THE Web Handling HANDBOOK

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The Web Handling Handbook

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If I have seen further it is by standing on the shoulders of giants.
—Isaac Newton, 1676

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1
Overview

What is a Web?

A web is a sheet of flexible material long enough to run in a machine for minutes, hours, or days. Normally, a web's width is many times greater than its thickness. Webs can range in thickness from 1 μm for capacitor film to over 25 mm for conveyor belting and from 1 mm wide for dental floss to 10 m wide for polypropylene film, a factor of over 10,000 in each case. Wound roll diameters can range from several millimeters for spools of adhesive tape to a few meters for paper and nonwoven webs.

Example webs are listed in Table 1.1 and described further in Chapter 2.

Many industries use different terms for the same material such as sheet, board, or plate, when it is too thick to wrap a roller without damage or the use of excessive force. Some final products run as webs, including magnetic recording tape, cine film and conveyor belts, which are "endless" webs.

What is Web Handling?

Web handling is the process technology of moving webs through a machine or web line. In this book, we will also include winding, the technology to produce rolls of web material.

The formation of webs from their starting materials, whether wood pulp, plastic pellets, molten metal, or fibers, eventually reaches a stage where the web is recognizable and able to support tension. From this point on, web handling technology is essential. Further processing steps may be carried out on the forming line, or on separate converting lines that permanently change web properties or dimensions, combine mul-

Table 1.1. Web materials.

- Paper
- Plastic film
- Metal foils
- Woven fabrics
- Nonwovens
- Carpets
- Flooring
- Fiber composites and prepregs
- Gauze, mesh and netting
- Foams
- Glass
- Multi-layer products

tiple webs into one, or apply coatings. A final product may require more than one line, often starting with a forming process, then moving to one or more converting lines, and ending on a machine that produces a package, sheet, or part. Table 1.2 lists common converting processes (including transformations and other operations). In recent years, the manufacture of optoelectronic devices on flexible substrates, such as photovoltaic cells and flexible displays, uses similar methods and has been called Roll to Roll (R2R) processing.

The role of web handling is to present the web correctly to each process step. It should be flat, straight, at the correct and steady location and speed, wrinkle and damage-free, and have an acceptable tightness (tension). There is often an additional role of providing a control parameter, normally speed or tension, in the step. Finally, web handling may need to deal with change produced during a step, for example width, thickness, or temperature.

Web handling technology can be considered to have its origins in the mechanization of production of long-established materials, such as cloth and paper, using rollers, nips, and winders familiar from manual batch processes. Using web lines allowed efficiency gains by carrying out processes continuously in sequence, similar to an assembly line. A timeline of important innovations is given in Appendix F. The older web industries, such as paper, textiles, and metal foil have largely grown separately, but have exploited technology transfer of converting processes and machines. Web handling forms the common ground among them, and also with the newer materials listed in Table 1.1.

Web handling is both art and science. The early history of paper, textiles, and foil processing was an art, based on experience, the results of trial and error, and a good feel for how the material and machines be-

have. Web handling as a science draws on engineering principles from several fields and applies them using equations and software, together with the knowledge of their applications and limitations. Over time, the fundamentals are becoming better understood, and more quantitative methods are becoming available. Appendix F also lists the important role played by large corporations, universities, trade organizations and individuals in developing, communicating, and applying the science that undergirds web handling.

Web handling sub-technologies include: web properties, roller design, web-roller traction, tensioning, nipping, guiding, spreading, winding/unwinding, and wound roll quality. These combine several engineering disciplines: mechanical, material, electrical, and control. Areas of mechanics include dynamics, deformable materials, and tribology (the study of friction, lubrication, adhesion and wear). Sensors can include force measurement, optics, ultrasonics, and image analysis and

Table 1.2. Converting Processes.

Converting Processes	Examples	
Liquid Addition	• Coating • Gluing • Moistening	• Priming • Printing
Vapor Deposition	• Atomic Layer Deposition • Chemical Vapor Deposition • Metal Evaporation	• Plasma Coating • Sputtering
Surface Modification	• Corona Discharge Treatment • Plasma Treatment	• Flame Treatment
Curing and Drying	• Curing by Heat, IR, UV, E-Beam, Moisture, Reactive Chemistry	• Forced-Air Drying • IR drying
Combining Webs	• Delaminating • Island Placement	• Laminating • Splicing
Mechanical Modification	• Calendaring • Creasing • De-curling • Embossing • Folding	• Knurling • Leveling • Stabilization • Stretching
Cutting Processes	• Die Cutting • Perforating • Punching • Scoring	• Sheeting • Slitting • Stamping
Product Formation	• Binding • Form & Fill Packaging	• Wrapping

recognition. The combination of sensors, actuators, system mechanics, and control is common to all web handling and is an example of "mechatronics." Special cases involving heat and mass transfer, humidity effects, and electrostatics are frequently encountered.

This book will survey the current knowledge of web handling and provide guidance on how and when to use these methods. Success will be seen to stem from an approach using both art and science.

The Benefits of Great Web Handling

Web handling is not considered a value adding process, since moving a web from point A to point B does not convert or change the web's properties. However, poor web handling can definitely subtract value. Poor web handling can cause scratches, wrinkles, web breaks, or many other defects that can lead a process to 100% waste.

Good web handling preserves product value and is able to do so even when the incoming material is slightly variable and imperfect. The resulting benefits include: reduced defect waste, increased output, more time spent producing good product, better reliability, less maintenance, more flexibility to swap between products and to bring in new products, and enhanced product quality and perception by the customer. Web handling needs to be part of day-to-day operation, but should receive extra attention during projects on the line. These projects could be: the design of new equipment and upgrades, extending the product range, increasing capacity and efficiency, and tackling the causes of defect material.

One purpose of this book is to set down engineering principles for handling webs of any material. Applying these principles has driven improved process capability, increased productivity through size, speed, and thickness changes, and overcoming barriers resulting from awkward properties and process requirements of unusual materials. Without these principles, each industry is reliant on trial and error, intuition, or easily mislaid knowledge held by one individual, a single team, or an organization. It may not be obvious that the same science applies to bath tissue and aluminum foil, 12 mm wide electrical tape and 5 m wide carpet, food packaging, and roofing materials. Yet in all cases, the science of web handling provides useful insights and in many instances it furnishes quantitative explanations, whereby it is possible to calculate the requirements for machine design and operating conditions, and also troubleshoot problems.

Conventions

The web travels along the length of a line in the *Machine Direction* (MD). The *Cross Direction* (CD) is at right angles to the MD in the plane of the web. Sometimes this is termed the cross-machine direction (CMD or XMD), lateral, width, or transverse direction (TD). The third axis is the *Z-direction* (ZD), alternatively known as the through-thickness direction (TTD). X, Y and Z coordinates are chosen along the MD, CD and ZD respectively, forming a right-handed set.

In this book, *rollers* refer to the turning cylinders that transport the web, and *rolls* are the packages of web created at a winder or dispensed at an unwind. In this text, the authors call the axial dimension of a roller the width, in order to be consistent with the web. However, it is recognized that others call it the length.

The terms upstream and downstream (also downweb) are relative to the direction of web travel. The web edges will just be referred to as left and right, looking downstream. There are many other options, but these are industry-specific (front-back, feed-blank, wet vs dry end) or refer to an arbitrary layout of the machine (drive, operator, machine-side, tending-side, gear side, or compass direction).

Units

This book uses SI (metric) units but also gives the equivalent in English (US customary, Imperial) units. Mathematical equations are in consistent units, for example, the appropriate base units such as m/s, N·m. The industries applying web handling often use measurements that need conversion to base units, such as m/min or mpm, kgf, and rpm. Dimensionless (unitless) quantities, such as "strain" and "draw," are often written and stated in percentages (e.g. 0.4%) but are always used in decimal form (0.004) in equations. A full list of conversions is given in Appendix C, and there are many online unit converters.

Web Line Basics

In a web line, the material moves continuously through a sequence of processes, transported by rollers. The line is normally divided into sections, where processes to change the web may be carried out. Subdivisions are also known as modules or stations. For example, a gravure

press may have a printing section, with 5 stations each printing a separate color.

Web Path

Most lines operate with the web taut (carrying tension), and the web path follows closely the cylindrical surfaces of the rollers and the tangent planes between them.

The wrap is the path on each roller that defines the wrap length and wrap angle subtended by it at the axis of the roller (Figure 1.1). The span is the planar web section between rollers. The span length is that of the tangent between the two rollers (Figure 1.2). These geometrical definitions are normally used, even though the web may stick to a roller, bend outside the contact zone, or sag appreciably in a span.

Each span has an aspect ratio, defined as the ratio of span length to web width. It is often referred to as L/w ("L over w").

The web line frequently ends with the formation of one or more rolls on a winder or rewind. The source of the web is either its forming process or a roll on the unwind.

Most information about the layout of rollers and the web path is shown in an elevation (side view). Most engineering drawing packages can also produce elevations from each end, and a plan (top) view. In this book, sometimes two additional views are shown, with the web path straightened out and apparently no wrap on the rollers. The first is a

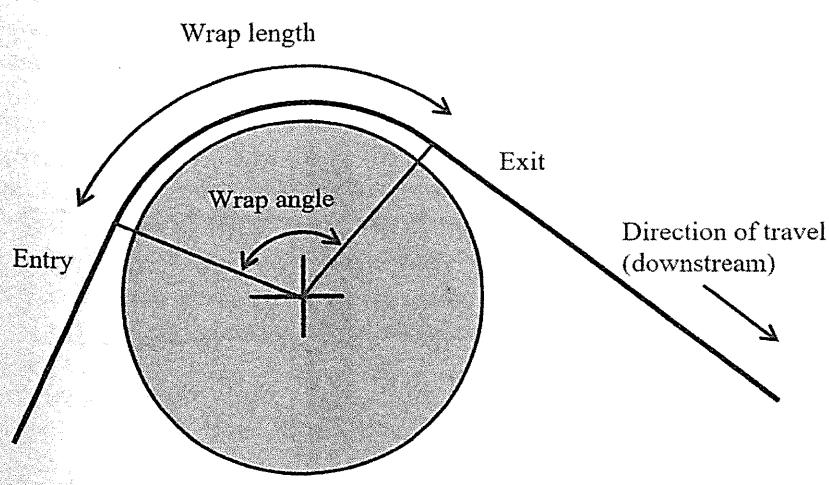

Figure 1.1. Definition of terms for a web passing around a roller.

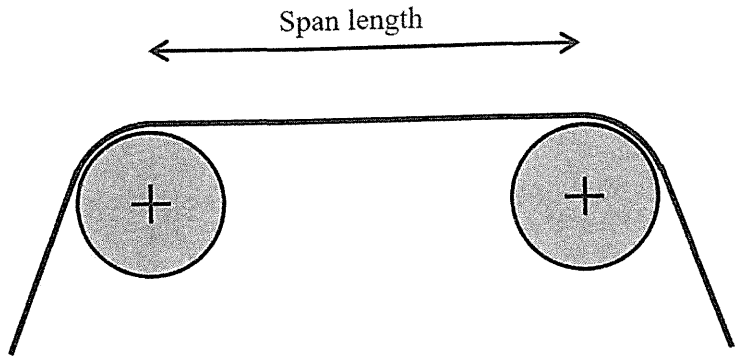

Figure 1.2. A web span between rollers.

modified elevation in which the web runs over the top of all the rollers. This is often used to show the drives and control logic, for instance, as part of a block diagram. The second is a "plan" view (Figure 1.3), which is used to show the causes and results of sideways steering, spreading, and wrinkling. The web path can be considered to be the actual position through the machine of the web centerline. This may deviate from its desired location, which is often straight down the middle (see curved dashed line in Figure 1.3).

Tension

The web is moved along the line by forces transmitted by friction on driven elements, and by torque supplied to the winder. To prevent runaway and allow control of tension, certain elements provide a braking force that opposes the web's motion, including a braking torque applied

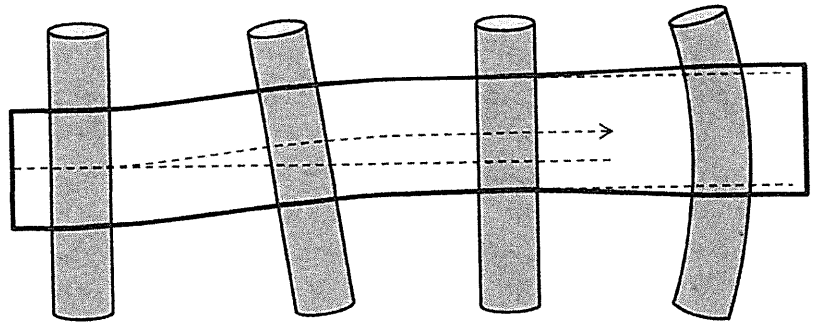

Figure 1.3. Schematic plan view of web showing steering and spreading.

to the unwind during steady running. The rollers that merely support the web or control its direction are often driven by contact with the moving web rather than having their own mechanical drive (i.e., idler rollers). Modern lines have electric motors to provide drive to rollers and winders. Separate brakes, or the braking function of motors, are employed. Electrical drives supply current to the motors, which is based on calculating the required values to operate the line in a controlled way. Chapter 6 covers this in detail.

Tension is a measure of the internal load in the web material as it transmits forces between driven elements. Two measures of tension are most commonly used: *tension force* in newtons (N), kilograms (kg or kgf), or pounds (lb). The second measure is *lineal tension*, which is equal to the tension force divided by web width and quoted in N/m, kg/m, or pli (pounds per lineal inch). The word "tension" can imply either, depending on the context. The authors recognize that this might lead to confusion, but it is accepted practice, and the ability to use both measures is essential to describing web handling. Thus, readers must be careful to understand which measure is meant when the word "tension" is used. In written materials, the units are often given or the meaning is clear from its use in formulas. In conversation, it is often necessary to ask which quantity the speaker is using. Tension force is measured using rollers mounted on load cells and is used in machine design to size equipment. Lineal tension (and stress, below) is most useful when considering the web material behavior in the line. (In equations, F is preferred for tension force, and T is used for lineal tension.) Figure 1.4 illustrates these tension definitions.

Tensile stress, defined as tensioning force over cross-sectional area, is the true predictor of the stretch or strain in the web and whether a web will yield or break (Figure 1.4). If either thickness or width doubles, tension force would need to double to maintain equal stress. Tensile stress is difficult to define for materials whose thickness is ill defined, such as with many nonwovens, textiles, and tissue. In that case, lineal tension is used, and the basis weight quoted.

The lineal tension and tensile stress calculated from the total force are average values. However, it is a common observation that the tightness of the web varies with location in the CD and sometimes in the MD also. Lineal tension and tensile stress are assumed to vary with position: the tension force on an imaginary small embedded rectangle of web is equal to its width multiplied by the lineal tension at that location. In this way, a CD tension profile, or plot of lineal tension against CD location, can be built up (Figure 1.4). Tension variation across the width is com-

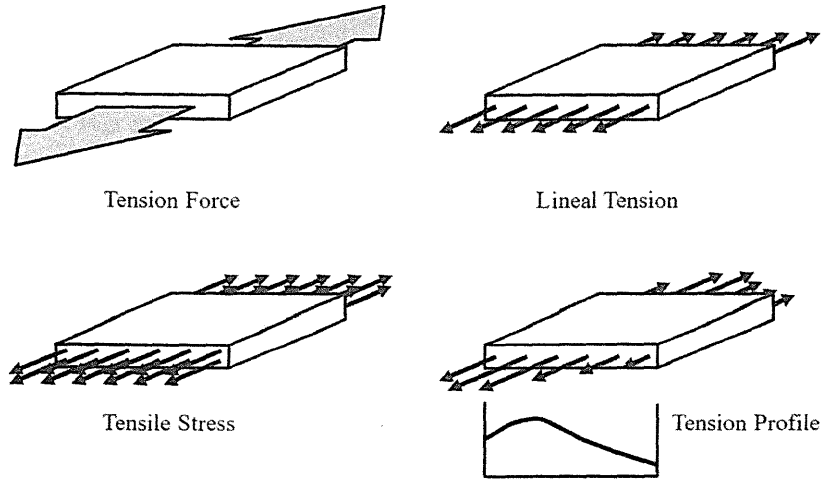

Figure 1.4. Tension in the web shown as tension force, lineal tension, and tensile stress; and a non-uniform tension profile.

monly due to a baggy web or misaligned rollers. A constant, uniform tension profile is ideal, but rare.

Tensile stress can also vary through the thickness (ZD) due to bending around a roller and from residual stresses created during processing. MD variations can occur from span to span due to roller bearing friction and roller inertia, and across drive points. Time variations can arise from the drives, out-of-round rolls, and other disturbances.

Average values of tension force, lineal tension and tensile stress are used for specifying running conditions, but the variations in MD, CD, ZD and time can be very important for web defects and breaks.

Steady and Non-Steady Operation

When a line is making good product, it usually runs at a constant speed. Ideally, the web CD position and its properties are unchanging. The tension at each point along the line is either constant in time or varying slowly in a controlled way (e.g., in the winding section). Tension may step up or down between sections of the line. These are *steady-state* conditions and are treated as independent of time. There can be dynamic effects due to the web's inertia, such as centrifugal force as the web wraps a roller or is shifted laterally by a web guide. However, these are negligibly small at all but the highest speeds, and a static analysis of forces would apply.

While the line is brought up to speed or slowed down to a stop, the inertia of rollers and wound rolls becomes important. These periods of acceleration and deceleration are often set by the drives.

Steady-state operation is never truly constant: variation is permissible if small enough but can lead to defects or even web breaks if too great. Typical periodic disturbances include: an out-of-round roll, unbalanced or eccentric rollers, drive speed or torque ripple, mechanical hysteresis, machine vibration, and imperfect control. There are also isolated events or transients, such as engagement of roll change equipment (e.g., winder turret or accumulator), a splice, and coating start and stop. These can upset tension, web position and the operation of processes, and cause permanent defects in the web, such as creases, stretched areas, tears, or breakage. The application of web handling principles allows the reduction of the magnitude and effects of disturbances, through the mechanics of the line and the control system.

Many webs, especially if they are brittle or weak, are prone to breaks, when the upstream and downstream parts of the web separate. The downstream part continues along the machine, loses tension because it is no longer connected to the braking element or unwind, and may accelerate to high speed if allowed by the drive system. The upstream part may continue to feed or run on, resulting in web piling up or wrapping up on a roller, which can damage equipment. Sophisticated control systems have web break detectors that bring all parts of the line to a halt with minimal damage. Breaks often initiate at weak points, holes, nicks, or tears, which are often found at an edge. Severe weaknesses may lead to failure, even in steady-state running. More commonly, breaks occur when the tension at the weak point exceeds a critical value, well above the average or nominal value.

The web line and its control system also have to perform in other modes, which are explained in Chapter 6. As part of threading up and splicing, the operator may activate take-up slack, stall tension (with one drive point stationary), or jog (slow running on demand). The control system may automatically implement the logic needed for roll changes, bringing coating heads into the line, and so on. Finally, the line must carry out emergency stops and react safely to other faults when they arise.

Width Setting

It is common for a web line to accommodate or produce different web widths. In products formed from liquids, such as paper and ex-

truded films, the width is sometimes adjusted ("deckled") by blocking the flow through the die by an insert at each edge. Confusingly, the term deckle can refer to both the inserts in the die and the width of the resulting web.

The operation of slitting cuts the web lengthwise, and produces narrower cuts, lanes, or strands if very narrow, and these wind onto separate slit rolls. After slitting, these lanes act completely independently of each other and are independent webs in their own right. The edges of the original web are often slit off as edge trims, either as part of the main slitting step or alone to remove unusable material after a process. Sometimes, trims are taken between the cuts. The term lane is also used for a portion of the web width extending over a considerable MD distance. A band or streak is a lane that differs from adjacent web in thickness, bagginess or tightness, or coating weight. A loose lane, for example, might extend in the machine direction for several spans and appear floppy compared to adjacent web.

Key Web Handling Principles

Web handling relies on several key principles introduced below. They are fully explained in later chapters, with examples and exceptions. Their use in troubleshooting, machine design, and process design is also covered.

Web Handling Goal

The goal of web handling is to present the web correctly to each process step. It should be flat, straight, wrinkle-free, and without damage. Speed, tension, lateral position, and width must be within acceptable ranges required by the process step, and achieved by some degree of control.

Tensioning (Chapters 2, 5 and 6)

The acceptable tension range for a web depends on the material's properties (yield or break stress), thickness, and width. A typical guideline is to run a web at 5–20% of its yield or break point. This gives a safety factor to allow for tension variation over time, stress profiles across the web's CD and through its thickness, variation along a series of rollers, and the statistical spread of break stress. Such a safety factor

is needed to avoid looseness in the web resulting from too low a tension or damage to the web due to high tension.

A web line is normally divided into tension zones, each with its own tension level appropriate for the process and material condition (e.g., temperature, moisture content) within it.

Measuring tension in each zone has many advantages. It provides valuable immediate process information and the option for closed-loop control. The tension measurement must be accurately zeroed and calibrated in the correct units, and the web path over the measurement roller must be constant.

The line's mechanical and electrical design should allow a range of operating tensions for different web thicknesses, widths, and materials. Tensions that exceed the motor torque available or are too small to set precisely because of signal resolution, friction, and inertia, limit the possible webs that can be run.

Web Mechanics (Chapters 4 and 5)

Tension in steady running is provided by braking the unwind roll, driving the rewind roll, and by frictional contact with surfaces (driven, idling or stationary). Controlled drive to rollers creates drive points, which separate the tension zones. The idler rollers in each tension zone are driven by contact with the web.

Most webs are *linear elastic* when running through the web machine, meaning that they stretch in proportion to the applied tension, recover completely when tension is removed, and permanent deformation and creep are small. The fractional length increase, or *strain*, is typically 0.1 to 1%.

Though rarely measured or even calculated, web strain is the key to understanding many web handling problems, including misalignment, speed ratio tensioning, curl, bagginess, compliant nip roller coverings, and multiple roll quality problems.

In steady running, the percentage change in web speed along a line is identical to the percentage strain change. For example, the rollers in a zone at higher tension run faster. Relative roller surface speeds are employed in *draw control* to set tension. This requires a speed precision better than 0.001%, obtained from modern electrical drives or accurate, adjustable mechanical coupling.

The steady running speed has little influence on the behavior of web in the machine. However, at high speed, air entrainment and vibration may become significant, causing problems. Inertia effects during ac-

celeration and deceleration can cause tension upsets, slip on rollers, and loss of lateral stability.

The force transferred during contact is provided by friction between the web and roller. At high speed, air can be dragged into the contact region, resulting in partial or total loss of friction force because of air lubrication. This reduced level of friction is termed *traction*, which decreases as speed-to-tension ratio increases.

The "normal force" for friction of a web wrapping a roller is provided by the tension acting in a curve, like tension in the skin of a balloon balancing the increased pressure inside. Nip rollers apply extra force, and vacuum rollers suck the web onto the surface, which greatly increase the normal force and hence the traction available, enabling effective separation of tension zones.

With good traction, points on the web move with the underlying roller's surface over at least part of the contact. A tension or direction change is accompanied by microscopic movement, termed *microslip*, as the web gradually extends or contracts. With poor traction, *full slip* occurs and the web slides at all parts of contact. It is difficult to achieve steady conditions when traction is lost, or if good traction is only intermittent.

Rollers and Nips (Chapters 3 and 7)

Good design of rollers and nips is important. Particularly critical factors are: bending (deflection) under the combined effects of weight, nip load, and web tension; surface hardness, roughness, groove pattern, and friction against the web; alignment, cylindricity, inertia and bearing friction.

Process nip rollers control web thickness or apply through-thickness pressure to the web. Higher nip loads, created by pushing two rollers together from their shaft or journals, are prone to CD variations from roller deflections, which can cause lateral movement and CD wrinkles. Many methods are used to reduce CD nip variations, starting with larger diameters and compliant coverings.

Guiding (Chapter 8)

Good traction keeps the web stationary relative to the moving roller surface. In order to achieve this in steady state running, the web approaches the roller with its center line perpendicular to the roller's axis. This is called the *normal entry rule*, which is shown in Figure 1.5 (al-

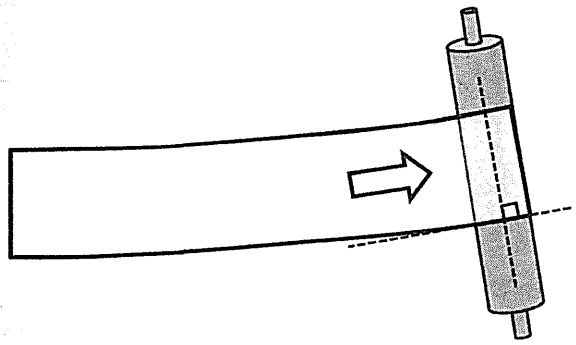

Figure 1.5. Web contacting a roller with normal entry at steady state.

ternatively the "parallel entry rule," because the web and roller surface velocities have the same direction). If the web approaches at a different angle, it will form a helix on the roller, analogous to the barber pole illusion. The entry point moves laterally, and therefore the web is not in a steady state.

A running web can shift laterally in response to path upsets. CD shifting causes include: misaligned and tapered diameter rollers, unwind and winding rolls, and other elements; changes in traction; heating and air jet variation in the CD; and splices with a CD or angular offset.

Passive and active web guides limit web movement; furthermore, active guides return it to the desired location. Some web paths must be controlled to better than a hair's thickness (100 microns or 4 mils) and others merely need to be kept from going off the edges of rollers.

Wrinkling and Spreading (Chapters 9 and 10)

Some changes in web direction, like that shown in Figure 1.6, result

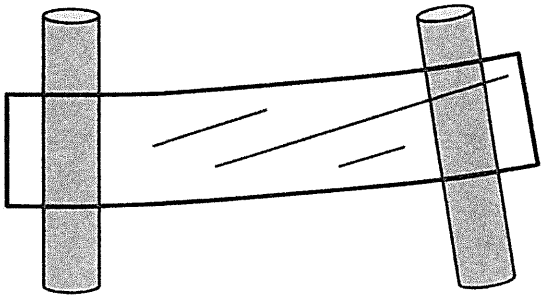

Figure 1.6. Web bending with a wrinkle forming.

in in-plane bending. This raises tension at one side of the web and lowers it at the other, especially near the entry to the span.

Thin webs cannot resist in-plane compression, for example generated by in-plane bending, and may form regular waves in the span (troughs), regions of slackness, and wrinkles on rollers (Figure 1.6).

Spreading devices prevent troughs and wrinkles, provide lateral tautness, and may also separate slit webs in the same path.

Winding (Chapter 11)

Webs are normally wound into rolls for packaging, storage, transport, and unwinding within or between operations. Web handling principles apply in winding.

Winding requires a good support at the roll's center (normally a core). Larger rolls need tension to be reduced (taper tension) as they build. Many require a winding nip roller to support the roll, reduce air entrainment, and thus preserve tightness and/or increase hardness.

Wound rolls develop internal pressure which creates the friction holding a roll's layers together. However, large pressures can collapse the core, and low pressures can let turns slip during winding and unwinding. If the pressure variation with radius is non-ideal, wrinkle defects can be generated.

Defects (Chapters 2, 4, 9 and 11)

Web handling and winding defects such as wrinkles, bagginess, and curl become permanent if set in by storage on a wound roll, elevated temperature, or ironed-in by pressure in a nip or wound roll.

Baggy webs (Figure 1.7) contain variations in MD length across the CD that make them prone to partial slackness or creasing at nipped processes. They can also cause problems with print registration, coating, steering and other processes. Bagginess is usually created by winding and storing a roll with lanes of very slightly increased thickness, or on occasion by the web manufacture and processing. Bagginess can be "pulled out" by raising tension, but this may risk damaging the web.

Curl is the tendency of the web to form a curved surface rather than remain flat (Figure 1.8). Its main causes are storage on a wound roll, and differential strains (either MD or CD) in laminated or coated webs caused by tension, temperature, and/or moisture. Raising tension normally reduces the visible curl on the line and reduces edge fold-over, but may increase CD curl in laminates.

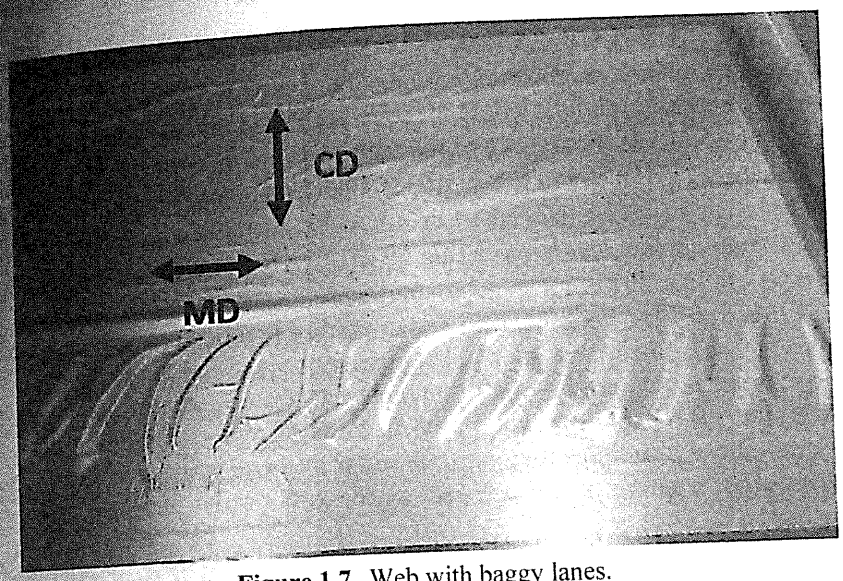

Figure 1.7. Web with baggy lanes.

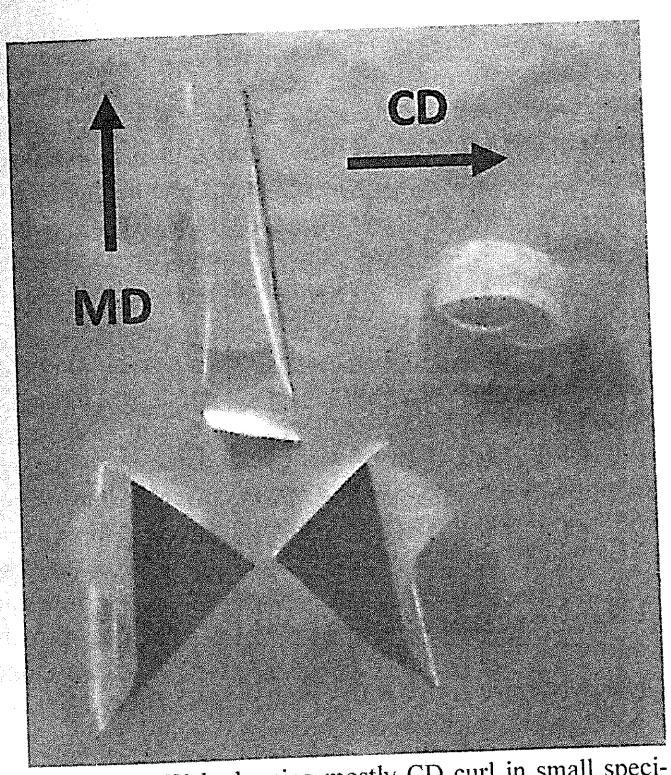

Figure 1.8. Web showing mostly CD curl in small specimens and from an X-shaped cut.

Scratch defects on the web surface are caused by full slip between web and roller, and their length is related to the speed difference. They are caused by the movement of the web over microscopic high points on the roller surface or debris particles. Shorter and less visible scratches or brush marks can be caused by microslip. Both web and roller surfaces may abrade, leading to a thin layer of web material on the roller, which can later break off as debris particles.

Of course, good engineering and operating practice are also essential, but web lines have special requirements over and above normal concerns such as sizing of components and frames, driving rotating machinery, and safe operation with hazards of nips and moving surfaces. These principles may be unfamiliar to those who have worked with other rotating machinery and systems that move discrete components.

Control of Conditions

Achieving the goal of presenting the web correctly to each process step implies that conditions can be set and adjusted as necessary. The main variables are speed and tension, with nip force, torque, roll diameter, air pressure and vacuum level encountered also. In an ideal world, these would be measured and displayed near the machine in engineering units, such as mpm, fpm, newtons or pounds. This enables different product conditions and machines to be compared, as well as the analysis of web behavior using established principles, equations and models—one of the main themes of this book.

However, provision of all these measurements would add considerable complexity and cost, and is implemented only to a limited extent, if at all. Meters and digital displays often show measured values as percentages, and the quantity shown is sometimes a parameter that is set on the machine, such as an air pressure or motor current. All measurements should be calibrated, but these machine parameters also have a multiplier and poorly-defined friction or loss to be subtracted to obtain the web variable. Even worse, some machine parameters are determinable only from the position of a knob, sometimes without a scale, or set within the electrical cabinet or by adjustable pulleys. Others depend on mechanical design, such as spring strength, subframe, and roller weights. In all these non-ideal cases, considerable investigation and measurement is needed to establish the true web parameter values.

Modern plant control systems can record and recall many web

variables. They can be linked together to produce derived units, such as lineal tension in N/m or lb/in from the tension force and the web width, or even stress by dividing by the thickness. However, these rely on the correct operation of another measuring device or on operator input, so there is a risk they will be wrong or misleading; for example, when the thickness increases as a result of coating. It is up to each manufacturing operation to decide how best to provide the measurement information.

Some machine parameters can be simply set to their desired values and will continue to provide those values unless there is an unexpected failure. Tension, however, frequently requires corrective action to keep it at the desired value. The power fed to a motor is varied to maintain the tension, as indicated by load cells or set at a dancer roller (see Chapter 5 Tension). Speed may also be controlled by a motor drive, with the measurement at the motor. The CD position of the web or the stand carrying the unwind, is adjusted to maintain web CD location at a sensor, using a web guide. A rewind stand may be moved sideways to follow an unsteady web edge location, again using a guide. These are all examples of feedback control systems, whose operation is very similar.

Control Principles

Details of particular web control methods will be described in subsequent chapters. The common elements are found in standard control theory, taught in engineering, mathematics, and physics courses.

The web line has several control variables, such as roller speed, web tension, and CD position, which need to be adjusted to keep the line running well. Each can be considered as the output of a combination of electrical and mechanical items and the web, termed a system (alternatively, plant or process). For a driven roller not carrying web, the system is simply the power circuitry, electric motor, mechanical transmission and roller. However, when the line is running, the system becomes the whole machine as well as the web, which connects the machine items together through its elasticity.

Feedback control provides the preferred, automatic method of maintaining each control variable at or near its desired value or set point. The control variable is measured by a sensor, and its value converted to an electrical signal (analog or digital) to feed into the controller. The set point is subtracted from the control value to produce an error signal. The controller then produces an output signal, which becomes the input to the system and changes the control variable. The measurement,

controller action, and signal output are carried out constantly. When sketched out, the signal flow forms a *closed loop*, also called a control or feedback loop (Figure 1.9).

The term feedback refers to the use of the measured signal as an input to the controller, in other words it is "fed back." Normally, the control action is to reduce an error and move the control variable towards the set point. The output change and error have opposite signs, and the action is termed negative feedback.

The properties of the system determine how the control variable responds to the actuator. The system may contain the power unit in the drive to provide the large currents needed, the motor, mechanical transmission, and finally the assembly of rollers and web. The action of the actuator (such as a motor, web guide, pressure regulator) on the control variable may not be instantaneous. Often there are inertia and friction effects that have an influence. If the output signal is too large or applied too quickly, the control variable may move further from the set point, or undergo a growing oscillation. These are examples of instability.

The controller action can have several components. The simplest is *proportional*, where the output signal is the error signal multiplied by a fixed number or gain. This is normally stable but settles to a condition where there is still an error signal. An *integral* term, the accumulation over time of the error signal multiplied by a factor, can be added, in order to remove this residual error. However, the controller response becomes more sluggish, with a longer response time. Finally, a *differential* term, the rate of change of error with time again multiplied by a factor, can be added. This anticipates a large corrective action when a deviation from the set point grows rapidly. However, it can be a source of instability. The most common combinations used are abbreviated to PID (proportional, integral, differential) and PI.

The activity of setting the proportional gain, response time, and other

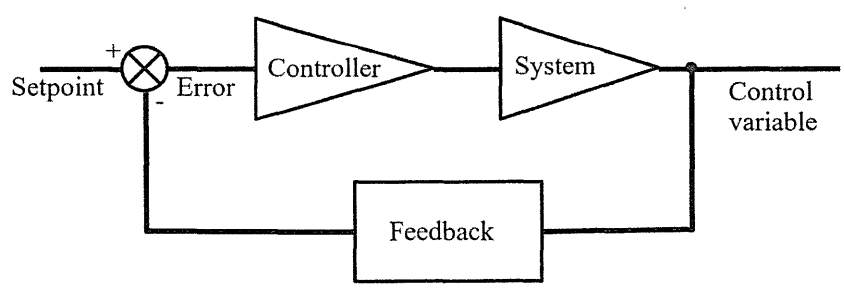

Figure 1.9. Schematic diagram of closed loop feedback control.

factors is referred to as tuning. The values are sometimes a compromise between the different products and conditions encountered on the line, but sometimes they are automatically adjusted to compensate for conditions such as line speed and winding or unwind roll diameter. There may be other controller parameters such as limits on the output signal and filtering of the error signal to remove noise that also need to be adjusted.

When there is no feedback of the control variable, the system input may still be adjusted to obtain the desired value, termed *open loop* control. The system may be sufficiently well-calibrated and stable that the output is closely determined, such as the torque of an electromagnetic brake or DC motor. Alternatively, the operator may be able to adjust the input to a specified value.

In both closed- and open-loop control, a related variable may be input to the controller. For example, the winding roll diameter signal is used to provide the correct winding tension. Alternatively, the controller may need to change the output signal to accommodate a predictable upset on the line, such as the start of a roll change or slowing. This is termed feedforward. Sometimes these methods involve calculations, for example, using friction compensation as a function of speed, and inertia compensation during acceleration and deceleration.

Modern systems frequently use digital signals until the final output to the actuator. Older systems use analog methods, and the controller uses a network of resistors, capacitors, and inductors for PID control. The drive system for the complete line combines outputs for all the motors and brakes, and allows for interaction between the sections of the line. That is, a tension change at one location propagates upstream and downstream. Controllers for web guides are often stand-alone, but may take a signal for the line speed.

Chapter 6 on drives contains much more information on controlling the key variables of web speed and tension. Most control systems nowadays are provided by large electrical engineering companies, and their implementation on the web line is carried out in conjunction with the machine builder. They provide just a few basic controls to the operators—everything else is hidden in the drive software. Adjusting those hidden parameters is sometimes the job of a user company's control specialist, if there is one. If not, the machine's builder is called in.

Webs and Machines

This brief overview served as an introduction to topics covered more

for a roller, from the mounting of the shaft down to the foundation of where it is housed.

Web Path Design

The simplest view of a web path is an elevation diagram showing roller positions, sequence, and rotation direction. The diagram also shows roller-to-roller span lengths and web-roller wrap angles. For some machines, such as large laminators, there may be more than one option for how the web threads through the rollers. This view of the web path can give a general sense of how simple or tortuous a process will be on the web. More practically, the web path diagram shows operators how to lace or thread the machine and is thus called a threading diagram. An example is shown in Figure 3.1. Other applications for this type of schematic include sales presentations, teaching, and note taking. Best practice is to number and/or name each roller position, including idler rollers. This allows rapid unambiguous communication among operators, maintenance, and engineering of what part of the machine they are referring to.

Good web path design is like 'art.' It is hard to define, but you know it when you see it. The customers of web path design, the web itself, and the operators, will also know good design when they see or feel it. The web will appreciate a well-designed web path by being oblivious; it will pass through without damage or evidence of the trip. Operators will appreciate a well-designed web path without notice; whereas, the poorly designed web path will induce daily pain and inefficiency for the lifetime of the machine.

Web path design is not just webs and rollers. Design also should consider the framework to support the roller and all the physical components near the web path, including cross members, sensors, conduit channels, loading systems, motors, and their gearboxes, ventilation,

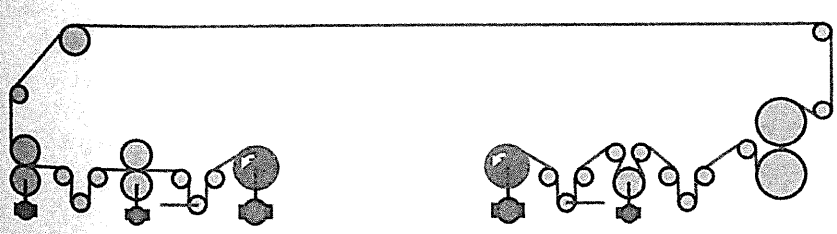

Figure 3.1. Example threading diagram.

lighting, and operators. This last element is also key to good operation. A well-designed web paths is easy to thread up, provides good sight lines to view the running web, and allows operators to tend to the value-adding processes trusting the web will enter, pass, and exit without trouble. Maintenance activities such as roller replacement, cleaning, and removing scrap after a break or wrap-up must also be considered.

The web path designer has a mission to connect the dots from start, through process steps, to the end. The start may be unwinding or web making. The end may be winding or cutting into discrete parts. A web path is about getting the web from Point A to Point B to Point C (and so on) through your company's process. If Point A and B are near each other, the span length or roller count options are few, but as distance between process points grows, the options for number of rollers, span lengths, and wrap angles grows very quickly.

Compact and efficient web paths are usually rewarded, but may not always be possible. Many web paths must route between process steps. Consecutive process steps may have exit and entry points that do not align well with each other. Long processes, such as drying and curing, may take the web several meters in one direction, requiring either an equally long return web path or an extension of the distance between unwinding and winding. Ceiling height is a major consideration, especially for existing buildings.

Web paths and path lengths may not be fixed. A product may require every process step available on a web line, whereas others will bypass single steps (e.g., skipping a printing station not being used for the current product) or a major portion of the web line (e.g., coating and drying only one side on a line with dual coaters and dryers).

A few guidelines for efficient web path design:

1. Identify required and optional process steps and their sequence.
2. Lay out entry and exit requirements and options for each process step.
3. Avoid excess path length between consecutive process steps.
4. Avoid elevation conflicts between consecutive process steps.
5. Combine roller functions where possible.
6. Minimize (but include) operator walkways.
7. Prefer overhead web paths to under platforms or tunnels. (Any contamination above the web can and will eventually fall onto the web.)
8. Minimize, but optimize, operator process access points. Consider

the arm length and height of operators. Design for threading assistance where needed.

9. Consider operator sight lines, especially between control stations and key processes.
10. Give every roller a purpose.

In looking to get from Point A to Point B, the web path designer must answer a couple of seemingly simple questions:

- What is an acceptable or nominal *span length* between rollers?
- What is an acceptable or nominal roller *wrap angle*?

Web path design would be simple if the answers were length-to-width ratio should be 1, and wrap angle should be 90-degrees. But the answer is more complex and nuanced, and is often prefaced with 'it depends...'

This chapter will help you understand optimal span lengths. Roller wrap angle considerations will also be covered in the Traction, Tension Control, Nips, and Wrinkles chapters.

Roller Functions

All rollers can be divided into two categories: transport and process. The key distinction is whether the roller is *intended* to change the web permanently.

The most common rollers are transport rollers, including all 'idler' rollers and some driven or nipped rollers. Contact with a transport roller is intended to be forgotten; that is, its effects on the web are elastic or temporary. One roller could move the web to the left; the next roller could return it to the right. One roller could increase tension, the next could decrease it. Web handling mechanics are far easier to understand when handling doesn't permanently deform the material or change its properties.

Process rollers are at the core of 'converting' or adding value to a web. The web changes are *intended* to be permanent. Process rollers usually have tighter tolerances than transport rollers in terms of some geometries (e.g., alignment, cylindricity, runout), though deflection tolerances may be similar.

Process rollers are also transport rollers, often with the strongest capacity to change tension or redirect the web CD position. Transport

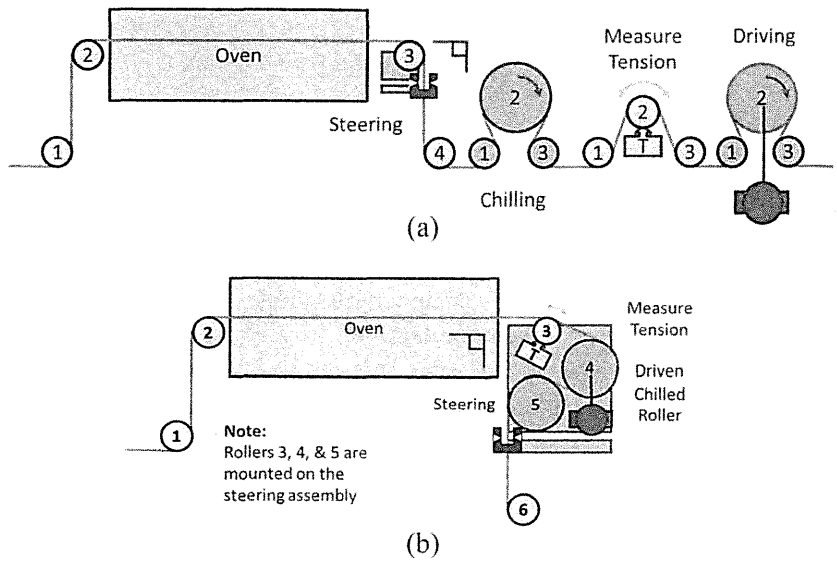

Figure 3.3. (a) Inefficient, non-integrated web path: 13 rollers, 12 spans; and (b) Efficient, integrated web path: 6 roller/5 spans.

Minimizing Roller Count

Counting rollers is one way to assess web machine design. Web lines should have efficiency in total web path length and roller count. Low roller counts satisfy the goals of simplicity, as well as lower equipment and ongoing operational costs. The roller that isn't there can't damage your web.

Fewer rollers have additional benefits. Transport rollers can either *do nothing* to the web or *damage* the web. Thus, a transport roller cannot improve the web. Transport rollers may scratch the web if traction is lost, wrinkle the web if the rollers are misaligned, or, the ultimate catastrophe, change the local tension enough to break the web. Even well-behaved rollers have a cost, or a series of costs. A roller's lifetime cost includes periodic maintenance (e.g., alignment, bearing lubrication or replacement). Plus, it also has the unseen cost of material and time losses each time the machine is threaded or started up.

In paper mills, almost no excess rollers can be found. Indeed, the function of nearly every roller is so identifiable that they are usually given names corresponding to the function that they perform. This even extends to transport rollers such as the 'before slitter table roller' that defines one end of the geometry of a slitter section on a two-drum or

duplex winder. In other manufacturing, one may find ten or twenty (or higher) percentages of rollers that have no identifiable function.

It is no small irony that while one would never add an excess process roller, such as including a printing deck when printing was not called for, that same thinking is not always extended to idler rollers. Extra idler rollers can, in some cases, be debilitating for lightweight webs due to bearing drag (and inertia during speed changes), which disrupts web tensions. Low-tensioned webs such as thin films and all tissue certainly qualify for extra attention to roller count and design. However, even very thick webs such as carpeting can easily fall prey to noticeably more wrinkles, for example in festoons and washing or rinsing processes (due to hygroscopic expansion wrinkles). So, rather than presuming roller count doesn't matter for our web at the design stage, we (buyer and supplier alike) should presume that it might and scrutinize every single one.

Optimizing Span Length

There is no 'optimum' distance between rollers, in either length-to-width ratio (L/W) or absolute distance. The range of acceptable spans is surprisingly large in many if not most machines. There are few hard and fast limits to span length being too short or too long, but certain issues become more frequent at either end.

The web handling discussions of distance between rollers may quickly focus on the aspect ratio of the span—the length-to-width ratio (L/W)—dividing the distance between rollers by the web or roller width. Within any industry based on a common web width, rules of thumb will state length-to-width ratio should be 0.5 or 1 or 2 or such. However, web widths can range from five millimeters (0.2 inches) to ten meters (400-in.). To advise a span length-to-web width ratio of unity ($L/W = 1$) can lead to rollers nearly running into each other (for narrow webs) or a circus tent of unsupported web (for ultra-wide webs). Thus, it is sometimes best to think about absolute span lengths.

What are the risks of short spans? Short spans tend to equate to more rollers, each with capital cost, possible additional lifetime cost, and risk of damaging the web. Rollers too close together can create the safety hazard of a nip point. Roller alignment requirements can be viewed as a percent of span length. Shorter spans have lower tolerance for imprecision in roller geometry and alignment. Shorter spans for long processes inherently lead to more rollers. More rollers mean more complicated

4
Traction

Introduction to Traction

Each of us is an expert on traction, managing our contact with various surfaces every day. We walk, run, drive cars, ride bikes, and grip objects, managing the force exchange of feet and the ground, tires and the road, and what we put our hands on. We know that ice, oil, gravel, and soap can act as lubricants, reducing the grip of our hands, feet, and tires. We know grip is a function of both sides of these interactions, changing with different shoes, tires, or gloves, and with changes in what we are contacting. This is traction—the understanding of friction and lubrication.

Similarly, in web handling, it is necessary to understand and manage the traction between web and rollers. This will include factors such as the forces between the web and roller caused by web tension, as well as the coefficient of friction between the web and roller. It also may include, in some circumstances, higher-order effects, such as air lubrication, adhesion, and centrifugal forces. Friction and lubrication are critical to good web control.

Over time, tire treads, shoes, and gloves wear out, as does even skin, which sheds from our hands. Addressing wear, of web or roller, completes the threefold application of tribology, the science of friction, lubrication, and wear, to web handling.

Traction in Web Handling

Traction is the combination of friction, adhesion, and lubrication (usually by entrained air) that creates, as well as limits, the maximum forces that can be sustained between a web and a roller. Optimizing traction is essential to most good practices in web handling and wind-

ing. This can't be overemphasized. A web cannot be controlled without traction forces.

Traction provides the forces to create tension, to guide and spread the web, and to hold most wound rolls together during winding, handling, and unwinding. Traction is available, but only develops into a force when called upon to oppose an applied force. For example, a web tension increase from roller entry to exit is balanced by a traction force acting in the upstream direction. Slippage of the web on rollers isn't all bad, just mostly: slipping (or near slipping conditions) can prevent the forces that hold in wrinkles or hold back the excess lengths of baggy lanes (see Chapter 9 Wrinkles). Finally, sliding is allowed on some spreaders (see Chapter 10 Spreaders) and even required on other components, such as turn bars.

Clearly, too little traction can cause many web handling problems. When a process loses traction, mostly bad things happen. It is less clear whether too much traction can also be a problem.

Low traction can cause loss of machine direction (MD) control of the web. Driven roller speed is no longer web speed. Slipping on the pacer, a driven roller used as the master speed reference, is the worst, with a process likely to stop or run away without programmed speed limits. If other drive points slip, they will fail to hold their tension, fluctuating with any variations in friction force. Flow-controlled coaters lose thickness control. Accuracy of web lengths or positions is lost. Winding rolls will cinch, either tightening or loosening, often followed by telescoping.

Low traction can lead to loss of crossweb direction (CD) control of the web. Even well-aligned rollers will lose their ability to guide imperfect webs. Webs will likely weave and wander, if traction varies over time or rollers go in and out of slip with the web. Uneven traction can pull to one side of the process, especially in long spans or a series of marginally wrapped rollers (e.g., in long ovens). Spreader rollers will lose their effectiveness, or worse, reverse their effect and induce wrinkles. Web guides will lose much, if not all, of their power to control web CD position. Any CD shifting before winding will be recorded in poor alignment of the roll's sidewall.

Slipping on rollers and within rolls creates subtle or obvious wear. Webs are scratched. Rollers are abraded, especially rubber-covered rollers. Webs and rollers shed particles, contaminating our processes and those of our customers.

Are there any problems from too much traction? High traction is not inherently a problem. Traction is like friction, it is potentially there,

but doesn't come into action until called upon. During some web handling events, high traction may not solely create a problem, but traction forces are often a prerequisite for a problem to occur. If a roller speed is unintentionally too high or low, due to control problems or errors in draw control set points, high traction will give the roller the ability to break or slacken the web. In the same condition, tension change on a low-traction roller is friction limited, thus avoiding web breaks or slack web. Note that in this full-scale sliding condition, the value of the tension is mostly indeterminate, so it may not be a good way to run even if it did avoid breaks or slackness.

The greatest benefit in web handling associated with loss of traction is how it can limit a roller's ability to wrinkle the web. Traction is required for nearly all wrinkle mechanisms. Webs bend and follow the direction of a misaligned roller, but bending may be limited by available traction. Rollers hold the web in a buckled shape, forming creases. This happens only if there is enough traction to exert the CD compressive stresses and prevent the web from sliding to flatness. Without traction, most wrinkles are unable to form. (More on this topic is addressed in the concept of the friction circle covered later in this chapter and in Chapter 9 Wrinkling).

Traction Safety Factor

The amount of traction needed for any roller depends on its function. Idler rollers should turn at web speed with sufficient traction force to drive bearings and overcome inertia. Driven rollers need enough traction to reliably allow the desired tension difference between upstream and downstream zones. Guiding rollers need sufficient traction to bend or twist the web spans. Spreader rollers need traction to pull out a gathered web or bend slit webs to their desired separation. Winding and unwinding rolls need traction to transmit torque through the layers of the roll. (This last topic will be addressed in the Winding chapter discussion of a roll's torque transmission capacity.)

The traction safety factor is one way to ensure enough traction exists on every roller to serve its intended function without fail.

Any safety factor is the ratio of what is available to what is required. The Traction Safety Factor (TSF) is a simple ratio that indicates the risk of a roller slipping (Walker, 2003). A TSF less than one predicts a roller will slip. If the TSF is near, but greater than, one, the slightest degradation in roller performance or traction will lead to web-roller slip. A high

An S-wrap drive point uses two consecutive driven rollers, one rotating clockwise and the other counter-clockwise, each with over 180-degrees of wrap. In the steel industry, bridle rollers are sets of 3 to 5 driven rollers.

These multi-roller drive points have the traction capacity of the combined total wrap angle. Many of these systems have the roller speed matched, but that will create more slippage on the downstream rollers. To share the micro-slippage between rollers, roller speeds should be designed or controlled with a slight draw, speeding up for tension increases and a slight negative draw for tension decreases, by the percent of half the anticipated web strain changes.

The greatest concern about S-wrap or bridle rollers without nips, is their inherent vulnerability to air lubrication and loss of traction. To avoid this weakness, most S-wrap or bridle roller sets have enough roughness or grooving to minimize undesired lubrication.

Traction of Nipped Rollers

Nipped rollers are a popular drive point option to grab and pull a web, allowing controlled tension differentials between tension zones. Nipped rollers are considered the most conservative option, if all one is concerned about is traction. High loads between rollers can create high frictional forces and the pressure created by nipped rollers is a strong deterrent to air lubrication and associated friction losses. This effectively means that slippage through nips is rare. However, nips are not at all conservative, if one is concerned about running baggy or other wrinkle-prone webs.

Nipped rollers create friction proportional to the load of the nip rollers. In a sliding block test, one unit of weight times the friction coefficient is the frictional force available and the force required to slide the block. Nipping rollers press together with a force given by the vector sum of nipping roller weight and leveraged pneumatic cylinder forces (and sometimes web tension), or, alternately by setting the rubber covering indentation. The potential friction between the rollers will be the force times the friction coefficient of the system.

If the effective nipped roller COF is 0.3, then 100 units of load (N or lbs) will enable a maximum friction force of 30 units. If the tension differential is 20 units (N or lbs), the nip system's friction capacity is greater than the differential, and the web should not grossly slip through the nip. If the tension differential is greater, say 50 units, then the nip

load would need to be increased to keep the nip's effective friction higher than the differential. Calculation of friction in nipped rollers can be carried out using the equation below:

$$F_{F,NIP} = \mu F_{NIP} = \mu N w \tag{4.20}$$

$F_{F,NIP}$ = Frictional force of nipped rollers, N or lbs
μ = Coefficient of friction
F_{NIP} = Nip force, N or lbs
N = Nip load in force per width, N/m or lbs/in
w = Width of nip, m or in.

The full effective traction of a nipped system is more complicated than a sliding block test and would consider the benefits of the belt equation [4.6] friction (if there is any wrap angle), the slip scenarios of three different contacting interfaces, roller deflection, and possible lubrication from air, liquids, or debris.

Often, nip loads for processes, such as calendering, are much higher than they need to be to avoid slippage. For example, if the tension differential is 10 units, a nip load of 1000 units is excessively high for traction purposes, but may be necessary to compact the material. High nip loads provide a large safety factor but often also create web handling problems from increased deflection, rubber covering wear, and web compression.

In many nipped roller assemblies, one of the two rollers is rubber-covered to conform to the variations of web thickness, roller diameter, and deflection. Rubber coverings will usually also have higher coefficients of friction than steel or chrome to most webs and this has an effect on traction, as seen in Figure 4.12.

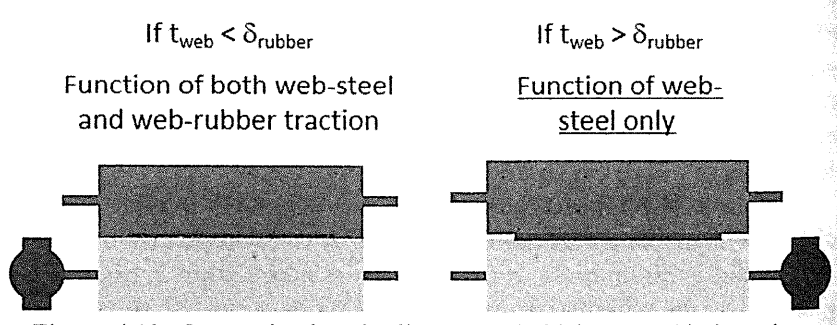

Figure 4.12. Contact in nipped rollers vs. web thickness and indentation.

The higher COF of rubber coverings may not increase the friction available to drive the web and avoid slip. In most steel-rubber nip systems, the steel roller is driven and the rubber roller is idling. One reason for *not* driving the rubber roller (in speed control) is that the effective diameter of the rubber roller depends on nip load, cover chemistry, and other factors, and is thus indeterminate. It is the friction of the web to the driven steel roller that connects the web to the motor. Friction between the web and rubber roller may be inconsequential.

Considering the combined web and nipping roller system, the slipping condition is potentially dependent on three interfaces: web side contacting steel driven roller, web side contacting rubber roller, and rubber-to-steel roller contact.

If the web is relatively thick (or the nip roller is narrower than the web), there is no frictional contact between the steel and rubber rollers. The steel roller will drive the web, and the web will drive the rubber roller. The critical slippage is between the web and steel roller. (More on the mechanics of rubber rollers is covered in Chapter 7.)

If the web is relatively thin (and both rollers are wider than the web), there will be contact between steel and rubber roller outside the web width. In this roller edge-contacting case, the rubber-to-web or rubber-to-steel COF is an important factor for slippage as web-to-drive slippage will require slip between rubber and web or rubber and steel.

Traction of Vacuum-Assisted Rollers

Friction is created by forcing two solid surfaces together. Wrapped and nipped rollers create friction from tension and nip load, respectively; vacuum rollers use the suction of a partial vacuum. A vacuum roller is porous and connected to a fan that evacuates air from the inside of the roller cylinder under the web contact area, creating a pressure differential between atmospheric pressure on the outside and the lower pressure on the roller side of the web (Eggen, 2009).

This description applies equally to vacuum plates, belts, and rollers. However, vacuum rollers have another important factor that creates surprisingly high friction—the belt equation [Equation (4.6)]. The belt equation describes how friction will increase exponentially with wrap angle increase. The same or greater is true for vacuum rollers (Cole, 2015).

Though atmospheric pressure is known and the internal pressure of a vacuum roller can be measured, the web is not subject to the full internal pressure since: (1) the web experiences internal pressure only

through the limited exposed area of the vacuum roller holes, grooves, or porosity; and (2) there is pressure loss through the roller wall and covering thickness. The effective area of vacuum rollers is greatly improved by a combination of both grooves and holes or some method to increase the effective area of the vacuum with a screen or porous sleeve. This is illustrated in the following equation:

$$P_{vac} = \left(\frac{A_{exp}}{A_{total}}\right)(P_{atm} - P_{int}) \tag{4.21}$$

P_{vac} = Effective additional pressure from vacuum roller, Pa or psi
P_{atm} = Atmospheric pressure, Pa or psi (1 bar, 100 kPa, or 14.7 psi)
P_{int} = Internal pressure of the vacuum roller, Pa or psi
A_{exp} = Portion of contact area where web is exposed to vacuum, m^2 or in^2
A_{total} = Total area of contact between web and roller, m^2 or in^2

These two effects lower the effective pressure differential and friction, as seen in:

$$\frac{T_{high} + P_{vac}r}{T_{low} + P_{vac}r} = e^{\mu\theta} \tag{4.22}$$

This equation looks like the calculations for effects of centrifugal force [See Equation (4.18)], but the signs are opposite. Where centrifugal force acts to lift the web off the roller, reducing traction, vacuum acts to pull the web down to the roller, increasing traction. Also, where centrifugal force is insignificant for many processes, vacuum rollers are usually highly effective.

The most common application of vacuum roller is where the web needs to be driven, but processing limits prevent contact with one side and wrap angle is limited. Vacuum rollers are often used to control the high-to-low tension change between a web coating and drying process, where one side of the web is freshly coated and can't be touched. Vacuum rollers may also control the low-to-high tension after the drying process. While not specifically web handling, vacuum rollers are common in sheet handling, 'island placement' in rotary converting, or applying tabbing or transfer tape in automated splicing or roll transfers.

Vacuum rollers are inherently good at preventing air lubrication, because they evacuate air to increase traction and at the same time exhaust the air between the web and roller. At higher speeds, there is a limit to

the distance that a vacuum roller can remove air from the web-roller contact zone, as the air may not have time and driving pressure to travel in the thin passage between web and roller across the roller's face to a groove or hole during the brief time of roller contact (as was noted in the earlier discussion of grooved rollers).

This completes the discussion of traction available. It has established that the incoming and outgoing tensions cannot take any values, rather they must lie within limits determined by traction. Given one tension, the upper and lower limits of the other are determined by the equations in this section. Traction allows all tension values in between these limits without full slip. However, attempting to operate outside the limits results in full slip, and the tensions cannot exceed above or below these limiting values. The next section explains the traction required.

Traction Required

The traction required varies greatly between idling and driven rollers and between simple transport rollers and rollers actively guiding or spreading. All rollers need traction sufficient to support the difference between input and output tensions without full slippage. Idler rollers need only support a small tension difference caused by bearing drag and inertia, whereas driven rollers may be designed to support a large tension change between tension zones or to drive a long sequence of idler rollers.

For the rollers of drive points, usually a high traction safety factor is desired. Rollers that redirect the web, bending the web to a new CD position for guiding or spreading, will also need additional traction. Some spreading rollers and undriven nipped rollers need extra traction proportional to the energy lost by deforming the rubber coverings.

Idler Roller Traction Requirements (Bearing Drag and Idler Roller Inertia)

A standard idler roller needs traction to prevent slippage and all its attendant troubles. The force required will be different at low speed vs. high speed, because bearing drag is a function of speed. At steady speeds, whether low or high, the force required to overcome bearing drag will be a function of the bearings and roller assembly. The force required to prevent slippage will be different during acceleration and deceleration conditions due to inertia.

As covered in Chapter 3, idler roller traction starts with the need to

surmount bearing drag torque at constant speed, but should have additional traction to maintain control during acceleration and deceleration. A traction safety factor of 3-5 is sufficient for most idlers, though in reality, some will have a TSF of over 100. Again, excessive traction has little benefit and may enable undesired wrinkling and CD shifts with imperfect rollers or alignment.

Driven Roller Traction Requirements

The demands for traction on a driven roller are usually much greater than those for idlers.

Where the traction force required for idler drag and inertia may be a small percentage of average tension, the rollers at drive points need to support the tension change from one zone to another.

Many unwinding tensions are low, to avoid over-torqueing and cinching, but the tension zones after unwinding, possibly feeding into a printing, coating, or slitting process, are often higher. If the drive point lacks sufficient traction, the second zone will not be able to control to its higher set point.

As shown in Figure 4.13, for example, if unwind tension is 100 N (22 lbs) and the second tension zone is set for 300 N (66 lbs), the drive point needs traction to support this change. There are two ways to view this tension change: as a tension ratio (3:1) or as an absolute change (200 N or 44 lbs).

If the COF is known, one can use Equation (4.9) to find the wrap angle required to support the tension ratio. If COF is 0.3, the required wrap angle is 3.66 radians or 210-degrees. If a driven roller has only 180-degrees, it will not be able to support this 3:1 change. Even if the wrap angle could be increased to 210-degrees, there would be no safety factor, which would lead to full slip with even the slightest loss of COF.

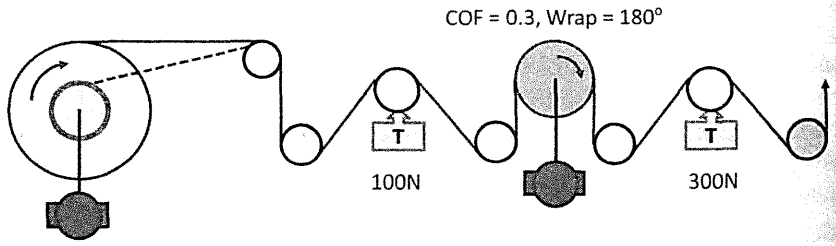

Figure 4.13. Example of tension change at drive point.

There are at least three options to improve the traction safety factor of this drive point: (1) increase COF and ensure lubrication effects are small; (2) add a nip roller; or (3) upgrade the drive point to a vacuum-assisted roller.

Nipped driven rollers are usually designed to support the absolute tension differential, instead of focusing on the tension ratio. In this example, there is a need to support the 200 N change from 100 to 300 N (44 lb change from 22 to 66). If the handler adds a nip roller and assumes the driven roller-to-web COF is 0.3, at least 700 N (150-lbs) of nip force are needed, plus some additional force to provide a safety factor.

Even when the tension set points on either side of a driven roller are equal, the traction requirements may be far above zero or 1:1.

In Chapter 3, the drag and inertia were shown to differ as a function of bearing drag and inertia during acceleration and deceleration. As more rollers are in the web path between a control point (e.g., load cell roller, dancer roller) and the drive point, the more the tensions at the entry or exit of the drive point will differ from the tension set points.

The tension change at a driven roller may be even more than expected. Two successive tension zones having the same tension set point would not appear to need much traction. However, tension set points control the tension *at* the load cell or dancer roller, which may be separated by the drag and inertia of several idler rollers from the driven roller, such as shown in Figure 4.14. In this web path, the drive point input or upstream tension is slightly higher from steady speed roller drag and much higher or possibly lower than set point during acceleration and deceleration, respectively. The drive point's exit or downstream tension has the opposite trend. In all cases, the tension change at the drive point is not zero or 1:1, making drive roller traction requirements greater than tension set points would indicate.

Loss of Traction and Slippage

There is more to friction and traction limits than the machine direction (MD) demands of idler or driven rollers. Rollers may also have significant CD traction needs. With this in mind, the traction safety factor should be:

$$\text{Traction Safety Factor} = \frac{\text{Traction Available}}{\text{Combined MD} + \text{CD Traction Requirements}} \tag{4.23}$$

5
Tension

Introduction to Tensioning

Tension is an important variable in nearly all aspects of web handling and many of the value-adding web-converting processes. Web handling should be called "tensioned" web handling, as there's almost no handling of webs that are not under tension. Upon unwinding, the first goal is nearly always to establish web tension. In paper or film making, web handling begins when the web is dry or cool enough to handle tension. At the end of most web handling operations, a roll is formed of web under tension.

This chapter looks at tension from the web, roller, and process viewpoints. But there is another, equally important, side to web tensioning, the electrical and control side of web handling, which will be discussed in Chapter 6.

Designing a Tension Control Plan

The tension control plan comprises all the line's drive points and how the drive points work together to control overall line speed and tension within each tension zone. A drive point is any core or roller where the web is connected to a motor, clutch, or brake through mechanical components and traction to control motion or force. A tension zone is the web connecting two consecutive drive points, where local tension is set by design (i.e., fixed) or by control (i.e., easily adjustable). Each drive point exerts a force on the web and provides a step down or up in tension between the zones entering and exiting the drive point. The force may be controlled directly or arise indirectly from the speed setting or inclusion in closed-loop tension control.

Tensioning needs to be tailored for each product. Clearly, tissue pa-

per and aluminum foil should not run at the same tension. Also, wider, thicker products will handle more tension than narrower, thinner products. Beyond product materials and geometry, many processes have specific tension needs, such as high tension to pull out bagginess or ensure roller traction without slippage, low tension to float on air bars or transport thermoplastic polymer films through ovens. In winding, many rolls are held together by the pressure of hundreds or thousands of tensioned layers forming the roll's structure.

A well-designed tension control plan, based on product and process, has four areas (Table 5.1):

Table 5.1. *Tension Control Planning.*

Planning Step	Details
1. Specify tensions and tension variations.	**1a. Process steps.** Define all the sequential steps of your process, including unwinding and winding. For each process step, define its tension requirements, which includes: **1b. Nominal tension.** For each process step, is the target tension low, medium, or high? (Medium tension is defined as around 200 N/m or 1 lb/in. Low or high tensions are more than 3× lower or higher than this tension.) **1c. Sensitivity to tension variations.** For each process step, will tension variations be likely, and is the process sensitive or insensitive to tension variations? Tension variations above or below ±10% are considered high or low variations, respectively.
2. Define tension zones by drive points.	**2a. Required drive points.** Unwinding and winding will always be drive points. Many process steps will include drive points, especially nipped processes. **2b. Optional drive points for process needs.** The required drive points (from step 2a) will create the minimum number of tension zones but may combine processes that have incompatible tension requirements within the same zone. Where two consecutive process steps are incompatible, adding a drive point separates them, allowing each to have their tension needs met. **2c. Optional drive points for drag and inertia.** Additional drive points may be beneficial where the drag or inertia of a single component or a group of elements becomes problematic, such as when the cumulative forces are a significant portion of available tension or traction. **2d. Drive point traction.** Review each drive point to ensure it has enough traction under all conditions to avoid slippage and loss of control. Choosing between driven unwrapped rollers (or roller cluster), nipped, or vacuum rollers is covered in Chapter 4.

(continued)

Table 5.1 (continued). Tension Control Planning.

Planning Step	Details
3. Choose how local tension is created and controlled.	**3a. One master.** One of the drive points will be the line master and all others will be tensioning drive points. In selecting the line master drive point, the most important factor is to choose a roller that is expected to have good speed control of the web under all conditions. **3b. Tensioners.** Moving upstream and downstream from the master, every additional drive point is a tensioner, following web or line speed, but also responsible for controlling a local tension zone. **3c. Control options.** Each tension zone has several choices of how to control local tension. First, each zone will control tension by changing either a force applied to the web or a speed ratio. Second, each zone will be controlled either in an open-loop or closed-loop control. Lastly, with closed-loop control, a zone has the option to respond to the feedback of direct tension measurement of a load cell or the position feedback of a force-loaded dancer roller.
4. Minimize undesirable tension variations from all sources.	Recommended tensions include a safety factor to account for variations from the tensioning system and also MD and CD effects. However, if the sum of variations exceeds this safety factor or the web's damage point is lower than expected, the web will yield, or worse—break. To understand MD and CD variations, no matter the cause, whether speed variations, runout, cylindricity, misalignment, or bagginess, if the error, viewed as a percent, is large compared to the strain of your web, it is likely important.

This chapter will walk through the four areas listed above, providing guidelines for a tension control plan, along with best practices for new or existing processes.

Specifying Tensions and Tension Variations

To get the benefits of tension, the line needs to run at an optimal tension, high enough to create traction on rollers and pull out mild to moderate bagginess, but also low enough to avoid permanent damage, not yielding or breaking the web.

Tension is most commonly set in units of force, but the predictable behavior of the web is based on tension as a function of the web's 'back-

bone' defined by its width and thickness. Considering web geometry (or not), there are several ways to quantify tension.

- *Uncalibrated Tensioning Variable*: Tension is set by a variable that adjusts web tension, (e.g., air pressure to a dancer roller), but may not be directly proportional (i.e., a zero setting creates greater than zero tension). These systems are common and work when they provide tension within an acceptable range with repeatability. However, it is difficult to trust their consistency over time or compare them to sister processes.
- *Uncalibrated Torque Variable*: Many times, the variable called 'tension' is instead a torque-controlling variable (e.g., air pressure to a center-braked unwind or differential winding shaft, current to a clutch). Confusing torque with tension is a widespread misunderstanding and source of problems in many web processes. Any uncalibrated systems will have questions of repeatability.
- F_T, *Force of tension*: Most web lines will display tension in units of force (Newtons, kilograms-force, or pounds-force). Tension is best measured as the resultant force on an idler roller mounted on load cells, taking incoming and outgoing web directions into account. Alternately, some systems display a 'tension force,' which is calculated from related variables (e.g., assuming tension from torque and radius measurements).
- T, *Force per width* (*lineal tension*): Many 'rules of thumb' for tension are stated in force per width (Newtons/meter of width or PLI = pounds per lineal inch of width), making the recommended tension force easily determined by multiplying N/m or PLI by product width.
- σ, *Force per area* (*stress*): To best predict how a web will react requires tension in terms of stress or force per cross-section area (see Chapter 1). Units include N/m^2 or Pascals, pounds per square inch or psi.

For a given load, as the web's cross-sectional area decreases, the force is distributed across less material (whether atoms, molecules, or fibers), creating higher stress and strain, and thus increasing the likelihood of yielding or breaking the web. Alternately, when a load is exerted over a larger area, stress and strain are lower, decreasing the risk of yielding and breakage. Though linear tension and stress units may be more appropriate for predicting web behavior, most lines will not set tension in these units. In the rare cases where these units are used, a

control system will need width, thickness, and radius values to convert lineal tension or stress to machine forces and torques. In considering a web's 'backbone,' some of the web thickness, such as an adhesive layer, may be more 'fat than bone' and should be ignored for tensioning purposes.

Thinking about tension in terms of stress is more difficult for materials without a definable or measurable thickness. Papers, tissues, textiles, and nonwovens are rarely quantified by thickness, instead using basis weight (i.e., mass per area). Basis weight is a good alternative to thickness for tensioning guidelines, as this number will be proportional to the number of fibers or threads per width that carry the forces of tension. For these products, the equivalent of stress or force per area would be force per width per basis weight (i.e., lineal tension/basis weight, termed *tensile stiffness index*, which was discussed in Chapter 2).

There are many tension-setting guidelines in the literature, but only for common or simple materials. Paper is a well-documented example where a trade organization, TAPPI, has charts for various paper grades as a function of basis weight or thickness. You can also find recommendations for foil, polyester, polyethylene, polypropylene, nylon, and others. Still, there are limitations with these recommendations. They do not consider application details such as web and machine condition and the mix of high- and low-tension defects experienced there. More importantly, many materials such as nonwovens, textiles, and tissue are seldom listed. Laminates are also not listed. While one can find a recommendation for paper and poly, a paper-poly laminate is not listed, and adding the two recommended tensions together does not work so well, because paper takes almost all of the load. Also, some coatings are brittle and may be damaged long before the web substrate is.

Recommended web handling tension is commonly cited as 10 percent of failure conditions (i.e., 10:1 average tension safety factor). Failure may be the obvious break condition, the less obvious yielding, or another critical material property that changes under high stress or strain. More subtle failure may require inspection of coated layers, lay-flat testing, or other critical product performance measurements. Tensile-elongation testing may show an obvious change in the substrate (i.e., web) from linear elastic behavior to yielding or breaking, but may not show failure of thin coated layers. Some materials, such as aluminum, will show non-linear, unrecoverable failure below the obvious yield point. With any damaging tension, one should consider the weakest link, which may be the web splice or areas damaged in roll handling.

If there is a most frequent tension level, with an equal number of

webs running at higher or lower tensions, it would be around 200 N/m (1 lb/in). Many web lines will need to run a variety of webs, some preferring tensions higher or lower than this. Many machines are designed around this tension, with a tension range starting 3× lower to 3× higher than this (60–600 N/m or 0.3–3.0 lb/in). To ensure equipment is designed for the needs of a specific product or process, actual web mechanical properties and limits are needed.

If all webs would run within a 10:1 range, it would not be necessary to discuss right-sizing tension specifications, because the best tension could be found by trial and error. But not all webs fall into this range. One should not expect to run greatly different webs on the same equipment, such as running both aluminum foil and bath tissue or running 250-micron and 12-micron films. Some thick and stiff webs prefer tensions higher than 2000 N/m (10 pli) or more. Some delicate or lightweight materials, such as tissue, will need low or ultra-low tensions below 20 N/m (0.1 pli). Unfortunately, it is unreasonable to expect converting equipment to operate over a 100:1 tension range (20–2000 N/m or 0.1–10 lbs/in). Thus, web handlers need to define a recommended tension for individual web products and processes, in order to determine if they will run within the typical tension range or need customized equipment designed to deliver the appropriate tension.

Any web has an ultimate MD strip tensile strength, found from tensile-elongation testing (see Chapter 2), defined in any tensioning units, but most often in force per width for a given product. Figure 5.1 shows examples of stress-strain curves for selected materials. Brittle materials will show little warning before breaking and should have recommended tensions based on ultimate tensile strength or stress. Ductile materials will first yield (permanently distorting) as tension or elongations increase, noted at the point where the stress-strain curve transitions from linear to non-linear, before ultimately breaking at higher elongations. Yielding is considered permanent damage to be avoided, but for most materials the ultimate break tension, which is more commonly known, provides a readily available tension to avoid.

Even in highly ductile materials, break conditions are typically less than 2× the yield stress, an amount easily covered by the safety factor. This would allow the far simpler to define/measure peak stress be used instead of yield stress. However, without knowing the critical yield strain, it is impossible to estimate the safe strain or draw ratios from break elongations.

If a web fails at 100 units, recommended tension is 10 units, whether defined in force, force/width, or force/area. Make certain that the units

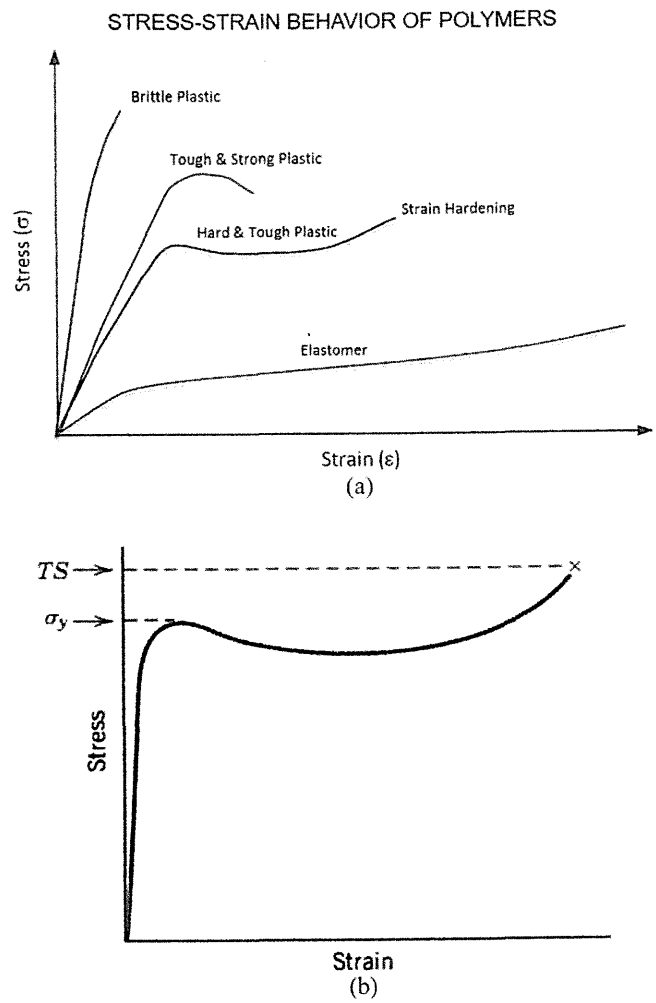

Figure 5.1. Typical tensile-elongation curves.

you are using from the test lab tensile tester are the same units or are converted to the same units as those used for machine tension settings! This 10:1 safety factor should be considered a starting point. In reality, optimal tension may be up to two times higher or lower, making the recommended tension range 5–20% of damaging (yield or break) tension.

This recommendation creates a tension safety factor of 5:1 to 20:1. At first glance, this safety factor appears overly generous, but later in this chapter reasons will be given as to why this large safety factor is justified.

Examples

If a polyester film is damaged at 150 MPa (20 kpsi), then recommended tension for that web would be 15 MPa (2000 psi) or approximately 400 N/m for 25-micron thick film (2 lb/in for 0.001-in).

If a bath tissue is damaged at 350 N/m tension (2 lbs/in), then recommended tension for that web would be 35 N/m (0.2 lbs/in).

Tensions above and below the 10% rule of thumb recommendation may have merit. Higher tension can reduce most wrinkle types by tension stiffening, and eliminate scratching and slippage by increasing idler roller traction. Lower tension can relieve wrinkles by reducing the traction available to pull or push on the web, and help with unwinding loose input rolls.

For webs comprised of multiple layers, whether co-extruded, coated, or laminated, the ultimate strength is less likely to be proportional to overall thickness and may not be the best guide for recommended tension, because low-strength layers or failure strain of brittle layers may dictate what is a safe tension.

Advantages of the Best Tension

Proper tensioning has many advantages, but too low, too high, or inconsistent tensioning underlie many web handling and winding problems. The benefits and problems are summarized in Table 5.2.

Understanding and visualizing the tension variations along a web line are critical tools of any web handling problem solver, especially for wrinkling and roll defects. Tension is often displayed as a single value of force or force per unit width. However, a single value is only the beginning of understanding tension. Just as the number on a thermostat does not represent the temperature in every location in a building, measured tension represents an average at a roller, but does not show how tension varies in the MD, CD, and ZD from web, equipment, and control imperfections.

It is easy to imagine how too high or too low average tension will cause problems. Thinking about tension variations is more complicated but important for avoiding web handling problems. Tension (and strain) will vary as the web is transported in the machine direction (MD), from the forces of processes, rollers, and gravity. Web tensile stresses and strains can vary through the web thickness (ZD) from bending around rollers or the wound roll, and from residual stresses in laminated or coated layers. Lastly, maybe the most important point to understand and

Table 5.2. Effects of Low, High, or Inconsistent Tensioning.

	Benefits of Proper Tension	Problems of Tension— Too Low, Too High, or Inconsistent
Web Dimensional Control	Tension elongates the web, and flattens and straightens moderate bagginess, curl, or other dimensional imperfections. Higher strained webs are less sensitive to equipment imperfections.	**Low:** Dimensional variations are revealed, including bagginess, curl, and general non-flatness. **High**: Width loss, yielding, and web breaks. **Inconsistent**: Difficult to hold MD registration for printing or die cutting.
Stiffness	Web gains stiffness from tension, running straighter, sagging less, and is more resistant to wrinkling.	**Low**: Web deviates more easily from centerline, sags in horizontal spans, and easily wrinkles. **High**: Web is more difficult to float with air pressure, possibly dragging or scratching on air bars and nozzles.
Traction	Web-roller contact creates traction required to control tension changes and bend the web in MD or CD without slippage. Winding rolls will have internal layer-to-layer traction and greater torque transmission capacity.	**Low**: Web guides and spreader rollers lose effectiveness, resulting in poor CD control and greater wrinkling tendency. Adhesive webs fail to peel at unwinding or from adhesive-side roller contact or make CD peeling variations more dramatic. Wound rolls have internal slipping defects (e.g. cinching, telescoping). **High**: Misaligned rollers have more traction to bend the web or prevent wrinkles from sliding out. **Inconsistent**: Roller may transition from traction to slippage, upsetting MD and CD and tension control. Adhesive webs may peel unevenly from roller contact, causes web CD shifts or wrinkles.
Tension Variations	Tension variations from MD or CD effects.	**Low**: Less tension force available to dispense to MD tension losses (e.g., roller drag, inertia, or sliding contact). Slack edges will occur at smaller variations in bagginess or misalignment.
Wound Roll Tightness	Wound rolls have proper tension to avoid too loose or too tight roll defects.	**Low**: Wound rolls have looseness defects (e.g., CD buckles, cinching, telescoping). **High**: Wound rolls have tightness defects (e.g., core crushing, core starring, more bagginess, MD buckles). **Inconsistent**: Wound rolls have rough edges from tension "noise." Large tension shifts during roll change and mid-roll set point alteration cause looseness defects.

Table 5.3. Sources of MD, CD, and Web Tension Variations.

Source of Tension Variation	Comments on Variations
Tension control variations	• Dancer hysteresis • Load cell miscalibration • Drive-control imperfections
MD variations	• Roller drag and inertia • Roller runout or eccentricity
CD equipment variations	• Roller misalignment • Roller cylindricity
CD web variations	• Bagginess, skew/camber, misaligned splices
ZD (thickness direction) web variations	• Bending over roller radius • Residual stresses, some of which are manifested as curl

diagnose is that tension can vary in the cross-machine direction (CD) from web bagginess, equipment variations, and imperfect splices.

A large tension safety factor is intended to keep a web safe from damage or breaks even when it has large MD, CD, and ZD tension variations (Roisum D. R., Combined Stresses of Webs Going Over Rollers, 2015). Each source of variation may be well within the safety factor, but when the extreme values occur at the same MD and CD location and time, they can combine to produce a damagingly high value, or slackness. Table 5.3 lists sources of average, MD, and CD variations.

Identify Process Steps and Their Tension Needs

The required process tensions start with unwinding and winding. Some intermediate processes will nearly always require a drive point, especially processes with nipping rollers or high inertia. Examples of web process tension requirements are given in Table 5.4.

Specifying Tension Zones and Drive Points

A minimum tension zones plan includes drive points only where required by processes, starting with unwinding, winding, and any process with a driven roller. Tension zones are added beyond the minimum requirements for three reasons: (1) if consecutive process steps are not tension compatible; (2) when the number of idler rollers (or other elements) in a zone are increasing; and (3) when a single drive point may not have enough traction to support the intended tension differential.