The Effects of Web Tension on Tack Forces During Printing

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Keywords: tack forces, pressure, web tension, picking

Abstract

The force required to separate a web stuck to a roll is generated by the negative pressure the adherent fluid applies to the web. The maximum negative pressure, called tack pressure, is an important indicator of maximum stress applied to the web surface during converting operations such as printing, coating, and adhesive processes. Tack pressure is measured with flush mounted pressure transducers when a web is present in the nip. It is influenced by a number of process parameters including viscosity, velocity, web tension, takeoff angle of the web, and roll cover compliance. The shape of the pressure distribution through the nip changes when a web is present. A simple expression was found to correlate the tack pressure with other parameters for both Newtonian and shear thinning fluids without a web (Gates and Bousfield, 2015). In this paper, this expression was extended to account for studies where a web influences tack pressure through web material properties and takeoff angle of the web take-up roller relative to the nip. Takeoff angle can affect shear forces applied to the fluid by the web, which in turn can influence tack development and actual web release angle from the inked roll surface.

Introduction

Tack is the viscous force resisting separation of a web from a roll surface in printing or coating applications. It has been heavily studied in literature; however its magnitude is rarely reported (Hartus and Gane, 2011). The goal of this work is to predict tack that occurs during printing and forward roll coating on a web. Various parameters can influence tack including fluid rheology, nip roller speed, web parameters such as takeoff angle, absorption coefficients, and stiffness and roll parameters such as elasticity and radius.

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Peeling tests and adhesive force measurements have long been measured (Zhao and Pelton, 2003). However, it is difficult to translate these test results to a press environment. In some probe-tack devices, tension is created by a weighted probe attached to a strip by a film of fluid, while in other cases a plate is mechanically moved. Composite tension and angle of attack have been investigated. In an earlier paper Gates and Bousfield (2015) it is demonstrated how web tension is important in z-directional peeling between parallel plates, this lead to the hypothesize tension will influence tack pressure during forward roll coating processes.

A few researchers have experimented with tensioned webs. Kerkes (1975) performed experiments with a viscoelastic strip in a nip. Mufutu and Jagodnik (2004) measured and modeled web traction experiments between a roll and web. Niemitso et al. (2000) studied fluid-structure interaction with paper webs and low viscosity fluids in the papermaking process. Despite these studies, over the last two decades only a few researchers have measured tack forces in a press directly (Aspler, et al, 1994, Johnson, 2003). Of these, only Ascanio et al. (2004) and Devisetti and Bousfield (2002) have measured and reported tack pressures in a nip using taped strips. They did not focusing on control of web tension in tack development as is the case in industry. Ascanio et al. (2004) investigated misting on a deformable roller with a web strip and Newtonian fluids. He used lubrication methods to predict pressure pulse measured with a piezo sensor embedded in one of the rolls. Devisetti and Bousfield (2002) also used a similar taping of a web. Web release from a roll was modeled and experimented with by Iyer and Bousfield (2010). Iyer performed experiments with a camera and size press, but the numerical model did not fit the experimental data well either in magnitude or trend. Experiments measuring pressure generated in a nip for highly viscous fluids with a web under known tension and specified takeoff angle are lacking in literature.

Experimental

Tack pressure is measured on a press consisting of a nip with a deformable rubber covered roll with shore A hardness of 36 is forced with air pistons mounted the two ends of its shaft. The rubber roll slides on linear slides when loaded against a rigid steel roll. An array of surface mounted piezoelectric pressure transducers of resonance frequency greater than 250kHz manufactured by PCB Piezotronics with model numbers 105C02 (sensors 1 and 4) and 105C12 (sensors 2 and 3) with sensitivities 50 and 5mV/psi respectfully are mounted inside the steel roll of radius 63.5mm and width 229mm to allow for pressure normal to the rigid roll surface to be measured. The pressure transducers are spaced on a linear 45o line with respect to circumferential and cross directions along the roll surface. The cross direction spacing of the sensors from 1-4 is: 12.7, 63.5, and 12.7mm between sensors where S2 is at the center of the nip as shown in Figure 1.

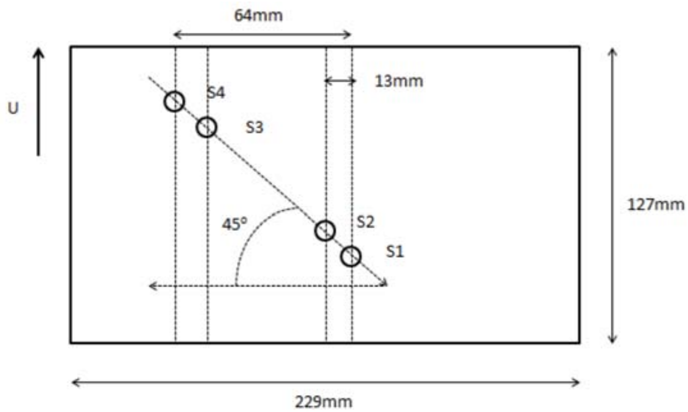

Fig. 1 *- Sensor orientation*

Pressure signals are run through a multi-channel PCB Piezotronics signal conditioner model 483A17 where amplification is set to unity for simplification of pressure conversions between sensors. A 150mm wide web loop is constructed with conveyor rollers wound through a press as shown in Figure 2. Tension is applied through a weighted dancer roller, spring loaded to minimize bouncing which can lead to large tension oscillations.

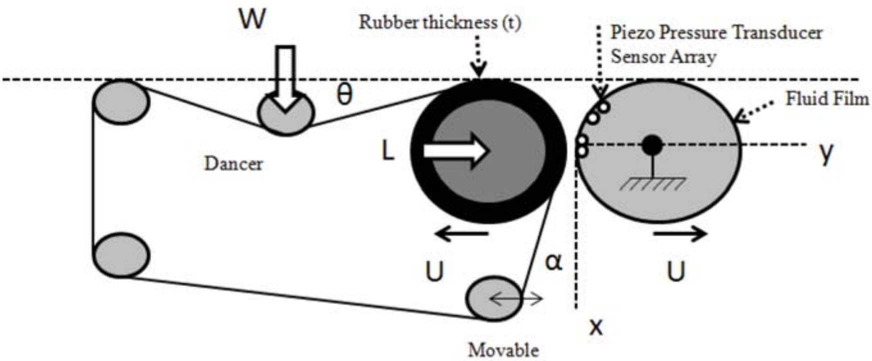

Fig. 2 *- Laboratory press with web loop.*

The web loop is wrapped around a series of rollers of radius 24.1mm. Tension is controlled by a weighted guide roll (dancer roll). Nip speed is digitally controlled in LabVIEW with Emerson EN-214 motor controllers attached to the axis of each nip roll. The angle that the web is pulled at relative to the nip is adjusted by the position of a guide roll near the nip exit. Web tracking is adjusted with a worm gear attached to one side of the roller in the upper left quadrant of Fig 2. Paper and plastic webs are looped around the rubber roll with various tensions and takeoff angles. Both shear thinning and Newtonian fluids with viscosities ranging from 0.1 and 200Pas are studied at nip speeds of 0.1 to 2m/s, and nip loadings ranging from 3.2-12.9kN/m are studied. An empirical correlation for coupling tack pressure and web parameters in continuous coating and printing applications is found.

The bottom conveyor roller (web take-up roller) can be adjusted along tracks to change the nip exit angle (α), while the conveyor roller in the upper left hand corner can be adjusted at one end to allow for web tracking control. Another conveyor roller is mounted to two vertical rollers riding in uni-strut tracks. This roller is spring loaded against large deformations up from the web surface to prevent bouncing. Hollow cylinders are attached to hollow tubes mounted to the vertical rollers holding the conveyor roller. This allows for tension to be increased by adding metal rods weighing 0.233kg to the cylinder with an initial weight of 2.562kg. Figure 3 was generated by statically measuring the effect of adding webs to the position of the weighted conveyor roller relative to the surface of the undeformed rubber roll as shown in Figure 2. From the angle (θ), the web tension is calculated using Eq. (1). The tensile stiffness of the web changes the angle θ in Figure 2 leading to different tensioness for different materials.

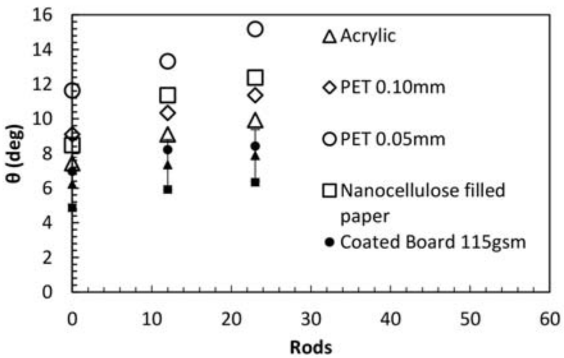

Fig. 3 *- Dancer angles for different loadings and web types*

A force balance between the web tension (T) and the weight applied (m), gives,

$$T = \frac{mg - 2k\Delta x}{2W\sin(\theta)} \sim \frac{mg}{2W\sin(\theta)} \quad (1)$$

The tension of the web is determined from the mass of the rods and chasis system (containing the hollow cylinders and conveyor roller mounted to the vertical rollers riding on uni-strut tracks) mass is multiplied by gravity (g) and the force excerted from both left and right springs of spring constant (k) divided by the web width (W). Web tension is varried between approximately 0.47 and 1.55 kN/m. The influence of the springs is not significant due to small disturbances from their relaxed length.

The rubber roll is loaded against the steel roll by applying pressure with two 58mm diameter pistons to each end of the rubber roll's shaft. The pressure is converted to the line load with the piston area and nip width. In the following experiments, lineload is varried from 3.2 to 12.9kN/m while in subsequent experiments the line load is fixed to 6.5kN/m unless otherwise mentioned. The line load is also checked by running the nip in a dry condition: the linear fit of the integration of the pressure pulse matched the applied line load within 4% for sensor 1, 3% for sensor 3 and 20% for sensor 4.

The set takeoff angle (α) is assumed to be positive in the direction shown in Figure 2, where the web is pulled away from the roll covered with fluid. The angle is negative if the roller is moved backwards and the web is pulled along the direction of the fluid covered roll. The actual release angle can be different from what is set, especially at low tension. If the web sticks to the steel roll for some distance, the actual release angle can be different from what is expected if the web comes straight out of the nip towards the take-up roll. The web takeoff angle is varried between 18 and -22 degrees where for more negative takeoff angles, the web is released closer to the applicator roll surface.

Different web materials were used to understand the influence of web stiffness and type including two plastic films, a wood free paper board and an aluminum web whose properties are shown in Table 1. The taber stiffness was measured with a taber stiffness tester using TAPPI/ANSI T489 om-13 and TAPPI T566 standards. The tension in the web corresponding to the number of rods applied during the test can be estimated from Figure 3 and Eq(1). For the 0.10mm polyethylene terephthalate (PET) film, values are estimated from the acrylic film values in the table.

Web Material	Caliper (mm)	Taber Stiffness (g-cm)	Width (m)	0rods- T(kN/m)	12rods T(kN/m)	23rods T(kN/m)
PET	0.10	3.4+/- 0.7	0.152			
PET	0.05	0.2 +/-0.1	0.152	0.41	0.75	0.98
Acrylic	0.11	15 +/- 3	0.152	0.64	1.09	1.48
Aluminum Flashing	0.15	70 +/- 4	0.152	0.97	1.68	2.31
Uncoated Board (200g/m^2)	0.39	194 +/- 12	0.152	0.76	1.35	1.86
Coated Board (115gsm)	0.31	53	0.152	0.68	1.21	1.74
Nanocellulose Filled Paper (24gsm)	0.06	0.8 +/-0.2	0.140	0.61	0.95	1.29

Table 1. *- Web Properties.*

Fluids are varied both with viscosity (μ) and fluid type, from Newtonian fluids including standard silicone oils and oil to shear thinning inks. Table 2 outlines the rheology of different fluids used in testing. If the fluid acted Newtonian the plateau viscosity was recorded, otherwise the viscosity at a shear rate near 1.s^{-1} was used. Rheology was characterized with a controlled stress rheometer (Bohlin CSV) using parallel plates or cone and plates. Parallel plates are used for viscosities below 50Pas while cone and plate are used for viscosities above 50Pas. Coldset inks were obtained by Sun Chemical with sample numbers 2008-615(2007-289) coldset and VCM 3250X Productivity M Magenta for magenta, VCY 3250 Productivity M Yellow for yellow, and VCC 3250X Productivity M Cyan for cyan ink. Boiled linseed oil was made by Barr Co. product number GLO45. Silicone oil (60.80Pas) was made by Brookfield Engineering Laboratories. The 10,000SUS oil was a generic flow rate standard.

In these studies an excess supply of fluid is added to the nip after the web is attached and the nip is loaded. The flooded condition is kept by monitoring the nip and adding fluid as necessary so a bead of fluid is always visible from the top of the nip. As one can immagine this is very messy with ink, and for speeds in excess of 2m/s this method does not work well due to misting and flow inertia. The pressure profile reported is the average of pressure profiles recorded using a LabVIEW program developed for signal analysis of the pressure data. Repeated trials are typically conducted and the average of those pressure values and corresponding standard deviation are reported. The pressure distributions are typically recorded with a slight delay from the start of the rolls, allowing the rolls to accelerate to speed, and web to be uniformly covered before measurements were collected. Sensor 1 is used for pressure pulse data unless otherwise mentioned.

Fluid	Viscosity/stdv (Pas)		Rheology Type
Silicone Oil Standard 60.80Pas	61.7	0.8	Newtonian
10,000SUS oil	7.1	0.2	Newtonian
Boiled Linseed Oil	0.0407	0.0006	Newtonian
Magenta Coldset Ink	64.9	8.2	Shear Thinning
Productivity M Magenta Ink	55.3	1.3	Shear Thinning
Productivity M Yellow Ink	72.7	18.8	Shear Thinning
Productivity M Cyan Ink	102.9	6.5	Shear Thinning

Table 2 - *Test Fluids Used in Study*

When the pressure distribution in the nip is recorded, of key interest is the sub-ambient pressure. Tack is defined as maximum negative pressure as (P_m). Tack generates stress on the paper. Coaters, printers, and adhesives experts are interested in being able to understand and predict the maximum stresses that a paper web must be able to withstand without delamination, and at under what press conditions this occurs.

Results and Discussion

Figure 4 shows tack pressure development with and without a web. With a web the maximum sub-ambient pressure or tack pressure occurs a significant distance from the positive pressure peak. A small secondary sub-ambient pressure pulse is seen prior to the tack pulse in this case. The primary sub-ambient pressure pulse is influenced by peeling, and less by flow rate as it is without a web. Typically the tack pressure without a web is larger than with a web. Depending on the web the peeling tack force may be larger or smaller than the normal tack force. This means the minimum tack pressure is a function of two competing mechanisms, the negative (sub-ambient) pressure development due to flow rate and the negative pressure development due to the film split. Sometimes with high tension or less negative takeoff angles (larger release angles form the applicator roll) the peeling is forced into the nip reducing or eliminating the normal tack pulse and leaving only a combination or peeling tack pulse.

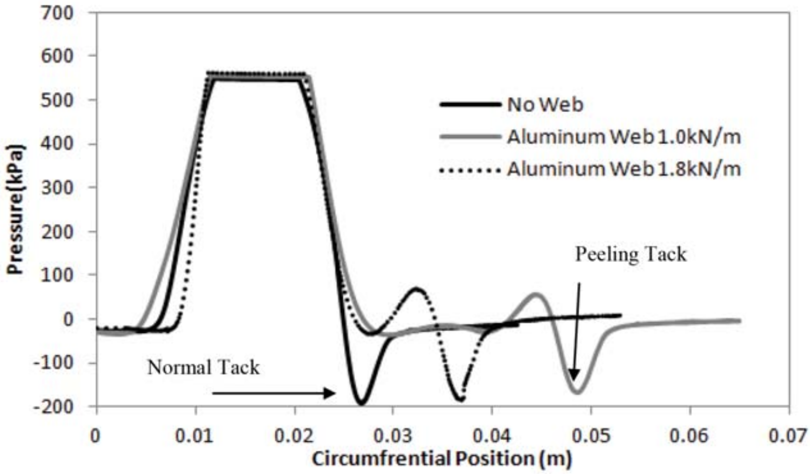

Fig. 4 *- Pressure vs. circumferential sensor position for 5 degree web takeoff angle, an aluminum web tensioned at 1.0kN/m or 1.8kN/m with 60.80Pas silicone oil coated at a speed of 0.5m/s.*

The absolute magnitude of the tack pressure is of key interest and is the focus of the results here. Figure 5 shows tack pressure for the different sensors (1 to 4) from the center to edge of the roll generated with 60Pas silicone oil with the aluminum flashing and a web tension of 1.0kN/m at an angle of 5o. Generally, larger tack forces occur at the center of the nip where there may be a larger fluid layer thickness due to compression of the rubber.

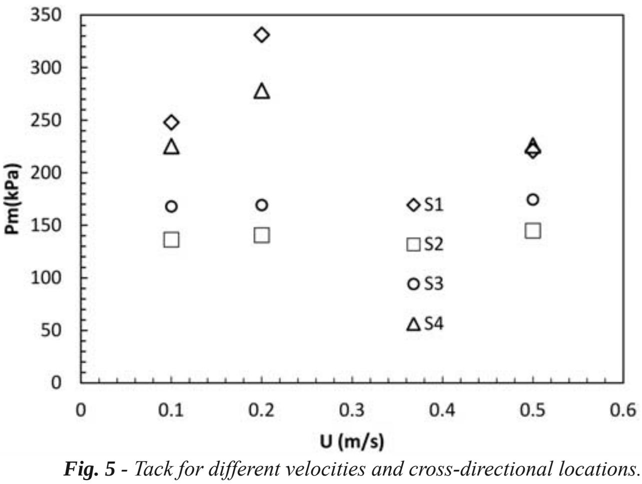

Fig. 5 *- Tack for different velocities and cross-directional locations.*

Figure 6 shows various sensors with a PET web at different tensions corresponding to approximately 0.6, 1.1, and1.5kN/m. There is more variation between sensors than between the range of tensions tested. Tension has a minor effect on tack pressure development. Subsequent studies use sensor 1 located at the center of the nip because it is usually flooded better than the sensors near the edge of the nip.

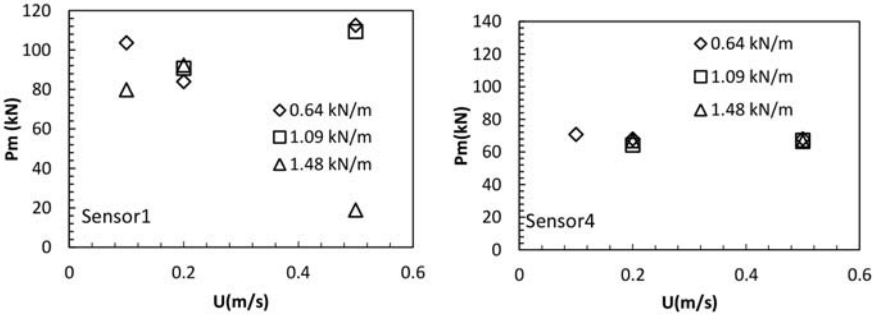

Fig. 6 *- Tack for different velocities and tensions with linseed oil. Different sensor locations are shown. (Average tack values are for one setup of the web and fluid application and are associated with averages of multiple tack pressure pulses during a few seconds of data acquisition with between 1 and 3 revolutions in this case depending on speed and data acquisition setup).*

Figure 7 shows the effects of velocity and tension on tack pressure with 10,000SUS oil on a PET web compared to shear thinning cyan, yellow, and magenta coldest offset inks using sensor 1. For shear thinning inks, the effect of velocity on tack pressure development is small. The effect of loading is also reduced for shear thinning inks.

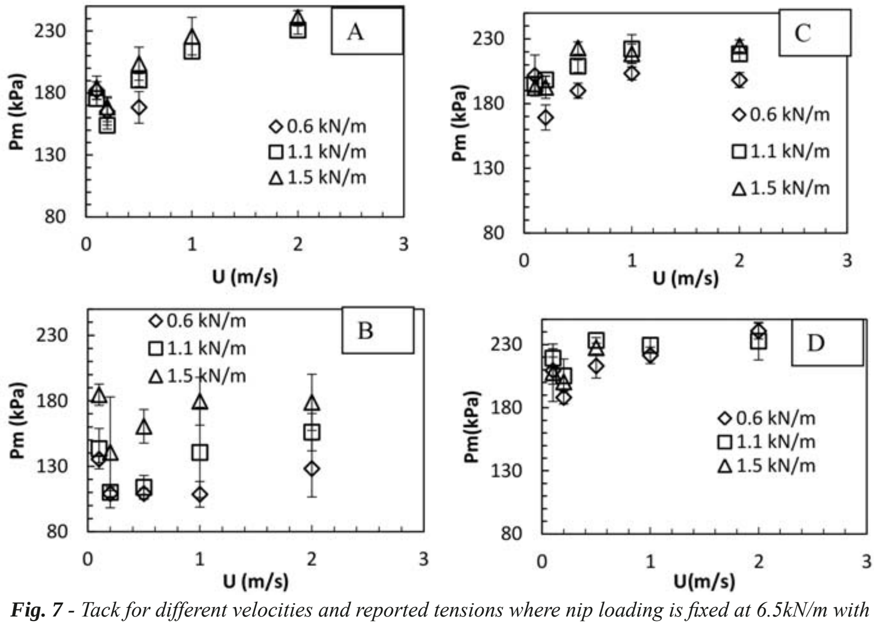

Fig. 7 *- Tack for different velocities and reported tensions where nip loading is fixed at 6.5kN/m with coldest inks and viscous 10,000SUS oil. Tests are performed using plastic PET webs where standard deviations are for one web application and average tack pressure values from about 6 fluid applications as is true of graphs with linseed oil bellow. Graph A is with 10,000SUS oil, B with yellow cold-set ink, C with cyan cold-set ink, and D with magenta cold-set ink.*

Larger tensions slightly increase tack force as shown most visibly for the yellow cold-set ink. While for the cyan cold-set ink the effect of tension is smaller. Large error bars for the yellow ink and ink viscosity may explain some of this variation.

Dimensionless parameters as shown in Table 3 are used to correlate results. Pressure is made dimensionless with viscosity, velocity, and roll radius. This is similar to the velocity-viscosity product discussed in the literature, but now takes into account the roll radius. Tension and line load are made dimensionless with velocity and viscosity. The elastic modulus of the rubber roll cover generates another group. The width of the web may play some role in the results.

Dimensionless Parameter	Equation	Max	Min
P_m* (Tack)	—	1E+7	10
T* (Tension)	—	1E-1	1E+5
L* (Line Load)	—	1E+1	1E+7
E* (Nip Elasticity)	—	1E-1	1E+4
α (Takeoff Angle)	α	20°	-20°
W* (Width Aspect Ratio)	—	2.4	

Table 3 *- Dimensionless Parameters*

Using the parameters in Table 3 the following figures are generated showing relations between the dimensionless groups. For sake of comparison tension is kept in dimensional form so each data point will not have a different T* value. Overall the effect of takeoff angle on dimensionless tack force is small compared to velocity and viscosity as shown in Figures 7-9 where L* and Pm* depend on viscosity and velocity.

Figure 8 shows dimensionless tack pressure as a functionof nip loading for various tensions. Tension increases the dimensionless tack pressureby around 230% in the range studied. An upper limit is approached as the tension increases. The results tend to collapse into a general relationship when plotted in terms of these dimensionless groups.

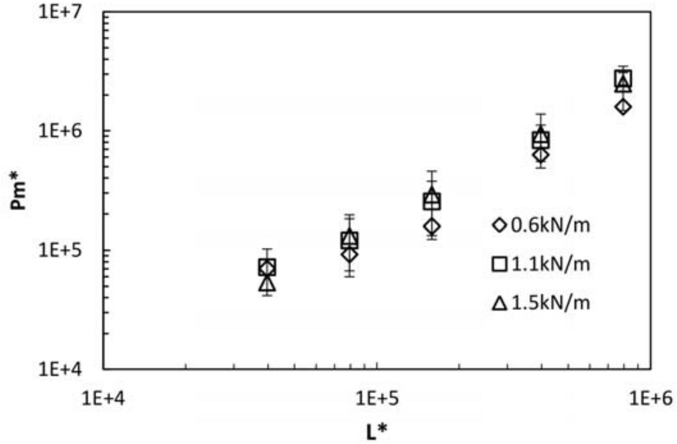

Fig. 8 *- Tack as a function of line load for different reported tensions at -22° takeoff angle, with an acrylic web and linseed oil.*

The effect of tension is diminished when the set web exit angle approaches 0° as in Figure 9. The tack values tend to follow a simple relationship with L* but may be independent of tension for small web takeoff angles. With a positive takeoff angles of 18°, decreasing tension results in lower dimensionless tack pressureas shown in Figure 10.

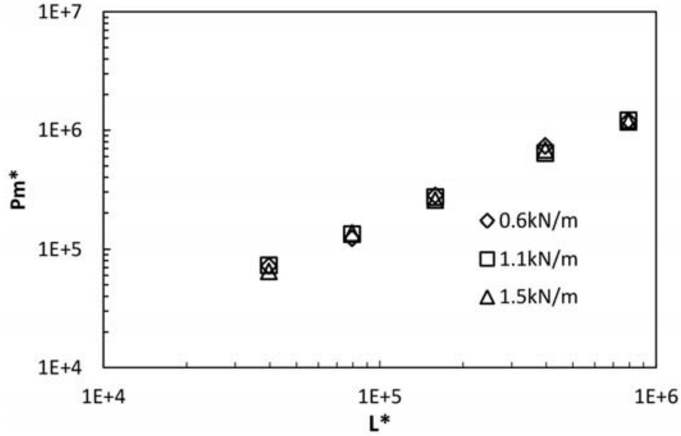

Fig. 9 *- Tack as a function of line load for different tensions at 0° takeoff angle. With an acrylic web and linseed oil.*

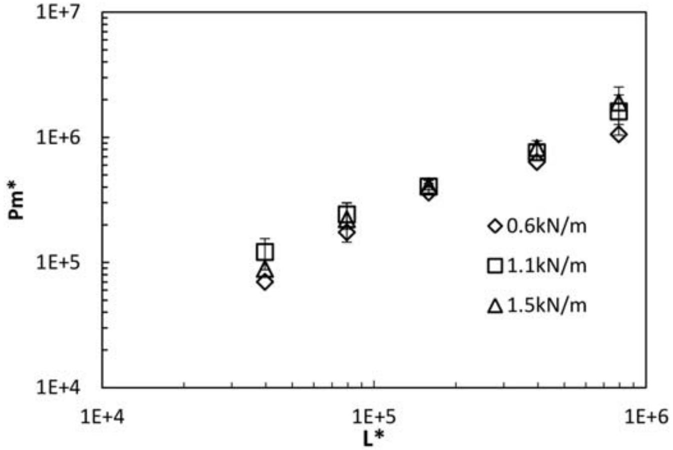

Fig. 10 *- Tack as a function of line load for different tensions at 18° takeoff angle. With an acryilic web and linseed oil.*

In summary, a 0° takeoff angle generates the lowest tack pressure for Newtonian fluids where corresponding results are independent of tension in the range of parameters studied. Small variations in tension may affect line load, and roll compression, generally the effect is smaller for smaller takeoff angles. Web tension affects release point depending on the takeoff angle. This generates variation in tack pressure with takeoff angle as shown in Figure 11 for the highest tension.

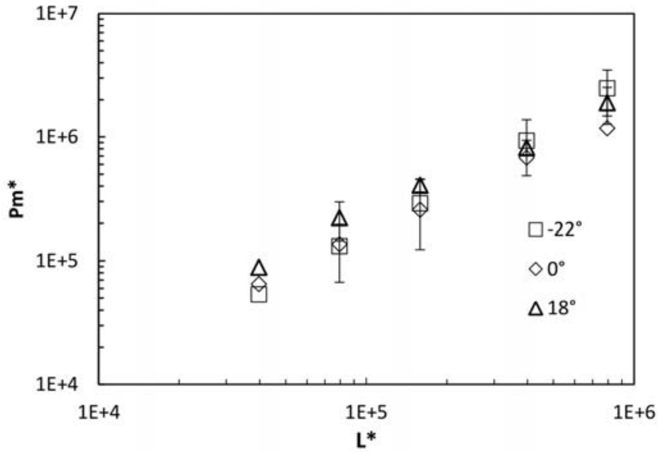

Fig. 11 *- Tack vs. line load for different takeoff angles. Experiments use an acrylic web and linseed oil. Optimum web takeoff angle for high tensioned webs is near 0°.*

Figure 12 shows for a viscous 10,000SUS oil, the effect of tension is insignificant for 5° web takeoff angle. This result was not expected in that at low tensions, the web sticks to the steel roll for some distance before peeling away. The change in behavior was expected to be reflected in a change of tack; however, it could be that the energy to form the thin film has to balance the work to peel the fluid away. Since the nip loading is constant, the pressing of the fluid against the web is constant. The effect of tension is more pronounced with larger takeoff angles. For this reason, in coating applications, tension may have more of an effect.

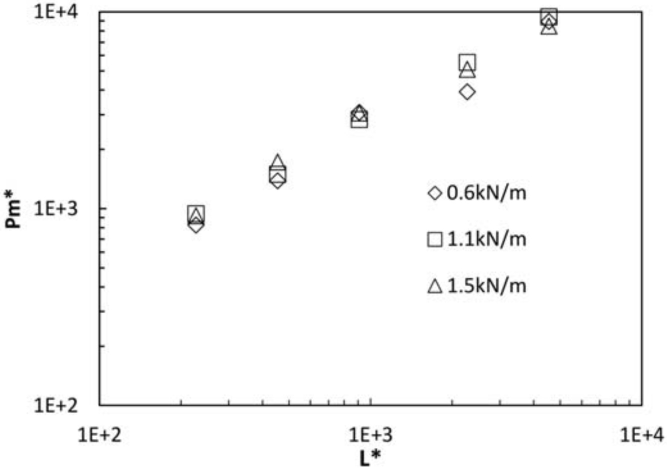

Fig. 12 *- Tack vs. line load for different tensions at 5° takeoff angle with viscous 10,000SUS oil. No significant variation of tack with tension is observed using a PET plastic web.*

Figure 13 shows tack pressure development for cyan offset ink on an acrylic web with different tensions and web angles. Again, there is not a signifiacant effect of tension on tack. There is an increase in tack force between -22° and 5° web takeoff angle. Positive takeoff angles result in larger forces for shear thinning inks. A positive angle forces the film split closer to the center of the nip further from the applicator roll. This may result in a faster film split with no time for the web to relieve stress by bending. It also may result in larger pressures due to faster more "z-directional" film splitting. If the film split is parallel to the roll surface we would expect larger pressures than if there is a shearing component of the film split due to the shear thinning reducing the fluid viscosity. The speed of the film split and corresponding position relative to the applicator roller also influences the film split time, although loading and web material have a relatively small effect on tack pressure.

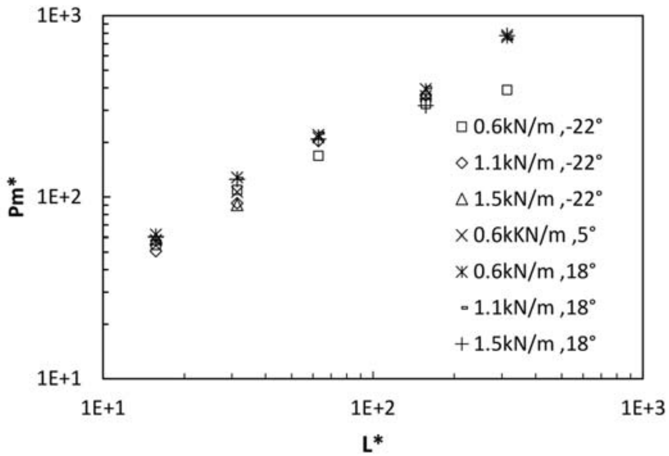

Fig. 13 *- Ink tack for various line loads, tensions, and takeoff angles. For cyan offset ink on acrylic web.*

Since tension has a minor influence on tack, dimensionless load and the elasticity are likely to be the driving factors on tack development. Plotting all of the results, we see that the web increases the tack pressure by a factor of 1.6 over tack pressure generated without a web. The effect of nip loading L* and roll elasticity E* become the key correlation factors. This basic model is improved upon by taking into account web parameters such as takeoff angle. Figure 14 shows the effect of takeoff angle on tack force for different Newtonian fluids. Positive takeoff angles give higher tack forces for shear thinning inks than the other angles. But negative angles give larger tack pressures for Newtonian fluids than the other angles. For Newtonian fluids a zero degree takeoff angle is optimum while for shear thinning fluids increased negative takeoff angle is optimum for reduced tack pressure. The correlation without web effects can be modified by a linear factor (D) to take into account web takeoff angle effects. Zero degree takeoff angle produces identical results to tack pressure development with no web and a symmetric nip.

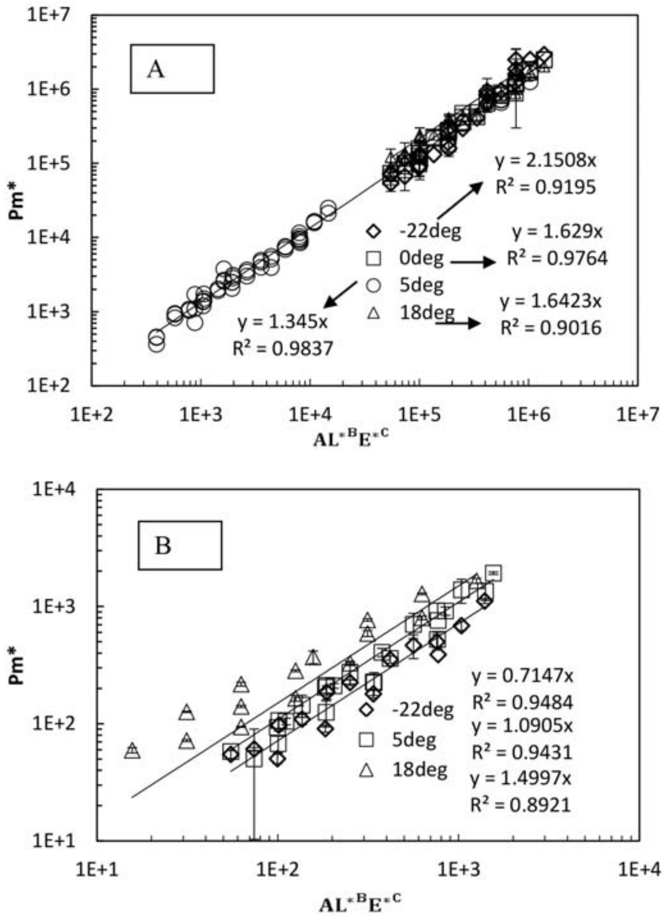

***Fig. 14** - Effect of takeoff angle and shear thinning ink on tack correlation.*
For Newtonain fluids (A) and cyan cold-set ink (B).

The effect of angle on tack pressure can now be used to estimate picking velocity between different presses by expanding the Newtonian web-free model to account for substrate (k) and angle effects (D). Web tension has negligible effects.

$$P_m^* = DkAL^{*^B}E^{*^C} \tag{2}$$

The effect of web type, paper or plastic is compared in Figure 15. While the difference is not large, paper has a trend that is about 15% larger than the plastic. However, it is possible the draining of oils into the paper leaves a more viscous fluid resulting in larger tack forces.

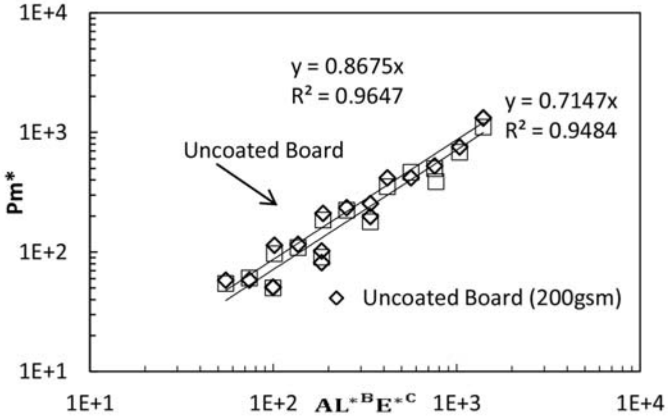

Fig. 15 *- Effects of web type on tack correlation. For uncoated paper board and PET plastic film.*

Line load is shown to have little effect on tack pressure. It is within experimental error as demonstrated by the lack of trend with line load in Figure 16. This result may be expected in that the nip loading should not nessesarily influence the exit flows.

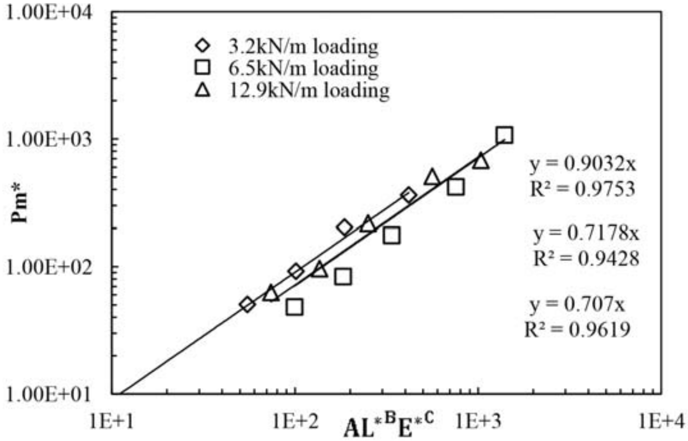

Fig. 16 *- Effects of line load and web on tack correlation. For cyan ink on a PET film.*

Our original hypothesis was that air would act to dampen tack pressure. However, paper increases tack force with coldest ink. This may be due to tack build increasing the apparent viscosity at the film split. Web tension affects tack force indirectly by affecting nip compression and line load, web release angle, and release location, but its effects are negligible for small nip angles.

Conclusion

The magnitude of tack was characterized in a laboratory device for a range of process parameters including nip loading, web tension and web takeoff angle for Newtonian and non-Newtonian fluids. Web tension had a small influence on the tack pressure. Velocity, viscosity, and the set takeoff angle are the largest drivers of tack along with some effect of web tension. Nip pulse with and without web have different negative pulse shapes. Negative tack pulses are more uniform and larger in magnitude without a web. Line load increases tack a small amount. Tack pressure increases with velocity except for shear thinning inks. Negative angles result in larger splitting velocity at a release point further from the nip, for shear thinning fluids tack pressure may be independent of velocity. Tack pressures with shear thinning fluids are lower for increased shear applied by the web at more negative takeoff angles as demonstrated by the magnitudes of tack pressure correlations for shear thinning fluids being 1/3 of Newtonian fluids for -22 o, 2/3 for 0 o, and 90% of values for 18o. At 18o the web tracks along the impression roller leading to negligible shear forces and shear thinning.

Excellent correlations of tack pressure can be formed using dimensionless groups for both Newtonian or shear thinning fluids, where the viscosity at 1.s-1 is used for the shear thinning fluids. This correlation can be modified to count for the effects of angle on shear thinning or Newtonian fluids or to account for web porosity effects on tack force. For Newtonian fluids positive takeoff angles result in larger tack pressures, but for shear thinning fluids the opposite is true. Here shear applied by the web at more negative angles lowers the tack pressure by reducing the viscosity more than reducing the gap at release increases it.

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