meniscus. If the die surface were nonwetting, this vortex might not form. More bead vacuum will pull the meniscus back to the lower edge and eliminate this vortex. When the feed slot opening is too large, more than five times the wet film thickness, then a vortex may form at the exit of the feed slot, as in Figure 7-11d. It always forms when the feed slot opening is greater than 0.2 times the wet film thickness. The different vortices can sometimes join and combine to form one large vortex.

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8

SURFACE TENSION DRIVEN DEFECTS

In coating operations the coating liquid is spread out as a thin layer on a moving web, thus creating large surface areas. These surfaces, have surface forces associated with them, as does every surface. These surface forces are called *surface tensions* and tend to reduce the areas of the surfaces. They can be the cause of a number of defects that occur in coating operation, such as convection or Bénard cells, craters, fat edges or picture framing, nonuniform edges in multilayer coating, dewetting and crawling, adhesive failure and delamination, and nonuniform coverage due to nonuniform base surface energies. This chapter explains these defects and their origins and possible remedies for them. It also explains the use of surfactants to alter surface tensions, and how surfactants affect these defects.

All systems tend toward a state of lowest energy, and to minimize the surface energy the systems tend to minimize the surface area. As spheres have the smallest surface area for a given volume, small volumes of fluids tend to have spherical shapes—thus drops and bubbles tend to be spherical. Surface tension is illustrated in Figure 8-1. The Greek letter σ (sigma) is frequently used to represent surface tension, while at other times the Greek letter γ (gamma) is used. If we imagine we are pulling the surface of a bubble or drop in the direction of the surface arrows in Figure 8-1, we see that there will be created an extra force directed inward, making the pressure on the inner or concave side of the curved interface higher than on the outer or convex side. The pressure difference across a curved interface is called *capillary pressure*. Thus the pressure inside drops and bubbles is higher than on the outside. This concept of capillary pressure is used to explain the shape of some cylindrical liquid surfaces in coating operations (Gutoff, 1992).

Surface tension and surface energy are sometimes used interchangeably. The term surface tension, in units of force per unit length, and the term surface energy, in units of force times distance per unit area, are equivalent. Surface tension is expressed as dyne/cm

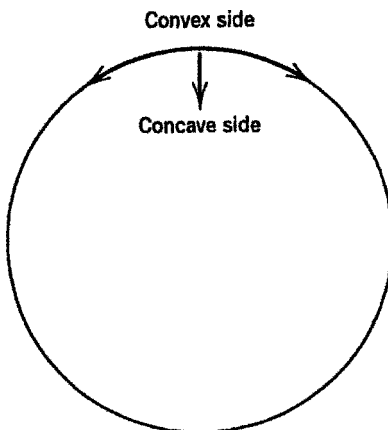


Figure 8-1. The concave side of a curved interface has a higher pressure than the convex side.

or, equivalently, as mN/m (millinewtons per meter). Now when we multiply dyne/cm by the unit factor of cm/cm

$$\frac{\text{dyne cm}}{\text{cm cm}} = \frac{\text{erg}}{\text{cm}^2}$$

we get erg/cm², which is energy per unit area, and when we multiply mN/m by the unit factor of m/m

$$\frac{\text{mN m}}{\text{m m}} = \frac{\text{mJ}}{\text{m}^2}$$

we get mJ/m² (millijoules per square meter), which also is energy per unit area. Numerically, all four of these terms are the same.

When we speak of liquids we usually refer to *surface tension*, but in reference to solids we often refer to *surface energy*, as it may be more difficult to visualize an undisturbed solid surface being in a state of tension. It may be easier to conceive of the surface of a solid as having a surface energy. But this is strictly a matter of personal preference.

SURFACTANTS

We cannot discuss surface tension without discussing surfactants, which are used to lower surface tensions. Surfactants—the term represents a contraction of *surface active agents*—consist of relatively long molecules. One part of the surfactant molecule is soluble in the solvent (usually water) and the other part is insoluble. Because of this dual nature, the molecules tend to concentrate at the surface of the liquid (or at an interface with a solid), where the soluble portions will remain down in the liquid and the insoluble parts will stick up in the air (or against a solid surface). Because the molecules congregate at the surface, they are called surface active. The insoluble portions of the molecules, which now cover the surface, have a lower surface tension than the solvent, and so the system surface tension is lowered.

Normally the insoluble portion of the surfactant molecule carries no electrical charge, and the soluble portion may or may not carry a charge. In *nonionic* surfactants the soluble portion has no charge; the solubility in water is conferred by un-ionized oxygen groups, such as ether linkages. In *anionic* surfactants water solubility is conferred by negatively charged groups, such as carboxylic or sulfonic acid groups. Electrical neutrality is maintained by positively charged ions (cations) such as hydrogen or sodium ions. Once the surfactant is in water it ionizes, meaning that these counterions, such as sodium or hydrogen, split off and are delocalized; that is, they “swim” around in the water and are not attached to a particular molecule. In *cationic* surfactants the water-soluble portion has a positive charge, such as by salts of derivatives of ammonia (quaternary ammonium salts and salts of amines). The counterions are now negatively charged anions such as chloride or bromide ions.

Because part of the surfactant molecule is insoluble in the solvent, the bulk concentration of surfactant remains low while the surface concentration is much higher. Once the surface is fully covered with surfactant, and the surface tension is as low as it will get, additional surfactant has to go into the bulk solution. But because portions of the molecules are insoluble, most surfactant molecules will come together to form *micelles*, with the insoluble portions of the molecules facing each other in the interior, and the soluble portions “sticking out” into the solvent. The concentration at which this occurs is called the *critical micelle concentration* and is often written as CMC. The critical micelle concentration can be found from a plot of surface tension versus concentration. The surface tension levels off at the critical micelle concentration. We usually want the surfactant concentration to be above the critical micelle concentration.

Surfactants may be added to coating liquids for other reasons than to provide good wetting of the web. Often coating liquids contain latices or dispersed solids. Surfactants are usually present as dispersing agents, to prevent the solids particles from flocculating and to prevent coagulation of the latex particles.

For more information on surface tension and its measurement, and on surfactants, one should consult any of the many good books available. One that the authors recommend is Adamson (1982).

SURFACE TENSION EFFECTS IN COATING

Surface tension plays a very important role in wettability. For a liquid to wet a surface, its surface tension has to be low relative to the surface energy of the solid. We can demonstrate this by looking at the surface forces acting at the edge of a wet coating on a plastic web, as in Figure 8-2. At equilibrium the forces acting to the left are balanced by the forces acting to the right. With these thin films we may neglect the force of gravity. There is only one force acting to the left, the surface tension or, if you will, the surface energy, of the plastic base. Acting to the right is the horizontal component of the surface tension, plus the interfacial tension between the solid and the liquid. If the liquid on the surface is to spread to the left, the forces to the left must be greater than the forces to the right. Thus we want the surface energy of the plastic base to be high, the surface tension of the liquid to be low, and the interfacial tension between the solid and the liquid also to be low. With aqueous solutions we add surfactants to lower the surface tension, as the surface tension of water is very high, 72 mN/m (or dyne/cm). Surfactants also tend to lower the interfacial tension. Also, for coatings of aqueous solutions, we often increase the surface energy of the base by oxygenating the surface. The oxidized surface has a higher

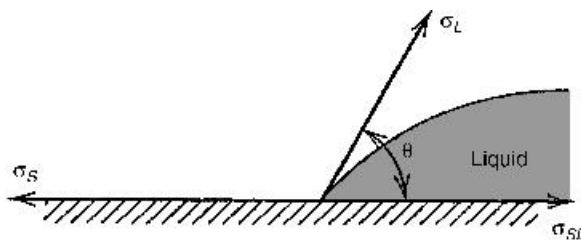


Figure 8-2. Surface forces at the edge of a wet coating. σ_L is the surface tension of the liquid, σ_S is the surface energy of the solid, and σ_{SL} is the interfacial tension. For spreading to occur, the force to the left, σ_S , must be greater than the forces to the right, $\sigma_{SL} + \sigma_L \cos \theta$.

surface energy than the unoxidized plastic. Impurities on the surface may be oxidized, and this can contribute to improved wettability. It has been suggested that oxidizing the surface may pit it slightly, and this increased roughness can aid in wettability.

We can oxidize the surface of the web by passing it through a flame and slightly burning the surface. This is called flame treatment. We can treat the surface with a corona discharge, where a high-frequency, high-voltage electrical discharge breaks down the resistance of the air and ionizes the air, and the reactive ionized oxygen oxygenates the surface. The increase in surface energy by the corona discharge, however, is often transient, as in some cases the oxidized molecules are thought to diffuse into the interior. Therefore corona treatment is often carried out on-line, directly before the coating operation. We can also increase the surface energy by coating the web with a thin, high-energy layer called a subbing layer. For photographic systems subbing layers consist of gelatin coated from a water-alcohol dispersion. The alcohol reduces the surface tension and evaporates on drying, leaving a high-energy gelatin layer on the film.

The surface energies of various materials are given in Table 8-1. In Table 8-1 we see that fluorinated surfaces have the lowest surface tension. This is why it is so difficult to coat on the fluorinated polymer Teflon, and also why fluorinated surfactants are so effective in lowering surface tension. Hydrocarbon surfaces also have a low surface tension, and therefore plastic bases must be treated before coating aqueous layers on them. We see in Table 8-1 that oxygenated and chlorinated surfaces have higher surface tensions, and metals have the highest surface tension. Table 8-1 shows that the surface tensions vary widely for the different hydrocarbons and for the different oxygenated and chlorinated solvents. The surface tension depends on which portions of the molecules are exposed at the surface. If an oxygenated molecule lies in the surface with the oxygen facing down into the liquid, then the surface tension will be that of the hydrocarbon portion of the molecule. This is likely to be the case with ethanol and acetaldehyde. In *i*-pentane the methyl $-\text{CH}_3$ groups are more likely to be in the surface than in *n*-hexane or *n*-octane, where there are more methylene $-\text{CH}_2-$ groups, and the surface tension is lower. The aromatic hydrocarbons, benzene, toluene, xylene, and styrene, with no methyl groups, have higher surface tensions. Note that metal surfaces have the highest surface tensions or energies. Thus metals, when clean, are easy to wet. However, it is very difficult to thoroughly clean a metal surface and maintain the surface free of contamination, especially by metal oxides.

Organic solvents generally have low surface tensions, and therefore surfactants are rarely used or needed in solvent systems. Also, many surfactants are not effective in solvent systems. However, some fluorinated surfactants do lower the surface tension of solvent systems very effectively.

TABLE 8-1 Surface Energies or Tensions

Material	Surface Energy or Tension (in dyne/cm)
Fluorinated surface, close packed	6
<i>i</i> -Pentane	14
<i>n</i> -Hexane	19
<i>n</i> -Octane	22
Benzene	29
Toluene	28
<i>p</i> -Xylene	28
Styrene	32
Ethanol	22
<i>n</i> -Octanol	28
Phenol	41
Ethylene glycol	48
Glycerin	63
Acetaldehyde	21
Furfural	41
Acetone	24
Acetic acid	28
Benzyl alcohol	39
Carbon tetrachloride	27
Tetrachloroethylene	32
Tetrachloroethane	36
Tetrabromoethane	50
Liquid sodium	191
Liquid potassium	400
Mercury	485
Liquid aluminum	860

In multilayer coatings, such as in slide and in curtain coating, the top layer has to spread over all the other layers, and so has to have the lowest surface tension of all. We can illustrate this in Figure 8-3. Multilayer coatings are usually aqueous. Since aqueous layers can usually mix together in all proportions, there is no interfacial tension between them. Thus for one layer to spread over another layer, we only require that the upper layer have the lower surface tension. When the top layer has spread over the other layers on the slide and on the base, none of the other layers is in contact with the air. In this case only interfacial tensions,

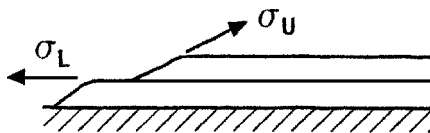


Figure 8-3. Spreading of one layer over another. For the upper layer to spread over the lower, when there is no interfacial tension, the surface tension of the lower layer, σ_L , must be greater than the surface tension of the upper layer, σ_U . From Gutoff (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Gutoff, Eds., Wiley-VCH, New York, with permission of John Wiley & Sons, Inc.

and not surface tensions, play a role, and there are no interfacial tensions between the different aqueous layers. With no interfacial tensions between the aqueous layers, the surface tensions of all the layers below the top can have any value whatsoever as far as spreading is concerned, as long as the top layer has the lowest surface tension. However, in curtain coating the stability of the curtain has to be considered. It appears that the curtain is most stable when all the layers have about the same surface tension, while for spreading the surface tension of the top layer should be slightly lower than the others.

These statements need to be modified somewhat. When a fresh surface is created—and in all coating operations fresh surface is created—this surface is not at equilibrium. It takes time for any surfactant to diffuse to the surface and thus lower the surface tension. During this time when equilibrium is being approached, the surface tension decreases with time, as surfactant diffuses to the surface. The surface tension drops from that of the surfactant-free liquid, when the surface is first formed, to the equilibrium value for an aged surface. This changing surface tension is known as the *dynamic surface tension*. Some surfactants diffuse very rapidly and the surface tension reaches its equilibrium value in under 10 milliseconds; others diffuse slowly and it may take hours to reach equilibrium.

We are interested in the surface tension of the coating liquid in the coating bead, on the web, and also on the slide in slide and in curtain coating. The surface of the coating liquid has a certain age measured from the moment the surface was first formed at the exit of a slot. Thus we are interested in the dynamic surface tensions at certain ages. But we rarely know the surface tension as a function of time, and so we usually use the equilibrium value that often is all we know.

SURFACE TENSION DRIVEN DEFECTS

A number of defects are caused by surface forces. Some of these, such as craters and convection cells or Bénard cells, are more common in solvent coatings where surfactants are rarely used. In aqueous coatings, surfactants are almost always used at relatively high concentrations—above the critical micelle concentrations—and the surface is saturated with surfactant. The surface tension in the surface then remains constant and rarely is the cause of any defects.

Convection or Bénard Cells

Convection cells (Figure 8-4) may appear as perfect hexagons (like a beehive), but also may appear as small circular spots. They were first observed by heating a thin layer of liquid from below. These cells are caused by density gradients resulting from the hotter, less dense liquid at the bottom rising through the cooler overlying liquid, as illustrated in Figure 8-4*b*. Convection cells also result from surface tension gradients, as illustrated in Figure 8-4*a*. The surface tension gradients can result from temperature gradients or from concentration gradients. When the wet layers are under 1 mm thick, as is the case in almost all coatings, convection cells are almost always due to surface tension gradients (Koschmieder and Biggerstaff, 1986).

The liquid motions illustrated in Figure 8-4 that cause these cells can be reduced by having thinner layers and by having higher viscosities and higher surface viscosities, since a given driving force (a surface tension driven force) will have less of an effect under these conditions. The surface tension gradients are sometimes caused by using mixed solvents that undergo concentration fluctuations during evaporation. Since the surface tensions of

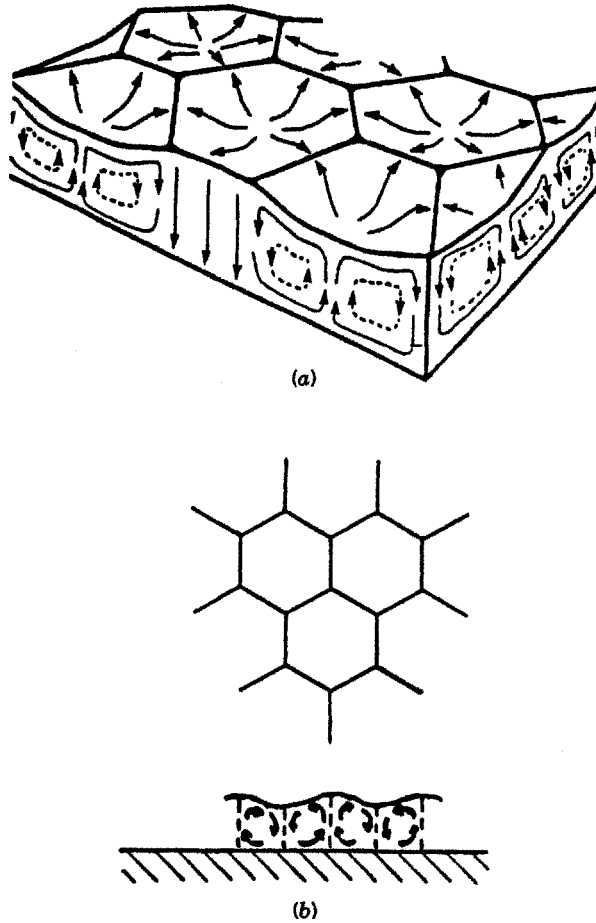


Figure 8-4. Convection or Bénard cells. (a) Surface tension driven cells, from a 3MTM Product Bulletin, St. Paul, MN, with permission. (b) Density driven cells.

the several components will differ, these concentration fluctuations will lead to surface tension fluctuations. Evaporative cooling may cause temperature fluctuations in the surface. Since surface tension is a function of temperature, this will also lead to surface tension fluctuations. Drying at a slower rate is often helpful in reducing the severity of convection cells. However, we always want to increase our production rates, which means we want to coat faster and to dry faster. Adding a lower volatility solvent is often helpful, and just changing the solvent composition can also help. Adding a surfactant will usually help, and some of the fluorinated surfactants are very effective in solvent systems. Of course, we have to make certain that the added surfactant does not ruin the quality of the final coated product.

Craters

We use the term crater to refer to a specific defect caused by a low surface tension spot on the surface, such that the liquid flows out from that spot to regions of higher surface

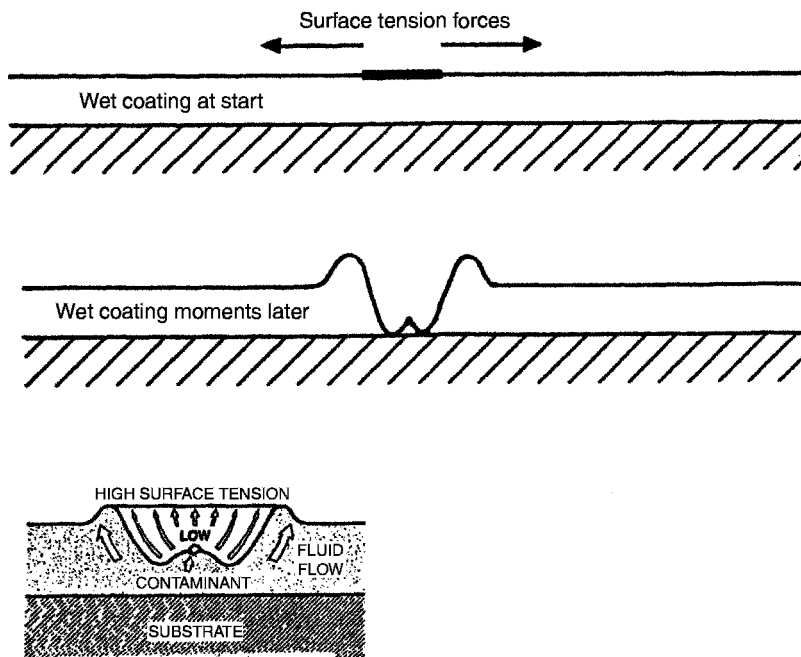


Figure 8-5. Crater formation. Bottom sketch from 3M™ Speciality Chemicals Division, Fluorad™ Product Bulletin, St. Paul, MN, with permission.

tension, as indicated in Figure 8-5. The low surface tension spot can be caused by a particle of dirt from the air, by an oil speck, by a particle of gel, or by use of silicone defoamers at concentrations above their solubility. The liquid will flow out from the low surface tension spot at remarkably high velocities; speeds as high as 65 cm/s have been measured (Kornum and Raaschou-Nielson, 1980).

The edge of the crater becomes elevated due to the acceleration of the surface liquid and the inertia or drag of the underlying liquid. The center thins and only a monolayer may remain on the web, although often a high “pip” that contains a dirt particle remains at the very center.

As with convection cells, craters can be reduced by having thinner layers and higher viscosities. Use of surfactants is beneficial, and clean room conditions should be observed to avoid airborne dirt. Often a change of surfactant or the use of an additional surfactant is helpful, perhaps because the new or additional surfactant better wets dirt particles or any dispersed solids. It is possible that in some cases pinholes are actually small craters.

At times it can be very difficult to distinguish between craters and bubbles that have risen to the surface and burst. These and all defects should be examined under a microscope.

Fat Edges or Picture Framing

Fat edges are sometimes called picture framing and are illustrated in Figure 8-6. Note that with uniform drying the evaporation rate should be uniform over the whole coating. And because the edge of the coating is usually thinner, the solids concentration at the edge

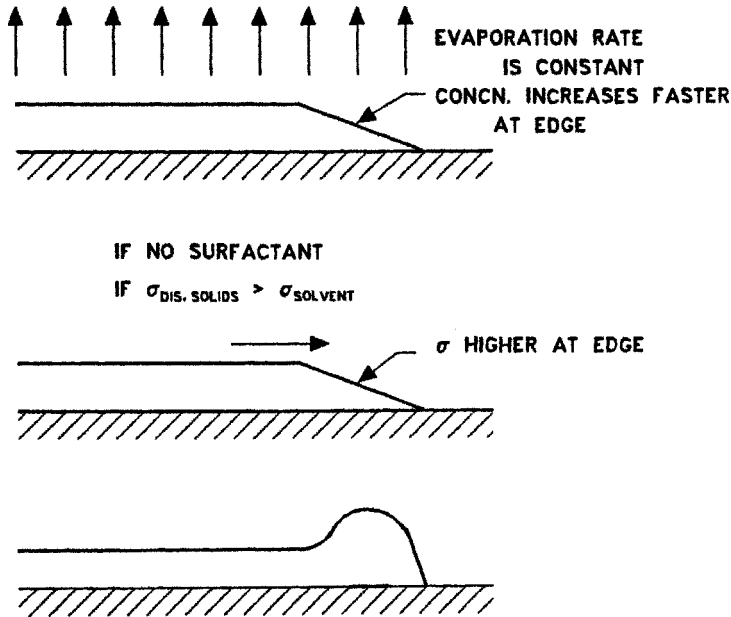


Figure 8-6. Fat edges or picture framing.

will increase faster during drying than in the bulk. When no surfactants are present, the surface tension at the higher solids concentration will usually be higher because the surface tension of the dissolved solids is usually higher than that of solvent. The higher surface tension at the edge will cause flow to the edge, giving a fat edge. Surfactant will usually eliminate this problem.

There are other causes of heavy edges in coatings, some of which are discussed in Chapter 6.

Nonuniform Edges in Multilayer Coatings

Figure 8-7 illustrates the boundary between two adjacent layers in a multilayer slide coating. The edge guide is used to prevent the layers from spreading beyond the desired width. There should be no interfacial tension between the two aqueous layers. At

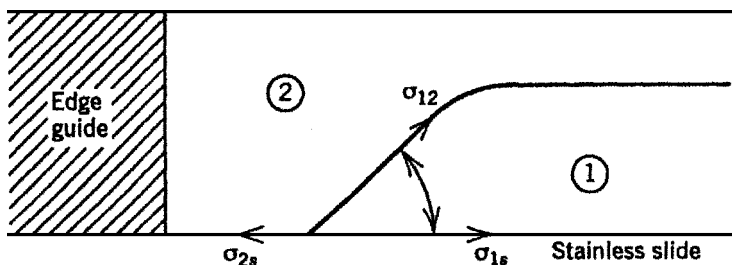


Figure 8-7. Surface forces at the edge of a multilayer system. If the interfacial tensions of the layers with the slide, σ_{1s} and σ_{2s} , are unequal, with no interfacial tension between the layers the contact line will move, causing a wide edge.

equilibrium, at the equilibrium contact line where the two layers and the stainless surface meet, the two interfacial tensions between the layers and the metal surface must be equal. If they are not equal, the interface will move in the direction of the higher interfacial tension. If the slide is long because there are many layers in the coating, this movement of the interface can be considerable. This means there would be a wide edge with a coverage differing from that of the bulk of the coating.

Measuring interfacial tensions between a liquid and a solid is not simple. However, if the same surfactant is used in all the layers, we may assume that if all the surface tensions are equal then the interfacial tensions between the liquid layers and the metal of the coating die would also be approximately equal. Thus, if there is an objectionably large edge effect in multilayer coating, one might want to adjust all the layers to the same surface tension, with the top layer having a slightly lower surface tension.

Dewetting and Crawling

Earlier we pointed out that for good wetting the coating fluid has to have a low surface tension and the base a high surface tension. If this is not done, the coating can dewet or ball up—that is, retract from the coated areas. The start of this process is illustrated in Figure 8-8. When this occurs over a large area, it is called crawling. Dewetting can occur when a web has a low surface energy due to contamination, such as by oil droplets.

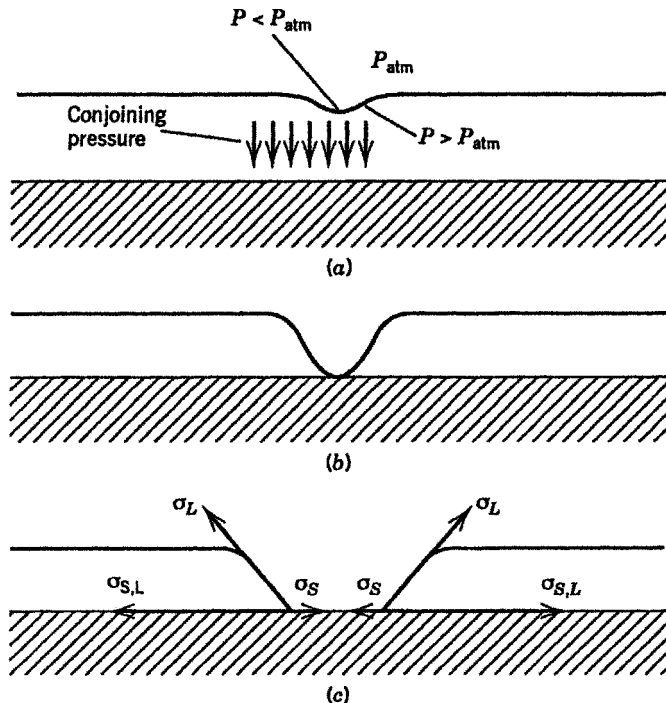


Figure 8-8. Dewetting and crawling. (a) Surface forces tend to heal a depression while conjoining pressure tends to amplify it. (b) Conjoining forces cause a hole to form in the coating. (c) Surface forces then cause the system to dewet.

When a layer is thick, dewetting cannot occur. Thick layers on a horizontal surface, such as water in a polyethylene beaker, will not dewet, because of the counteracting force of gravity. Surface forces (Figure 8-8a) aid gravity in preventing dewetting in thick layers. If a depression has formed in a liquid layer, the pressure under the concave edges will be above atmospheric pressure, as the pressure on the concave side of a curved interface is always higher than on the convex side. For the same reason the pressure under the convex center will be below atmospheric pressure. Thus liquid will flow from the high-pressure, elevated regions to the low-pressure, depressed regions due to the surface forces as well as by gravity. The surface will thus heal itself.

In thin layers, other, short-range forces come into play. They are called disjoining pressure and conjoining pressure. The disjoining pressure tends to keep two surfaces apart. This tends to prevent dewetting. The conjoining pressure tends to bring two surfaces together. This aids dewetting, for once the top surface of the liquid touches the solid, one has a dry spot (Figure 8-8b), and then the surface forces illustrated in Figure 8-8c come into play. However, the conjoining pressure normally does not play a role until the film has thinned to a thickness under 1 μm , according to Kheshgi and Scriven (1991). They point out that this is likely to occur if the film has projections from the surface, such as by bubbles in the coating, or if the surface tension at a spot on the surface is lowered by dirt from the air (as in the formation of craters) or by local temperature or concentration gradients (as in the formation of Bénard cells).

Dewetting and crawling do not take place at the point of application of the coating to the web, but shortly after. Surprisingly, it is possible to coat aqueous liquids on Teflon without the use of a surfactant—but almost immediately after coating, the liquid will dewet. The surfactant in aqueous coatings, in the strictest sense, is not needed for coating; it is needed to prevent dewetting and crawling immediately after coating. It is also needed to help in adhesion of the coating to the base.

Dewetting can also occur with one liquid over another. In multilayer slide and curtain coating, dewetting can occur on the slide, if the surface tension of the top layer is not lower than that of all the other layers. This was discussed earlier in connection with Figure 8-3. Valentini et al. (1991) showed that this occurs when the dynamic surface tension of the upper layer is greater than about 1.2 or 1.3 times the dynamic surface tension of the lower layer.

Adhesive Failure and Delamination

Delamination, or detachment of a layer from the layer underneath, is caused by poor adhesion between the layers. As explained by Schonhorn (2005), adhesion failure can best be explained in terms of a weak boundary layer. Surface layers often differ significantly from the bulk material. Wetting the surface, such as by using surfactants, is a necessary but not sufficient requirement to get a good coating. Commonly used surface treatments such as corona treatment or flame treatment cross-link or remove the weak boundary layer on the surface, as well as oxygenate the surface. When an untreated plastic web or the untreated side of a treated plastic web is coated, it is possible to make what appears to be a good coating, but the adhesion will be very poor and the coating can come off the base when a piece of coated web is shaken vigorously.

It is also possible in multilayer coatings to get delamination between layers if the chemistry of the adjacent layers is not correct; that is, if the compatibility of the components is inadequate. With liquid on liquid we would not expect to have boundary

layers, and here we believe the poor adhesion to occur when the binders in adjacent layers are at least partially incompatible. Suitable surfactants may reduce this incompatibility.

Nonuniform Base Surface Energies

If the surface energy of the base is nonuniform, the attractive force between the coating fluid and the web will fluctuate. The contact line of the coating liquid with the web will then oscillate back and forth, causing coverage fluctuations. These fluctuations in coverage will be random and may be enough to ruin the coating. Usually nonuniform base surface energies are caused by contamination. Examples are contamination by oil vapors from a bearing and contamination by particles of a plastic that were abraded off in the coating area. In this latter case pinholes were the result.

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9

PROBLEMS ASSOCIATED WITH STATIC ELECTRICITY

Static electricity can cause many problems in the coating industries. Besides the well-known hazard of explosions caused by static discharges in flammable vapors, static charges in the web can also cause coverage nonuniformities in coating, pickup of dirt and dust by plastic film base, problems in stacking of cut sheets, problems in film tracking, jamming of sheet ejection devices, fogging of photosensitive materials, pinholes in release coatings, and so on. Shocks to personnel can be more than annoying; the involuntary reaction to the shock can cause a major accident. The magnitudes of the static charges needed to cause these problems are shown in Table 9-1.

High-speed coating lines have many locations that are ideal for generating static electrical charges. Charges form when two dissimilar surfaces separate, and web, which often is made of nonconducting plastic, separates from every roll over which it passes. If the surfaces are not grounded, charges can build to high levels. Humidity in the air leads to the adsorption of moisture onto the surface of the web, raising its conductivity. Thus the static charges on the surface can leak away and dissipate. Static problems are far more prevalent in the winter when the air is dry than in the summer when the relative humidity tends to be high. Control of relative humidity is one means of controlling static.

Fire and explosion are a major concern in any solvent-handling area. Sparks caused by static electricity usually have enough energy to ignite solvent vapors. Discharge may occur whenever the charge on the web is high enough to overcome the breakdown resistance of the surrounding air. The discharge is usually to the ground. The ground might be a metal roll or a metal portion of the frame.

In addition to the static discharge as the source of ignition for a fire or explosion to occur, a flammable solvent–air mixture must be available. The solvent concentration must

TABLE 9-1 Static Voltages and Associated Problems

Minimum Voltage (V)	Associated Problem
30	Coating coverage nonuniformities
400	Jamming of ejection devices
500	Dust and dirt pickup
600	Fogging of photosensitive coatings
1000	Problems in registration of sheets
1500	Fire and explosion hazard
2000	Stacking problems with cut sheets
4000	Problems in packaging
6000	Problems in tracking (controlling film travel)
7000	Arcing

Sources: Kistler (1996) and Keers (1984).

be above its lower explosive limit, and the oxygen content must be high enough to support combustion. Thus to prevent the possibility of fire or explosion, one must ensure that static charges with enough energy to cause ignition cannot build up, or that sufficient ventilation is provided so that the solvent concentration in the air cannot reach the lower explosive limit, or that the oxygen content of the air is reduced to a low enough level (about 5%) where it will not support combustion. Low oxygen levels are normally found when the coating is made in a nitrogen atmosphere. When a nitrogen atmosphere is used, the solvent is usually recovered by condensation from the exhaust, and the “dry” nitrogen is recirculated.

Like charges repel each other and unlike charges attract. A charged object can induce an opposite charge in a nearby neutral object. If this object is electrically isolated, it will remain electrically neutral, and thus one side will have one charge and the distant side will have an equal and opposite charge. This neutral object will now be attracted to the original charged object because of the opposite charge on the near side. Thus charges on the web will attract the coating liquid, and nonuniform charges will attract the coating liquid unevenly, leading to nonuniform coverage. On the other hand, a uniform charge on the web, or a uniform electrostatic field between the backing roll and the grounded coating die, will uniformly attract the coating liquid. This is the basis for electrostatic assist in coating (Nadeau, 1960; Miller and Wheeler, 1965).

When coated web, if charged, is cut into sheets at the end of the coating line, the sheets, all with the same charge, will repel each other and stacking the sheets will be difficult. The sheets will tend to slide off the top of the stack. In equipment ejection devices where the sheets are pushed, rather than pulled, the charged sheets will tend to adhere to the device and cause jams. Similarly, charged web in the coating line may have difficulty tracking properly because it will be attracted to, and want to adhere to, the rolls and guides. This is mainly a problem on low-tension coating lines with thin or weak webs. At usual web tensions this is not normally a problem, for the web tension will tend to overcome the attractive forces due to static electricity. However, problems can arise at a laminating station where, before two sheets with like charges enter, the sheets can repel each other and balloon apart.

Charged web will attract dirt of an opposite charge from as far away as 15–25 cm (6–10 in.), and this dirt is very difficult to remove because of the large attractive forces. Dirt particles as small as 1 μm on the web cannot be tolerated in high-quality products such as photographic films and magnetic tapes. Web cleaners should discharge the web before trying to remove the dirt. Many web cleaners do not even try to do this, and even when they

do, they are unable to remove the bound charges that cause some of the difficulty. Even the best of web cleaners do not do a perfect job. With charges remaining on the web, it is impossible to thoroughly remove all of the dirt.

In cases where dirt or dust pickup is undesirable—and this includes most operations—static eliminators should be installed just after the unwind stand. Charge neutralization here will reduce pickup of dust from the air. Clean room conditions reduce the dust level in the air and therefore reduce the amount of dirt pickup by the web. Clean room (or at least semi-clean room) conditions (somewhere in the range of level 1000 to level 10,000 cleanliness) are recommended for all dirt-sensitive coating operations. This includes almost all coating operations.

In the photographic industry, the blue arc of a static discharge can fog or expose light-sensitive films and papers. This can occur on the coating line as well as in subsequent operations. It can even occur in the camera. Some individuals can build up an abnormally high static charge on their bodies. There are available meters that measure the static charge on a person. The person stands on an insulated platform and touches a probe, and the meter indicates the static charge. A person who does build up a high body charge should be equipped with devices used to remove static charges from personnel, such as are discussed later in this chapter, in the section on *Free Charges*, if that person has to work in sensitive areas. Most of us do not build up such high charges.

The discharge of charged webs can have sufficient energy to burn pinholes in release coatings on the web surface. There may be a sufficient number of these pinholes to allow adhesion of the product to the underlying web, rather than permitting separation.

In many industries the quality of production decreases in the winter months. This has been tracked down to the low humidity in winter months, allowing an increase in static charges. Moisture in the air tends to adsorb onto surfaces, causing a decrease in the surface resistivity. In winter, with its very low humidity, surface resistivities tend to be high, allowing static charges to build up to a high level. Many of us have experienced static discharges in winter when approaching a metal object after walking on a carpet. To avoid this type of static problem, it may be worthwhile to consider using a humidifier to add moisture to the air in winter. This is practical to do in small areas.

FORMATION OF CHARGES

Static charges can be developed by many different methods, such as:

1. *Separating Two Surfaces.* When two dissimilar surfaces are separated, one will have a greater affinity for electrons or ions than the other, and they will each become charged with respect to the other. It is difficult to distinguish between this method and charging by friction.
2. *Friction (Triboelectric Charging).* When two dissimilar materials are rubbed together, a large charge can be built up, as when we use a hard rubber comb in our hair on a dry winter day. This type of charging is very common.
3. *Fracture.* When a solid is broken or an adhesive bond is broken, electrons are frequently emitted, leaving two highly charged surfaces.
4. *Induction.* If a neutral solid particle or liquid drop enters a region where there is an electric field, the end nearest the negative electrode will become positively charged

and the end nearest the positive electrode will become negatively charged, while the particle overall remains neutral. The particle or drop is said to be polarized. If the electric field is nonuniform, as, for example, if one electrode is pointed, the particle will be attracted to the region of the strongest field, toward the pointed electrode. Let us assume the pointed electrode is positive. When the particle gets close to the pointed positive electrode, the field strength may be great enough for electrons to be removed from the particle. This field emission charging will leave a net positive charge on the particle, and it will then be repelled by the pointed, positive electrode.

5. *Pressure.*
6. *Stretching.* Stretching an uncharged material can cause charge formation.
7. *Impact.* Dust particles impinging on a charged surface may become charged, depending on how long they are on the surface. Conductive particles become charged faster than nonconductors.
8. *Freezing.* During the freezing of water, a large potential difference has been found between the ice and the water. This has been suggested as a mechanism for the large charge buildup during thunderstorms.
9. *Electrostatic Field.* This will induce polarization in neutral particles, will align dipoles, and will charge particles that are in contact with the electrodes.
10. *Spraying.* When liquids are sprayed, the resulting cloud of droplets is usually charged.
11. *Corona Charging.* A corona is an electrical discharge that occurs in regions of strong electrical fields, usually produced by pointed conductors or fine wires. A reddish or violet discharge is usually seen in air. The current is carried by ionized gas molecules. These ionized molecules can transfer their charges to particles or surfaces.
12. *Ion and Electron Beams.* Particles or surfaces bombarded by a stream of ions or electrons will pick up the charges from the beam.
13. *Thermionic Emissions.* When a material is heated, the electrons move faster. If the velocity of the electrons in the direction perpendicular to the surface is high enough, they will escape through the surface. This is the basis of the hot cathode in vacuum tubes. The material will be left positively charged unless it is connected to a source of electrons—such as ground.
14. *Photoelectric Charging.* Electromagnetic radiation such as light, and more particularly x-rays, when striking the surface of a material may transfer sufficient energy to the electrons in the surface to permit them to be ejected, leaving the material positively charged.

When separating two surfaces, as when unwinding a web or even when web passes over a roll, the ions and electrons that are present in the interfacial region are not evenly distributed between the separating surfaces. Positive charges will tend to accumulate on one surface, and negative charges on the other. The same effect occurs when rubbing one surface on the other. The faster the rubbing or the greater the speed of separation, the greater the charge buildup, as a slow separation allows the charges on the different surfaces to partially neutralize each other. The greater the conductivity of the surfaces, the more uniform will be the surface charge, and the less chance the surface will hold the charge. If the surface is conductive and grounded, the charge will leak away to ground. In coating

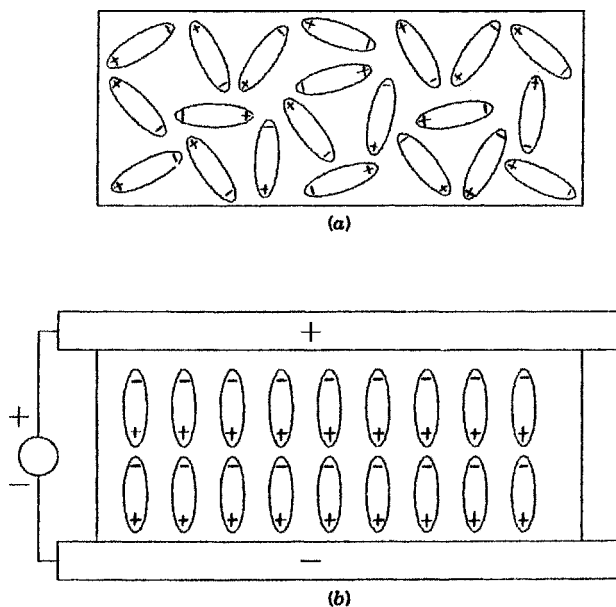


Figure 9-1. Orientation of dipoles in an electric field: (a) unoriented film and (b) film in a strong electric field.

operations, both surfaces are usually in contact with grounded metal rolls, and so there will normally be no significant surface charges in those cases where the surfaces are conductive. However, in most plastic webs the voltages that develop can be quite high, in the hundreds or even thousands of volts.

Static charges are of two types, free and bound. Free charges are the type we have been discussing, caused by an excess of electrons or of ions at the surface. Free charges tend to move under the influence of an electrostatic field—a voltage gradient—and will flow to ground given a conductive path. (Positive ions will not flow to ground, even though we speak of them as doing this. Instead, electrons will flow from ground to the object to neutralize the positive ions. The effect, however, is the same.) In contrast, bound charges are not mobile. They are formed by the orientation of dipoles in the solid material. By a dipole we mean a molecule that, while electrically neutral, has an excess of negative charges in one region and an excess of positive charges in another region. Most large organic molecules, such as polymer molecules, and many small molecules, such as water, fit this definition. In any solid polymer such as a sheet of film, normally the dipoles are randomly oriented as in Figure 9-1a. However, under the influence of a strong enough electric field, the dipoles will become oriented and the sheet of film will become charged, as in Figure 9-1b. These bound charges are not mobile and will decay only by disorientation of the dipoles. By itself, this may be a very slow process. Sheets of plastic may retain their bound charges for years.

ELECTROSTATIC FIELDS

A dc or direct current field is formed, as in Figure 9-2a, by having two electrodes a set distance apart. If the voltage difference between the electrodes, one of which is usually

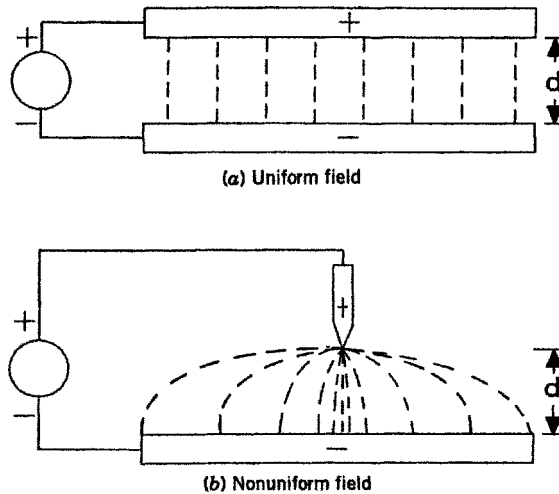


Figure 9-2. (a) Uniform and (b) nonuniform electrostatic fields.

grounded, is V volts and the distance apart is d cm, then the field strength is V/d volts/cm. However, if one electrode is pointed, as in Figure 9-2b, the field strength near the pointed electrode, surprisingly enough, is greatly magnified and now depends inversely on r , the radius of the point of the electrode. The maximum field strength between the pointed electrode and the flat electrode will be directly under the pointed one. There the field strength will equal $(V/d + V/r)$. Thus if the voltage difference between two flat electrodes is 1000 volts and the electrodes are 1 mm (40 mils) apart, the field strength between two flat electrodes will be 1000 volt/0.1 cm, or 10,000 volt/cm. However, if one electrode is a needle with a tip radius of 0.01 mm (0.4 mil), the field strength would now be

$$\frac{1000 \text{ volt}}{0.1 \text{ cm}} + \frac{1000 \text{ volt}}{0.001 \text{ cm}} = 1,010,000 \text{ volt/cm}$$

With pointed needles, very high field strengths can be attained. This is why lightening rods on the roofs of buildings are pointed. The grounded lightening rods build up the field strength between themselves and the clouds, to better attract the lightening.

Between a needle and a flat electrode the field will be very nonuniform, as indicated in Figure 9-2b. However, if instead of one needle thousands of needles—or better yet, very fine wire brushes—are used, the field will be extremely uniform with a magnitude equal to that directly under the tip of a single needle.

SURFACE RESISTIVITY

Free charges on the surface will readily dissipate or leak away if the surface is sufficiently conductive. The resistance of a surface layer to the flow of electricity is called the *surface resistivity*. Materials that are conductive will conduct electricity on their surfaces as well as in the bulk. But materials that are nonconductive can still have surfaces that will conduct electricity. Surfaces with a surface resistivity under about 10^6 ohm/□—called

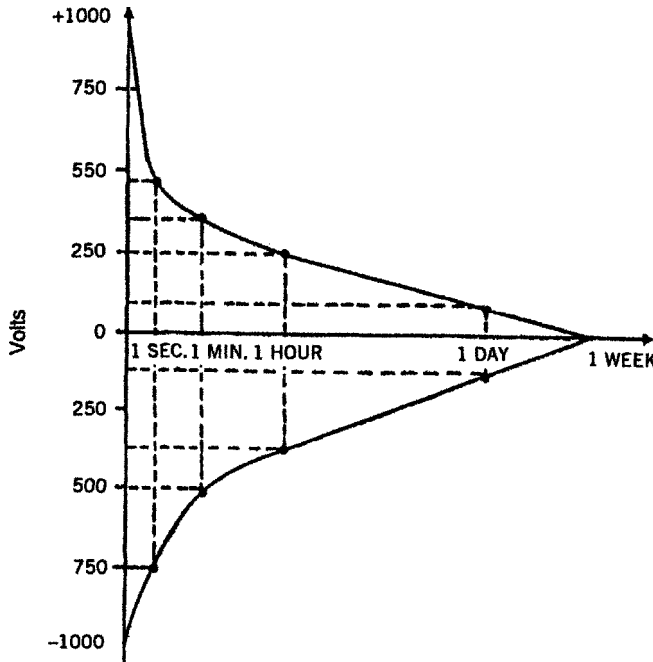


Figure 9-3. Decay of static charge, when the surface resistivities are 10^9 – 10^{11} ohms/square. From Kisler (1996), with permission of the author.

ohm/square, and this term will be defined later—are considered electrically conductive. Surfaces between 10^6 and 10^{10} ohm/ $\square$ are adequately conductive to rapidly dissipate static charges. Surfaces with resistivities above about 10^{13} ohm/ $\square$ will not dissipate electrical charges and these materials can hold static charges for a significant amount of time.

Figure 9-3 shows the complete decay of charge in a period of about a week when the surface resistivity is 10^9 – 10^{11} ohm/ $\square$, and Figure 9-4 shows that with surface resistivities of 10^{13} – 10^{16} ohm/ $\square$, although there is some decay of charge, a high residual charge remains indefinitely.

How is surface resistivity measured? Let us first review the measurement of bulk or volume resistivity. Volume resistivity is the resistance to the flow of electricity of a 1 centimeter cube of material. It is calculated by measuring the resistance, R , of material of cross section A between two electrodes d cm apart. The bulk or volume resistivity, ρ_v , is then

$$\rho_v = R \frac{A}{d}$$

with units being resistance times length, or ohms-cm. The volume resistivities of a number of solids are given in Table 9-2.

Surface resistivity could be measured as in Figure 9-5, with R being the electrical resistance between electrodes L cm long and d cm apart. The surface resistivity is then

$$\rho_s = R \frac{L}{d}$$

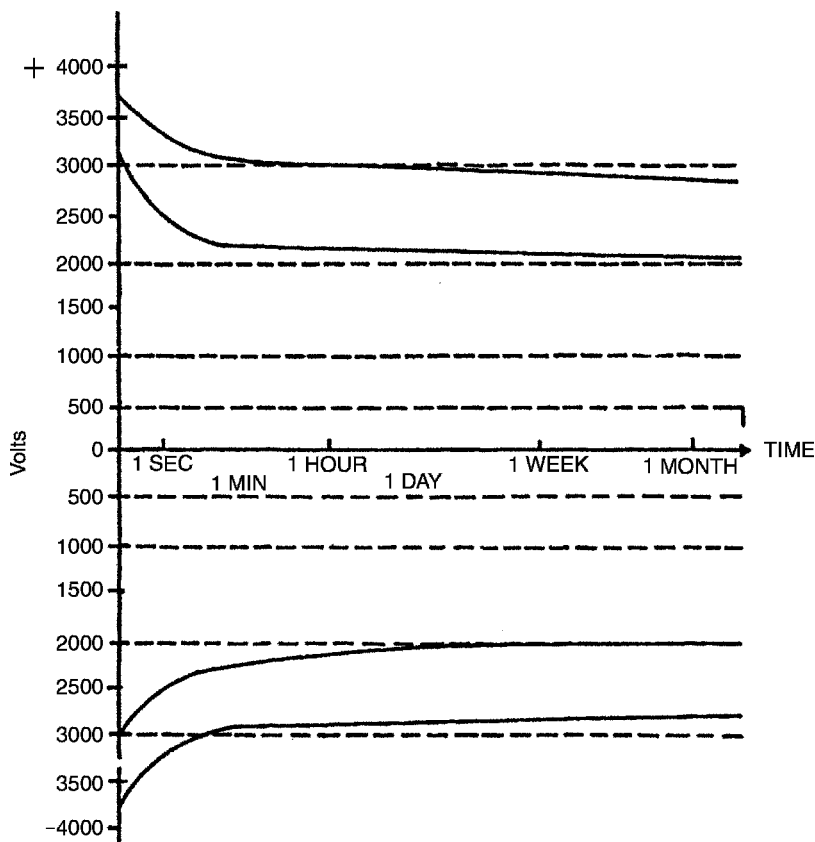


Figure 9-4. Decay of bound static charges, when the surface resistivities are 10^{13} – 10^{16} ohms/square. From Kisler (1996), with permission of the author.

TABLE 9-2 Volume Resistivities (in ohms-cm)

Conductors	
Silver	1.59×10^{-6}
Copper	1.72×10^{-6}
Gold	2.44×10^{-6}
Aluminum	2.82×10^{-6}
Steel	1.2×10^{-5}
Mercury	1.0×10^{-4}
Carbon	3.5×10^{-3}
Semiconductors	
Germanium	4.6×10^1
Silicon	2.3×10^5
Dielectrics	
Dry wood	3×10^6
Polymethyl methacrylate	1×10^{13}
Glass	2×10^{13}
Polyester	1×10^{14}
Nylon	4×10^{14}
Teflon	$> 10^{15}$
Polystyrene	$> 10^{17}$

Source: Kisler (1996), with permission of the author.

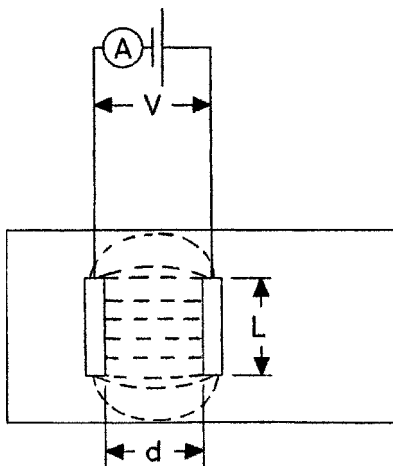


Figure 9-5. Surface resistivity and a nonuniform field.

and the units would simply be ohms, the same as the units of resistance. However, when L and d are equal so that the resistance is measured over a square area, it does not matter what the size of the square is, and the units of surface resistivity have come to be called ohm/square or ohm/□. While the term *square* has no dimensions and could just be dropped, its use does avoid confusion with the units of resistance. Thus the denominator *square* has no units and only serves to distinguish surface resistivity from resistance.

In Figure 9-5 the electric field near the edges of the electrodes is very nonuniform, as indicated in the sketch. A concentric cylindrical probe, as shown in Figure 9-6, completely avoids this problem.

As previously mentioned, the surface resistivity decreases greatly with increasing humidity. At higher humidities more water is adsorbed by the surface, greatly increasing the conductivity. As the relative humidity increases, the surface resistivity of many materials will drop greatly, with the magnitude of this decrease depending on the material.

MEASUREMENT OF STATIC CHARGES

An electrostatic voltmeter is used to measure electrostatic charges. It measures the total charge and does not distinguish between free and bound charges. The probe of the meter does not touch the surface but is held 1–3 mm ($\frac{1}{32}$ – $\frac{1}{8}$ inch) above the surface of the object mounted on a grounded metal plate (Figure 9-7). For on-line measurements on the coating machine, the probe is held above the web traveling over a grounded roll. The outside metal of the square probe is always at a high voltage, so personnel should be warned that the probe should not be touched. Also, the probe can easily be damaged and is expensive—it costs many hundreds of dollars—and so should be handled with great care. On plastic films the electrostatic charges can vary greatly within short distances. On films 75 μm (3 mils) thick with surface resistivities of 10^{14} ohm/□ or more, charges can vary from +5000 to –5000 volts within a space of micrometers.

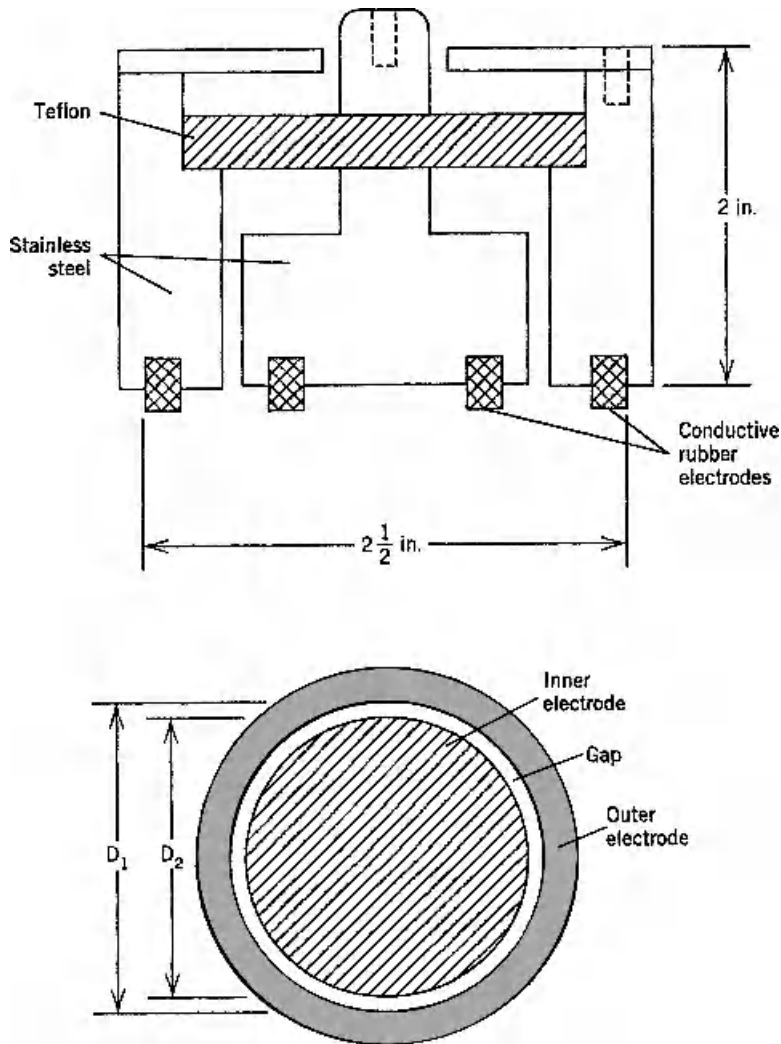


Figure 9-6. Cylindrical probe for surface resistivities. From Kisler (1996), with permission of the author.

The electrostatic charge can be read from the electrostatic voltmeter, or it can be recorded on a strip chart, or it can be logged into computer memory. Most strip chart recorders have too slow a response for accurate readings at line speeds over about 0.5 m/s (100 ft/min).

When an electrostatic voltmeter is not available, one can get a qualitative picture of the charge and its distribution on a film by sprinkling a dry xerographic toner on a sample of the film and then shaking off the excess. Figure 9-8 shows the results of this test with a polyester film base that gave coating problems. These charges will not decay appreciably with time, as was seen earlier in Figure 9-4.

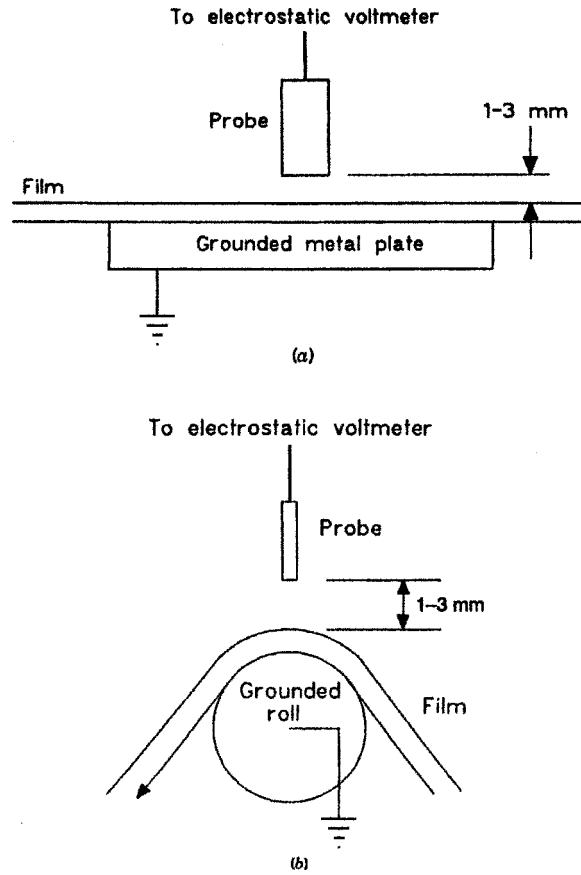


Figure 9-7. Use of the electrostatic voltmeter probe: (a) in the lab and (b) on a coating machine.



Figure 9-8. Toner test for charges on a web. From Kisler (1996), with permission of the author.

REMOVAL OF CHARGES

Free charges are relatively easy to remove; it is just necessary to provide a conductive path to ground. Bound charges are difficult to remove; to do so it is necessary to disorient the dipoles. And as charges can build up in the moving web, the charge removal should take place as close as possible to the region where the static charges cause problems. This is often the coating stand.

One should try to remove all charges and one should also reduce the buildup of new charges in the system. All rolls should be aligned as well as possible, since friction between the web and a poorly aligned roll will generate charges both on the web and on the roll. Metal rolls should be grounded so that these charges cannot build up; an ungrounded metal roll can act as a van der Graff generator and build up very high charges, which will then arc to ground. To ground a metal roll through its metal shaft requires more than just grounding the bearing block. The bearing lubricant should be conductive to ensure a good ground connection. Conductive greases containing special carbons or silver particles are available.

The coverings on nonmetallic rolls should be chosen such that the buildup of charge by friction is minimal. This can be determined by actual test, or one can rely on published triboelectric series, where materials close together in the series develop the least charge. Unfortunately, the series order is not always reproducible, and also cleanliness and humidity are very important for the order. A typical series is given in Table 9-3, from Hendricks (1973). Unfortunately, it is incomplete; it does not list poly(ethylene terephthalate), a polyester, also known as Mylar, and it does not list polypropylene.

Free Charges

In order to bleed away surface charges, a conductive path to ground can be provided either by grounding the surface, by making the surface conductive and grounding it, or by making the air conductive.

A grounded roller will bleed away surface charges from the surface it contacts. But it will not discharge the opposite surface. The second surface must also pass over a grounded roll.

As mentioned earlier, pointed electrodes are more effective than flat electrodes in creating strong electrostatic fields. Thus grounded tinsel has long been used to discharge a surface. The tinsel does not actually have to touch the surface, as long as it is close to it. The sharp tips of the grounded tinsel cause the electrostatic field induced by the charge on

TABLE 9-3 Triboelectric Series

Rabbit's fur	Cotton
Lucite	Wood
Bakelite	Amber
Cellulose acetate	Resins
Glass	Metals
Quartz	Polystyrene
Mica	Polyethylene
Wool	Teflon
Cat's fur	Cellulose nitrate
Silk	

Source: Hendricks (1973), p. 67.

the web to be high, which increases the likelihood of ionizing the air and allowing the charge to bleed away across the small air gap. When placed on both sides of a polyester web, it can also reduce the bound charges to under 1000 volts. This, of course, is still a high charge. However, there are many gaps between the tips of the tinsel, and with a nonconducting surface there will be many areas that are not discharged. Tinsel has been largely replaced by fine metal brushes. The many rows of bristles ensure full coverage of the surface. The metal bristles should be no more than 10 μm in diameter to develop a high field strength when they do not contact the surface. The brushes can be used in contact with the surface or they can be a short distance away. The fine bristles are so flexible that they will not scratch the surface. It is best for the brushes to contact the surface, unless there are other reasons, such as actual charge buildup by friction or possible surface contamination, for having a separation. Conductive cloth contacting the surface has also been used but is less effective.

The surface of the web can be made more conductive by increasing the humidity of the air in the coating alley. Conditioning the air tends to be expensive and is usually not done unless it is required for reasons other than static control. Surfaces can also be made conductive with special antistatic treatments, such as by a coating of quaternary ammonium salts or of cuprous chloride. These surface treatments may be unacceptable because they may alter the final properties of the coated web.

Ionizing radiation ionizes the air, making it conductive and allowing it to discharge the surface. Ionizing radiation can come from americium or from polonium bars, or, less often, from x-rays, beta rays, gamma rays, or ultraviolet rays. Americium-241 emits hazardous gamma rays as well as the desirable alpha particles, and suitable shielding must be provided. Polonium-210 gives off only the soft alpha particles and is not hazardous. It does have a short half-life of 138 days and therefore must be replaced at least once a year. Most radioactive bars have been banned from use because of their radiation hazards. They also are not as effective as one might want, because their effect is often inadequate for high-speed coating operations.

Corona discharges will ionize the air and can also charge the surface; the corona discharge occurs in a separate apparatus, and the ionized air formed is then blown against the surface to discharge it. Most corona devices use alternating current (ac). It takes about 3500 volts to obtain a corona. Most of the power supplies operate at 4000–8000 volts. Thus, as indicated in Figure 9-9, the alternating current generates a corona in only that part of the cycle when the voltage is above ± 3500 volts. Direct current (dc) corona generators, on the other hand, are effective at all times. Two dc corona units, one giving a positive corona followed by one giving a negative corona (or vice versa), will be more effective than an ac unit giving both positive and negative charges. Such dc units are now becoming available and are recommended.

The location of static eliminators is very important, for when the charged web comes close to or contacts a roll, the electrostatic field strength becomes much lower, and the web will not attract the ionized air molecules that will neutralize the surface charge. For effective charge neutralization, Keers (1984) recommends that the eliminator bar be at least 15 cm away from any roller or guide and should be 2.5 cm above or below the web. Usually it is necessary to have the bar on only one side of the web.

To remove static buildup from personnel, conductive floor mats or ionized air blowers are recommended. If the operators wear heavy insulated soles, then a conductive shoe strap, running from the inside of the shoe to the bottom of the outer heel, should be provided in order for the conductive mat to be effective. The strap does not have to contact the skin; it

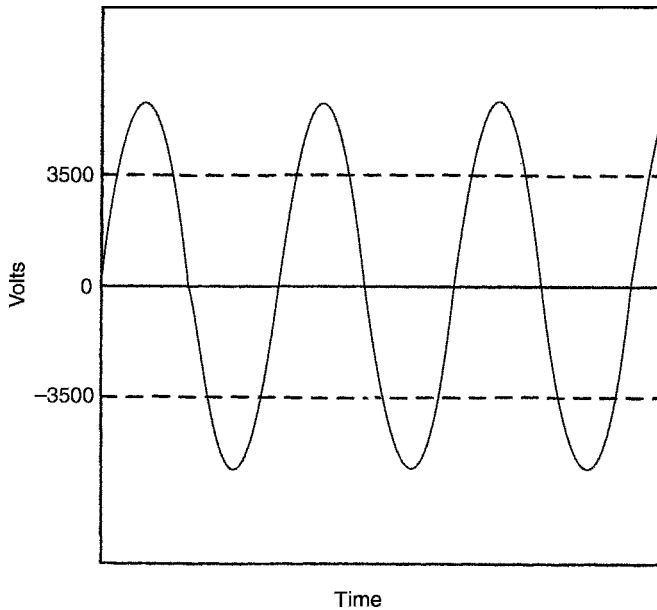


Figure 9-9. The ac corona unit is ineffective during that portion of the cycle when the voltage does not exceed the threshold needed for a corona.

will ground the person through the stocking. The ionized air blower would normally be used for discharging static on operators only if it is used for other purposes as well.

Bound Charges

To discharge the bound charges of a web by disorienting the dipoles is much more difficult, and currently there is no commercially available equipment to do this. First one has to

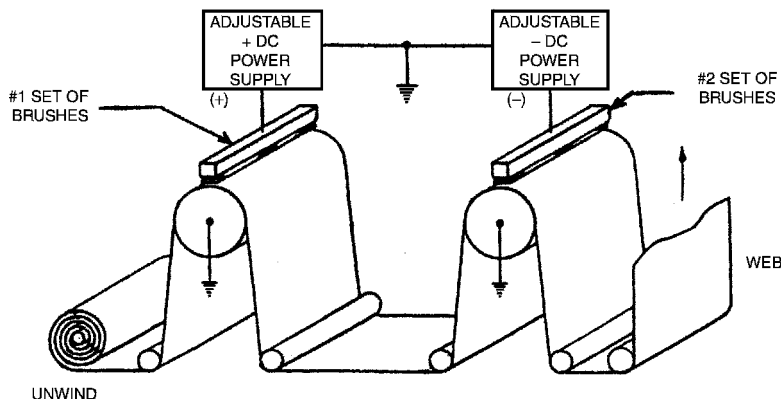


Figure 9-10. Discharging the free and bound charges on a web by first charging the web to a uniform high potential and then discharging it. From Kisler, S., Method and apparatus for uniformly charging a moving web, *U.S. Patent 4,517,143*, May 14, (1985).

charge the web to a uniform charge in an electrostatic field; that is, charge the web to a charge higher than any existing in the web. Then the web is discharged by an opposite field (Gibbons et al., 1972), with the field strength set to bring the final charge to approximately zero, as indicated by an electrostatic voltmeter. Very fine stainless steel brushes held about 3 mm above the surface of the web on a grounded metal roller are suggested for charging and discharging. The power supply would be adjusted to give a uniform charge on the web. In many cases the voltage from the power supply should be in the range of ± 1000 –2000 volts. The discharging voltage with an opposite polarity would be sent to a similar set of brushes but downstream of the first set. The voltage would be close to that of the first set or slightly higher. The setup could be similar to Figure 9-10 (Kisler, 1985). Here the two sets of brushes, one positively charged and one negatively charged, are against different grounded rolls. However, Kisler (1996) also shows a system where both sets of brushes are against the same grounded roll.

Voltages of several thousand volts can be extremely hazardous. The current needed to charge or to discharge a web is minuscule. The power supply should have a safety feature that does not allow a current flow above about 3 mA. This will not injure a person, but it is still enough to give a good shock and make a person jump. Extreme caution should be taken to avoid contact with any object at a high voltage, including the surfaces of the electrostatic voltmeter probe.

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10

PROBLEMS ASSOCIATED WITH DRYING

The primary purpose of dryers in a coating line is to supply heat to evaporate solvent from a coating, thus transforming the coated liquid into a dry coating. Dryers also may be used to heat cure or cross-link coatings after they are solidified. The solvents must be removed without adversely affecting the performance properties of the coating and without introducing defects into the coating. The drying step is important in defect formation because it is the last step in the process where the chemistry and the physical properties of the product can be affected. The only steps after drying are converting the product to the final size and shape needed by the customer and packaging it to protect it from damage before use. When the final coated product is defective, often many of the raw materials are not recoverable. The result will be an additional cost penalty for disposal besides the cost of the materials and of the operations. Some materials, such as polymers, precious metals such as silver, magnetic oxides, and the coating support itself, may be recycled, but this too adds to the cost.

The energy required to volatilize the coating can be introduced by three mechanisms:

- *Convection*, in which the heat is transferred to the wet coating by directing hot air at the coating and/or at the backside of the web
- *Conduction*, in which the heat is transferred to the back of the web by direct contact with a heated surface, such as a hot roll
- *Radiation*, in which the heat is transferred by electromagnetic radiation to the coating from electric heaters or gas burners

Convection with hot or warm air is most commonly used in drying. The hot air not only transfers heat to the coating but also carries off the evaporating solvent. With heating by conduction or radiation, some air is still needed to carry off the solvent. Because of the

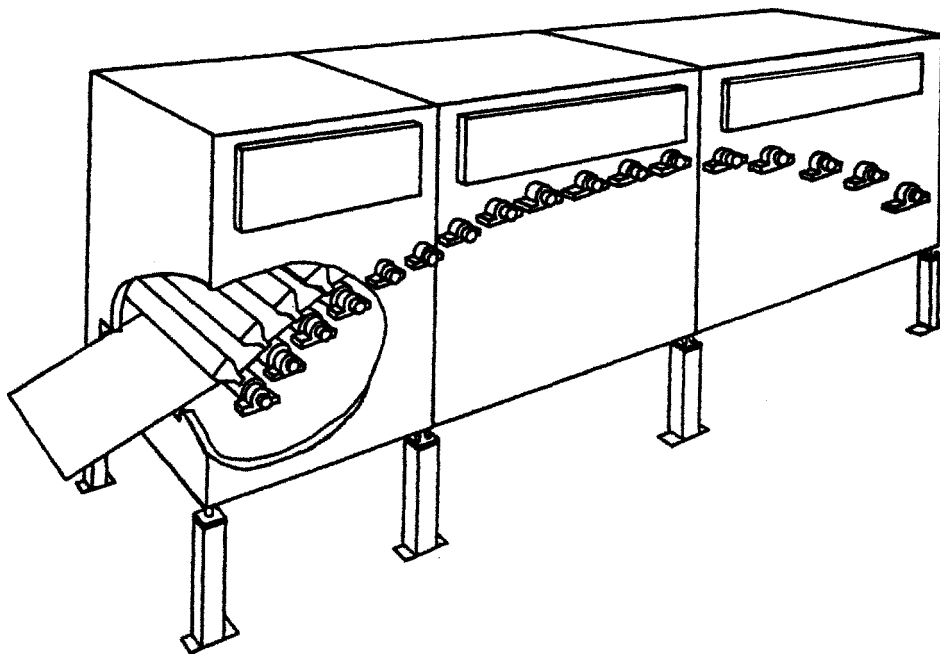


Figure 10-1. Single-sided arch dryer showing the air nozzles.

high heat transfer coefficient of impinging air, the temperature of the air need not be too high and overheating of the coating is avoidable. Hot air convection dryers have been in use for a long time and there are a wide variety of air nozzles and jets, in many configurations. The two general types are single-sided dryers, illustrated in Figure 10-1, and two-sided or flotation dryers, as in Figure 10-2. In single-sided dryers, the air impinges on the coated side of the web and rolls are used to support the web. In two-sided dryers, the air impinges on both sides of the web and serves to float the web and thus aid in its

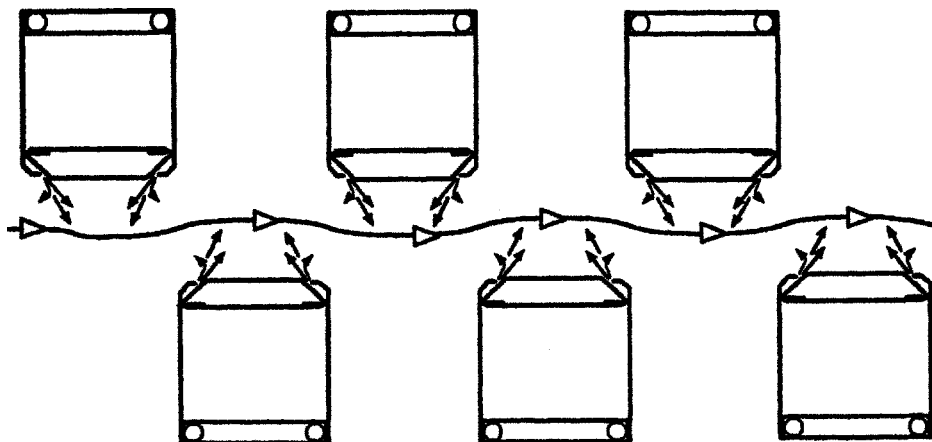


Figure 10-2. Two-sided floatation dryer showing the air nozzles.

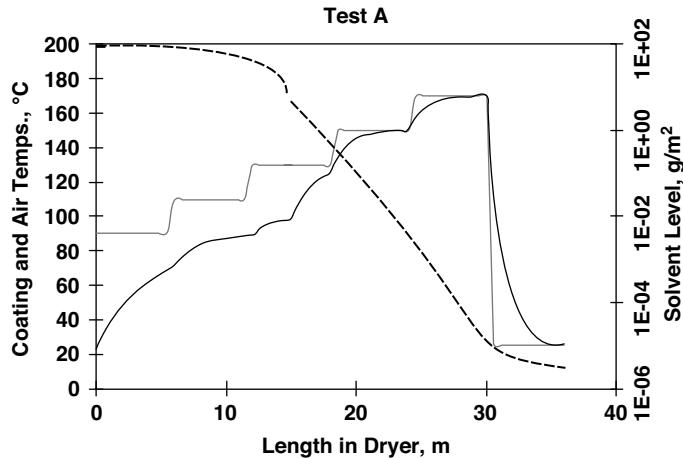


Figure 10-3. Drying curve from a simulation.

transport through the dryer. Two-sided drying increases the heat transfer rate compared with single-sided drying and also results in a higher web temperature.

In the constant rate period, the mass transfer coefficient is directly related to the heat transfer coefficient. Mass transfer controls the rate of evaporation of the solvent from the surface. The combination of the heat and mass transfer processes determines the behavior of the coating in the dryer. Figure 10-3 is a simulation of the web coating temperature versus dryer length for a dryer with five drying zones and one equilibration zone. It shows the variation in coating temperature as the coating moves through the dryer and allows us to distinguish different drying regimes. Figure 10-3 also shows the air temperature in each dryer zone, as well as the solvent level in the coating at all locations. The sloping air temperature line at the start of each zone is an artifact of the model; for the plot, the data points are only sampled every tenth of a zone.

The *predryer* is the space between the coater and the dryer where the coated web is in transition from the coater to the dryer and is not shown in Figure 10-3. This space is typically short and is often overlooked and not considered a part of the drying process. However, some drying may take place there and it can be a source of problems, defects, and drying variability. This area is exposed to the normal room air, which can be a source of contamination. In addition, any air motion can disturb the coating and possibly cause physical defects.

The *constant rate period* is the initial drying period where the wet coating behaves as a pool of solvent. In this “pool” the diffusion of solvent to the surface is faster than the rate of evaporation, which therefore is rate limiting. The rate-limiting step is always the slowest one. The rate of heat transfer to the surface thus determines the rate of evaporation. Once the surface appears dry—the surface gloss due to the wet coating becomes dull—the dry point is reached. The rate of diffusion to the surface now becomes rate limiting, the constant rate period is now over, and we enter the falling rate period. This continues to the end of the dryer.

From this definition we see that all of the dryer up to the point where the surface appears dull is in the constant rate period, even though the drying rate may vary greatly, and certainly changes as we go from one drying zone to another, with higher air

temperatures in each succeeding zone. It is even possible to never attain an equilibrium temperature and drying rate, all the while being in the constant rate period. This occurs, for example, when coating photopolymer on 0.5-mm aluminum sheet, with its very high heat capacity, where the heat capacity of the thick aluminum support (times the small temperature difference) is much greater than the heat of vaporization of the solvent.

When equilibrium is reached in the constant rate period, as it does in many cases, the coating and support are at a temperature lower than the air temperature, such that temperature difference times the area times the heat transfer coefficient (this gives the rate of heat transfer) equals the rate of evaporation times the latent heat of the solvent. For single-sided drying, the temperature of the web and the coating is the wet bulb temperature of the air with respect to the solvent used. With aqueous coatings where water is the solvent, the temperature is the usual wet bulb temperature that depends on the air temperature and the water content—the relative humidity—of the air.

In the *falling rate period*, diffusion controls the movement of the solvent to the surface of the coating, there is reduced evaporation of solvent, and the drying rate falls. Because there is less evaporation, much of the heat input now goes to raise the temperature of the coating. The location of the end of the constant rate period and the start of the falling rate period can be found by the rapid rise in the temperature of the coating. This occurs in the third zone at 14.92 m in Figure 10-3. We can see the location of the zones by looking at the air temperatures.

The term *heat-up zone* just refers to the first section of any drying zone where the temperature approaches its equilibrium value. We see in Figure 10-3 that the temperature is rising in all of zone 1, the end of zone 2 may be at equilibrium, and the end of the constant rate period in the middle of zone 3 may also be at equilibrium. In the falling rate period, the end of zone 3 is not at equilibrium, but in the ends of zones 4 and 5 the coating attains the air temperature and equilibrium is reached. In zone 6, a cool-down zone, equilibrium is also reached at the end of the zone.

The extent of the heat-up zone depends strongly on the heat capacities and thicknesses of the support and of the coating. In the example cited earlier of a photopolymer coated on 0.5-mm aluminum sheet, the heat capacity of the thick aluminum was so high that the temperature of the coated aluminum could be accurately calculated by assuming that uncoated aluminum was being heated in the dryer with no evaporation taking place. The whole dryer was a heat-up zone.

Aqueous and solvent systems behave differently in the dryer. In aqueous drying, most of the drying is in the constant rate period, while in solvent drying, most, and sometimes all, of the drying is in the falling rate period. Why?

Water, with its very low molecular weight, diffuses very rapidly and, because of its very high heat of vaporization, evaporates very slowly. In an aqueous “pool” where the surface remains wet, there is very little resistance to diffusion, but there is a high resistance to evaporation. This is the constant rate period, and for these reasons most of the drying is in the constant rate period. On the other hand, organic solvents all have much higher molecular weights than water, which makes them diffuse much slower. Also, organic solvents all have much lower heats of vaporization than water, allowing them to evaporate much faster. Thus most of the drying in solvent systems is in the falling rate period.

The *equilibration zone* is an additional zone after the main drying zones. Its low-velocity, relatively cool air is designed to bring the coating to storage conditions before it is wound up on the rewinder. This zone can (1) cool the coating and, with aqueous coatings, (2) allow the coating to reach moisture equilibrium with the air. It can also

- (3) provide heat input for curing, for fusing latex coatings, or for driving off surfactant and
- (4) provide space for electron beam or ultraviolet curing of the coating.

The *post dryer regime* is the space between the end of the dryer and the rewind roll. In this area the substrate and the coating are exposed to normal ambient conditions, which can affect the web in terms of both equilibration to ambient air and contamination defects.

Fundamental data on the coating solution and on the substrate are needed to understand some potential causes of drying problems. The thermal properties of the substrate, specifically the melt temperature (T_m), the glass transition temperature (T_g) above which polymer chains can rotate and the web is soft and easy to distort, and the decomposition temperature (T_d), should all be known. Normally the dryer temperatures should be below the glass transition temperature of the substrate to prevent distortion. The thermal properties of the coating solution and of the solvents should be known, such as the melting point (T_m) and decomposition temperature (T_d) of the dry coating and the normal boiling point (T_b) of the solvent. When these are compared to the dryer temperatures, it can indicate potential problems. This is of particular concern in the latter stages of drying when the coating is in the falling rate period. If the dryer temperature is similar to the melt temperature, the coating can remelt and be distorted.

Important components of the dryer include the control systems, the process measurement instruments, the web transport system, the heating and ventilating hardware to heat and to move the air and remove the solvent, and the environmental control systems. All of these can contribute to the formation of defects in the coating.

DRYER CONTROL AND SOLVENT REMOVAL

The primary function of the dryer is to remove essentially all of the solvent from the coating by the end of the dryer without damaging the product. It is unacceptable for the coating to leave the dryer in a wet state. The consequences of a coating leaving the dryer wet are far more severe than overdrying. If the coating is wet, it will stick to any face or wet-side rollers between the dryer and the rewind operation. The dirty face roll will damage subsequent product when wet material on the roll transfers back to the product, or at least marks it. Winding a wet product often causes the wound roll to fuse together, making unwinding for further processing and packaging impossible. Such product will be scrapped, resulting in a cost penalty. When rolls become contaminated from wet coating, the coater should be shut down, the rolls should be cleaned as quickly as possible, and corrective action should be taken to increase the drying rate or reduce the wet load. If heavy edges do not dry, the edges can be removed before the coating enters the dryers by edge doctors, or by blowing them off by small jets of air. This latter process can be messy.

Too high a drying rate leads to the possibility of overdrying the film by removing too much solvent too early and having the final coating exposed to high drying temperatures for too long a time. This high-temperature exposure can lead to deterioration of the physical properties such as adhesion and coating strength, to physical damage to the coating by remelting and flow of the coating, and to unwanted chemical reactions that can occur at too high a temperature.

The preferred situation is to precisely control the drying rate so that the residual solvent in the coating at the end of the dryer is at the desired level. In aqueous systems, often this is done by controlling the location of the end of the constant rate period (the dry point) to be at the same location in the dryer for all products. In solvent coatings, the end of the

constant rate period occurs early in the dryer, and therefore the location of the end of the constant rate period is not as useful for control purposes. In that case, the solvent concentration can be measured at the end of the dryer and the drying controlled to give the desired residual solvent. Another approach is to control the temperature at a suitable location in the dryer to a set value, which is known to give the desired degree of dryness at the end of the coater for that particular product.

The location of the end of the constant rate period should be the same all the way across the width of the coating. It should not fluctuate. However, variations in the coating weight profile in both the machine and transverse directions, as well as variations in the air velocities across the nozzles or slots, will cause variations in the location of the end of the constant rate period across the web.

There will always be some level of residual solvent in the dry coating, as the solvent can never be completely removed. When the solvent is water, the coating will eventually come to equilibrium with the moisture in the air. On some aqueous coaters, air at the temperature and humidity of the storage areas is blown onto the coating in the last or equilibration dryer zone, so that the residual moisture will not change in storage. Some binders will retain more solvent than others.

In order to provide the necessary information to troubleshoot dryer control problems, an explanation is needed of some of the important features of the system that provides drying air to the web. There is no one dryer system used for all applications, but the key elements, concepts, and definitions described here are applicable to many systems. For a more detailed explanation see Cohen (1992) and Weiss (1977).

The key elements in a dryer system are:

- The air impingement nozzles that deliver the warm air to the surface of the wet coating and/or to the back side of the web.
- Fan and motor assemblies to move the air throughout the dryer ducts to the nozzles.
- Coils to heat and/or cool the air.
- Ducts and dampers to control the flow of the air, carry it to nozzles, and return it to the heating, ventilating, and environmental systems.
- Filters to remove dirt and other contaminants from the air and provide the purity level needed.
- A system to remove solvent from the exhaust air.
- Environmental control devices, such as thermal oxidizers.
- Sensors to measure and record air temperatures, web temperatures, nozzle air velocities, duct air velocities, and solvent levels at several points in the dryer.
- Dampers to control the flow of air to the different dryer zones.
- A system to detect the location of the end of the constant rate period—the dry point.
- Independently controlled dryer zones in which the impingement air velocity, temperature, and solvent concentration can be maintained within a practical operating range without significantly limiting, or being limited by, the adjacent zones. For maximum effectiveness, a dryer should have several independent zones.

A typical system, which contains many of these elements, is shown in Figure 10-4.

There are several methods of detecting the location of the end of the constant rate period; that is, where the web temperature starts to rise rapidly. Of course, the start of a

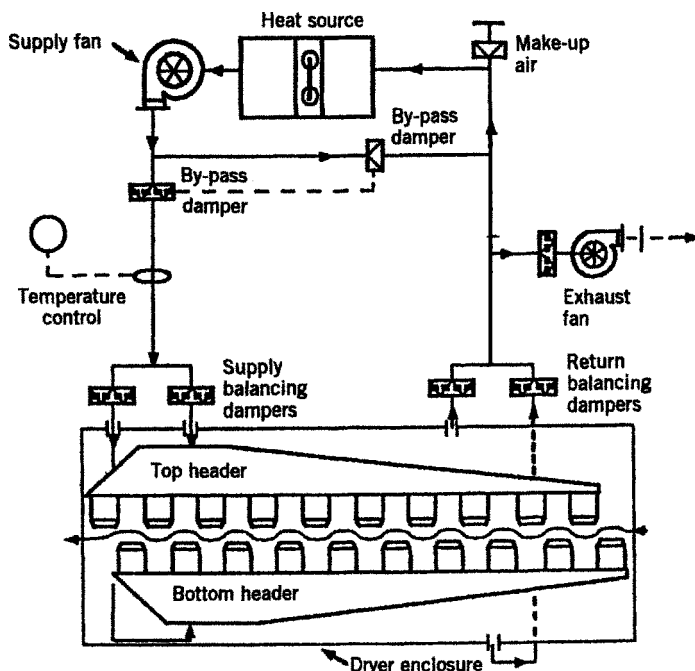


Figure 10-4. Dryer air-handling system.

new dryer zone with a higher air temperature has to be excluded. Infrared thermometers, thermocouples in the rolls contacting the film, and thermistors mounted close to the web will all work. Thermistors mounted close to the web do not read the web temperature but do read the exiting air temperature. In the constant rate period, this will be very close to the web temperature, and in the falling rate period, this will be reasonably close. It is a technique that has been satisfactorily used. In one case, measurement of the return air temperatures gave good results. With all of these systems, the drying conditions are set to give a specific location for the end of the constant rate period. All these systems can be automated and can be controlled by a computer. The data can be recorded continuously. The solvent content of the coating can be monitored with an appropriate detection method, such as microwave absorption for water, and the coater can be controlled to give a specific solvent concentration at a specific dryer location. This is usually only done at the end of the dryer.

In some cases, one can also use the "hand" method, in which the backside of the coating is touched to determine where the temperature starts to rise rapidly, or is touched near the edge of the coating side to feel whether the coating is wet or dry. Obviously safety is of great concern here, because a hand can easily get crushed between the support and a rotating roll or at other pinch points. Also, if the temperatures are high, there is a danger of burning the skin. The moving web can easily cut the skin.

The eye is also a good detector and one can visually observe differences in surface reflectivity that often exist between wet and dry coatings.

The overall dryer capacity is expressed as kilograms or pounds of solvent per hour that can be removed. This in turn is a function of the volume of air being delivered to the surface of the film, its temperature and solvent level, the effectiveness of the nozzle

configuration in use, and the amount of any additional heat delivered to the coating, such as by infrared heating. For this discussion, all the heat is assumed to come from the drying air. Then the rate of heat transfer to the coating is

$$Q = hA(T_a - T) \quad (10-1)$$

where A is the area of a dryer section, width times length (m^2 or ft^2); h is the mean heat transfer coefficient ($\text{W}/\text{m}^2\text{-K}$ or $\text{Btu}/\text{h}\text{-ft}^2\text{-}^\circ\text{F}$); Q is the rate of heat transfer to the coating (W or Btu/h); T_a is the temperature of air at the nozzle exit ($^\circ\text{C}$ or $^\circ\text{F}$); and T is the temperature of the coating ($^\circ\text{C}$ or $^\circ\text{F}$).

This equation applies rigorously to steady-state conditions. The important variables are the temperature difference between the dryer hot air and the coating, the area of the dryer, and the heat transfer coefficient, which is a measure of the efficiency of the dryer. Where conditions are not constant, because of the small heat capacity of the thin coating and the thin substrate, the equation can still be used over small areas over which the conditions are reasonably the same. Using suitable approximations for the average temperatures, the equation will give reasonable values when applied to a full drying zone, and then the total rate of heat transfer can be estimated by summing the values over all the zones.

The heat input by the drying air goes to heat the web and the coating and to evaporate the solvent. As it usually takes relatively little heat to raise the temperature of the web and the coating, since both are usually very thin with low heat capacities, another useful approximation is to estimate the dryer capacity by dividing the rate of heat input, found above, by the latent heat of vaporization of the solvent.

$$\text{Rate of evaporation} = \frac{Q}{\lambda} \quad (10-2)$$

where λ is the latent heat of vaporization (J/kg or Btu/lb).

The latent heat of vaporization is the amount of heat required to evaporate 1 kilogram or 1 pound of solvent, in units of joules per kilogram or Btu per pound. The result is the weight of solvent that can be evaporated per unit time. This value is used to characterize the performance of a particular dryer since it can easily be compared to the drying load generated by the coater. It is also useful in determining the needs of the dryer solvent removal system. More accurate values can be had using dryer simulation software.

The actual drying load is the weight of solvent coated per unit time minus the residual solvent in the dry coating. Assuming the residual solvent is negligible, which it usually is, then the drying load is the weight of solvent coated per unit area, times the width of the coating, and times the coating speed.

The heat of vaporization of the solvent is very important and it varies somewhat with temperature. A solvent, such as water with its high heat of vaporization of about 1060 Btu/lb, requires six times as much heat to evaporate 1 pound as does methylene chloride with a low heat of vaporization of 170 Btu/lb. Organic solvents tend to have low heats of vaporization. For the same dryer conditions, aqueous coatings will require either a longer dryer, or operation at a lower coating speed, or higher air temperatures to remove the same amount of solvent. These relations are semiquantitative only. More accurate methods of calculating drying are needed for precise control and optimization of a dryer. However, they can be used as a basis to define the important variables and concepts for dryer control in a troubleshooting process.

The dryer capacity has to exceed the required drying load for reliable and stable operation. If the heat input is too low, the coating will be wet and a correction to the drying conditions must be made. If the coating suddenly is no longer dry as it leaves the dryer, this can be due to a reduction of the heat input into the dryer, or to an increase in the solvent loading. The troubleshooting approach is to identify the specific coater parameters that can influence each of these and determine what has changed.

Factors that reduce the heat input are:

- Reduction in the temperature of the impinging air.
- Reduction in the velocity and volume of the air impinging on the film. This will reduce the heat transfer coefficient.
- Increase in solvent concentration of the impinging air. This will increase the coating temperature in the constant rate period by reducing the rate of evaporation and thus the evaporative cooling.
- Incorrect set point for dryer temperatures and air velocities.
- Blockage of the return air, reducing the effective air velocity at the film surface.

Factors that can increase the solvent loading are:

- An increase in coating weight.
- A reduction in solids content of coating solution. If the dry coverage remains the same, this greatly affects the solvent loading. Thus a 50% reduction in solids from 10% to 5% increases the relative solvent loading from $90\%/10\% = 10$ to $95\%/5\% = 19$ or by a factor of $19/10 = 1.9$. However, if the wet coverage remains the same and thus the dry coverage drops proportionately, the solvent loading changes relatively little. For the same 50% decrease in solids concentration, the solvent concentration increases from 90% to 95% and the solvent loading only increases by $(95 - 90)/90$ or 5.6%.
- A change in transverse direction coating weight profile, resulting in lanes of increased coating weight.
- Defects, such as streaks or spots, which will cause localized areas of heavy coating weight.

The heat transfer coefficient is a function of the dryer design and of the air velocity. The component of the heat transfer coefficient that is inherent to the design should not change; however, the heat transfer coefficient is approximately proportional to the air velocity to the 0.8 power.

To troubleshoot a reduction in heat input, the temperatures should be checked to ensure that the instrument set points are correct and are the same as those listed in the standard operating procedures for the product being coated. The dryer air temperature records should also be checked to ensure that the desired set points are being obtained. The air temperature thermometers, air velocity probes (or plenum pressure gauges, if pressure is used for control), and air solvent level (such as humidity) instruments should be calibrated to ensure that the readings displayed are accurate and that the instruments are in fact operational. A good rule of troubleshooting is to have a questioning attitude in regard to the accuracy of all readings, particularly when there is a problem. The velocities of the air delivery nozzles, jets, slots, and so on should be checked to ensure that they are at

standard conditions and delivering the correct amount of air to the web surface. A good method of monitoring the consistency of air delivery to the surface is to identify key nozzles in each zone and to measure them periodically, say, once a month. This data is then used to establish a baseline and normal variability, so that deviations can be detected if they should occur. This data can be maintained in a spreadsheet with the average and standard deviation being continuously calculated and made available when needed.

Possible sources of reduced airflow are leaks in the plenums and air-handling equipment, open doors in the heating and ventilating units, contaminated filters that have a high resistance to flow, dampers coming loose and blocking flow, fan blades coming loose on the shaft of the motor, bearings seizing in the motor, and even obstacles in the ducts. When checking dampers, the position of the handle may not indicate the position of the damper. There have been many cases where a disconnected handle incorrectly indicated an open damper. Look inside the duct to check the actual damper, if at all possible. The area of the dryer should not change; however, reduction of airflow to a zone or to a series of nozzles can have the same effect. Check to ensure that air is flowing to the web surface. A particularly useful calculation is to check the actual drying load for each zone using a mass balance calculation. For this, measurements of air volume, temperatures, and solvent content on both the inlet and return air are needed. The solvent loadings in the coating at the start and end of a zone could also be used, but this data is usually much more difficult to obtain. The actual drying load can easily be calculated as shown in Table 10-1. This type

TABLE 10-1 Drying Load Mass Balance Calculation

<i>Process Data for an Aqueous Coater</i>	
Air conditions to the dryer	
Dry bulb	105 °F
Dew point	30 °F
Humidity (from psychrometric chart)	0.00346 lb water/lb dry air
Air flow	15,000 ft ³ /min
Return air conditions from dryer	
Dry bulb	85 °F
Dew point	50 °F
Humidity (from psychrometric chart)	0.00766 lb water/lb dry air
<i>Calculations</i>	
$\begin{aligned}\text{Mass flow of air} &= \left(15,000 \frac{\text{ft}^3}{\text{min}}\right) \left(60 \frac{\text{min}}{\text{h}}\right) \left(0.075 \frac{\text{lb dry air}}{\text{ft}^3}\right) \\ &= 67,500 \frac{\text{lb dry air}}{\text{h}}\end{aligned}$	
$\begin{aligned}\text{Moisture pick-up in dryer} &= 0.00766 \frac{\text{lb water}}{\text{lb dry air}} - 0.00346 \frac{\text{lb water}}{\text{lb dry air}} \\ &= 0.00420 \frac{\text{lb water}}{\text{lb dry air}}\end{aligned}$	
$\begin{aligned}\text{Total water removal} &= \left(67,500 \frac{\text{lb dry air}}{\text{h}}\right) \left(0.00420 \frac{\text{lb water}}{\text{lb dry air}}\right) \\ &= 284 \frac{\text{lb water}}{\text{h}}\end{aligned}$	

of calculation can also be used to verify that all of the components of the air-handling system are functioning correctly. The coils used to heat or cool the air can be fouled from deposits from the heat transfer fluid inside these coils. This is similar to what occurs in a car radiator. As this fouling builds up, the efficiency decreases for heating or cooling. A quality control chart on the return part of the system will permit diagnosis of these effects.

To troubleshoot dryer problems from solvent loadings, the coating weight of the finished product and the solids concentration of the coating solutions should be measured on all batches and monitored with a quality control chart or by on-line coating weight measurements as described in Chapter 3. Typically, a couple of points at the start and at the end of the rolls are sufficient for the coating weight determination. This will give an indication of the true coating weight, which can be a contributing factor. A complete transverse direction profile should be run to isolate its effect. The drying load in every zone should be calculated from the recorded data. An increase in drying load is also an indication that the coating weight is high.

One strategy sometimes used to avoid dryer control problems with a new product is to keep the line speed slightly below the nominal steady-state speed, about 5% less, until the coating process produces the desired coating weight across the sheet and drying is complete before the end of the dryer. The economic incentive for starting at full line speed does not warrant the risks associated with starting too fast and not drying completely. Therefore the process is started at a conservative speed and then the speed is increased to the desired level as quickly as possible, while checking that the residual solvent in the dry product is within specifications.

For aqueous coating processes, the residual moisture level in the product is usually relatively high. It is often detrimental to product quality to dry the coating much beyond the moisture level in equilibrium with normal humidity air. In solvent coating, on the other hand, the level of residual solvent in the final product must be kept below some maximum level for environmental and quality reasons.

DRYING CONDITION CASE HISTORY

This section describes a dryer control case history. The problem investigated was a high air temperature in a plenum in a drying zone, which led to overdrying of the product. When the problem was brought to the troubleshooter's attention, there was some confusion as to when the problem started and whether the standard procedure limits were realistic, and whether it was possible to obtain the specified conditions. Therefore the first step was to gather some historical data and analyze it. For this aqueous system, the data are shown in Figure 10-5 and clearly show that there was a process change at roll 75. The air temperature and the dew point both increased significantly.

The next step was to characterize the process and define the reason for the change. The problem seemed to be associated with the air-handling system. Therefore small portable data loggers were placed before and after all coils in the heating and ventilating system, to characterize their performance over an extended period. As this was an aqueous system, relative humidity and air temperatures can be used for solvent concentrations. Air velocity measurements established that the air velocity at the nozzle exit to the web and the total air volume were in the specified operating range. Figure 10-6 shows the temperatures of the air entering and leaving the cooling coil in the air-handling system. These show that there

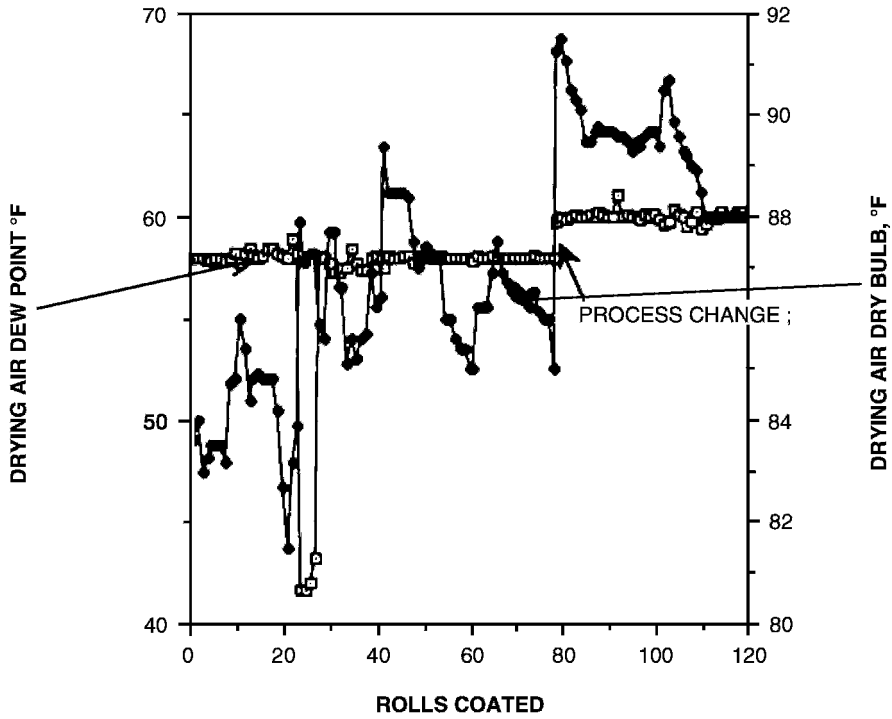


Figure 10-5. Drying air temperature and dew point versus roll number.

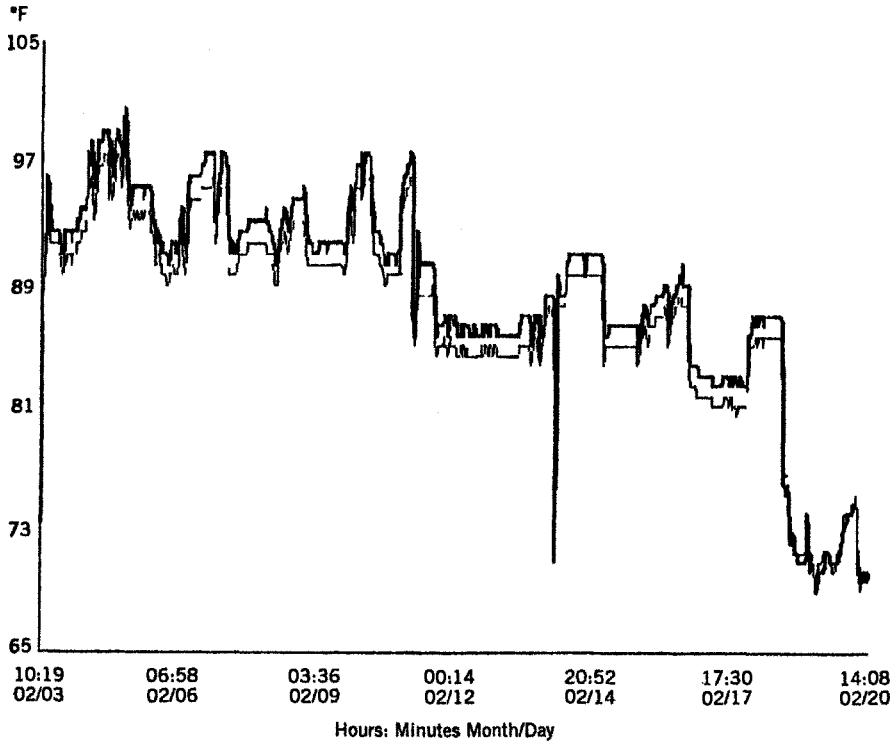


Figure 10-6. Air temperatures in and out of the cooling coil.

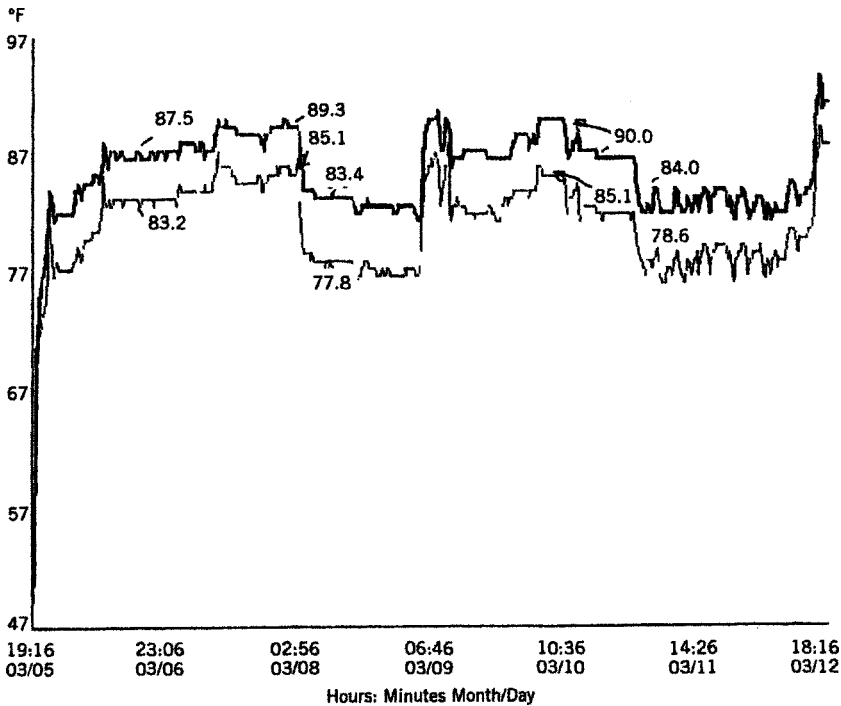


Figure 10-7. Air temperatures in and out of the cooling coil after cleaning the coil.

was a temperature drop of about 1.5 °F across this coil, even though the design calculations show at least a 5 °F drop. This suggested that the reason for the higher temperature was that the coil was malfunctioning. Also, a check of the coater logs indicated that there was some routine maintenance performed on the coolant lines at the time of the observed change. It was postulated that this poor performance was the result of a restricted flow of the coolant in the coil. This could have been from normal scale since the coil had not been cleaned in a long time. It also could have been the result of scale in the upstream piping loosened during the maintenance operations that had been carried into the coil and was blocking the flow. The coil was cleaned and the unit functioned correctly, as can be seen in Figure 10-7, where the temperature drop in the coils was now in excess of 5 °F. This problem can occur on any type of coil and can lead to either over- or underdrying. A nonfunctioning cooling coil will give higher than desired temperatures leading to overdrying, and a nonfunctioning heating coil will give lower than desired temperatures leading to underdrying.

Problems with the coils can also be diagnosed by monitoring the temperatures and flows of the cooling or heating medium into and out of the coils, as well as the air temperatures and flows. The heat transfer rate and heat transfer coefficient can then be calculated. The measurement and calculation are more complicated with steam than with a liquid medium but it is still possible. If the flow monitoring sensors are not in place, it can be time consuming and expensive to install them. The measurement of the temperature change of the drying process air across the coil is an easier method to use and is preferred. Data loggers can easily be installed in any location, and all of the desired data can be obtained and the calculations done rapidly.

DRYING DEFECTS

The maximum solvent removal capacity of a typical dryer can be determined using the approach described earlier. However, in actual practice the dryer may not be operating at this capacity, and drying itself may not be the rate-limiting step—the bottleneck of the coating process. This can occur when the drying process, while operating well under capacity, is on the verge of causing some defect in the coated film. Although there are dryers that operate at their maximum solvent removal capacity, many do not. Often a close look at the drying limitations shows some unspoken reason for not operating at higher line speeds. Usually, this unspoken constraint corresponds to the onset of a defect.

There are a variety of factors that can lead to this situation. In addition, heat transfer, mass transfer, and diffusion effects in the drying process can be and are important. Once the energy is transferred into the coating, the solvent has to migrate to the surface of the coating for it to evaporate and transfer into the drying air. If this migration and transfer can occur easily, then it will not be the rate-limiting step; the rate of heat transfer will be the controlling process. When the migration and rate of mass transfer is the limiting step, the introduction of more energy into the system does not increase the drying rate. It just heats the wet coating and its temperature rises. This occurs in the falling rate period. In aqueous systems, the coating is semisolid and appears dry. In solvent systems, this can occur when the coating still contains a high level of solvent, and can even occur throughout the entire dryer. The variation in the controlling mechanism is most apparent in the behavior of the web temperature in the dryer and can result in distinct regions of drying, as shown in Figure 10-3 and discussed earlier. For a more detailed discussion of drying, see Cohen (1992).

During drying, stresses build up in the coating. As the film dries the coating shrinks. It tries to shrink in all directions, but it cannot shrink in the plane of the coating because of adhesion to the base. As a result, the coating is stressed. Tensile stresses remain in the plane of the coating while the support goes into compression. The magnitude of these stresses will depend on the material, on the amount of shrinkage, on the properties of the binder system, and on the time–temperature relationships. The stress will decrease somewhat with time due to relaxation mechanisms occurring. The residual stresses, if not relieved, can lead to a variety of defects.

One of the problems in discussing defects is the naming problem and the use of jargon names, as discussed in Chapter 2. Since there is no agreed upon naming convention, the most common names that have been encountered in our experience and in the general literature will be used in this discussion.

The first step is to try and separate the defects caused by coating from those caused by drying. There is no rigid or guaranteed formula to do this. One good guideline is that typically the coater problems can easily be seen at the applicator. Chatter, streaks, ribbing, bubbles, spot defects, and heavy edges are all obvious. If it cannot readily be seen at the applicator, consider drying as a possibility. In addition, the problem-solving procedure should point to the proper point in the process. Often the different parts of the process contribute to the defect and there is no one process step that causes the defect. While mottle is a drying defect, one way to reduce it is to adjust the formulation rheology.

Describing the defect instead of giving it a name will also help. Knowledge of the type of defects that can be caused by drying will help define the source. Designed experiments can isolate the source. As mentioned previously, stopping the web and drying in place can help locate the cause. For this discussion, we define drying defects as those that are caused

in the drying regimes described above. This means that the web path from the dryer entrance area through the dryer to the windup is included. The problem-solving process should always begin by finding the characteristic dimension of the defect and proceeding through a systematic investigation of the physical phenomena that can be expected to dominate over that scale. The next few sections discuss some of the major drying defects, which are typically encountered in the normal drying process.

Air Bar Rubs

Air bar rubs are irregular diffuse “scuffs” on the surface of the film caused by the wet coating rubbing against the air bars in the dryer. They tend to be discrete with finite edges and have a gouged appearance. They can be in clusters or continuous and run in the machine direction. They are a particular concern with air flotation ovens because the distance from the web to nozzle is small, on the order of 0.5 in. or 12 mm, and a small flutter will lead to contact and wet spots on nozzles. The nozzle contacting the wet coating and disturbing the surface causes them.

Characteristically, these rubs may tend to get worse with time. The deposit on the air nozzle will build up with each contact, grow larger, and eventually form a stalactite, which actually touches the web and causes a streak. The easiest way to verify air bar rubs is to shut down the coater, open the dryer, and look for the contact point in the same locations as the observed defects.

There are several possible causes of air bar rubs. A poor web transport system can cause a vibrating web. Oscillating tension control and low tension can lead to an unstable web, resulting in contact. In floater dryers, the slot velocities of the top and bottom air bars need to be balanced to ensure a stable web. If the balance is changed in a couple of the air bars, the web may become unstable in that area and hit a nozzle. It is good practice to monitor the air velocities of representative nozzles so that changes can be detected. If an air bar rub occurs, check the air velocity in that region to ensure that it is correct. The alignment of the nozzles is also important. The nozzles should all be on the same centerline within accuracy specified by the manufacturer. Usually this is not a problem after the dryer has been started up, but it is a concern for a new dryer. The quality of the base can also be a factor in air bar rubs. If the base is not uniform and if it does not lie flat, problems can occur in the dryer, since the out-of-level spots will react differently to the air pressure. Try a different lot of base.

The factors that lead to curl in the dryer can also lead to air bar rubs. Typically, the curl is at the edges of the film and can be intermittent. If the rubs are at the edge, consider the steps outlined later for eliminating curl.

Blushing

Blushing refers to a “frosted” or hazy surface that results from water condensing on the coating in solvent coating. In the initial stages of drying, perhaps even before the entrance to the dryer, the coating will cool down to supply the heat necessary to evaporate the solvent. In single-sided aqueous coating, the coating temperature reaches the wet bulb temperature of the air. In solvent coating, it reaches the wet bulb temperature of the air with respect to that particular solvent. As the air normally has no solvent, the temperature of the coating can be quite low, especially for highly volatile solvents, even considerably below the freezing point of water. On humid summer days, this can be well below the dew

point of the air, and water will condense out of the air onto the coating. This water will evaporate in the dryer but will often leave a hazy surface.

To avoid blushing, a number of companies do not coat certain products in summer. Another solution is to dehumidify the air.

Bubbles and Blisters

Bubbles are spot defects where the contaminant is a gas such as air in the coating solution, and not a solid or an incompatible liquid. Usually the gas is introduced into the coating in the solution preparation step or in the feed system to the coating applicator. This gas causes a bubble that can remain in the coating bead of a slide coater to cause streaks. Bubbles can also be introduced in the coating process by entraining a thin film of air under the coating solution. In addition, it is possible for the drying process to introduce bubbles into the coating. With a high temperature in the dryer and a volatile solvent, it is possible for the temperature of the coating to approach the boiling point of the coating solution and for bubbles of solvent vapor to form. All of these bubbles will grow as the gas expands and then will break through the surface. An example of this behavior is shown in Figure 10-8. Initially there is the full bubble with the coating solution forming a dome over it. As the

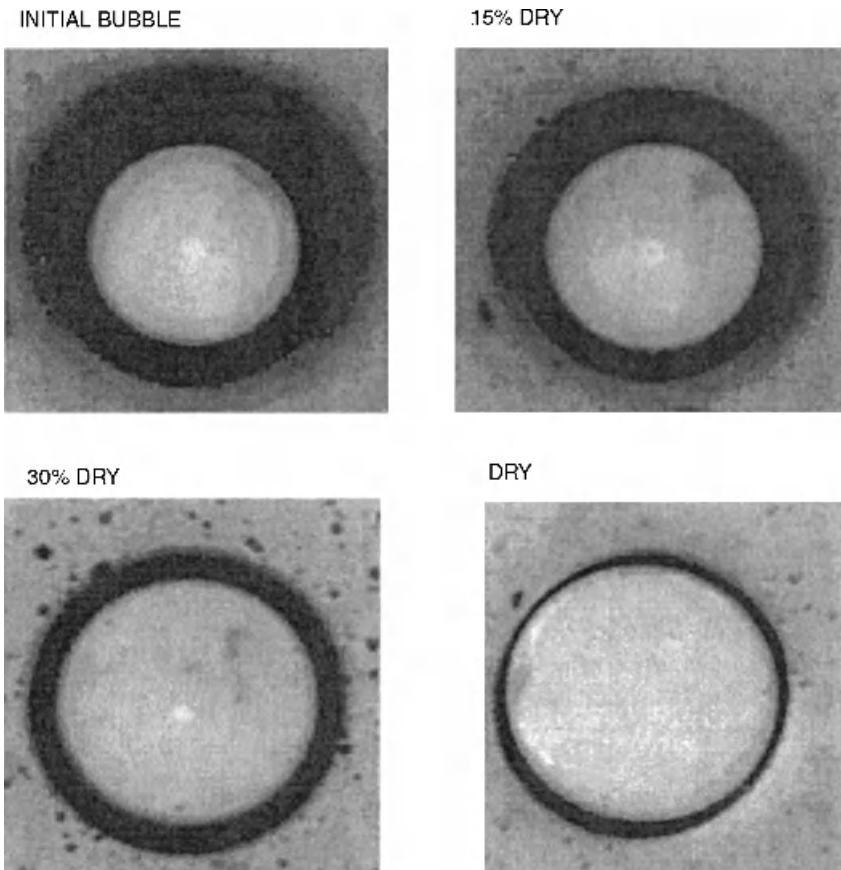


Figure 10-8. Effect of drying on a bubble.

drying progresses, the gas expands and the dome collapses. Another possible source for air can be the coating solution. If it is saturated at the coating station, then, at the higher temperature in the coating, bubbles can form. They too will expand at the higher drying temperatures and will appear in the dryer. Bubbles can also form in the coating lines where the pressure is reduced, such as in valves where the liquid velocity increases, and these bubbles may not redissolve.

One method to diagnose the sources of bubbles is to stop the coater, dry the coating in place, and mark the various drying zones. If the bubbles or blisters are present before the dryer entrance, then they were introduced prior to the dryer. If they are not seen at the dryer entrance but are seen at the end of the dryer, they are likely to be caused by boiling of the solvent. This technique will help give some insight into the fundamental cause.

To eliminate the dryer-induced bubbles, the solvent composition and the dryer temperature must be controlled so that boiling does not occur. If boiling is suspected, lower the dryer temperature and slow the coater down. Also, keep the temperatures low in initial stages of the dryer, so that any bubbles present will slowly diffuse to the surface while the viscosity is low and the surface can flow out and fill in the spot. If bubbles do occur, degas the coating solution to remove any bubbles. Pulling a vacuum on the coating solution for some period of time can do this. It can also be done using ultrasonic energy to move the bubbles out of the flow path (Hohlfeld and Cohen, 1993). If neither of these is available, it may be possible to let the solution stand in a relatively shallow kettle for several hours, to allow the bubbles to rise to the surface. Drawing off the solution from the bottom of the kettle will give a coating solution relatively free of bubbles. Measuring the thermal properties of the coating solution and its components will help us understand how to avoid this defect.

Cockle or Wrinkling

Wrinkles are small ridges or furrows in a substrate and coating that are caused by the shrinking or contraction of the substrate. Another large class of drying defects with similar effects results from permanent deformation of the web caused by distortions while held at high temperatures—sufficiently high that it is softened. Common examples would be deformation set into the web by tension wrinkles (troughs) that occur in spans of film between rollers (often due to misaligned rollers), and deformations set into the film when it passes over a roller while hot. A particularly intriguing example is a defect sometimes called “Venetian blinds.” Film affected by Venetian blinds exhibits alternating bands of tension wrinkles and lateral smoothness as the film moves through a span. These defects are always associated with a physical problem in the web transport system. Usually, the source of the defect can be pinpointed by measuring the spacing between the defects and finding where in the process such a spacing can occur.

Curl

Curl is the tendency of a coated film to bend toward the coated side instead of lying flat. It results from residual tensile stresses existing in the coating as explained previously. If these are in the coating, the curl will be toward the coated side. Curl is resisted by the stiffness of the base. Curl can be seen both in the dryer and in the finished product. In a dryer, the edges of the film can curl toward the coated side to the extent that it will rub against the air nozzles, leading to film defects. It can also occur after the coating is dried

and the film is converted into the final form. Occasionally, the entire sheet of film will “curl up like a cigar,” although typically only the edges turn up. There are two components of the curl that need to be discussed. The first is the generation of tensile stress in the coating, and the second is the effect of the stress on the overall product structure.

The effect of stress can be understood by comparing the curl of the film to that of a bending beam. This effect is used to measure temperature by fabricating a strip out of two metals that expand or shrink differently as the temperature is changed. The differential change in length between the two metals puts one in compression and the other in tension, exerting a bending moment toward the one in tension, which causes the strip to curl. Only if the metals are the same, and thus the contraction or expansion is the same, will there be no bending moments. This analogy can be extended to a coated product structure, which in its simplest form is composed of a support and a coated layer (Umberger, 1957). The tensile stress generated in the coated layer puts the support in compression, and, depending on the modulus of elasticity and the thickness of the support, the structure will tend to curl as a response to the force. A stiff support with a high modulus, such as of polyethylene terephthalate, will curl less than paper or acetate. Curl is illustrated in Figure 10-9.

As explained earlier, the residual in-plane tensile stress in the coating is due to the shrinkage of the coating as it dries while it still covers the same area on the web. The general understanding of curl is due in large measure to the work of Croll (1979). Studying simple systems, Croll reasoned that it is the deformation of the coating after solidification that leads to curl. While still soft and rubbery, that is, above the glass transition temperature, the solid structure allows enough molecular motion to relieve the tensile stresses that tend to form. Only after the coating loses enough solvent to reach the “glassy” state do the residual stresses remain. As the coating dries, the glass transition temperature increases until, with many materials, it is well above room temperature in the dried state. Croll neglected the stresses generated before the coating reached the glass transition point and treated the material as a linear elastic solid from that point on. This led to the general picture of curl being caused by residual stress development.

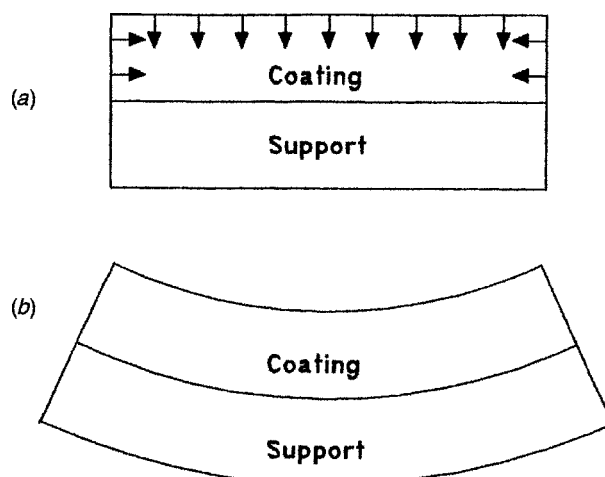


Figure 10-9. Curl illustrated. The coating shrinks during drying (a) and goes into tension. The support is therefore put into compression, and the system curls toward the coating side (b).

In terms of solving curl problems, the basic structure of the coated product determines the inherent tendency toward curl both in the dryer and in the final application. Good examples are photographic products. These are very sensitive to curl because of the inherent sensitivity of gelatin layers to the moisture content of the air. As the relative humidity of the air decreases, the photographic emulsion and other gelatin-containing layers lose moisture, contract, and generate stresses leading to curl. Thus photographic prints tend to curl more in the dry air of wintertime and less on the humid days of summer. To counteract this curling tendency, a gelatin layer is often coated on the opposite side of the support. This provides a counteracting tensile force on the other side. Even though the layers on both sides are contracting, there is no net effect on the product, except to put the support in compression. With these materials rehumidifying the coating can also control curl. This tends to swell the coating and also tends to soften it. Both of these effects tend to reduce residual stresses in the coating. Conditioning the material at a high temperature can also relieve stresses. This should be above the glass transition temperature to permit appreciable molecular motion. Adding a plasticizer to the formulation, such as moisture to a gelatin coating, softens it, allowing increased molecular motion. Theoretically, minimizing the volume change of the coating after solidification can minimize curl, but it can never be truly eliminated in a single-sided coating.

As already mentioned, the shrinkage forces that are generated during drying can lead to curl both on the coater and in the final use. Mild curl may not be seen in the dryer or after it, because the web tension needed to transport the web acts as a counteracting force to keep the web flat. However, at times severe curl may be seen in the coater and can be a problem. Moisture is a plasticizer for a wide range of materials, and variations in the air humidity can lead to shrinkage or swelling and can cause curl. This can occur both in and after the dryer. Again the photographic system is a good example. A polyester support is coated with gelatin-containing layers. These contract at low relative humidity due to loss of moisture and tend to curl. When the finished product curls, check the relative humidity. Winter can be a problem for certain products. It may be necessary to use humidifiers in the coating rooms. In the coater, an uneven drying profile can lead to additional stresses and curl. Check the coating weight uniformity to determine if this is a problem.

Rapid drying causes more residual tensile stress than does slow drying, because less time is allowed for stresses to be relieved before being locked in. Thus, if curl is a problem, gentler drying in the zones where the structure forms and is set, around the end of the constant rate period, would be desirable. Thus, in these zones, lower temperatures and a higher solvent concentration in the drying air can minimize curl. Check the location of the end of the constant rate period, and also confirm that the coating weight is on target. As explained earlier, curl is generally toward the coated side.

The solvent content of the air on the dry or back side of the web can also affect curl, even though it may have no effect on the drying process itself. This occurs when the support, or a coating on the back of the support, absorbs solvent. This is particularly noticeable with aqueous coatings on paper. If the dryer air has less moisture in it than it would have in equilibrium with the paper, the paper support will lose moisture and tend to shrink, and the system will tend to curl toward the dry side.

An increase in web tension on the coating line can "pull out" some of the curl. Since the base properties strongly influence curl, these properties should be checked when curl is encountered. These include the thickness uniformity, the modulus of elasticity (Young's modulus), the tensile strength, and the elongation to break. These properties should be checked in both the machine and the transverse directions.

The inherent product structure—the substrate thickness, coating weight, and coating location—can also influence the curl behavior of the product. A thin, low-modulus substrate can easily be distorted by the drying forces, particularly if it has a thick coating on it. Conversely, a thin coating with a high-modulus substrate is more capable of resisting drying forces and will not deform.

Mud Cracking

Mud cracking refers to an irregular breakup of the coating into small plates still attached to the substrate. It is similar to the appearance of a field of mud after it dries out in the sun. The cracks can be very close together, or they can be more than 5 mm apart. The tensile stresses that occur in drying were discussed under curl. When curling cannot relieve these stresses because the substrate is too rigid, they may exceed the cohesive strength of the coating (or of one layer in the coating) and the coating may crack. Mud cracking most commonly occurs in weak coatings on rigid supports. It is often seen in coatings where there is not enough binder to fill the spaces between the solid particles and air is drawn into the coating during drying. A common occurrence of mud cracking is in the clearcoat/topcoat of multilayer automotive paint systems. In this case, the topcoat is both damaged and thinned by ultraviolet light, breaking the backbone of the polymer chain. At some point, the topcoat can no longer support the stress and cracks develop.

Mud cracking can be reduced by the same factors that reduce curl. In addition, it is sometimes helpful to add particles to the coating liquid. The type and amount of particles have to be determined by experiment.

Delamination

Delamination is closely related to curl. If the tensile forces in the coating are greater than the strength of the adhesive bond between the coating and the support, then the coating can separate from the support, resulting in delamination. Delamination is often seen at the edge of a coating, for the residual stress rises sharply at the edge. This type of delamination results from the failure of the adhesive bond between the substrate and the applied coating. It is sometimes observed that a small strip of the coating at the edge will delaminate from the base. Usually, the strip will remain cohesively attached to the coating. The same considerations for reducing curl by reducing the stresses also apply to delamination problems.

Delamination can also occur between coated layers, and not only between a coated layer and the support. This is a cohesive failure of the applied coating.

There are some unique factors that can contribute to the delamination and adhesion failure problems. The surface properties of the support are very important. The surface must have not only a high surface energy but a proper balance of surface forces. Surface treatments such as by flame, plasma, or corona are often used to improve wettability and adhesion. If adhesion problems occur, these processes should be subjected to a troubleshooting process to determine if any changes in them correspond with changes in adhesion. The effects of corona treatment are often not permanent and corona treatment should be done on-line, just before the coating station. Tests on the wettability of the surface should give some indication if this is a factor. Surfactants are often used to improve adhesion.

At times a thin, high surface energy adhesive or subbing layer is coated on the support to improve adhesion. This layer helps bond the coating to the substrate. For products that

have this adhesive layer, if failure occurs, verify that the layer is indeed on the coating and that it is uniform and the correct coverage. Also, check that the correct side of the support has been coated. There are instances when the primary test is that the adhesive layer is always wound on the outside of the roll. When a roll with the adhesive layer on the inside is used occasionally, it can lead to trouble. There may also be problems with the adhesive properties of the coating. Simple peel tests with tape can give a clue to this. If the coating comes off when a piece of tape is placed on the coating and rapidly pulled off, and normally does not occur, then the source of the problem has been found. If the support is suspected, try a different lot of the support. Also check the wettability of the surface. However, an acceptable support is needed to use as a standard of comparison to determine whether chemical or physical differences have occurred. The time since the application of the adhesive layer or the treatment process can be important, since adhesion can decrease with time.

Changes in the coating solution can also lead to these types of defects. One of the factors in good adhesion is good wettability of the support by the coating solution. If the surface tension is too high, it will not wet and can lead to adhesion and coating problems. Similarly, if the surface of the support is contaminated, it can prevent wetting and reduce adhesion. Contaminants in a coating solution do not always show up as coating quality problems; they can lead to wetting and adhesion problems. Check both the surface tension and the viscosity of the coating solution and make up a new coating solution batch with different lots of raw materials.

Dryer Bands

Dryer bands are areas of nonuniformities that appear as lanes running in the machine direction. Depending on the system, they may have a rough surface, have a difference in reflectivity, or just appear as hazy lanes. It is also possible that they will not be visible but will appear in use as lanes of different properties, in products that are sensitive to drying conditions. Dryer bands are most common when round holes or nozzles, rather than full-width slots, are used for the drying air. The distinguishing characteristic of dryer bands is their uniform spacing across the web, and also the correlation of their spacing with that of a physical characteristic of the dryer. When circular jets are used for the air nozzles, the dryer bands appear with a thickness approximately equal to the diameter of the air nozzles. The band itself can be caused by a difference in drying rate or by an actual disturbance in the surface of the coating caused by the air jet. Dryer bands are less common with full-width slots, although they can still occur. They are caused by nonuniformities in distribution across the web of the air impinging on the web, and, with round nozzles, in the reinforcement of that nonuniformity over a wide range of nozzles. If the airflow disturbs the surface of the wet layer, the dryer bands can be caused by a single row of nozzles; however, if the dryer bands are caused by differences in the rate of drying, then usually several rows of nozzles are needed to form the bands.

Dryer bands are the direct result of the maldistribution of airflow in the dryer, either in the delivery system or in the exhaust system that removes the air. Depending on the nature of the defect, the airflows, air temperatures, or coating composition may need to be adjusted. However, they are often an inherent characteristic of the dryer hardware design, and modification in the hardware to improve airflow uniformity should be considered. The air velocity in that dryer zone may need to be reduced to eliminate the dryer bands.

The flow of the wet coating caused by the force of the impinging air increases with the air velocity and also with the thickness of the coating and decreases with liquid viscosity. To reduce dryer bands then, one should reduce the air velocity. This reduces the drying rate in the constant rate period at the beginning of the dryer. Also, the coating viscosity should be increased to make the coating more resistant to flow, and the coating solution should have a higher solids concentration to give a thinner coating, which is less susceptible to deformation. Increasing the solids concentration simultaneously increases the viscosity, both of which are desirable. Further down the dryer, as drying continues, the solvent evaporates and the coating becomes thinner and more viscous and therefore is less likely to be disturbed. Air velocities can be higher in succeeding zones. Dryer bands usually appear at the beginning of the first drying zone, where the viscosity is lowest and the wet layer is thickest. However, if the air velocity is high enough in the later zones, dryer bands can occur there.

Dryer bands have also been seen at the start of the falling rate period. In the falling rate period, the coating temperature approaches the air temperature. Because of this higher temperature, it is possible for the viscosity to be low enough for dryer bands to occur, even though the solvent concentration is much less than at the start of drying. Also, in the falling rate period, the drying rate is controlled by the rate of diffusion of solvent through the coating to the surface. The diffusion rate of the solvent is a strong function of the solvent concentration. The solvent concentration in the layer at the surface will be in equilibrium with the solvent concentration of the drying air. When this is zero, the solvent concentration at the surface will be zero, the diffusion rate through this surface layer will be very low, and drying will be very slow. Also, the surface layer will act as a surface skin over a soft coating, and this skin can easily be deformed to give dryer bands. Increasing the solvent level in the air will increase the surface concentration of solvent, which will increase the diffusion rate and thus increase the rate of drying. There will no longer be a surface skin, with a fairly uniform, relatively high solvent concentration throughout the rest of the layer. The solvent will now have a "high" concentration only near the base, and the coating will not be as soft. It will therefore be more resistant to dryer bands. Thus, strange as it may seem, increasing the solvent concentration in the drying air increases the drying rate at the start of the falling rate period and also reduces the tendency to form a skin and to form dryer bands.

In the final stages of drying, dry air has to be used. Obviously, the solvent level in the coating cannot be reduced below that in equilibrium with the drying air. To get a dry coating, there has to be no solvent in the drying air in the last drying zone.

Dryer Remelt

Dryer remelt is a distortion of the coating surface which occurs in the falling rate period or when the coating is dry in the drying oven. It occurs because the coating film temperature is close to a transition temperature of the coating, and the impinging air velocity causes the coating to distort. For defects to appear, the whole coating does not have to be melted. The surface needs only to soften slightly, and high velocity air impingement can distort it.

Remelt is seen either as dryer bands or as cross-web bars that may appear to be similar to chatter. It can occur at any part of the process. Even though the coating is dry and a solid at the end of the dryer, the coating temperature increases in the falling rate period to that of the air temperature. If these temperatures exceed the glass transition temperature at that particular solvent level, the coating can flow and distort. To eliminate these defects,

the glass transition temperature of the coating at various solvent levels should be known and compared with the temperatures in the dryer. If there is an overlap in temperatures, lower the dryer temperature. If the glass transition temperatures are not known, a scan of the coating in a differential thermal analyzer at various solvent levels will give this information.

Remelt can occur in those coatings that are chilled to solidify the liquid coating into a gel before entering the dryer, in order to allow higher air velocities in the early stages of drying. Remelt occurs when the temperature of the gelled coating exceeds its melting point. An example of chill-setting is in the coating of photographic systems. The gelatin binder dissolved in water forms a solid gel when chilled below the setting temperature. The system is coated at about 40 °C, which is above the melting temperature, and the coating is in the liquid state. Chilling the coating before it enters the dryer converts the liquid to a semirigid solid gel. If the coating heats up in the dryer to above the melting temperature, the coating will convert back to a liquid, and then dryer bands can easily form from high-velocity drying air. Fortunately, the temperature of the gelled coating is well below the temperature of the drying air due to the loss of heat needed to vaporize the water. In fact, in single-sided drying, the coating temperature is the wet bulb temperature of the air.

Dryer Contamination Spots

Spots and discontinuities are defects that are often found in coatings. Their size can vary from easily visible with the unaided eye to so small that magnification is needed to easily view them. Drying spots arise from a contaminant in the airstream impinging on the wet coating and disturbing it. Airborne dirt is a typical contaminant and examination of the defect will often show the particle in the center. This is a difficult area to precisely diagnose, since contaminants in the original coating solution cause similar defects. The contaminant itself can be small and covered by the thick wet coating. However, as the coating dries, its thickness decreases and the defect becomes visible. The contaminant can be in the impinging air. Therefore filtered air should be used to minimize spots by keeping particles out of the airstream. Also, the dryer should be under a slight positive pressure so that air blowing out of the dryer will keep unfiltered room air off the coating and thus will help reduce spots. If the dryer cannot be at a positive pressure, it should at least be kept as close to neutral as possible, to avoid sucking room air into the dryer. It is easy to check this by hanging a thread over the dryer openings; the thread is light and will quickly respond to the slightest air currents, showing whether air is flowing out of or into the dryer.

It is also essential to keep the dryer clean. The wet coating can rub off on the nozzles, dry, and then drop back on the coating, causing spots. The dried coating in the dryer can also cause streaks if the nozzles are close together and the contamination is large. Keeping the dryer clean will eliminate this defect. Also, be aware that the entire heating and ventilating system can be a source of spot-causing defects. Ducts can get dirty, and since they are usually hard to access, they are not often checked. Routine cleaning should include the ducts wherever possible. Filters are effective but they are not foolproof. They can get damaged and the seals can leak, permitting dirty air to enter the system. When spot defects are found, check the filter pressure drop. If it has increased, change the filters. Also check all the seals and door gaskets for their integrity. Replace them if there is any doubt. The key to solving spot problems is to characterize all of the samples and to be aware of all the contaminant-causing spots. This information can then be used to compare with the

current defect. When cleaning hard-to-access hardware such as air delivery ducts and nozzles, take samples of any dirt or contaminant and characterize them and put the results in a database, so they can be compared with future defect material. It may not be possible to obtain samples in the future. Having this data in the files will help to solve future problems. The major dryer process units, fans, coils, environmental unit, and solvent control systems, can also contribute to contamination, such as through oil in bearings and desiccants.

Dryer Condensation Spots

Condensation spots have a clear center with high edges and splashes around the center. The spots give the appearance of a drop impinging on a wet surface. Characteristically, these are random in overall occurrence, but when they appear they repeat in the same general area.

They occur when there is a solvent buildup in the dryer, which is chilled below the solvent saturation temperature. This leads to the solvent condensing and dropping onto the coating. This can occur if the outside walls of the duct, at or near room temperature, are below the saturation temperature of the air. This is more likely to occur in relatively stagnant regions of the air return system. It also can occur at the wall separating the dryer from the chiller, if a chiller is used. These defects are hard to analyze, since in most cases by the time the process is shut down and dryer doors are opened the solvent has a chance to evaporate and can no longer be detected. This defect is characterized by the appearance of a clear center surrounded by splash marks.

Haze

Haze here refers to an internal haze in the coating rather than a surface haze, which results from blushing or from reticulation. Haze can have at least three distinct causes, depending on the nature of the coating. In coatings that have a latex binder, the latex particles must coalesce into a continuous phase in the early stages of drying. Incomplete coalescence manifests itself in haze. Haze can also result from a phase separation, as in overspray. Additives that are more soluble in the coating solvent than they are in the polymer binder may separate out as drying proceeds. In addition, haze can result from microscopic voids that occur when the volume fraction of dispersed solids exceeds a critical value, which may be far higher than 50%, depending on the shape and size distribution of the solids. There is simply not enough binder to fill the space between the solid particles, so that air penetrates into the voids, resulting in haze that can be detected with the naked eye. However, the physical defect that causes this haze is typically too small to see.

Mottle

Mottle is an irregularly patterned defect on the surface of the coating that can be gross or quite subtle. At times it can have an iridescent pattern, depending on its severity. The scale can be quite small to quite large, on the order of centimeters. It is believed to be caused by a nonuniform airflow blowing the coating around in early stages of the drying process when the coating is still quite fluid. The nonuniformity of the air motion causes a slight motion in limited areas of the web, the effects of which appear as mottle. Mottle is usually a fluctuation in coverage. Sometimes mottle is not visible in the dried coating but is seen

later when the product is used. A uniform airstream would affect the entire surface and would not cause such a defect. One should first investigate the predryer, the region between the coating applicator and the initial drying zone. Air motion can occur in this area, and air can blow out of, or into, the dryer entrance slot. Air motion in this area can be checked by holding a thread at the entrance slot.

If the predryer is open to the room, consideration should be given to enclosing this area to minimize air motion. This does not have to be elaborate and can be as simple as a plastic sheeting attached to the framework between the coater and the dryer. This will also protect the web from airborne dirt. If air blowing into or out of the dryer entrance door is causing the mottle, the air pressure should be carefully balanced so that no air motion occurs. A slight motion into the dryer is preferable to flow out of the dryer, as such a flow is with the motion of the web. If mottle occurs in the first dryer zone, the velocity of the drying air should be reduced.

As with dryer bands, mottle is reduced by making the coating more resistant to motion. This can be done by concentrating the coating liquid so as to have a thinner layer, and by raising the viscosity of the coating liquid. Concentrating the solution also increases the liquid viscosity, and so this method is highly recommended. Lowering air velocity to the web to reduce the distorting force can also be effective.

Orange Peel and Crinkling

Orange peel refers to a rough finish in the dried coating that is generally associated with surface tension driven flows, although the usage of the term is not well controlled. Orange peel is not a regular hexagonal pattern. It tends to be exaggerated at high drying rates and, in particular, with higher air velocities in the dryer. Orange peel may occur in bands. Crinkling is a phenomenon that occurs when a thin skin forms on the surface of the wet coating. Crinkling is produced intentionally to produce a rough surface for painted metals, such as on typewriters. Crinkling is normally not seen in thin film coatings.

Overspray

Overspray is a drying defect so named because affected film looks like a painted surface that has been inadvertently exposed to an incomplete second coat of paint. The term is commonly used in the paint industry. As a drying defect, “overspray” results from a phase separation where some additives become insoluble in the coating as drying proceeds. The insoluble materials exude out of the film. Overspray may appear similar to blushing, but the cause is completely different. Adjusting the formulation of the coating usually controls overspray, although it may be possible to avoid it by judicious choice of drying conditions. Overspray may be considered a milder form of a defect that has been referred to as “scrambled eggs,” in which the coating phase separates on a gross scale to produce a curdled appearance.

Reticulation

Reticulation is a somewhat irregular pattern of distortions in the coating that occurs not in drying, but in uneven swelling of a previously dried layer, such as in processing an exposed photographic film or paper. The pattern appears as sharp wrinkles or cracks in the coating. When heavy, it has the appearance of chicken tracks. These tracks will lead to an

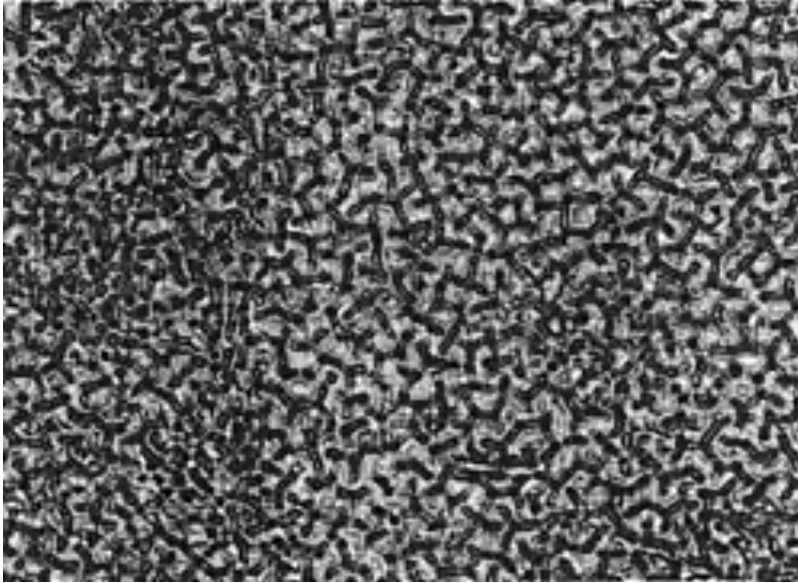


Figure 10-10. Reticulation in a processed photographic film. From E. D. Cohen and R. Grotovsky, *J. Imag. Sci. Techn.* 37, 133–148 (1993), with permission of the Society of Imaging Science and Technology.

objectionable haze. Reticulation is a concern with photographic systems and was first studied by Sheppard and Elliot (1918). A typical example of reticulation is shown in Figure 10-10. Reticulation results from the surface of the coating buckling as a result of the stress in swelling of a dried film. The reason that reticulation is discussed under drying defects is that, in the photographic field, the susceptibility of the coating to reticulation is controlled in the dryer. That is, the conditions in the dryer control the mechanical properties of the coating and the level of residual stress in the coating. Both of these determine whether or not reticulation will occur.

Reticulation is particularly hard to troubleshoot because it is not seen until the product is rewet and swells. When reticulation occurs, the rate of drying has to be reduced to reduce the residual stresses. This can be done by lowering the drying temperatures or by increasing the solvent concentrations in the air. Also, hardening or cross-linking can be a factor. The use of cross-linking agents should be checked to ensure that the proper amounts and levels are used. A simple statistically designed experiment can help define the correct drying conditions and levels of cross-linking agent. Coating formulation modifications to increase the modulus of the coating to resist the deforming forces can be tried.

There is also a mild interaction between reticulation and delamination. The driving force for both of these is the stress generated by drying. There are two types of adhesive bonds—those between the support and the coating, and those between the coating components. The specific failure from the stress will determine the defects that result. Both types of bonds are stressed during drying and also during subsequent swelling. Failure of the adhesive bond between the coating and the support results in delamination. Failure of the adhesive bond between the coating components can result in reticulation.

Surface Blow-Around

In most coating systems, the coating does not gel at any point in drying; rather, the coating becomes progressively more viscous as drying proceeds. In such systems, gross disturbances of the surface by airflows can be much worse than those called mottle. This defect usually occurs at the beginning of the dryer, where the coating is most dilute and the air velocity is high. The scale of surface blow-around can vary from quite small to quite large. It is minimized by reducing the airflow to the surface in the initial stages of drying and increasing the airflow gradually throughout the dryer. A higher viscosity in the coating solution will also help.

Microscopic Defects

Drying can also create a class of very small microscopic defects that are too small to be seen with the naked eye. Depending on the application, defects in this very small size range may not present a functional problem. However, there are some applications where this size defect can be a problem. Applications such as photographic film, compact discs, and magnetic tape are very sensitive to microscopic defects because the size of the stored information is the same size or smaller than the defect, and such defects will lead to malfunction of the product. The next paragraphs discuss some of these defects.

Starry Night Starry night refers to apparently clear spots left in photographic film as a result of “matte” particles from an overcoat layer being pushed down by drying stresses (Christodoulou and Lightfoot, 1992) into the silver halide layer, thus pushing aside the silver halide crystals. The matte particles are used to give a rough surface, allowing uniform contact during film exposure in a vacuum frame by providing channels for the air to escape from the center of the film. The defect appears as a series of random white holes of 1–10 μm diameter that are seen against the black exposed film background. They look very much like the night sky; hence the name “starry night” or “galaxies.” They appear white because the silver halide crystals that were present had been pushed aside, and therefore there is no black developed silver there. While starry night is not visible to the naked eye and can only be seen by a microscope, the effect is to reduce the optical density of the exposed and processed film, and this has an adverse effect on its performance.

The term “windowing” is commonly applied to a similar defect in the paint industry. It is a typical drying defect for most coatings that have particulates in them. Reducing the drying rate, which reduces the stresses in curl and in reticulation, also reduces the severity of starry night. In particular, reducing the drying rate toward the end of the drying process is particularly important. If the solvent concentration, here water, in the drying air is low and the air temperature high, then the surface will dry out and will tend to force the larger particles to migrate down along the wet–dry boundary into the coating. Increasing the solvent concentration in the air or reducing the air temperature keeps the solvent concentration in the surface higher for a longer period of time. The matte particles themselves also play a role. If starry night is encountered, the particle size distribution of the matte must be checked to ensure that it is within quality control limits. Large particles are a particular problem. A small increase in the fraction of large particles leads to a large increase in the severity of starry night. If possible, check the particle size of the matte in the coating solution. It is possible for an ineffective dispersion process to give large agglomerated particles, even though the raw material is acceptable.

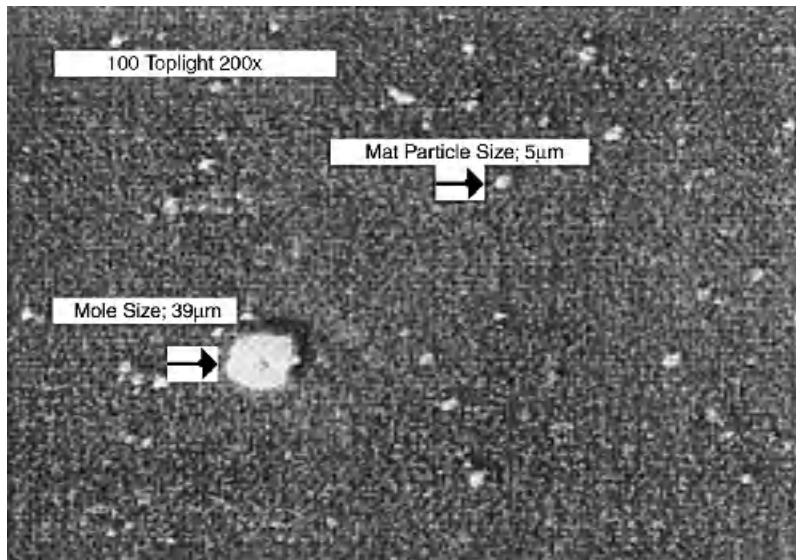


Figure 10-11. Defect caused by a particle that was initially incorrectly identified as starry night. From E. D. Cohen and R. Grotovsky, *J. Imag. Sci. Techn.* 37, 133–148 (1993), with permission of the Society of Imaging Science and Technology.

Pinholes There are also a wide variety of pinhole defects, which, in photographic films, can appear to be similar to starry night but obviously have different causes. Correct identification is essential. It is important to analyze the defect and to ensure that it is indeed what you think it is. An example of this is shown in Figure 10-11. A white spot defect in a photographic film was called starry night and was submitted for analysis as a standard part of the troubleshooting process. The digital image analysis showed that the defect was larger than starry night, had a particle in the center, and was not starry night. The problem was not dryer induced but was traced to an incomplete dispersion and poor filtration. Trying to correct the problem by reducing drying stresses would never have cured it. The cure would have been delayed, perhaps until it would have gone away on its own.

In one case, pinholes occurred when an anionic surfactant was used to reduce the surface tension of a coating solution that was a dispersion. When a nonionic surfactant that gave the same surface tension was substituted, pinholes still resulted. But use of both the anionic and nonionic surfactants gave a pinhole-free coating, even though the surface tension remained the same. Presumably, the adsorption of the surfactants on the dispersed particles was different.

In another case, pinholes were traced to dust from a slitting operation falling onto the uncoated web, causing microscopic areas of nonwetting.

THE ROLE OF DRYER SIMULATION IN TROUBLESHOOTING

As a result of the widespread availability of moderately priced powerful computer systems, the use of computer technology to assist in troubleshooting drying problems is

DRYWEB: Models the Drying of Coated Webs v. 1.11 May 19, 2003
 SI or English units, can handle it Test A
 Calculates transients See Notes below, at A:A58
 Programmed by E. B. Gutoff, all rights reserved

Wet coating weight 100.0 g/m² SOLVENT (use macroQ to change)
 % solids 10.00 Dowanol DPMA 50.00 % by wt
 Solids sp. heat 0.50 2-heptanone 50.00
 Solids density 1.20 g/cm³ 0.00
 Base id plastic Total 100.00
 Base thickness 100.0 μ m
 Base spec. heat 0.40 DIFFUSIVITY CONSTANTS
 Base blk density 1.300 g/cm³ A, cm²/s 20000 E-8
 Coating speed 2.000 m/s B 2.00
 Ambient temp. 23 C E, J/mol 15000
 Vapor press factor 0.25
 If it is used Constant Rate period ends 14.92 m into dryer.
 w, Web width 45 mm
 For computations
 Delta time 0.020 s
 Number slices 12 - There must be 3 to 14 slices.
 Number of zones 6 - Use MacroE to change
 Ref air velocity 10 m/s

Zone	Length m	Cum Length m	Air Velocity m/s		T-Dry Ctg C	T-dry Base C	T-web at end C	Solvent at end g/m ²	Ref h @ 10 m/s W/m ² -K	
			ctd side	back side					ctd side	back side
1	6.00	6.00	10.0	10.0	90.0	90.0	70.3	83.50	100.0	100.0
2	6.00	12.00	15.0	15.0	110.0	110.0	88.6	45.04	100.0	100.0
3	6.00	18.00	20.0	20.0	130.0	130.0	125.2	0.44	100.0	100.0
4	6.00	24.00	25.0	25.0	150.0	150.0	149.8	0.00	100.0	100.0
5	6.00	30.00	25.0	25.0	170.0	170.0	169.9	0.00	100.0	100.0
6	6.00	36.00	25.0	25.0	25.0	25.0	25.8	0.00	100.0	100.0

Figure 10-12. Dryer model input and output.

becoming more widespread. In at least some industrial organizations, computer-based models are being used to simulate the drying process in manufacturing and in pilot coaters. Since all dryers are slightly different, specific models are needed for each dryer. However, there are computer programs that use a basic template that can easily be modified to model a specific coater.

These models are used to predict the rate of drying, the coating temperature, and the solvent level in the coating throughout the coating process, as was shown earlier in Figure 10-3. The model can also give the location of the start of the falling rate period, as is shown for that same system in Figure 10-12, which is a printout of a computer input and output. The models can be modified to give the solvent concentration in the exhaust air. The input conditions needed include, as seen in Figure 10-12:

- Wet coating weight.
- Solids concentration in the coating solution.
- Solids specific heat and density.
- Solvent composition (this should also bring up the solvent physical properties from an internal database).
- Web thickness, specific heat, and density.
- Line speed.
- Number of dryer zones and length of each zone.

- Air slot velocity in each zone on the coating and backsides.
- Air temperature in each zone.
- Solvent content of the air. For solvent systems the solvent content is normally taken as zero. For aqueous drying, a simpler model, which only calculates the location of the end of the constant rate period, is often used, and that model calculates the relative humidity and the wet bulb temperatures of the drying air from the dry bulb temperatures and the dew points.
- Dryer heat transfer coefficients at a reference air velocity. This allows the calculation of the actual heat transfer coefficient in each zone from the actual air velocity.

The output from these models often includes a plot of the coating temperature, the solvent level in the coating, and the drying air temperature versus dryer length, as was shown in Figure 10-3. These models can be used to determine the effect of drying process changes that are being considered to ensure that product is adequately dried. It is far more effective to learn that a proposed reduction in air velocity will give a wet film at the end of the dryer in a simulation than it is to do it on-line. It is cheaper to model a dryer than to run plant experiments. Also, it permits evaluation of drying profiles that might not be available in actual equipment and can be used to justify process upgrades. Models are being developed for both simple and complex systems.

Computations for constant rate drying can be done by hand, or on a simple spreadsheet (Cary and Gutoff, 1991). For the complete drying process, including the falling rate period, the simulation is more involved (Gutoff, 1996), as indicated in by the spreadsheet shown in Figure 10-12. More sophisticated models have been developed using computational fluid dynamics and commercially available programs. Companies involved in web drying have developed drying programs internally. Most dryer manufacturers have such programs.

THE ROLE OF RADIATIVE HEATING IN DEFECT REDUCTION

The addition of infrared (IR) heaters to an impingement dryer provides additional heating capacity that can reduce the serious defect of an underdried coating. These heaters can easily be added to the dryer in the predryer section and can be interspersed among the convection units in the constant rate period. These IR heaters transfer heat directly from emitter to wet coating. They operate at wavelengths of 0.7–8.0 μm . They provide rapid drying and efficient use of space, are a low-cost investment, and can be simply retrofitted. Their role in defect reduction is to provide additional capacity so that drying conditions can be optimized to minimize defects.

For example, if the coating has a low viscosity and is being blown around to give mottle or surface blow-around, then the IR heater can start the drying process without the use of impinging air, which will disturb the coating. If high dryer temperatures in a later zone are leading to remelt, the IR heaters can do some drying and permit lower temperatures in the last zone. If higher coating weight is needed and the coater is dryer limited, these IR heaters can provide additional capacity.

The main safety issues related to ir heating have to be fully investigated.

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11

PROBLEMS ASSOCIATED WITH WEB HANDLING

by GERALD I. KHEBOIAN

Problem-solving techniques and the diagnostic tools used in problem solving were described in Chapters 2 and 3. Add to these tools electronic instrumentation, machine alignment equipment, and, most importantly, the power of your own observation using your gifts of sight, smell, touch, and hearing.

On a day-to-day basis, look at tension indicators, ammeters, coating flow indicators, temperature indicators, zone air pressure indicators, and speed indicators. Are they the same today as they were yesterday? Are they stable or do they seem to be wandering? If a computer is used to log process data, check operating conditions frequently to ensure that the machine is running normally. If no indicators or computer records exist, it is difficult to determine whether something has changed when process or web transport problems occur.

Is the web transport normal in the dryers, or is the web ballooning and dragging over flotation section nozzles? Is the web tracking to one side or dangerously close to running off the machine? Is there a strong odor of solvents? If so, has the dryer oven air balance changed?

Who or what caused the change in oven balance?

Has the dryer tension level changed? Is the web tracking to one side or the other, or is it tracking on the centerline of the machine? If the machine has impingement dryers, is the web forming deep catenaries between carrier rolls? All these conditions in dryers often lead to scratching, variable speed web transport, poor drying, and unstable tension systems throughout the machine. Such conditions may indicate that the web tension is too low. Is the web floating over the support rollers? This may indicate that dryer balance conditions have changed. The web may wander from side to side and may slide off the machine when a new web is spliced in at the unwind. The web may also slide off the machine when the machine is accelerated from zero speed to process speed. Idler rollers not only support the web in the

machine direction but also provide lateral restraint during steady-state and transient periods. Transient conditions are acceleration, deceleration, transferring, and splicing.

Maintaining an awareness of machine performance can help in defining problems when they occur. Knowing what the process conditions are when the machine is running well will help you recognize what may be wrong when it not running well.

Web handling problems can be caused by any part of the web transport system. Frequently the problem is not identified but “something” is done so that the web can run. The action taken often does not solve the actual problem but does relieve the symptom. If enough such “solutions” are implemented, the machine may become difficult to run because many of the machine parts have been misaligned and process parameters have been adjusted to make product. Eventually, the machine may need to be completely realigned and retuned in order to restore the machine and the process to optimum conditions.

The web handling system consists of the unwind and rewind, the coating and drying equipment, the tension and speed control systems, and the drive system. Web handling depends on proper machine alignment and on the physical characteristics of the web and of the coating formulations. Anything that can cause web wrinkling, delaminating, scratches, edge cracks, web breaks, uneven slit edges, dusty slit edges, damaged coated web, ballooning of web in the dryer, or mistracking are all part of the web handling system.

What are some factors that cause web handling problems?

1. A machine was installed out of alignment.
2. A machine sits in a building that is settling, thereby causing machine misalignment.
3. A machine sits in a building that was built in a swamp or on a tidal river. Tidal conditions or changes in the water table cause the building structure to deform under the machine, leading to machine misalignment.
4. Equipment or process changes to the machine by production, engineering, or maintenance personnel are not communicated to the operating personnel, such as exhaust damper settings, settings for steam coils, changing rollers, changing pumps, changing or recalibrating transducers, or changing fans, belts, or pulleys.
5. A new product or a new process is introduced to the machine. The machine may not be well suited to the new product or process.
6. The coefficient of friction of the driven side of the web may change dramatically if the coating chemistry changes. The change in friction factor may reduce the ability of drive rolls to transport the web. A new coating chemistry may also allow static electricity levels to increase to a point where winding the web is difficult.

These are but a few of the major reasons for web handling problems. There are others.

WEB

Web (Figure 11-1) is any foil, metal, paper, plastic, textile, or wire that is presented to the machine in a continuous flexible form for coating, laminating, plating, or covering, or any other process. The film coating industry and the textile, metal sheeting, and wire industries share common problems, although the nomenclature for similar processes is often different.

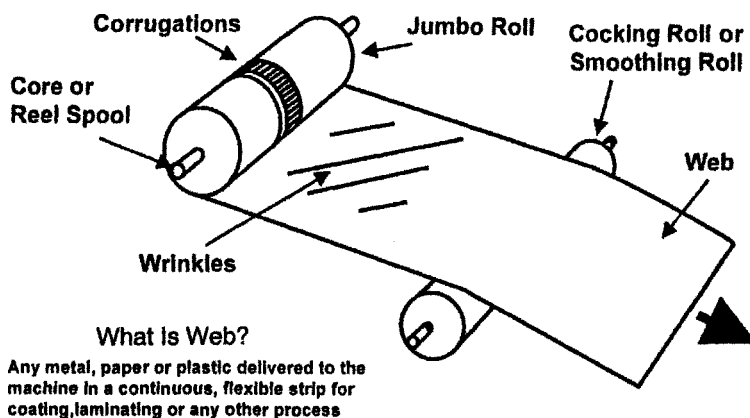


Figure 11-1. Definition of web. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

Web Characteristics and Problems Associated with the Web

Wrinkling, creasing, web breaks, and mistracking are a few problems that can be caused by web characteristics. Wrinkles in the base web can be caused by web camber, nonuniform basis weight, uneven cross-machine web thickness profile, and an uneven moisture profile. Severe wrinkles have been observed when a change in the coating formulation resulted in very high static levels at the winder. This static caused such severe wrinkling that the web could not be wound and the machine was shut down until the problem was identified. The problem was traced back to a technician who changed the coating formulation without communicating the change to anyone. *The instructions for the coating called for the pH to be no more than a certain value.* pH was controlled by the use of a specific amount of a chemical. The technician placed additional chemical into the formulation to be sure that pH was not more than the specified value. The resulting wrinkling caused the machine to be shut down for more than a week, until the change in chemistry was discovered.

Web breaks can be caused by all of the above characteristics, as well as poor vendor splices and vendor-produced edge cracks in the web.

Mistracking can be caused by web camber, by the frictional characteristics of the driven surface of the web, and/or by the drive roll frictional characteristic.

Base Web Defects that Cause Wrinkling If the web in the base roll has camber, nonuniform thickness profile, nonuniform basis weight profile, or nonuniform moisture profile, a wrinkle problem may exist. One can feel “corrugations” or hard and soft spots in the “jumbo” roll if camber or uneven profiles exist. Wrinkles form as the web is transported through the machine. If the wrinkles form before a nip point or coater applicator, they will form a crease and may cause a web break.

Wrinkles can be caused by the machine or by the web itself. A machine out of alignment may cause wrinkles in much the same manner as a web that is cambered, or has an unacceptable web caliper or a web moisture or web basis weight profile.

The difficulty of identifying the cause of wrinkling comes from a belief that the web is not the problem. The web is almost never identified as a cause of wrinkling because there are specifications that are written for the web and it is assumed that the vendor-supplied

web is in specification and is perfect. In actual fact, the incoming materials quality control is frequently ineffective or nonexistent.

Specifications for the incoming base are not policed, tested, or updated to ensure that the incoming material is appropriate for the needs of an ever-changing product mix. Nor are web problems communicated to the incoming materials quality control department to allow them to work with vendors to produce better web.

The web specifications are frequently developed by an inexperienced incoming materials inspector from specifications supplied by the vendor of the web. It does not follow that if the vendor stays within his own specifications, then the web is acceptable for all coating processes.

If the coating operation “purchases” its web from an in-plant machine, it may be difficult to reject web that is unsuitable for processing. If the web is produced within the coating mill, then a neutral quality control function must exist between the web producer and the coating process that follows. If the “neutral source” is responsible for the production of the web, they may overrule the specifications and ask the coating plant to process web that is out of specification. Losses normally chargeable to the web manufacturing operation fall on the coating process.

Each coating plant must understand the parameters of acceptable web and set up “practical” web specifications for the process and the vendor. Practical specifications represent a commitment by the vendor and client to establish web parameters that can be processed satisfactorily without making the production of the web impossible or economically unfeasible.

The responsibility for determining web specifications falls on the user of the web. If the specifications cannot be met by one vendor, try other vendors. Paper webs are often made on more modern machines that can limit defects delivered in the base roll to the user. Similar improvements are being made in the manufacture of plastic webs. Find vendors who can make the webs that increase productivity, increase yields, and reduce your cost of goods sold. *Note:* A web manufacturing plant has little incentive to make machine changes for a coating plant that uses a very small quantity of the manufacturer’s output. If the web manufacturer can sell 100% of his output without making modifications, the small user must find another supplier or learn to process the web in-house.

Web problems are often masked because the operators will do what they need to do to make salable product. They may misalign the idler rolls, put the rolls out of level, change process speeds, or change tensions and air-handling conditions in order to produce a product. Such techniques will be used until the machine is so out of specification that production comes to a stop! At that time a task force will be formed, the machine will be blamed (“it never ran right”), all rolls will be realigned and leveled—and the wrinkle problem may still exist.

The real causes for wrinkling may be:

1. The coating formulation has changed sheet characteristics.
2. The web specifications are not complete or are unrealistic.
3. The web specifications are not policed.
4. Web is used that is not in compliance with specifications.
5. Misaligned machine rolls are used, or drive rolls are used whose frictional characteristics have changed.
6. The machine is not compatible with a new product or process.
7. Both the web and the machine are at fault.

Causes of Web Defects Web defects such as camber, cross-machine thickness and moisture variations, and cross-machine basis weight variations occur during the manufacturing process. The web manufacturer has a limited ability to keep the web within the specified parameters with existing equipment. Modern equipment has a better ability to monitor the uniformity of the web and then to make the necessary adjustments to restore the web's desired uniform characteristics.

For instance, a paper web is manufactured by mixing fibers with water to a consistency of 0.5% fiber and 99.5% water. That mixture is pumped onto a flat traveling screen (a Fourdrinier section) where some of the water is drained from the mixture. The paper web is then transferred to a press section where additional water is pressed from the web before it is passed into a steam heated dryer section where additional water is removed from the paper web. The web may then be passed to a precoating press and to a calender, to give a smoother surface finish, and is then wound into a jumbo roll before being delivered to the coating process. Each of these steps can cause defects that will be described in the following text.

Web Attributes

Web Camber Camber (Figure 11-2) occurs in the web manufacturing process. Older machines tend to produce more cambered web than new machines. For instance, the processing of paper web in a paper machine requires the web to run through a dryer section. The web is run at speeds in excess of 1500 FPM (feet per minute) through the dryers. On older machines, the web tends to float through the dryers as the web is heated and the water evaporated. On older machines, the temperature on the drive side of the dryer can be higher than the temperature on the operator's side of the machine. Thus the drive side of the web dries faster than the web on the operator's side of the machine. Paper web tends to shrink laterally (sidewise) and longitudinally (lengthwise) as it dries. Since the paper on the drive side of the machine dries faster than the paper on the operator's side, there is more shrinkage on the drive side of the web. This difference in shrinkage produces a web that is shorter on the drive side than it is on the tending side. That difference is called camber. If the camber is severe, it may be difficult or impossible to process the web into a useful product.

Modern machines have more uniform temperatures across the dryers and the web is not allowed to float through the dryer section. This combination of better temperature control

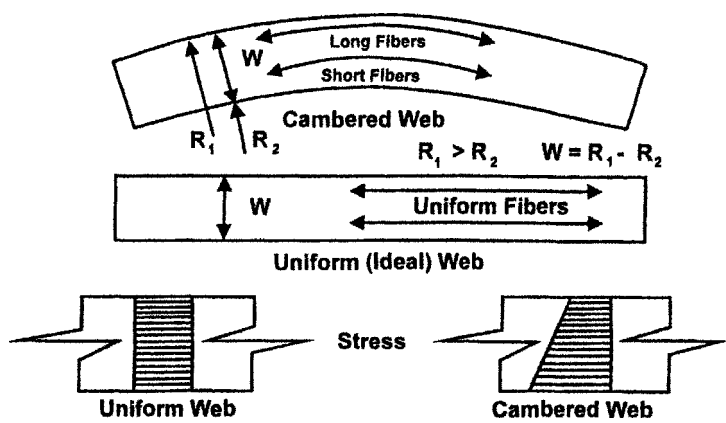


Figure 11-2. Camber occurs when one side of the web is longer than the other side.

and the containment of the web on the surface of the dryer creates more uniform drying while allowing less web shrinkage than was experienced in the older machines. This is a simplistic explanation of the drying phenomenon. Volumes have been written on drying and drying techniques that explain the process in much more detail than is presented here.

Web camber is an attribute of the web that makes the web want to track to one side of the machine. Camber can be identified by laying a 25-foot long straight line on the floor. Cut a 25-foot length of web from the base roll and lay one edge against the straight line. If the web forms an arc around the line, the web is said to have camber. If the web forms an arc that runs to the left, the left inside of the arc is said to be the tight side and the right outside of the arc is called the loose side. If you measure the inside and outside of the 25-foot sample, you will find that the inside dimension is shorter than the outside dimension, and the outside edge is longer than the inside. In a fully wound jumbo roll, a cambered roll frequently will have a “spongy” edge while the other edge is “hard.”

If we try to run this cambered web on a coating machine that is perfectly aligned and level, the web will tend to run toward the left side of the machine. If we are pulling the web through the machine, the web will want to track left while we are trying to pull the web straight. This will produce diagonal wrinkles. If these wrinkles encounter a nip, the wrinkles will be pressed into a crease that can cause a web break or a defective product. Devices such as “cocking” rolls (Figure 11-3) are designed to remove wrinkles caused by cambered web. They do this by uniformly distributing the forces across the web. This action makes the stress across the web more uniform. Without the cocking roll, the tension on the tight side of the web would be higher than the tension on the loose side. These devices are limited as to how much camber they can remove depending on the web and the location of the cocking roller within the machine. The camber in a web can vary between web manufacturers and between base lot numbers of a given web manufacturer. That means the operator will continually adjust the cocking roll to compensate for varying camber. Some cocking rollers are mechanical control systems that automatically adjust themselves to control the wrinkling of the web. I have seen the manually operated cocking rolls remove wrinkles but personally have not seen an automatic system in operation.

It is better to specify acceptable limits of camber than to depend on the cocking roller to remove an infinite amount of camber. Establish practical specifications for the web and then use the cocking rolls to trim up the web.

Some webs are cambered to the left, and others are cambered to the right. It will be necessary to readjust the cocking rollers to compensate for the change in direction of the camber.

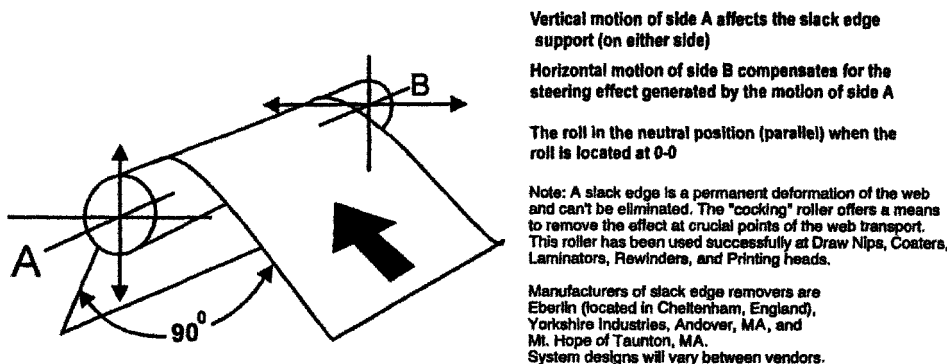


Figure 11-3. Cocking rolls are one way to eliminate a slack edge.

Some problems caused by cambered web are:

1. Diagonal wrinkles and creases that result in web breaks at nips and in blade coaters or extrusion type coaters.
2. Diagonal wrinkles and creases that result in coating voids that prevent effective processing of the web. For instance, a coating void on release coatings prevents labels from releasing from the coating void. Such a defect will result in returns from the label manufacturer.
3. The loose edge of the web will fracture when it hits a web guide nozzle as the web passes through the machine.
4. The difference in length between drive side and tending side makes it difficult to get an accurate registration of multicolor printing processes on a web. Camber combined with poor tension control can lead to poor printing results. Printing processes differ from coating processes in that coating processes need smooth perturbation-free web transport. Printing processes have the added need for exact position control of the printed feature at each print head.

One can deal with the effects of camber as follows.

1. Identify and group incoming rolls by process characteristics such as vendor, the date made, and the machine that made the roll. If the rolls were cut from a wider parent roll, keep track of the individual cut numbers from that roll.
2. Run all rolls with a common vendor, date, machine, and cut position at one time. When all rolls with a common characteristic are run, then run the next set of rolls to completion. Many coating and printing plants have spliced rolls into the machine in random fashion and then found that the roll characteristics between vendors and lot numbers vary so much that it is impossible to guarantee trouble-free transportation of the web.
3. Test each new batch of vendor-supplied material to determine if it meets your specifications. Do this testing in your incoming materials testing area or before the material is delivered to the machine for processing.
4. Do not begin modifying the machine before you know the parameters of your incoming material.
5. You may find that the material you have is off-specification and is the only material available that can be converted into product. Your vendors may have a delivery schedule that will cause you to shut down unless the defective material can be processed. In this case, you may be forced to try some temporary machine changes in order to continue to produce product. If changes are made to the machine, document them so that the machine can be returned to its ideal condition when qualified vendor material is received. If enough changes are made, the machine may need to be realigned to allow the machine to transport the web properly.

Web Cross-Machine Thickness Profile Variation Web cross-machine thickness profile variation (Figure 11-4) can be measured by taking a full-width sample of the web from the roll and measuring the thickness of the web at frequent locations across the web. A device as simple as a micrometer is effective, as is a computerized thickness profile instrument that produces a thickness profile chart. It is important to identify significant thickness variations in a short span. For instance, if a web is supposed to have a nominal thickness of

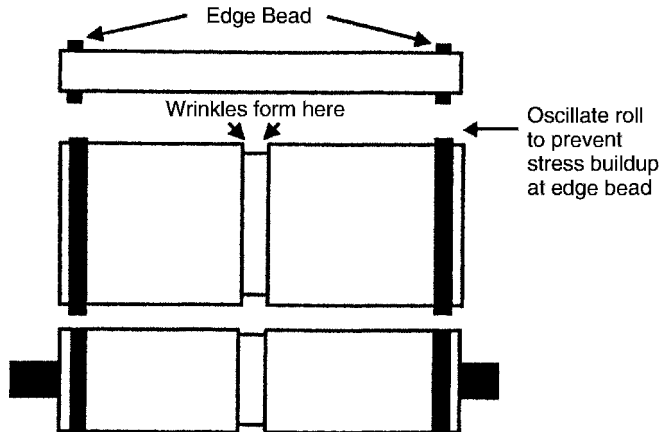


Figure 11-4. When the caliper varies across the web, wrinkles can form in the soft areas. Oscillating the roll can reduce the effect of edge beads.

2.5 mils (0.0025 in.) and it is 2.8 mils thick (0.0028 in.) at one spot and 2.4 mils thick next to that very spot, that is a significant difference. The 2.8-mil thickness will show up as a “hard spot” on wound roll. A 10% variation is significant enough to cause a hard spot on the surface of the wound roll.

Web thickness profile variations of paper web can be caused by uneven forming of the web or by the pressing and calendering that is part of the paper machine process. It can also be caused by variations in the moisture content. If the press or calender rolls are not ground properly, the web thickness may vary in a cross-machine direction. All rolls are supported on the ends in bearings. When the roll is suspended by the ends, the roll may develop a “sag.” Each roll must be ground to present a straight face to the web for each operating nip pressure. If the roll is not ground properly, the roll may be larger in the center than on the ends or can be smaller in the center than on the ends. Each condition can create thickness variations. A roll with a large center will crush the web in the center. A roll with large diameters on the edges will crush the edges of the web. When the roll is ground with a larger diameter in the center, it is said to have a “crown.”

Examples of problems caused by improper crown or nip pressure are the following.

1. If the press or calender is operated at too high a nip pressure, the edges of the web will be crushed and will be thinner than the center of the web.
2. If the press is operated at too low a nip pressure, the center of the web may be crushed, causing a thin spot in the center of the web. If the web is run through a coater, straight wrinkles will form in the center of the web that can form creases at a nip. If the web is bisected, we will also bisect the thin section of web in the center. The left side of the bisected web will have a thin right edge. The right side of the bisected web will have a thin left edge. The thin edges will feel soft in a fully wound roll.
3. Improper crowning and nip pressure can cause the web to crush at the quarter points, causing thin spots in the web at the quarter points. If the web is run through a coater, straight wrinkles will form that can become creases at a nip. If the web is bisected, the thin quarter points will become the center of the two resulting rolls. If

the web is slit into three or four cuts, the thin section will appear at the edges of the web. Each of these cuts should be identified by lot number, and whether it was slit from the drive side, in the middle, or from the operator's side of the web. Run each roll with identical characteristics as a group. That will reduce the web transport problems that are caused by randomly introducing rolls with different characteristics to the machine. Thickness profile variations can also be introduced at the calender if the calender rolls are improperly crowned or if improper nips are used for a given calender roll crown.

4. Straight wrinkles will form on each edge of the hard spot that will form creases at nips that will cause web breaks or coating voids. Operators may try to "pull" the wrinkles out by increasing tensions between sections. Higher tensions tend to reduce the amplitude of the wrinkles but may increase the chance of web breaks and may affect registration if the process includes a print operation. The reduction in wrinkle amplitude may prevent creasing at a coater nip or other nips within the machine. Devices such as spreader rolls are routinely used at the inlet to a coating section, or drive roll, to spread out the wrinkles before the web enters the nip.

Basis Weight Profile Variation In making a paper web, the forming process delivers a very liquid formulation to a moving screen. The process may not deliver a uniform density of fiber to the traveling screen. It is possible that the fiber distribution across the web is heavy in some places and light in other places. This variation in fiber density across the web is called cross-web basis weight variation. One can feel these dense places as hard spots in the circumference of the wound roll. The less dense spots will feel very soft in the circumference of the wound roll. Many times the hard spot in the roll will look like the cable stitch in a sweater. The result of the hard and soft spots across the web can result in wrinkles in the longitudinal direction. These wrinkles can form into hard creases at a nip or process point, causing coating voids or web breaks. It is certain that the variations in basis weight and moisture profile variations can cause variations in the absorption of water in an aqueous coating process. Paper web will expand when wet. The paper expands as it absorbs water but it is restrained from moving laterally. As a result, the excess material due to expansion must go somewhere. The excess material goes into the formation of wrinkles.

These wrinkles can break at a following coater unless web spreading devices remove the wrinkles at the following section. The operators will often increase tensions between sections to "pull out" the wrinkles. Variations in the thickness of the web can also cause coating problems. In slot and slide coating (see Chapter 6), there is a narrow gap between the coating die and the web traveling around the backing roll. Thickness variations in the web will cause equivalent gap fluctuations, and this can cause chatter.

Surface of the Web A basic tenet of coating defect-free film is that the web itself should be defect-free. In most coating systems, defects in the web will cause defects in the coating above them. Rarely are defects in the web eliminated or reduced by the subsequent coating and drying process.

It is good practice to routinely take representative samples of the uncoated support and have them available for analysis, so that when web is suspected there is a set of samples available to establish the normal characteristics of the support. A small number of samples should be taken for each base lot in routine production and more often when support problems are suspected.

Variability and changes in the surface layer can lead to the following types of defects:

1. Adhesion failure between the substrate surface and the applied coating
2. Coating nonuniformities because of nonuniform wettability
3. Coating nonuniformities because of nonuniform static charges on the web
4. Spot defects from contamination on the substrate surface
5. Coating nonuniformities because of variability of any coated barrier and/or adhesive layers that may be present

All coatings usually require a specific range of adhesion between the coatings and the support to meet their end use properties. When this varies outside specified limits, there is a defect, and the web should be considered as a possible factor, along with all of the coating and drying processes. The defect can be poor adhesion in a system that requires high adhesion, such as paint to steel in automobiles or photographic emulsion to film base in photographic systems. It can be too high an adhesion in systems that require low adhesion, such as with release layers. The first step is to check the adhesion to the representative support and to the retained samples from previous production runs using basic lab tests. These tests can be as simple as coating on a small sample, drying it, and then checking the adhesion by trying to pull off the coating with a piece of tape. More complex tests in which the actual force required to remove the coating can also be run. The thickness of the support layer, the quality and composition of the raw materials, changes in composition, age of the support, and curing conditions are all obvious factors that need to be considered. In addition, the support needs to be checked to ensure that the correct side of the base was coated on, and that the surface is indeed what it should be.

Variability of the wetting properties of the surface can lead to coating instabilities. Small differences will show up as subtle defects such as unstable edges and mottle. Wetting variability can also lead to gross failures such as the inability of the applicator to form a uniform coating. In case there is gross coating failure and the inability to form a uniform coating bead, consider the possibility of changes in the surface layer wettability as well as changes in the properties of the coating solution and the coating process conditions. Using the retained samples and the suspected web, the wettability can be measured as described in Chapter 3.

It is also possible for the surface to be contaminated. This can lead to a wide variety of spot type defects. Ideally, the surface should be clean and have no foreign material. However, the coating can pick up a wide variety of contaminants in manufacture, during slitting into different widths, and during transfer to the unwind stand. These contaminants can be dirt from the air, lubricants used in the process, lint from the packing material, or dust from abraded coating material that builds up on rolls and is transferred back to the web surface. It is useful to understand the method of manufacture so as to be aware of possible contaminants. This contamination of the surface with foreign material can affect the coating in several ways. It can cause a physical defect in which the applied coating is disturbed by the particle and leads to an absence of coating surrounding the particle, as in Figure 11-5. It can lead to pinholes. A foreign organic material on the surface can result in high surface tension, leading to a repellency spot, as seen in Figure 11-6.

When troubleshooting localized spot defects, the support should be considered as a possible contributing factor. The uncoated support should be examined visually and with a microscope to determine if there are defects on the support that are similar to those seen on

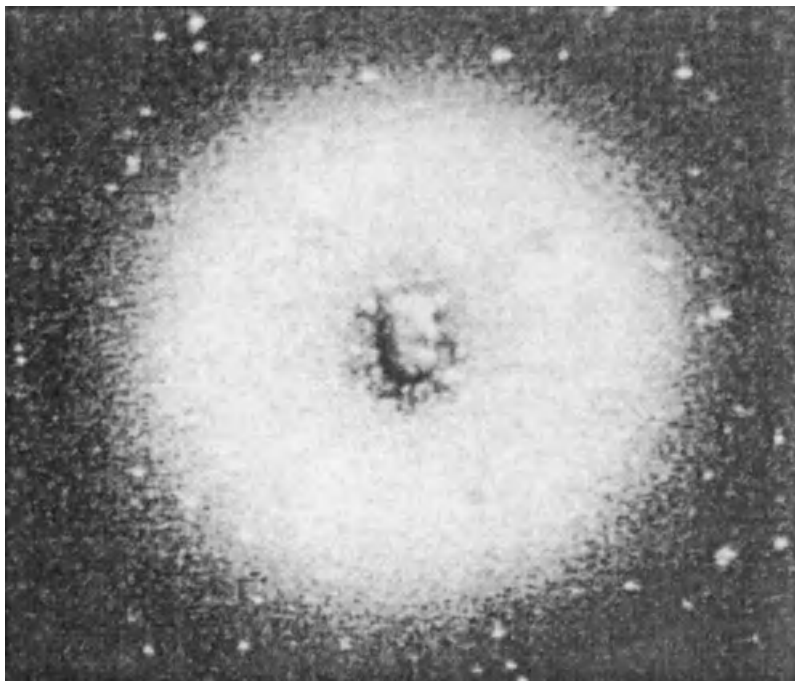


Figure 11-5. Defect caused by a particle on the surface of the web.

the final coated product, as in Figure 11-7. The same analytical techniques that are applied to the coating defect should also be used to characterize the support. This is easy when a sample of support is available and the same defects are seen in the coating and on the support. It is more complicated when there is no uncoated sample. However, it is still possible to analyze the base under the defect by removing the coating using abrasion techniques, chemicals, or selective enzymes. Also, microtome and freeze-fracture techniques can be used to get a cross section of the defect and give a sample in which all layers can be studied.

Plastic Web Plastic web may be produced by extruding material onto a drum and then stretching it to the desired width using a “tenter” frame. The tenter frame has grippers that clamp the edges of the extruded web and then stretch it laterally as the web moves toward the rewinder. Plastic web is considered to be perfectly flat. But it can have thickness variations and camber due to the nature of the extrusion, casting, and stretching process. Plastic web will tend to shrink laterally if the process heats the web to a point where the web becomes soft and compliant. That point is called the *glass transition temperature* of the plastic. Many processes require high temperatures for the desired chemical reaction of the coating structure. Those temperatures can exceed the glass transition temperature of the material and require us to carefully apply tension control (or speed control) techniques if we are to avoid deforming the material, causing web breaks, or causing excessive lateral shrinkage.

We apply tension control, speed control, torque control, and combinations of these techniques to various web transport processes using different materials later in this chapter.

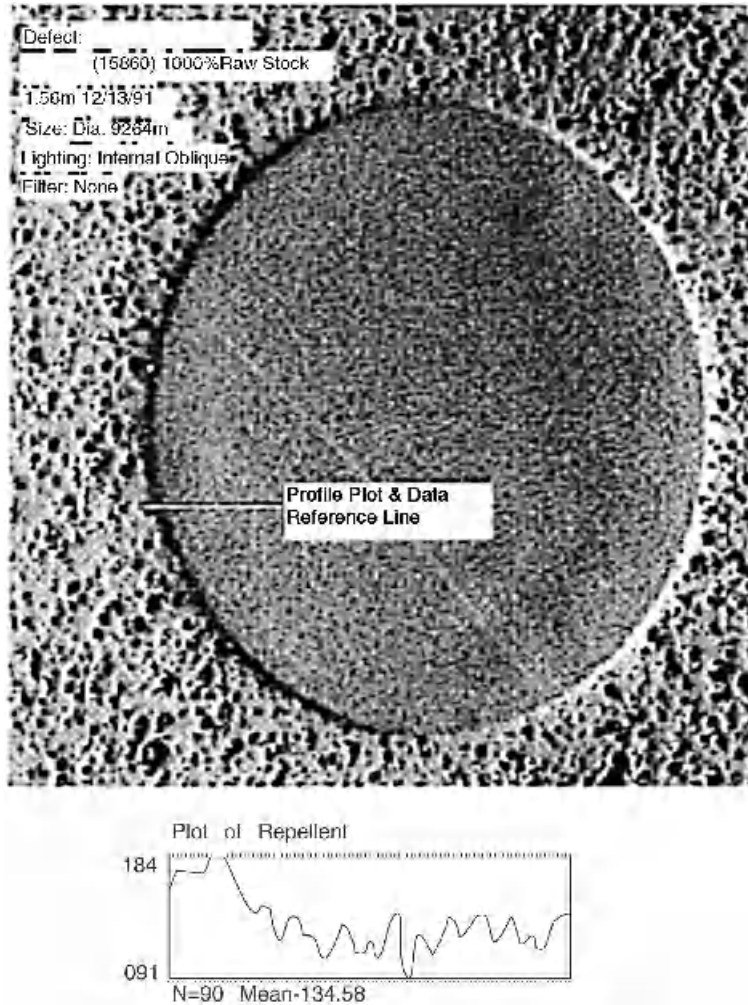


Figure 11-6. Repellency spot caused by contamination of the web. From Cohen and Grotovsky (1993), *J. Imag. Sci. Techn.* **37**, 133–148. Reprinted with permission of IS&T: The Society for Imaging Science and Technology, sole copyright owners of *The Journal of Imaging Science and Technology*.

WEB TRANSPORT SYSTEMS

Web transport systems consist of the web, the rolls that deliver power to the web, the motors that deliver power to the rolls, and speed and tension sensors to provide feedback to the controllers that control the motors.

1. The web transport system includes the web itself. How easy is it to transport the web through the machine? What is its coefficient of friction? What effect does a layer of coating have on its “driveability”? Is the coated surface less driveable? Can we increase tensions to help transport the slippery web, or does the process limit us to the average tension values for such a material?

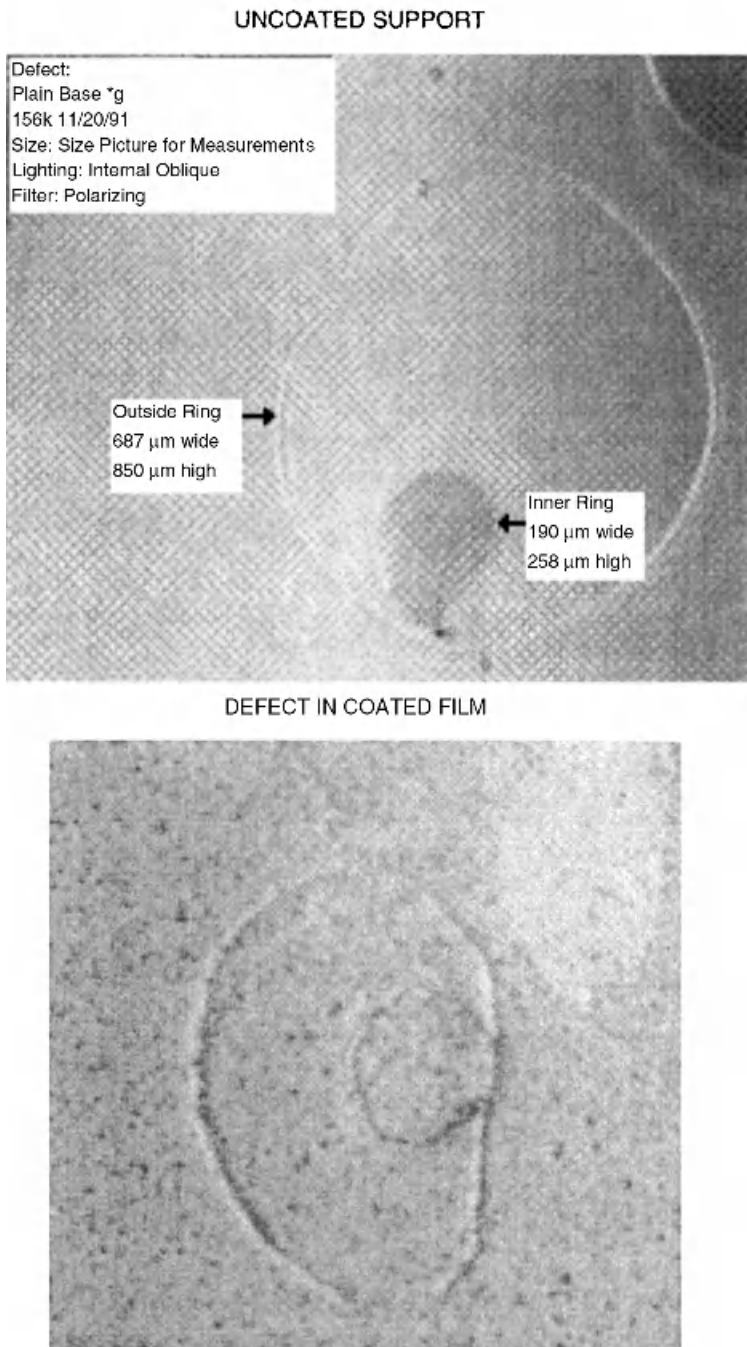


Figure 11-7. Defect on the base that shows up in the coated film.

2. The web transport system also includes the power transmission machinery such as unwinds, vacuum rolls, vacuum tables, pull rolls, coaters, and rewinds, which transport the web through the machine. What characteristics provide reliable, consistent, defect-free, and cost-effective motivation of the web through the machine? What type of drive section will encourage the operator to consistently include the section in the web path instead of bypassing it because it causes web breaks or defects in the finished product?
3. The motors, gears, and couplings that drive the machinery must be selected to provide the best results for the end product. Motors and gears must be matched to requirements of the process.
4. The selection of dancer rolls, force transducers, tachometers, encoders, torque sensors, or load measuring devices is important to the performance of the power supplies that control the motors and drive rolls.

Tension

Tension through a machine is the force that is applied to the web between adjacent machine sections. This force tends to stretch the web and is usually expressed as force per unit of web width.

Most webs are transported through the machine using tensions that are high enough to allow the web to track properly but are low enough to minimize web breaks. Figure 11-8 shows some typical tensions for a wide variety of materials. These tensions are average values and may differ depending on the temperatures within the process, the length of span between driven rolls, or conditions of the web when it comes to the coater. The units often used are pounds per linear inch (PLI), ounces per linear inch (OLI), grams per linear inch (GLI), kilograms per meter (KGM), and newtons per meter (N/m).

It is important to record the operating tension values for each product and to determine if the machine and web are performing normally. Tension information can be used to design new processes and equipment and in problem-solving machine problems. A knowledge of how each product runs may help determine if a machine process can be speeded up with a minimum capital outlay for drive equipment.

Suggested Rewind Tension Levels			Suggested Unwind Tension Levels		
Product		Tension (PLI)	Product		Tension (PLI)
Paper	15#	0.5	Paper	15#	0.25
	20#	0.75		20#	0.5
	30#	1.0		30#	0.75
	40#	1.5		40#	1.0
	50#	2.0		50#	1.25
	60#	2.5		60#	1.75
	80#	3.0		80#	2.0
Board	8pt.	3	Board	8pt.	2
	12pt.	4		12pt.	2.75
	15pt.	5		15pt.	3.25
	20pt.	7		20pt.	4.75
	25pt.	9		25pt.	6.0
	30pt.	11		30pt.	7.25

Product	Ib/ml/in.	Copper Wire*	
		AWG	Tension
Acetate	0.5		
Aluminum foil	1.0	5	30 lbs
Cellophane	0.75	10	20
Cryovac	0.1	12	12
Glassine	1.5	14	9
Mylar (polyester)	0.75	16	6
Nylon	0.25	20	3
Polyethylene	0.25	24	4.8
Polypropylene	0.25	30	1.25
Polystyrene	1.0	36	0.25
Pliofilm	0.1	40	0.1
Saran	0.1		
Vinyl	0.1		

* Run Aluminum wire at 1/2 to 1/3 of copper tension levels. Multi-strand cables are run at the sum of the tension of all strands. Example: 5 conductor, all 20 AWG copper, 5 x 6 = 30 pounds.

Figure 11-8. Typical tensions for a number of different webs.

Tension can also be expressed as total tension, which is the product of tension per unit width times the total web width. For example, a tension of 3 PLI exerted on a web width of 100 inches = 300 lb total tension. Thus total tension is used to calculate brake, clutch, or motor size. Total tension times web speed is the power, or rate of doing work, that the drive motor or braking system must do.

Reasons Why Operators Must Change Tensions in Order to Successfully Transport Web

1. High temperatures in the process may cause the operators to run at low tensions to prevent deformation of a plastic web.
2. Laminating a thin elastic web to a thicker inelastic web may require lower tensions if delamination is to be prevented.
3. If paper web is too dry, it will be brittle and weak. Edge cracks can be a starting point for web breaks. Operators will reduce tensions on dry paper web in the hope that edge cracks and web breaks can be avoided.
4. Operators will increase tension if wrinkles are present in the web, hoping that the extra tension will eliminate the wrinkles.

Let us look next at the machine sections that transport the web through the machine. For purposes of this discussion, we assume that a coating line consists of an unwind stand, pull rolls, a coater, dryers, a laminator, and a rewind section.

Unwind Stand

The most important function of the unwind is to introduce the web to the rest of the process. The unwind may have only one arbor if the process is to be stopped at the end of each roll. That is the way many *research* or *test coaters* are operated. In the research mode, one roll of web may be coated with many short samples of prototype coatings. The wound roll is removed from the machine and the coatings are evaluated to determine which coating has the most desirable attributes.

Many *production* operations are continuous processes and cannot be shut down at the end of each roll. It is too costly to dump pans of coating, reduce air temperatures, and pay the operating crew and support departments while the machine is idle. Unwinds on continuous processes must provide continuous web to the machine by allowing splicing and transferring from a spent core to a new incoming jumbo roll. Depending on the product's value, the unwind will have two, three, or even four arbors on which new rolls are held in preparation for a splice. The extra positions ensure that if a poor transfer is made from a core to a new roll, a splice can be made immediately, from a third position, to minimize waste and losses. Modern unwind splicing systems have improved so much that two-arbor unwinds are most frequently used. Triple unwinds may be used if experience with the web indicates splicing problems may occur due to the quality of the wound web. Typical problems may be that the new roll telescopes or has "blocking defects" that make it necessary to remove the roll from further processing. A third position on the unwind makes it possible to quickly splice in a new roll.

Splicing adhesives should be selected carefully. Many of the early liquid adhesives had a shelf life that was adversely affected by time and temperature. Solvent-based adhesives were stored in air conditioned rooms because the summer heat caused rapid deterioration

in the holding power of the splice adhesive. Frequent web breaks occurred when splice patterns pulled apart immediately after a splice was made. Modern splicing tapes have improved splicing consistency.

One of the most common faults of unwinds is the method selected for tension control. A simple unwind is supplied with a manually adjusted brake, which requires constant attention from the operator. The brake may consist of a leather strap around a part of the core, or a pneumatic or electric brake that is adjusted by the operator. Invariably, the operator must also fill out a log, check on coating quality, and spend time in the inspection booth at the rewind end of the machine. It is not difficult to see that the unwind will receive little attention from the operator unless the web breaks. If the operator ignores the unwind, the tension will increase in inverse proportion to the roll diameter.

The braking torque, which is constant, is equal to the total web tension times the lever arm, which is the roll radius (half the roll diameter). Thus

$$\text{braking torque} = \text{tension} \times \left(\frac{\text{roll diameter}}{2} \right) = \text{constant}$$

and therefore

$$\text{tension} = \frac{2 \times \text{braking torque}}{\text{roll diameter}}$$

For instance, if the jumbo roll is 50 inches in diameter and is wound on a 5-inch core, that represents a diameter change of 10:1. If the operator does not adjust the manual control, tension will increase by a factor of 10. That can introduce the following problems:

1. The web is extensible and shrinks laterally at increased tensions. As the tension increases, the web gets narrower until it is too narrow to make product. Consider the case of a foam laminator that makes a blanket out of two layers of foam laminated to a center scrim. If the tension is increased to objectionable levels, the blankets will be too narrow for full size or oversize beds, and even for twin beds. Ideally, the unwind should have an automatic tension control system that senses and controls tension within acceptable limits. If the material is too weak and compliant, it may be necessary to control the speed between sections very precisely in order to guarantee the exact width required.
2. The web is part of a multicolor printing process. As the unwind tension increases, the web stretches and begins to affect the registration of the print on each print station. Printing will be out of registration, causing defective product.
3. The web is part of a medical test membrane manufacturing process that must have a predictable pore size in order to give repeatable test results. If the tension increases with a change in the roll diameter, the pore size will change and the medical test results will be variable. In fact, in the case of membranes, it is doubtful whether the operator can maintain the tension constant enough to guarantee the accuracy that is required of this critical process.
4. The web is part of a laminating process. As the tension increases with diameter change, delaminations can occur because the webs will revert to their original state

at different rates when the tension is released. If the structure does not delaminate, it may provide an objectionable level of “edge curl.”

5. The web being slit shrinks laterally as the tension increases. Lateral shrinkage will ensure that the edge trim will be lost and the product will be out of spec. If the material has “memory,” the lateral dimension will expand, causing the material to be out of spec. For instance, photographic film is designed to fit into a plastic cartridge with dimensions within certain tolerances. Those tolerances may be exceeded if the film stretches laterally after it has been slit. If the tolerances are exceeded, each image may jam as it is ejected from the camera.
6. Most materials will not sustain a 10:1 change in tension without an increase in web breaks. Certainly, weaknesses in the web will be exploited by high values of tension.

Why do we persist in using manually operated unwinds when our new processes and products demand more precise tension control? It is because we have equipment that satisfied the needs of the older products and processes. Rather than replace the older equipment with new equipment, we constantly tend to force them to somehow run the new product. We then accept the losses that come from using inappropriate equipment as part of the cost of being in a high-quality market. When we speak of old equipment we are talking about equipment that is 40–50 years old. Many of the materials that exist now were not in existence 40–50 years ago. The problem is compounded by the desire to “make do” with what we have because we want to keep capital expenditures to a minimum. On the other hand, management can be justifiably suspicious if we demand a new machine for every new process.

How does a company have ideally suited machinery when new products are being introduced almost daily? We are seeing that converting plants are more willing to accept short runs (job shop runs) because they must do so in order to stay in business.

The answer frequently is to make *gradual* changes to machinery as there are *gradual* changes in processes or products. In a global manufacturing economy, survival depends a great deal on flexibility.

When to Use Drive Motors on an Unwind Stand Should the unwind use a motor or a brake for tension control? A brake can be used as long as the product is not damaged. The product can be damaged during acceleration or if the braking system cannot reduce its braking torque to zero. How can a brake cause defects in the product?

Let us consider the roll with a core that is one-tenth of the diameter of the full roll. The brake torque, at full roll, is set to yield the proper tension in the web. As the roll unwinds and becomes smaller, the brake torque must be reduced in order to keep the tension constant. Frequently, the brake is oversized to handle a wide tension range (say, 0.5 to 3 PLI) and the web is run at low tensions. If the web is run at 0.5 PLI, it is possible that the frictional drag torque of the brake and power transmission system will be fairly high even if the pressure (or power) to the brake is turned off. There have been cases where the frictional drag torque was so high that it produced values of tension higher than desired. The web began to shrink laterally and to cause web defects. Registration problems can develop if tension rises at the end of the roll. A brake is designed to hold back against the rest of the line. Its ability to hold back allows web tension to be developed. However, it is frequently necessary to reduce braking to zero and even to apply a motivating force on many light-tension applications. That means a tension control system must be capable of

applying power to the web in a braking mode (regeneration) or a positive mode (motoring). Motor driven regenerative systems can provide braking or motoring. Brakes cannot provide a positive effort.

Defects can be produced during acceleration. When the roll is accelerated at the unwind, power must be applied to overcome the inertia of the unwinding roll in addition to the power that is required for tension control. If a brake is used at the unwind, it cannot supply the motoring effort that is required to accelerate the roll. The machine must supply that effort through the web that connects the unwind to the rest of the machine. Rapid acceleration of the unwinding roll may cause the tension in the web to increase. Tension may increase to a point where the web is damaged or even broken. Printing presses frequently see out-of-registration defects during acceleration, because web tension increases throughout the machine. The tension increase causes the web to stretch temporarily. The web stretches and shrinks as a function of tension changes and can cause the printed pattern to be out of registration. Motor driven unwinds minimize tension transients that come from acceleration. Further benefits are derived by using properly designed dancers and draw roll systems before the main coating or printing stations. Thus brakes can be used very successfully on slow-speed machines where the web, splicing transients, and acceleration are not a problem. Brakes are also used on high-speed machines where the web has lateral stability and where the machine can be accelerated slowly. We have seen 6000 FPM winders using braking systems, but the web is strong and the acceleration rate is reasonable. These intermittent duty winders process the web into shipping diameters and widths.

Motors are being used on more unwinds when the material has little lateral stability and where the “memory” of the web can cause it to introduce registration defects in printing processes. Many production facilities are rejecting the notion that splicing losses are part of the process. Productivity increases are possible if more attention is paid to the materials that are run and the methods that are used to process those materials.

Motors are also required on high-speed coaters, where flying splices require the incoming roll to be accelerated to line speed prior to a splice attempt. High-speed coaters can run from 2000 to 5000 FPM, but unwind motors are being used more frequently on coating lines that are designed for operating speeds of 300–500 FPM.

Web Control

The unwind and rewind are the “bosses” on the coating line. The transients that are generated by splicing or transferring at the unwind and rewind will affect the entire machine. Production engineers continue to be surprised to see how an unwind splice or rewind transfer can influence the coater or print station. A multipen recording oscillograph can show how each section is affected as the transient passes through the machine from the unwind to the rewind. It is necessary to provide properly designed dancer rollers or load cell systems that will isolate the machine from the unwind/rewind transients that may produce product defects. If no product defects are produced, isolation may not be a necessity. The new computer controlled drives can measure the effect of the splice transient on the rest of the process and can be programmed to cascade the tension transient corrections to all other sections on the machine. This technique has been used successfully to minimize both the tension transient amplitude and the tension interaction between adjacent sections. Tension interaction depends on the speed of the machine, the material being processed, and the length of web between driven sections. Knowledgeable

application of computer control can compensate for all these factors and definitely contributes to more stable machine performance.

Core Selection and Build-Down Ratio

The jumbo roll comes to the coater wound on a core. These cores can be a source of dirt and product defects. Cardboard, metal, and plastic cores all can produce fibers or chips that will fall onto the web and cause dirt defects in the final product. Web cleaning devices have been installed, which remove dust and dirt from the web. The cleaning devices are located before the coating stand. The best experience with cleaners has come from web cleaners that incorporate a method of neutralizing static electricity followed by a system that removes the dirt from the web. In order to keep away from potential dust and dirt sources, the web threading path is designed to keep the web about 1–2 feet above the floor. That also allows the operator to keep the areas under the web clean and free of dust.

The ratio between the maximum wound roll diameter and the core diameter is called the build-down ratio. Equipment manufacturers and drive suppliers prefer to use large-diameter cores in order to keep the build-down ratio small. Larger core sizes do not need a proportional increase in maximum wound roll diameter to store the equivalent length of web. A small build-down ratio allows selection of standard drives or brakes without the need for special controls to accommodate large build-down ratios. We are seeing an increase in the core size that is used in converting operations.

Draw Rolls, Pull Rolls, Capstans

The terms *draw rolls*, *pull rolls*, and *capstans* are used interchangeably. Draw rolls are used in a coater to allow differential tension to set up tension zones or to motivate the web when there are long sheet leads between driven sections. Draw rolls are used to accelerate, draw, and isolate the unwind from a hot process. An example of a hot process would be a hot calender stack that is used to treat plastic web. A draw roll is needed to provide the power to accelerate the unwinding web. If no draw roll is used, the plastic web will lose lateral dimension because the power to accelerate the unwinding roll must come from the web itself. An act as simple as placing a hand tachometer against the surface of the unwinding roll will also cause the web to shrink laterally. A draw roll placed between the unwind and calender will isolate the two sections and prevent the lateral shrinkage of the web.

Draw rolls can be nip rolls, S-wrap rolls, single rolls, vacuum rolls, or vacuum tables. Nip rolls, vacuum rolls, and vacuum tables are used to overcome the boundary layer of air that accompanies a moving web. The trapped layer of air frequently contributes to wrinkling, creasing, and web slippage. If these problems are to be avoided, the draw rolls must be designed to handle the different tensions that the process demands of that section, and web spreader rolls may be needed at the section to eliminate wrinkles.

Web Slippage and What Slip Affects We consider web to be slipping when the web is running at a speed that is different from that of the driven section. Slip affects the deposition of coating, the drying of the coated web, and the tracking of the web through the machine. Slip can also occur when the web slips over undriven or idler rolls. We can expect to see scratches on the web when undriven rolls slip.

Devices such as web guides and web spreader rolls cannot function properly if the web slips, or floats, over them. We have seen slipping web run to one side of the machine and

break even as the web guides were trying to correct web position within the machine. Thus slippage affects not only our ability to coat and dry but also our ability to deliver wrinkle-free web that is aligned properly with the coating process.

Web slipping over the master section of the machine also affects unwind splicing and rewind transfers. This is because the splice and transfer systems use the master section speed signal as an input to the unwind and rewind speed match systems. Slippage will create a speed mismatch that can cause transients on a splice or transfer attempt. The result can be a splice breakdown at the unwind, a missed transfer at the rewind, wrinkle formation that enters a nip and breaks down, or a tension transient that the tension control systems cannot accommodate. The result of all of these malfunctions is usually a web break.

The way to avoid slippage is to ensure that a section is selected that can be an effective master section. Frequently, a coater is designated as a master section even though it cannot cope with tension transients due to splicing, acceleration, and high differential tensions. When a coater is selected as a master, it is sometimes helpful to link it electronically to a nip roll or other draw roll section to form a “group” master.

Nip Rolls Nip rolls (Figure 11-9) are especially effective on high-speed machines where the web drags in a boundary layer of air that allows the web to float and make it impossible for unnipped rolls to control the web. The paper industry, converting industry, and laminating industry use nip rolls to help transport the web and to set up tension zones within the machine. Nip rolls are *not* used where the machine applies a cosmetic or optical coating that cannot be touched once the coating is applied. Nip rolls consist of a driven chrome plated roll in partnership with an undriven rubber-covered roll. In cases where the coating quality can be affected by a nipped section, S-wrap rolls, suction rolls, and suction aprons are used to provide isolation of tension zones. Cosmetic quality is important to photographic papers, sunglass lens material, filter papers, labels, and multistation printing presses.

Nip rolls are usually designed for a maximum nip pressure of 15 PLI. That pressure will help isolate the tension on the inlet side of the nip from the tension on the outlet side of the nip. Be aware that *every* pull roll has a limit as to how much differential tension it can develop before the sheet slips in the nip. Slip is a real problem that has been experienced by many in the web handling field. The most effective web motivators are the unwind and rewind. The rewind, in particular, can overwhelm the rest of the machine if the tension is set significantly higher than the rest of the machine. Slippage is a factor at paper mills

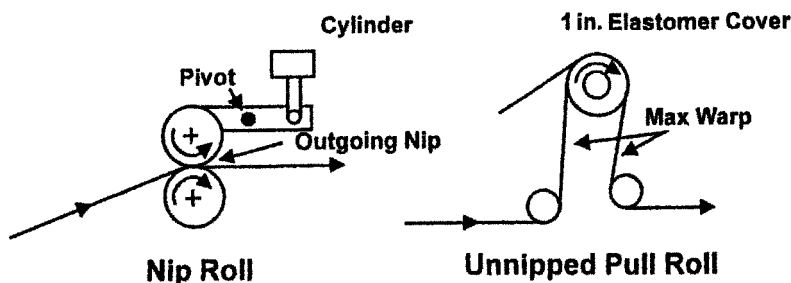


Figure 11-9. Nip rolls and elastomer covered unnipped rolls with a high wrap are used to drive the web. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

running paper web at 4000 FPM or at converters running lightweight web at 10 FPM. It is common to see the operator at either type of plant run high tension at the winder in order to process a good wound roll. Winding tension is usually higher than process tensions. The high winder tension can cause the sheet to slip through the nips and accelerate the web to speeds that are limited only by the limits of control that are imposed on the winder. If the web slips through the nips, we can be sure that there will be defects such as scratches, wrinkles, creases, poor web guiding, and web breaks. Unwind transfers and winder splicing can become “events.” Operators say that the unwind or rewind “went crazy” when a splice was initiated during a slip condition.

Machinery builders generally try not to have a long straight run from the section preceding the draw roll to the draw roll nip. Long straight paths drag air into the nip, especially at high speeds. The air will “boil” as it enters the nip, causing wrinkles, creases, and web breaks. That is why short runs (draw) are used between sections and why the roll is wrapped at the entry point of the pull roll to minimize the boundary layer of air. Machinery manufacturers often will direct the web over an entry roll and then have an entry wrap angle before the nip. That extra roll and redirection minimize the air that is dragged into the nip. The roll at the nip entry is frequently a “bowed roll,” which can lay the web flat in the nip, thus reducing the possibility of wrinkles and creases. It is good practice to place spreader rolls before each process point or drive roll to ensure the most wrinkle-free web transport system.

Nip rolls can cause or worsen defects.

1. Wrinkles or creases due to poor web characteristics, due to web slippage, boundary air layer, or wrinkling due to machine transients such as unwind splices can increase.
2. Wrinkling can also occur within the nip if the nip rolls are ground with improper “crowns.” The crown is determined by the operating nip pressure and natural deflection of the roll. Operating experience will determine what types of nip pressures are best for the process. The operator can determine if the rolls are not crowned properly by using special paper to take a nip impression. This paper is called *nip impression* paper.
3. Wrinkling can occur in the nip if one roll is skewed (not parallel) relative to the other roll. In this case, the faulty roll must be realigned. Nip impression paper can also expose a skewed nip.
4. Wrinkling can be formed when an unwind splice passes through a machine. Operators tend to open the nip or bypass it if the wrinkles lead to web breaks. If the nip section is the machine lead section or is tension controlled, opening the nips or bypassing the section can disturb the transporting of the web. At the very least, the web will slip through an open nip at low levels of differential tension.
5. The web will be marked by lumps of coating or dirt that accumulate on the roll surface or by cuts that occur to roll covers when operators splice a web on a roll surface. The roll cover is damaged when the operator cuts the web with a razor or utility knife. Similar defects also come from unnipped rolls that collect dirt or coating or are gouged when they are used as splice tables. A splice table should be provided at convenient locations in the machine to discourage splicing on machine rolls.

Unnipped Rolls (Elastomer Rolls) Unnipped rolls (Figure 11-9) are used frequently on low-speed machines and where coating quality can be affected by anything that contacts

TABLE 11-1 Chemical Resistance of Basic Roller Covering^{a,b,c}

	Gasoline/Naphtha/Kerosene	Toluene	Methyl Ethyl Ketone	Perchloroethylene	Trichloroethylene	Mineral Oil	Vegetable Oil	Glycerin	Ethyl Alcohol	Sulfuric Acid	Phosphoric Acid	Hydrochloric Acid	Acetic Acid	Chromic Acid(12%)
Buna N ^d (nitrile)	Exc.	Good	N.R.	Fair to poor	N.R.	Good	Good	Exc.	Good	Fair	Good	Fair	Good	N.R.
Neoprene ^e	Good	N.R.	N.R.	N.R.	N.R.	Fair	Fair	Good	Fair	Fair	Good	Fair	Good	Fair to poor
EPT ^f	N.R.	N.R.	Good	N.R.	N.R.	N.R.	Good	Good	N.R.	Fair to poor	Good	Fair	Fair	Fair to good
Hypalon ^g	Good	Fair to poor	N.R.	N.R.	N.R.	Good	Good	Good	Good	Good	Good	Fair	Fair to good	Fair
Urethane ^h	Exc.	Good	Fair to poor	Fair to poor	N.R.	Fair	Fair	Good	N.R.	Fair to poor	Fair to poor	Fair to poor	Fair to poor	Fair to poor
Silicone ⁱ	Fair to poor	N.R.	N.R.	N.R.	N.R.	Fair	Fair	Fair	N.R.	Fair to poor	N.R.	Fair	Fair	N.R.

^aAmong the factors to be considered in determining a roll cover for use with the chemicals listed below are: (1) primary chemical, (2) presence of auxiliary chemicals, (3) temperature of operation, (4) presence of abrasive materials, (5) cycle of operation, (6) product contamination (Would cover affect customer's product?), and (7) possibility of rolls being used interchangeably (with any two or more chemicals).

^bBuna N is used at the standard spreader roller cover. All other covers *must* be special order *only*. Standard durometer for spreader roller covers is 55–60 Shore A.

^cN.R., not recommended.

^dBuna N: Temperature range, 250 °F max. Abrasion, fair to good; color, off-white.

^eNeoprene: Temperature range, 250 °F max. Abrasion, good; color, gray-black.

^fEPT: Temperature range, 300 °F max. Abrasion, good; color, blue-green.

^gUrethane: Temperature range, 220 °F max. Abrasion, excellent; color, amber.

^hHypalon: Temperature range, 300–350 °F max. Abrasion, excellent; color, brownish-tan.

ⁱSilicone: Temperature range 500 °F max. Abrasion, poor; color, dull red.

the coated side of the web. Low speed is considered to be speeds under 200 FPM. In this case, the coated side of the web is not touched by any *driven* roller once the coating is applied. These rollers use a wide variety of elastomer coverings and a high degree of wrap to provide the grip that is required to effectively control the web. As in the case of the nip rolls, bowed rolls and short draws are used before the unrippled rolls to ensure that wrinkles and creases are not formed. The unrippled drive roll is inserted into the web path where a large natural wrap angle exists. This may be at the exit of a dryer or within a dryer that is arranged in a clam shell fashion. The web will wrap a drive roll 180° at the end

TABLE 11-1 (Continued)

Potassium Hydroxide	Amonium Hydroxide	Sodium Hypochlorite	Sodium Carbonate	Sodium Chloride	Aluminum Chloride	Aluminum Sulfate	Triethanolamine	Formaldehyde	Natural Wax	Petroleum Wax	Oxidized Starch	Chlorinated Starch	Ozone	Water at 212 °F
Good	Good	Fair	Fair	Good	Good	Good	Fair to Good	Good	Good	Good	Good	Good	Poor	Fair
Good	Good	Good	Good	Fair	Fair	N.R.	Good	Fair	Good	Good	Fair	Fair	Fair	Fair to good
Good	Good	Good	Good	Good	Good	Fair	Good	Fair	Fair to poor	Fair to poor	Good	Good	Exc.	Exc.
Good	Fair	Good	Fair	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Fair to poor	Fair to poor	Fair to poor	Fair	N.R.	N.R.	Fair to poor	Good	N.R.	—	—	—	—	Fair	N.R.
Fair to poor	Fair	—	Fair	—	—	—	Fair to poor	—	—	—	—	—	Fair	Good

of a clam shell dryer. The temperature limits of the elastomer cover should be considered. Vacuum rolls might be needed if the dryer temperature exceeds the elastomer roll temperature limits. Soft elastomers are limited to temperatures of 180–200 °F (82–93 °C). If touching the coated side of the web with *any* roll is intolerable, we may need to use a vacuum belt or vacuum roll, in place of an unnipped roll, to motivate the web. The vacuum belt or vacuum roll will be positioned against the uncoated side of the web.

The use of elastomer covers such as those listed in Tables 11-1 and 11-2 are used to provide a good grip on the web in order to transport the web through the machine.

TABLE 11-2 Material Comparison Chart

Property	Material ^a							
	Neoprene	Nitrile	Hypalon	Thiokol	EPDM	Silicone	Polyurethane	Hydrin
Tensile strength	G-E	F	G	P	F	P ^b	E	G
Hardness range	10-95	20-100	45-85	15-80	25-90	35-95	10-95	50-90
Maximum service temperature (°F)	250	250	300	212	350	500 +	212	275 +
Ozone resistance	F-G	P	F-G	E	E	E	E	F-G
Cut resistance	G	F	G	P	F	P ^b	E	F-G
Tear strength	G	F	G	P	F	P ^b	E	F
Resistance to compression set	G	F-G	F	P	G	E	F-G	F
Abrasion resistance	G-E	F	G	P	F	P ^b	E	F
Resistance to heat buildup	E	P	P-F	P	F-G	G-E	E	F-G
Swell resistance to:								
ASTM No. 1 oil	F-G	E	F-G	E	P	G	E	E
ASTM No. 3 oil	F	E	F	E	P	F	E	E
Reference fuel B	F	G-E	P	E	P	P	E	G-E
Ketones: methyl ethyl ketone	F	P	F	E	E	F	P	P
Aromatics: Toluene	P-F	G	P	G	P	P	E	G
Aliphatics: Hexane	G	E	G	E	P	P	E	E
Esters								
Ethyl acetate	G	P-F	F	E	E	G	P-F	P
Cellosolve	E	F	G	E	E	E	P-F	P
Chlorinated solvents								
Methyl chloride	P	P	P	G	E	F	P	P
Trichloroethylene	P	P	P	P	P	P	P	P
Glycols: diethylene glycol	E	E	E	E	E	E	G	E
Alcohols: isopropyl alcohol	G-E	G-E	E	E	E	G	G	G-E
Water: distilled (75°F)	G	G	E	E	E	G	G	G
Caustics: 10% NaOH	G-E	G-E	E	G	E	E	P	G
Acids: 10% H ₂ SO ₄	G-E	G-E	E	G	E	E	P	G

^aRatings: E, excellent; G, good; F, fair; P, poor.

^bAt elevated temperatures, these properties equal or exceed those of most other elastomers.

Polyurethane roll covers have excellent properties for drive rolls but are limited to low temperatures. Other elastomers are satisfactory in a high-temperature environment but may quickly lose their ability to grip the web. Some plants have had success by spiral grooving the elastomer rolls to give the boundary layer of air an exit path without causing the web to float over the roll. Some plants have also placed a vacuum box under the unnipped roll to evacuate the air from grooves. Speeds up to 500 FPM have been used with grooving and a vacuum system.

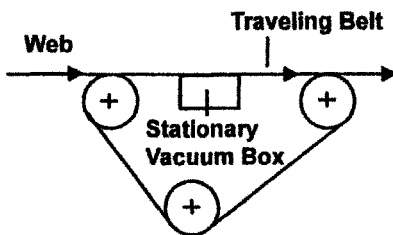
When elastomer rolls become smooth, they become ineffective drive sections. Many plants replace them with suction rolls and/or suction aprons. If elastomer rolls continue to be used, a preventative maintenance program must be established that examines the rolls to determine if they are becoming “shiny” and are slipping. Operators will sand the covers in place while rotating the roll at very slow speed.

If the process can tolerate chrome-plated rolls, two chrome-plated idler rolls should be used to provide the maximum wrap angle on the drive roll. This should work well before the coating stand. In many cases a two- or three-roll S-wrap configuration will be used before the first coater. Each roll will be covered with elastomer. The dominant roll cover is considered to be “sacrificial” and, as it becomes worn, will pass the web transport load onto the next elastomer-covered roll. We have seen 36-inch diameter S-wrap rolls with both rolls covered in a cork covering that were effective at speeds up to 6000 FPM.

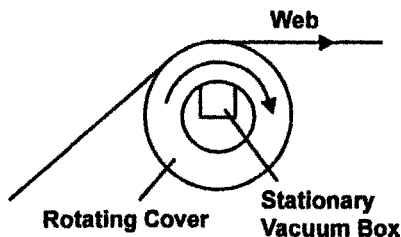
All drive rolls must be kept clean and free from coating lumps and must not be used as splice tables. All poorly maintained drive rolls can cause product defects.

Suction Rolls Suction rolls (Figure 11-10) are used where elastomer rolls are not effective. Suction rolls consist of a drilled shell that is covered by a screen or by a sintered bronze cover. Suction rolls have been effective up to 3000 FPM. Suction rolls can cause defects.

1. Scratches result if the roll slips against the web. This usually happens when a vacuum roll is applied to a position in the machine where the web has a minimum wrap around the vacuum roll and is then subjected to more differential tension than the section can control.



Vacuum Table Drive



Vacuum Roll

Figure 11-10. Vacuum rolls and vacuum tables are used to drive the web. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

All drive rolls require a sufficient wrap for good web control. Adding vacuum to a well-designed drive section enhances its control of the web. Adding vacuum to a poorly designed drive section can only lead to poor drive performance when the roll begins to slip. Resist the temptation to use small-diameter suction rolls because they are less costly than large-diameter suction rolls. Large suction rolls (12 in. or larger) with 180° wrap will have the ability to handle large differential tensions while treating the web gently. Small rolls with a small wrap angle are only capable of supporting small levels of differential tension and tend to cause scratches on the web when they slip.

Involve your supplier of vacuum tables and vacuum rolls in the application. The supplier will need to know what material you are processing, how fast the web will run, what tension levels you will use, and the web's coefficient of friction. Your equipment supplier should be able to help you select the best roll diameter or table length for your vacuum drive sections.

2. If the vacuum roll is located directly after a coater, the pattern of the screen cover may show up on the coating surface. The smooth sintered bronze cover, with its small pore size, has less of a tendency to affect freshly applied coating. Some success was achieved by placing a felt cover over the outer screen of the vacuum roll. This produced a good grip on the web and reduced the tendency to mark the web.

Suction Aprons or Tables Suction aprons or tables (Figure 11-10) are frequently used whenever very small degrees of wrap are available to nip rolls, unipped rolls, S-wrap rolls, or vacuum rolls. The flat vacuum apron presents a large flat surface to the web and motivates the web whenever there is little or no wrap angle available. Examples of such a condition are the horizontal space between two consecutive drying zones or a vertical drop from a top drying zone to a bottom drying zone. Another location can be at the dryer exit just before a laminator or rewind. Vacuum tables have been used routinely at speeds up to 2000 FPM. Some vendors have recently claimed higher speeds for their vacuum tables.

Paper machines run vacuum rolls and vacuum tables at speeds over 6000 FPM, so it seems certain that coating lines should expect elevated speeds from these devices. Material selection for the screens and vacuum boxes are important considerations for the reasonable life of the screen materials.

Examples of defects caused by vacuum tables are similar to the vacuum roll. Scratches and coating deformation can occur if the web slips or the section is located close to the coater where the freshly applied coating can be distorted by the combination of vacuum and a coarse screen pattern.

The vacuum roll and vacuum apron both have the ability to vary the width of the internal vacuum box in order to compensate for a range of web widths that are run on typical converting operations. The operator must match the width of the vacuum box area to the sheet width. If the vacuum box opening is wider than the sheet, vacuum will be short circuited and the roll will slip, causing mistracking or scratches on the web.

A special caution is in order for those who want to use a web cleaner to clean the web before it is coated. Do not tie the web cleaner into the vacuum roll vacuum fan. The volume requirements of the web cleaner are much higher than the volume requirements of the vacuum rolls. When web cleaners are connected to a vacuum roll vacuum fan, the vacuum may be reduced to a point where the vacuum roll becomes an ineffective drive section.

Increasing the Reliability of Draw Roll Sections

If a draw roll is needed to assist the web through the process, then it is important to decide what type of draw roll is best for the application. Too often, a vacuum roll or vacuum table is rejected because it costs too much. Alternate types of rolls are used, causing problems such as scratching or wrinkling, and are then bypassed. Evaluate how a draw roll configuration will perform with your process. Plastic webs may slip over chrome or elastomer rolls even at low speeds because the boundary layer of air cannot escape through the nonporous web. A vacuum draw roll or apron may be a better application unless it is located directly after a coating stand. A vacuum apron with a sintered cover may work well after the coater. Try a test run at the vendor's plant to confirm it. Nip rolls after unwinds may crush and fracture the splice pattern as it proceeds into the machine. An S-wrap or vacuum roll may be a better selection.

Manufacturers of paper coaters design nipped draw rolls into them for speeds up to 4000 FPM. However, the same manufacturers are trying unnipped rolls using extremely tacky elastomer covers. Most manufacturers apply spreader rolls, such as bowed rolls, before the draw roll section.

No matter what the configuration of the draw roll, the condition of the rolls must be policed. If the draw roll is being bypassed, was the bowed roll removed, thus allowing wrinkle formation at a nip? Are roll surfaces dirty or damaged? Are suction roll covers cut and puncturing the web? Are elastomer covers aging and becoming "polished"? Are they losing their ability to motivate the web? What is the alignment condition of the machine? When was it last checked?

Machine operators are rewarded for meeting production goals. They frequently will take whatever steps are necessary to ensure that goals are met even if it means bypassing the draw rolls when they begin to slip or if they cause problems. An engineer or maintenance technician must "walk" his/her assigned area and determine if any problems have occurred or will occur. Part of the job is to read the operating log and to talk to the operators. The aim is to find out if the operator has taken any action that makes the machine vulnerable to defects in the future. Action can be planned and implemented by the support staff that will reduce the chances of defects.

In an era where cost is important, it becomes difficult for an engineer to spend time examining machine logs and looking at web moving through a machine when a large amount of his/her time is spent on breakdown jobs. Cost or difficulty does not eliminate the need for the production, process, and maintenance personnel to routinely inspect machine conditions.

Tension Isolation

Draw rolls are used to separate a coating operation into identifiable tension zones. This capability is called *isolation*. Isolation is valuable only when there is a need for zoning. Many processes that run a constant level of tension throughout the machine do not require the extra complexity of draw rolls. However, if we are laminating webs of different characteristics, heating a plastic web until it is soft and compliant, or coating a paper web that may stretch or become weak when it is wet, then isolation can be useful. Draw rolls may also be helpful when low tensions are used in the machine. This is especially true when thin films are being processed at low tensions. Here, extra draw rolls may provide web transport assistance when drive points are far apart. The paper industry used a rule of thumb that required a drive section every 20 feet to ensure proper tension control and web transport. We

are seeing that to be true on machines that are designed for speeds above 3000 FPM. Drive sections on these coaters must be specifically designed to transport web without slipping. In particular, steam heated drum dryer sections, with felts, are receiving special treatment to prevent slippage. The dryer is separated into two sections—the dryer drums and the dryer felts. The drive system is arranged to allow one section to be the master and the second to be a follower. The dryer drive control is arranged to allow the operator to split the total section load between the dryer drum motor and the felt drive motor so as to ensure that the dryer section operates as a slip-free drive section that is capable of providing effective isolation at a reasonable differential tension. We have noted significant improvement in web tracking through the machine when the dryer drive consists of a drum drive and felt drive.

The following are examples of different tension zones.

1. Unwind versus the rewind tension.
2. A loosely wound roll may unwind at a lower tension than the entry side of the first coater.
3. The entry side of a coater versus the exit side where the wet paper may weaken and stretch.
4. The dryer exit versus the entry point of the rewind.
5. The entry side of a laminator versus the exit side of the laminator. Differential tension across the laminator will depend on the characteristics of each material being laminated and the tension needed to make the web track properly. If different materials are being laminated together, one web may require a lower tension than the other if delamination is to be avoided. The resulting laminated structure may or may not require a higher tension at the laminator exit, depending on the laminating process and the tension needed to track the heavy laminated structure.
6. A draw roll before the rewind, or reel, on the coater will allow the operator to have one tension in the coating process while a different tension is being run to wind the roll. The nipped or suction roll, before the rewind (or reel), also serves to buffer the machine from a failed rewind transfer or a web break between the rewind and draw roll. The draw roll isolates the web break to the rewind itself and eliminates the time that it takes to clean and rethread the entire machine.

Differential Tension We have mentioned tension isolation and where it is used. If a drive section is designed to isolate one part of a process from another, then the section must be able to maintain a tension on the inlet side that is different from the tension on the outlet side of the section. That ability is called *differential tension*. Differential tension is the difference in the web tension between the ingoing side of a section and the outgoing side of the same section (Figure 11-11). Every section is limited to the differential tension that it can control. When that differential tension limit is exceeded, the web will break away, the section will slip against the web, and the section will no longer control web speed or web tension.

Drive sections that isolate parts of the process must be designed to accommodate the levels of differential tension that the process demands. How much differential tension can a section handle? We need to know the following:

1. Is the drive roll a nipped section, a suction roll, an S-wrap, or a suction apron? Will the vacuum level in a suction roll affect the coating on the sheet?
2. What is the coefficient of friction of the web?

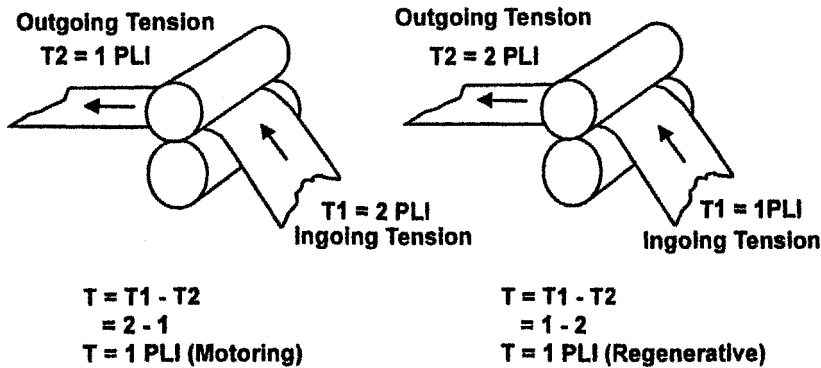


Figure 11-11. Differential tension is the difference in the web tension between the ingoing side of a section and the outgoing side of the same section. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Gutoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

3. What is the coefficient of friction of the drive roll?
4. What is the diameter of the drive roll?
5. Has the roll become old and “polished” and suffered a reduction in coefficient of friction?
6. How fast is the machine running, and what is the boundary air effect?

Most coating machines tend to run best when we set the tensions throughout the machine at the same level. For instance, if 1 PLI is run at the unwind, then 1 PLI is used at the coaters, the draw rolls, and the winder. Running the same tension throughout a machine is called a *flat tension profile*. Using the same tension throughout the machine reduces the differential tension that any section must handle during steady state and increases its chance of handling tension transients during splicing, transferring, acceleration, and deceleration of the web. If the section is handling a large differential tension during steady-state conditions, any transient can cause the section differential to increase beyond its capability to control the web and the section will slip.

We know that elastomer roll covers eventually age and become polished while they process web. A roll cover inspection program must be established in order to identify rolls that may begin to slip or are slipping. Roll slippage will occur if the roll surface appears shiny or exhibits surface scratches. Surface scratches indicate that the roll is already slipping and a shiny cover indicates that the roll is probably losing its ability to handle the desired differential tension.

Driving Web-Carrying Rolls Within a Dryer

Impingement dryers may require tendency drives on the web-carrying rolls if very low tensions are run in the dryer zones. Tendency drives drive the shafts of idler rolls, with separate bearings supporting the rolls on the shafts. Thus the drives bring the rollers to approximately the line speed, and the web has only to supply a very low torque to adjust the roll speed to the web speed. Tendency drives eliminate slippage of the web on the idler rolls.

Low tensions and high impingement pressures will tend to cause the web to accumulate between web-carrying rolls and will cause mistracking. The addition of a drive to the web-carrying rolls seems to improve web transport through the dryer. We have seen machines where the idler rolls were driven within very long impingement drying sections. Such a drive helped transport the web, scratch-free, through the dryers with excellent tracking at low tension levels. Attempts to eliminate the idler roll drive have resulted in web scratching, lateral web wander, and an increase in web breaks each time the machines were accelerated.

Consider the case where a machine was specified for a tension range of 0.25–3 PLI. Attempts to run below 0.75 PLI resulted in the web forming deep catenaries in the dryer section. The dryer web-carrying rolls were undriven. The weight of the hanging web exceeded tension setpoints below 0.75 PLI. We noted that the web entered the dryer section but did not exit it. We were fortunate that this machine's normal tension was 1 PLI or higher. If tension below 1 PLI had been required, the web-carrying rolls would have required a tendency drive. In any event, the machine could not accommodate the tensions that were specified by the client and vendor.

Undriven rolls frequently stop turning and cause scratches in the product. A tendency drive reduces the potential for scratching.

The Rewinder

The rewinder is the exit point for the wound rolls. If the process is intermittent in nature, such as a pilot coater, a single set of arms is enough to wind the jumbo roll. If the process is continuous, the rewind will need at least a pair of arms to ensure that the process will be uninterrupted. If the product is costly and easily damaged as a result of a poor start, the rewind may have three or four pairs of arms.

Use of Accumulators at the Rewind and Unwind Some materials are easily damaged if a wrinkled start occurs on the core. In those cases, the rewind is stopped while the rest of the machine continues to run. Double-sided tape is often used to make the web adhere to the core during a transfer operation. Some materials cannot tolerate the thickness of double-sided tape on the core. The tape will cause a high spot on the core that will damage some coated products during the transfer and winding process. Thus an accumulator is located between the rewind and the machine. The accumulator is kept in a collapsed condition until a rewind transfer sequence is initiated and the rewind decelerates and comes to a stop. As the winder decelerates to a stop, the accumulator stores the web that is approaching the rewind. When the operator successfully completes the wrinkle-free and tapeless transfer, the rewind is restarted. The accumulator stops storing web and returns to a collapsed position in preparation for the next transfer.

Note: We have seen cases where the accumulator is a dancer roll as well as a web storage device. In those cases, *during a rewind transfer*, it is necessary for the integral function of the rewind dancer position control to be inhibited until the accumulator is in the tension control range. Releasing the integrator function too soon will cause the rewind control to “run away” or “saturate.” Saturation occurs when the winder stops and the accumulator (dancer roll) begins to store web. The accumulator is now away from the control position so the tension controller sees an error and calls for a correction. The correction cannot be made because the winder motor is stopped. When “transfer is complete,” the winder is put back on tension control with the tension controller at full

output, and the motor speeds up to maximum speed. Operators say the rewind “goes crazy” when they complete the transfer. It is doubtful that the resulting tension transient will be controlled before the accumulator crashes against mechanical stops—or before a frightened operator can pull his/her hands away from the spinning core. Operator safety is a real problem with runaway core speed. To maximize operator and equipment safety, the tension control integral function is inhibited and the winder tension operates as a proportional controller until the accumulator is the control position. The characteristics of a proportional controller allow the winder to be introduced to the machine unobtrusively. The control position can be recognized by locating a limit switch at the control position.

The unwind frequently will utilize an accumulator to produce a zero speed butt splice. The accumulator in this case is kept in the “filled” position and it is emptied when the unwind is stopped. Thus the machine keeps running as the unwind is stopped and the operator splices the incoming roll to the expiring web. Accumulators require much space and are limited to the equivalent of 1 minute running time at the fastest operating speed. If the transfer is not completed before the accumulator fills, an “accumulator full” switch signals the drive to stop. A high-speed manual transfer is sometimes used to initiate new operators on the coating line. Large audiences tend to congregate to see the first attempts of the new operator and a great deal of gleeful backslapping occurs if a successful transfer is made.

Note: If the accumulator at the unwind is also used as a tension controller, the precautions for the winder tension control should also be implemented at the unwind. Inhibit the integrator and use a switch to determine when the accumulator is in the control position.

It is necessary to design the accumulator so that it does not adversely influence the tension range of the machine. We have seen cases where the accumulators had so much friction in the moving roll carriages and the air cylinders that it was impossible to run the tension levels that were specified in the machine. In those cases, the tension specifications were 0.25–3 PLI but the accumulator friction could not accommodate tensions below 1 PLI. Fortunately, the operating tension was above 1 PLI and the accumulator did not limit the existing process. However, as lightweight webs of thinner caliper are run on this machine, the accumulator will need to be modified in order to accommodate lighter tensions. Use of low-friction cylinders and rustproof guide rods need to be considered if low tensions are to be run.

Surface/Center Rewinds Surface rewinds typically cause wrinkling at the core and are not used for winding coated webs that need to be wrinkle free. However, most coaters that coat web for publication grade papers use the surface rewind.

Surface/center rewinders start winding the web in the surface mode and then finish the roll in the centerwind mode. Some surface/centerwinds use both surface and center winding while the roll is building. The surface driven roll is typically controlled by a dancer roll and the centerwind is torque controlled. This combination tends to build a good wound roll structure for materials that are otherwise difficult to wind. Surface/center rewinds are sometimes used to get a firm start. After the firm start, the operator has the option to retract the winding roll from the surface wind and to complete the roll in the centerwind mode.

The newer rewinds contain a “pack roll” that functions as a surface driven rewind while the centerwind drive functions as a typical centerwind. It is necessary to determine the proper percent of power that each drive will contribute to the winding roll. Much of that depends on the material being wound and how much taper tension will be required.

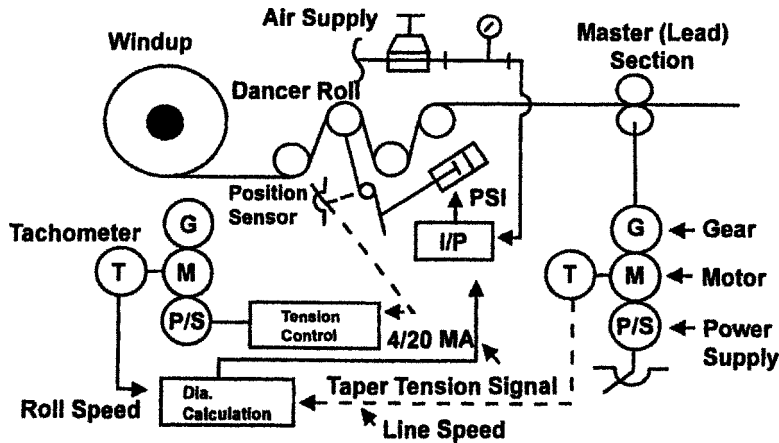


Figure 11-12. The taper tension system compares the line speed with the speed of the winding roll, calculates the diameter, and reduces tension in conformance with a taper tension controller.

Center-Driven Winders Center-driven winders are tension controlled by force transducers or dancer rolls. These sensors can sense tension changes during transient periods such as transfer, acceleration of the machine, or when the rewind turret is rotated. A taper tension system maintains proper tension under steady-state conditions as the roll diameter builds.

The taper tension system (Figure 11-12) compares line speed with the speed of the winding roll and calculates diameter. It reduces tension in conformance with a taper tension controller. Sometimes, the taper tension system incorrectly responds to temporary transients such as acceleration or turret rotation. Drive vendors have provided circuitry that locks out the taper tension system during transient periods. Techniques have been developed to minimize the influence of turret rotation by placing a variable speed drive on the turret and to control it with the tension sensors.

Additional special control is required at the centerwind when a transfer is made. When transfer is initiated, the paste roll pushes the web against the core, causing the tension to increase. When the web touches the core, it isolates the tension sensor from the winding roll. The tension sensor senses an increase in tension and causes the tension controller to reduce tension. The web will go slack between the winding roll and the paste roll. As a result, the web will be slack when the cutoff knife attempts to complete the transfer cycle. The knife will not sever the slack web and the transfer will be missed. The machine will need to be stopped and rethreaded.

Modern drive systems transfer from tension control by dancer or force transducer to a current memory circuit that is enabled when the transfer is initiated. The current memory circuit will hold the winding motor current constant while the transfer is completed. The rewinder is returned to its normal tension control mode when the knife severs the web. It is conceivable that the integral function on the winder may need to be inhibited during the transfer operation.

Drives for Laminators

The laminating process consists of two webs that are fed through two rolls that press the two webs together. The process can be “wet” or “dry.” If an adhesive is added to the nip

between the two webs, then it is a wet process. If the adhesive is applied to the web at a coating station and then delivered to a laminator, it is a dry process. In some cases one web is laminated to a “carrier web,” is coated, and later is separated from the carrier web at the end of the process. The carrier web supports the web while it is being processed.

When to Drive Both Laminator Rolls If the existing process provides good laminations that are free from delaminated sections, then the existing drive is fine for your product. However, if you are experiencing delaminations, it is time to examine your laminated structure and the laminator drive system. Most laminators have a single drive to motivate the section. Let’s evaluate what is happening at the laminator. First, a drive is connected to one of the laminator rolls. Then the second undriven roll is pressed onto the first roll to form a nip. The undriven top roll is driven by the nip of the driven roll. That means that the undriven roll represents a load (or drag) to the driven roll. If we introduce the webs to the nip that is formed between the driven roll and the undriven roll, the undriven roll will now be driven by the web that is in the nip. More accurately, it will be driven by the top layer of web in the nip. The flow of power from the bottom roll will pass to the bottom layer of web, through the adhesive that bonds the two layers, through the top layer of web and to the top roll. The load that the top undriven roll exerts on the top layer of web will apply a braking effort (or drag) to the top of the web. It is possible that the drag will cause the top layer of web to slip relative to the bottom layer of web. That slippage is delamination. In this case, it will be necessary to provide both rolls with drives. That can be done by connecting the top roll to the bottom roll drive through a clutch or by installing a separate motor to drive the top roll.

A separate drive on the top roll must be adjusted to supply the frictional losses of the top roll and some of the nip losses. If the top roll drive is adjusted to provide an excess amount of load, power will be added to the top layer of web, and a delamination can occur.

Note: If a top roll drive is not used, it may be a good idea to supply it with a drive journal, “just in case” a new product or new process is introduced to the machine that requires a driven top roll.

Coating Roll Drives

Coating roll drives also require special attention. Blade coaters on paper webs may require a special control to prevent the trailing blade from gouging the drum when the machine is stopped. If the gears and couplings have backlash, the drum can back up when it reaches zero speed. If the blade is still in contact when the drum backs up, the blade can (and in some cases does) gouge the drum. To prevent gouging, the drive control must generate a signal as it approaches zero speed. The speed signal is used to retract the coating blade just before the coating drum stops.

Backlash from gears, couplings, and belts is also a problem on coating lines that apply optical quality coatings to a moving web. Backlash can cause chatter marks on the coated web.

Coating Defects—Sources and Some Solutions

Blade coaters, photographic film coaters, label stock coaters, plastic or metal film coaters, and textile laminators all apply a coating that affects the cosmetic quality of the finished web. Coating chatter (Figure 11-13) will result in inferior cosmetic qualities and will cause the customer to return the web to the manufacturer. Coating chatter shows up as periodic light

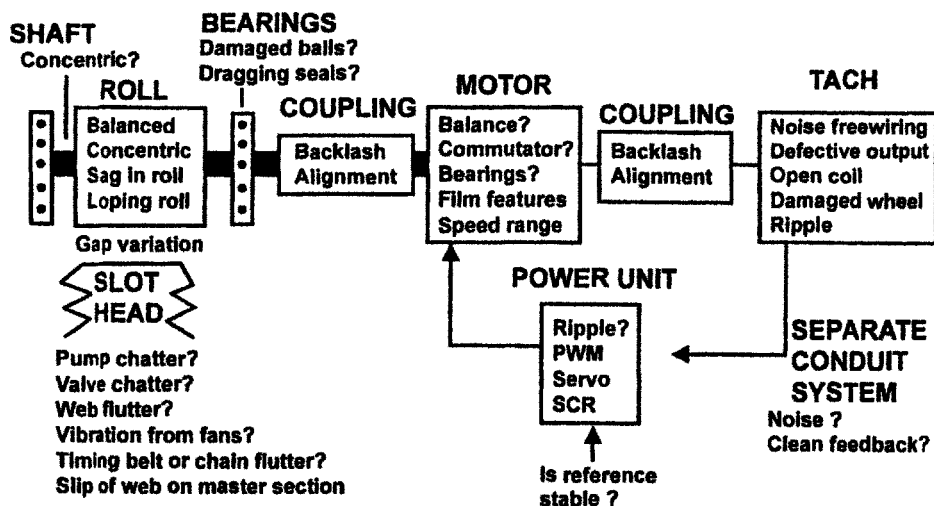


Figure 11-13. Sources of some coating defects. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

and dark coating bands on the web. Coating chatter can be caused by the coating roll, the drive motor, the control equipment, the drive power supply, and the power transmission equipment such as belts, couplings, gearboxes, chains, and universal joints. Chatter can also be caused by adjacent section drives that transmit vibration through the web or by mechanical equipment that transmits vibration to the coating stand through structural members.

Backlash Exists in Timing Belts, Gearboxes, and Geared Couplings If the coating roll is connected to the drive motor through any type of gear, the profile of the gear teeth may show up as chatter on the coated web, particularly when the drive motor is lightly loaded. Drive motors are frequently lightly loaded on slot coaters. The drive motor will supply the frictional losses of the coater. Very often, the tension at the coater outlet is increased, which further reduces the load on the coating roll drive. As a matter of fact, the load on the coater may be reduced to the point where it is operating at zero load. With light loads, the torque requirements can shift between motoring and braking. When the load shifts, the gear teeth first drive on the forward side of the gear tooth and then hold back on the back side of the tooth. The changing of the tooth contact must pass through the backlash region. Backlash “slop” or clearance causes a nonlinear velocity (a perturbation) that results in the coating chatter. Some operators compensate for slop by increasing the tension at the ingoing side of the coater. This strategy increases motor load, which keeps the gear in contact with one side of the tooth, thus reducing the effect of backlash. If increasing the tension does not solve the problem, then the gears must be eliminated.

We have seen chatter occur when heavy-duty timing belts were used to drive an air-knife coating roll. The gear-like teeth in the heavy-duty timing belts were so well defined that the coating stand actually rumbled when the drive was in operation. Chatter was eliminated by replacing the heavy-duty timing belts with standard-duty timing belts. In other cases where chatter was a problem, timing belts were replaced with flat belts. Flat belts seem to provide smoother drive performance than the timing belt. Other engineers

have reported that they have reduced chatter by turning the timing belt over and simulating a flat belt surface with the back of the timing belt. New timing belt designs, using a rounded tooth design, have reduced the tendency of timing belts to chatter. We have also seen nonlinear velocity when timing belts, flat belts, or chains were used on “long belt centers.” A long belt center exists when the drive pulley is very far from the driven pulley. Long belt center belts tend to pulsate as they rotate. The use of a belt idler pulley will reduce the amplitude and increase the frequency of the disturbance to a point where it might not be seen as chatter. However, on very critical applications, a direct drive between the motor and the roll may be the best answer to achieve smooth, perturbation-free coatings.

Chatter that is the result of using gears, gear type couplings, timing belts, or chains can be eliminated by replacing the “sloppy” devices with zero backlash devices and direct drive motors. Care must be taken to ensure that the zero backlash devices are very stiff so that they do not vibrate during periods of acceleration and deceleration. This vibration is called *torsional vibration*. Let us simply say that an elastic coupling or shaft can begin to vibrate when it acts in concert with the drive control system. The drive control system sees the vibration as a speed error and tries to correct it by accelerating or decelerating the shaft or coupling. The vibration of the coupling or shaft becomes out of phase with the drive system correction, and the result is a system that has gone into torsional vibration and will stay that way until the machine is stopped, until the coupling or shaft is destroyed, or until a stiffer drive transmission device permanently replaces the elastic member.

A shaft or coupling that seems very stiff and hard to us may appear to be a rubber hose to the drive control system. A coating roll drive needs a control system that is extremely responsive. An elastic power transmission system compromises the system’s ideal performance. Long drive shafts, or couplings with rubber inserts, or with leaf springs, or with flexible disks, can create and have created problems when applied to high-performance drive systems. If torsional vibration exists, drive response will be reduced to less than optimum values. A reduced response may not be adequate and the elastic members must be replaced.

Improperly aligned couplings can cause velocity perturbations that translate into coating variations. Connecting the coating roll directly to the drive motor through a properly designed coupling can eliminate gear reducers, backlash, torsional vibration, and coating chatter.

Chatter Caused by the Roll Chatter caused by the roll can be due to conditions such as defective bearings, roll unbalance, and a nonconcentric coating roll. Bearings that were installed improperly on the roll or are no longer within specifications due to normal wear must be replaced to achieve good coating results.

Roll Unbalance Those of us who have driven automobiles have seen what can happen when the front tires become unbalanced. The tires will vibrate when we approach certain speeds. The same is true with coating rolls. If the roll is unbalanced, it will vibrate at certain speeds. In addition, we can see the effects of the unbalance as we rotate the roll by hand. As we rotate the roll we will feel a point where we need to exert force to push the roll uphill (applying positive torque). As we continue to rotate the roll we suddenly reach a spot where we must apply a braking effort (apply negative torque) to keep the roll from rotating by itself. This alternating motoring and braking torque requirement is another area that causes chatter when slop exists in the drive system. In addition, the unbalanced roll

presents a load that alternately requires a positive torque and a negative torque to rotate the roll. A drive system must alternately supply positive or negative torque if it is to keep the drive rotating smoothly. However, like slop in gear reducers, the unbalance can excite the drive into “torsional” vibration and cause serious damage to power transmission components or to the roll itself. A buildup of dirt or coating solids on the coating roll may also cause roll unbalance. Keeping the roll surface clean will avoid roll unbalance or impressions that occur when a coating lump embosses the web during the coating process.

Nonconcentric Rolls A nonconcentric roll can be caused by bent roll journals or by the fact that some rolls will sag or deflect if they are kept stationary too long. It is difficult to imagine a metal roll deflecting. Metal rolls will deflect as readily as a rubber hose when a length of hose is suspended between two points. The longer the span, the more noticeable the deflection or sag.

This type of roll is frequently supplied with a “Sunday” or “inching” drive to keep the roll rotating during periods of inactivity. Such activity frequently exists on the weekends, during plant shutdowns, or when the machine is idle for maintenance purposes. This drive is important enough to cause many coating mills to assign the plant security staff the responsibility to check the drive as part of routine plant inspection during downtime periods. A slow-speed drive prevents the deflection inherent with some coating rolls if they are stationary for too long a period.

Coating Roll Drive Systems

The drive system can also provide a source of noncontinuous velocity that results in uneven coating. To satisfy extremely precise coating needs, the drive motor may require precise balancing, special bearings, and skewed armature slots. Such a motor is said to have “film industry features” to provide smooth rotation. A servo quality motor may be required even to the point of selecting a motor with minimal or no commutator ripple. Modern drive systems advertise perturbation-free performance over a 1000 to 1 or 2000 to 1 speed range. Older drive systems were rated 20 to 1 or 30 to 1. Perturbation-free claims are all relative. See Table 11-3 for comparisons. It is best to find a place to test these claims. Many vendors have test facilities that are designed to allow customers to test drying equipment, coating equipment, web transport equipment, and drive systems. Drive manufacturers, machinery builders, coating manufacturers and even customers have pilot coating facilities that are made available to anyone with questions about a new process or equipment.

The output of the power supply to the motor may contain enough ripple to affect coating quality. Single-phase SCR-type direct current power supplies have a very high ripple content at lower coating speeds, and this ripple will reduce coating quality. Power supply ripple can be reduced by going to three-phase SCR, pulse width modulated (PWM) power supplies, or servo quality power units. Many servo quality drives are designed to operate at extremely low rpm without “cogging” (velocity perturbation or stop-go operation). The recent development of ac vector drives has given an additional option for precision coaters. However, low-speed operation of these drives should be evaluated for cogging of the motor. Standard ac motors are not balanced well enough to be used on critical coating applications. The performance of ac, dc, or servo motors must be evaluated to determine which motor will give the best performance for *your* coating process. By eliminating those motors that will not satisfy your needs, you will determine which type of drive is to be used.

TABLE 11-3 Comparison of Drive Features

	1 Phase SCR dc	3 Phase SCR dc	dc Servo	Brushless Servo	Vector ac
Motor	dc	dc	dc	Brushless	ac Induction servo
X-Proof	Yes	Yes	Yes, or purge	Purge	Yes, or purge
Microcontroller	Least complex	Midrange complexity	Midrange complexity	Higher complexity	Highest complexity
Horsepower	Fewest diagnostics	More diagnostics	More diagnostics	More diagnostics	Most diagnostics
Application	$\frac{1}{4}$ to 75	3 to 600	$\frac{1}{4}$ to 30	$\frac{1}{4}$ to 16	1 to 50
	Low power, general applications	Mid-high power, general applications	Low-mid power, general and high performance	Same as dc servo and high-speed position applications	Same as brushless in higher HP
	Medium performance	Medium performance	High performance	Highest performance	Very high performance
Speed range	20:1	30:1	1000:1	2000:1	1000:1
	Cogging at low end	Some cogging at low end			
Gear reduction	Needed	Needed	Little or none needed if enough torque	Little or none needed if enough torque	Little or none needed if enough torque
Regeneration	To ac line	To ac line	To snubber or bus	To snubber	To snubber or dc bus
Power factor	Low, 0.68 avg.	Low, 0.68 avg.	0.95 constant	0.95 constant	0.95 constant
	Higher at higher speeds	Higher at higher speeds			
Efficiency	72–78% at full power	72–78% at full power	Up to 80%, depending on motor and bus	Highest, up to 83% Constant with speed	Up to 80%
	Less at low speeds	Less at low speeds	Fairly constant with speed		
Speed feedback	Resolver, pulse tach, or analog tach	Resolver, pulse tach, or analog tach	Resolver, pulse tach, or analog tach	Pulse encoder	Pulse encoder
Relative price, Non-X-proof	Lowest	Mid to high	Mid to high	More than 1-phase dc	Competitive with servos
		Similar to dc servo	Similar to 3-phase SCR dc	Less than 3-phase SCR or dc servo	Standard motor is poorly balanced
		Economies available in dc servo	Economies available in dc servo		

Care must be taken in applying *all* types of drives to coating applications. Newer technologies require some research into the advantages and disadvantages of these drives. An understanding of the pros and cons of each drive will result in a good and cost-effective match of technology to the application.

Feedback Devices The perturbations in rotational velocity of couplings or belts that drive velocity feedback devices can create “ripple” in the output of the velocity feedback device. If a digital device is used as a velocity feedback, then its signal converter may contain enough ripple to influence drive system velocity. If a digital reference is converted to an analog reference for the drive, the resulting analog output may contain an unacceptable amount of ripple. If a highly responsive velocity control system responds to the ripple of the feedback or set point devices, the application of coating may be so nonuniform that it will create cosmetic defects in the finished product. The nonuniformity may cause the quality control group to scrap the product.

It is imperative that the velocity feedback device be connected to the motor with a stiff coupling that is aligned perfectly. It is not uncommon to use laser alignment equipment to align drive equipment. The use of belt driven tachometers is acceptable for paper machines and for many coating lines, but for the coating rolls on converting lines, a direct driven encoder is the most trouble-free method of feeding back velocity signals. There are a variety of analog and digital velocity sensing devices for mounting on motors. Many of these devices show better maintenance characteristics when they are direct connected rather than belt connected to the motor, as the tachometer bearings fail more often on belt driven units. Many mechanics apply belt drives with excessive tension. We have seen cases where the tachometer shaft is deflected due to belt tension. The tachometer or encoder bearings are not designed to withstand excessive belt tensions and, as a result, will fail in a short amount of time.

Coating Supply System The coating fluid supply system to the coater can provide sources of coating chatter. Unstable feed valves, positive displacement pumps, and unstable drives for the pumps can cause coating variations. Unstable feed valves or feed valve control systems can permit surges that cause variations in coating thickness. It is important to match the characteristics of the coating to the characteristic of the feed valve. Valve curves and a knowledge of the coating fluid characteristics will help to avoid coating problems.

Positive displacement pumps, such as gear pumps, may transfer the gear-tooth profile through a slot head to the web.

Unstable drives on positive displacement pumps may cause surges and transfer thickness variations through a slot head to the web. Some coatings may require precise drives for the supply system pumps so that they will operate smoothly over a wide speed range.

Transmission of Vibration Through Structural Members to the Coating Stand If dryer fans are mounted in the ductwork of the machine and the ductwork is supported from the coating stand, the fans can cause the ductwork and coating stand to vibrate. Any vibration at the coating stand or coating head support can cause coating chatter.

The practice of mounting fans in ductwork is evident on lab or test coaters where space is limited or the machine is portable. If any coating stand is not mechanically isolated from the rest of the machine, vibrations caused by the surrounding machinery will cause the

coating stand to vibrate. These vibrations are transmitted to the web and they can cause coating chatter. Do not attach support members to the coating stand; instead, design an isolated coating stand structure that is separated from the rest of the machine and building if that is what is required to eliminate vibration. Elaborate machine isolation pads are available and some consultants specialize in designing buildings and machine isolation systems that reduce vibration to tolerable levels.

EFFECT OF DRYER DESIGN ON COATING QUALITY

Dryer nozzle design can affect the quality of wet coatings by causing uneven airflow that disturbs the wet layer. Impinging air can cause such defects as “railroad tracking.” Railroad tracking occurs when a hole or slot spreads the coating in one location on the web. That spread will show up as a straight line, running in the machine direction, on the dried coating. It is important for the coating plant to test the coatings on different drying systems at the vendor’s plant. Test a wide range of coatings rather than just the one you believe might cause a problem.

A great deal of concern always surrounds the effect of flotation dryers on coatings that are on the web and can flow. This concern centers around the question of whether these dryers will displace the coating as the web travels through the dryer. Here again, a test at the vendor’s facility will uncover any problems that are anticipated and also many problems that were considered to be nonexistent.

TROUBLESHOOTING “SUDDEN” COATING PROBLEMS

It takes a great deal of patience and familiarity with the machine to identify the source, or sources, of coating defects. Knowledge of both the machine and process are needed to determine whether a mechanical or process problem is causing the defect. A recurring mechanical failure will cause a coating defect. It is important to identify that failure and the frequency of that failure, and to establish a preventive maintenance schedule that anticipates such an event. The implementation of a preventive maintenance schedule will encourage inspection, adjustment, replacement, or cleaning of the equipment in question so as to *minimize* future failures.

Devices such as friction brakes or magnetic particle brakes need periodic maintenance to maintain their performance at acceptable levels. Items such as brake friction linings should be resurfaced or replaced while magnetic particles must be replaced with new magnetic particles. Bearings must be inspected, cleaned, lubricated, and replaced on a routine basis.

Motors, tachometers, and force transducers must be examined and kept free of dirt, worn parts, defective bearings, and worn belts if system performance is to be kept at an optimum level. Brushes for dc motors and tachometers should be examined on a timely basis and should be replaced as recommended by the equipment builder.

Awareness of any changes that might have occurred just before a defect was noticed is important. It is extremely important for production personnel to know if machine modifications are planned for a shutdown period. The following activities are usually timed to occur during shutdown periods, such as during planned summer and winter shutdowns.

1. Change a coating roll or drive roll. If the roll, bearings, or power transmission equipment is not installed properly, coating quality will be affected. It is my belief that this type of change should be performed by experienced personnel familiar with modern alignment instruments and the critical needs of the process. In some ways I lament the loss of the apprenticeship programs that provided training for entry level trades personnel. We have too often adopted the “let’s see what the new guy can do” attitude to the frustration of the production personnel and to the cost to the corporation.

2. Were process air filters changed? If so, is the filter medium and the filter seal compatible with the process. Consider the case where the purchasing department sent out for competitive bids for a filter with inadequate specifications. A vendor said that he could meet the specifications with a less expensive line of filters. The filters were purchased. To our chagrin we discovered that the “identical” filter medium was fine but the filter gasket contained a chemical that would cause serious fogging problems on the photographic film that was coated. We discovered the change in filter brands when an air-handling mechanic complained that he needed more machine downtime to install the new filters. When we examined the new filters, we discovered the difference. Installation of the filters would have resulted in serious financial loss to the company.

3. Was new equipment added to the machine? If so, what effect will the new equipment have on web tension, web guiding, or wrinkle formation? Will the operators be able to thread the web through the section safely and conveniently? New capital projects are too frequently carried out with little involvement on the part of those who are most affected by the changes—the operators.

4. Was maintenance performed on the machine? Were rolls realigned or leveled? If so, who asked for the realignment? Were there tracking or wrinkling problems or was the realignment a result of “preventive maintenance”? If the operators have no complaint about web tracking, the maintenance staff should document out-of-level and misaligned rolls for review with the production department. If the data is consistent with problems that the operating crew sees, proceed to level and align the rolls. It is not uncommon to have the maintenance staff check machine alignment and level once a year or once every two years. This check will not only expose problems that occur when roll bearings are replaced during the year, but it will also expose problems with a new building “settling” over time.

5. Were brakes and clutches rebuilt? If so, will the brakes and clutches require different values of power or air pressure? It is important for maintenance and production to communicate with each other about work being done during shutdown so that the production group will be aware that something is different. That difference may require changes in operating techniques and control system set points by the operating crew.

6. We have seen cases where fan bearings were replaced during a shutdown but the mechanic forgot to replace the fan drive belts. Production was delayed until an air-handling mechanic was summoned to install the belts. Luckily, fan pressure was monitored as part of the control strategy. This monitor would not allow the coater to start up without proper fan pressure. Otherwise it may have been possible to coat the web with improper drying conditions. Significant losses would have occurred without proper monitoring of the fan.

7. Was instrumentation recalibrated during a plant shutdown? Consider the case during a summer shutdown, where an instrument technician discovered that the dryer zone temperature sensors were reading 20 degrees low. Actual temperatures were 20 degrees higher than indicated. The technician recalibrated the sensors so that they read accurately, but he did not tell the operators what he had found. The operators returned from vacation

and set up the machine with the temperatures that were approved for the product. Drying was affected and product quality was poor. Drying was identified as a problem but the operating crew was not authorized to make drying set point changes. The machine was shut down and a committee was formed, which confirmed the problem and authorized new set points. In the meantime, production was lost at a time when the company was trying to build inventory for end-of-the-year holiday sales. Here again, the operating crew must know what calibrations will be performed during shutdown, what problems were found, what was done to correct the problems, and what temperature set point is now appropriate. Operators should also be instructed by the maintenance group as to how to proceed into production with the newly calibrated instrument system. As a matter of routine procedure, the machine should be operated on a test run before going into a production phase. The test should be designed to confirm the satisfactory operation of the machine and to determine if anything has changed in the two-week shutdown. This test reduces the waste that comes from starting production on costly products, which use resources that are both expensive and difficult to obtain (gold, silver, or materials that are supplied by vendors who have limited production capabilities).

Can any of these events cause a web coating defect? Absolutely! And solving these problems may require a major troubleshooting effort requiring human resources, vendor involvement, diagnostic equipment, and cooperation of the management, maintenance, production, and engineering disciplines.

Monitoring Speeds and Tensions of Web

We tend to process webs at specific speeds and at specific levels of web tension. It should be no surprise that we are interested in the speed of the motor, how much torque the motor is applying to the web, and what is the measured web tension.

A Speed Monitoring System Modern speed monitoring systems consist of a microprocessor-based controller that accepts a speed-related signal from each motor driven section and some sections that are driven by the web. These systems are available with a wide range of alarm and report generation capabilities. Reports can be generated when an event such as a web break occurs. The report will highlight the speed of all sections just prior to the event. Speed monitoring systems are ideal for older coating machines that do not have process computers to provide this function. They may also be ideal for modern coaters when the operator wants a continuous display of speed. Continuous display of speed is important during the startup and debugging phase and while trying to solve product defect problems or trying to identify the cause for a web transport problem. A speed monitoring system is also used, after commissioning, to identify drive performance problems with a section speed controller or its tachometer.

Monitoring the Speed of Idler Rolls Many monitoring systems include a speed signal from a roll that is driven by the web. If the idler roll slips, the speed signal will be inaccurate. Select a roll with a high degree of wrap to ensure accurate speed indication. Slip can then be detected quickly by monitoring the speed differences between the master drive section and the idler roll. Some monitoring systems provide an alarm or computer output to indicate slippage beyond acceptable limits. Such an alarm is very valuable when an idler

roll stops turning and scratches the web as the web is dragged over it. Coating machines with long dryer sections have dozens of idler rolls that may stop turning due to a lack of lubrication or a failed bearing. The monitoring system helps identify the problem.

High-speed machines tend to drive their web-carrying rolls so that they will be accelerated and decelerated in a reasonable time without damaging the web. Undriven web-carrying rolls on high-speed machines coast to a stop so slowly that they represent a hazard to an operator who might be anxious to clean up the machine after a web break. A motor that drives the web-carrying rolls will quickly decelerate the roll to a stop and will supply additional braking for an emergency stop mode.

Monitoring for Slip Conditions on High-Speed Coaters High-speed machines monitor the speed of the master and the tension-controlled sections. If a tension-controlled section is running at speeds that are different from the master drive, we know that the section is slipping. Slippage can result in scratches, wrinkles, mistracking, and web breaks. If all the tension-controlled drives are running faster than the master, then we know the sheet is probably being pulled through the machine—most likely by the rewind. Rewind tension may be high and unwind tension may be low.

If the tension-controlled sections are running slower than the master, then we know that the sheet is probably being slowed down by the unwind. Unwind tension may be high and rewind tension may be low.

It is important to establish and control acceptable operating parameters for speed and tension for the coating machine in order to ensure satisfactory web transport.

In summary, a speed monitoring system will help on startup and debugging, can assist the operator during production runs, will provide a warning if speeds wander outside an acceptable operating envelope, and can be used by operators and maintenance personnel as a problem-solving tool.

Tension Monitoring Systems We have said that tension is the force applied to the web between adjacent sections. It is important to know and record the machine operating tension for each product between each section. It is important to document these values using instruments or computers, and it is even more important to know the proper operating tension for each product and process. Routinely examine drive data to establish that normal levels of speed, tension, and motor load exist for each product and process.

All tension monitoring systems measure the total tension that is applied to the web (Figure 11-14). If the coating machine processes only one web width, the tension can be displayed as unit tension (as PLI) or total tension (as total pounds). The operators and engineers can easily see what values of tension are being used to transport the vendor-supplied web. Tension data will be used to select motor size and brake/clutch size when machine design speed is increased, or when new machines are purchased. A knowledge of how each product is run may allow us to rebuild the machine to operate at higher process speeds without increasing the size of existing drive equipment and process equipment. Knowing the operating loads on drive and process equipment may show that the prime movers are running at less than full load. These prime movers can be utilized during a machine upgrade at substantially lower cost and significantly less downtime than would be required for replacement equipment.

Replacing an existing drive system requires extensive capital investment and downtime with its attendant loss of production. *Rebuilding* an existing drive may require little or no interruption of production time and much less capital cost. Drive rebuilds frequently can be

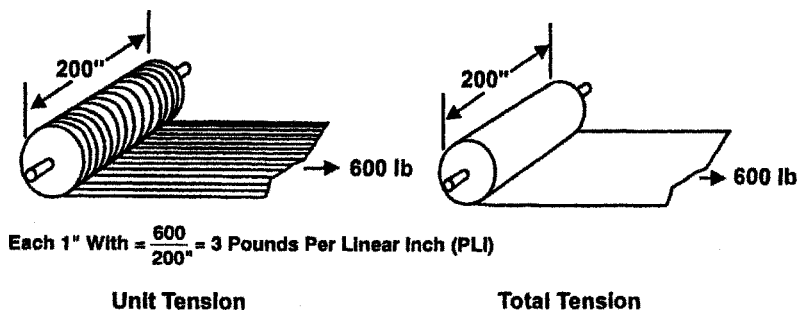


Figure 11-14. Unit tension is the total tension divided by the width of the web. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Gutoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

accomplished during scheduled summer and winter shutdowns *if* existing equipment can be utilized. Monitoring speed, tension, and load operating data provide us with the information that helps us make informed decisions that improve productivity at the lowest installed cost.

Specifying the Tension Range The selection of a tension indicating system begins with a realistic definition of the operating tension range that will be required by the web. If too wide a range of tensions is specified, machinery builders may need to design and implement costly multirange tension control systems, which may not be ideal for the actual operating conditions.

The machinery builder may also need to supply robust web-carrying rolls that may have an adverse effect on light tensions that are run for thin films. Light tensions may also require motor driven unwinds and motor driven web-carrying rolls.

We have seen cases where the operating tensions were actually 0.75–1.25 PLI. Specifications called for a range of 0.25–3 PLI. We discovered that the actual tension range capability was limited to 0.5 PLI to something in excess of 3 PLI. The vendor had cheated toward the high side of the tension specification. The components of the tension sensing and correction system would have been better matched to system requirements if a range of 0.5–2 PLI had been specified.

If the machine processes products of different widths, tension systems must be able to display the proper tension regardless of web width. For machines that accommodate multiple web widths, it is common to display tension in total pounds. For machines that are blessed with a computer system, the tension is displayed in PLI and the process computer menu requires web width as one of the parameters.

Why Is Tension Control Needed?

1. Tension control provides a valuable tool to the operators, the machinery builder, and to the drive vendor.
2. Tension control allows the operator to thread the web through the machine and start production more quickly than if a pure speed controller were used.
3. Tension control corrects for the tension transients that occur when the coating applicator is applied to the web, when splicing at the unwind, or when transferring at the rewind.

4. Tension control allows the machine to process webs of different widths, weight, and caliper.
5. Tension control corrects for the normal variations that occur in paper and plastic webs during the coating operation.
6. Tension control is valuable for the drive vendors who use it to compensate for factors that are within their control yet may go unnoticed except through changes in web tension. The older analog speed regulated drives drifted so much that radical changes in web tensions occurred. Drift was so dramatic that web breaks occurred unless some form of tension control was used to keep the tension at the set point.
7. Tension control compensates for the tension transients that occur when the machine is accelerated and decelerated. The tension control system ensures that machine sections, with different inertias, will successfully accelerate the web to process speed and then will successfully decelerate the web to a stop when the coating run is complete. High-inertia sections may not follow the acceleration/deceleration ramp as closely as the sections adjacent to them. If high-inertia sections make machine acceleration and deceleration difficult, it will be necessary to set the acceleration/deceleration ramp at a rate that will allow all sections to move in synchronization. If all sections vary during transient periods, tension changes can be severe enough to cause a web break.

Effects of Wiring Practices on Tension Control Manufacturers of modern electrical drive systems and computer control systems have definite guidelines for the wiring of power and control devices. They recommend that power device wiring be separated from signal level wiring. Separation is needed to ensure optimum system performance. Signal wiring is further separated into digital and analog signals. Some system users have chosen to disregard these guidelines and have combined wiring for motors, solenoids, and lighting with signal leads.

When all wiring is combined in today's system, the system performance will be compromised when "electrical noise" interferes with and modifies electrical signals that are used to control the process. We have seen the coating flow to the coating head disrupted when a motor at the winder was jogged. Power cables and signal cables had been combined into one raceway. We saw a signal transient on the flow meter feedback signal each time the motor was jogged. Coating flow increased momentarily each time the transient occurred. The flow meter signal cable was placed into a separate raceway and the electrical noise problem was eliminated.

We also note in Figure 11-15 that the tracking of a coater was seriously influenced when the wiring to the drive motors was combined with the wiring to the drive system tachometers. We discovered that the coater lead section was running slower than the #4 draw roll. The draw roll pulled the web through the machine at a speed that was about 20 FPM faster than the master. Coating was being applied with a slot head. Coating coverage was lower and out of specification, because of the slip condition that existed. Web breaks were common on this machine.

We also discovered that this machine had faulty analog controllers that tended to "drift," causing variations in speed over the course of a production run. We replaced these controllers, added tension control to the machine, and provided the operators with an easy-to-thread and flexible operating unit. *Note:* The drive manufacturer was aware of the drift problem but corrected it only at those plants where customers complained about poor control.

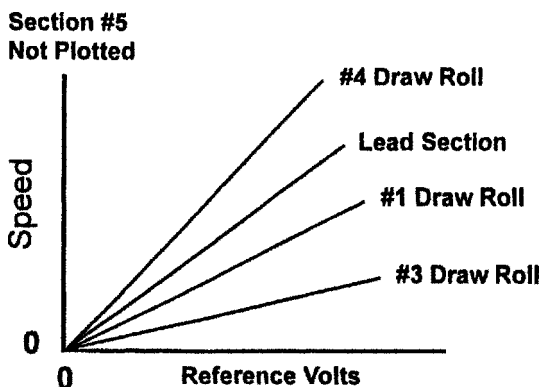


Figure 11-15. Drift, and electrical noise that is due to running the power cables and the signal wires in the same conduit, can greatly affect motor speed. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

TAPPI *Recommended Wiring Practices for Automatic Control and Regulator Systems* (#406-12) is an industry recommendation for control system wiring practices. Noise problems will be minimized if recommendations in this guideline are followed.

When Do You Use a Pure Speed Control? A block diagram of a basic speed regulator is shown in Figure 11-16 and should be used in the following applications:

1. When web stretch or shrinkage is intolerable during processing. This requirement typically reflects process or product limitations rather than drive control considerations.
2. When the web is being stretched to a specific ratio between adjacent sections in a process. Speed controller attributes will easily maintain the specified ratio.
3. When process conditions create a pliable web, the attributes of tension control may produce undesirable web stretching or even web breaks. The attributes of a tension controller may cause variable stretch ratios.

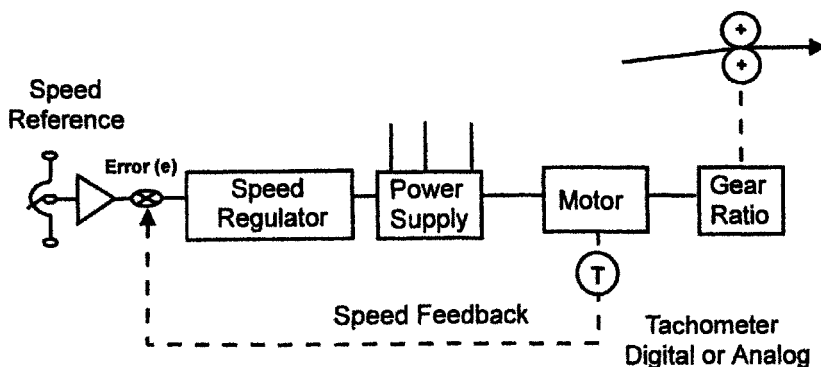


Figure 11-16. Block diagram of a basic speed regulator. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

4. To avoid web breaks when the web is so weak that it can barely support its own weight.
5. For the lead or master section of the machine.
6. Whenever a process creates or treats a pliable web whose characteristics change with each roll introduced into the machine, applying constant tension can produce variable results. Sometimes a speed regulator may be the only tool capable of producing good results. In any case, an installed tension indicator will help monitor the machine process.
7. If the machine has multiproduct requirements, a drive system should be designed that is capable of running in either tension or speed mode, depending on web, process, and product needs.

Speed regulators compare an incoming speed reference signal to a motor speed feedback signal. If the feedback signal indicates that the motor speed is low, the speed regulator increases power to the motor to accelerate it to the speed set point. If the feedback signal indicates that the motor speed is too high, the speed regulator will reduce power to the motor to decelerate it to the speed set point.

There are *common problems that occur at startup* that can be corrected by establishing a disciplined startup and checkout process. Most wiring is checked and verified by the construction technicians before power is turned on, so problems are kept to a minimum. However, an occasional error can occur. During startup and checkout, operate only one section at a time. This will eliminate many problems that can occur when many tachometer cables enter a drive cabinet. Some tachometer cables are not connected or may be connected to the wrong section. Keep in mind how a speed regulator functions to match feedback and reference levels. If there is a difference (error) between the speed reference (set point) and the speed feedback (process signal), the speed regulator will adjust the power to the motor so that the reference and feedback are matched.

1. Frequently, the wiring for the tachometers is not connected to the drive controller. When the drive controller tries to match speed reference and speed feedback, the drive speed controller sees no speed feedback signal from the disconnected wiring. The drive speed controller treats this condition as a signal loss that indicates that the feedback signal is too low. The speed regulator continues to increase the power to the motor in an attempt to match the two signals. The signals cannot be matched if the tachometer is not connected to the speed regulator. Therefore the speed regulator eventually increases power until the section is running at maximum speed. The section will continue to run at maximum speed until the section is stopped and the problem is corrected. This “runaway” condition can cause web breaks, web slip, or major machine damage. One way to avoid this problem during startup is to use a meter to manually check the wiring at the terminal board so as to confirm that the correct tachometer is connected to the speed controller. Slowly rotate the motor by hand and measure the voltage at the terminals of the speed regulator. Observe if the meter deflects and ensure that the polarity of the tachometer signal is correct. If the section is too difficult to rotate by hand, run the drive at slow speed and determine that the tachometer is connected to the correct speed regulator and that the tachometer voltage is the correct polarity.

2. Tachometer wiring is connected with the incorrect polarity. The results will be identical to the condition where the tachometer is not connected at all. The section will accelerate to maximum speed. Check the tachometer voltage level and polarity at the speed regulator to identify this problem.

3. Tachometer wiring is run in a common wiring raceway. It is a common problem to incorrectly intermix tachometer wiring from adjacent sections. Tachometer #1 may be connected to motor #2 and tachometer #2 may be connected to motor #1. The result is that both sections will seem to have defective tachometers. Here again, the section will accelerate to a maximum speed and stay there until the problem is corrected. This problem can be exposed by running only one section at a time. Let us assume that tachometer #2 is connected to motor #1. When motor #1 is run by itself, tachometer #2 will be stationary. No tachometer voltage will be present at the speed regulator and the section will accelerate to maximum speed. Shut the drive off and have the electricians verify the accuracy of all wiring. Once an error is found in the wiring, it is common to commit the same error on all sections. This error also occurs when the sections on a machine are assigned names by the machinery *builder* that differ from the names assigned by the drive *vendor*. Section names become even more cloudy if the machine *user* becomes involved in naming equipment while the machine is being installed. For instance, a coating roll may be called a coater roll or the #2 pinch roll. Pull rolls may be called draw rolls, capstans, nip rolls, vacuum rolls, or vacuum tables. In the absence of a clearly defined name for a section, an electrician may arbitrarily assign a name. The electrician has usually won the opportunity to wire a machine on the basis of his submission of the lowest bid. His profit will be reduced or may disappear if he attempts to clarify questions of nomenclature. He will work to ensure the maximization of his profit. He does not gain profit by taking the time to clear up questions. As a matter of fact, if the mistake can be blamed on poor documentation on the part of the client, the electrician will be paid for corrective work efforts. Such work is frequently corrected on an overtime basis because it occurs when a full operating crew is assembled and waiting to apply coating. The contractor will be paid if incorrect nomenclature results in the need to rewire some equipment. Rework is one way contractors have to recover profit from a very competitive bid.

4. Infrequently, a tachometer will have a problem with its signal output. We have seen cases where a tachometer has failed totally. When the speed controller tries to match the speed reference with the speed feedback, the defective tachometer output is zero volts. The speed controller will cause the section to accelerate to maximum speed just as though the tachometer was not wired to the speed controller at all. The tachometer must be replaced. The problem can be identified by measuring the tachometer output while the section is at full speed. A zero or very low reading will indicate a defective tachometer. Problems of this type can occur due to poorly seated brushes on the tachometer or failed windings. Replacement of the brushes and seating them properly may solve the problem. If it does not, replace the tachometer.

5. Occasionally, a tachometer will have an intermittent problem. One winding may be defective, which will cause the tachometer speed feedback signal to *decrease* once per revolution. The decrease will be of a definite period and amplitude. The decrease in voltage will indicate that the speed of the tachometer is low. The speed controller will compare the speed reference to the varying speed feedback and will see a decrease in signal level once every tachometer revolution. In effect, the tachometer is indicating a speed variation where no variation exists. The speed controller will try to correct for the once-per-revolution variation and will increase power to the drive motor for each speed feedback perturbation. When power increases to the motor, it accelerates to a higher speed. When the motor accelerates, the perturbation passes and the tachometer is now running at too high a speed. The voltage level of the tachometer is too high and the speed controller reduces power to the motor, which slows down. The speed controller is causing section

speed to “surge.” Surging can cause web breaks, web slippage, or machine damage (if the web is strong enough).

Consider the RPM of a 3-foot circumference coating roll running at 180 FPM. The roll will run at 60 rpm or 1 rev/s. Consider the ability of modern speed controllers that correct for step changes in speed within 1/2 second (or faster for servo type drives). Such a controller can cause rapid cyclical changes of power that can cause major damage to the power transmission equipment as the controller tries to correct for intermittent speed *feedback* variations that incorrectly indicate section speed variations.

6. Digital encoders or digital tachometers can have the same difficulties as the standard tachometers. Wiring can be misdirected and digital feedback devices can also be damaged. If an interface card is used to convert the digital pulse train to an analog signal, the card output can fail or contain enough ripple to cause the speed controller to make the section surge. Digital speed feedback devices develop a certain number of pulses per revolution (PPR). Encoders commonly provide 60, 120, 300, or 600 PPR. If precise speed control is not required, 60 PPR is often used for pump and fan applications. Higher pulse rates are used where accuracies of 1% speed control are required over the operating speed range of a coating or laminating machine. It is the coordination of the speeds between adjacent sections that demands such precision.

Much higher PPR rates are available for positioning motor shafts or when product tolerances demand high accuracy. Such applications are incremental motion machinery or multicolor printing machinery, which require registration of a series of dies or print heads to a specific position on the traveling web. Such digital devices are rated in the thousands of PPR and carry a marker pulse to define the position of a shaft or the position of a spot on the web. These digital devices are frequently incorporated into web defect monitors that indicate the position of a defect in the roll and the length of the defect.

7. Speed errors can be generated by electrical noise. We previously mentioned seeing signal wires run parallel to motor power cables. When the motor is started, stopped, or jogged, the current that is carried in the power cables induces a voltage in the signal cable. The longer the parallel run, the worse the generated noise. Noise that is superimposed on an existing tachometer signal will cause an intermittent jump in signal voltage. The speed controller will respond to the “noise” and will momentarily change the speed of the drive motor. The result can be a web break or worse. We have seen an operator jog the machine. That jogging action placed noise on the feedback tachometer of the coater. We saw momentary and intermittent changes in coater roll speed as well as intermittent changes in coating flow to the coating applicator. The solution to the problem was to separate the signal wiring from the power wiring. The problem was identified by monitoring motor loads and feedback signals with a multichannel oscillograph. Once the frequency and amplitude of the noise were related to the jogging of the winder, the solution was obvious.

Equipment Lists Avoid Problems and Help Plant Personnel

Misnaming the sections at any time creates a nuisance and extends the startup effort into costly late night problem-solving sessions. Misnaming can be avoided if the machinery purchaser, the engineering consultant, the machinery builder, the drive manufacturer, and peripheral equipment manufacturers preassign a name to each section and to each piece of equipment during the early stages of the project. It is the user who must name the

equipment in accordance with the user’s standard production department nomenclature. A knowledgeable user representative should be present during construction to quickly answer questions concerning equipment identification and location. It is common to supply an equipment list that identifies each motor, fan, pump, machine section, drive cabinet, load cell, dancer roll transducer, and instrument.

Each equipment list identifies the equipment as to selected name, commercial name, and catalog number, its location in the building, and special features. This list is used by plant maintenance personnel to quickly identify standard components, such as drive belts, pulleys, and bearings when maintenance or replacement is required.

Frequency and Direction of a Speed Perturbation

This section is a condensation of a paper titled “Solving Problems of Automatic Control Drive Systems”, by Boyce Tharpe (2004), a retired senior drive service engineer, who describes how to identify the source of a disturbance by identifying signature patterns of operating load and speed. Certain patterns will identify problems of the driven section or of the drive system. This paper is presented as part of the TAPPI Paper Machine Drives Short Course. TAPPI is located at Technology Park, Atlanta, Georgia.

Review again in your mind how a speed controller functions. A speed reference is compared to a speed feedback. The difference between the two signals (called error) is used to correct the speed of the driven section.

In order to determine what the problem is with a varying speed condition, we must record a number of section parameters. We must record section speed feedback, section motor load (or motor current), and section speed reference. These signals will help us establish if disturbances are random or cyclical. Random disturbances may be the noise generated by a motor being jogged. Cyclical disturbances may be generated by a defective bearing or a roll that is unbalanced. If we record the speed reference, the motor load, and the speed feedback, we will have valuable data. The data can be used to determine what the problem is.

When a tachometer is defective, it is helpful to use a second speed indicating source, similar to a digital speed and draw indicating system, to confirm if the information from the feedback tachometer is accurate. A defective tachometer output may show a momentary loss in section speed when no such speed change exists. That defective output will cause the section to speed up. The independent tachometer will show that the section is truly speeding up due to the defective tachometer.

We should also examine the data to see if the speed changes produce motor load changes that are in the same direction or the opposite direction. For instance, is a random speed increase accompanied by an increase in motor load? If that is so, it is what one would expect if something were changing within the drive controller or in the master reference signal. This points to an electrical malfunction within the drive reference circuit. Defects can be in the components that make up the reference network, from signal noise in the reference circuit, or from defects in the controller itself. Is a speed increase accompanied by a decrease in motor load? This phenomenon may be explained by a defect in the feedback circuit. Is the tachometer voltage changing? We expect that a random loss of tachometer feedback will result in a random increase in motor current if the speed controller is to maintain speed at the set point level. Recording data in any controller network will yield information that allows one to analyze problems. But the data is meaningless unless you understand what can cause the changes that are on the recording

oscilloscope chart. An understanding of what each signal level does will help you identify a cause-and-effect relationship.

Problems that Occur After the Machine Is in Production

All connections on an electrical drive are checked to ensure a tight electrical connection. The connections are checked during a normal summer shutdown when the drive cabinets are vacuumed and cleaned. During one such cleanup, an apprentice electrician was told to tighten every screw in the cabinet. The electrician dutifully tightened every screw in sight, including those marked "System Stability," "Maximum Speed," "Offset," and Bias." Without realizing it, the electrician had adjusted all major parameters of the twelve-section drive system. The startup following this preventive maintenance procedure was disastrous. The machine drive was unstable and out of synchronization. The machine had to be shut down and readjusted as though it were the initial startup.

Tachometers are rated to produce an output of 50 volts per 1000 rpm or 100 volts per 1000 rpm. The tachometers are identical in appearance and are designed to mount on the back of a motor. There have been cases where a 100 V/1000 rpm tachometer replaced a 50 V/1000 rpm tachometer. The result is that the 100 V/1000 rpm tachometer will generate twice as much feedback signal at any speed as the 50 V/1000 rpm tachometer. With *twice* the feedback, the section will run at *one-half the speed*.

1. Belts have been removed from equipment like fans, pumps, drive rolls, and tachometers.
2. Cables have been disconnected from load cells and dancer roll potentiometers.
3. Drive rolls and coating rolls are replaced with different diameter rolls than those in the machine during startup. If these rolls are driven, the drive speed must be recalibrated to allow synchronization of the new diameter roll with the adjacent sections.

TYPES OF TENSION CONTROL SYSTEMS

Three types of tension control are applied to drive control systems.

1. Motor current regulation (Figure 11-17)
2. Swing roll or dancer roll control (Figure 11-18)
3. Force transducer or load cell control (Figure 11-19)

Machine builders and drive manufacturers debate the merits of these methods. Some advocate using dancer rolls in all tension control locations, while others insist that force transducers are superior. All are excellent when used properly.

Current regulation is used wherever it is impossible to locate a dancer or load cell because of process conditions. In particular, this type of control is used where the web is still wet and cannot be touched, usually at the end of a dryer section.

Dancer rolls are frequently used at the unwind and rewind because these sections are most likely to cause a transient during a splice or transfer operation.

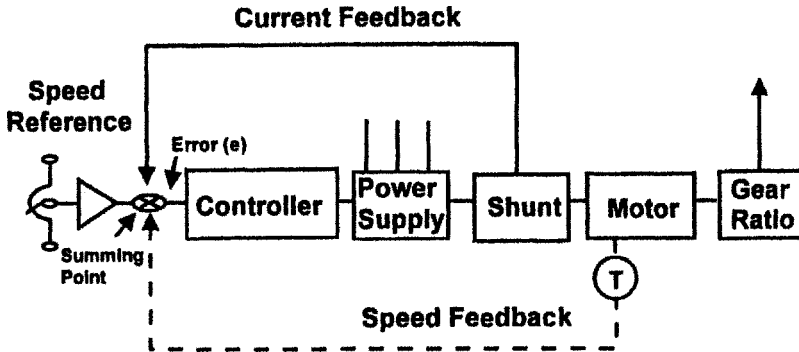


Figure 11-17. Block diagram of a speed regulator with current control. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

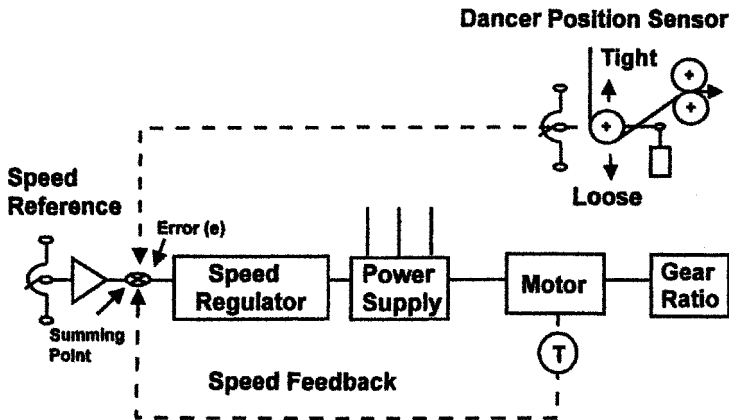


Figure 11-18. Block diagram of a speed regulator with dancer trim. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

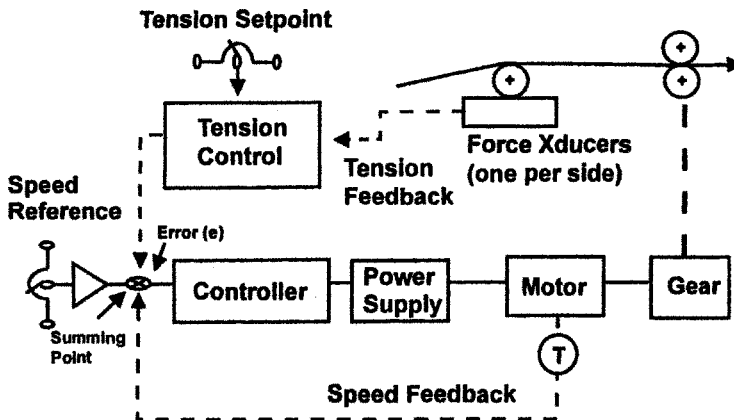


Figure 11-19. Block diagram of a speed regulator with force transducers and tension trim. From Kheboian (1992), Reprinted from *Modern Coating and Drying Technology*, E. D. Cohen and E. B. Guttoff, Eds, Wiley-VCH, New York, 1992, with permission of John Wiley & Sons, Inc.

Force transducers are used on the interior sections of the machine because they fit into the web path easily. However, the modern fast-response drive system has utilized force transducer tension control throughout the machine, including unwinds and rewinds.

Motor Current Regulation

Current regulation is simple, easily implemented, and effective. It may be the only way to control web tension if process conditions do not allow a tension sensor to touch the web. Current regulators are used on rewinds with great success and are used wherever a dancer roll or tension sensing roll cannot be designed into the web path.

A current regulator controls the current to a value as set by the operator. It uses total motor current to infer the amount of tension in the web. However, total motor current equates only approximately to actual tension. It is equal to tension load and the losses in the system, but a current regulator cannot differentiate between tension and losses. If load losses in the system are a small part of motor current, then a current regulator can effectively control web tension. If load losses are a large part of total motor current, a current regulator should be used only if no other method of tension control is possible.

Current regulators have no direct tension readout, do not provide storage, and cannot differentiate where the load comes from (frictional load that comes from bearings, rotary joints, tension, and cleaning doctors).

The current regulator must have compensation circuitry to supply added current during acceleration or when roll cleaning doctors are used on an intermittent basis.

The operator must check for tension losses due to defective bearings, cold oil or grease in reducers after a weekend shutdown, or changing friction from steam joints, and must adjust the current to establish tension at the desired level until the problem can be corrected. It is common to start up a machine with a higher current during a cold startup and then reduce the current as the machine warms up.

Dancer Roll Control

A dancer roll is a force balance system, where the force of the web pulling in one direction is balanced by the loading of the dancer pushing in the other direction. The dancer has the ability to store web to minimize the influence of transients due to acceleration, deceleration, unwind splices, or rewind flying transfers. A disadvantage is that the dancer roll does not have direct tension readout. Tension is derived by calculations that are converted into a family of tension versus air pressure curves.

Drive vendors ask machinery builders to design the dancer loop to store the equivalent of 1 second of web storage based on maximum line speed. That amount of storage is not always available (or needed), so compromises are made based on factors that depend on the web material and the rates of acceleration/deceleration.

The dancer control system also compensates for step changes in load due to doctor loading, nip closings, changes in coater blade loading, and higher than normal condensate loads in a dryer. It does this by sensing changes in tension and adjusting the section speed to reestablish tension to the set point value. Dancers also prevent tension changes from occurring when a driven roll is replaced with a similar roll of a slightly different diameter. The change in diameter will mean that the roll speed will be different, thus inducing a change in tension. The dancer will compensate for any reasonable change in driven roll diameter. When an elastomer roll becomes an ineffective drive section, the roll is replaced

or the defective cover is reground. In either case, the roll diameters will be slightly different. Normally, a technician synchronizes the drive for the new roll diameter. Rolls that are replaced in the middle of the night rarely are “synchronized.”

Dancer position is precisely monitored by the dancer roll position sensor. This system of sensing and control is sometimes called a position regulator.

The design of the dancer system must consider the types of materials that are used, the tension range, and the amount of storage required for good transient response.

Problems with dancers occur when the designers of the system forget the minimum values of operating tension. Cylinders that load the dancers must be friction-free or at least have a friction that has a residual torque that is significantly less than the torque that is required by the lightest operating tension.

If lightweight and extensible materials are run at low tensions, the dancer design must not allow the stretchy material to cause instability. In some cases, a free loop will be used at “zero” tension on low-tension applications. The new lightweight carbon materials are being used to construct lightweight dancer rolls. This further enhances the ability to achieve good low-tension performance. The lightweight, low-mass dancers require less force to move than the heavyweight dancers used on many machines.

We have seen dancers where the air cylinder friction prevented use of low operating tensions.

Designers have also forgotten to consider cylinder friction, the weight of the roll or the weight of the roll support arms when determining the size of the dancer loading cylinders. The resulting air pressure versus tension charts are inaccurate.

The dancer position sensor is frequently connected to the dancer via a spring-loaded cam-operated mechanism. This mechanism can stick and will provide faulty position information to the controller, causing poor tension control of that section. It is better to positively connect the dancer position sensor with a coupling or a link. The positive connection will ensure the reliable sensing of dancer roll position.

The dancer position sensor is connected to the dancer roll so that the sensor is centered at exactly the midpoint of dancer travel. Thus if the dancer roll has a total of 12 in. motion, the midpoint of the sensor will be set at 6 in. of travel (the midpoint of the dancer travel). If the operator wants the dancer to be offset from the midpoint, electrical adjustments are available to provide the desired offset.

Modern dancer roll control is combined with a speed regulator to provide a machine with a stable control system. The system uses a set point in the drive to establish desired speed. A tachometer feedback is compared to the set point and ensures that the drive is running at the desired speed. The operator adjusts the tension set point to establish the tension level of the web. That adjustment is usually a pneumatic pressure control that pressurizes the dancer roll-loading cylinder. The dancer roll will move to the midposition. The dancer position sensor will feed back position information, which will cause the drive to impart enough force into the web, which pulls in one direction, to balance the force of the cylinder that is pulling in the opposite direction. When the dancer is in the midposition, the system will be satisfied and tension will be at the set point level. If the dancer moves from the midpoint, a dancer position sensor will provide a signal that will cause the controller to adjust power to the motor so that the dancer roll will return to the midpoint. Typically, dancer control on draw rolls and other constant diameter sections will be set to trim motor speed $\pm 3\text{--}5\%$.

Dancer rolls for unwinds and rewinds must have enough compensation to control the drive from maximum roll diameter to core size. Modern dancer control of unwinds will sense, or calculate, unwinding roll diameter and use that information to adjust the speed of

the unwind drive as the unwinding roll gets smaller. The diameter information eliminates the need for the unwind dancer control to compensate for the full roll build-down, resulting in a much more stable unwind drive. The dancer roll signal is introduced to the unwind drive system as a $\pm 5\%$ trim control. The winder drive also uses a diameter-based system with $\pm 5\%$ trim, thus resulting in a much more stable winder drive.

Older dancer roll systems allowed the dancer to control the drive motor from 0% to 100% speed. This system was very difficult to stabilize under all operating conditions. Transients such as splices, transfers, acceleration, and deceleration would destabilize the dancer circuits, causing slippage, wrinkles, or web breaks. Machine sections would be bypassed because of these problems. We have had great success modifying old drives to modern standards by converting from 100% dancer control to speed control with dancer trim.

On the unwind or rewind, the introduction of diameter as part of the control strategy provides very stable tension control over a wide machine speed and tension range.

Example of the Use of a Dancer in Close Proximity to an Air Roll A dancer roll is a device that will store web when tension transients occur. An air roll also stores web when transients occur. An air roll is usually found in dryers where the web must change direction up to 180° . The air roll is a stationary device that supports the wet side of the web on an envelope of air. That envelope of air is supplied by an air-handling system that delivers air to the wet side of the web through slots that are machined in the face of the roll. Thus the web changes direction without ever touching the face of the air roll. A dancer roll and an air roll that are mounted close to one another are two web storage devices in close proximity. The two devices are destined to interact and become unstable. The dancer roll will be trying to control a drive whenever a transient occurs. The air roll will be trying to store web at the same time. Tension control will become unstable and may generate a web break.

Using Air Roll Air Gap Control as a Dancer in the Dryer Success has been achieved by eliminating the dancer roll and by using the air roll as a dancer. This is done by providing an air pressure sensor that measures the air pressure between the face of the air roll and wet side of the web. The operator may adjust the amount of tension by controlling the air gap between the air roll face and the web. A large gap between the air roll face and the web represents low tension and a small gap between air roll face and the back of the web represents high tension. Using air gap control also reduces concerns about contact of wet sheet with the dancer roll.

The following problems can occur after the machine has been in production.

1. The dancer roll control position has changed. The dancer pot has been replaced and has been improperly centered. A technician must use a meter to check the center position of the pot versus the center position of the dancer.
2. The dancer position has changed and the pot is centered properly with respect to the dancer midpoint. Someone may have adjusted the pot position to a perceived operating point without asking an operator to verify the position, or there may be a problem with the position amplifier. Center the pot with the existing adjustments or replace the position control amplifier.
3. The dancer roll goes against one stop when the line is run.
 - a. Check the position sensor to ensure that it is centered and is not defective.
 - b. Check to see if a drive roll was changed during a shutdown.

If a large diameter drive roll was replaced by a smaller diameter roll, the percent change in diameter may exceed the compensation capability of the dancer roll circuit. For example, let's say that we have a 6-in. shell covered with a 1-in. thick rubber cover. That equals an 8-in. roll. If we replace the 8-in. roll with an older roll whose cover has been ground a number of times, say, to 7-in. diameter, the change from 8-in. to 7-in. represents a difference of 12.5%. Most tension control systems will compensate for 3–5% or up to 10% maximum. Thus the diameter change will compromise our ability to control tension. If a smaller roll is replaced by a larger roll, the same problem can exist. The larger roll may require more compensation than the system can supply.

4. Dancer control is erratic and jerky. The dancer does not “float” with the web off the machine, but seems to stick in any position to which it is moved. Check the loading cylinders to see if friction or binding is occurring. Some cylinders have internal diaphragms that can twist and jam against the inner cylinder wall when air pressure is removed from the cylinder. When binding occurs, tension control is erratic. It is a good idea to design a loading circuit that keeps air pressure in this type of cylinder at all times.

Other pneumatic cylinders have metal scrapers where the piston rod exits the cylinder. The scraper may be binding. Remove the scraper. This same type of pneumatic cylinder may have high-friction chevron packings on the piston. The packings may have dried out and are binding. Replace the high-friction chevron packings with Teflon packings and have the interior barrel chrome plated to further reduce friction. One set of chevron packings can be eliminated to provide a cylinder with minimum friction and drag.

5. New lightweight products do not run well on the machine. The dancers are jerky at low-tension settings. There is a tendency for the web to get tight and then loose between distant drive sections. This points to a dancer system where there is too much friction in the loading system or the cylinders are so large that the cylinders are operating at pressures less than 10 psi. Low air pressures can result in “sticky” cylinders and erratic operation. Also, there may be a conflict between how much force is required to move the web and how much is required for the process. Thinner webs may require low tensions for the process but may require high tensions to motivate web between distant drive points. What may be required is an additional drive point within the machine or a drive that motivates all idler rolls between sections. We have seen cases where there is so much friction in the idler rollers that the tension system “stalls” the web. In effect, the force in the web that comes from tension is less than the drag force due to the friction in the idler roll bearings. Add impingement dryers to this equation and you will find impressive loops of web forming between idler rolls. The tension in the web is less than the force generated by the velocity of the impingement air on the surface of the web. Once the web starts to hang between rolls, we have the added factor of web weight to deal with. Forces due to web weight may exceed the tension set point.

6. Operators complain that a new dancer doesn't develop enough tension to move heavyweight product through the machine. Tension can be developed on the night shift but not during the day. The web is a heavyweight material and is lifted about 40 feet into a dryer entry position. Check calculations for tension and cylinder sizing. Sometimes the weight of heavy webs is not included in the calculation of a loading cylinder. Wide and thick webs that are processed through towers, with long vertical runs between drive sections, are very heavy. Consider the weight of the web in the selection of the loading cylinder. The cylinder may need to develop enough force to move the weight of the web

and supply the tension required. Too often, only the tension component is considered in the selection of a tension control system.

The selection of the loading cylinder size may be marginal. It may be adequate at night when compressed air pressure increases. Air pressure increases at night because less machinery is in operation at night and the demands on the air compressor are reduced. The problem of adequate sizing of dancer rolls for tension systems is a very common occurrence.

Force Transducer Control

Force transducer tension control is more expensive electrically but not as expensive mechanically as the dancer roll system. Two force transducers are mounted on a roll that is in the web path. Transducer rolls can be fitted into an existing web path without difficulty. Their signals are summed and sent to the tension regulator that adjusts motor power output to satisfy the operator's tension set point. Unfortunately, some hydraulic and electronic load cells get out of calibration easily. Some types are subject to drift and should be selected carefully. It is important to be practical in the selection of tension range in order to size the transducers properly. The roll weight must be kept within acceptable limits of vendor recommended "signal-to-tare" ratios. If the roll is too heavy, it will be difficult to separate the signal from the force transducers into the two components: roll weight and tension forces. Force transducers cannot store web and thus cannot absorb transients.

The output of each cell can be displayed to show whether an unbalanced load is being applied by an imperfect web; for example, a cambered web may have a "soft" edge and a "hard" edge. Cambered web tracks through the machine tight on one side of the machine and loose on the other. The tight side exerts more force on its transducer than the loose side. Additional rolls may be supplied to fix the wrap angle of the web over the roll to ensure that the force being measured is always directly proportional to web tension. It is important to maximize the force vector that is measured due to web tension and to ensure the signal-to-tare ratio is compatible with the transducer manufacturer's specifications. It is also important to keep the wrap angle constant on tension sensing rolls located in a multiproduct machine where multiple threading paths exist. If the wrap angle is different for each web path, then the web tension feedback will be incorrect for all but one web path.

Because the force transducer measures web tension directly, it ignores many of the load losses that bother the current regulating system. However, rolls mounted on transducers must be balanced very precisely. Dynamic roll balance is especially important on rolls used as tension feedback devices for tension control systems.

Unbalanced tension sensing rolls falsely indicate a tension variation on each revolution when no variation exists. Adverse effects of tension roll unbalance can be reduced by using the viscous damping systems that are part of the force transducer product line.

Force transducers are now applied to all sections of the machine, from the unwind to the rewind. The fast response capability of modern drive systems make force transducers effective in applications that once required the storage capability of dancer rolls. The drive vendor, machinery builder, and user must integrate their efforts to ensure that the electromechanical design of the drive system maximizes the response capability of the modern drive system.

The user must ensure that the process can withstand the fast response times of modern drives. For example, softly wound jumbo rolls that are introduced to the machine may

telescope during acceleration or during the splicing cycle. Process demands will determine whether dancer rolls or force transducers are the control of choice.

For narrow webs, up to 12-in. wide, single-transducer designs are available. The sensing roll can be cantilevered or mounted directly on the load cell frame. The force transducer system performance can be optimized by selecting a realistic range of operating tensions. The force transducer produces a signal when a tension force is applied to it. The total deflection of the transducer is about 5 thousandths of an inch (0.005 in.) when the maximum rated force is applied to the cell. There is a tendency to specify a range of tensions that is wider than the actual operating tensions. If the actual operating tension is significantly lower than the rating of the cell, the cell will be operating with a very narrow range of deflection. The signal from the cell will need to be amplified to provide a usable signal, but any error or drift that is inherent in the system is also amplified. This drift tends to cause the web to become excessively tight or slack during a production run. We have recalibrated force transducers once a day in order to keep the web under control. We have found that temperature, cell design, and amplifier design all created significant drift problems when the transducer was too large for the application. If tension meters indicate tension when no web is on the machine, then it is time to recalibrate the tension system. Modern tension amplifiers have less of a tendency to drift than the older amplifiers.

Calibration of the system begins by setting the signal and meter reading to zero with no web on the sensing roll. It is wise to check the tension system calibration every week to see if drift is a problem. If drift is discovered, check the actual operating tensions versus the specified tensions. Record the signal from the force transducers and the amplifier. Determine if one or the other is drifting. If the cell output is constant and the output of the amplifier is wandering, then you have amplifier drift. If the force transducer output wanders with no web on the machine, then the force transducers are drifting. We have seen both components drift in the past. Ask the manufacturer of the force transducers and amplifiers if modern components have been redesigned to minimize drift. The vendor is in a position to tell you what has been done to minimize the problem.

We have also seen some load cells show a propensity to provide a signal offset on an intermittent basis after a transient occurred on the machine. These cells had a mechanical flaw that would cause the cell to bind and to show an offset in the signal output after a transient. If the operator leaned against the roll when threading the machine, an offset would appear. The offset exceeded the value of tension we were trying to control. The offset might disappear when the next transient occurred. The cells controlled a winder and affected the quality of the wound roll, causing softly wound rolls that would telescope. These cells were manufactured during the period that lasted from 1987 to 1990. We told the vendor what we were seeing and the vendor acknowledged the problem and advised that the cells had been redesigned. We replaced the load cells after we (1) reduced the size of the force transducers to reflect the actual tensions being run (we found that the actual operating tensions were less than specified and that the load cells were sized more for the weight of the roll than tension control); and (2) reduced the weight of the sensing roll so that the ratio of the roll weight to the tension force was more desirable (signal-to-tare ratio). Prior to the roll weight change, the force due to roll weight was 30 times the force due to web tension.

Force transducers are wired to the tension amplifier with a small gauge shielded cable. When this cable fractures, the signal will be intermittently connected and disconnected from the tension amplifier. Consider the separate case of an unwind that would suddenly increase

tension to a maximum level, causing web deformation or web breaks on a 17-mil thick aluminum foil. We discovered that the tension signal would suddenly drop to zero and then reappear. Tension went to maximum (15 PLI) and then dropped to zero. The problems were solved by replacing the cells and the wiring. Operation improved, but we noted that serious signal drift existed. The amplifiers were replaced and the drift problem was eliminated.

Sizing Strain Gauge Load Cells The size of strain gauge type load cells depends on the total force applied to the load cell. The total force consists of the tension load and the effect of the weight of the roll. Some vendors will take the tension force vector and double it to ensure that the cell will not be damaged by high-tension transients or by running tensions that are higher than specified. This practice may lead to the selection of cells whose rating dwarfs the force applied by operating tensions. If the user exaggerates the maximum operating tension and the strain gauge manufacturer doubles the exaggerated value, the load cell will be too large. In effect, we are weighing a rabbit on a scale designed to weigh an elephant. Here again, the signal available can be amplified. However, this will also amplify the offsets, drift, errors, and signal distortion from all sources. If an unbalanced sensing roll is bouncing on the force transducers, that signal will also be amplified.

Vendors are reluctant to tell you that you may be running into trouble with a wide ranging tension specification. They are afraid to lose the job to their competition. The message is that you should know your process and the process operating conditions, and work with the vendor to select the best components for your operation. *Note:* If a wide tension range is needed for a multiproduct machine, the load cell vendor may recommend two tension rollers to satisfy the total range. One will be used for higher tensions and one for lower tensions.

SECTION CHARACTERISTICS THAT ENSURE GOOD WEB TRANSPORT CONTROL

Master or Lead Section

The master section on any process line will set the speed of the web through the machine. It does so by having such a positive grip on the web that it moves 1 foot of web for every foot of roll surface travel. If the grip is broken, the section loses its ability to control web velocity and the web will slip past the section. If the master section is the capstan after the unwind, it will draw 1 foot of web from the unwind and deliver 1 foot of web to the following section. Sections that positively control the web are:

- The unwind or rewind (surface or center driven reel)
- A nip section (if the nip is closed)
- A calender stack
- A blade coater
- Impregnating coaters

We should qualify some of these comments by saying that blade coaters or nipped draw rolls seem to slip at speeds above 3500 FPM. Short dwell blade coaters seem less able to control web transport than blade coaters that have high web wrap angles on the coating drum.

Nipped sections, calenders, blade coaters, and surface-wound reels have been used as master sections because of their ability to control web transport. In cases where a blade coater slipped at high speeds, the master function was shifted to other sections. A good lead section must maintain its grip on the web at all speeds up to the maximum design speed even when subjected to transients during acceleration, deceleration, or at any stable speed. The lead section must be capable of adding torque (motoring) or holding back torque (regenerating) to the web in order to control web speed.

Using Load Cell Control in Close Proximity to an Air Roll As is the case with using dancer rolls close to an air roll, using a load cell control near an air roll can only result in unstable operation. The storage capability of the air roll interferes with the attempts of the load cells to control web tension. Here again, use air roll gap control as a tension control system.

Using load cell control on large vertical runs in a dryer requires special attention. Like the dancer roll system, we must account for the weight of the web as well as the amount of tension that must be run. If the load cell is used to provide tension information and an air gap is used to control the drive section, that will provide the operator with the best combination of control and information. Be sure that the weight of the product added to the weight of the sensing roller does not result in selecting a force transducer that is oversized. The actual signal from tension control may be dwarfed by the signal from web weight and roll unbalance.

Defects that Occur When the Master Section Slips If the master section is unable to control web velocity and the web slips, then defects such as a thick or thin coating, over-drying or underdrying, web scratches, coating scratches, and poorly wound rolls can be expected. Web breaks are common when web slip causes tension control systems to become unstable. Worse yet, it may be impossible to track the web as it slips through the machine longitudinally and laterally.

When slip exists, the machine may operate at lower speeds, but transients will cause the web to slip from side to side and eventually break. If slip is bad enough, it may not be possible to perform tasks as simple as threading a machine.

In summary, the master section in the machine must be able to transmit the torque from the motor, through the roll and into the web without letting the web slip. The total drive system for the master includes the drive motor, the drive shaft, the drive roll, and even the web itself. The drive for the section does not end at the motor shaft.

Sections with Limited Ability to Control Web Transport or Tension

A section that will control tension needs to have the same characteristic as the master or lead section. *It must not slip.* Some sections seem to perform well at slow speeds and then begin to slip as operating speeds increase. Slip begins to occur when the boundary layer of air that is carried along by the web begins to provide a pressure pad between the web and the driving surface. That pressure pad acts as a lubricant that causes the section to slip. Sections that tend to slip are:

1. Unnipped nip rolls and vacuum sections with small wrap or low vacuum.
2. Single elastomer rolls at higher speeds.
3. Controlled gap coaters (impregnating coaters, gate roll coaters).

4. An unfelted dryer section. (Dryers slip above 600 FPM. Tension control is needed for acceleration and deceleration.)
5. Felted dryers that run above 3000 FPM with only one drive. Dryer drives are now being reconfigured into two components: a felt drive and a dryer drive. As such, the total section load is measured and split between the two component drive sections. Load split is determined by the best operating results.
6. Unfelted single dryers that are backups for high-velocity impingement dryers.

Dealing with Sections that Have Limited Ability to Control Tension Sections with limited ability to control tension must be limited as to what they are asked to do and by defining their true operating parameters. Select a practical tension range for the machine. If all web is run at 1 PLI, a range of 0.5–2 PLI instead of 0.5–3 PLI may be more practical. Too large a range will have the following effects:

1. It will eliminate current regulators. (Current regulators can accommodate a limited range of current.)
2. It will eliminate force transducer control. (These may have marginal value as tension indicators; selection may be difficult if the transducer is to satisfy the highest and lowest tension and still provide adequate transducer overload capacity.)
3. It may compromise the ability of the dancer roll to handle the high end or low end of the tension range. Dual dancer loading systems are used to provide a high and low range of tension. These systems have met with mixed success and mixed enthusiasm at the mill level.

Generally, tension control specifications call for a tension control system to provide $\pm 10\%$ tension trim, separately adjustable, for each section. Ten percent tension trim may cause sections to become unstable and lose control of the web. Experience in the paper industry and some converting plants indicates that the values of trim that are listed below are adequate for machines whose speed differential from the unwind to the windup is less than 1 FPM.

Draw rolls	3–5% usually
Blade coaters	3–5%
Single unfelted dryers	0.5–1%
Unfelted dryer nests	1–3%
Felted dryer nests	1–3%
Long impingement dryers run at low tensions	5% up to 25%
Calender	1–5%

Tension trim values must exceed any drift that exists in an analog system. If the drift of the drive system exceeds the tension trim, tension control will be unpredictable. Typically, there is too much tension trim incorporated in the dryer tension regulator, and this causes web control problems during acceleration and deceleration.

At line speeds above 3500 FPM, it was common to see all sections slipping to some extent. The web tends to track poorly when this occurs, and the only tool that the operator has to correct tracking is to increase web tensions at the windup. Significant increases in windup tension can contribute to increased web breaks even as the increased tension improves web tracking. If all sections are slipping, the web is not being supported or

controlled by the interior sections of the machine. Only the windup and unwind have control of the web. That represents a long and unsupported draw condition. If unwind tension is normal (say, 2 PLI) and the rewind tension is increased to 10–15 PLI, one can expect the web to break away and accelerate to a speed that is limited only by the range of windup tension control. One can visualize this phenomenon if you consider that it takes almost no effort to keep a 1-ft span of rope in a taut condition. However, if the span of rope is 100 feet long, it takes significant effort to keep the rope taut.

Web transport improvements are seen as felt dryer drives are retrofitted with the modern dryer drive concept, that is, a felt drive and a dryer drive.

On machines where dryer drives have been provided with the modern dryer/felt drive combination, windup tensions have been decreased to predictable values. Modern dryer drives become an effective master section within the machine that sets sheet speed and allows adjacent sections to perform properly. When sections within the machine control the web, web tracking and web control become reliable.

If single elastomer rolls slip, then vacuum rolls or vacuum tables are being used as replacements.

It is important that large inertia sections like dryers and calenders be limited as to how much tension trim will be provided by the tension control system. If these large sections break away and slip, it is questionable if the tension system will be able to limit the transient that will occur when the section stops slipping. We have seen dryer sections slipping at 10% above line speed during a deceleration period. Web breaks occurred when the sheet adhered to the dryer surface as the machine decelerated to 500 FPM.

Sections that Always Slip or Almost Always Slip There are times when simply reducing the range of tension trim is not enough to allow a tension controlled section with marginal tension control capabilities to regain control of the web.

If the section always slips, try using only speed control to control the section. If the section is speed controlled, it will always be close to web speed and will not scratch the web even if a slight difference in speed exists. If the section does not always slip but breaks away easily, we can revise the controller to be less precise.

All modern controllers use operational amplifiers as the heart of the control system. These amplifiers are more precise than the old proportional amplifiers, but the integrating attribute of the amplifiers may never allow marginal sections to perform properly. There is success when tension controllers are converted from integral to proportional control for the control of machine sections with limited ability to contribute to good web transport.

The softer characteristic of the proportional controller together with the tension trim limit has allowed sections with marginal tension control capabilities to control tension. For high-speed coating lines, the combination of proportional control with tension trim limit may be particularly effective for the older dryer drum drives (dryers that do not have a separate felt drive). On any line where nipped rolls such as coaters and pull rolls tend to break away easily, the combination of proportional control and tension trim limit may provide stable performance to a machine that cannot otherwise support the demands that an integrating controller places on it. Proportional control and tension trim limit may be the control of choice when operating personnel do not have an active system for inspecting the covers of elastomer rolls and for correcting for the reduction in coefficient of friction that normally occurs with time, temperature, or abrasion. The goal is to have a machine that runs consistently, and if a machine performs better with the less precise proportional system than it does with integral control, use the proportional control.

DRIVE FEATURES THAT GIVE THE OPERATOR ADDITIONAL TOOLS

Jog forward and jog reverse capability at each section helps the operator when the web is hand threaded through the machine. Jog forward and jog reverse on a centerwind allows the operator to easily peel off defective web and to obtain a sample of web from each roll for a routine quality check.

Ammeters and tension meters help the operator to determine whether the machine tensions are balanced and if operating section loads are normal. High section loads may indicate an impending failure in the system.

Ammeters and tension meters will also show the frequency and direction of any tension changes and load changes. This helps the operating staff to determine where a problem exists.

Have available an independent speed monitoring system that can be used to check the performance of a drive when its own system components are defective.

Use a handheld tachometer for rapid checks of section speeds when problems occur.

Tools that Are Used for Troubleshooting Drive Problems

1. *Multichannel Oscillograph.* A six-channel recorder is a popular device that allows the technician to view speed, tension, and load data while trying to determine the source of a problem. It is especially valuable during the initial drive system startup. It simplifies synchronization of the drives during acceleration and deceleration to and from process speeds.
2. *Digital Multimeter and Analog Multimeter.* These are to be used for the preliminary troubleshooting effort. They allow the technician to look at speed, tension, and controller parameters quickly.
3. *Oscilloscope.* This is used to look at digital data to determine whether the digital systems are operating properly.
4. *Digital-to-Analog Converters.* These are permanently installed and allow the technician to record speed data from digital speed feedback devices.

Optical Alignment Tooling and Laser Technology

Machine Alignment: Avoiding Many Web Handling Problems Precision machine alignment is important to the process of transporting web through a machine if we are to avoid the introduction of coating defects, wrinkles, creases, and mistracking. Modern optical equipment uses optical tooling and laser technology to ensure that machines are installed and maintained in alignment. The alignment process eliminates installation flaws that create uneven web stress.

What does a good installation do?

1. A good installation ensures that each section is installed on the machine centerline so that no lateral offset exists between sections. Such offset introduces uneven stress that will result in wrinkles, creases, and mistracking.
2. A good installation ensures that each section is installed level with adjacent sections.
3. A good installation ensures that every section is square with adjacent sections.

Frequently, sections such as impingement or flotation dryers are mounted on stilts above the unwind, coaters, and rewind. The dryer sections often have been located offset or skewed from the lower sections. Offset or skewing causes web distortion as it travels from the coater up to the dryer *entry*, resulting in web handling problems. In addition, the web is distorted as it travels from the dryer *exit* back down to the winder. Distortion causes wrinkles that must be removed before the web can be wound wrinkle-free, at the winder.

Experience: Dryers Installed with the Dryer Centerline Skewed from the Machine Centerline A poorly aligned dryer made web tracking so difficult that the operators removed suction drive rolls, suction tables, and nip rolls from the machine to prevent web breaks that occurred when the web wrinkled and creased in the dryers and then cracked in the nip sections.

Cocking rollers were added throughout the machine to force the web to track properly. Rewind tension was raised far above normal industry standards (five to six times) in order to keep the web from running off to one side of the machine. The increased tension at the rewind was so high that the web speed accelerated to something above the operating speed set point. Web slip occurred because no nips or suction rolls existed to anchor the web and to isolate the rewind from the unwind section. Web speed was not well controlled. The increased web tension caused wrinkles to appear on the winder. A bowed roller was installed at the winder to reduce wrinkling before the web was transferred to a taped core. *Note:* Within one year, we found three identical machines in three different coating plants that had identical problems because the dryers were not installed properly.

A precisely installed machine can limit the amount of web distortion and will allow nips or suction drive sections to help transport the web and they will act as an anchor that prevents lateral drift of the web. Nips (and suction draw sections) provide lateral stability and tension isolation to the web so that a more balanced tension profile can be run throughout the coater. Without nips, it is the ingenuity of the operators that keeps the machine operating. Does the machine absolutely require nips? No! But the machine does require some type of S-wrap or suction roll that will provide isolation and will discourage lateral movement of the web.

Changes in web characteristics (frictional and static characteristics) can cause tracking problems until the cause of the problem is identified. Changes in operating personnel during vacation periods can expose machine runnability issues until the experienced operators return to work or when the new operators identify the machine “operating personality.”

Note: One additional problem can exist on a centerwind, when a skewed dryer is run at very high tensions. The extremely high tensions result in uneven forces on the centerwinder’s arms. Those uneven forces can cause the winder frame to twist, thus causing further misalignment. Transverse wrinkles can become evident. The centerwinder must be reinforced if wrinkling is to be prevented. Ideally, the dryer will be realigned, but that has not happened in any of three cases mentioned above. The preference has been to accept the misalignment and to use quick and easy repairs to maintain machine production.

Alignment Problems Due to Building Location in a Swamp or Tidal River New coating plants can be built on sites that are less than ideal. Some plants have been situated in swampland or in a tidal river. The result was that the coater building distorted as the water table changed. The alignment of the machines was seriously affected as the building distorted. Structural changes were made to the buildings to stabilize machine conditions, but the machinery required constant attention to stay in alignment.

There are many national companies who specialize in precision alignment of large machinery. Precision Plant Services, OASIS, Optimation Technology, and Alignment Services of America are a few. In addition to these companies, many consulting engineering firms and millwright service companies provide optical alignment services as part of their service portfolio.

The Alignment Process The following paragraphs are a condensed version of a training guide *Improved Machine Performance Through Optical Alignment*, by Christopher K. Thomas (2005) of Precision Plant Services Inc., Roswell, Georgia, with permission of the author. The guide describes the alignment process of a paper-making machine, including a size press (a roll coater that is used to apply precoating to the web prior to its shipment to a converting plant or to an in-plant coating machine). These paragraphs introduce us to the tooling and terminology of an optical alignment system. The term “component” refers to a machine section or rollers on the machine.

Optical tooling refers to the instruments used in optical alignment. To inspect a component's *vertical alignment*, or *level condition*, a sight level is used. This instrument compares the distance from the tending and drive sides of the component to a level plane seen through the sight level. The difference between these distances is the level condition of the inspected component. For the inspection of the *horizontal alignment*, or *parallel condition*, the theodolite is used. This instrument compares the distance from the tending and drive sides of the component to a vertical plane seen through the theodolite. The difference between these distances is the parallel condition of the inspected component. The theodolite requires the use of a reference datum. Most often this datum is a *machine baseline* or *reference line*. When compiled, the data from the scribe lines, sole plates, and dryer faces often portray sweeping curves either toward or away from the machine. These curves are a result of the settling and shifting of the machine. A straight line is then deduced from these curves and is selected to represent the machine centerline.

With accurately calibrated instruments used by properly trained technicians, the alignment condition of a component can be measured, in both the vertical and horizontal directions, to within 0.001 in. or 0.025 mm. The abilities of optical alignment are wide ranged. The role most often filled by optical alignment is that of diagnostics or troubleshooting. The cause of a recently evident or even chronic difficulty, involving either production or maintenance, is commonly related to improper alignment. One area of limitation for optical alignment is drive train alignment. While a gearbox and/or motor may be aligned using standard optical methods, a more suitable method of alignment in this instance is laser alignment. However, while laser alignment is designed solely for this purpose, standard optical alignment can successfully fulfill this role when necessary.

Simply put, optical alignment is a tool and, as with any tool, knowing when to use the correct tool for the job is a key factor in obtaining the best results from its use. *Optical alignment is best used to fulfill the three major roles of documentation, diagnostics, and maintenance.* Documenting the alignment condition of a machine provides an overview of the machine. The tendencies of the machine's settlement and shifting are also shown through periodic documentation. Furthermore, machine alignment documentation provides data from which to make informed decisions. As a *diagnostic tool*, optical alignment can isolate and detect the cause of most production problems, as well as provide the required actions needed to correct the problems. Baggy edges, uneven coating depositions, profile inconsistencies, excessive shell wear on nip rolls, poor felt, wire or sheet tracking, inefficient water removal, poor drying, poor web transfer between

sections, wrinkles, web breaks, and marking of the sheet, such as barring, can all be attributed to misalignment. Through the proper use of optical alignment, the source of these problems, which have a direct effect on production totals as well as product quality, can be detected and removed. Optical alignment is also a very useful tool for *maintenance personnel*. When a component is replaced, relocated, or otherwise moved, the alignment condition becomes unknown. Without properly realigning the component, machine performance may be inadvertently affected in a detrimental fashion. The use of PI tapes and spirit levels is not an adequate replacement for optical alignment. It is true that these devices are used with some success, but problems can accumulate over time, unless a periodic optical alignment is used to confirm the horizontal and vertical alignment condition of the overall machine.

The Baseline The machine baseline or reference line is a series of monuments, a minimum of 3, normally installed in the tending side aisle of the machine (Figure 11-20). The baseline is simply a reference line that is parallel to the overall machine centerline. Without this common reference, accurate comparisons of the parallel conditions of all the machine components is not possible. If a baseline is already present for a machine, this line should be verified every twelve months. The need for annual verification arises from the settlement and shifting that notoriously accompanies machines. This movement

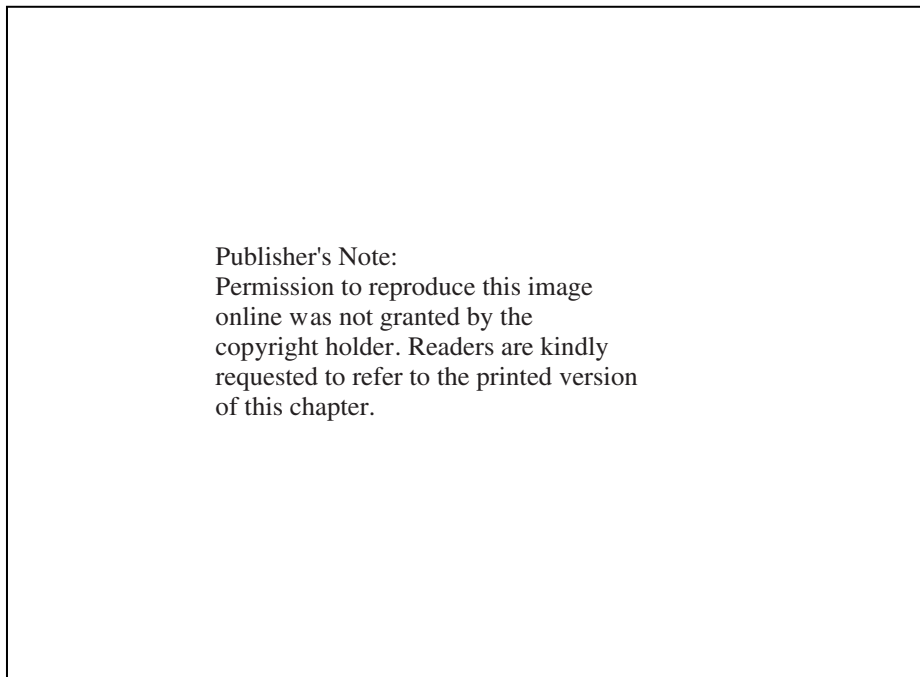


Figure 11-20. Reference line installation and/or verification. From C. K. Thomas (2005), *Improved Machine Performance Through Optical Alignment*, an internal training guide of Precision Plant Services with permission of the author.

will cause the baseline to shift, resulting in a baseline that is neither straight nor continuous over its entire length. Furthermore, the baseline will most likely not remain parallel with the machine centerline. The use of a segmented baseline will result in false data and misalignment. Establishing a baseline and verifying a baseline are extremely similar.

When possible, master scribe lines (lines inscribed during installation on the tending side machine track sole plates) are used. The distance from these scribe lines to the existing baseline is measured and evaluated for straightness. If establishing a baseline rather than verifying one, a temporary line is established from this data. If master scribe lines cannot be located, the machined edge, normally the inside edge of the sole plates in conjunction with the general tendency of the dryer roller faces, can be used to establish or verify a baseline. When compiled, the data from the scribe lines, sole plates, and dryer faces often portray sweeping curves either toward or away from the machine. These curves are a result of the previously mentioned settlement and subsequent shifting of the machine. A straight line is then deduced from these curves and is selected to represent the machine centerline.

Checking the Alignment of a Size Press (Roll Coater) on a Paper Web An alignment inspection of the size press should include, in addition to the fixed and nip rolls, the lead-in and lead-out rolls (Figure 11-21). Furthermore, the last three dryers immediately upstream and the first three dryers immediately downstream from the size press should be included in the inspection. The inclusion of these dryers will provide data concerning the sheet transfer

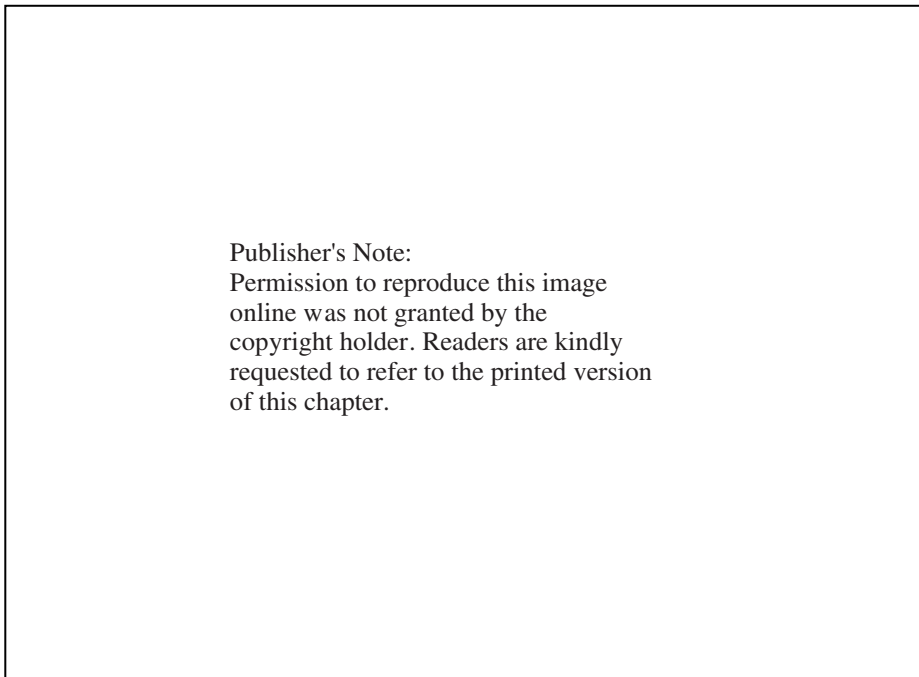


Figure 11-21. Typical size press configuration and components. From C. K. Thomas (2005), *Improved Machine Performance Through Optical Alignment*, an internal training guide of Precision Plant Services with permission of the author.

into and out of the size press. The fixed roll of the size press should be inspected for level and parallel. The nip or pivot roll can then be moved into the closed or operating position and inspected for a “scissor” condition. If misalignment is found between the fixed and nip rolls, the pivot points of the nip rolls should be inspected. If the pivot roll requires adjustment, it should be made at the pivot points. If the fixed roll is in need of alignment, a “step” key may be necessary. Misalignment between the fixed and nip rolls of the size press results in uneven starch (coating) application and premature roll cover deterioration.

An integral part of a size press (coater) inspection is the alignment condition of the rolls. Because the sheet is rewetted in the flooded nip, the sheet is extremely susceptible to wrinkling, wet breaks, and baggy edges. Therefore the alignments of the lead-in and lead-out rolls play a key role in producing a quality product. *This is true whether the web is a paper, textile, film, or foil.*

The rolls should be level and square to the baseline. However, if the fixed roll is misaligned in relation to the baseline or to true level, the rolls should be aligned relative to the fixed roll. If the alignment of the dryers does not match the condition of the fixed roll, it may be necessary to provide a transition into and out of the size press. This procedure is not advised and is not recommended unless no other alternative is available. The size press is a poor location at which to place a transition due to the previously mentioned susceptibility of the rewetted web to wrinkle and break.

Optical alignment is a tool that, if used correctly, can isolate and correct a great number of runnability problems experienced by machine production and maintenance personnel. Often, the results of problems are easily seen. Optical alignment is a time-proven method by which to detect and alleviate the causes of many of the problems described in this chapter, not simply hide the symptoms. Moreover, if used on a regular basis, optical alignment can prevent many of the aforementioned problems by assuring the alignment of the components as they are replaced or relocated. Furthermore, proper alignment of machine components alleviates the unwarranted and excessive wear of items such as bearings, gears, and couplings, whose replacement can require costly downtime that is otherwise unneeded.

Knowing How Your Machine Operates Can Avoid Problems in the Future At one time, within any given coating plant, there was a tendency to buy equipment from a vendor who was most familiar with the plant operation. The vendor had supplied the existing machinery and may even have modified it. The vendor also had established good relations with the engineering, maintenance, and production personnel. The vendor had a good idea of what might be needed for any new capital projects. In effect, the vendor was a part of the mill operating team and became the favored supplier. Times have changed. Cost drives the purchase of new equipment.

Today, equipment is being purchased from vendors who do not have the intimate knowledge of a mill's operating needs. Indeed, the vendor may have minimum experience within the industry to define what is needed for your new capital projects. The new vendor may be a local entity rather than a nationally known company with expertise in coating industry needs. So, it is up to the mill operating personnel to define what is needed. *Know your machine!* If you cannot explain what you want to yourself, how will you ever explain what you want to a machinery builder, a drive vendor, or a contractor? We are seeing a disturbing trend for mills to order equipment from vendors with inadequate or incorrect specifications. That happens when those specifying the machinery have neither the knowledge nor the time to specify what is needed. Today's manufacturing organization is

running with reduced personnel. Each worker has multiple jobs and has little time to put project needs into a specification. A worker's primary responsibility is to maintain product output. Thus taking care of mechanical breakdowns or routine maintenance supercedes the writing of specifications. The specifications are written in fragments of time.

The result is that the equipment comes in without the attributes that are needed to satisfy a new process. The solution is either to create a partnership with a vendor or to seek outside help in determining what equipment is needed for the new process. Outside help can come from a consultant familiar with the industry and the new trends in the industry, and who has access to all plant disciplines. The consultant can then provide the time and expertise to help develop a specification for the approval of plant personnel. The specification will be as good as the efforts of the consultant and the inputs of plant personnel can make it.

SUMMARY

Good machine performance can be achieved only when the sheet coming to the coater is reasonably uniform and consistent and when the machine itself is aligned properly. A uniform web will result in fewer web breaks and more uniform coating and drying. Each mill must establish web specifications that yield the best finished product. Close attention must be paid to holes in the web, edge cracks, and machine splices. Experience has shown that machine efficiency is best where web specifications are realistic and are policed.

Experience has also shown that regular verification of machine alignment is beneficial to the process of transporting web.

This chapter discusses some fundamental ideas of web transport and some problems that exist within the machine. The operators and technicians must understand the needs of the machine so that they can contribute to the solution of problems when problems occur. Understanding begins by knowing the established operating conditions and techniques. Operators and technicians should be able to use devices such as ammeters, voltmeters, speed indicators, and/or a computer log to determine if the machine is operating properly. The computer can supply a shift log that outlines the product run, the speeds, temperatures, tensions, coating flow, downtime, web breaks, and running time. Improper readings should signal a need to investigate further with the use of recording oscillographs, optical tooling, and other instrumentation. Characterization and documentation of an existing machine's parameters is one way to determine when a process is performing properly or is in trouble. Ignoring the data supplied by operators' devices or computer log will only lead to frustration when a problem occurs.

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12

THE ROLE OF PROCESS SUPPORT EQUIPMENT

INTRODUCTION

A coating line consists of two basic categories of equipment. The first is the major process equipment, that is, coating solution applicators, coating stand, dryers, unwinder, rewinder, and web transport system. The second category is equipment that supports the major process equipment, that is, filters, pumps, surface treaters, mixers, process control instrumentation, and so on. This category also includes items that are not process equipment but are essential for the main equipment to function, such as quality control procedures and training, and defect measurement systems. Table 12-1 is a complete listing of the process support equipment categories and typical hardware for each category.

Often the defect troubleshooting procedure and reduction efforts are focused on the major process equipment such as the unwind, web transport, the coating applicator, and the dryer. As a result, the process support equipment is often ignored or given a low priority, even though it can have a significant impact on coater performance and may be a contributing factor to defect formation. Another consideration is that some important support equipment that could help reduce defects is often not installed. Therefore technical efforts to add this equipment when needed, and to improve the equipment when installed, can be a significant factor in eliminating and preventing defects and producing a high-quality, low-cost product. Technical efforts in this area can be very effective because the cost of the equipment is small compared to the cost of the coater and the savings can be significant. In addition, improvements in this area can rapidly be accomplished. A particular advantage of this approach is that improvements can be implemented proactively to improve quality by reducing defects and reducing dependence on reactive troubleshooting procedures. A program to prevent harm before a crisis occurs is far more preferable and efficient than repairing the damage after the crisis. The resources spent on a proactive approach can have excellent returns.

TABLE 12-1 Coater Support Equipment

Surface treatment	Support station	Process instrumentation
Flame	Precision applicator settings	Line speed/ web tension
Corona discharge	Vibration isolation	Dryer H&V control
Plasma	Rigidity	Dry point detection
Web cleaner	Cartridge	
Static control		
	On-line measurement	Contamination control
	Coating weight	dryer air filtration
	Defect detection	coater air filtration
	Viscosity	
Solution mixing	Coater room	Quality control
High shear	Temperature control	S.P.C.
Low shear	Relative humidity control	6-sigma
Cleaning equipment	Airflow	Test methods
Filtration	Particulate control	
Solution delivery	Coater rolls and bearings	Data management
Filtration	Roll surface	Computer data acquisition
Debubbling	Uniformity and balance	Statistical analysis
Pumping	Bearings and lubricant	Defect database
Temperature control		Remote access
Viscosity control	Personnel training	
In-line cleaning		
	Procedures	Roll storage
	Equipment	Environmental control
	Testing	Contamination control

Note: **General equipment categories** are in bold type; specific equipment examples are in regular type.

This chapter discusses how the effective use of support equipment can help reduce defects and improve product quality and productivity. The various types of support equipment are defined along with a discussion of the types of defects that each piece of equipment can influence. Specific defects will then be discussed with a focus on the role of the support equipment in preventing and eliminating them.

DEFINITIONS

The starting point for this discussion is to define the specific support equipment systems.

Equipment in general is defined as the items that are needed for the performance of a task or are useful in effecting an end. Using this definition, the potential support systems are not limited to hardware and can include training procedures, quality control systems, and test instruments. Therefore the support equipment to be discussed in this chapter is the equipment and ancillary subsystems that are needed to sustain the effective operation of the major coater elements, the roll unwind, coating applicator, dryer, roll windup, and web tracking.

Surface treatment systems are used to apply a variety of treatments to the substrate. They are typically applied before the coating station, either in the web coating line before the coating applicator or off-line. There are several functions that can be affected by surface treatment systems, such as wettability, adhesion, web cleaning, and static susceptibility.

To improve substrate wettability and adhesion, there are three basic processes: flame, electrical discharge or corona, and plasma treatments. The basic function of these techniques is to increase the surface tension of the support (sometimes called the dyne level as surface tension is measured in dyne/cm) and its uniformity on the substrate, thereby improving adhesion and wettability, and thus coating quality and uniformity. These techniques can affect the chemical nature of the surface by oxidation or reduction, and functional groups can be deposited on the surface. The roughness of the surface can be affected, and some cleaning of the surface can be accomplished. It is also believed that the adhesion is increased by the removal or cross-linking of a weak boundary layer on the surface.

Web cleaning is another surface treatment system and it is used to remove contaminants. A wide variety of both contact and noncontact systems are available and in use. The preferred situation is for the substrate to be manufactured free of contamination. However, the subsequent handling, storage, and unwinding can introduce contaminants. The web cleaning systems can mitigate the effect of these contaminants. Although few are happy with their web cleaning systems, it is important to have them.

Static control systems are used to reduce the static charges on the substrate. These charges can attract contaminants that will lead to defects, and nonuniform charges can cause defects. There are two types of static control system. To neutralize or remove free or surface charges, one can blow ionized air on the substrate or use grounded static tinsel, static string, or preferably extremely fine stainless brushes to conduct free charges away. Internal or bound charges, due to aligned dipoles, can only be removed by charging the web to a uniform charge and then neutralizing this charge with an opposite charge (see Chapter 9).

Several types of equipment are used to prepare the solutions or dispersions that are to be coated. The final solutions must be uniform, stable, and contaminant-free. Mixing kettles with varying levels of shear are needed, depending on the characteristics of the solution. A simple solution of solids, binder, surfactant, and active ingredients that are dissolved in a solvent can be prepared with low shear rate equipment. If the solution contains particulate matter, then high-shear equipment is usually required. If a rapid acting cross-linking agent is used, then an in-line mixer before the applicator may be required. Appropriate procedures are needed because the ability to prepare a uniform stable dispersion may require a specific order of ingredient addition, shear rate, and mixing time. In addition, systems to clean the kettles and lines are needed. This is a critical step in the coating process because defective solutions or dispersions will not be approved for the subsequent process steps.

The solution delivery equipment moves the solutions from the mixing kettles to the coating applicator. Specific equipment is described in Chapter 4. Pumps must provide uniform flow without vibrations to the coating applicator. Filters to remove contaminants, temperature control systems, in-line viscosity measurements, and flow rate measurements are all used. Again, appropriate cleaning equipment is required.

The support station is the equipment on which the coating applicator rests. It performs several functions that are essential for good coating quality. It maintains the rigidity and stability of coating applicator during the entire coating campaign. It permits precise setting, measuring, and maintaining of the many coating applicator variables.

Equipment to characterize the important properties of the coating on-line is available and coming into widespread usage. It is no longer necessary to do some characterizations off-line. Rapid characterization leads to early problem detection and solution, and to a

reduction in waste product. On-line instruments to measure coating weight and defects are available.

General process instrumentation includes the instrumentation to control the dryer heating and ventilating equipment parameters, such as the temperature, solvent level in the air (humidity for aqueous systems), dry point, and air velocity. It also includes the equipment to control substrate speed, tension in the coater, and edge alignment. In addition, sensors to measure key variables that are not controlled are needed. A general comment about the instrumentation is that it must have the ability to control the process within the required range for quality products. If a web speed accuracy of 2% is needed and instrumentation can only measure and control to 5–10%, then the needed performance will not be possible. This applies to all control systems.

Contamination control equipment is also an essential part of the coating line and the building environment. High-efficiency particulate air (HEPA) filters are normally used. They allow a high volume of airflow, stop small particles larger than some predetermined size from passing through, and can be used to reduce contamination from the air onto the wet web. The building air should also be filtered to reduce contamination in the building and building equipment. Equipment to control the relative humidity, particularly in winter when dry air can cause static that attracts dirt to the substrate, is needed.

The environment surrounding the coating station should have similar filtration equipment to control contamination and should also have equipment to control temperature and relative humidity.

Coater rolls and bearings are an essential part of the support system for a coating line. The rolls are critical to unwinding and rewinding the substrate master rolls and maintaining substrate roll quality. They are also a key component of the web transport system and the coating station web alignment system. Rolls are critical to most coating application systems. Poor roll quality, rough or scratched surfaces, too much bearing run-out, poor crowning, or out-of-round rolls adversely affect coater quality and operability. Having high-quality rolls can improve coater quality and operability. In addition, the bearings are critical to maintaining roll performance, and poor bearings can be a source of contamination.

Statistical quality control systems are used to identify quality trends and to ensure that the product shipped to customers meets their specifications. Among the techniques used are histograms, Pareto charts, cause-and-effect diagrams, defect concentration diagrams, scatter diagrams, and control charts.

The coater line is a complex manufacturing process. An ongoing program to train personnel in all aspects of the process operation helps ensure that all of the equipment is run correctly and that operational errors are minimized.

Detailed procedures that specify the process operating conditions for all products are also a key part of the support system. The procedures should be accurate, easy to read, and readily available. This is particularly important when a coating line makes many products. Using the wrong procedure will adversely affect quality.

Data management systems are used to collect and store all of the data generated in the coating process. This includes data from process control loops and process variable measurements. It includes product performance properties, defect images, and technical information. The system should be widely available and include statistical routines to analyze data.

Roll storage conditions are also part of the support system. The storage conditions, ambient temperature, and relative humidity under which the rolls are stored will influence the substrate quality and thereby affect coating quality.

DEFECT SUPPORT EQUIPMENT INTERACTIONS

The support equipment can function in two roles. The first is that the appropriate use of support equipment can reduce or eliminate defects, and the second is that inconsistency and inadequate design in the equipment can lead to defects. The lack of proper support equipment, where needed, will also lead to defects. Therefore the addition of needed equipment that had not been installed can prevent or eliminate defects. All of the equipment will not affect all of the defects; typically, each class of equipment will affect only certain defects.

An important principle in the effective use of support equipment is to understand how it can affect the various types of defects. To illustrate this, Table 12-2 shows the interaction of the process support equipment with various defect types. The support equipment categories are on the vertical axis and defects on the horizontal axis. An **X** in the table indicates that specified support equipment influences that defect. This table shows that several different types of support equipment can affect any one defect and often a particular support equipment can influence several defects.

The table also shows that the following classes of equipment can influence all defects:

- Training of all personnel who manufacture, design, and sell products.
- Accurate easy-to-understand operating procedures for all of the equipment and for product operating conditions. These should be accessible and kept up to date.
- A quality control system to ensure that physical quality levels and performance properties are within specifications.
- A data management system that integrates all process data with yield losses by type and product. It should also contain records of plant or R&D previous experiences, which have helped reduce defects.

SUPPORT EQUIPMENT EFFECT ON DEFECTS

This section discusses some typical defects and how specific support equipment can be used to eliminate or reduce these defects. More detailed discussions of most of these defects can be found in the earlier chapters.

Mechanical Chatter

This appears as straight transverse direction bars across the web. It usually is caused by vibrations being transmitted to the coating bead, inducing bead vibrations (filling and emptying) and thus differences in coating weight. The vibration sources can be from pumps, drives, building and dryer heating and ventilating systems, rolls and bearings, and exterior sources. To control these vibrations:

- A rigid coating station, preferably on its own foundation extending down to bedrock and isolated from vibrations of the rest of the building, is needed.
- There should be uniform tension in the web and no vibrations or surges.
- All rolls should be balanced and should not stick, vibrate, or wobble.
- Vibration sources should be isolated or removed.

TABLE 12-2 Support Equipment Interactions

Support Equipment	Chatter		Physical Uniformity	Ribbing	Point Defects		
	Mechanical	Serpentine			Bubbles	Spots	Scratches
Surface treatment							
Flame, corona dicharge plasma		X	X			X	
Web cleaner			X			X	
Static control							
Mixing							
High shear			X		X	X	
Low shear			X		X	X	
Cleaning equipment			X		X	X	
Filtration			X		X	X	
Solution delivery							
Filtration					X	X	
Debubbling					X		
Pumping	X				X		
Viscosity/temp. control		X	X	X			
Support station							
Precision applicator settings	X	X	X	X			X
Vibration isolation	X		X				
Rigidity	X		X				
Contamination control							
			X			X	X
Coater room							
Temperature, RH control			X			X	
Particulate						X	
Airflow						X	
Cartridge			X				
Process instrumentation							
Web tension	X		X				X
Line speed	X		X	X			X
Dryer H&V							
Dry point							
On-line measurement							
Coating weight			X	X			
Web defect inspection	X	X			X	X	X
Coater rolls and bearings							
	X		X			X	X
Roll storage conditions							
			X			X	
Personnel training	X	X	X	X	X	X	X
Procedures	X	X	X	X	X	X	X
Data management	X	X	X	X	X	X	X
Quality control systems	X	X	X	X	X	X	X

Serpentine Chatter

This appears as irregular transverse or cross-web bars. It is caused by operating outside the stable operating region, giving rise to hydrodynamic instabilities. To control serpentine chatter:

Poor Physical Uniformity

This refers to the overall aesthetic or visual appearance of the coating. The following factors improve appearance:

- Use surface treatment to improve wetting.
- Prepare uniform dispersions in mixing.
- Control viscosity to maintain coatability.
- Maintain optimum applicator settings.
- Control web tension and line speed uniformity within tight limits.
- During roll storage, protect the substrate from contamination, physical damage, and temperature extremes.

Ribbing

This refers to a series of uniform machine direction lines across the width of the substrate. They are caused by a hydrodynamic flow instability in the bead that results in a sinusoidal transverse direction variation of the coating weight. Ribbing is very common in all coating methods. To control ribbing:

- Ensure procedures specify process conditions to stay in coatability window.
- Control viscosity and temperature.
- Maintain precise applicator settings.
- Maintain tight control of roll speeds.
- Avoid diverging flow in coating gaps.
- Avoid excessive viscoelasticity.

Bubbles

These are clear round spots with no coating. Gas pockets in feed lines to the applicator or boiling in the dryer causes them. To control bubbles in solutions:

- Eliminate cavitation in mixing or pumping.
- Deaerate the solutions to remove bubbles.
- Properly set up the solution feed line size and layout. This includes ensuring no leaks and purging the lines of air pockets.
- Control the dryer to ensure coating temperatures are well below the boiling point of the solvent at the particular solvent concentration in the coating. The boiling point rapidly increases as the solvent concentration in the wet coating decreases.

Contamination Spots

This covers a large class of point defects in which there is a foreign body in the coated product. Names of these defects are lints, fibers, dirt, squiggles, repellents, oil spots, and comets. Contamination can have many sources. To reduce contamination:

- Surface treat to clean the substrate.
- Filter all solutions to remove contaminants.
- Filter the coater room air and dryer room air.
- Have ongoing contamination control procedures.
- Protect the substrate from contamination during roll storage and transportation.
- Eliminate static buildup in the coating line that can attract dirt to the substrate.
- Ensure the bearings are not spraying lubricant on the web.

Low Overall Productivity

The support equipment influences productivity—the volume of product coated per unit time. A reduction in productivity can arise from long periods of coater downtime, inability to maintain standard conditions, and reduced line speed. To improve productivity:

- Control the location of the dry point and ensure that the line speed is maintained.
- Precisely control the line speed and dryer conditions.
- Use quality control systems to detect deviant trends and correct them before defective product is made.
- Provide training for coater operators and accurate and easy-to-understand training procedures.

Defects Due to Static Electricity

Static buildup in the coater can generate a variety of defects—dirt, pinholes, tracking, “photo effects”—and can cause fires in solvent coaters. Static charges can build up in the coater from the separation of two dissimilar materials, that is, substrate and rolls. These charges can attract dirt leading to contamination defects. When the static buildup is discharged, it can damage the film, expose photoactive materials, and cause fires. To control static:

- Remove surface charge with static neutralizers.
- Ground the rolls so the charge is bled from the coater.
- Maintain high relative humidity in the coater air.

Chapter 9 covers static charges in more detail.

Scratches

Scratches are linear gouges in the surface of a coating or in the surface of a substrate. They can be from short to long in length, and they can be repetitive in nature. They are differentiated from streaks by the fact their sides tend to be jagged. In addition, they may not be very deep and may be hard to detect. They are caused by a difference in the roll speed and web speed, leading to slippage that causes scratches. A hard contaminant on a roll can gouge the substrate that is in contact with the roll.

To control scratches:

- Ensure that all rolls are clean and free from contaminants.
- Ensure that all rolls in the coater rotate freely.
- Ensure that there are no bad bearings.
- Monitor the web handling system to check for roll slippage and correct where needed.
- Check the web tension.

Streaks

Streaks are long narrow bands running in the coating machine direction. They typically have a low coating weight in the center and a high sharp edge and can be detected visually. They can be continuous or intermittent and can vary in width. The major cause of streaks is particles such as bubbles, dirt, agglomerates, and gels that are trapped in the bead, leading to the gouging of the wet coating, thus forming the streak.

To eliminate streaks:

- Treat the substrate surface to remove contaminants and to improve coatability.
- Ensure that all solutions and dispersions are well mixed.
- Filter all solutions to remove contaminants.
- Debubble solutions.
- Clean the substrate so that particles are not carried into the coating bead by the web.
- Clean the applicator.

Mottle

Mottle is an irregular pattern of coverage variations on the surface of a coating that can vary in size up to several centimeters. In severe cases it can cause an iridescent pattern. It is caused by nonuniform airflows disturbing the wet coating.

To control mottle:

- Monitor and control the coating viscosity and temperature.
- Increase the solution concentration to reduce the wet coverage and thus the thickness of the wet layer.
- Increase the solution viscosity.
- Reduce the airflow velocity in the early stages of drying.
- Ensure uniform airflow from the nozzles.
- Enclose the area between the coating head and the dryer to reduce the motion of air on the wet coated substrate.
- Control the drying conditions.
- Balance the air pressure within the dryer to that of the room, so as to reduce the airflow into or out of the dryer, where the wet coating enters the dryer.

Coating Weight Nonuniformity in Premetered Applicators

Coating weight nonuniformities are variations in the applied coating thickness, which are outside the specifications required for the product end use. There are several types of variations that are typically measured and specified. The first is the variation of the average coverage over the entire web. The second is the variation of the coating weight in the transverse direction, or the cross-web profile. The third is the variation in the coating weight down the web, or the machine direction profile. The units of the variations can be expressed as a percent from the mean, or better yet, in terms of standard deviations, or as 95% confidence limits.

In premetered coating, all of the solution sent to the applicator is deposited on substrate. The design of the premetered applicator is a critical variable in determining coating weight uniformity. Process support equipment that influences coating weight is as follows:

- Pump selection. The pump delivery uniformity must be better than product specifications. Gear pumps give the best flow uniformity to the applicator, but plastic lines may be necessary to dampen out fluctuations caused by the meshing of the gear teeth.
- Measure and control the flow to the applicator.
- Measure the coating weight with an on-line gauge.
- Use in-line mixing prior to the applicator to give a uniform coating solution.
- Use a rigid precision support station to maintain the applicator settings throughout the entire production run.
- Maintain a uniform line speed. Since the pump is metering a constant volume of coating solution, substrate speed variations will result in coating weight variations.

Coating Weight Nonuniformity in Self-Metered and Doctor Coaters

For precise control of the coating weight:

- Measure the coating weight with an on-line gauge.
- Use an in-line viscometer and thermometer to measure the viscosity and the temperature.
- Use temperature control for the feed systems.
- Debubble the coating solution.
- Maintain a uniform line speed.
- Use a rigid precision support station to maintain the applicator settings during the entire production run.
- Ensure rolls and bearings have minimum run-out and have uniform diameters.

Air Bar Rubs in a Floater Dryer

Air bar rubs are irregular scuff marks on the surface of the film. They have finite edges and have a gouged appearance. They can be in clusters or continuous and run in the machine direction. They also tend to get worse with time.

To reduce air bar rubs:

- Clean air floater dryer nozzles to remove any buildup on the nozzles.

- Ensure that uniform tension control is maintained during a production run.
- Maintain an optimum air balance between the top and bottom nozzles.
- Ensure the substrate has no curl or planarity defects.

Dry Point Variability

The dry point is the location in the dryer where the coating is considered to be dry. Specifically, it is where the constant rate period ends and the falling rate period begins. It can be determined by a sharp rise in film temperature or change in appearance from glossy to dull, or by the feel of the coating. If the dry point moves toward the end of the dryer, then the product can be wound too wet, and this would not be acceptable. Similarly, if the dry point moves back toward the front end of the dryer, the product will be overdried and unacceptable.

To precisely control the location of the dry point:

- Have a good dry point measurement system and control loop.
- Have precise control of the line speed.
- Have precise control of the dryer conditions.
- Ensure a uniform and consistent coating weight.

SELECTION OF EQUIPMENT

The installation of new support equipment and the upgrading of current support equipment depend on the needs of your process. The selection should be based on an economic analysis of yield losses and the requirements for the technical performance of the product. Analysis of yield data will indicate which of the losses have the most economic impact. The highest losses or those most important to the business should be identified and a development and implementation program instituted. This program should focus on installing missing equipment and upgrading existing equipment. Even though several types of equipment influence a specific defect, it is not necessary to install them all. Experimental data can establish which equipment has the maximum effect and is the most economically efficient.

13

COATING DEFECTS DATABASE

NEED FOR COATING DEFECTS DATABASE

The ability to utilize the technical data from previous defect troubleshooting episodes is essential for an ongoing effective troubleshooting program. Easy access to this information will reduce the time required to solve current problems, by providing historical information to use in the current troubleshooting effort. This is particularly true of the analytical data, which constitutes a major part of the time and funds expended in a problem-solving cycle. These data are of two types: the text data—such as chemical analysis, procedures, and operating condition data—and graphical or pictorial data—such as micrographs and spectra. They are very characteristic of specific defects. If the complete data set from a previous cycle is available, it may be possible to identify a defect just by comparing the initial microscope images with previous images. If the defect images from the past and current defects are similar, it is likely that the defects are the same and the same solutions might work. A basic simplified set of tests could then be run to verify the defect. Running only those tests that gave the best results in the previous cycles can also reduce the analytical time and cost for the second stage analysis. It is therefore recommended that a readily available *Coating Defect Database* be established, which contains historical information in summary form. This database is in addition to the final closing report for any one defect. It is intended to make the previous information readily available for the current problem-solving team. It should be designed to focus on the characterization data and the solution that was found. A principal reason for having this database is that one picture is worth a thousand words. Defects are often hard to describe using words only. Comparing defect images is much better than reading about them or trying to describe them over the telephone. Also, it is typical in most coaters for certain types of defects to repeat themselves and to have similar causes. Access to this historical

knowledge will help isolate the cause and can lead to a rapid solution. It also may suggest tests to run and new questions to ask about the current defect.

Prior to the availability of computer databases, images were stored in hardcopy in notebooks. While these volumes contained useable information, accessing them was difficult and they were not available to personnel at other sites.

The ideal format for this *Coating Defects Database* is a computer database in which each individual record can contain both text and images. The contents should be easy to search so that specific information can easily be extracted. Thus the search could be for all mention of chatter, of bubbles, and so on, and only those records would be displayed. This is much easier and more effective than scanning pages in a looseleaf notebook. In addition, it is simple to add new material to the database, and it is easy and inexpensive to copy and distribute files from the database or just selected portions of a particular file.

There are a wide variety of commercially available, suitable database programs, which function on personal computers or on larger centralized computers. The images from a digital image analysis system (Cohen and Grotovsky, 1993) are in computer format and can easily be incorporated into most databases, along with the other analytical data.

The defects database can be as simple or as complex as the user desires; however, it is our experience that databases at either extreme are not effective. A simple database does not provide enough information to be useful, and a complex database may contain too much information and be hard to use. The ideal system contains all of the needed information in an easy to understand format. For the database to be effective, it must be up to date with data on a wide variety of defects. An easy to use database will be used, will grow, and will become more and more useful.

Another valuable function for the database is as a training aid for personnel. Part of the job for coating operating personnel is to eliminate defects while operating the coater. After a year or so of operation, several types of defects will have been found along with the methods to eliminate them. Instead of forming a problem-solving team, the operators will be able to use past history—their experience—to solve some defect problems. As experience is gained with more products, the operators will learn to solve the problems that have occurred previously. This experience is available only as long as the same people work on the coater. However, as people change jobs, this experience is lost and new operators have to be trained. This defects catalog should be used as part of the training procedure and will be a valuable reference while experience is being gained.

There are several possible templates to use for this database. The exact configuration depends on the local needs of the users; Figure 13-1 is a possible template that was developed in FileMaker Pro. This database can run on a PC, on a Mac, or on a Network. There can be one record for each defect occurrence or an overall record, which is upgraded as more information is obtained. The record should briefly describe the defect, contain images of the defect, name the defect and give its source, supply the chemical analytical data, and summarize how the problem was solved. There should also be a reference to more detailed information, such as the report from the problem-solving team, or to summary reports. The record can also have the names of local experts who can be called on for help. The size of a record depends on the needs and preferences of the user. It can be as short as two or three computer screens, or it can be as long as several pages. A template and directions for adding new information should be included in the system. Each occurrence of the defect should have its own record. Defects are statistical in nature, and several occurrences are needed to get the true indication of what is happening. A record does not have to be complete to be entered. It is often useful to enter what is known about a

DEFECT DATABASE RECORD

Defect I.D.	Base Flake
Description	A coated particle was observed on dry coating, Product type CDA-2, substrate 4 mil polyester, coater #1
Classification	Discrete point defect, Contamination on substrate
Defect picture	
Analytical data	Microscopy suggested particle on substrate surface. Coating removed with solvent. Verified particle on substrate. Infrared microscopy indicated flake is Polyethylene Terephthalate. Visual analysis of uncoated substrate showed particles on surface. Two rolls only.
Cause	Contamination deposited on substrate during manufacture. Resulted from edge trim problems.
Action Taken	Changed substrate rolls, contacted manufacturer, and considered adding substrate cleaning hardware to coating line.
Miscellaneous comments	If substrate manufacturer does not improve quality, consider a new source.

Figure 13-1. Defect Record Base Flake. From the AIMCAL Defects Lexicon, with permission.

defect and what was done about it. A simple record on chatter in a specific product, giving frequency, a record of coater data, and a note indicating that a bearing was changed in the coating roll, may help someone the next time chatter is seen. Another approach is to develop a unique record for each type of defect. This summarizes all available information and is updated as appropriate.

A required field in the defect database record is to classify the defect according to its characteristics. This permits a rapid comparison of a new defect with those in the existing database. There are many ways to classify defects and there is no agreed upon naming convention. Table 13-1 gives a useful characterization scheme, which classifies the defect according to the basic characteristics of shape, direction, location, process influence, and substrate effects. Examples are given for the various classifications. For example, chatter is a continuous, linear, transverse direction defect. Ribbing is a continuous, linear, machine direction defect. A streak can be a continuous or intermittent, linear, machine direction defect. Defects can have multiple classifications. For example, air entrainment is a bubble type defect and a process specific coating defect.

TABLE 13-1 Defect Classification

Category	Examples
1. Linear continuous	
a. Machine Direction	Streaks, ribbing
b. Transverse direction	Chatter
c. Diagonal	Diagonal chatter
2. Linear intermittent	
a. Machine direction	Scratches
b. Transverse direction	
c. Diagonal	
3. Discrete point defect	
a. Spot	Bubble spots, gels
b. Contamination coating	Lints, dirt
c. Contamination substrate	Repellent spots
d. Other types	Repeat spots, blooming
e. Pattern and diffuse defects	Mottle, orange peel, dryer bands
4. Process specific defects	
a. Raw materials	Repellents, Bénard cells
b. Coating	Air entrainment
c. Drying	Mottle, dryer bands
d. Web transport and winding	Wrinkles, scratches, repeat spots
e. Metallizing process	Blooming
5. Substrate defects	
a. Plastic	Gauge bands, polymer spots
b. Paper	Wrinkles
c. Metalized	Railroad tracks

The records can be searched for a specific classification and all records displayed under this classification. This is useful for general types of defects when an exact match is not found. This complicates the classification. To search this type of database one can specify keywords of interest, such as bubbles, chatter, streaks, and spots, or the product type, and the computer will search all records and display those that meet the specified criteria.

DEFECTS DATABASE: EXAMPLES

Some examples of specific entries in a defects database provide more detail about the database and the records that it contains. Since coaters and the products coated are unique, the specific defects and the methods to eliminate them tend to be unique. Therefore each defect occurrence should have a unique record. A series of typical records are presented to show some different types of database entries that can be created. The focus is on the type of information that a record can contain.

Again, the basic requirement for selecting a specific computer database is the ability to store both text and graphics and the ability to search for keywords. Most databases are flexible and will permit the user to design a form to match the user's needs.

In entering the graphics into a specific record, the preferred picture is an actual micrograph of the defect. When this is not possible, it is acceptable to enter a sketch or drawing. This may be necessary when the defect is subtle, such as mottle or a light chatter, or covers a large area, such as wrinkles, where micrographs will not show the defect. A sketch is better than not having a picture. This was done for repeating spots, which are a good example of a basic entry. The defect is described and sketched, and a calculation is shown that can help locate the source of the problem. The entry suggests that when a repeating spot is found, it probably comes from a contaminated roll. Thus calculating the roll diameter with a circumference equal to the repeat spacing helps locate the roll.

The specific fields in the defects database can hold large amounts of data, which are viewed by scrolling through the field. In the following examples, a condensation of the record is shown, and additional text that is contained in the complete record and not viewed is discussed.

After there is sufficient data with a specific defect type, a summary record that encompasses all information from the occurrences can be created. A summary database entry can also be far more descriptive and can summarize information from a whole series of defect cycles. This should be done when sufficient data has been accumulated so that the pattern and mechanisms of formation are understood. It is also useful to summarize the information when there are many examples of a particular defect. It is much easier to view one summary record than to examine a number of records.

Base Flake

Figure 13-1 shows the defect record for a base flake. In this defect, a flake of substrate is on the surface of the substrate to be coated. The coating goes over the flake and gives the defect. The flakes are applied at substrate manufacturers and they should run a troubleshooting procedure to locate the cause. Web cleaners on the coating line might help also.

Roll Repeats

Figure 13-2 shows the defect record for roll repeats. This type of defect is caused by a contamination on the coating roll that imprints on the coating, giving a spot-like imperfection. The distance between repeats is equal to the circumference of the roll.

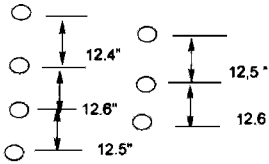
Bubbles

Figure 13-3 is the defect record for a bubbles incident.

Bubbles are defined as “a small body of gas within a liquid,” or “a thin film of liquid with air or gas,” or “a globule within a solid.” In coating solutions, air can become trapped leading to bubbles. These can stay with the liquid and end up in the coating as defects. Typically, in the dryer the skin of the bubble containing the air breaks and leads to a clear round spot that is called a bubble. Bubbles are very common in aqueous solutions that contain surfactants to increase the wettability on the support. Bubbles are particularly common in low-viscosity solutions but occur over a wide range of viscosities, and are more difficult to remove at higher viscosities. They are an ongoing problem in most coating applicators.

Most bubbles can easily be seen by eye, but they are analyzed by microscopy to show up the contrast between the normal coating and the thin coating in the bubble. Bubbles can come in a variety of shapes and many specific forms. They vary in size from 50 to 1200 μm . All share the basic characteristic of a thin coating in the center where the gas was

DEFECT DATABASE RECORD

Defect I.D.	Roll repeat
Description	Repeating spots were found in two areas of the coated web. Product UCF-5 coated on Coater number 2
Classification	Discrete Point Defect. Other types, Web Transport & Winding
Defect picture	
Analytical data	Defect mapping of the two lanes of repeats gave an average spacing of 12.6 inches. This is circumference of 4-inch idler rolls , $\pi \times$ roll diameter
Cause	Dirt detected on one 4-inch idler roll in lanes corresponding to defect lanes. Dirt imprinted coating.
Action Taken	Cleaned idler rolls

Miscellaneous comments	Roll Diameter, inches	Roll Circumference, inches	Roll Type
	3	10.2	Idler rolls
	4	12.6	
	6	18.5	Vacuum roll
	8	25.1	
	10	31.4	Coating roll

Figure 13-2. Defect Record Roll Repeats. From the AIMCAL Defects Lexicon, with permission.

trapped, and most show the collapse of the upper skin when the bubble bursts. Bubbles tend to be round because of surface tension.

The difference in appearance arises from the properties of the coating, the size of the bubble, the location in the wet coating, and the temperature of the dryer. If the coating is weak, as the air heats up and expands in the dryer, the bubble will break and the solution will drain down to surround the clear spot. If the coating is strong or forms a solid gel, the bubble may remain intact and not break.

When bubbles are discovered, since they represent air trapped in the coating liquid, the process has to be checked for all potential sources of air. This starts with the kettle used to prepare the coating. Examine the process during mixing and check for foam and air entrapment. Check that the agitator is turning at the standard speed, as too high an

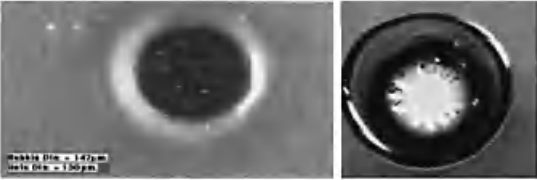
DEFECT DATABASE RECORD	
Defect I.D.	Coating Bubbles
Description	A round white spot defect was seen scattered across web of product UDT-2 in Coater 3. First reaction was bubbles. They also increased as run progressed. Observed after applicator.
Classification	Discrete Point Defect, Spots, Process Specific Defect Coating
Defect picture	
Analytical data	Microscopic analysis indicated that all of the defects were bubbles. They had round center and a heavy circle where the coating ran back. In some of the bubbles, the coating had solidified before it completely drained.
Cause	Bubbles are small pockets of air which are trapped in coating solution. In this case a high mixing agitation rate and poor control of recycle was causing bubbles.
Action Taken	Agitation rate of mixer was lowered. In addition, recycle line was moved from above holding kettle to below the surface of the coating solution. Both reduced bubbles
Miscellaneous comments	

Figure 13-3. Defect Record Bubbles. From the AIMCAL Defects Lexicon, with permission.

agitation rate will entrain air. During coating, the agitation rate—if an agitator is used—should be the minimum required to maintain the dispersion homogeneous.

Bubbles are lighter than the liquid and so will tend to rise to the top of the vessel. Thus the coating solution should be drawn off the bottom. Also, after preparation, the liquid should stand for some fixed time to allow the bubbles to rise to the surface. A vacuum pulled on the vessel during this period causes the bubbles to expand and thus rise much faster to the surface. Check that the standard standing time was followed. Check that the withdrawal point of the vessel is at or near the bottom.

The lines that lead from the mixing vessel to the feed reservoir and from there to the coating stand can contain air. These lines should not enter below the surface of the next vessel. If the lines discharge above the surface, air can be entrained by the liquid as it falls to the surface. It is best to have the lines discharge horizontally and tangentially to the wall of the vessel, as the liquid will then flow down the wall too slowly to entrain air. The lines should be checked to make sure that there are no leaks and all connections are tight, so that air cannot leak in as it could if the pressure in the line goes below atmospheric. The lines should not have any points where bubbles can accumulate. When solution is first

introduced, it should be recirculated back to the feed vessel to clear the lines. Pulsing the lines—having an intermittent high flow rate—helps clear them of air.

A pump is often used to feed the coating liquid to the coating stand. Air can be sucked into the pump suction if the connections are loose or the pump seal is worn. Also, cavitation can occur at the vanes of the pump to form bubbles. Cavitation is always bad as it causes erosion of the pump vanes. If dissolved air is present, these bubbles will contain air, which may not re-dissolve.

During drying, dissolved air can come out of solution to form bubbles. The solubility of any gas decreases with increasing temperature. At the higher temperatures of the dryer, air can come out of solution. It is desirable to have as little dissolved air as possible. It is sometimes helpful to reduce the level of dissolved air by pulling a vacuum on the coating vessel or using an in-line degasser.

Air can also be introduced under the coating during the coating operation. This very thin sheet of entrained air then breaks up into fine bubbles. These very small bubbles are able to dissolve in the coating liquid even when it is saturated with air, as the solubility increases as the size decreases, due to surface energy effects. At higher coating speed, more air is drawn in to form larger bubbles, which are too large to dissolve. This problem is normally observed only when the coating speed is increased.

Bacteria Bubbles

Figure 13-4 is a defect record for a bubble-like defect that was caused by a center of bacteria and degraded gelatin.

AIMCAL DEFECTS LEXICON: GUIDE TO WEB COATING TECHNOLOGY

Description of Lexicon

An example of a more extensive web coating database is the *AIMCAL Defects Lexicon: Guide to Web Coating Technology* (Cohen and Howe, 2005). This is a computer-based user-friendly reference, which provides a variety of information on the web coating process. It is intended to assist in accurately identifying and eliminating web coating defects by providing representative images of web coating defects, their causes and cures, and standardized definitions of these defects. It also contains standardized definitions of web coating process terms and unit operations.

The Lexicon consists of four main sections:

- A glossary that contains standardized definitions of coating defects, representative images of these defects, and definitions of coating process terms
- A troubleshooting guide that contains the defect standard name, defect images, alternate defect names, defect cause, and actions to eliminate the defect
- An image section that contains only defect images
- A search system to locate specific defects and definitions

Need for Lexicon

As discussed in Chapter 2, there was no source of standard names or a naming convention for defects. Therefore defects are named based on the observer's impression of the defect, past experience in the manufacturing unit, or colloquial names that are specific to an

DEFECT DATABASE RECORD	
Defect I.D.	Bacteria Induced Bubbles
Description	A bubble-like defect was detected randomly distributed across the web in GELC-2 coated on coater 1. It appeared with the unaided eye to be bubbles. Therefore, standard procedures to remove bubbles were tried and were not effective.
Classification	Discrete Point Defect spots, contamination coating, Process specific defect coating.
Defect picture	
Analytical data	The "bubbles" were examined under Microscope and found to have a liquid center. When the bubble was pierced a black liquid with strong odor ran out. The liquid was found to be gelatin decomposed by bacteria.
Cause	A buildup of gelation which had been degraded by bacteria was found in feed lines to applicator. The lines had not been cleaned or replaced in several weeks.
Action Taken	Flow lines were replaced and all kettles, filters, and holding tanks cleaned. Procedures were changed to incorporate line replacement and cleaning.
Miscellaneous comments	This defect shows the advantage of basic analytical characterization. If assumption of defect being standard bubbles was not checked, the defect would have taken much longer to diagnose and eliminate.

Figure 13-4. Defect Record Bacteria Bubble. From the AIMCAL Defects Lexicon, with permission.

industry. This results in the widespread use of jargon to describe the defect. Consequently, the same defect can have many different names, and conversely many different defects can have the same name. This lack of a standard naming convention leads to an inefficient troubleshooting process and can result in wasted effort. It also complicates communications between people working to eliminate the defect and makes it harder to find literature references and technology on the defect.

Another consequence of the lack of standard names is that the names given to the defect often imply both the cause of the defect and the corrective action to be taken. If the name is incorrect, then the corrective action taken will be on the wrong problem and the defect will not be eliminated. Individuals can also interpret a defect name differently. The same term, such as "ribbing", can suggest different defects to different people, depending on the experience of the observer. The ambiguity of a name also complicates communications in efforts that involve different sites, companies, and countries.

The Lexicon is intended to solve these problems by providing standard defect names and descriptions and images of a wide range of defects so that the users can compare their defects with typical images of those defects and accurately name the defect. It provides a

Troubleshooting Guide The troubleshooting guide provides detailed information on coating process defects. This section is designed to permit the user to correctly identify a defect that he/she is working with and to obtain information to help eliminate the defect. In those cases where defects have multiple names, the name with the most common usage is the standard name. Alternate names are also listed.

Each defect has a separate record, which contains the following defect information:

- Standard name
- Alternate names
- Description
- Cause
- Actions to eliminate
- Several representative pictures of the defect

The entries are also classified according to the scheme in Table 13-1 to assist in searching this section. Figures 13-5 to 13-9 are examples of some typical records of some common defects—starry night, repellent spot, gel slugs, cascade, and air entrainment.

Defect Record: Starry Night	
GRAPHICS: Graphics for this defect:  THUMBNAIL Click on thumbnail to view full size image.	DEFECT DETAIL Standard Name: Starry Night Other Names: Galaxies, windowing, white spots Defect Class: Discrete Point: Spots, Process Specific: Drying,
	Defect Description & Attributes: Starry night is round clear spots which are seen against a darker background. It is common in photographic film, where the white spots against the black background look like the night sky. The defect is also seen in any multilayer system which has a particulate containing overcoat. Windowing in paints is a similar defect. A characteristic of the defect is many small spots. It is rarely a single spot.
	Defect Cause: Starry night is caused by the stresses generated during drying driving particles from the top layer into the bottom layer. This particle disturbs the coating and pushes aside the undercoat. The penetration usually occurs in the later stages of drying when the surface layer dries out and the balance of the coating is still wet and soft.
	Action to Eliminate: To eliminate this defect, a high drying air solvent concentration is needed in the last drying zone to minimize surface dryout. Particle size of the matte is also a factor. Larger particle size and agglomeration of particles can enhance the severity of the defect.

Figure 13-5. Troubleshooting Guide Starry Night. From the AIMCAL Defects Lexicon, with permission.

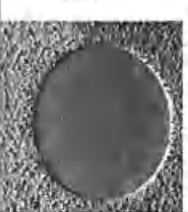
Defect Record: Repellant Spots	
GRAPHICS: Graphics for this defect:  THUMBNAIL Click on thumbnail to view full size image.  THUMBNAIL Click on thumbnail to view full size image.	DEFECT DETAIL Standard Name: Repellant Spots Other Names: white spot, bubble spot, clear spot, craters Defect Class: II Discrete Point: Spots, Contamination Coating, Contamination Substrate, II Defect Description & Attributes: A repellant spot is a round or elongated area where there is no coating or reduced thickness. The center can be completely or partially free of coating and the defect frequency can vary. Defect Cause: A repellant spot is caused by a contamination on the surface of the support which created low tension area that repels the coating so that it does not wet the surface and causes the spot. It can also be caused by a contamination in the coating solution which separates after application and causes the coating not to wet the base. Action to Eliminate: To eliminate repellants the source of the contamination needs to be determined by chemical analysis of the coating solution, raw materials, and the support. Once the source is located it should be eliminated. Surfactant adjustment, either level or type, will help. Base cleaning systems can have a positive effect also.

Figure 13-6. Troubleshooting Guide Repellent Spot. From the AIMCAL Defects Lexicon, with permission.

Defect Image Section In many instances, there are more defect images than could be included in the defect records of the troubleshooting guide. This section contains all of the defect images and they are grouped according to their classification and name. It is intended to help identify a new defect and determine the standard name by comparing it with the images in this section. This will help the user locate defects with characteristics similar to the new defect under investigation.

A typical record in this section is shown in Figure 13-10, which gives several images of streaks. This clearly shows the common characteristics of streaks and the many variations in streak characteristics that can occur.

Search Capability

There are several different methods that can be used to retrieve information from the Lexicon. The glossary section is alphabetized and can be browsed. It can also be searched using keywords. The troubleshooting guide is indexed for ease in searching and it can also be searched by either keywords or by specific classes of defects. An example of a typical search is given in Figure 13-11.

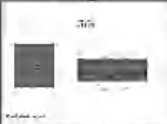
Defect Record: Gel Slugs	
GRAPHICS:	DEFECT DETAIL
Graphics for this defect:	Standard Name: Gel Slugs
	Other Names: Comets, fisheyes, dirt specks, spots
	Defect Class:
	Discrete Point Spots, Contamination Coating,
	Process Specific: Coating,
 THUMBNAIL Click on thumbnail to view full size image.	Defect Description & Attributes: Gel slugs are small round to oval defects which have an undissolved polymer particle in the center of the defect. The balance of the defect has no coating. No coating in the center. These particles are usually partially swollen and in a gel state. They tend to be randomly distributed but occasionally occur in lanes depending on the flow pattern of the applicator. Microscopic analysis shows a soft particle in the center of the clear area. Infrared microscopy can identify the nature of the contaminant particle.
 THUMBNAIL Click on thumbnail to view full size image.	Defect Cause: Gel slugs are caused by particles of undissolved polymer settling on substrate and driving out the coating solution. The defect size is much larger than the size of particle at the center. In the solution preparation some of the polymer binder swells to form a gel slug and does not completely dissolve. This gel slug is suspended in the coating solution and settles on the base.
 THUMBNAIL Click on thumbnail to view full size image.	Action to Eliminate: To best way to eliminate the gel slugs is to ensure that all of the polymer is dissolved in the solution preparation procedure. This may require some special steps such as pre-swelling the polymer, time of addition times, and controlling order of ingredient addition. Filtration is also helpful in removing the gels, but because they tend to be compressible they often pass through the filter medium if pressure is high and filter size is high.

Figure 13-7. Troubleshooting Guide Gel Slugs. From the AIMCAL Defects Lexicon, with permission.

Defect Record: Cascade	
GRAPHICS:	DEFECT DETAIL
Graphics for this defect:	Standard Name: Cascade
	Other Names: Herringbone, Seashore,
	Defect Class:
	Linear Continuous: Transverse Direction,
	Process Specific: Coating,
 THUMBNAIL Click on thumbnail to view full size image.	Defect Description & Attributes: Cascade is a periodic cross-web defect with a sawtooth pattern. It can appear similar to chatter but is more irregular. Particularly common with reverse roll coater.
	Defect Cause: Cascade is a coating instability in which the bead oscillates and traps air under the bead leading to the defect. The air influences the thickness of the bead and the coated thickness on the support. It occurs at high capillary numbers and high ratios of the metering roll speed to the applicator speed.
	Action to Eliminate: To eliminate cascade lower the coating speed and reduce the ratio of metering roll speed to the applicator speed. A coatability window diagram for a reverse roll coating process is below. It indicates the regions of cascade and defect free film and can be used as a guide to eliminate defects.

Figure 13-8. Troubleshooting Guide Cascade. From the AIMCAL Defects Lexicon, with permission.

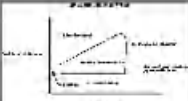
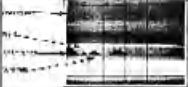
Defect Record: Air Entrainment	
GRAPHICS: Graphics for this defect:  THUMBNAIL Click on thumbnail to view full size image.  THUMBNAIL Click on thumbnail to view full size image.  THUMBNAIL Click on thumbnail to view full size image.  THUMBNAIL Click on thumbnail to view full size image.	DEFECT DETAIL Standard Name: Air Entrainment Other Names: Herringbone, Seashore, bubbles, air pockets Defect Class: Discrete Point: Spots, Other Types Process Specific: Coating, Defect Description & Attributes: Air entrainment is a series of small air bubbles in the coating. They can be a few random bubbles scattered through the coating or can be many and significantly disrupt the entire coating. They differ from "bubbles" in that they tend to have a high frequency and they have a different cause. Defect Cause: The defect is caused by the air on the surface of the substrate not being completely removed as the coating is applied. The remaining air film forms bubbles and is distributed throughout the coating. It occurs at high web speeds and is a form of coating instability. Air entrainment can also appear during lamination, if all of the air is not removed in the lamination zone. It occurs because of too high a laminating speed and wrap angle in the laminator. Action to Eliminate: To check if the bubbles are from air entrainment, lower line speeds, which should reduce defect levels. To eliminate air entrainment, the coatability window should be determined and the coating conditions adjusted to stay in the defect-free region. Other actions are: • pre-wet the substrate • use electrostatic assist with the coating applicator • roughen surface of substrate • increase surfactant levels For lamination, reduce laminating speed and adjust wrap angle.

Figure 13-9. Troubleshooting Guide Air Entrainment. From the AIMCAL Defects Lexicon, with permission.

Availability

The Lexicon is available for purchase from AIMCAL as a compact disk. This format was chosen because it provides high-quality images at a reasonable cost and can readily be upgraded, and user search capability is easy and powerful. A networking version is also available. New entries can be added to both versions so that a user can create a custom database to meet specific needs. Information on obtaining the Lexicon is on the AIMCAL website www.AIMCAL.org.

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- Cohen, E. D., and C. A. Howe (2005). *AIMCAL Defects Lexicon: Guide to Web Coating Technology*, AIMCAL, Charlotte, N. C.
- Cohen, E. D., and R. Grotovsky (1993). Application of digital image analysis techniques to photographic film defect test method development, *J. Imag. Sci. Technol.* **37**: 133–148.

14

DEFECT PREVENTION

INTRODUCTION

The quality, product performance, and economic requirements for products produced by the web coating process are continually increasing. As a result, it is essential to maintain an ongoing *defect reduction program* to minimize web coating defects. The web coating process is a high technology process with many process elements that can either contribute to defects or help in their elimination. Often a specific defect can be caused by several process elements and many variables need to be optimized for effective defect reduction.

As a result, the defect elimination process can be complicated and requires an ongoing formal structured defect reduction program to be effective. The most successful program should be proactive and focused on preventing and minimizing defects before they occur. There are several reasons for using this approach:

- Defects can result from multiple process interactions and may not have a single unique cause.
- Some defects are specific to a specific coating method.
- Defects can also be specific to the coating process used.
- Elimination of defects requires an understanding of the mechanism of defect formation and the underlying physical principles.
- A strictly empirical approach to defect formation is expensive and slow and might not eliminate defects over the long term.
- All process elements are critical and their role needs to be understood. Optimizing just one element will not lead to success.

- Defects rarely cure themselves without external intervention.
- Experience has shown that for successful operation of a coating line all of the process elements must be understood and integrated with each other.

The defect reduction program should be an essential part of the product scale-up and manufacturing processes. It should be applied to new products as they are scaled up and can be applied to current products as they are being manufactured. As defects are eliminated through the troubleshooting process described in previous chapters, what is learned should be incorporated into the overall defect reduction program.

This program takes a formal structured approach to managing and eliminating defects. It has the following steps:

- Define the product and process requirements that are needed for success in the marketplace.
- Ensure availability of valid analytical techniques to measure and characterize properties and process variables at the required precision and accuracy.
- Ensure that the web coating process can meet the required specifications.
- Use the appropriate coating method.
- Develop and implement operational procedures.
- Quantify and understand defect losses.
- Use a structured troubleshooting protocol.
- Set up a computer database to store and share information.
- Implement improved process improvement technology.
- Use statistical process control.
- Develop fundamental process understanding.

DEFINE PRODUCT AND PROCESS REQUIREMENTS

The initial step in the process of defect reduction is to develop the requirements that are needed for the product and the process that is used in their manufacture. These will quantitatively specify the maximum level of specific defects that can be tolerated and still meet customer satisfaction and economic success. The input for these requirements should be developed with input from all of the company functions, including research and development, manufacturing, sales, and management, and should consider potential as well as existing customers.

The major technical categories (areas) to be included in these requirements are:

- Product characteristics
- Raw materials
- Coating solution (dispersion preparation process)
- Coating and drying process
- Web handling
- Quality and defect levels
- Miscellaneous

The product characteristics are intended to broadly define the basic requirements of the product. The basic structure of the product, such as the number of layers, the substrate, and the composition should be specified. The requirements for coating weight uniformity in the machine direction, in the transverse direction, and for the roll-to-roll average all need to be specified. Another key parameter needed is an estimate of the anticipated volume, because the coating process for a low-volume product is much different from that for a high-volume product.

The quality and uniformity of the starting raw materials have a significant effect on defects and quality. The raw materials—polymers, pigments, cross-linkers, solvents, and surfactants—all need to be identified. The quality level required needs to be established and potential sources of supply should be established. Key properties to specify are level and uniformity of active ingredients, the maximum level of impurities that can affect the product, no contamination, no dirt or oil, and so on. Small differences in composition can lead to major product performance differences. The substrate quality has a major influence on defects. The substrate must be of uniform thickness and planarity, with no defects such as gauge bands or wrinkles. The substrate surface should be clean with adequate adhesion and should be able to be coated.

The requirements for the solution preparation or dispersion process need to be established. Most coating solutions are dispersions of solid particles in liquids that often contain dissolved binders. These dispersions need to be in a stable, useable form. This part of the process can vary in complexity from a simple mixing step, where the particles are easily dispersed or dissolved in the liquid, to complex dispersions that require the use of protective colloids and a high-energy input to achieve adequate disaggregation. If the coating solutions do not meet the requirements, the subsequent coating and drying process cannot compensate and the product will not be satisfactory.

There are several sets of data that are needed to determine the requirements for the coating and drying process. Data on the composition, coverage, and rheology of the coating solutions(s) are needed so that the coating application method and dryer and process conditions can be established. Characterization data of the support to be used is also very important. Data on support surface energy and wettability are needed to ensure that the coating solution will wet the support and maintain the required adhesion. The physical properties, such as tensile strength, and thermal properties, such as melt temperature (T_m), glass transition temperature (T_g), and decomposition temperature (T_d), are important for determining dryer tension limitations, to avoid distortion of the web under the temperatures needed to dry the product.

Rheological properties of all solutions are needed to ensure the coating method can produce a defect-free coating. The data on volume requirements will lead to the coater line speed required to meet customer demand.

The requirements are needed for the coating web handling system that transports the web through the dryer. The length and weight of the incoming substrate roll, the thickness of substrate, the line speed, and any tension limitations need to be specified. The quality level needed for the product should be specified and, where possible, with quantitative values and an indication of the precision needed. The quality level specified should be appropriate for the usage of the product. For example, an adhesive coating can tolerate higher defect levels than can a medical imaging film.

The requirements should include:

- Important performance, visual, and cosmetic properties of the final product that must be achieved to meet customer needs.
- The best estimate of defect levels that can be tolerated, expressed in quantitative terms such as physical defects per square foot, or the maximum size defect allowed. For subjective defects such as mottle or chatter, a relative rating can be used and standard goal values determined.
- Overall coating quality uniformity.
- For coating weights, the average values and tolerances in the machine direction and transverse direction, as well as the overall roll average and tolerance, are all needed.

TABLE 14-1 Product Process Requirements

Requirement	Goal Value
Product structure	
Number of layers/side	1
Coatings both sides	Yes
Dry coating weight, mg/cm ²	0.5
Wet coating weight, mg/cm ²	5.0
Uniformity M_d , T_d , roll-to-roll %	4.0, 3.0, 4.5
Solution composition	Pigment, acrylic binder, surfactant
Percentage solids	10.0
Solvent	Acetone, MEK
Viscosity	500–2000 cP, shear thinning
Surface tension, dynes/cm ²	35–40
Mixing needs	Standard mixing and high-shear dispersion
Volume required, M sq/ft/day	2.0
Coating width, inches	12–60
Substrate PET 3 mils	
Roll length, feet	15,000
Surface tension, dynes/cm ²	40–50
Thickness uniformity, %	3
Quality	Optically clear, no gauge bands, cockle, etc., no spots or dirt
Coating temperature, °F	75–80
Dryer needs	Three zones
Temperatures, °F	300 each
Air velocity Z1/Z2/Z3, ft/min	1000, 5000, 5000,
Cooling zone	Yes
Solvent capture burn or recycle	Yes
HEPA filtration	Yes
Make-up air, %	5–15
Conversion cost needed, \$/ft ²	0.03 maximum
Yield goal, %	85
Quality level overall	High-quality minimum defects
Chatter, ribbing	None
Streaks	1 light per 1000 l.f.
Bubbles, spots, comets	2 @ < 5 mils per 1000 l.f., 1 @ 5–30 mils, 0 > 30 mils

- ISO certification requirements, if any.
- Any requirements that are specific to the product and not included in the above.

There are several formats for recording information. There can be a complex written document or a simple table as shown in Table 14-1. The final document should be available on the company intranet for easy access by all. This is a dynamic document and should be modified as more information becomes available.

ENSURE AVAILABILITY OF VALID ANALYTICAL TECHNIQUES

Once the basic requirements are established, the next step is to ensure that the specified parameters can be measured rapidly and accurately with the precision needed. The sensitivity and precision of the method need to be better than the product requirements. For example, if the required uniformity for the coating weight profile is $\pm 3\%$, the method accuracy should be at least 2%. If the accuracy is $\pm 10\%$, then achieving the desired goal is not possible even if the measured values indicate that it is acceptable. If the properties cannot be measured with adequate accuracy and precision, then new test methods must be developed or new requirements established.

There are two general methods of testing—off-line and on-line. The preferred methods are the on-line ones. Such methods are available for coating weight, defect detection, and viscosity measurements. They provide rapid accurate results, and for some defect classes can be more sensitive than a visual analysis. These were discussed in more detail in previous chapters. The off-line tests are run on roll samples and can be done for all specified parameters.

For subjective tests such as chatter, spots, comets, and bubbles, standards for acceptable and unacceptable material should be prepared to help the quality inspectors and to help ensure that all samples are rated the same.

ENSURE WEB COATING PROCESS MEETS SPECIFICATIONS

There are also requirements and needs for the coating line. These also need to be checked to ensure that the process can achieve the desired conditions.

Examples of these parameters are:

- Coating line speed
- Web transport tension and edge guide sensing and control systems
- Dryer temperature, air contamination level, and air velocity measurement and control
- Dryer solvent level
- Room environmental temperature, relative humidity, and contamination control

Again, if available tests are not capable of meeting specifications, then new test methods must be developed or new requirements established.

TABLE 14-2 Basic Coating Methods

Gravure	Roll coating
Forward	
Reverse	
Offset, reverse and direct	
Mayer rod	Hot melt
Slot die	Doctor blade
	Knife/metering bar
Knife over roll	Extrusion
Air knife	Curtain standard
Curtain precision	Saturator
Spray	Screen
Slide multilayer	Coextrusion
Flexo	Comma
Microgravure	
Total specific configurations ~1000	

USE APPROPRIATE COATING METHOD

A key requirement in the prevention of defects is to ensure that the appropriate coating method is used. As shown in Table 14-2, there are many different coating methods and over 1000 possible configurations. All of these can apply a coating under some set of conditions. However, these conditions may not be appropriate for the particular process.

Each coating method has an optimum region, a coatability window, in which it will produce defect-free coatings in a reproducible manner. Figure 14-1 shows an operating window for a slot die coater. As you approach the boundaries of this region, the quality deteriorates and defective material is produced. (See the discussion on Limits of Coatability in Chapter 6.) There is some variability in this boundary region and quality can vary. Effort spent to reduce defects in this boundary area will have a

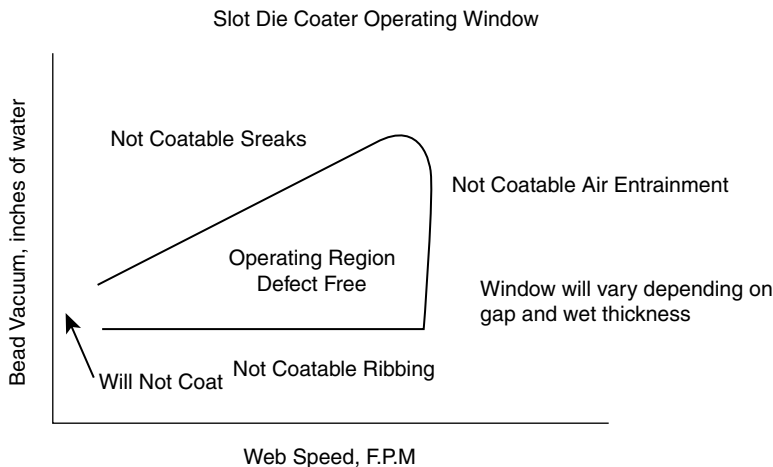
**Figure 14-1.** Coatability window.

TABLE 14-3 Coating Applicator Requirements

Property	Goal	Acceptable
Number of layers	2	2
Maximum line speed, ft/min	1000	800
Coating weight uniformity, %	3	5
Minimum wet coating thickness, μm	10	15
Minimum solution viscosity, cP	50	100
Maximum solution viscosity, cP	2000	1000

low success rate. Similarly, if you move fully out of the region, defective material will be produced.

Therefore it is essential that requirements for the coating process as shown in Table 14-3 be used to select an appropriate coating method. Table 14-4 shows the operating range for a variety of coating methods. These can be used to screen coating methods to select the best ones for the specific application. Table 14-5 outlines a procedure for selecting a coating process.

DEVELOP AND IMPLEMENT OPERATIONAL PROCEDURES

Functional operational procedures for all the process hardware elements and all the individual products are essential to prevent defects. The machine operators need to have accurate and easy-to-follow procedures to set all of the conditions on the coater, such as web speed, tension, edge guide settings, applicator settings, drying conditions, unwind conditions, and rewind conditions. Most coating machines manufacture a variety of products and typically each has its own set of unique operating conditions. Using the applicable procedures and settings will help prevent the occurrence of defects. The preparation of the coating solutions also requires unique procedures for each product. There are often key steps for the preparation of a dispersion or solution that are essential for it to be stable and coatable. The only way to ensure the solutions are made correctly is to follow the procedures for all operations.

There are many computer and software programs that can be used to store procedures and have them available for use in the coater area. The important principle is that all procedures be clear and unambiguous, so that everyone will carry out the same steps in the same way. After the procedures are developed, all operations personnel should be trained in their use. The procedures should also be upgraded and modified as needed.

There is often a tendency to ignore the procedures or to take short cuts. This tends to occur when operational problems and defects are occurring, in an attempt to regain lost production. This is clearly the wrong time to ignore procedures, for it will make any problems more severe. Therefore a process is required to ensure that the procedures are followed and that all are accountable for doing.

QUANTIFY AND UNDERSTAND DEFECT LOSSES

In order prevent defect occurrence, it is essential that a system be in place to show the exact type of defect losses that are being encountered and the specific product families on

TABLE 14-4 Coating Ranges

Method	Viscosity Range (cP)	Line Speed (ft/min)	Wet Coverage (μ m)	Uniformity (%)	Cost Category	Number of Layers	Substrate Effect
<i>Premetered</i>							
Curtain, precision	5–5000	200–1000	5–500	2	H	1–18	N
Curtain, standard	150–2000	300–1300	25–250	5	I	1	N
Extrusion	50,000–300,000	125–1825	13–523	5	H	1–5	N
Slide	1–500	20–1000	25–250	2	H	1–18	N
Slot die	15–20,000	20–1700	10–250	2	H	1–3	N
Spray	10–300	50–400	50–340	10	L	1	S
<i>Self-Metered</i>							
Comma direct/indirect	1000–300,000	30–1000	20–?	10	L	1	N
Direct roll hot melt	2000–250,000	20–1220	1100	5	I	1	N
Forward roll	20–2000	100–1500	10–200	10	L	1	N
Reverse roll	200–50,000	20–1700	14–450	10	I	1	N
Reverse roll hot melt	2000–250,000	20–1220	1100	5	H	1	N
Reverse roll precision	200–50,000	20–1700	14–450	2	H	1	N
Dip	40–1500	45–600	10–150	10	L	1	N
Nip roll	100–500	100–2000	70–170	5	I	1	N
<i>Doctored</i>							
Air-knife metering mode	1–500	40–400	0.1–200	5	L	1	L
Air-knife squeegee mode	5–500	125–2000	10–50	5	L	1	S
Blade/knife	500–40,000	350–5000	10–750	10	L	1	L
Dip & scrape	25–500	50–600	45–250	10	L	1	S
Dip & squeeze	10–3000	50–1000	45–450	10	L	1	S

Floating knife	500–1500	10–2000	50–250	10	L	1	S
Kiss coater	50–1000	100–1100	5–75	10	L	1	N
Knife over blanket	500–10,000	10–200	50–250	10	L	1	N
Knife over roll	100–50,000	8–400	26–750	10	L	1	N
Mayer rod	50–1000	10–1000	4–80	10	L	1	N
<i>Hybrid</i>							
Gravure direct, chamber doctor blade	10–200	25–2300	1–75	2	I	1	N
Gravure, direct	1–500	25–2300	3–65	2	I	1	N
Gravure, offset	50–13,000	10–1000	3–206	2	I	1	N
Meniscus	1–50	3–170	6–25	10	L	1	N
Micro-Gravure™	1–4000	1–330	0.8–80	2	H	1	N

TABLE 14-5 Selecting the Right Coating Method

Establish requirements and basic data	Determine Capability of Methods	Compare Requirements with Capability	Select 2–3 to Test and Evaluate	Use Best Method
Independent	Published tables	Several methods	Best from	Characterize
Coverage	Vendor data	Spread sheet	previous	process
Number of layers	Company data	Wagon wheel diagram	outside sources	coatability
Quality	Literature	Random walk	Experimental design	window; change if
Volume	Anecdotal	Delphic	Reproduce results	needed
Substrate			Coatability window	
Drying curing				
Economics				
Timing to market				
Depenent				
Wet layer thickness				
Line speed				
Solvent				
Rhelogy				
Hardware				
Safety and environmental				

which they are incurring. A system that has general classification categories, such as coating, drying, or mixing, or substrate, is insufficient. The system should quantify defect losses by type of defect and by product. The data should be entered and stored in a computer database so that all personnel can easily access it. Also, the data should be available for statistical analysis so that underlying trends as to type of losses and defect-susceptible products can be identified. This information will help to identify plant problems and will assist in developing a priority list for technical efforts to reduce losses.

An essential part of this defect loss system is to identify the defect by its physical characteristics. The major categories are:

- Linear continuous defects
- Linear intermittent defects
- Discrete point defects
- Pattern and diffuse defects
- Process specific defects
- Substrate defects

Each category has further subclassifications to help differentiate the defect type. For example:

- Linear continuous defect
 - Machine direction
 - Transverse direction
 - Diagonal
- Discrete point defect
 - Spot
 - Contamination coating
 - Contamination substrate
 - Other types

Any one defect can have multiple classification terms. Table 14-6 is a summary of the classification system and specific defect types included. By using this type of system, general trends can be identified and product-type differences identified. Again, there are computer databases to record and analyze this type of data.

USE STRUCTURED TROUBLESHOOTING PROTOCOL

Even with a defect prevention program in place, incidents of defect will occur. Therefore it is essential to have an effective troubleshooting protocol in place to determine the cause of the defect and to eliminate it. This will also provide more information to use to upgrade the defect prevention program. The previous chapters in this book discuss this in detail.

USE COMPUTER DATABASE TO STORE AND SHARE INFORMATION

There is a large quantity of technical data generated in implementing a defect prevention program and in using programs to troubleshoot defects. Effective use of this data can help develop programs to reduce defects and to minimize the impact of future defect episodes. If available, the knowledge learned from previous episodes can rapidly be applied to the current defect episodes. This reduces the time required to eliminate defects, reduces losses, and saves money. This information can also be used to train personnel.

Past experience can help with current problems but may not be available or easily accessed in the time or at the location required. Often the information needed is stored in hardcopy and cannot easily be located. In addition, the hardcopy may not be at the site where it is needed. Therefore the goal of the computer database is to store information developed, product requirements, pilot plant and manufacturing data, analytical data, defect data, technical reports on coater operation, and so on and to share defect information.

This database should be computer based and located on the company intranet. There are many available programs that can store and easily retrieve the needed technical information. A good approach is to have a series of small databases that focus on specific topics, requirements, defects, and analytical results, and a master program that guides the user to the appropriate specific database. The vast majority of current technical

TABLE 14-6 Defect Loss Categories

Category	Examples
<i>Physical Defects</i>	
1. Linear continuous	
a. Machine direction	Streaks, Ribbing
b. Transverse direction	Chatter
c. Diagonal	Diagonal Chatter
2. Linear intermittent	
a. Machine direction	Scratches
b. Transverse direction	Scratches
c. Diagonal	
3. Discrete point defect	
a. Spot	Bubbles, gels, comets
b. Contamination coating	Lints, dirt
c. Contamination substrate	Repellent spots
d. Other types	Repeat spots, blooming
4. Pattern and diffuse defects	Overall uniformity
5. Process specific defects	
a. Raw materials	Repellents
b. Coating	Air entrainment
c. Drying	Mottle, dryer bands, orange peel
d. Web transport and winding	Wrinkles, telescoping, repeat spots
e. Metallizing process	Blooming
6. Substrate defects	
a. Plastic	Gauge bands, planarity, contamination, winding
b. Paper	Wrinkles
c. Metallized	Railroad tracks
7. Product properties	
a. Coating weight	
b. Haze	
c. Adhesion	
8. Production properties	
a. Line speed of standard	
b. Set-up time	
c. Maintenance schedule	
d. Maintenance unscheduled	

information that would go into this database is generated in digital format and can easily be entered into the database after it is on-line and running. Adding past data may be more difficult if it is only available in hardcopy. Chapter 13 describes in more detail databases for coating defects.

IMPLEMENT IMPROVED PROCESS TECHNOLOGY

Even though the coating process is an old well-established process, significant new technology is continually becoming available. Existing coaters may not have all of the hardware and technology needed for the current product and process requirements. Thus implementing this new technology will lead to a more effective process and a reduced level of defects. The program to add new technology should be ongoing and should implement new technology when it can be justified and when there is capital available.

The program described at the start of this chapter should identify problem areas and provide an economic justification for improvement projects. Once these needs are identified, then technology and hardware to solve the problem can be identified and installed. The discussion in Chapter 12 identifies new technologies and hardware that can be installed.

This program should not be a one-time event. It should be an ongoing effort to continually upgrade the coater to prevent the occurrence of defects. A good opportunity to upgrade a coater is during a routine maintenance shutdown. When replacing worn-out parts, consideration should be given to using higher quality items, instead of just replacing them with the identical parts. The labor cost to install the new or old parts is the same, and the cost of an improved part can easily be justified.

USE STATISTICAL PROCESS CONTROL

The use of statistical process control (SPC) to optimize and control the coating line performance will lead to improved product uniformity, stability, consistency, and overall performance. SPC is an optimization technique for continually improving a process by utilizing statistical tools to monitor, control, and analyze data in order to make inferences about process behavior. The four basic steps in SPC are (1) measuring the process, (2) eliminating variances in the process to make it consistent, (3) monitoring the process, and (4) improving the process to its best target value.

There are several statistical tools that are commonly used in SPC.

- Flowcharts show the flow of material or information through a sequence of operations. They are an excellent visualization tool and are useful in the initial process analysis.
- Run charts are simply plots of process characteristics against time or in chronological sequence. They are useful in revealing trends and relationships between variables.
- Control charts are used to detect whether a process is statistically stable. They differentiate between variations that are normally expected of the process due to chance and common causes that change over time due to assignable or special causes.
- Cause-and-effect diagrams or fishbone diagrams are also called Ishikawa diagrams after their inventor, Kaoru Ishikawa. They are excellent aids for problem solving and troubleshooting and can reveal important relationships among various variables and possible causes. They can provide additional insight into process behavior and possible defect causes. Figure 14-2 shows a typical fishbone diagram to improve line speed.

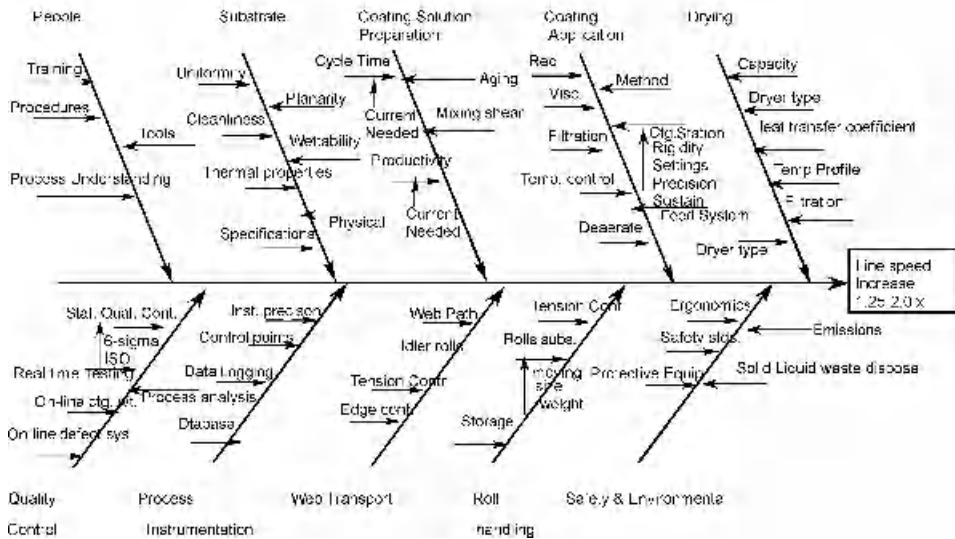


Figure 14-2. Cause-and-effect or fishbone diagram for a speed increase.

All of these and other statistical process control tools can be used to improve process efficiency and reduce defects.

DEVELOP FUNDAMENTAL PROCESS UNDERSTANDING

A strictly empirical approach to reducing defects is expensive and time consuming and may not be effective. The coating process has too many variables and interactions to effectively study and reduce defects. Therefore knowledge of the underlying fundamental principles of the varying unit operations in the coater is needed to achieve a cost-effective program to reduce defects.

In recent years, there has been a significant improvement in the understanding of the underlying physical principles and mechanisms of all aspects of the coating process. The fluid flow mechanisms in most of the coating processes have been defined and computer models and simulations are available to help understand defect formation. Sophisticated visualization techniques to study the coating bead have also been developed and help us understand how defects are formed. A basic understanding of the drying process has been developed, and computer simulations have been used to study drying defects such as starry night. Models are available to accurately predict drying behavior, such as film temperatures, location of the dry point, and effects of varying input parameters such as concentration, solvent, air temperatures, and velocities. Similarly, the fundamental mechanisms of the substrate unwinding, transport, and rewinding have been developed.

An understanding and utilization of the fundamental principles and mechanisms and how they apply to a specific process are essential to a successful defect prevention and

troubleshooting process. Both academic and industrial personnel have developed these fundamental mechanisms. Their works are published in books and journals. In addition, a wide variety of technical meetings are held each year, where both the latest results are presented and past efforts are reviewed. Organizations that sponsor these meetings are:

- International Society of Coating Science and Technology (ISCST)
- Industrial Partnership of Research in Interfacial and Materials Engineering (I Prime) of the University of Minnesota
- Association of Industrial Metallizers, Coaters and Laminators (AIMCAL)
- American Institute of Chemical Engineers (AIChE)
- Technical Association of the Pulp and Paper Industry (TAPPI)

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