DYNAMIC COEFFICIENT OF FRICTION INCLUDING THE EFFECTS OF AIR ENTRAINMENT BETWEEN A ROLLER AND WEB

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PREFACE

The dynamic coefficient of friction between polyester and an aluminum roller, and polypropylene and an aluminum roller was determined. The air film that develops between a web and roller prevented the use of any existing coefficient of friction measuring device. Therefore a measuring device was developed that does include the effects of air entrainment between the web and roller.

Each web was tested against the aluminum roller at various web velocities, web tensions, and wrap angles. The measuring device produced excellent results and any further research looks promising.

I would like to thank Dr. James K. Good for providing an interesting and useful research project. His assistance and encouragement throughout the study is also appreciated. I would also like to thank Mike Jackson for any assistance and support in the construction of the measuring device.

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CHAPTER I

INTRODUCTION

The dynamic coefficient of friction is a means of classifying materials in terms of the ease in which they will slide over each other. The coefficient is defined as the ratio of the sliding friction force to the normal force exerted between the two bodies.

The sliding friction force is the force required to maintain the relative velocity between the two bodies. The sliding friction is considered to be independent of the contact area under moderate pressures and independent of the rubbing velocity at low velocities. The friction also decreases as the velocity increases. Studies have shown that the coefficient of friction is sensitive to many variables. Some of these variables are surface finish, temperature, surface contamination, and geometry.

The importance of knowing the dynamic coefficient of friction can be found in web-handling. As a web passes over a roller an air film develops between the two. If the air pressure between the web and the roller is great enough the web will be lifted off of the roller. The floating of the web makes it harder to control. A slight disturbance such as a draft of air may cause the web to wander and wrinkle. In industry today with webs being made wider and run at higher velocities, it is useful to know the dynamic coefficient of friction(with the effects of air entrainment) of materials and the variables which may induce the air entrainment. Knowing the coefficient of friction will help optimize the web-handling process.

Literature Survey

Measuring Devices

Several methods for determining the dynamic(kinetic) coefficient of friction between two surfaces were found in the literature survey. These methods range from having a sled sliding on a plane to a pendulum system. But, none of the methods found deal specifically with measuring the coefficient of friction between a roll and a web with the effects of air entrainment.

ASTM[10] has a standard test method for determining the kinetic coefficient of friction of plastic film and sheeting. The apparatus(Figure 1) consists of a sled, a plane, and a force measuring device. The test specimens are attached to the bottom of the sled and to the top of the plane. The sled is pulled over the plane while the plane is held stationary or the plane is moved while the sled is held stationary. The force that is required to maintain the constant relative velocity between the sled and the plane is then recorded. The coefficient of friction is then calculated as the ratio of the measured force to the weight of the sled.

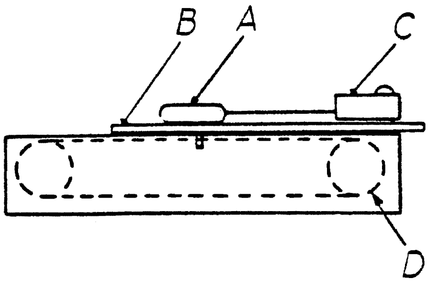
The sled is a metal block 2.5 in. by 2.5 in. and .25 in. thick with an eye screw so that the force measuring device can be attached. The plane is 6 in. by 12 in. and .040 in. thick. It is made of polished plastic, wood, or a metal sheet. The plane is covered with a piece of glass to provide a smooth contact surface for the sled. The force-measuring device may be a spring gage, universal testing machine, or a strain gage. The drive speed is set at 0.5 ft./min. with a tolerance of 0.1 ft/min. A sheeting specimen is defined as having a nominal thickness of greater than 0.254 mm and a film is defined as being less than 0.254 mm thick. New test specimens are installed for each test run.

ASTM[9] has another test method for measuring the kinetic coefficient of friction of plastic solids and sheeting. This test is divided into two procedures, one for the determination of variable-velocity coefficients and another for determining the coefficient at a constant velocity but over an extended period of time. The second procedure shows the effect of wear and temperature on the coefficient of friction. The measuring device used is a variable speed frictionometer(Figure 2). The frictionometer has a rotating drum and a pivot arm where the test specimens are attached. The pivot arm can be adjusted so that the normal force(N) between the drum and the pivot arm can be varied. The pivot arm is attached to a pendulum which is allowed to rotate as the tangential frictional force(F) changes. A pointer on the pendulum indicates how many degrees(θ) the pendulum has rotated. The coefficient of friction then varies as a function of theta. Taking moments about the center of rotation of the drum shows the frictional force to be

$$F=Wd/R \tag{1.1}$$

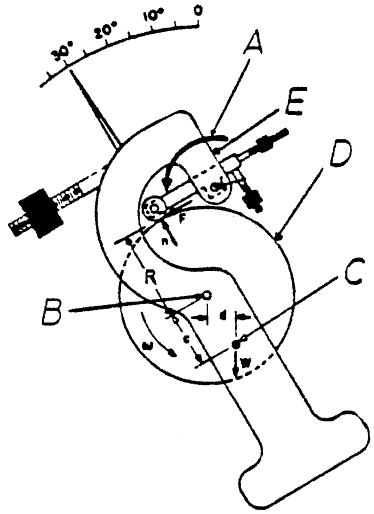
where

$$d=c\sin(\theta) \tag{1.2}$$



A. Sled
B. Plane
C. Strain gage
D. Constant Driver

Figure 1. One method of assembly of apparatus for determination of kinetic coefficient of friction without effects of air entrainment.



A. Spring applied torque for adjusting the normal force
B. Axis of rotation
C. Pendulum
D. Drum
E. Pivot arm

Figure 2. Frictionometer.

Then substituting (1.2) into (1.1) gives the frictional force as a function of theta.

$$F=Wc\sin(\theta)/d \tag{1.3}$$

Schenck[7] describes another type of pendulum apparatus for determining the kinetic coefficient of friction between two test specimens. The apparatus(Figure 3) consists of a lightweight aluminum rod and a constant-force pendulum head. The constant-force is accomplished by having a pressurized air chamber within the pendulum head. The test specimens are attached to the pendulum head and to the surface of the floor. When the pendulum is released from position 1, it only reaches position 4 due to the frictional losses in the apparatus. If the pendulum were lowered and allowed to interfere with the surface then the pendulum would only reach position 3 because of the frictional loss. The work done by this frictional loss is

$$U_{a.b}=\mu_k Nd \tag{1.4}$$

and the loss in potential energy is

$$V_{3.4}=Mg(h_4-h_3) \tag{1.5}$$

Equating (1.4) and (1.5) yields

$$\mu_k=Mg(h_4-h_3)/(Nd) \tag{1.6}$$

Variables Influencing Air Entrainment

Daly[2] discusses the traction of webs with various permeabilities passing over a roll as a function of speed. He found that webs with a high permeability had more traction at a given speed than non-permeable webs. As a web passes

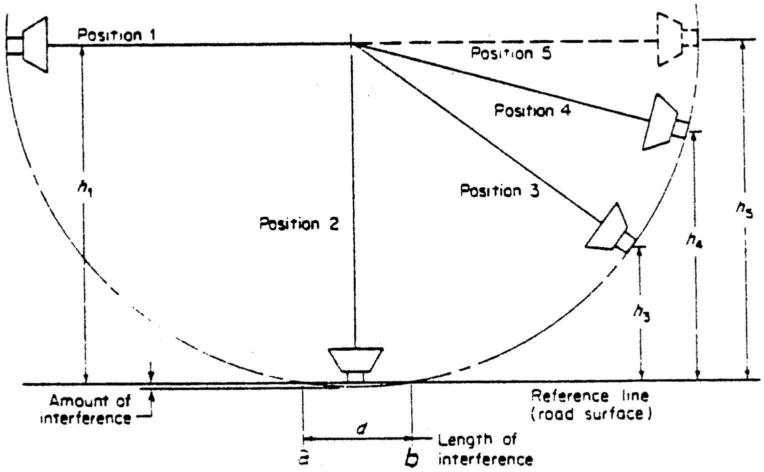


Figure 3. Pendulum apparatus for determining the kinetic coefficient of friction without effects of air entrainment.

over a roll a certain amount of air builds up between the two and causes them to separate. In permeable webs there is less build up of air because the air can pass more easily through the web than in non-permeable webs. Higher speeds also contribute to the webs reduced traction. It was also shown that a greater wrap angle allows the air more time to leak from between the roll and the web, thereby reducing the floating effect of non-permeable webs. The floating effect is less evident in the permeable webs as the wrap angle increases. An air film also occurred more readily between non-permeable webs and the roll as the roll diameter increased. The larger roll diameter makes a larger surface area for the air pressure to act against, therefore less air pressure is needed to lift the web.

Problem Statement

The following study will determine the dynamic coefficient of friction with the effects of air entrainment that occurs between a web and a roller.

Approach to the Problem

The dynamic coefficient of friction will be measured using a web-handling machine that has all of the necessary modifications needed for the test procedure. Polyester and polypropylene will be tested against an aluminum roller.

The coefficient of friction will be studied as a function of variables that may influence the air entrainment.

These variables being the web velocity, wrap angle, and web tension.

Organization

The remainder of the study will contain the following. The experimental test procedure and the instrumentation used in the test are described in Chapter II. Chapter III contains the experimental results, and the conclusions are in Chapter IV.

CHAPTER II

EXPERIMENTAL PROCEDURE

The measuring device was developed on the basis of an equation which is referred to by various names depending on the application. Some of the applications being a braking device where a band is wrapped around a drum, or a belt and pulley system. In these two cases a coefficient of friction is known and an unknown tension is found. In this study the tensions will be measured in order to calculate the coefficient of friction.

Band Brake Equation

The forces acting on a segment of the web are shown in Figure 4. The forces in the z-direction are assumed constant, so that the normal force between the web and roll is the same along the width. This is a good assumption since the tension in the web is distributed evenly.

Summing forces in the y-direction gives

$$(T+dT)\sin(d\theta/2)+T\sin(d\theta/2)-dN+r\omega^2 dm=0 \qquad (2.1)$$

The force due to the acceleration directed towards the center of the roller is negligible, and Equation (2.1) reduces to

$$(T+dT)\sin(d\theta/2)+T\sin(d\theta/2)-dN=0 \qquad (2.1a)$$

and summing forces in the x-direction yields

$$(T+dT)\cos(d\theta/2)-T\cos(d\theta/2)-F=0 \qquad (2.2)$$

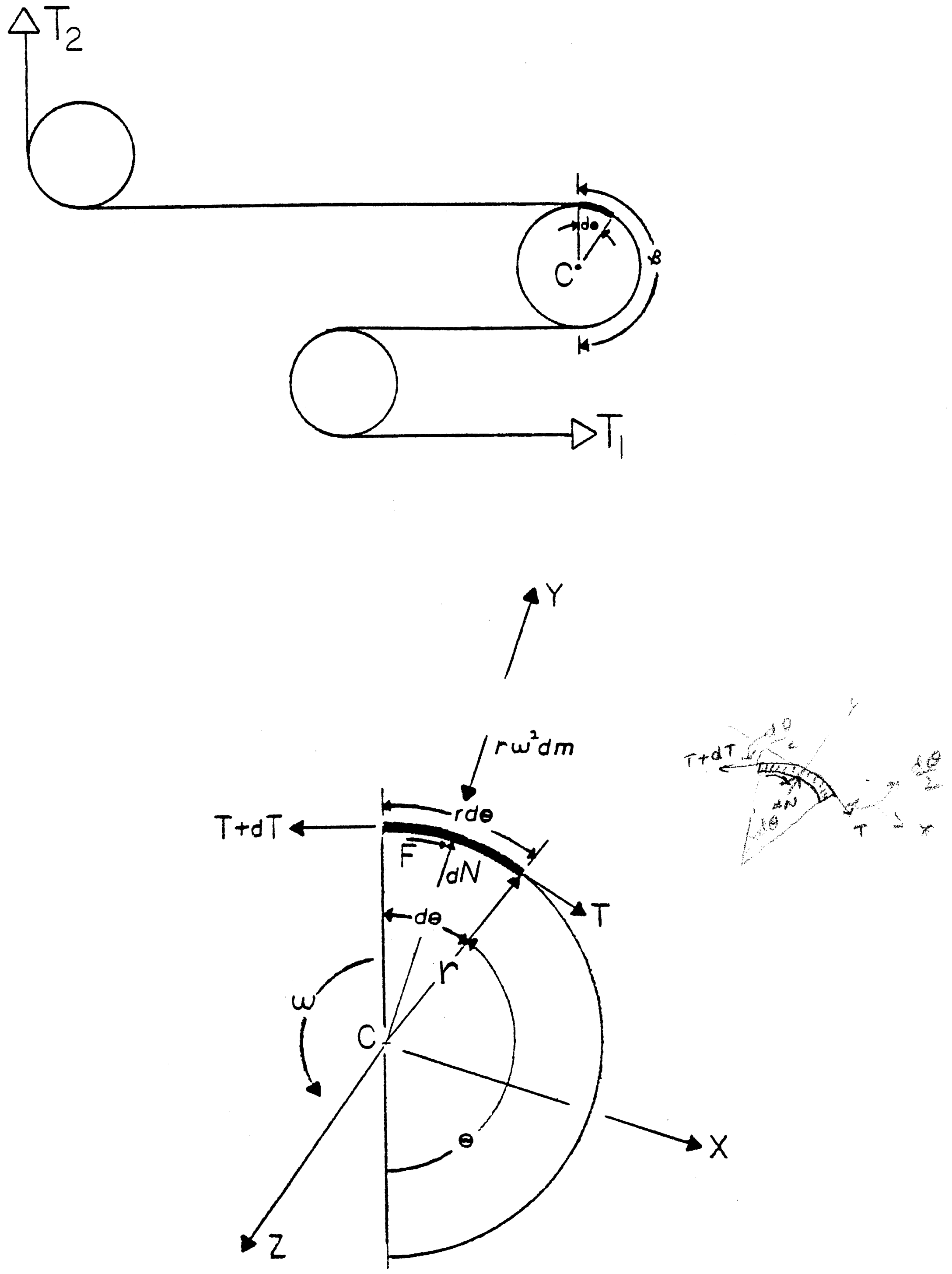


Figure 4. Forces Acting on a Web Segment

where $F=\mu_k dN$

Substituting (2.2) into (2.1a) thereby eliminating dN yields

$$(\cos(d\theta/2))dT-2\mu_k T\sin(d\theta/2)-\mu_k(\sin(d\theta/2)dT=0 \qquad (2.3)$$

Then for small angles

$$\cos(d\theta/2)=1 \qquad (2.4)$$
$$\sin(d\theta/2)=d\theta/2 \qquad (2.5)$$

Now substituting (2.4) and (2.5) into (2.3) gives

$$dT=\mu_k Td\theta+(1/2)dTd\theta \qquad (2.6)$$

Then ignoring dTdθ because it is very small yields

$$dT=\mu_k Td\theta$$
$$\int_{T_1}^{T_2}(1/T)dT=\mu_k\int_0^{\beta}d\theta$$
$$T_2/T_1=e^{\mu_k\beta} \qquad (2.7)$$

Summing moments about the center of the roller gives the tension and torque relationship.

$$\mathbb{T}=r(T_2-T_1) \qquad (2.8)$$

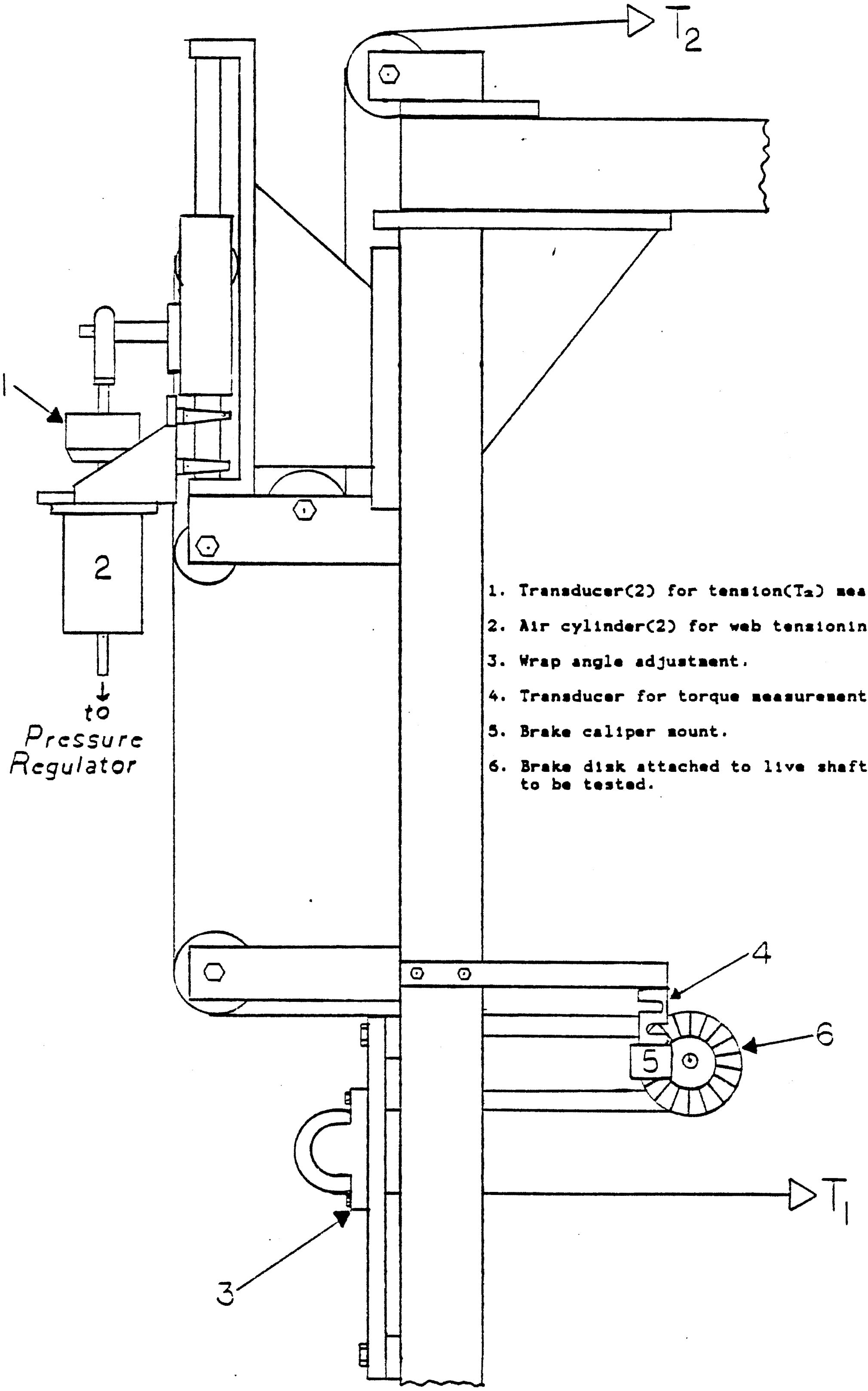
Then substituting (2.8) into (2.7) and solving for the coefficient of friction gives

$$\mu_k=(1/\beta)\ln[T_2/(T_2-\mathbb{T}/r)] \qquad (2.9)$$

Then by experimentally measuring the torque($\mathbb{T}$), the tension(T_2), and by measuring the wrap angle(β) and the roller radius(r), the coefficient of friction can be determined.

Description of Measuring Device

The measuring device is a continuous loop web handling machine capable of running up to 1000 fpm. The drive motor provides adequate torque to maintain a constant web velocity during testing. A simplified schematic is shown in Figure 6



1. Transducer(2) for tension(T_2) measurement.
2. Air cylinder(2) for web tensioning.
3. Wrap angle adjustment.
4. Transducer for torque measurement.
5. Brake caliper mount.
6. Brake disk attached to live shaft of roller to be tested.

Figure 5. Experimental Apparatus

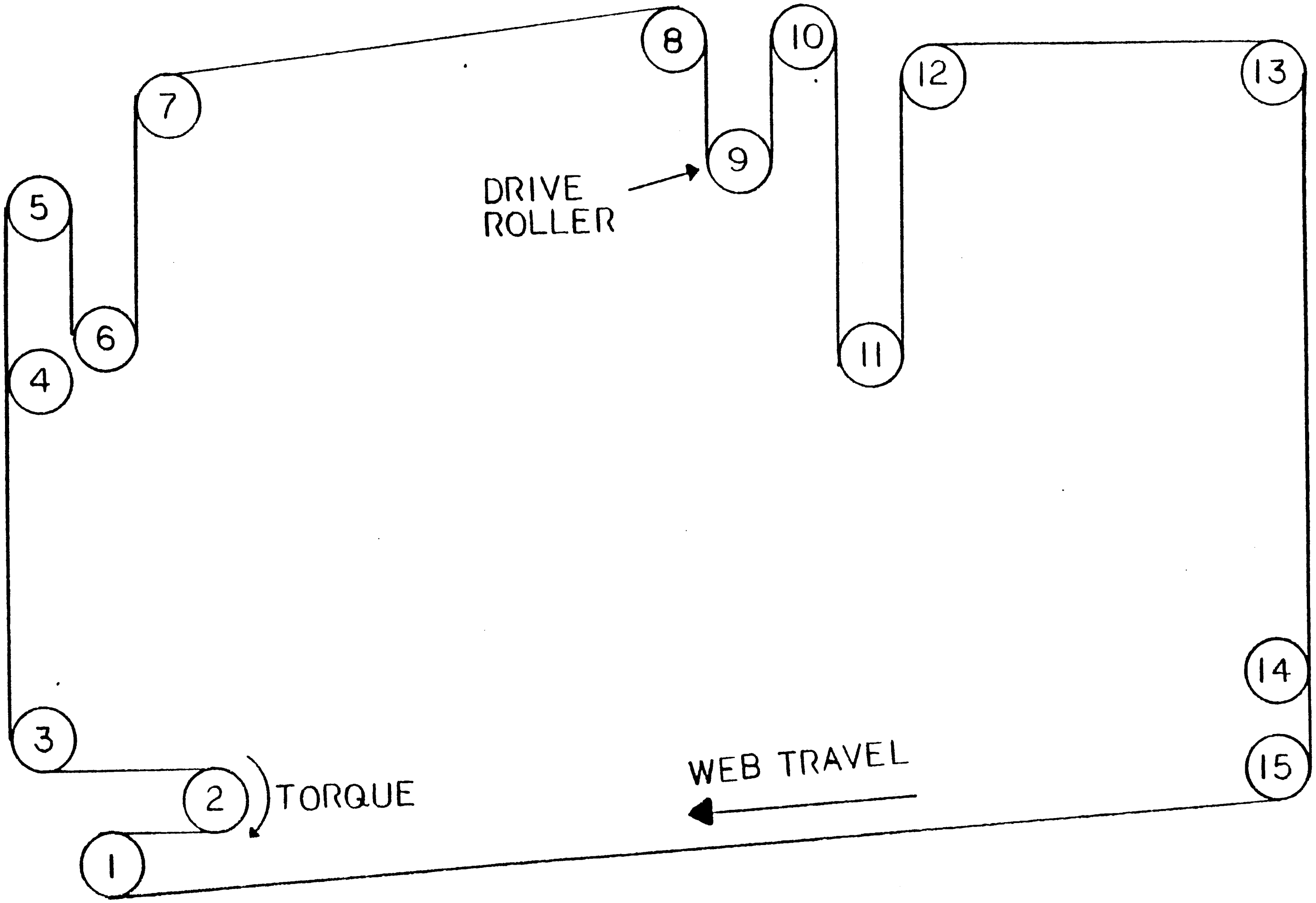


Figure 6. Web and Roller Configuration

and a more detailed schematic is shown in Figure 5. The machine also has the following features necessary for the experimental measurements.

1. Roller 2 is the roller that is to be tested against the web. The roller has a live shaft in which a pneumatic brake is attached. The brake is controlled by a pressure regulator. The brake is used to slow the roller just enough, so that slippage occurs between the roller and the web. Slippage occurs when the tangential surface velocity of the roller is less than the web velocity. The roller velocity is measured by a small direct current motor which is attached directly to the end of the shaft. The motor is connected to a volt meter and the output is calibrated by a multiturn potentiometer, so that it reads out in feet per minute. At the point in which slippage occurs, it is necessary to know the torque that was needed to slow the roller. By attaching a force transducer to the brake caliper, the tangential force caused by the brake can be measured. Then by knowing the length of the moment arm between the caliper and the shaft, the torque is known. The transducer is connected to a strain indicator and is calibrated to read out in in-lbs.

The actual torque(T) necessary to cause slippage is the bearing torque(T_B) plus the applied brake torque(T_{AP}).

$$T=T_B+T_{AP} \qquad (2.10)$$

A relationship for the bearing torque is shown in the next section.

2. Roller 1 can be moved up and down in its slotted

track, so that the wrap angle around the test roller 2 can be adjusted from 145 to 180 degrees.

3. Roller 5 is attached to the dancer, which is a sliding mechanism that allows the web tension to be adjusted. The adjustment is made by the two air cylinders that are controlled by pressure regulators. A force transducer is mounted to each air cylinder rod which directly measures the web tension(T_2). The transducers are connected to strain indicators which are calibrated to read out in pounds of tension.

4. Roller 9 is the drive roller, it has a special covering that prevents slipping between the roller and the web. When the back torque is applied at roller 2 the downstream web tension(T_2) increases and the upstream web tension(T_1) decreases. The web tension between rollers 2,3,4,5,6,7,8,and 9, which represents the downstream tension, are equal and the tension between rollers 2,1,15,14,13,12,11, 10, and 9, which represents the upstream tension, are equal provided that the web does not slip on the drive roller. In reality, the web tensions around the upstream rollers are not quite equal and the web tensions around the downstream rollers are not equal. There are small tension losses around each roller, but the losses are negligible compared to the magnitude of the tension levels that will be measured. According to Reynolds[6] the tensions will not be equal for elastic materials. The tension in the web around the roll is proportional to the stretching of the web, with the

proportionality constant being dependent on the cross-sectional area of the web and its material properties.

Determination of the Bearing Torque

The bearing torque can be determined by

$$T_B = I_{zz}\alpha \tag{2.11}$$

where I_{zz} is the mass moment of inertia of the roller about the z-axis(Figure 7) and α is the angular acceleration of the roller about the z-axis.

The angular acceleration was determined by connecting a chart recorder to the output of the d.c. motor that is used to measure the roller velocity. The roller is then set spinning and the velocity is recorded as a function of time as shown in Figure 8. The velocity curve was then curve-fitted to a third degree polynomial.

$$V=16.6722-.9586t+.0081721t^2+.00017361t^3 \tag{2.12}$$

where V is in ft/s and t is in seconds.
The velocity equation was then differentiated to get the tangential surface acceleration.

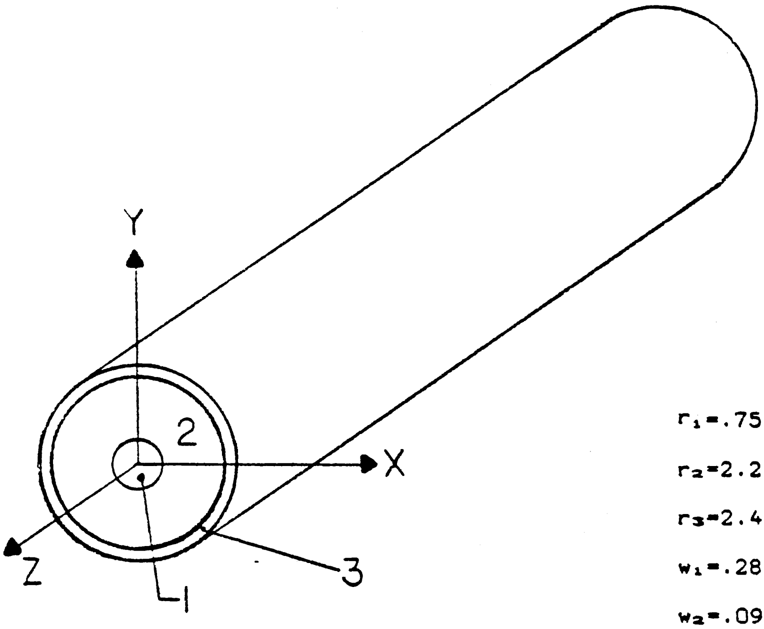
$$a=dV/dt=-.9586+.0163t+.00052083t^2 \tag{2.13}$$

where a is in ft/s^2 and t is in seconds.
The angular acceleration is then

$$\alpha=a/r=-4.4242+.0754t+.0024t^2 \tag{2.14}$$

where α is in rad/s^2 and t is in seconds.

The roller consists of two aluminum end plates, an aluminum cylinder, and a steel shaft as shown in Figure 7. The mass moment of inertia of the roller is



$r_1 = .75$ in

$r_2 = 2.2$ in

$r_3 = 2.45$ in

$w_1 = .282$ lb/in^3

$w_2 = .098$ lb/in^3

$w_3 = .098$ lb/in^3

$l_1 = 37$ in

$l_2 = .75$ in

$l_3 = 37$ in

Figure 7. Roller Component Dimensions

Figure 8. Decrease in Roller Velocity With Time Due to Bearing Friction

TABLE I

BEARING TORQUE

t (sec)	Vel (fpm)	T_B (in-lb)
0.0	1000	.196
1.0	950	.193
2.0	900	.189
2.6	850	.187
3.6	800	.183
4.6	750	.178
5.4	700	.175
6.4	650	.170
7.4	600	.166
8.5	550	.160
9.6	500	.154
10.6	450	.149
12.0	400	.141
13.2	350	.133
14.6	300	.125
16.0	250	.115
17.8	200	.103
19.4	150	.091
21.4	100	.076

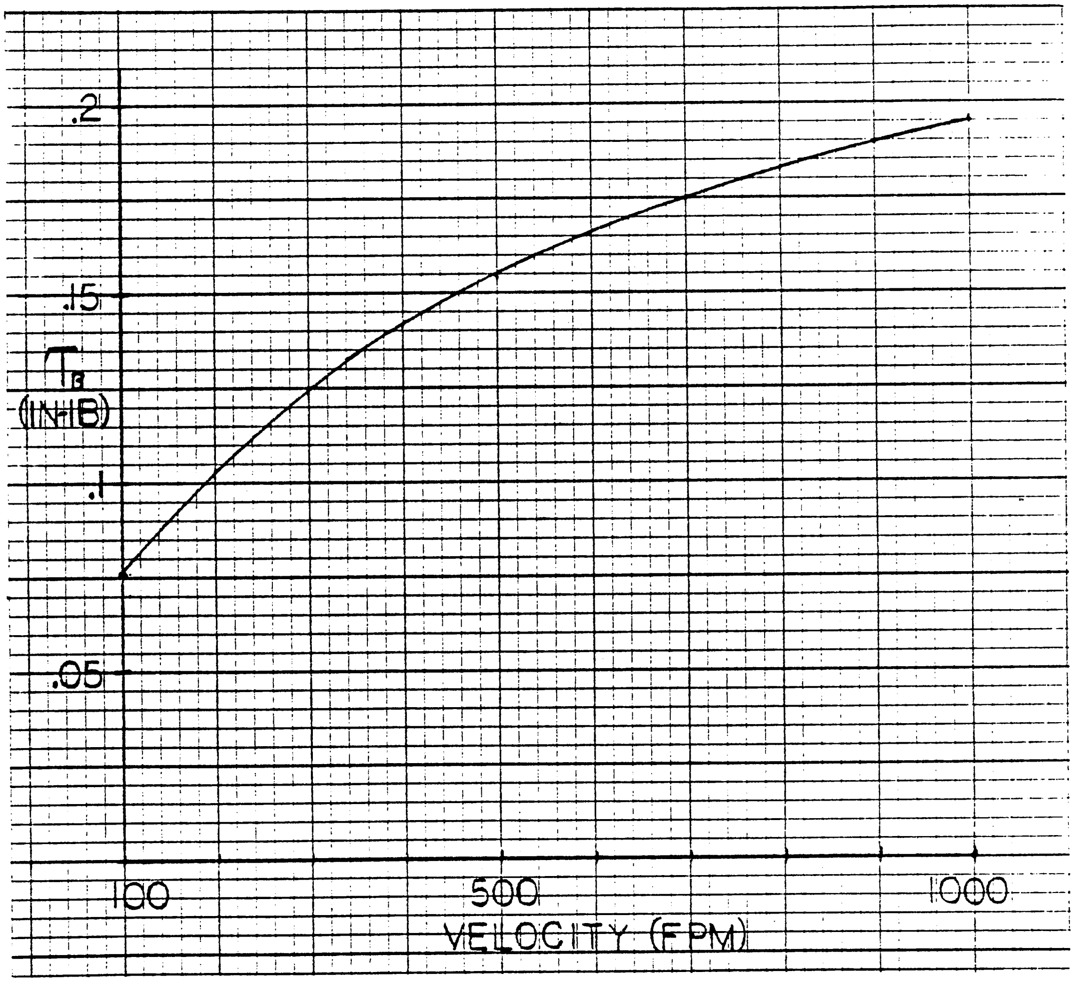


Figure 9. Bearing Torque as a Function of Velocity

$$I_{zz}=(I_{zz})_1+(I_{zz})_2+(I_{zz})_3$$

$$I_{zz}=(1/2)m_1r_1^2+2[(1/2)m_2(r_2^2-r_1^2)]+(1/2)m_3(r_3^2-r_2^2) \quad (2.15)$$

where $m_1=w_1\pi r_1^2l_1$ (2.16)

$$m_2=w_2\pi(r_2^2-r_1^2)l_2 \quad (2.17)$$

$$m_3=w_3\pi(r_3^2-r_2^2)l_3 \quad (2.18)$$

substituting (2.16),(2.17),and (2.18) into (2.15) yields

$$I_{zz}=(1/2)\pi(1/386)[w_3(r_3^2-r_2^2)^2l_3+2w_3(r_2^2-r_1^2)^2l_2+w_1r_1^4l_1] \quad (2.19)$$

Then substituting the necessary values into Equation (2.19) shows the moment of inertia to be

$$I_{zz}=.04432 \text{ in-lb-s}^2$$

and the bearing torque is calculated with Equation (2.11). The bearing torque values are found in Table I and Figure 9.

Experimental Measurement

Before any measurements are taken, the instruments are allowed to warm-up to reduce any drift. Then the instruments are checked for calibration. Then referring to Figures 5,6, and 10, the measurements are performed as follows.

1. The desired web tension is set.

2. The web velocity is then set. The roller velocity is compared with the web velocity to make sure that slippage between the web and roller is not already occurring.

3. The torque(T_{AP}) to the test roller is gradually increased until the roller velocity drops below the web velocity. Slippage is now occurring and the torque and tension(T_2) is recorded.

4. Steps 1 thru 3 are repeated for different web

velocities, web tensions, wrap angles, and webs.

5. The torque(T) is calculated by Equation (2.10) and the coefficient of friction is calculated using Equation (2.9).

1. Pressure regulator control valves and pressure gauges to air cylinders
2. Pressure regulator control valve and pressure gauge to pneumatic brake
3. Strain indicators calibrated to 1/10 of a pound for measuring web tension(Ta)
4. Strain indicator calibrated to 1/10 of an inch-pound for measuring torque
5. Voltmeter calibrated to measure roller velocity in feet per minute

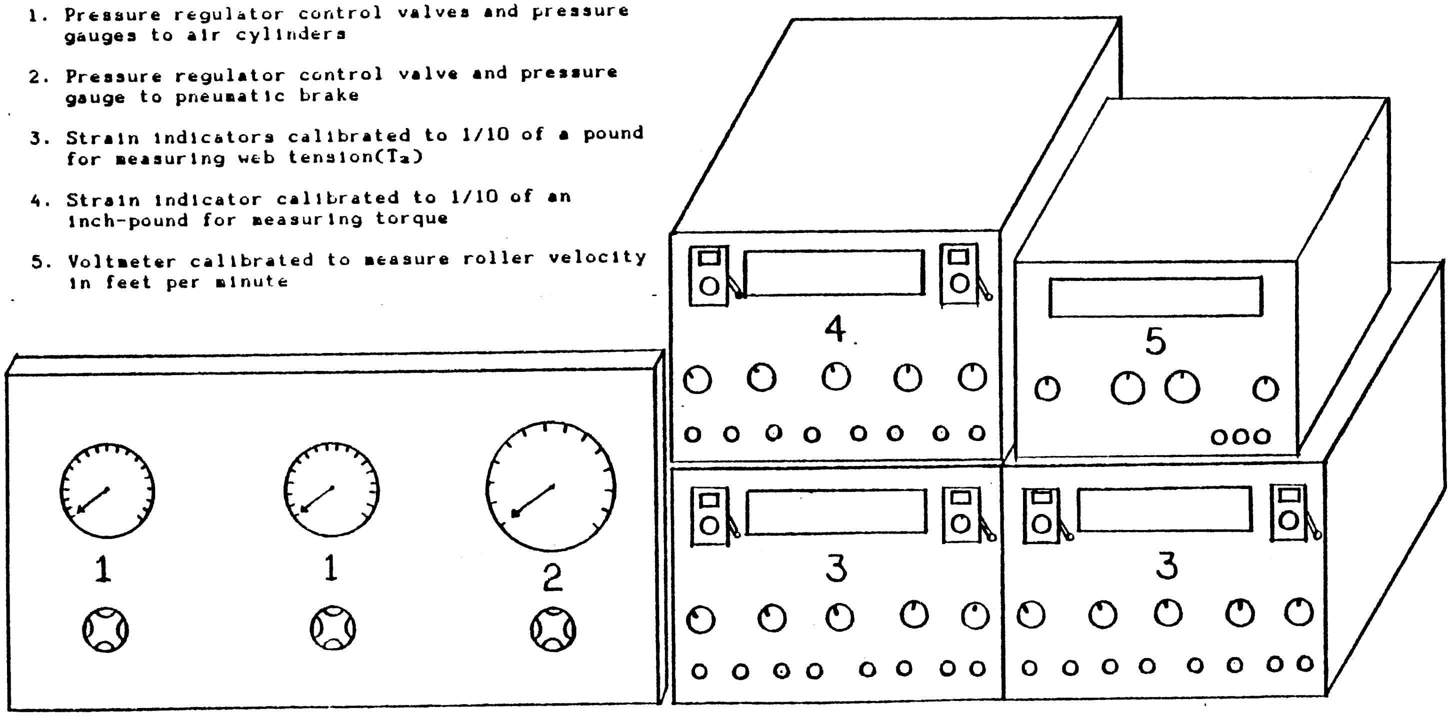


Figure 10. Instrument Control Panel

CHAPTER III

EXPERIMENTAL RESULTS

The coefficient of friction measurements for polyester on aluminum and polypropylene on aluminum were completed and successful. An attempt was made to measure the coefficient of friction of paper on aluminum, but a high enough web velocity could not be obtained to show any significant results. Polyester with a 6 in. width and .0005 in. thickness was also tried, but the wrinkling of the thin web made it difficult to run the web much more than a minute. An attempt was also made to measure the coefficient of friction between polyester and cork, and polypropylene and cork, but the coefficient of friction on the cork test roller turned out to be higher than the coefficient of friction between the web and the drive roller. Therefore during the test procedure the web slipped on the drive roller when the back torque was applied to the test roller.

The bearing torque turned out to be a sizeable portion of the total torque at high velocities. Table IX shows the percent error to be as much as 22% at 1000 fpm if the bearing torque is not included.

A repeatability test was done for the polyester on aluminum with the results shown in Table VIII and Figure 29. The standard deviation was the greatest at the lower velocities. A standard deviation of .0047 with a mean value of .0613 was found at a velocity of 150 fpm.

The data shown in Figures 11,12,13,20,21,and 22 show that the coefficient of friction increases with tension and decreases as velocity increases. The figures also show that the coefficient of friction is more sensitive to velocity changes at lower velocities than at high velocities.

The data shown in Figures 14,15,16,23,24,and 25 show that the coefficient of friction increases with an increase in wrap angle and is also more sensitive to velocity changes at lower velocities than at high velocities.

The data shown in Figures 17,18,19,26,and 28 show that the coefficient of friction is more sensitive to changes in tension at lower velocities, whereas in Figure 27 this is not quite as clear. A summary of the results can be found in Table X.

TABLE II

COEFFICIENT OF FRICTION OF POLYESTER ON ALUMINUM WITH 180 DEGREE WRAP ANGLE

VEL	T=1.11 lb/in			T=1.67 lb/in			T=2.22 lb/in		
FPM	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k
100	4.28	10.2	.060	10.88	16.0	.103	19.28	21.6	.144
150	2.79	10.2	.038	6.89	15.6	.063	13.79	21.2	.098
200	2.10	10.1	.028	5.10	15.4	.046	10.60	20.9	.074
250	1.22	10.1	.016	4.22	15.4	.038	7.72	20.5	.053
300	.83	10.0	.011	3.23	15.2	.029	6.73	20.5	.046
350	.63	10.0	.008	2.93	15.2	.026	5.43	20.4	.037
400				2.34	15.1	.021	4.54	20.4	.030
450				1.75	15.1	.015	3.85	20.3	.026
500				1.25	15.0	.011	3.25	20.3	.022
550				.76	15.0	.007	3.06	20.2	.020
600							2.67	20.1	.018
650							2.27	20.1	.015
700							2.38	20.1	.016
750							1.58	20.0	.010
800							1.68	20.0	.011
850							1.69	20.0	.011
900							1.49	20.0	.010
950							1.59	20.0	.010
1000							1.30	20.0	.009

TABLE III

COEFFICIENT OF FRICTION OF POLYESTER ON ALUMINUM WITH 160 DEGREE WRAP ANGLE

VEL	T=1.11 lb/in			T=1.67 lb/in			T=2.22 lb/in		
FPM	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k
100	5.18	10.4	.081	9.88	15.8	.106	18.28	21.3	.154
150	2.89	10.2	.044	6.39	15.4	.066	9.59	20.7	.075
200	1.80	10.1	.027	4.50	15.3	.046	6.90	20.6	.053
250	1.02	10.0	.015	2.82	15.0	.029	4.62	20.3	.035
300	.73	10.0	.011	1.93	15.0	.019	3.73	20.2	.028
350	.33	10.0	.005	1.43	15.0	.014	2.83	20.2	.021
400				1.24	15.0	.012	2.44	20.1	.018
450				.95	15.0	.009	2.05	20.1	.015
500				.65	15.0	.006	1.55	20.0	.012
550				.66	15.0	.006	1.56	20.0	.012
600				.37	15.0	.004	1.27	20.0	.009
650							1.27	20.0	.009
700							1.18	20.0	.009
750							.88	20.0	.006
800							.78	20.0	.006
850							.69	20.0	.005
900							.49	20.0	.004
950									
1000									

TABLE IV

COEFFICIENT OF FRICTION OF POLYESTER ON ALUMINUM WITH 145 DEGREE WRAP ANGLE

VEL	T=1.11 lb/in			T=1.67 lb/in			T=2.22 lb/in		
FPM	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k	Torq. in-lb	T_2 lb	μ_k
100	2.38	10.3	.039	6.78	15.6	.077			
150	1.29	10.1	.021	2.99	15.2	.033	6.79	20.6	.057
200	.60	10.1	.010	2.00	15.1	.022	3.80	20.1	.032
250	.32	10.1	.005	1.22	15.1	.013	3.02	20.1	.025
300				.93	15.1	.010	2.13	20.1	.017
350				.53	15.1	.006	1.83	20.0	.015
400				.34	15.0	.004	1.54	20.0	.013
450							1.35	20.0	.011
500							1.05	20.0	.009
550							.96	20.0	.008
600							.87	20.0	.007
650							.67	20.0	.005
700							.67	20.0	.005
750							.58	20.0	.005
800									
850									
900									
950									
1000									

TABLE V

COEFFICIENT OF FRICTION OF POLYPROPYLENE ON ALUMINUM WITH 180 DEGREE WRAP ANGLE

VEL	T=.83 lb/in			T=1.11 lb/in			T=1.39 lb/in		
	Torq.	T_2	μ_k	Torq.	T_2	μ_k	Torq.	T_2	μ_k
FPM	in-lb	lb		in-lb	lb		in-lb	lb	
100	3.98	15.2	.036	5.28	20.2	.036	7.88	25.5	.043
150	2.09	15.0	.019	2.79	20.0	.019	4.09	25.3	.022
200	1.30	15.0	.011	2.00	20.0	.013	2.80	25.2	.015
250	0.82	15.0	.007	1.12	20.0	.007	1.92	25.0	.010
300	0.33	15.0	.003	0.93	20.0	.006	1.43	25.0	.008
350				0.53	20.0	.003	1.13	25.0	.006
400				0.34	20.0	.002	0.84	25.0	.004
450							0.65	25.0	.003
500							0.55	25.0	.003
550							0.46	25.0	.002
600							0.37	25.0	.002

TABLE VI

COEFFICIENT OF FRICTION OF POLYPROPYLENE ON ALUMINUM WITH 160 DEGREE WRAP ANGLE

VEL	T=.83 lb/in			T=1.11 lb/in			T=1.39 lb/in		
	Torq.	T_2	μ_k	Torq.	T_2	μ_k	Torq.	T_2	μ_k
FPM	in-lb	lb		in-lb	lb		in-lb	lb	
100	3.88	15.2	.039	4.98	20.3	.038	7.98	25.4	.049
150	1.79	15.0	.018	2.49	20.0	.019	4.09	25.2	.025
200	0.80	15.0	.008	1.40	20.0	.010	2.10	25.1	.012
250	0.32	15.0	.003	0.82	20.0	.006	1.52	25.0	.009
300				0.53	20.0	.004	0.93	25.0	.005
350				0.23	20.0	.002	0.73	25.0	.004
400							0.54	25.0	.003
450							0.35	25.0	.002
500									
550									
600									

TABLE VII

COEFFICIENT OF FRICTION OF POLYPROPYLENE ON ALUMINUM WITH 145 DEGREE WRAP ANGLE

VEL	T=.83 lb/in			T=1.11 lb/in			T=1.39 lb/in		
	Torq.	T_2	μ_k	Torq.	T_2	μ_k	Torq.	T_2	μ_k
FPM	in-lb	lb		in-lb	lb		in-lb	lb	
100	2.78	15.0	.031	4.68	20.2	.039	4.98	25.3	.033
150	1.29	15.0	.014	1.99	20.1	.016	3.09	25.2	.020
200	0.70	15.0	.008	1.20	20.1	.010	2.10	25.1	.014
250	0.32	15.0	.003	0.62	20.0	.005	1.22	25.0	.008
300				0.33	20.0	.003	0.73	25.0	.005
350							0.43	25.0	.003
400							0.34	25.0	.002
450									
500									
550									
600									

TABLE VIII

STANDARD DEVIATION AND MEAN OF REPEATABILITY MEASUREMENTS FOR ALUMINUM AND POLYESTER AT 1.67 LB/IN OF TENSION WITH A 180 DEGREE WRAP ANGLE

	Coeff. of Friction				
VEL	1	2	3	MEAN	STD DEV
150	.063	.065	.056	.0613	.0047
200	.046	.049	.042	.0457	.0035
250	.038	.033	.031	.0340	.0036
300	.029	.024	.023	.0253	.0032
350	.026	.017	.019	.0207	.0047
400	.021	.014	.016	.0170	.0036
450	.015	.011	.012	.0130	.0021
500	.011	.007	.009	.0090	.0020
550	.007	.005	.008	.0067	.0015

TABLE IX

COMPARISON OF COEFFICIENT OF FRICTION CALCULATED WITH AND WITHOUT THE BEARING TORQUE. VALUES OF POLYESTER ON ALUMINUM AT 2.22 LB/IN OF TENSION WITH A 180 DEGREE WRAP ANGLE

VEL	Torque			Coefficient of Friction		
	W/O	With	% Err	W/O	With	% Err
100	19.2	19.28	0.41	0.143	0.144	0.69
150	13.7	13.79	0.65	0.097	0.098	1.02
200	10.5	10.60	0.94	0.073	0.074	1.35
250	7.6	7.72	1.55	0.052	0.053	1.89
300	6.6	6.73	1.93	0.045	0.046	2.17
350	5.3	5.43	2.39	0.036	0.037	2.70
400	4.4	4.54	3.08	0.029	0.030	3.33
450	3.7	3.85	3.90	0.025	0.026	3.85
500	3.1	3.25	4.62	0.020	0.022	9.09
550	2.9	3.06	5.23	0.019	0.020	5.00
600	2.5	2.67	6.37	0.017	0.018	5.55
650	2.1	2.27	7.49	0.014	0.015	6.67
700	2.2	2.38	7.56	0.015	0.016	6.25
750	1.4	1.58	11.39	0.009	0.010	10.00
800	1.5	1.68	10.71	0.010	0.011	9.09
850	1.5	1.69	11.24	0.010	0.011	9.09
900	1.3	1.49	12.75	0.009	0.010	10.00
950	1.4	1.59	11.95	0.009	0.010	10.00
1000	1.1	1.30	15.39	0.007	0.009	22.20

TABLE X

EFFECTS OF VARIABLES ON DYNAMIC COEFFICIENT OF FRICTION OF POLYESTER AND POLYPROPYLENE ON ALUMINUM

Coefficient of Friction	Polyester	Polypropylene
More sensitive to velocity changes at low velocities	X	X
More sensitive to changes in tension at low velocities	X	X
Increases with wrap angle	X	X
Increases with an increase in tension	X	X
Decreases with an increase in velocity	X	X

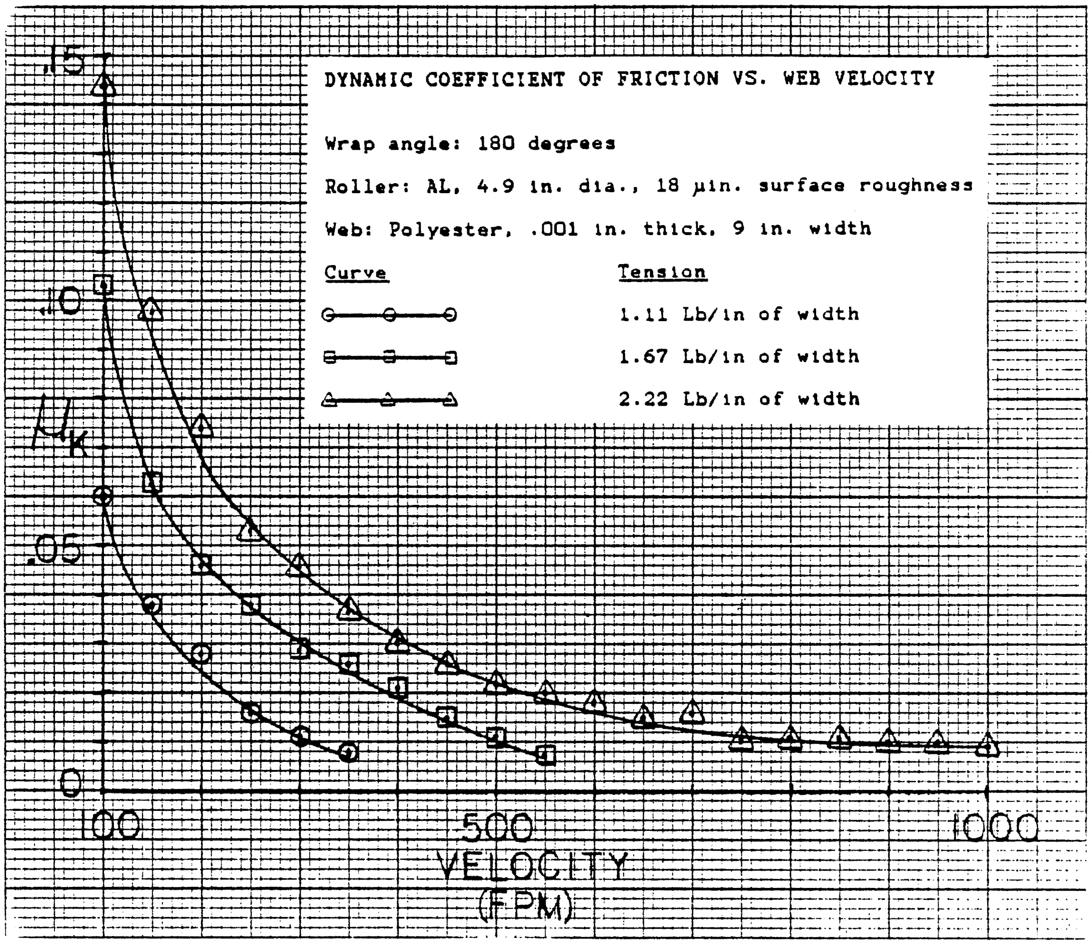


Figure 11. Coefficient of Friction vs. Velocity at a 180 Degree Wrap Angle of Polyester on Aluminum

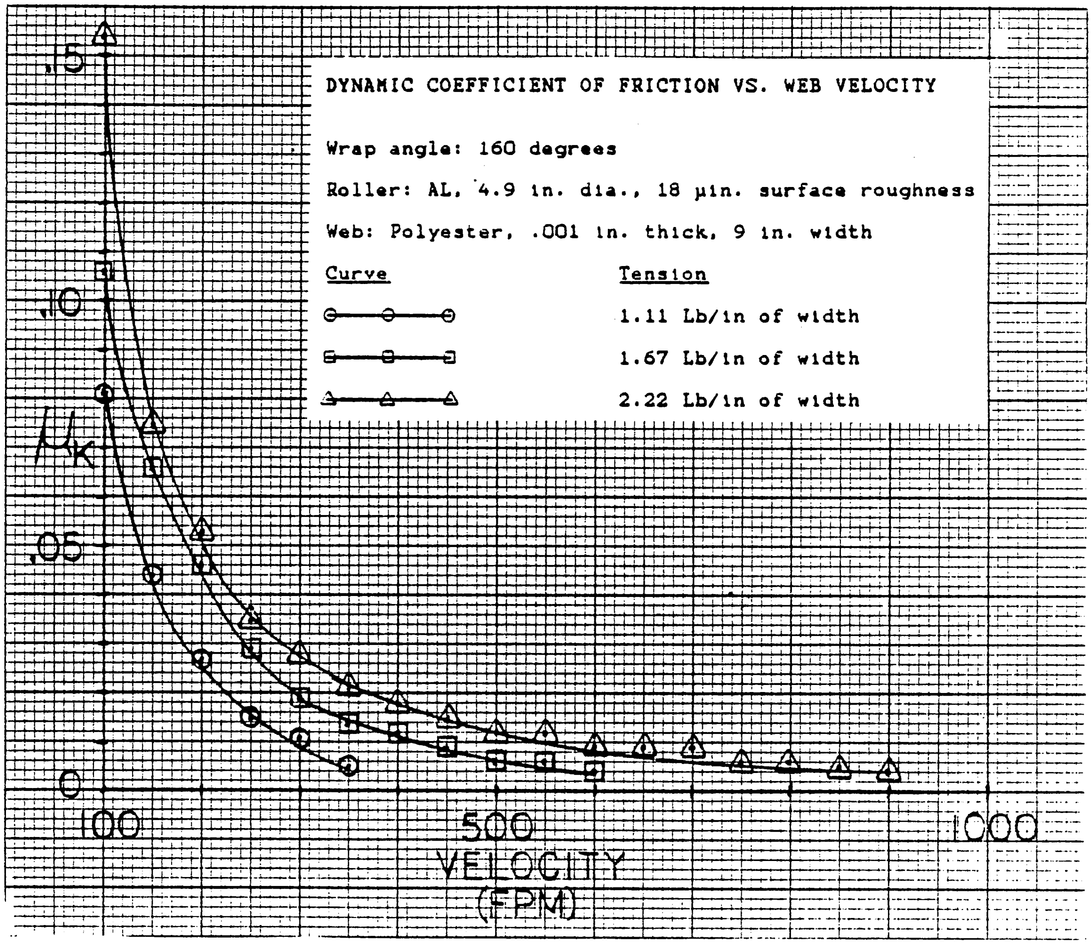


Figure 12. Coefficient of Friction vs. Velocity at a 160 Degree Wrap Angle of Polyester on Aluminum

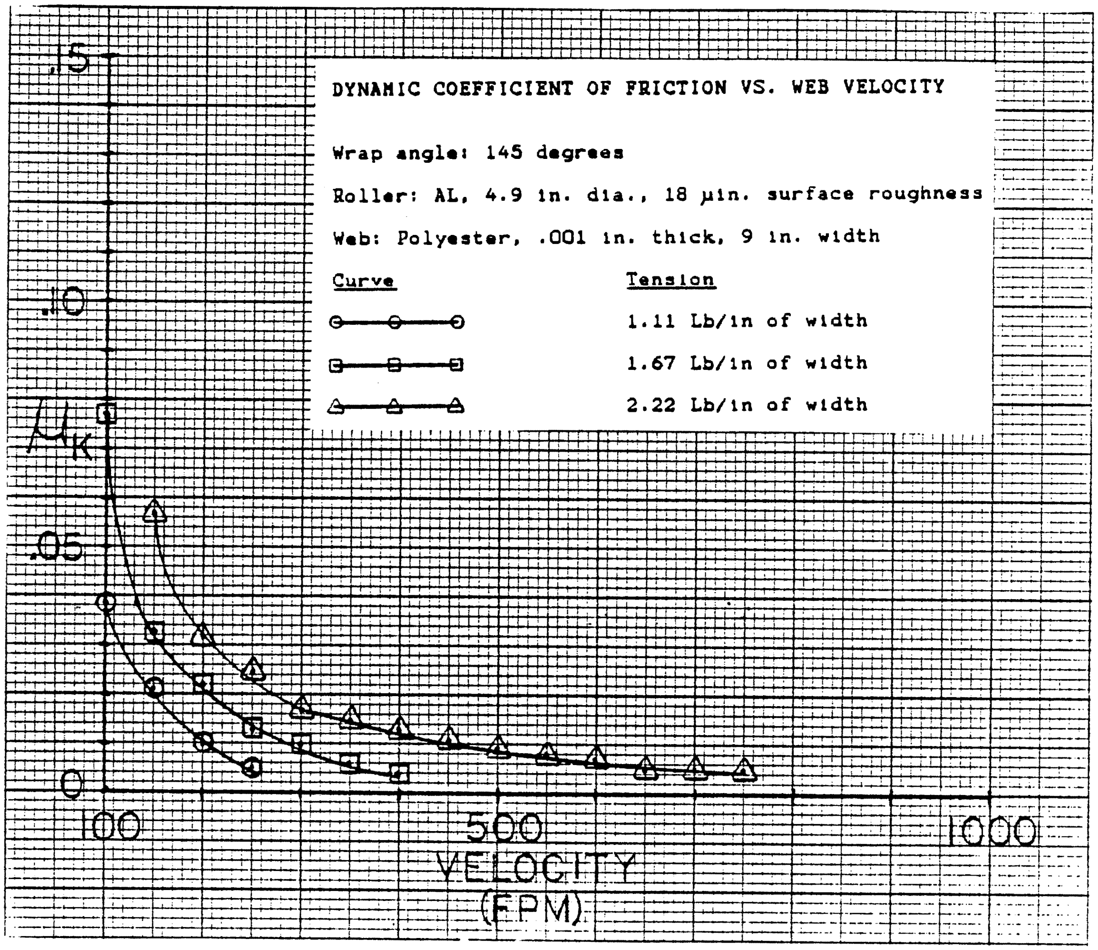


Figure 13. Coefficient of Friction vs. Velocity at a 145 Degree Wrap Angle of Polyester on Aluminum

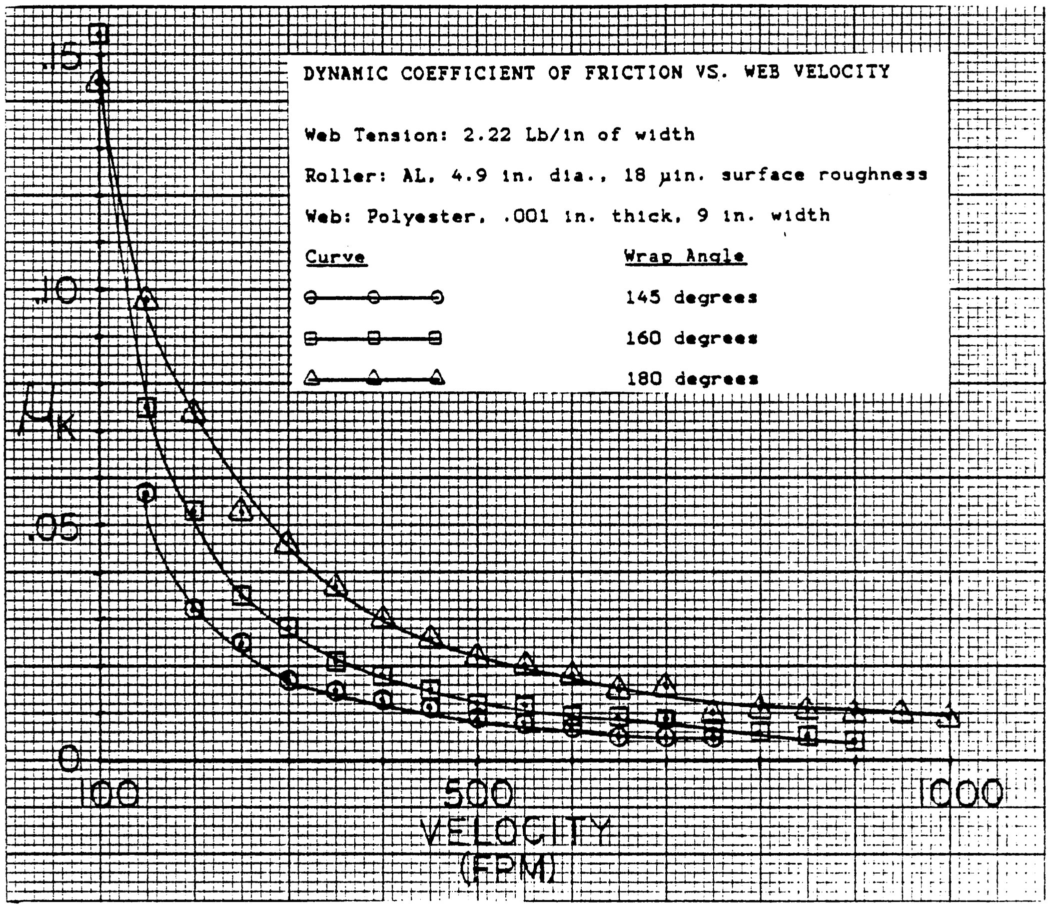


Figure 14. Coefficient of Friction vs. Velocity at 2.22 lb/in of Tension of Polyester on Aluminum

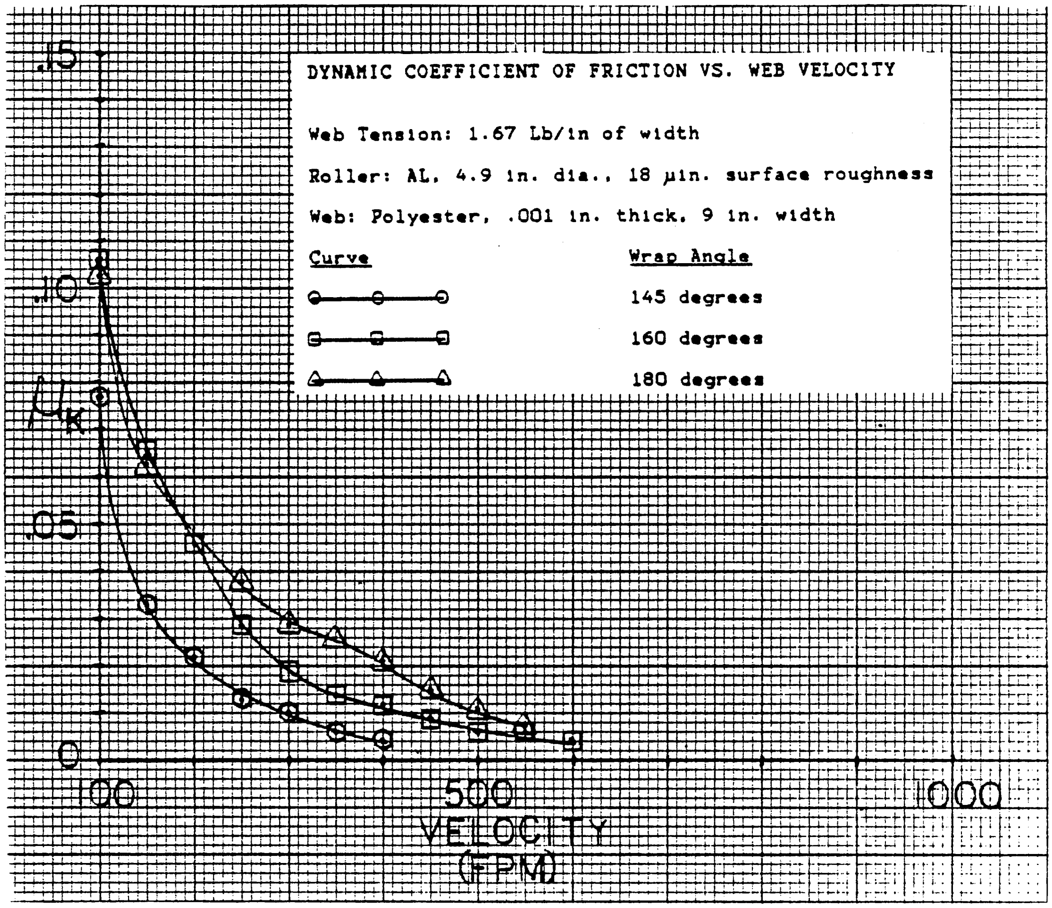


Figure 15. Coefficient of Friction vs. Velocity at 1.67 lb/in of Tension of Polyester on Aluminum

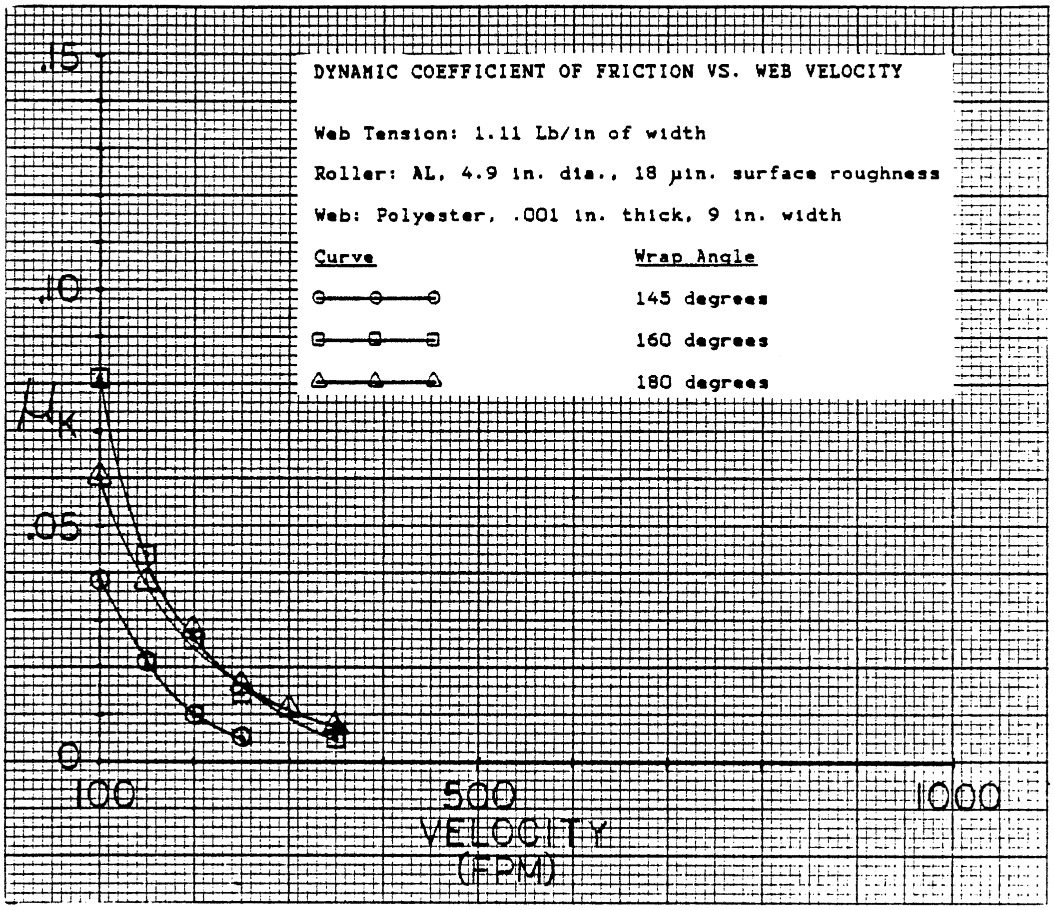


Figure 16. Coefficient of Friction vs. Velocity at 1.11 lb/in of Tension of Polyester on Aluminum

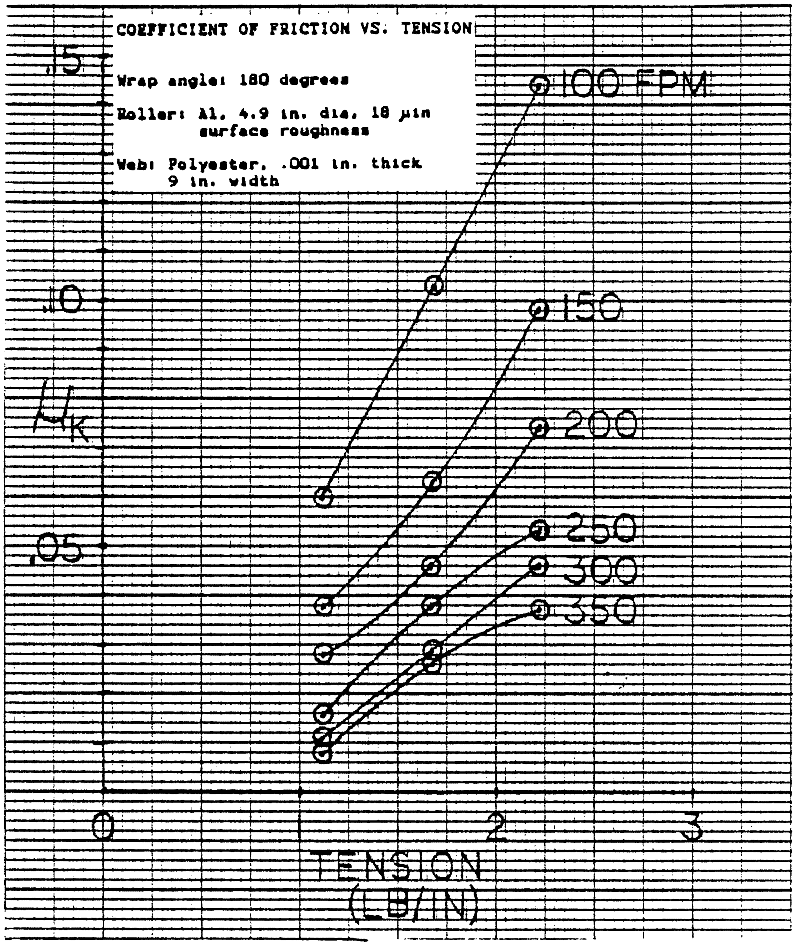


Figure 17. Coefficient of Friction vs. Tension at a 180 Degree Wrap Angle of Polyester on Aluminum

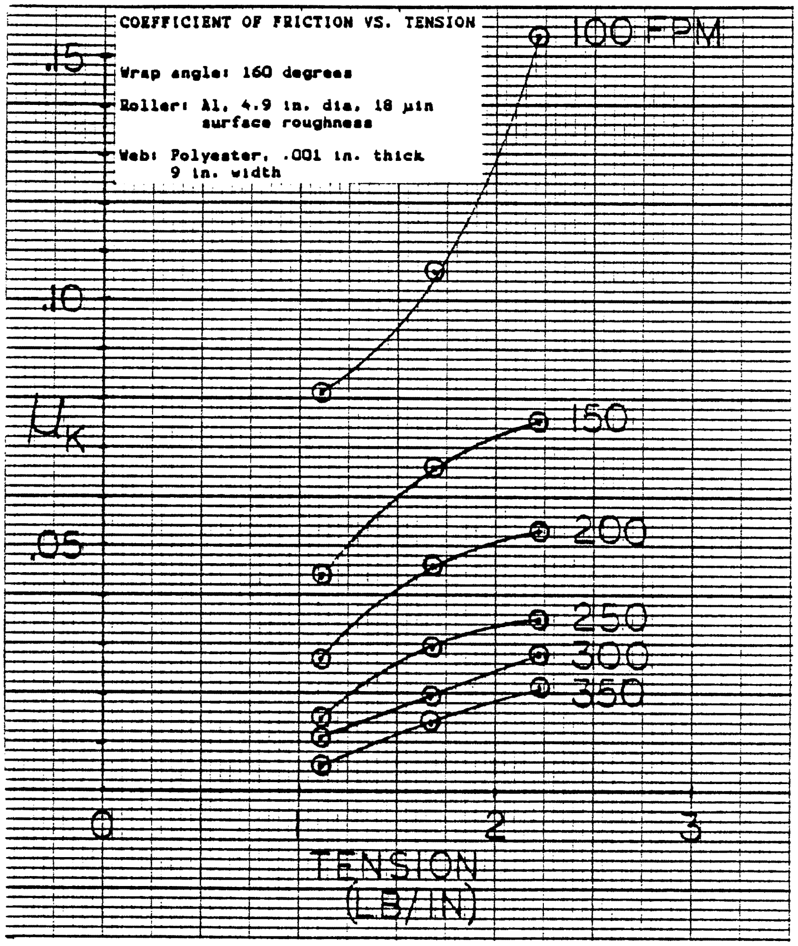


Figure 18. Coefficient of Friction vs. Tension at a 160 Degree Wrap Angle of Polyester on Aluminum

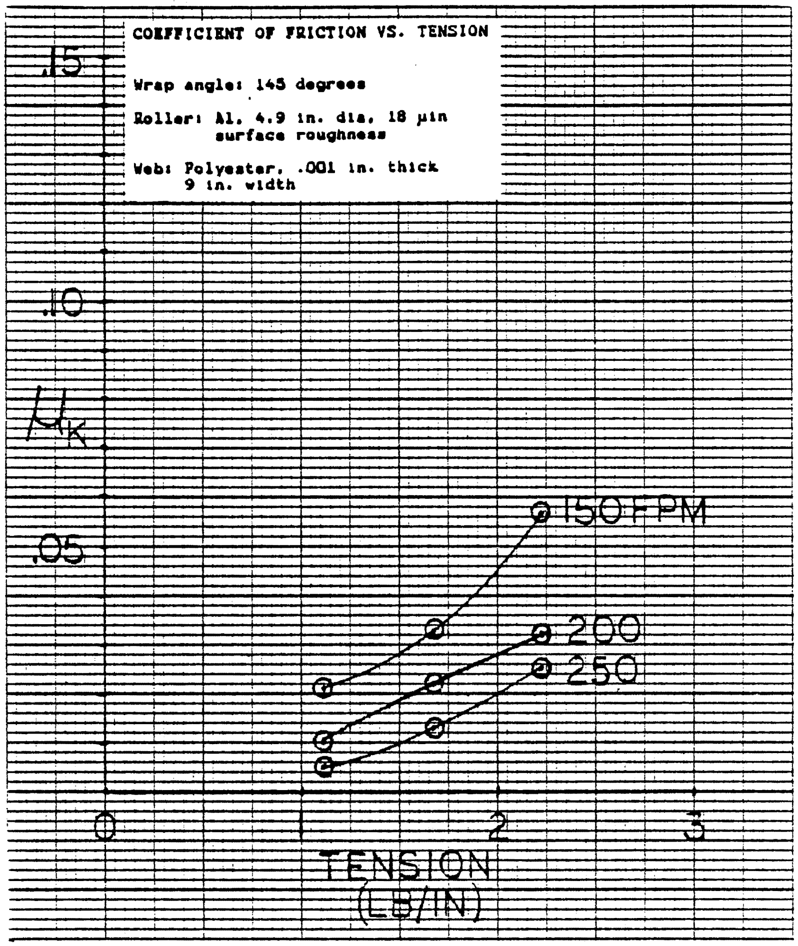


Figure 19. Coefficient of Friction vs. Tension at a 145 Degree Wrap Angle of Polyester on Aluminum

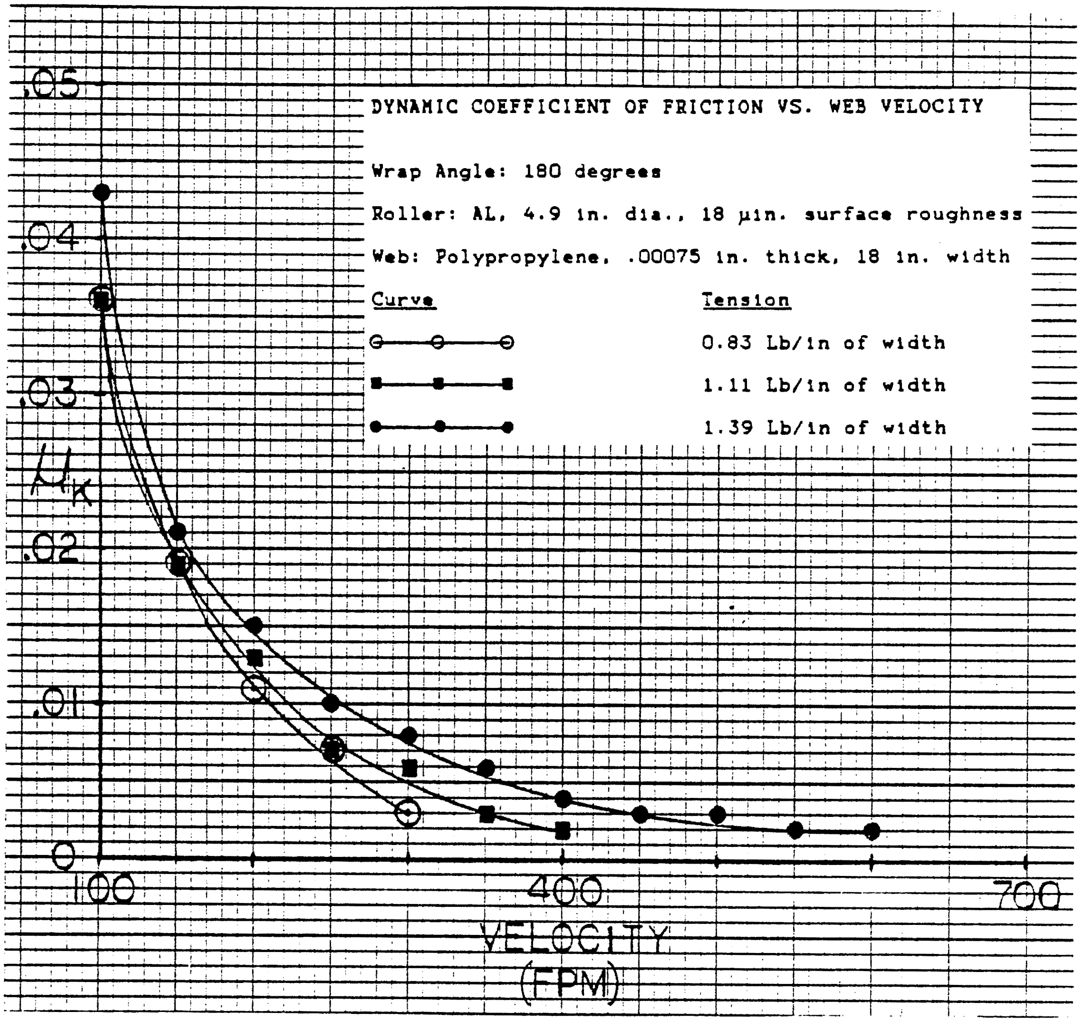


Figure 20. Coefficient of Friction vs. Velocity at a 180 Degree Wrap Angle of Polypropylene on Aluminum

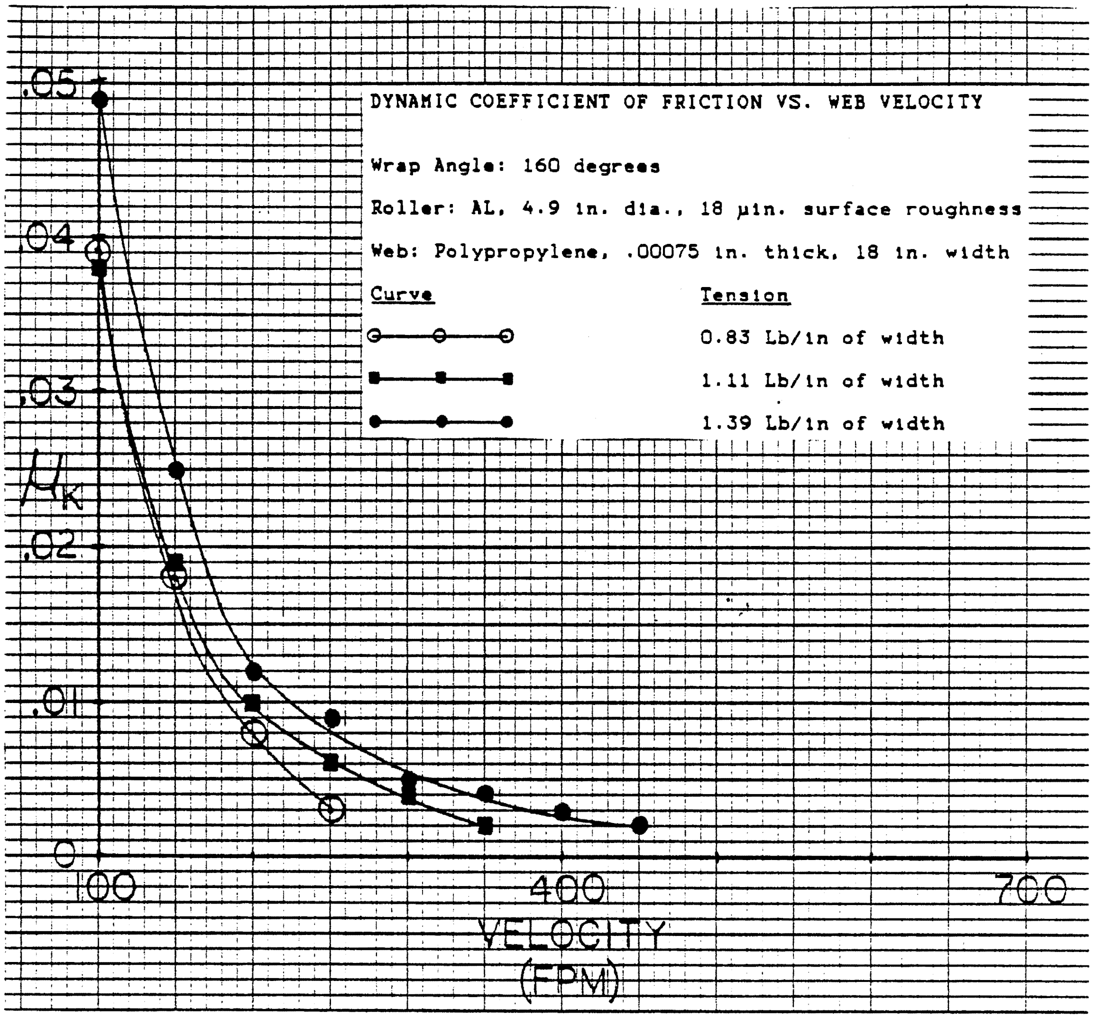


Figure 21. Coefficient of Friction vs. Velocity at a 160 Degree Wrap Angle of Polypropylene on Aluminum

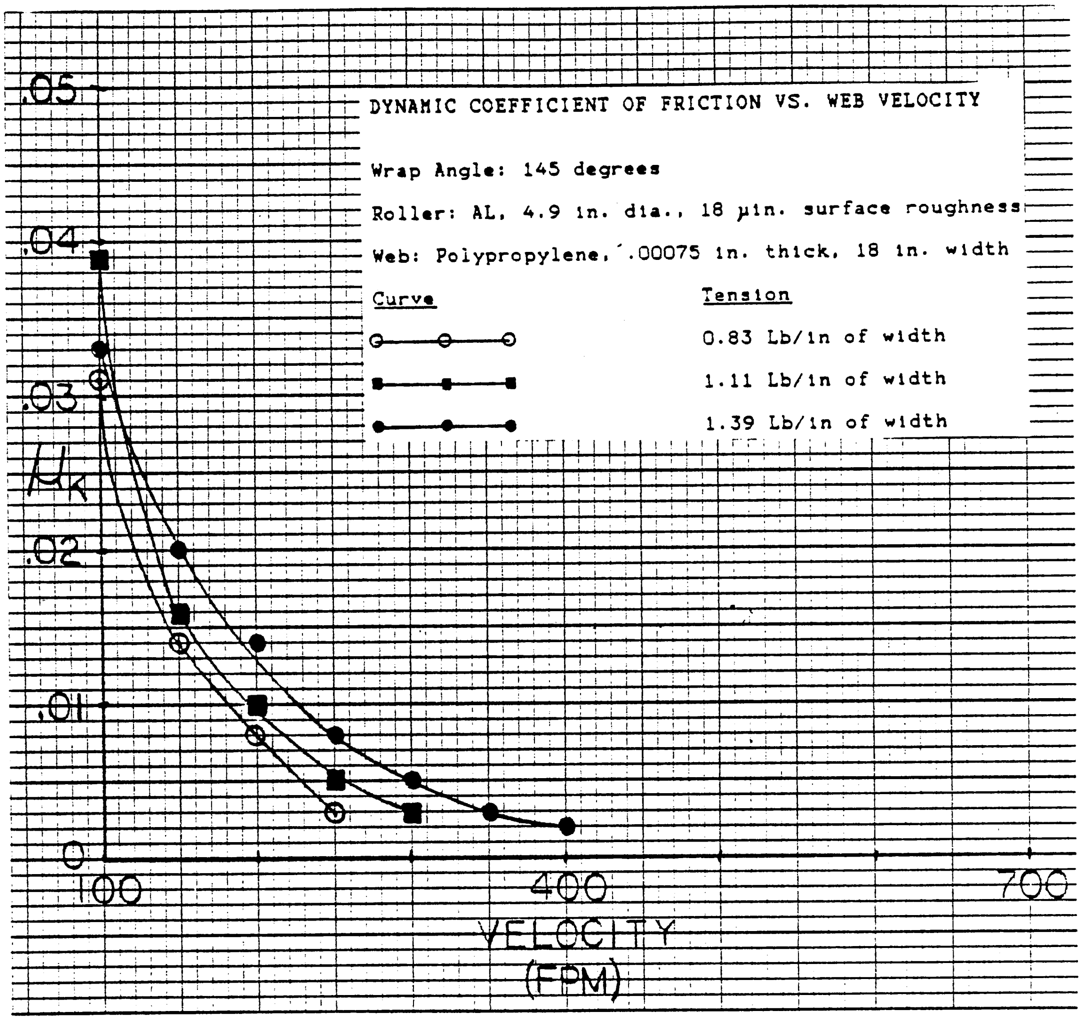


Figure 22. Coefficient of Friction vs. Velocity at a 145 Degree Wrap Angle of Polypropylene on Aluminum

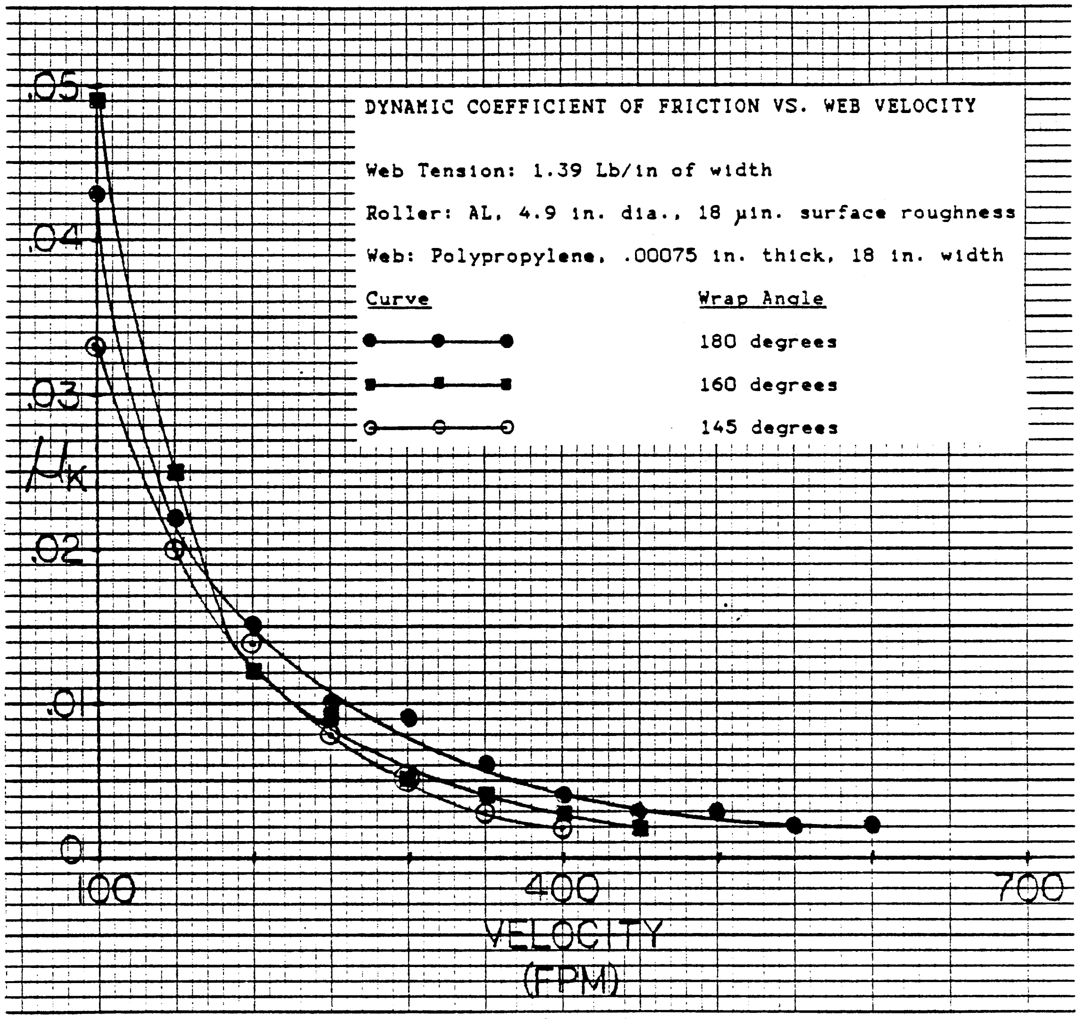


Figure 23. Coefficient of Friction vs. Velocity at 1.39 lb/in of Tension of Polypropylene on Aluminum

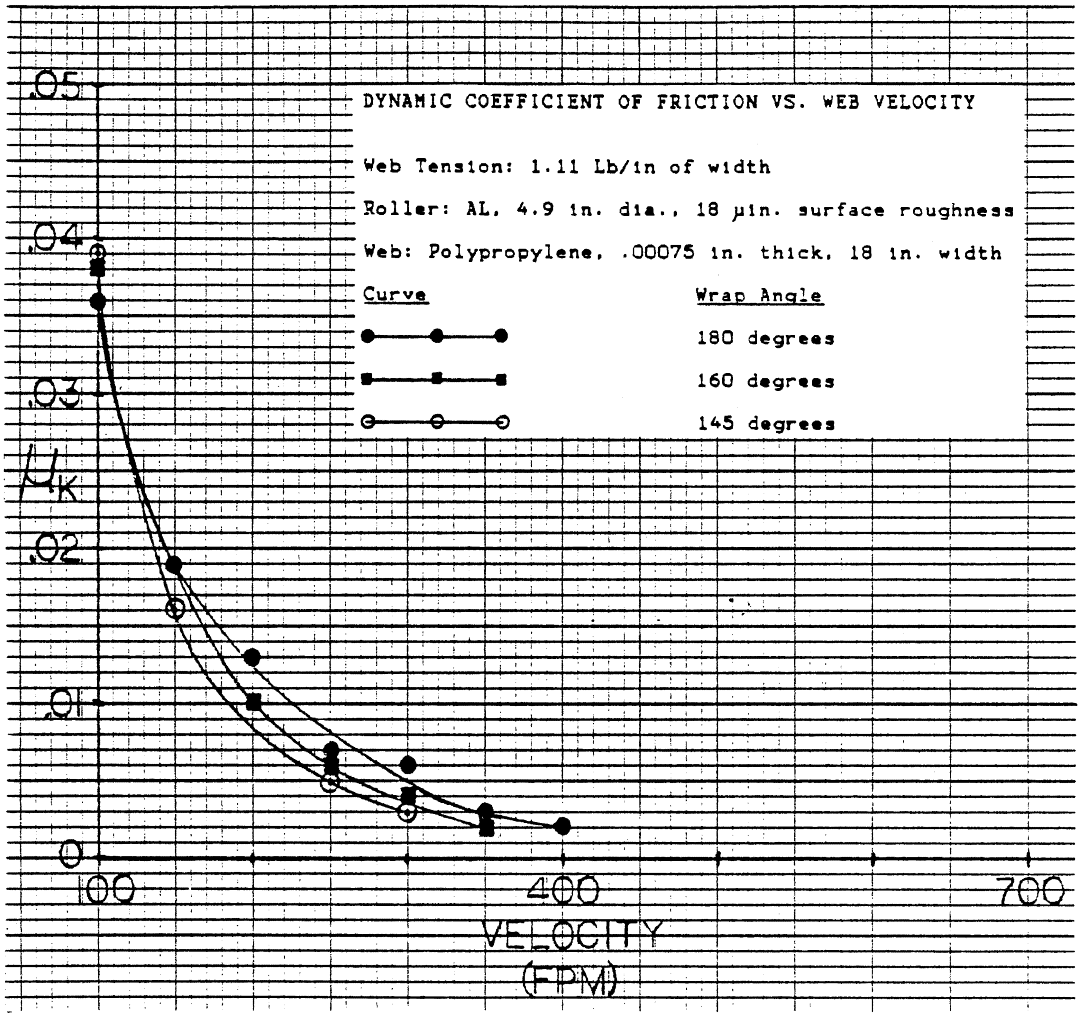


Figure 24. Coefficient of Friction vs. Velocity at 1.11 lb/in of Tension of Polypropylene on Aluminum

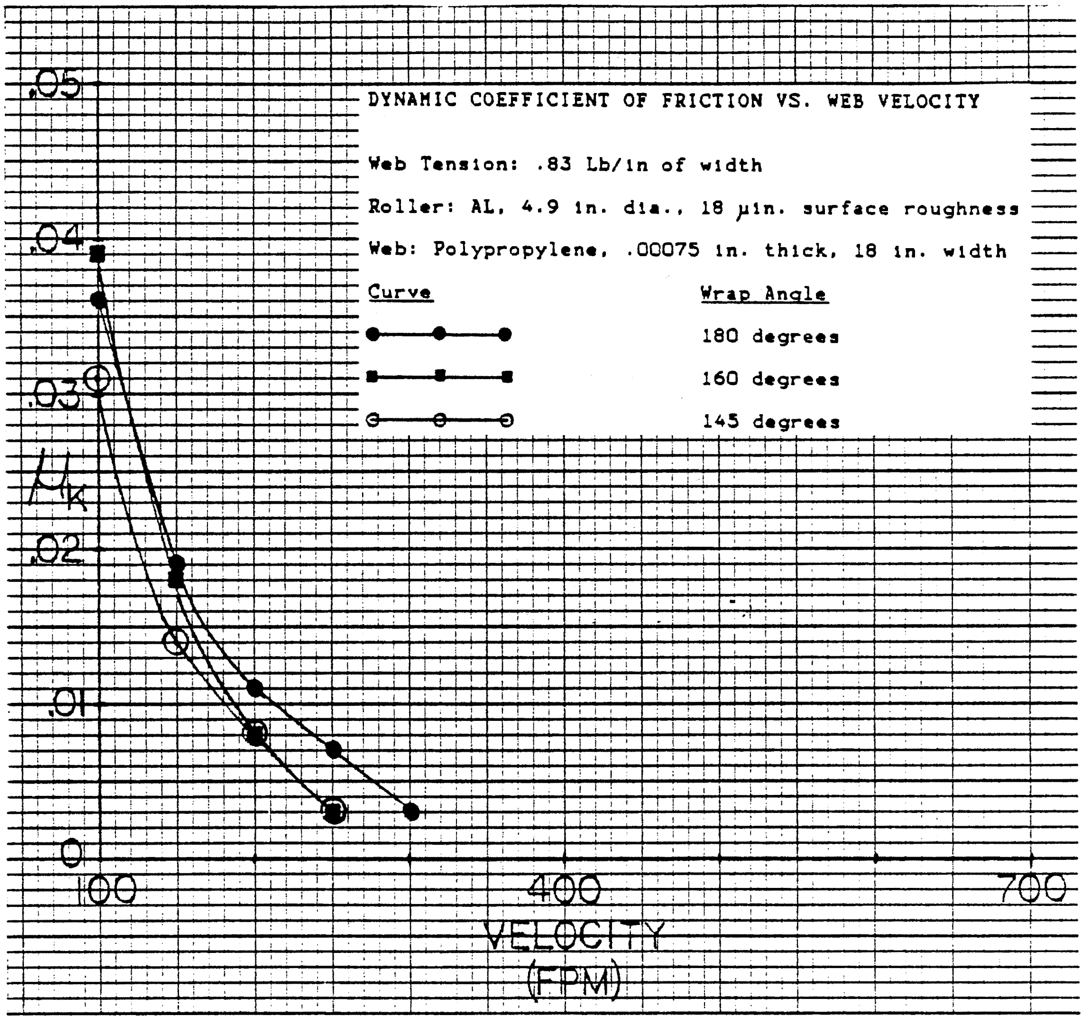


Figure 25. Coefficient of Friction vs. Velocity at 0.83 lb/in of Tension of Polypropylene on Aluminum

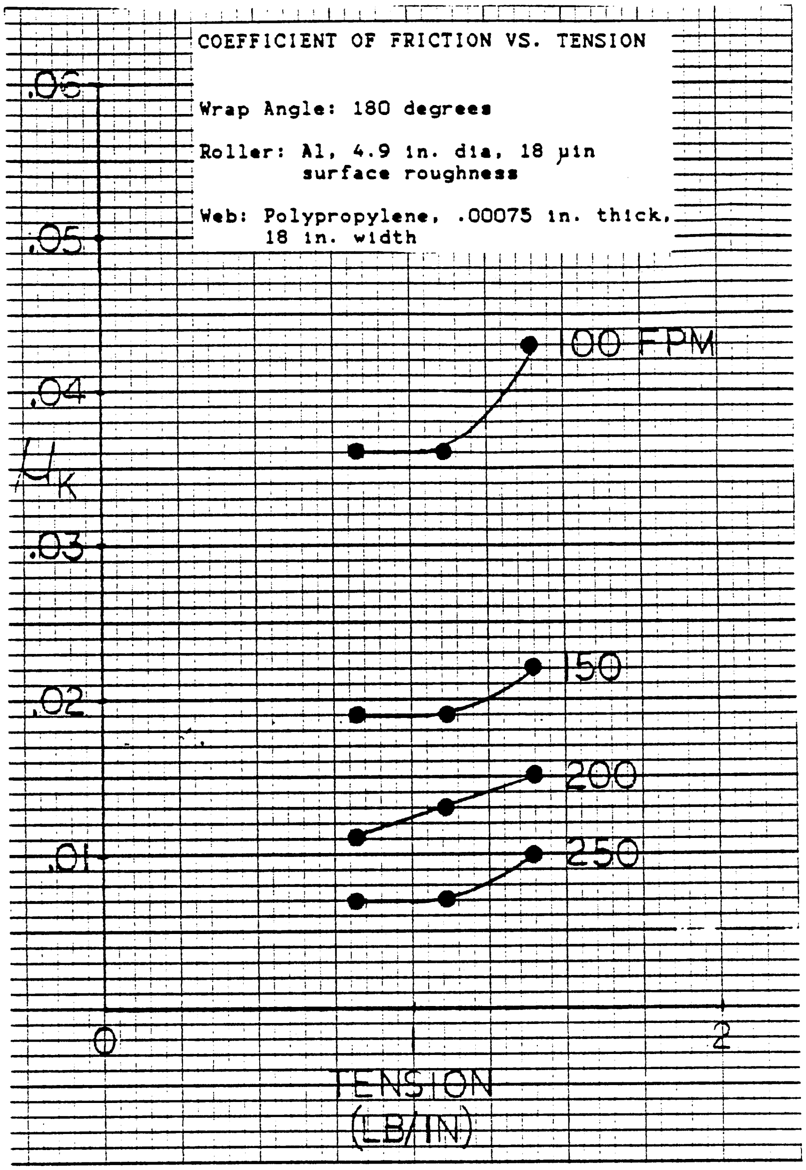


Figure 26. Coefficient of Friction vs. Tension at a 180 Degree Wrap Angle of Polypropylene on Aluminum

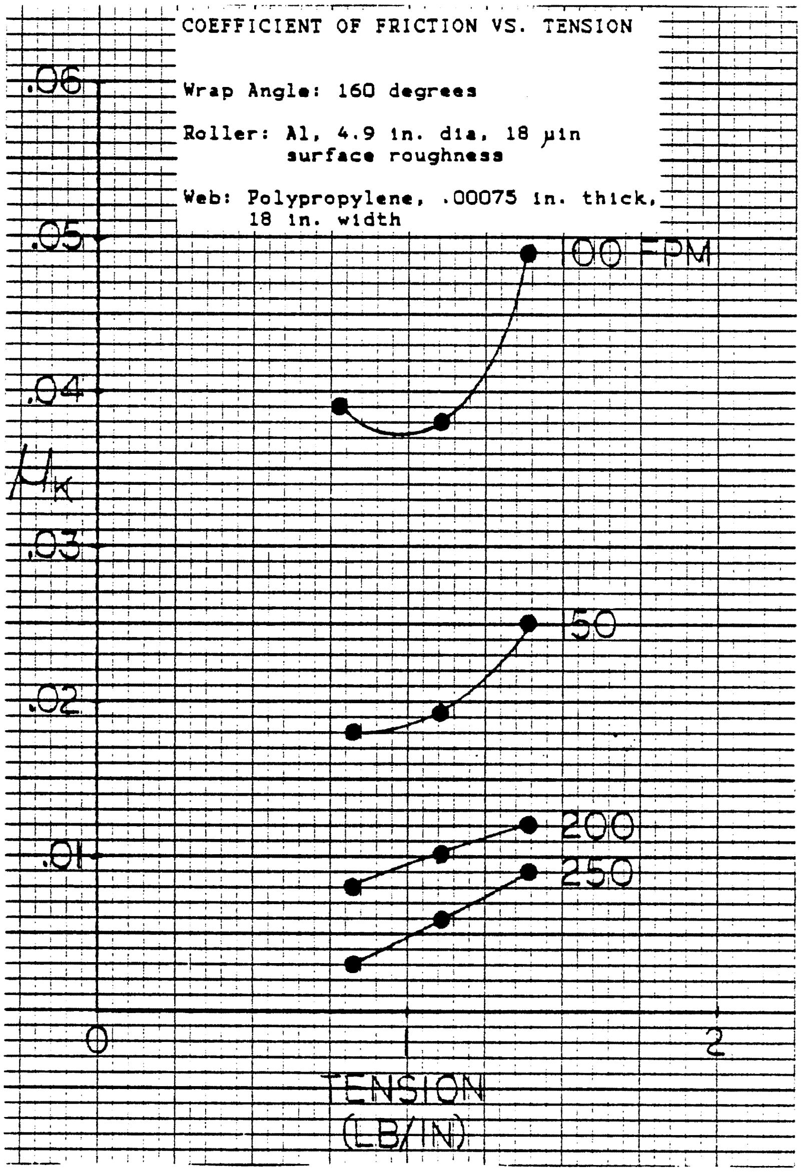


Figure 27. Coefficient of Friction vs. Tension at a 160 Degree Wrap Angle of Polypropylene on Aluminum

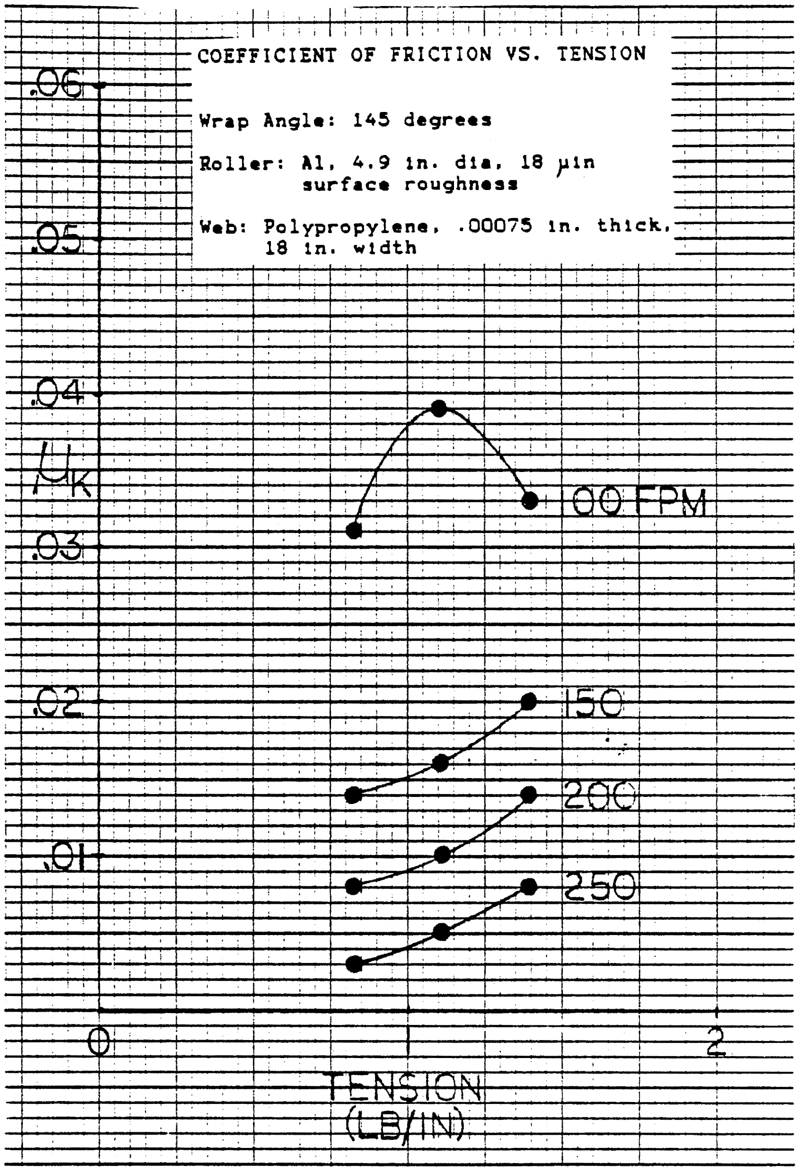


Figure 28. Coefficient of Friction vs. Tension at a 145 Degree Wrap Angle of Polypropylene on Aluminum

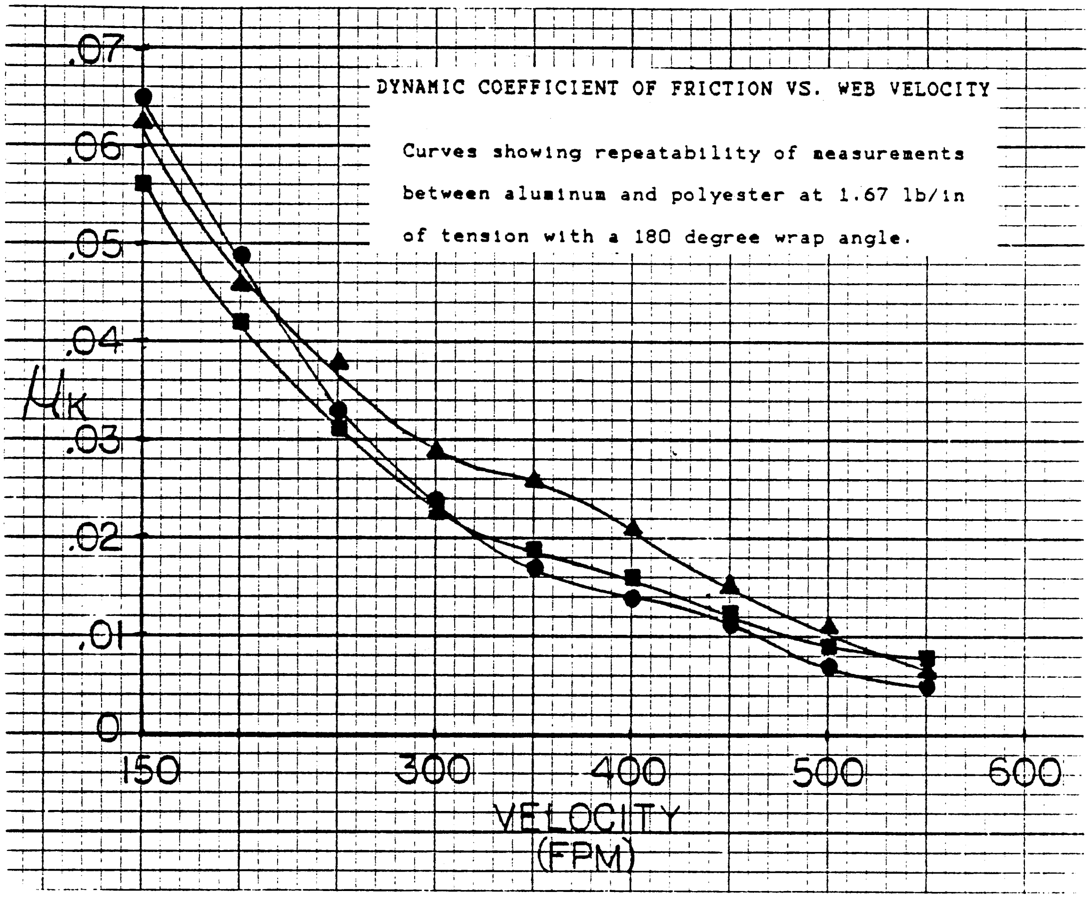


Figure 29. Repeatability Measurements for Dynamic Coefficient of Friction

CHAPTER IV

CONCLUSIONS/RECOMMENDATIONS

As stated in the results, the coefficient of friction is higher at greater wrap angles, greater web tensions, and lower velocities. But there were a few data points that seem out of place particularly at the lower velocities. A good example of this is in Figure 23, where the coefficient of friction at 100 fpm with a 180 wrap angle is less than the value with a 160 degree wrap angle. Most of the error at the lower velocities can be explained by the lack of accuracy in the velocity readings. The web and roller velocities were calibrated to read within one fpm, but due to the fluctuation in the velocity readings, the velocity could only be read within 5 to 10 fpm. Therefore at lower velocities a 5 to 10 fpm change in velocity was a greater percentage decrease in the velocity than it was at higher velocities. So at lower velocities slippage was not detected right when it occurred, but sometime afterward. Therefore more torque was applied than was needed to cause slippage. The higher torque reading also causes the tension(T_2) to be higher. At lower velocities there is also a greater increase in torque for each 5 fpm velocity decrease than at higher velocities. Therefore at lower velocities the coefficient of friction may error slightly on the high side. A better means of measuring the roller and web velocities is needed for future measurements. A more accurate velocity reading would reduce the amount of judgment needed in deciding when the web starts to slip on the roller.

The bearing torque did prove to be significant at higher velocities. Even though the bearing torque was measured with only the weight of the roller acting against the bearings and not with the force of the web adding to the resultant radial force, the values found for the bearing torque are reasonable. The bearing torque is a larger percentage of the total torque at higher velocities than at lower velocities because the bearing torque increases as velocity increases and the slip torque decreases as velocity increases. Even though the torque can be corrected by adding on the bearing torque, a better alternative would be to reduce the bearing friction of the braked roll. Replacing the ball bearings with gas bearings would improve the measurement accuracy at high velocities and eliminate any concern about the bearing torque.

Since Daly[2] showed that the traction between a web and roller increases as wrap angle increases, the coefficient of friction was expected to be higher at the greater wrap angles, as was found in the results of this study. Daly explained that a larger wrap angle allowed more time for the air to leak out thereby reducing the floating of the web. But it is not known how much of the increase in the coefficient of friction is caused by the air leakage or by some other factor. One factor could be the dependency of the coefficient of friction on contact area. The coefficient of friction is usually considered to be independent of the contact area under moderate pressures, but with the inclusion of an air film the coefficient of friction becomes dependent on the contact area. Therefore part of the increase in the coefficient of friction may be due to the dependency on contact area between the roller and web. The size of the contact area is changed with different wrap angles, web widths, and roller diameters. Even though the coefficient of friction can be measured without being concerned with the dependency of the contact area, it would be interesting to know how much of an effect it does have on the friction. The coefficient of friction needs to be measured with various web widths, roller diameters, and more wrap angles for future measurements.

No conclusions can be made in comparing the coefficient of friction between polypropylene and polyester. The polypropylene is twice as wide and has less tension per unit width than the polyester. It would be useful to know whether the wrap angle at a given tension has more of an effect on the polyester than on the polypropylene. The comparison of webs with everything else being equal needs to be studied to show any difference between the coefficient of friction of various webs.

The web-handling machine needs to be modified to increase the web velocity to at least 8000 fpm, so that the coefficient of friction for paper can be determined. An improved non-slip drive roll also needs to be installed, so that higher coefficients of friction, as was the case with a cork covered test roller, can be measured. A brake that is capable of smaller torques is also necessary for very small coefficient of friction readings which occur at high velocities. The smaller values would come closer to showing the point where the web starts slipping over the roller on its own. The addition of force transducers to measure the upstream web tension(T_1) would also give a better feeling of what the web tensions are doing. The additional tension measurement would also provide a check on the torque reading.

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