METHODS OF REDUCING ROLL FAULTS CAUSED BY POOR THICKNESS PROFILE

By
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Abstract

When material with varying thickness is wound, the resulting deviations from a perfect cylindrical roll cause long-lived defects in the web when it is unwound. These include baggy lanes and wrinkles; also roll stacking may be poor. Averaged, rather than single scan, thickness profile is needed to predict the faults. This paper will describe how the faults can be reduced by a combination of changing product formulation and winding conditions, and improving the thickness uniformity.

Introduction

The thickness uniformity of web products needs special attention to avoid rendering the product unfit for use or visually unacceptable. This is a cause for concern during initial manufacture and later converting processes. Examples of the latter include extrusion coating, application of adhesive and laminating. Thick printed layers can also disturb the thickness uniformity. Most of the variations in thickness average out with time and as successive turns are wound onto a roll. However, the variations that persist with time build up and distort the shape of the growing roll. It is these diameter variations that are damaging to the web: when it comes onto the wound roll, as further turns are wound on top, and during storage. The following sections describe the most common faults and their mechanisms. Further information, alternative defect names and underlying causes, can be found in [1].

Wound roll defects from poor thickness profile

Diameter variations and gauge bands

Lanes of increased thickness normally produce rings of increased diameter in the roll, called ridges or high spots. The web must increase its strain in the machine direction (MD) at those locations as it wraps the roll. When the web is unwound, it shows baggy lanes (known as gauge bands) from the set-in strain at the ridges.

The ridges are higher for greater thickness deviation, higher winding tension (strain in the web) and lower radial modulus. However, the ridges are always lower than expected from the thickness deviation. This has been explained in an approximate theory developed by TNO, Delft [2]. The fractional increase in thickness $a$ produces a fractional increase in roll diameter $b$ given by:

$$\left(1 + \frac{b}{e}\right)^2 = e^{K_2 (a-(1+\nu)p)}$$

$e$ is the web strain in the MD, $\nu$ is Poisson’s ratio, and $K_2$ is the coefficient of pressure $p$ in the radial modulus $E_r$. Radial modulus is the gradient of the stress-strain curve measured by compressing a stack of web layers, and is often well-fitted by the relation:

$$E_r = K_2 p$$

The radial modulus is dependent on the applied pressure, and this non-linearity is essential to model the stresses in wound rolls, as reviewed in [3].

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Figure 1 plots the percentage diameter increase against the thickness increase, as predicted by the theory. The diameter increase in the ridge is much higher at larger $K_2$ and web strain. A more accurate prediction of the effect of thickness profile is available from winding models with width dependence [3].

![Diameter increase in ridges](image)

*Figure 1: Predicted diameter increase plotted against thickness increase for different values of $K_2$ and web strain.*

The fractional increase in roll diameter at a ridge is equal to that in the circumference, and therefore also equal to the additional strain. When the roll is unwound, part of the additional strain is recovered, but part is set-in as a result of viscoelastic or plastic material behaviour. This non-recovered strain produces the baggy lane, or gauge band. For viscoelastic materials, the amount of strain set-in increases with storage time and temperature on the roll. They also exhibit recovery, so the severity of gauge bands will reduce once the web is laid flat.

A criterion for an acceptable amount of extra length in the gauge band has not been established. It might be judged that a baggy lane that forms a wave with a 100 mm period and 1 mm height is just acceptable: this corresponds to an extra length of 0.03%. A strongly viscoelastic material such as LDPE may form this from a diameter increase slightly greater: a more elastic material such as PET may need 0.1% or higher. Data on 3 paper grades [4] show that 40 to 50% of applied strain is set in after a week’s storage: these would require a ridge height of 0.06 to 0.08%. The sum of the average web strain and extra strain in the ridge may exceed the elastic limit of some metal foils, resulting in permanent elongation in the gauge band.

**Pressure variations leading to blocking**

The pressure is greater under a ridge than in the rest of the roll. This can cause inter-layer adhesion, resulting in “blocking”: preventing uniform unwinding, and sometimes tearing the web. There can also be local disruption of interlayer slip in the outer turns of the roll. Instead of smooth, uniform movement, some areas stick and others slip, resulting in the build up of a “bump” (or slip knot) at one location around the circumference, normally at the roll edge. This can be amplified by the bounce of a lay-on roller.

TNO also developed a theory for the pressure increase $\Delta p$ in a ridge, relative to the average value $p$ [2]:

$$\frac{\Delta p}{p} = e^{K_2 a} - 1$$

This is plotted in figure 2 for two values of the radial modulus parameter $K_2$. At low values of $K_2 a$, the percentage pressure increase is $K_2$ times the percentage thickness increase. At larger values, it increases exponentially with the thickness increase. The pressure under a severe ridge can easily reach 5 times the average value. It is not sensitive to the winding tension.
**Figure 2**: Predicted pressure increase plotted against thickness increase for different values of $K_2$.

**Wedged roll and poor stacking**

If the web thickness is larger towards one edge, the roll will grow with diameter increasing towards that edge. The thickness variation may have a steady gradient, or a high spot near that edge. The resulting “wedged” roll is expected to steer the web towards the larger diameter edge, just like a tapered diameter roller. Simple theory [5], ignoring any slip on the roll or preceding rollers, gives the steady state lateral displacement $y$ as:

$$y = \frac{bL^2}{6W}$$

It is larger for longer entry span length $L$ and smaller width $W$. At the roll start, the diameter is uniform and therefore there is no lateral displacement. At the end of the roll, if a diameter variation of 0.1% has developed in a 100 mm wide roll with a 1 m span length, the displacement will be 1.5 mm. The sidewall will move out gradually from the core to the outside.

Theory also predicts there will be a sideways force developed to keep the web entering square. The steady state model predicts web of Young’s modulus $E$ and thickness $h$ will develop a force equal to:

$$F = \frac{EhW^2}{6L}$$

This is larger for wide webs and short spans: however, the effects of shear become significant and should be included [6]. The force can exceed 100 kg. As it increases, the roll itself may deform into a dish shape [7]. The sidewall departs gradually from straight. The thrust load may also deform the chucks and sideframes. The resultant movement may be gradual, contributing to dishing. It may be sudden in one or more steps which relieve the load, by a sideways shift of part of the roll or the sliding of the core on a supporting shaft leading to telescoping (a sudden departure from sidewall straightness). In severe cases, the thrust load can be large enough to damage the equipment, crushing the core in the axial direction or deforming side flanges, support arms etc.

**Other profile-related faults**

Softer portions of the roll are more prone to develop wrinkling faults, and are also more liable to be deformed during handling, for example when the roll is placed on the floor. TD (transverse direction) wrinkles (starring, spokes) are likely on wide, low thickness regions at one or both edges of the roll. They are nearly always seen on uncoated edges of a roll, as a result of the lower total thickness. MD wrinkles (tramlines, corrugations) are usually located in narrower thin spots away from the edges. Unpublished
work by the author and former colleagues has demonstrated a correlation between the severity of MD wrinkles and the standard deviation of the average TD profile in thin polyester films.

**Solutions to profile-related faults**

There are a number of potential solutions to wound roll defects linked to profile. Some are within the province of winding, but others require attention to the process steps that determine profile and the product design. A combination of methods is most likely to succeed.

1. **Improve thickness profile**

   This is described in the later parts of the paper. Plastic film thickness is often controlled by a die with actuators, such as bolts, adjusting the local gap between the die lips based on the output of a scanning gauge downstream. Non-uniform thickness may be introduced during printing, where the ink thickness in printed features may sum over the layers in the roll. The thickness profile can be improved by minimizing the dried ink thickness and avoiding features that stack up at a particular TD location.

2. **Change product structure or formulation**

   The design of the product affects the radial modulus parameter $K_2$. A low value will improve all profile-related defects. This can be achieved by making the web thinner or increasing surface roughness.

   A second aspect that can be improved is the setting-in of strain on the roll, hence reducing gauge bands. Grades with less pronounced viscoelastic behaviour or a higher elastic limit are available for many materials.

   However, the freedom to make these changes may be limited by other aspects of performance, such as optical clarity, tensile strength and cost.

3. **Reduce winding tension**

   This reduces the roll diameter increase, and the pressure at all points across the width, benefitting gauge bands, wedged roll and blocking. However, there is a lower limit below which the roll will have insufficient integrity, and/or pre-existing baggy lanes are not pulled out.

4. **Lay-on roller**

   Lay-on rollers are used to partially exclude air from rolls of non-porous webs wound at high speeds, to increase roll hardness at lower winding tensions, and to use friction to hold the web at the correct lateral position so improving stacking. Lay-on rollers will exert more pressure on the ridges, and this may cause some local yielding of the points of surface roughness in contact, effectively reducing the local web thickness. The tendency of a wedged roll to dish should be less with a lay-on roller, because the incoming web is no longer steered to the larger diameter edge.

5. **Side flanges**

   Especially on narrow rolls, side flanges can keep the incoming web close to the correct location and hence limit dishing. However, they may be damaged by the large lateral forces developed in wide rolls.

6. **Oscillation**

   There are a number of methods to move the web from side to side so that the lanes of thick web do not stack up over each other. They are most effective for very narrow defects such as die lines. As the defects get wider, there is conflict between effective smoothing of the profile and loss of material in edge trims. There can be additional steering problems from the curved web portions where the direction of movement changes, both at the winder and in subsequent converting processes.
Blown film lines often have rotating dies to continuously sweep any profile defects across the width. They do not have the same issues with trims and steering.

7. Shorter storage time

With viscoelastic webs such as film and paper, the severity of gauge bands can be reduced by taking the web off the roll as quickly as possible after winding. Thus, shortening the storage and transport times will be beneficial. Time spent at elevated temperature (and humidity for moisture-sensitive materials) should be avoided: setting-in is accelerated by a factor of 10 by a temperature rise of 10 to 20°C.

Characterising profile

Web thickness profile can be broken down into 5 components:

1. Underlying TD profile, important for roll defects.
2. Variation in the MD which is uniform across the width. Periodic components arise from variations with time in the speed of machine elements such as the extruder and rollers, temperature and draw ratio.
3. Variation in the MD which is not uniform across the width, for example from rocking motion.
4. Random variation.
5. Noise in the measurement, for example from counting statistics of a nuclear gauge.

A single trace from an on-line scanning gauge contains contributions from all 5. The underlying TD profile can be revealed by taking an average of several scans. A simulated example in figure 3 shows how the 20-scan average gets close to the true underlying TD profile. The standard deviation (sigma) falls from 0.62% for a single scan to 0.18% for the 20 scan average. According to statistical theory, a plot of variance (sigma-squared) against the reciprocal of the number of scans in the average should be a straight line with the intercept equal to the variance of the underlying TD profile. Figure 4 shows that this is indeed the case.

![Figure 3](image)

*Figure 3:* Simulated single scan profile (lowest curve) and averages over more scans. The uppermost curve shows the underlying TD profile.

![Figure 4](image)

*Figure 4:* Linear rise of variance with the reciprocal of the number of scans in the profile average.
Improving profile

In continuous plastic film extrusion, the average profile can remain steady for many days unless there is a significant process change or interruption. The automatic control system has reached the limit of its ability to correct defects, and for further improvement the whole process must be considered. This includes the measurement, actuator, control system, any supplementary measurements such as manual location of die bolt and edge trim weighing, and other process steps such as drawing and heat-setting.

Web Handling Issues

Some aspects of web handling are important for accurate measurement of profile. It is important that the control system does not take action to correct errors that are not actually present!

Firstly, the web must stay in a fixed location under the gauge and be free from wander. If the web moves a significant distance sideways under the gauge because of poor lateral control, profile control action will be taken at the wrong location.

Secondly, the web must be flat under the gauge. A common problem is troughing of thin webs between rollers. The gauge measures the amount of material in the path of the beam, and so at point B in figure 6 will measure greater than the true thickness at A. Typical troughs are 2 mm high with a spacing of 100mm, leading to a 0.4% error at B. The profile control system will attempt to maintain constant thickness. As a result, if the troughs are stationary, the web will form thin lanes 50 mm apart. If they are moving, the whole troughed region will be 0.2% thinner. These values are significant for roll defects.

![Figure 5: Thickness error at the maximum slope of a trough (section through TD).](image)

Thirdly, any part of the material emerging from the die that is not measured by the gauge must be properly accounted for. If the edge trim does not pass under the gauge, or its thickness is too great to be measured accurately, the mass in the edge trim must be input to the controller some other way. There is a chance of error if the trim slitting blades are moved, the web shifts relative to them, or the mass measurement is no longer current.

Using the profile curve

Some useful diagnostic information can be obtained from the average thickness profile and the plot of actuator settings. Investigation should be focused on TD locations where the profile has a particularly large or broad deviation from the mean, where the actuators have reached or are close to their limit (zero or saturation), and where adjacent actuators are driven high and low.

Additionally, a Fourier transform of the profile can pick out regular repeats in the TD. These may indicate the effects of process features, such as the spacing of air nozzles or roll channels. A strong component at a spacing of 2 die bolts indicates a mapping error.

Further clues to improving profile can come from statistical charting. A particularly useful method is the well-known Cumulative Sum (CUSUM) chart for underlying TD profile. Sudden changes in gradient indicate a process change at that time: making the profile either better or worse. The improvement programme would seek to identify all causes, and remove those making the profile worse.
Conclusions

- Thickness variations can cause roll diameter and hardness variations, which contribute to several wound roll defects
- Diameter variations, and hence gauge bands, can be reduced by better thickness profile, lower radial modulus (product design), lower tension, the use of a layon roller, and oscillation.
- An average over many scans is needed to give the relevant underlying TD thickness profile
- Profile improvement must look at the whole process, including web handling, not just the control system

The product formulation and process improvements outlined in this paper will lead to a reduction in thickness profile related roll faults, lower internal rejection rates and customer complaints.

References