Taping Rollers for Traction and Spreading

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Introduction:

Line operators commonly apply tape to rollers to spread the web. Two kinds of patterns are often seen. One is circumferential and the other is axial. The circumferential pattern consists of a band extending underneath the web at each edge. The lateral pattern consists of lateral strips of different length in a chevron-like pattern extending from each roller edge into the web. In both cases the idea is to approximate a concave profile (concave rollers spread the web).

When I set out to write this paper, I envisioned a straightforward series of tests to directly measure flotation height profiles of moving webs on taped rollers. My thought was that by understanding how profiles varied over two basic patterns – axial strips and circumferential bands - some general conclusions could be developed that would apply to any pattern. However, as with many technical endeavors, this has turned out to be a much more difficult task than anticipated. A number of interesting measurements were made on axial tape patterns from which some tentative, but useful, conclusions can be drawn. However, more work is needed.

One of the most important factors in the behavior of webs on rollers is air film lubrication (flotation). Air is transported by both the web and the roller surface into the gap between them. At low speeds the effect is usually insignificant. But as speed increases, traction will decline and eventually the web will completely lose contact and literally “fly” over the roller surface. This is a subject that has attracted much attention over the years and it is well-understood. Many papers [1] [2] have been written on it, beginning with Daly [3] in 1965. At the heart of all this work is something called foil bearing theory. This is a remarkably effective simplification of hydrodynamic theory that is used extensively in the analysis of fluid film lubrication. It has even been extended to annular grooving, which has been demonstrated to be an effective method for venting the air film on high speed rollers (so that the web regains contact with the roller surface). An excellent design methodology for this technique is described in a 2003 IWEB paper by Rice and Gans [4].

Can lateral vents be just as effective? This question might seem irrelevant, because annular grooving is proven and reliable. But, operators use lateral taping and it appears to work, even in the presence of air flotation. Unfortunately, some of the simplifying assumptions of foil bearing theory break down when lateral ridges and grooves are present. So, it can’t be used for these cases with any confidence (at least not in its present form). This brings us back to the main purpose of this paper, which is to provide measurement data that will shed some light on this question.

Measurement equipment:

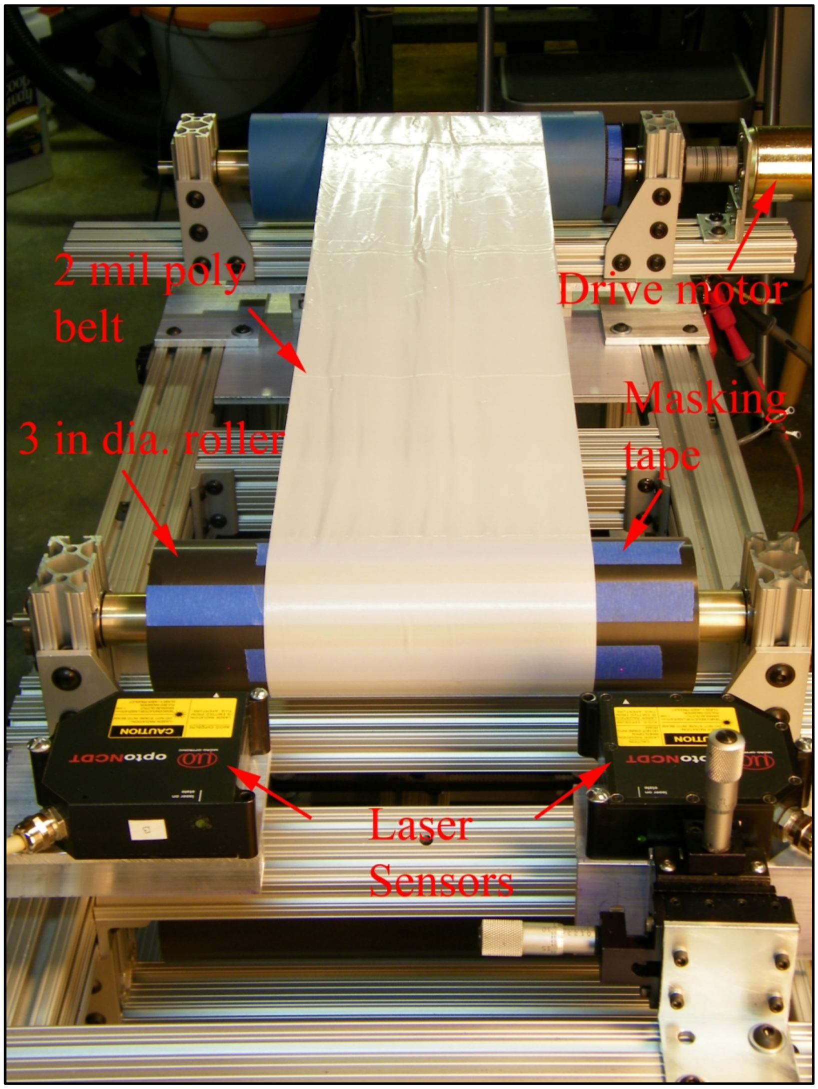

Figure 1
Test setup for measuring circumferential surface profile of polyethylene belt

<u>The belt</u>

The test setup is shown in Figure 1. A 50 inch (1.27 m) seamless belt was cut from a polyethylene compactor bag. Width was 6 inches (152 mm). Thickness of the film became an issue during the tests. It was shown on the box label as 0.0025 inch (0.041 mm). But, depending on test conditions, measured values ranged from 0.0016 inches (0.041 mm) to 0.002 inch (0.051 mm). This will be discussed later in more detail. The belt was mounted on two 3 inch (76.2 mm), hard-anodized aluminum rollers. One roller was driven with a small Pittman motor rated for continuous operation at 3,310 rpm.

Torque was adequate to get close to this maximum speed. Maximum belt speed with the motor at maximum rated voltage was approximately 2,600 ft/min (13.2 m/s).

The coefficient of friction between the belt and the roller surface was 0.12. The coefficient between the belt and the masking tape was also 0.12 (odd but true).

<u>The sensors</u>

Two Micro-Epsilon laser triangulation sensors Model ILD 1800-10 were used to measure surface height. Their measuring spot size is 0.0011 inch (30 µm) diameter. Range is 0.4 inch (10 mm) with a resolution of 0.00008 inch (2 µm). The sample rate is 5000/sec.

<u>Tension and damping</u>

The driven roller shown in Figure 2 was mounted on low-friction linear slides and equipped with opposed springs to provide belt tension. Motion was damped by attaching a 3 x 5 inch (76 x 127 mm) plate to the moving assembly so that it was 1/16 inch (1.6 mm) above the fixed mounting plate. The gap was filled with petroleum jelly, providing a damping factor close to unity.

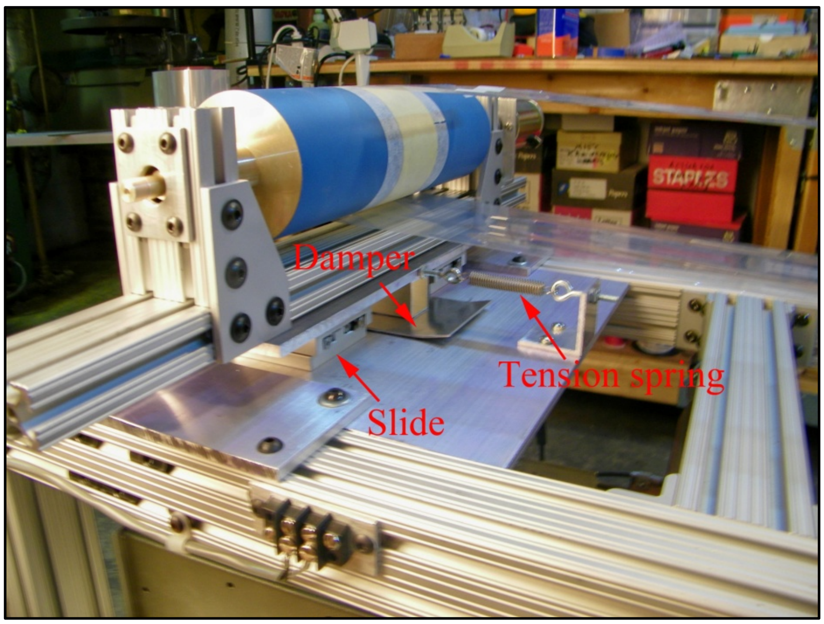

Figure 2
Drive roller showing one tension spring and damper

To keep the belt centered on the roller, a slight crown was created by adding tape to the center section.

The measurement process:

Sensor functions

Referring to Figure 1, the sensor on the left looked at only a single piece of tape on the roller surface. It was used to trigger the measurements made by the second sensor and to measure the roller speed. The sensor on the right made the measurement of surface height. It could be shifted laterally to measure either the bare tape or the belt.

Zeroing

Since every measurement had to be made in relation to the roller surface, special care was taken in establishing the zero reference before tests. The controller provides a feature that permits the sensor signal to be set to zero at any point within its range by pressing a button. This would be done for the bare roller surface just prior to each test run. When measuring on the belt, it could be temporarily slipped aside to make the roller surface accessible for the zero setting.

Eccentricity

The roller was slightly eccentric. The left sensor, which was 1 3/8 inch from the end, showed 0.002 inch (0.051 mm) peak-to-peak variation. The right sensor, which was 1 1/2 inch from the end when it was viewing the bare tape, showed 0.0004 inch (0.01 mm) peak-to-peak variation. No provision was made for eliminating this from the data.

Noise

Measurement noise was a problem. There were gauge bands in the polyethylene and creases from being folded in a carton. Belt tension couldn't completely remove the effects of the creases because it had to be kept low enough to attain reasonable air film thickness. Values were 0.1 and 0.2 pli (0.018 to 0.036 N/mm). So, there was too much variation to draw conclusions from a single revolution of the roller. This problem was solved with scan averaging. One complete set of data would be taken for each revolution of the roller and averaged with the next. This was done for 50 revolutions. Each scan was triggered at the same point of the roller circumference. So the noise would be averaged out, leaving only the net effect of the tape pattern and film.

Effect of film translucency

The white polyethylene film, in spite of its white pigment, is slightly translucent. The laser sensor is affected by this. Some light passes through it and is scattered back to the surface by the background or the second surface of the film, causing the distribution of light in the spot to change. The effect is most significant when the film is resting on the surface of the roller. When the thickness is measured by zeroing the sensor on the roller surface and then sliding the belt into the measurement area, the thickness reading is approximately 0.0016 inch(0.041 mm). But, the true film thickness ranges from 0.002 to 0.0025 inch (0.051 to 0.064 mm). Similar errors occur when there is air under the film. This was checked by cutting a very small window in a piece of optically clear PET of known thickness and then inserting it under the film. So, when studying the data in the graphs, there is an uncertainty on the order of 0.0015 inch (0.038 mm) in the height measurement depending on what is under the film. This is regrettable. However, in the author's opinion, it does not change any of the main conclusions of the paper.

A quick review of foil bearing basics:

Time and space won't permit a detailed discussion of foil bearing theory. But, a few of the basic relationships should be discussed to provide a meaningful context for understanding the test results that are about to be presented.

As illustrated in Figure 3, the air film thickness of a web that has completely separated from a smooth roller surface tends to be uniform over almost the entire angle of wrap. There is an entry zone where the film tends to converge to its steady state thickness in a very small fraction of the wrap angle. Near the exit, the film thickness tends to take a dip just before the gap opens up.

Every roller has some roughness. It may be so small that the finish looks mirror smooth. But, at high enough magnification, peaks (asperities) and valleys will be seen. So, even at low speeds, there is a small amount of air flow under the web. The web lifts off the roller surface (off the peaks of the asperities) when the pressure due to the velocity of the air in the gap exceeds the pressure due to web tension. As the gap increases, the pressure drops until it is in equilibrium with the tension pressure.

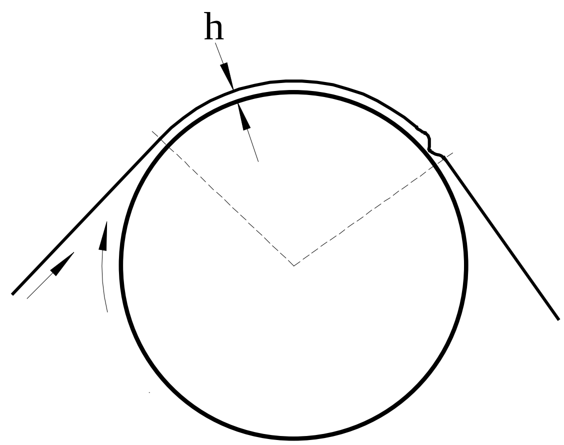

Figure 3
Web floating on entrained air film

When air entrainment becomes significant, everything changes. Traction is lost and the normal entry rule no longer works. Spans may no longer be isolated and if the air film becomes thick enough, rollers lose their ability to flatten the web.

<u>The foil bearing equation</u>

If a web is nonporous it is easy to calculate the thickness of the entrained air film with the foil bearing equation (sometimes known as the Knox-Sweeney equation). Every web handling engineer should be familiar with it. The film thickness, h for a roller is given by,

(1) $$h = 0.643R\left(\frac{6\mu(2V)}{T}\right)^{2/3}$$

Where R is the roller radius in meters or inches, V is web speed in m/s or in/s and T is web tension in N/meter or Lbf/inch.

μ is the dynamic viscosity of air = 1.8 x 10^{-5} kg/(m·s) or 2.611x10^{-9} in units of lb/(in·s)

The factor of 2 beside V in equation (1) accounts for the fact that both the web and the roller surface are moving. When making calculations for a D-bar, where only the web is moving, this should be replaced by unity.

Centripetal force

Centripetal force is usually assumed to be a concern only at the high speeds of paper lines or for dense materials like steel. However, it should not be totally ignored in converting applications. It turned out to be significant in the tests reported in this paper. It can be incorporated in (1) by subtracting a term from the tension, T.

(2) $$T = T_w - d\rho V_w^2$$

Where T_w is the usual tension in pli or N/m, d is web thickness, ρ is its density and V_w is its speed.

An example

To illustrate with one of the situations from the tests reported in this paper. V = 2,500 ft/min (500 in/s), R = 1.5 inches , T_w = 0.2 pli, d = 0.002 inch, ρ = 9.325 x 10^{-5} lbmass/in^3. Equation (2) would then be,

(3) $$T = 0.2 - 9.32 \times 10^{-5}(0.002)(500)^2 = 0.2 - 0.047 = 0.153\,pli$$

Using this result in (1) yields,

(4) $$h = 0.643 \times 1.5\left(\frac{6 \times 2.611 \times 10^{-9} \times (2 \times 500)}{0.153}\right)^{2/3} = 2.1 \times 10^{-3}\,inch$$

Note that the centripetal term in (2) is 23% as large as T_w.

Test results:

Two types of tests will be presented. In one, half the circumference was covered with masking tape (Scotch Blue #2090). The taping is shown in Figure 4.

In the other test, eight equally-spaced strips of the tape were applied parallel to the roller axis. This is shown in Figure 1.

Half-circumference test:

Results for the half-circumference taping with tension at 0.2 pli are shown in Figure 5. The dashed lines are the calculated values of air gap using the foil bearing equation (includes 0.0016 inch of film thickness). Their colors correspond to those of the measured data.

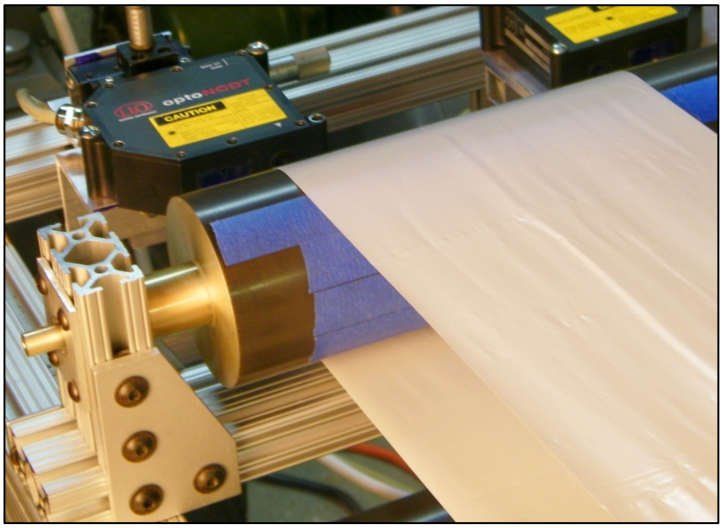

Figure 4
Masking tape applied to 180 degrees of the roller circumference

It is important to keep in mind that although the abscissa is labeled “distance on the circumference”, the point of measurement is fixed relative to the wrapped portion of the roller and the distance refers to movement of the web and roller past this point.

<u>Behavior on the untaped part of the roller</u>

The calculated values agree well with measured gap over much of the uncovered part of the roller with dips near each edge of the tape. The dips are probably due to a pressure drop associated with the sudden change in the roller profile. The minimum thickness at 182 ft/min (0.93 m/s) is smaller than 2 mils because of the effect of film translucence.

<u>Behavior on the tape</u>

When the film is on the taped portion, its behavior is much different. At speeds below 1,700 ft/min (8.64 m/s), the film does not rise from the tape surface. This is undoubtedly due to the fact that the tape surface is very rough. The web rests on the highest asperities while the air flows through the valleys. Above 1,700 ft/min, the web lifts off the asperities in the last two-thirds of the taped portion.

<u>A narrow zone of traction</u>

There is one point in Figure 5 where the film appears to be in contact with the tape at all speeds. It is at the leading edge of the taped portion, where the height is 0.0052 inch. All of the curves intersect there. This is could be due to a low pressure zone, where the air on the leading edge of the masking tape is being sucked into the gap behind it. Something similar to this is discussed in the foil bearing literature. Muftu and Hinteregger [5] discuss a “sub-ambient” foil bearing where the pressure over a flat recording head drops below the ambient pressure because the recording tape creates a diverging channel at the leading edge of the tape gap. The droop ahead of the dips in the untaped portion is probably caused by the onset of this phenomenon.

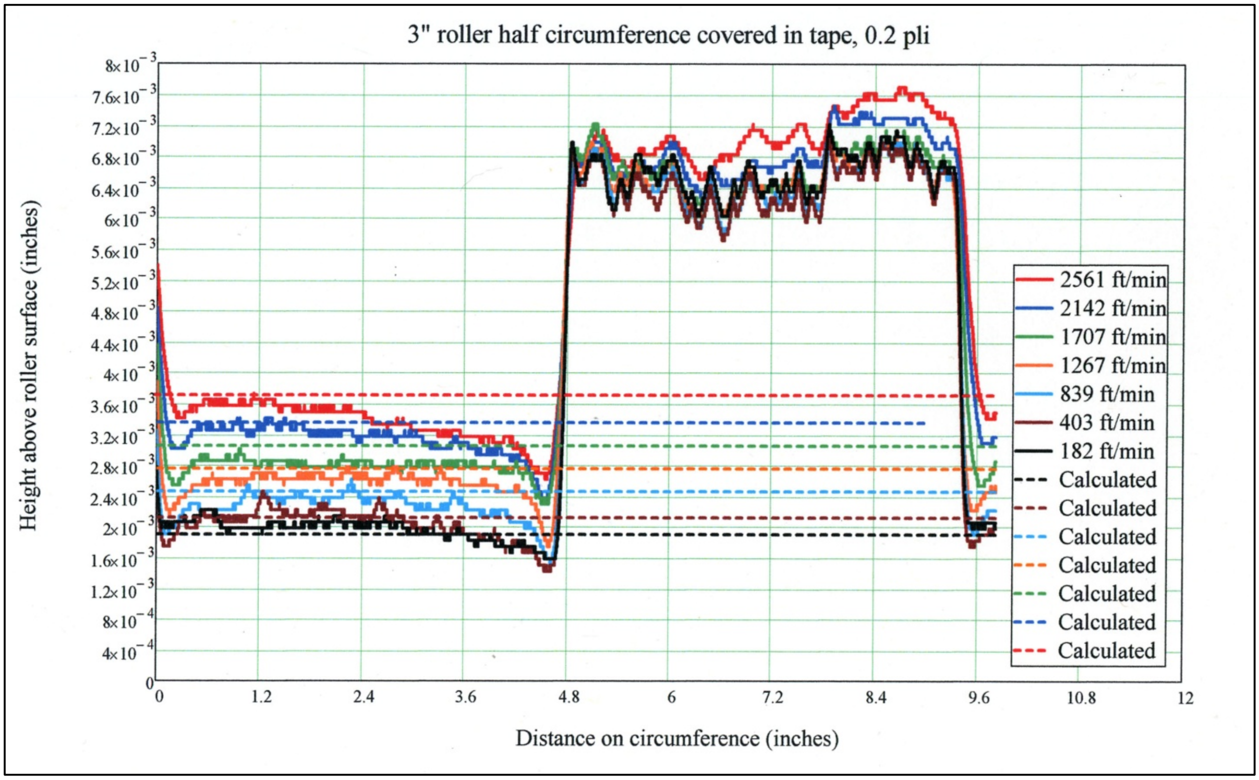

Figure 5
Test results for roller with half its circumference covered with masking tape

Another factor that could contribute to contact at the tape edge is that the web makes a sharp bend at the transition from the tape surface to the gap. This bend has a very small radius. The radial pressure that opposes the air film pressure is tension/radius. So, the pressure at the bend could become much higher than that on the rest of the surface.

Eight-strip test at 0.2 pli:

For this test, eight strips of the ¾ inch (19.1 mm) masking tape were applied parallel to the roller axis (illustrated in Figure 1). The tape was not applied with great precision. A disk was marked at 45 degree intervals and mounted on the roller shaft. Using this as a rough guide for spacing on the circumference, the tape was aligned by eye with the roller axis as it was applied to its surface. Results for a static belt tension of 0.2 pli (35 N/m) are shown in Figure 6. The dashed lines, once again, are the calculated values of air gap using the foil bearing equation plus film thickness. Figure 7 is an enlarged view of part of the data.

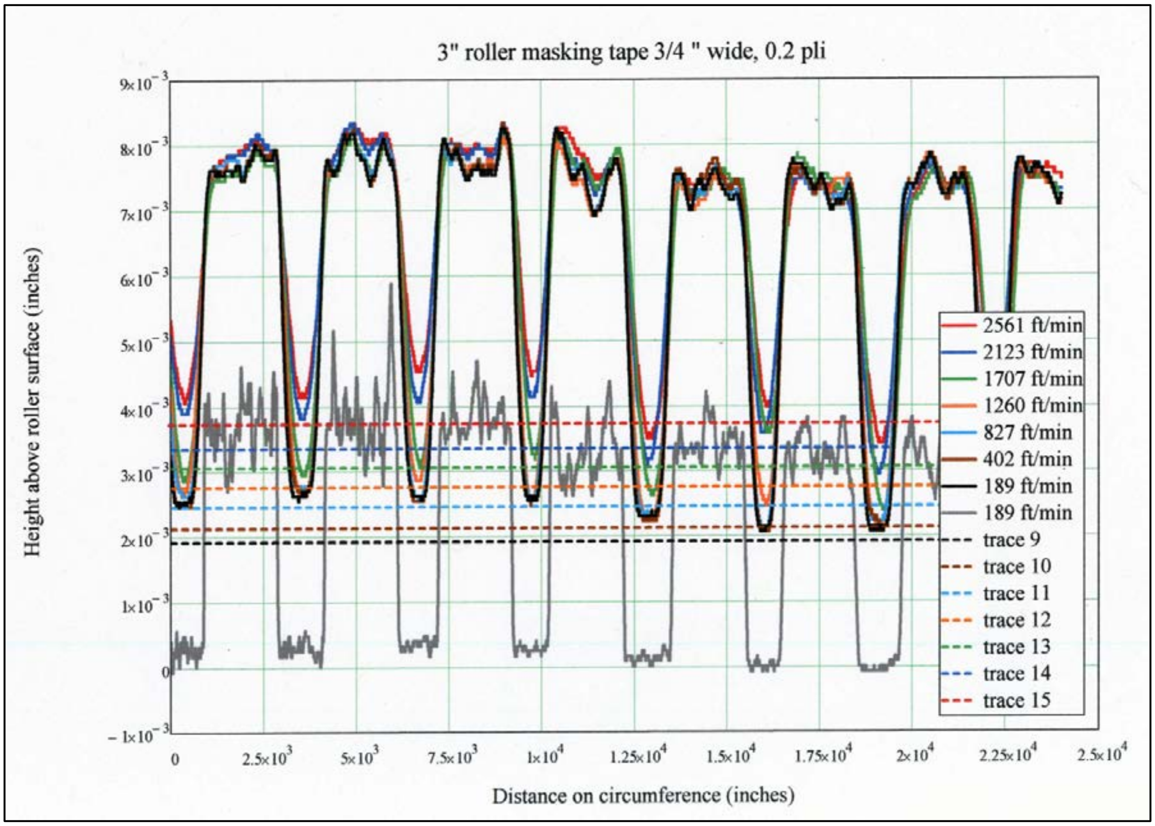

Figure 6
Eight strips of masking tape at 0.2 pli

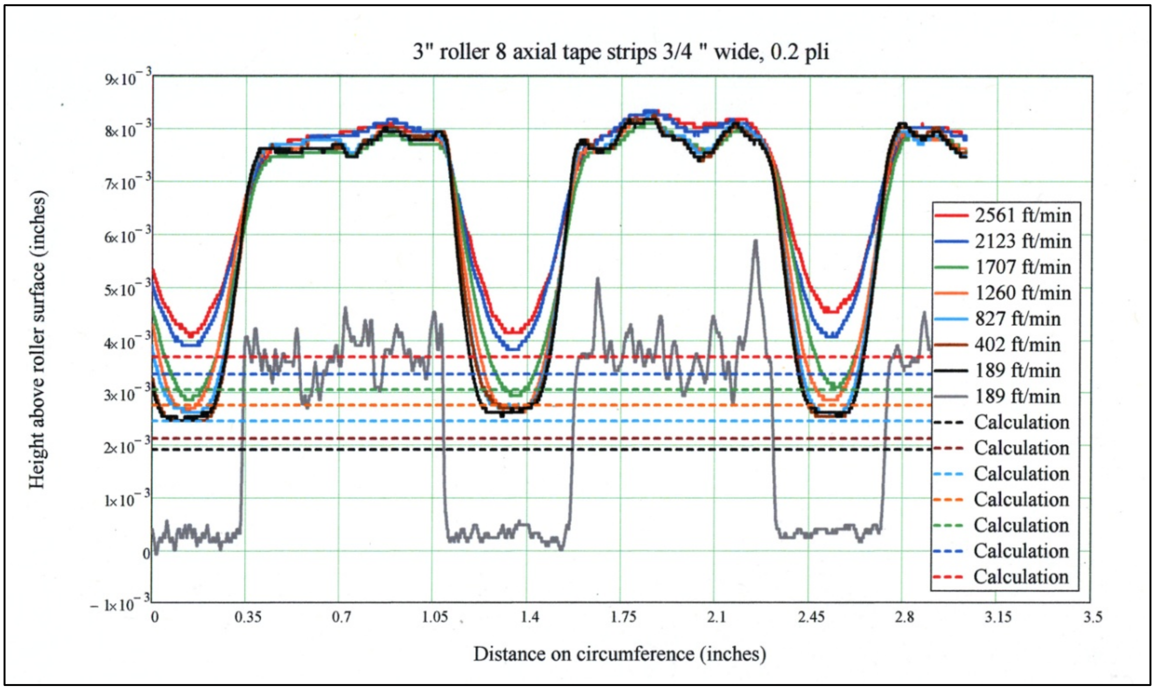

Figure 7
Enlarged view of part of Figure 6

Behavior in the gaps

The film is pulled down into the gaps between the tape. But it does not appear to be reaching the roller surface at low speeds even though the geometry of the scale drawing of Figure 7 indicates this should happen. Also, at higher speeds the foil bearing equation does not predict height.

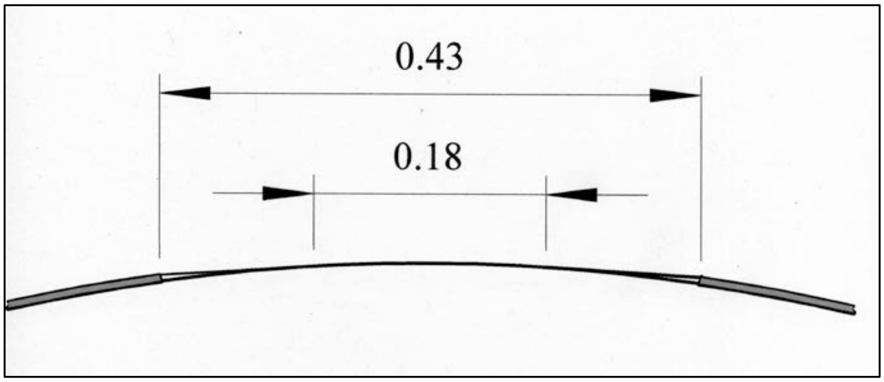

Figure 8
When stationary, the film is in contact with the roller for approx. 0.18 inch

Narrow zones of traction

The eight-tape test of Figure 7 shows the same intersection of curves as with the half-circumference taping. In this case, it is seen on both the leading and trailing edges of the tape. The intersection is seen most clearly on the first strip of tape. Looking at Figure 6, as the strips get further in time from the trigger pulse, the intersection widens a bit. The drive motor speed was unregulated and the variability in time probably increased as the delay after triggering became larger. This may mean that the intersection on the trailing edge of the half-circumference test shown in Figure 5 was better than the data indicates.

Behavior on the taped portion

As in the case of the half-circumference test, the roughness of the tape surface allows the web to stay in contact at all but the highest speeds. Above 1700 ft/min the film is showing signs of lifting off the top surfaces. However, it continues to maintain contact at the edges.

Eight-strip test at 0.1 pli:

Results for a static tension of 0.1 pli (17.5 N/m) shown in Figure 9 and Figure 10 are very similar to those at the higher tension. For speeds below 1,700 ft/min the peak film heights over the tape are the same. The lowest speed valleys are also close to the same. But, at moderate and higher speeds they are significantly shallower. The most important difference is in the height of the film over the tape at 2,429 ft/min (12.3 ft/min). It is clearly floating 0.0005 inch (0.013 mm)over the tape. But, it still catches the edges of the tape.

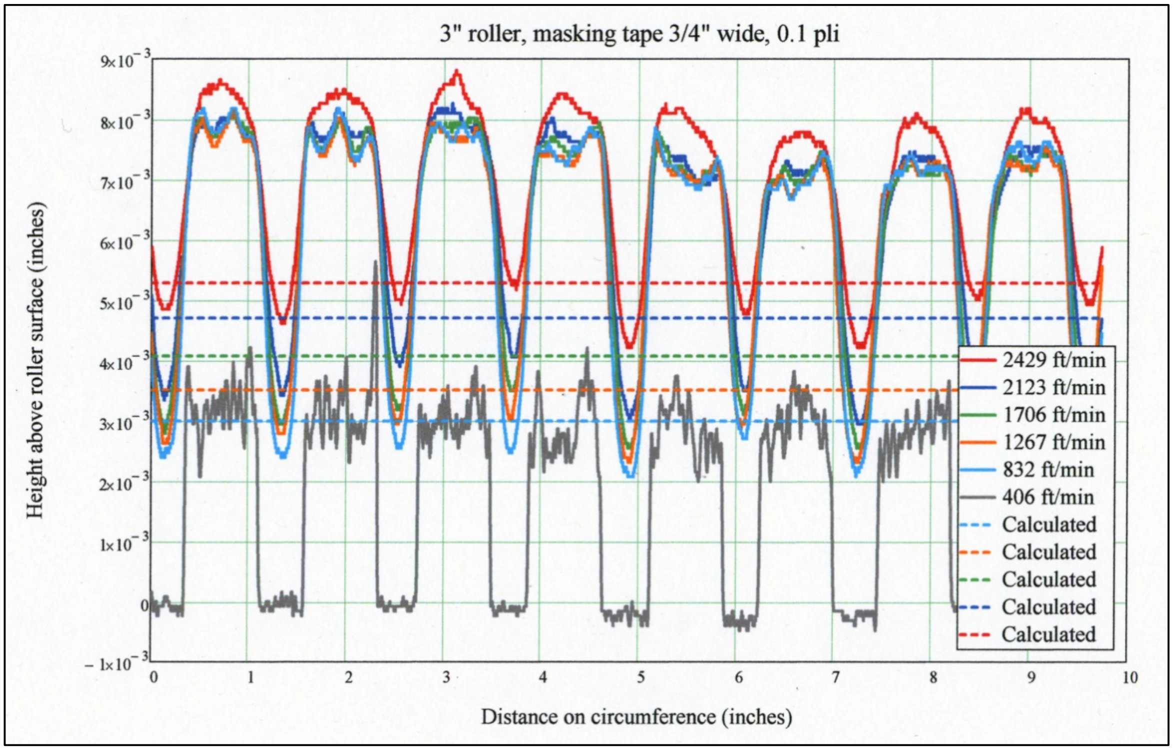

Figure 9
Eight strips of masking tape at 0.2 pli

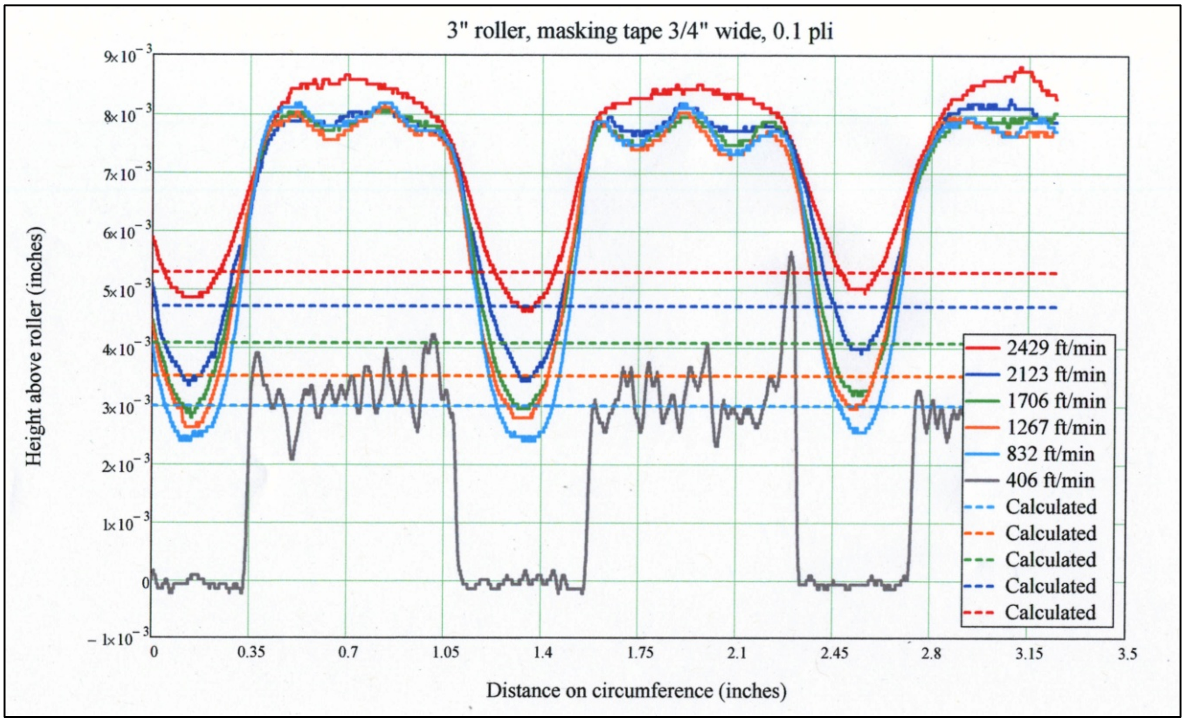

Figure 10
Enlarged view of part of Figure 9

Roughness of the tape and the roller

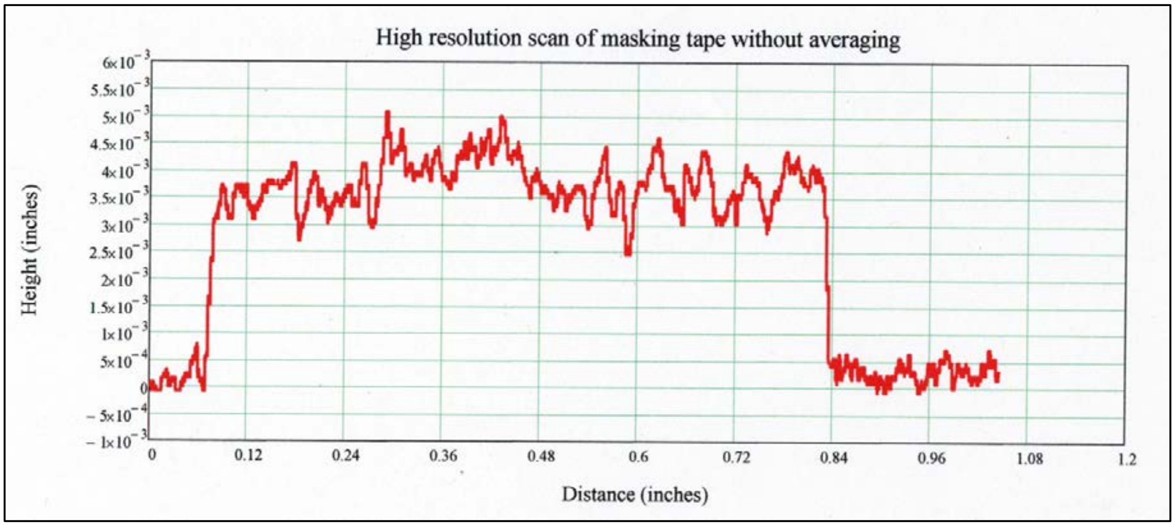

Figure 11
High-resolution scan of tape profile

The rms roughness of the top surface of the tape is 0.440×10^{-3} inch (0.01 mm). For this particular scan the maximum and minimum were 5.1×10^{-3} inch (0.13 mm) and 2.5×10^{-3} inch (0.064 mm) respectively.

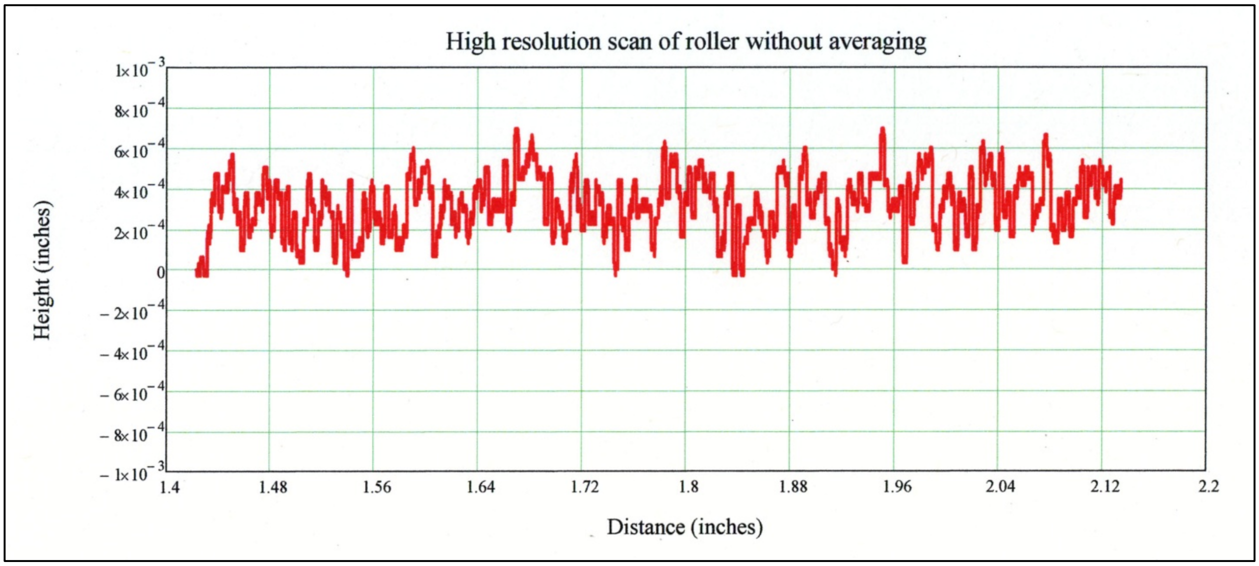

Figure 12
High-resolution scan of roller surface

The rms roughness of the surface of the roller is 0.146×10^{-3} inch (3.7 μm). For this particular scan the maximum and minimum were 0.7×10^{-3} inch (17.8 μm) and -0.03×10^{-3} inch (-0.76 μm) respectively.

Circumferential bands

No measurements were made on circumferential bands. I would like to have gathered some data on behavior at both the web edge and the inner edge of the tape. But, as this work progressed it became apparent that expensive apparatus would be required to horizontally scan and trigger the main measuring sensor.

Some important aspects of behavior can be predicted from work that has been done on annular venting [4] and one important conclusion that can be gleaned from the horizontal strip measurements is that masking tape is particularly effective because it has such a rough surface.

Conclusions

1. One obvious conclusion is that masking tape has a very rough surface that enables it to vent entrained air very effectively.
2. Narrow zones at lateral tape edges can maintain contact with the web at speeds where the foil bearing equation predicts a complete loss of contact.
3. When simulating a concave roller with tape, horizontal chevron patterns may be able to maintain traction at speeds higher than the foil bearing equation would predict (even when the effect of the roughness of the tape is included) because of contact at the tape edges.
4. These results may not apply to webs that can't bend to conform well to the tape profile.

Smooth tape should not be used.

More work is needed. In particular, tests should be made that include a provision to measure the torque at which slipping begins and a better sensor is needed or, alternatively, webs that are more opaque.

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