COATING AND DRYING DEFECTS
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

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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.

Edgar B. Gutoff
Edward D. Cohen

October 1994
ABOUT THE AUTHORS

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.
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.
- A fundamental understanding 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
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