Introduction

This book is divided into 3 sections: Machines, Mechanics and Measurement, as well as a CD of winding models. Each section is complete enough to stand alone as a book. Yet each compliments the others by viewing some of the same issues from different perspectives, thus the reason for occasional redundancy. Sometimes different perspectives are merely in the nature of knowing things differently; by observation, analysis or measurement, respectively. Sometimes the differences reflect the knowledge, experience and intuition of the two authors who blend their contributions in different proportions in different sections of this book.

Although we may know the world differently, by observation, analysis or measurement, we hope that the conclusions reached will be the same. Hope is all we can do because for a given issue there may be no overlap between these three different realms of knowledge. It is not unusual for observation not to be supported by analysis or measurement simply because science has yet to be employed for that issue and the science of winding has still much work ahead of it. Hope is all we can do if we test analysis against experiment against observation. To do more would invite bias. We will let the results speak for themselves. What we expect is that these three realms do not disagree when they do overlap. If so, we would have more work to do before trusting the results. The good news is that little of the work in this book conflicts with itself. Even more comforting is that most of the work presented is compatible with experience, analysis and observation. In other words, the work is verified by different realms of knowledge.

The Machines section should be easily understandable to anyone who is familiar with that type of machinery. It does not require any special education or training to use and would thus be useful to the operator, process engineer or marketing manager alike. If you have no familiarity with winding, being brand new to the industry, the only requirement will be a modicum of mechanical aptitude. In that case a fuller understanding will await some hands-on experience as few things can be learned solely from a book.

The Mechanics section is rigorous. We make no apologies here because that is the nature of the engineering view of the world. Here we need little or no experience whatsoever, but education is required. A bit of college engineering or science will make this section more meaningful. Like almost all things, web handling, engineering mechanics and physics are the tools of the trade. Even so, there are many conclusions reached that will be useful for all, even if you do not fully understand how we got there.

The last section of the book is Measurements. Easily readable by all, it is also perhaps the most widely applicable. Roll quality is everyone's business and measurement of quality should also be. This section is very hands-on and also very application dependent. Some methods work much better for some applications while not at all for others. Experience, trial and error persistence and especially statistical reasoning will help to guide the practitioner to the best measurement tool for their situation.

All sections review their subjects through the lenses of both application and history. The cited literature is extremely complete. All sections are current as of this writing, with one tiny exception. The very latest modeling is not included because it is held exclusively for sponsors of the WHRC for a short time before being made public.

The enclosed CD contains winding models. These models are provided so that you can observe how material properties, winder type, and environmental effects such as air entrainment and changes in storage temperature affect the stresses in a wound roll. When you ask if the output of the winding model is truly representative of conditions within your rolls I would tell you that nothing in this world is truly free. The results of all models are limited by the quality of the input data the user provides. Some web material properties have been provided on a worksheet so that you can explore the use of the models without having to go to the laboratory to measure inputs during the learning process. When you feel confident that you are applying the winding model correctly and wish to model the winding of your webs it will be time for you to have property measurements made for your webs. Those that understand paper formation, film extrusion, and web coating know how much these processes can affect the web properties. As an example, one might assume all polyester films would have similar properties; this is untrue. Surface roughness is a designed property of plastic films and is achieved by including small diatomic particles, whose size has been classified, in the extruding process. Without changing web thickness this can cause the K_2 factor of the radial modulus to range between 30 and 300. For paper webs, coatings and calendaring can greatly affect web properties. Even the properties of metal webs are affected by the machinery in which they are made. The message is that if you wish to accurately model your rolls, you will have to invest time and resources to measure the properties of your web that are inputs for these models. You will find Chapter 6 informative when it is time to measure these properties.

Zen and the Art of Winding

For 5,000 years thin materials such as papyrus had been made in batches and cast into sheets. With the invention of the Fourdrinier paper machine by Louis-Nicolas Robert in 1798, webs could be made continuously for the first time. A wound roll served well for three manufacturing needs. First, it took up the continuously produced web as fast as it was made. Second, it stored the material in a compact and convenient form. Third, it served as a buffer between continuous manufacturing and discrete consumption. Without the winder the enormous economic advantages of continuous manufacturing over batch production would not be realized [1].

Paper and textiles were among the first materials produced as a web, and thus, wound. Steel and plastics followed. Now a wide variety of materials are wound. Not only did the range of materials expand, so did the range of roll sizes. The first rolls could be lifted by hand. Now parent rolls from large paper machines exceed 10 meters (400 in) in width, 3 meters (120 in) in diameter and 120 tons. Rolls from the metals industry are smaller but similarly heavy. However, wound rolls can also be quite small as shown by familiar examples such as cassette tape (polyester film) and cash register tape (bond paper). Less expected but even smaller rolls include some capacitors used in electronic circuit boards and some types of paper lollipop sticks. Table 1.1 gives some examples of more unusual wound rolls. In addition to the extreme ranges of composition and sizes, winding speeds can vary by orders of magnitude. Some processes are so slow that it is difficult to see web movement unless you look closely. In the paper industry, however, speeds regularly exceed 2,000 mpm (6,000 ft/min) and some commercial winders are able to run at

TABLE 1.1 Some unusual wound rolls.

Paper rolls the size, weight and speed of a delivery truck
Rolls in the metals industry that take days to cool
Lollipop sticks that have no hole
Capacitors smaller than the eraser on the end of a pencil
Cores such as those on the inside of toilet paper rolls
Fiberglass house insulation
Asphalt roofing
Skeins of yarn
Fishing reels
Candy and gum as rolled strips

twice that speed. Winding web thickness is no less impressive, easily ranging from less than 10 microns (0.0004 in) (thin film, foil) to more than 100 mm (4 in) (fiberglass insulation) thick.

It would seem that the vast scope of wound roll materials, sizes, speeds and other factors would not be constrained by a single set of physics. However, we now know through experimental evidence that a comprehensive physical model can be used to explain how the winding world operates. In other words, the physics underlying the winding of sheet steel and toilet tissue are the same. It is this physics that we seek to explain in this book.

THE TNTs OF WINDING

Almost all winders fall into one of four common classes. Here we use the word *class* as both a mechanical description as well as a description of what controls are available to vary the tightness or density of the wound roll. These controls are commonly called the TNTs of winding, which stands for Tension, Nip, Torque and speed as illustrated in Figure 1.1. The lower case "s" reminds us that only some materials are strongly speed dependent.

In the descriptions that follow and for the rest of the book, we will use the word *roll* to refer to the wound roll of product. We will use the word *roller* to refer to a bearing supported cylinder which transports the web usually made of metal. This terminology is not universal because some industries shorten the word roller to roll, in effect having one word mean two different things. To compound the problem, a roller may be called many things depending on the industry, the machine, the component referred to and the individual. For example, a large roller might be called a

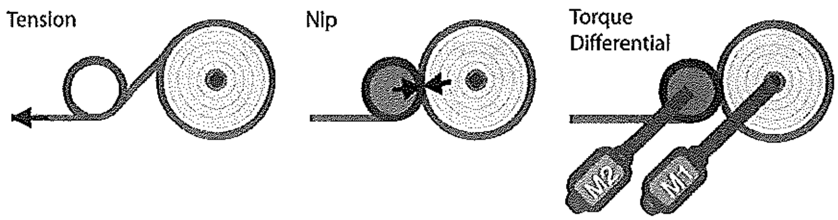

FIGURE 1.1 The TNTs of winding. Tension, nip, torque and sometimes speed are the primary controls for wound roll tightness.

can or drum. The roll may also be given other names such as *reel*, *package* or *doff* used to refer to paper, textile and nonwoven rolls, respectively.

The first T in the TNTs of winding stands for simple incoming web *tension* as might be measured by a load cell roller if the winding machine were so equipped. The reader will note that here when we refer to tension, we are usually using it as a shorthand for machine direction (MD) web tension just prior to entering the windup section. This usage is opposed to some other tension that might be measured at some other time or at some other location. The N stands for the *nip* formed between a roller and the winding roll. This roller is variously known as a drum, layon roller, pack roller, rider roller and other terms, depending on the industry and the type of equipment. The second T stands for *torque*. This is a very confusing term because it is not strictly a torque but rather a shorthand for the *torque differential* between two motors. There are two main types of winders that can produce a torque differential: the center-surface winder and the two-drum winder. While the mechanical designs of these winders differ, the effect on the winding roll is similar. To add to the confusion, *torque differential* is called *winding force* by one large winding machine builder. Finally, some older two-drum winders have drums that are geared together with a small speed differential instead of torque differential.

The small "s" stands for *speed*. This serves as a reminder that some winding systems are speed sensitive. In particular, entrainment of an air layer with the winding web may reduce the tightness of the wound roll. The most speed sensitive applications are the high speed winding of wide, smooth and thin webs such as polymer films, but metal and paper webs may also be affected. This reduction of roll tightness can become noticeable beyond ~30 mpm (100 FPM) on winders that do not have a nip roller or an effectively functioning nip. There are also centrifugal and rheological speed effects that can affect winding, but the number of ap-