

**EFFECT OF RUBBER COVERED NIP ROLLERS  
ON WOUND-ON-TENSION IN CENTER  
AND SURFACE WINDING**

By

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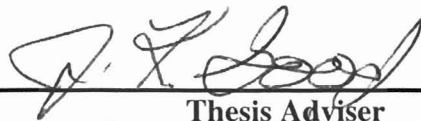
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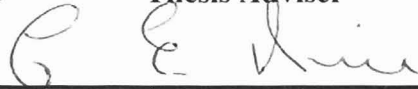
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Thesis Approved:



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## TABLE OF CONTENTS

Chapter	Page
<b>1. INTRODUCTION</b>	<b>1</b>
<b>2. LITERATURE REVIEW</b>	<b>4</b>
2.1 Overview on Wound Roll Models.....	4
2.2 Overview of Web Line Tension Effect on Wound Roll Stresses.....	7
2.3 Overview of Speed Differential in Rubber Covered Rollers.....	10
<b>3. EXPERIMENTAL PROCEDURE</b>	<b>23</b>
3.1 Winding Machine Description and Winding Conditions.....	23
3.2 Modulus of Rubber Covered Rollers.....	26
3.3 Web Thickness and Width.....	28
3.4 Web Materials Used and their Applications.....	29
3.3 In-Plane Modulus( $E_t$ ) Test.....	30
3.4 Radial Modulus( $E_r$ ) Test.....	31
3.5 Friction Tests.....	33
<b>4. RESULTS AND DISCUSSION</b>	<b>35</b>
4.1 Wound-on-Tension dependency on Wound Roll Radius and Nip Load Sequence.....	35
4.2 Angle of Wrap Dependency.....	37
4.3 Web Material Effects.....	42
4.4 Impact of Grooves, Cover Thickness and Hardness.....	44
4.5 Study of Foam Roller on WOT Behavior.....	48
4.6 Discussion.....	49



<b>5. CONCLUSIONS &amp; OBSERVATIONS FOR DESIGN</b>	<b>51</b>
5.1 CONCLUSIONS.....	51
5.2 OBSERVATIONS FOR DESIGN.....	52
<b>FUTURE WORK</b>	<b>53</b>
<b>REFERENCES</b>	<b>54</b>
<b>APPENDIX A</b>	<b>56</b>

## LIST OF FIGURES

Figures	Page
Figure 2.1: A Center Winder With an Impinging Nip Roller	9
Figure 2.2: WHRC WIT Apparatus used by Good, Hartwig and Markum	10
Figure 2.3 Rubber Block Under Action of Uniform Pressure	12
Figure 2.4: System of Rubber Deflection of Loaded Rolls, studied by Beucker	14
Figure 2.5: Speed Differential as a function of Load and Cover Thickness	15
Figure 2.6: Speed Differential as a function of Load and Hardness	15
Figure 2.7: Definitions of Variables for Lindley's theory	16
Figure 2.8: Definition of Variables for Johnson's Theory	17
Figure 2.9: Drawing of Nip Roller Mechanics used by Ning Cai	18
Figure 2.10: Simplified Mechanics of Nip Roller used by Ning Cai	19
Figure 3.1: View of WOT Experiment with Grooved Rubber Roller B	23
Figure 3.2: Front View of Grooved Rubber Roller G with all dimensions in inches	24
Figure 3.3: Right Side View of Roller G showing the radial thickness of rubber in inches	24
Figure 3.4: Winder Set-up used at WHRC	25
Figure 3.5: Stress-strain curve for Newsprint for in-plane modulus test	31
Figure 3.6: Radial Modulus of Elasticity for LWC	32
Figure 3.7 Friction Measurement Test	34
Figure 4.1 Effect of Wound Roll Radius on WOT for Surface Wound Machine Finished Coated Paper with Different Rollers	36

Figure 4.2 Center Wound FCP showing the Decreasing WOT with Increasing Nip Load	36
Figure 4.4 Wrap Effects on Surface Wound Machine Finished Coated Paper at $T_w = 1$ pli	38
Figure 4.5 Wrap Effects on Surface Wound Machine Finished Coated Paper at $T_w = 3$ pli	39
Figure 4.6 Wrap Effects on Center Wound Machine Finished Coated Paper at $T_w = 3$ pli	40
Figure 4.7 Wrap Effects on Center Wound Machine Finished Coated Paper for Rigid Aluminum Roller	41
Figure 4.8 Variation of WOT at High Nip Loads for Rubber Covered Roll F with Rigid Aluminum Roll and at Different Wrap Angles $180^\circ$ and $45^\circ$ during Center Winding .	42
Figure 4.9 Surface Wound Results for 4 Paper Grades for Rigid Aluminum Roll and Un-Grooved Rubber Roll ( Roll F) at 1 pli Web Line Tension and $180^\circ$ wrap angle	43
Figure 4.10 Variation of WOT at High Nip Loads for Center Wound MFC and FCP at 3 pli Web Line Tension and $180^\circ$ Wrap Angle	44
Figure 4.11 Variation of WOT for Surface Wound MFC at 1 pli Web Line Tension and $180^\circ$ Wrap Angle	45
Figure 4.12 Variation of WOT for Surface Wound MFC at 3 pli Web Line Tension and $180^\circ$ Wrap Angle	46

Figure 4.13 Variation of WOT for Center Wound MFC at 1 pli Web Line Tension and 180° Wrap Angle	47
Figure 4.14 Variation of WOT for Surface Wound News at 1 pli Web Line Tension and 180° Wrap Angle	48
Figure 4.15 WOT Plot for Foam Roller H for Center Wound News at 1 pli Web Line Tension and Wrap Angle 180° .	49
Figure 4.16 WOT Plot for Center Wound News at 1 pli Web Line Tension and Wrap Angle 180° .	50
Figure A-1: WOTM Machine at WHRC	58
Figure A-2: WOT Experiment with Grooved Rubber Roller B and Wound Roll	58
Figure A-3: Another View of WOT Experiment with Grooved Rubber Roller B	59
Figure A-4: WOT Measurement Set-up at WHRC	59
Figure A-5: Another View of WOT Measurement with Wound Roll Set-up at WHRC	60
Figure A-6: View of Wound Roll with Wrap Angle and Nip Loading Set-up at WHRC	60
Figure A-7: Wrap Angle at 180° in WHRC set-up	61
Figure A-8: Wrap Angle at 45° in WHRC set-up	61

## LIST OF TABLES

Table	Page
3.1 Details of Different Rollers used for measuring WOT in WHRC Winder	26
3.2 Value of $E_{rr}$ for Nip Rollers Used during Experiment	27
3.3 Thickness and Width of Various Web Materials	28
3.4 Results of In-Plane Modulus Tests for Various Web Materials	30
3.5: Coefficients of $K_1$ and $K_2$ in Pfeiffer's Equation	32

## NOMENCLATURE

$T_w$	Winding Tension (psi)
$\mu$	Coefficient of Friction
$\mu_{st}$	Static Coefficient of Friction
$\mu_k$	Kinetic Coefficient of Friction
$\mu_{A/w}$	Aluminum to Web Kinetic Coefficient of Friction
$\mu_{w/w}$	Web to Web Kinetic Coefficient of Friction
$K_1$	Pfeiffer's Coefficient – A material constant and it is the value of pressure on the sheets when the strain is reduced to zero (psi)
$K_2$	Springiness factor, Dimensionless
WOT	Wound-on-Tension (pli)
WA	Wrap Angle of web around the nip (Degrees)
$E_t$	In-plane Modulus (psi)
$E_r$	Radial Modulus (psi)
NIT	Nip-Induced Tension (pli)
h	Web Thickness (in)
s	Radial Distance (in)
N	Nip Load (pli)
$\epsilon$	Strain
t	Cover Thickness (in)

$E_{rr}$	Modulus of Rubber (psi)
$g^2$	Ratio of $\frac{E_t}{E_r}$
$r$	Radius of the roll (in)
$\delta\sigma_r$	Radial stress or pressure (psi)
$u(1)$	Radial Deflection of the roll at the core (in)
$E_c$	Core Stiffness
$\sigma_{ri}$	Radial stress in $i^{\text{th}}$ lap of wound roll (psi)
$\delta\sigma_{ri}$	Incremental inter-layer pressure (psi)
$\epsilon_c$	Compressive strain
$P_c$	Compressive pressure (psi)
$N$	Nip Load (pli)
$\theta$	Wrap angle (Degrees)

# CHAPTER 1

## INTRODUCTION

Rubber covered nip rollers have a number of applications within web lines. Any material in continuous flexible strip form is a Web. Materials like paper, textiles, metal foil, tapes, plastic film, and non-woven materials are examples of Webs. Web handling is the science involving the mechanics and dynamics of transporting webs from unwind stations, through machinery, to rewind stations. Rubber covered rollers are often used to nip the web against a metal surfaced roller that is driven, to achieve a certain web velocity or web tension.

Winding determines the quality of web rolls in a web handling industry. Several types of winding include center winding, center winding with a nip roller and surface winding. In center winding with impinging nip roller, the driving torque is given to the core while the nip roller is free to rotate. In surface winding, the torque is given to the nip roller and the core is free to rotate. The Wound-on-Tension(WOT) is the tension of the web in the outer layer of a winding roll. Past research[1] has shown that the value of wound-on-tension for rollers wound by center winding is greater than that for surface winding under the same winding conditions. While winding with a nip roller, there can be an increase in wound-on-tension due only to the nip, without increasing the web line tension. A nip roll can also exude the air entrained into a wound roll during high speed winding. Rubber covered nip rollers are often used on winders where vibration may be a



problem. The resiliency of the rubber cover also increases the contact area between web roll and nip roll for a given nip load, compared to a metal surfaced roll, thus reducing the maximum contact pressure which can affect web quality.

Rubber covered rollers have been studied by Ning Cai[2] and Kaya[3]. Ning Cai[2] found that the nip induced tension mechanics is the intrinsic property for winding with a nip roller, and the mechanics can be applied to both center winding with nip rollers and surface winding. He also found that the compliance of the nip roller had no effect upon the nip induced tension. He concluded that the compliance of the nip rollers had no effect upon the wound roll stress in center winding, with an un-driven nip rollers, and surface winding. His studies were done at a low nip load of 6 pli.

Research done by Omar Sedat Kaya[3] has shown that, while using the rubber covered nip rollers, the value of WOT was similar to the WOT values measured using a solid aluminum roller at low nip loads, as Ning Cai[2] found. But, while operating at high nip loads (in his case 30 pli) and high wrap angle ( $180^{\circ}$ ) there was a significant increase of WOT values with solid rubber covered rollers, when compared to a solid rigid aluminum roller. The complexity of the rubber covered roller is the rubber itself. Rubber is nearly incompressible and rubber often changes in shape, which is often mistaken as a change in volume. The increase in WOT is due to the constriction of rubber causing the web to speed up, and frictional forces to develop between the web and the surface of the rubber roll that results in an increase in web tension and WOT.

From the previous research of Kaya[3], it is seen that the incompressibility of rubber causes the web to speed up locally, hence causing the increase in WOT. Rubbers can be made to compress by grooving circumferentially or having voids cast into them, as in the case of urethane foams. If the rubber is made to compress without speeding up, then the grooving or voids should prevent the increase in WOT found with solid rubber covers. This issue was investigated and results are documented and presented in the forthcoming chapters.

## CHAPTER 2

### LITERATURE SURVEY

Prediction of stresses in wound rolls has been an interesting topic for a long time. Wound roll quality and performance are related to the level and distribution of in-roll stresses. It is the in-roll stresses which determine the structural integrity of the wound roll and make it an effective package. It is also this same stress which can cause damage to a web when not controlled properly. So, it is very important to find a way of controlling the in-roll stresses.

#### 2.1 Overview on Wound Roll Models:

Web material parameters have been known to affect the wound roll stresses, since the advent of wound roll models. The web material properties are documented in this research. In 1986 Hakiel[4] composed a wound roll model in the form of a second order differential equation in radial pressure of the form:

$$r^2 \left( \frac{d^2(\delta\sigma_r)}{dr^2} \right) + 3r \left( \frac{d(\delta\sigma_r)}{dr} \right) - (g^2 - 1) \delta\sigma_r = 0$$

Equation (2.1)

where  $g^2$  is the ratio of  $\frac{E_t}{E_r}$

$E_t$  is In-plane Modulus

$E_r$  is Radial Modulus

$r$  is radius

$\delta\sigma_r$  is radial stress or pressure

This differential equation requires two boundary conditions for solution. The first boundary condition results from equilibrium of the outer layer:

$$\delta\sigma_r = \frac{T_w}{S} * h \quad \text{Equation (2.2)}$$

where  $T_w$  is Web Tension (psi)

$S$  is Radius of Outer Layer

$h$  is Web Thickness

The boundary condition in Equation 2.2 is valid only for center winding with no lay on or rider roll. The second boundary condition results from enforcement of compatibility between the first layer of the wound roll and the core upon which the roll is wound:

$$u(1) = \sigma_r(1) / E_c \quad \text{Equation (2.3)}$$

where  $u(1)$  is Radial Deflection of the roll at the core

$\sigma_r$  is Pressure beneath outer layer

$E_c$  is Core Stiffness

He normalized the deformation( $u$ ) by dividing by the radius; thus both sides of this equation are dimensionless. The pressures( $\delta\sigma_r$ 's) throughout the roll are solved as each layer is added on. The pressures are then added to the pressures which resulted from previous solutions. He obtained the radial stress in the  $i^{\text{th}}$  lap of wound roll by the

summation of incremental inter-layer pressures. This solution is shown in Equation 2.4 .

$$\sigma_{ri} = \sum_{i=1}^n \delta\sigma_{ri} \quad \text{Equation (2.4)}$$

where  $\sigma_{ri}$  is radial stress in  $i^{\text{th}}$  lap of wound roll

$\delta\sigma_{ri}$  is incremental inter-layer pressure

Execution of Hakiel's model shows that the web tension is the most sensitive input parameter in terms of impact on the internal roll pressure and stress. The in-plane and radial modulus of elasticity also affect the stresses but to a lesser extent.

The radial modulus is one of the parameters which decides the stresses in a wound roll. In this research, the model of Pfeiffer[1] is used to determine the value of radial modulus. He plotted some compressive stress-strain curves for paper on semi-logarithmic graph paper and found that they were fairly straight lines. He found an exponential relationship between the compressive pressure ( $P_c$ ) and compressive strain( $\epsilon_c$ ), from the linear plots. When the vertical pressure scale was made logarithmic and the same data were plotted, the stress-strain diagram turns into an almost straight line. The mathematical model is truly straight, and equations 2.5 and 2.6 show how to go from the general equation of a straight line to the equation of the model.

$$y = mx + b \quad \text{Equation (2.5)}$$

$$P_c = K_1 e^{K_2 \epsilon_c} \quad \text{Equation (2.6)}$$

where  $m$  = slope of curve

$b$  = y intercept

$\epsilon_c$  = compressive strain

$P_c$  = compressive pressure

$K_1$  = residual pressure

$K_2$  = constant( Springiness Factor)

The value of  $K_1$  is equal to the pressure on the sheets when the strain is reduced to zero. One would expect this pressure to be zero, but there is a slight pressure on a vertical stack, in this case due to the weight of the sheets themselves. In the present research, this model has been used to evaluate the radial modulus of five different kinds of paper used in WOT measurements.

## **2.2 Overview of Web Line Tension Effect on Wound Roll Stresses:**

The tension in the web between the unwinding and winding station namely, web line tension ( $T_w$ ) is the most sensitive parameter in winding models. In this research, the effect of web line tension under various wrap angles and different rollers has been studied. So, it is very important to study the effect of web line tension on winding models from previous research.

The WOT measurement model in the WHRC lab has been used in this research for measurement of WOT with various solid and grooved rollers and papers. The model of WOT measurement with nip induced mechanism was first proposed by Good, Wu and Fikes[5]. They gave the first basic understanding of the nip induced tension mechanism with their analytical and experimental results. The mechanism was discovered as an

elongating machine direction strain caused by compressive Hertzian-like contact stresses which exists beneath the nip roll location on the lower side of web which in intimate contact with wound roll. A new boundary condition was formulated for wound roll stress models in which the tension in the outer wrap was set equal to the sum of the incoming web stress and the saturated value of nip induced tension. The new boundary condition relied on the coefficient of friction, and the nip loading was presented as

$$\sigma_r |_{r=s} = \{T_w |_{r=s}\} + \frac{\mu N}{h} \frac{h}{s} \quad \text{Equation(2.7)}$$

where  $N$  is Nip Loading and

$\mu$  is the Kinetic Coefficient of Friction

$h$  is web thickness

$s$  is the radial location of outer wrap

$T_w$  is Web Line Tension

The WOT measurement has been done on both surface and center winding in this research. It is important to know the model of the WOT in both winding conditions. The WOT measurement for center wound rolls is the model proposed by Good and Fikes[6]. With their experiments on Center Winding with un-driven nip roll, they gave an equation for Wound-on-Tension ,  $T$

$$T = T_w + \mu N/h \quad \text{Equation(2.8)}$$

Where  $T_w$  is the Web line Tension,  $\mu$  is the coefficient of friction,  $N$  is the nip load per unit width,  $h$  is the web caliper which yields units of stress for the tension.

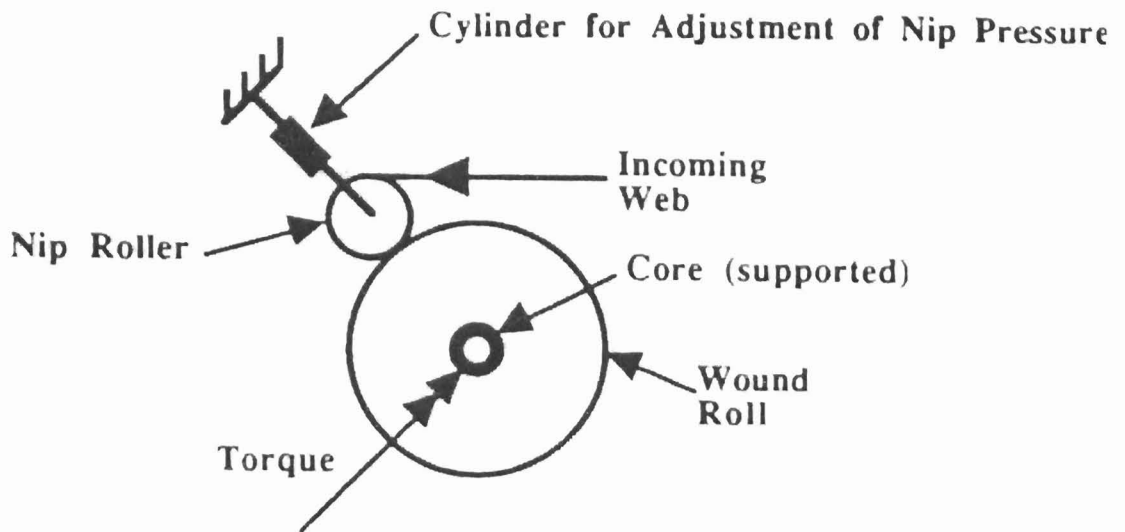


Figure 2.1: A Center Winder With an Impinging Nip Roller

The effect of web line tension in center and surface winding become clearer with the non-interfering method of evaluating roll structure, for both surface and center winding with a nip, by Good, Hartwig and Markum[7]. They used the experimental setup shown in figure 2.2. They concluded that Wound-on-tension in center winding with an un-driven nip appeared to be function of web tension and less a function of nip load. In surface winding WOT appeared to be a function of nip load but was nearly unaffected from web tension. The equation for WOT for surface winding was given as

$$\text{WOT} = \text{NIT} \quad \text{for } 0 < N < 10 \text{ pli} \quad \text{Equation(2.9)}$$

$$\text{WOT} = \text{NIT} + \frac{T_w}{e^{\mu_{wn}\theta}} \frac{N}{58.3} \quad \text{for } 10 < N < 33.3 \text{ pli} \quad \text{Equation(2.10)}$$

Where  $\text{NIT} = \mu N/h$



$T_w$  is Web Line Tension

$\mu$  is the kinetic coefficient of friction between web layers

$\mu_{wn}$  is the kinetic coefficient of friction between web and nip

$N$  is the nip load per unit width

$h$  is the web caliper which yields units of stress for the tension

$\theta$  is wrap angle

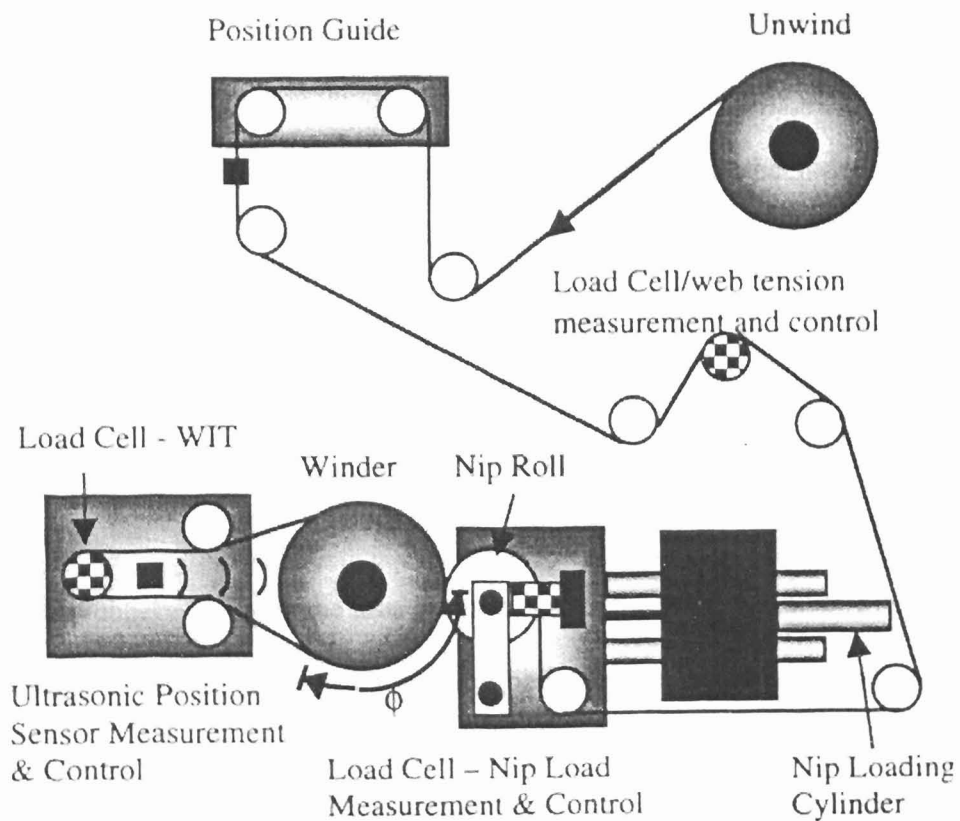


Figure 2.2: WHRC WIT Apparatus used by Good, Hartwig and Markum

From the Equations 2.9 and 2.10 for surface winding it can be seen, for lower nip loads, the WOT is equal to the nip induced tension. At higher nip loads, WOT is dependent on nip induced tension and web line tension. Also the equations are just empirical representation of WOT for particular material of news and nip roller (aluminum in this case) used in that work.

### **2.3 Overview of Speed Differential in Rubber Covered Rollers:**

By Kaya's[3] work it is known that the local speeding of the rubber roller is the cause for an increase in WOT, when winding at high nip loads. The study of differential speed of the rubber covered nip in contact with a wound roll, has not been documented well. The differential speed of a rubber covered roll in contact with a metal surface roller has been studied and facts have been documented in the past.

In the year 1964, Foreman [8] studied the application of rubber covered rolls to pinch rolls and bridles and explained the differential in speeds as a result of the lengthening of the rubber surface in the area of contact with the strip. Foreman[8] studied the rubber covered rolls and established a relation between the rubber compression and the velocity of the strip passing through them. He stated that the increased length of contact between the compressed rubber and the strip passing through the rollers is the reason for the increased velocity in the strip.

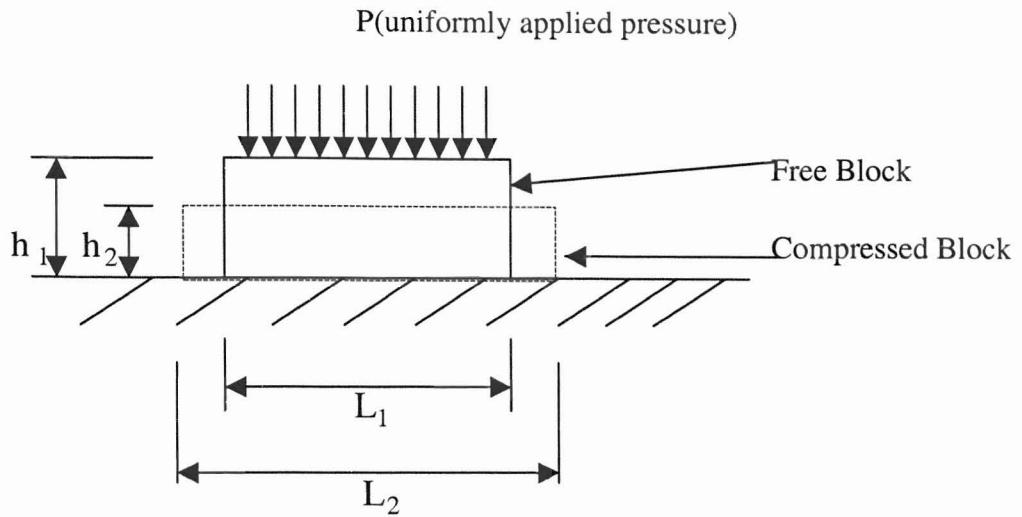


Figure 2.3 Rubber Block Under Action of Uniform Pressure

Foreman studied a block of rubber to illustrate this principle. In the uncompressed state the block has dimensions of  $h_1$  and  $L_1$  and in the compressed state it deforms to  $h_2$  and  $L_2$  respectively. He neglected the friction between the surfaces in contact and assumed that the block is so confined that no change occurs in the plane perpendicular to the paper. Since there is no volume change under this condition, the area of the compressed block will be equal to the area of the uncompressed block.

$$h_1 L_1 = h_2 L_2 \quad \text{Equation (2.11)}$$

Using Hooke's Law:

$$E\varepsilon = \sigma \quad \text{Equation (2.12)}$$

where  $\varepsilon = \frac{(h_1 - h_2)}{h_2}$  and  $\sigma = p$  Equation (2.13)

Substituting Equation 2.13 in Equation 2.12 he got

$$L_2 = \left( \frac{P}{E} + 1 \right) L_1 \quad \text{Equation (2.14)}$$

From the above equation, he concluded that the surface of a rubber under compression will increase in length and that the increase will be in some proportion to the applied pressure. Foreman, also stated that a longer surface contact area creates a phantom roll of apparently larger diameter but with same rotational speed. However, the velocity of the strip will be greater than the apparent surface speed of the roll, in proportion to the lengthening of the rubber surface in the area of contact.

Foreman said that the velocity of the strip is dependent on factors like radius of roll, covering thickness, covering durometer and roll pressure. The velocity of the strip with the dependence on covering thickness and durometer, matters as in the present work, rollers with different durometers and with grooved rubber rollers two different of thickness of rollers have been studied for WOT values.

Eleven years later(1975), Bharat Bhushan and N. H. Cook[9] developed a modified friction model for two mating spheres. They assumed that the contact takes place at the peak of the asperities. They stated the result of this model as, if the adhesion stress/shear strength of the weaker material is greater than 1.5 then adhesion has a strong influence on friction. It was, also, found that the coefficient of friction was independent of the load. This work gives the influence This paper gives the influence of friction for two different strengths of material, which is very relevant for this present work when rubber hardness variation was studied.

In 1986, Beucker[10] studied cross machine variations in the cover construction and surface contours. He investigated the length increase of rubber when used as the nip and stated that the surface speed of the metal roll was greater than the surface speed of the rubber roll.

He studied the speed differential with cover thickness and loading. Figures 2.5 & 2.6 show that the speed differential is dependent upon the hardness as well as on the loading and thickness. He said that the coefficient of friction is the parameter that is defined with the slippage between two different surfaces. In the present work, rubbers of different hardness and thickness have been used for nip rollers. Some of them are grooved, and it is interesting to note the results of speed differential for the five web materials used.

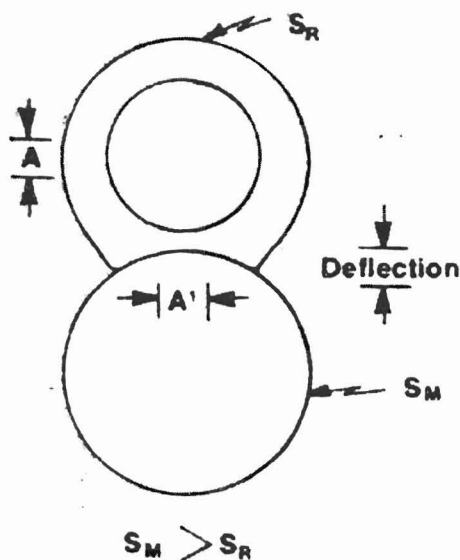


Figure 2.4: System of Rubber Deflection of Loaded Rolls studied by Beucker [10]

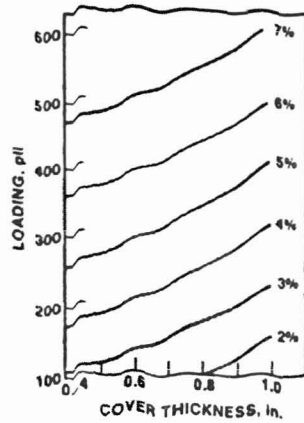


Figure 2.5: Speed Differential, as a function of Load and Cover Thickness[10]

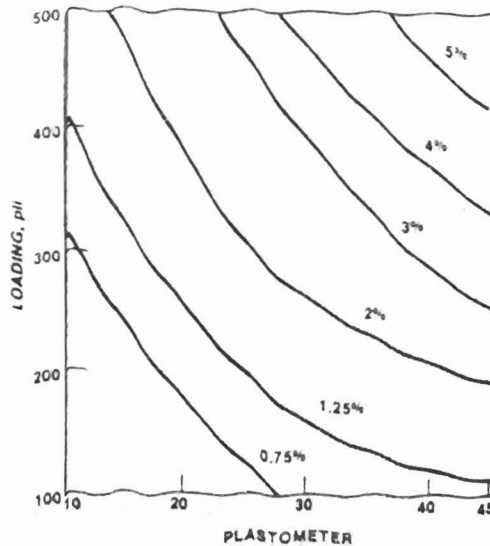


Figure 2.6: Speed Differential, as a function of Load and Hardness[10]

Good J.K.[11], documented some of the properties of rubber and also examined two dimensional algorithms that relate to both force and deformation of rubbers rolls in contact with other rolls. He found that Young's Modulus is highly dependent upon the Shore hardness and is independent of rubber type. He used the slope of diametral strain

versus the compressive strain data to estimate Poisson's ratio. It was found to approach 0.5 for rubber materials.

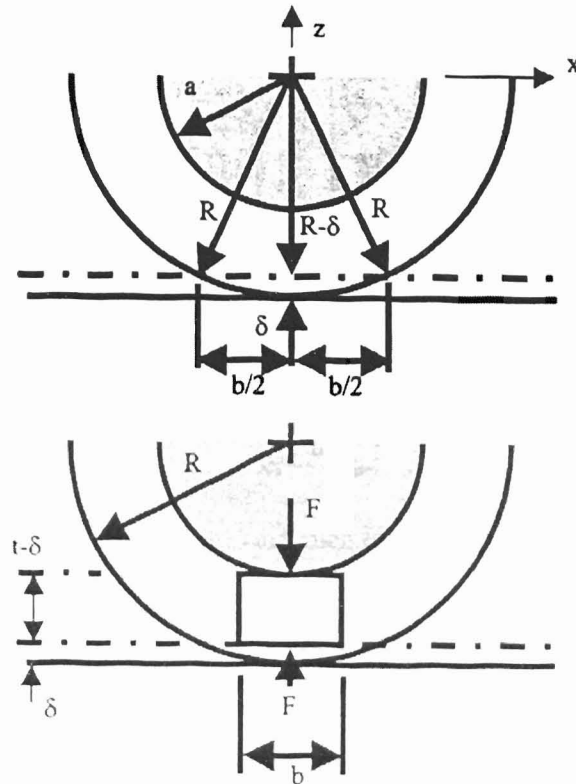


Figure 2.7: Definitions of Variables for Lindley's theory

Good modified the force/deformation relationship by accounting for the Young Modulus effect in Johnson's and Evan's expressions and they are

$$F = \frac{1}{3} \frac{(1-\nu)^2}{1-2\nu} \frac{E_o(1+kS^2)}{1-\nu^2} \frac{(2\delta)^{3/2} \sqrt{R}}{t} \quad \text{Equation(2.15)}$$

$$F = \sqrt{\frac{2}{R}} \frac{E_o (1 + kS^2)}{1 - \nu^2} \frac{2[R^2(1 + \nu) + a^2(1 - \nu)]}{(R^2 - a^2)} \delta^{3/2} \quad \text{Equation(2.16)}$$

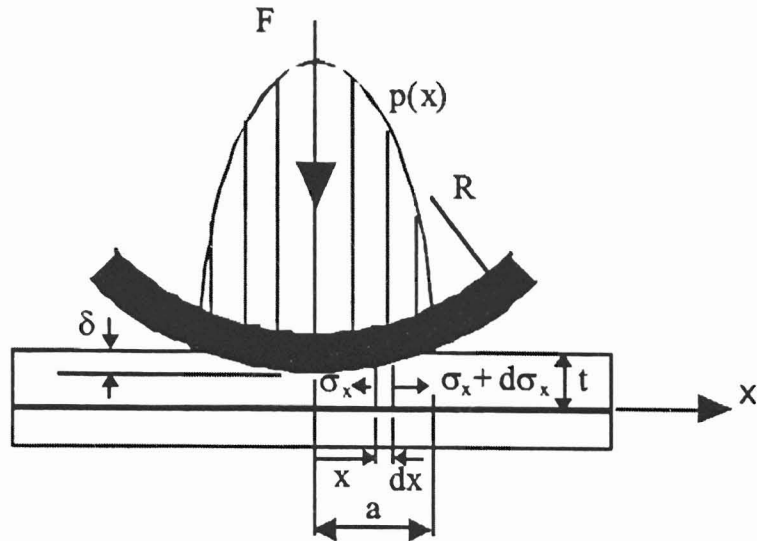


Figure 2.8: Definition of Variables for Johnson's Theory

Good found that the two dimensional force versus deformation relationships of Johnson and Evans appeared to be applicable up to strains of 6-7%, provided that the confinement of rubber is accounted for in the modulus.

It is important to be aware of past research on rubber covered nip rolls on wound rolls. Ning Cai[2] did a empirical study on the effect of nip roll compliancy upon center and surface winding. He calculated the nip load from the following equation

$$N = \frac{T_w * \sin \alpha_6}{\sin \alpha_1} + \frac{6.49 * F * \sin \alpha_4}{10.75 * \sin \alpha_1} \quad \text{Equation(2.17)}$$

Where:  $T_w$  = Web Line Tension

$F$  = Force due to gas pressure in the cylinder

$$L = \sqrt{6.25^2 + 1.75^2} = 6.49''$$



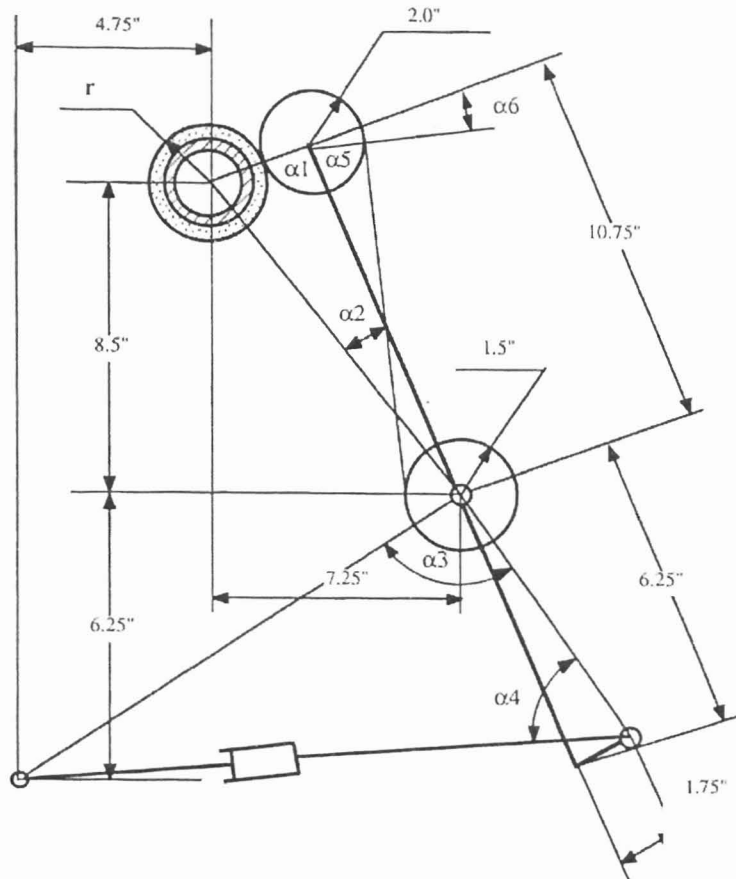


Figure 2.9: Drawing of Nip Roller Mechanics used by Ning Cai

He also developed a FORTRAN program to calculate the actual nip load applied on the web roll as a function of roll radius. Using the notion of web slippage over the nip roller, the surface winding was modeled as

$$WOT = \frac{\mu_{p-p} N}{h} + \frac{T_w}{e^{\mu_{a-p} \theta}} \quad \text{Equation(2.18)}$$

Where  $\frac{\mu_{p-p} N}{h}$  is nip induced tension

$\mu_{p-p}$  is the kinetic coefficient of the friction between paper and paper

$\mu_{a-p}$  is the kinetic coefficient of friction between paper and aluminum nip roller

$\theta$  is the angle of wrap around the nip roller, which is shown in Figure 2.10

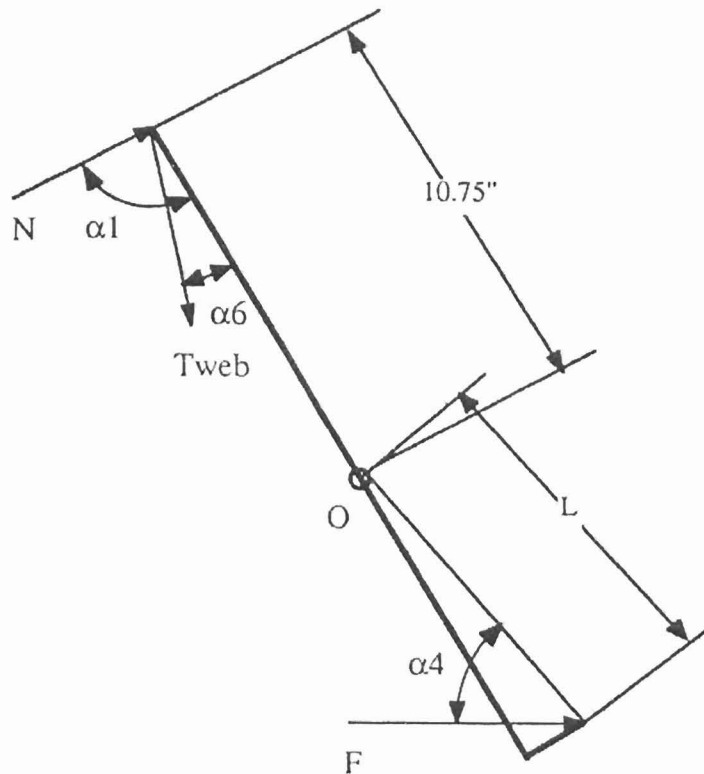


Figure 2.10: Simplified Mechanics of Nip Roller used by Ning Cai

Cai concluded that compliance of nip rollers has no effect upon the wound roll stress in center winding with an un-driven nip roller, and has minor effects to the wound roll stress in surface winding. As per the above equation, the coefficient of friction between surface driven roller and the web did affect the wound-on-tension than the nip compliancy. His study pertained to a low range of nip loads. He found

the WOT values to be almost the same for both a solid aluminum roll and solid rubber covered rolls, in both center and surface winding.

Kaya [3] in 1999 studied the WOT in surface winding for newsprint, using different types of nip rollers. He saw that the penetration of the rubber cover, due to the nip load, caused the web in the nip contact zone to speed ahead of the web. This increase in velocity resulted in slippage between the web and the surface driven roll. The friction forces added to the WOT. He concluded that, for a rubber covered nip roll, the wrap angle has an effect on WOT at high nip loads. At low nip loads, rubber covered nips behaved like a aluminum roller , since the nip load was not sufficient to deform the nip roller.

The difference of WOT for a 4” outer diameter aluminum and a rubber covered roller was more apparent at high nip loads and high wrap angle(180 degrees in his case) than the lower wrap angle ( 45 degrees in his case). Kaya concluded that this increase in WOT is due to the local speeding of rubber, which in turn caused the lengthening of rubber in the lateral direction. This is interesting from the point of view of the increase in WOT given by solid rubber rolls. So, the present research the rubber groove effects are studied, to give more evidence of the behavior of rubber.

Good[12], stated that the relative increase of velocity of a web moving through rubber covered rolls is approximately equal to the circumferential strain in the contact zone.

$$\frac{\Delta V}{V} = \varepsilon_{\theta\theta, \text{avg}} = \frac{\delta}{4t} \quad \text{Equation (2.19)}$$

where  $\frac{\Delta V}{V} = \frac{V_{\text{web}} - V_R}{V_{\text{web}}}$ ,  $\delta$  = the maximum deformation of the rubber covering  
and  $t$  = cover thickness.

The conclusion is that the penetration of rubber, due to the nip load especially at high nip loads, will cause the web in the nip contact zone to speed ahead of web. This speeding up of the web results in slippage between the web and nip roller, and friction forces add to the WOT. So, the radius of these rollers will increase from the original 4" and this increase in radius and local speeding causes the high WOT at high nip loads during surface winding. The effects are seen more obviously in surface winding than in center winding, as the wrap angle of surface nip roller would be sufficient to increase the WOT, due to frictional forces.

From the discussion above, WOT is dependent on nip load for metal surfaced nips and the evidence that rubber covered rolls can increase WOT if (1) they are significantly impinged and (2) the wrap angle of web about the nip roller is sufficient. The rubber covered rollers in contact with metal surface rollers have been proven to have a local increase in velocity in the contact zone which, Kaya[3] postulated to be the source of the additional WOT. The objective of this research is to determine the validity of Kaya's[3] postulate by comparing the WOT's measured using rigid metal surface nips and nips with solid rubber covered rollers, to covers with grooves and open cells that can allow the rubber to deform laterally without speeding up in the circumferential direction.

## CHAPTER 3

### EXPERIMENTAL SET-UP

#### 3.1 Winding Machine Description and Winding Conditions:

The winder at the WHRC lab is capable of winding webs in both center and surface winding modes. The web line tension and the nip load of the winder are held constant using closed loop controllers. The winder, also, has the capability of installing various nip rollers with various angle of wrap of the web about the nip roll. The WHRC winder has undergone several modifications in its set-up and control over the years.

The winder is shown in figure 3.1 with the various components labeled. The complete explanation of this experimental set-up has been given by Balaji[13]. In this work can give us more explanation of the winder components individually. In the present work, the thrust has been given more to the nip rollers and angle of wrap of the web around the nip roller.

**Nip Roller:** The nip rollers are used to apply nip load over the width of the roll being wound as seen in Figure 3.1. They are pivoted on a swing arm and held by two vertical columns and the whole compact structure of nip roller mechanism is mounted on linear guides. The nip rollers used for this research were Aluminum Shell roller, Rubber Covered rollers of hardness 30 and 62 Durometer Shore A, and Grooved Rubber Covered rollers of hardness 55,62 and 86 Durometer Shore A. A material with low Poisson' s ratio

(Polyurethane Foam) was used as a rubber cover to see the effect on the WOT. The Poisson's ratio of rubber was found to be 0.46 for rubber from the documentation of Good[12] on his work on modeling rubber covered nip rollers. The table 3.1 above gives information on the different rollers used for the experiments. The Figures A-2 and A-3 in the appendix shows the Grooved Rubber Covered roller B winding FCP. The rigid roll in this research work refers to the solid aluminum shell roll of 4" in diameter.

**Grooved Nip Rollers:** The rubber was grooved circumferentially and grooves were all of uniform width. The direction of the grooves were circumferential to remove air entrainment. All the grooves were vertical, and parallel to the end face of rubber covered roll. Grooves were spaced equally from each other.

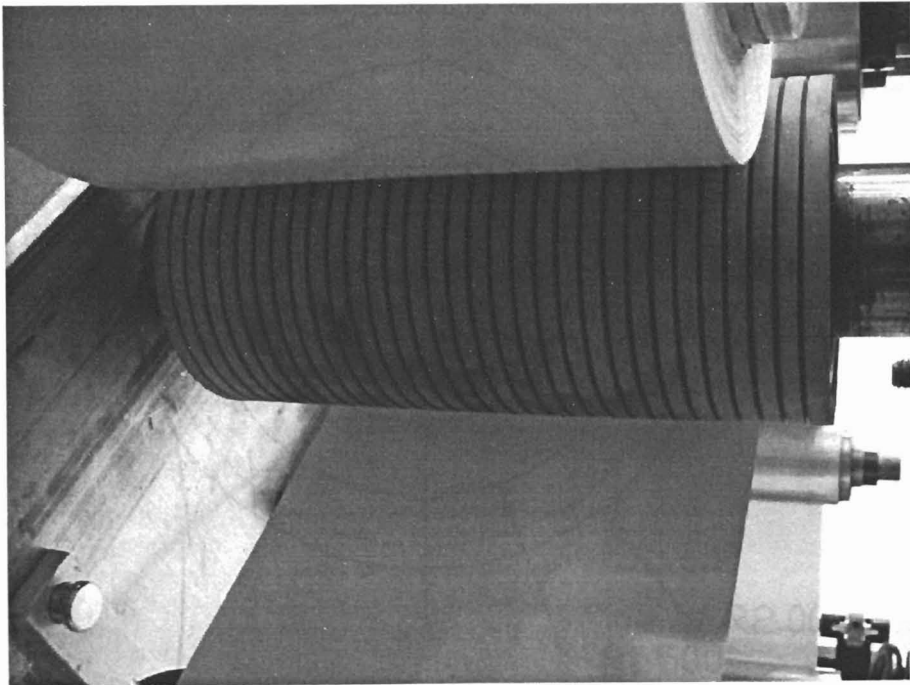


Figure 3.1: View of WOT Experiment with Grooved Rubber Roller B

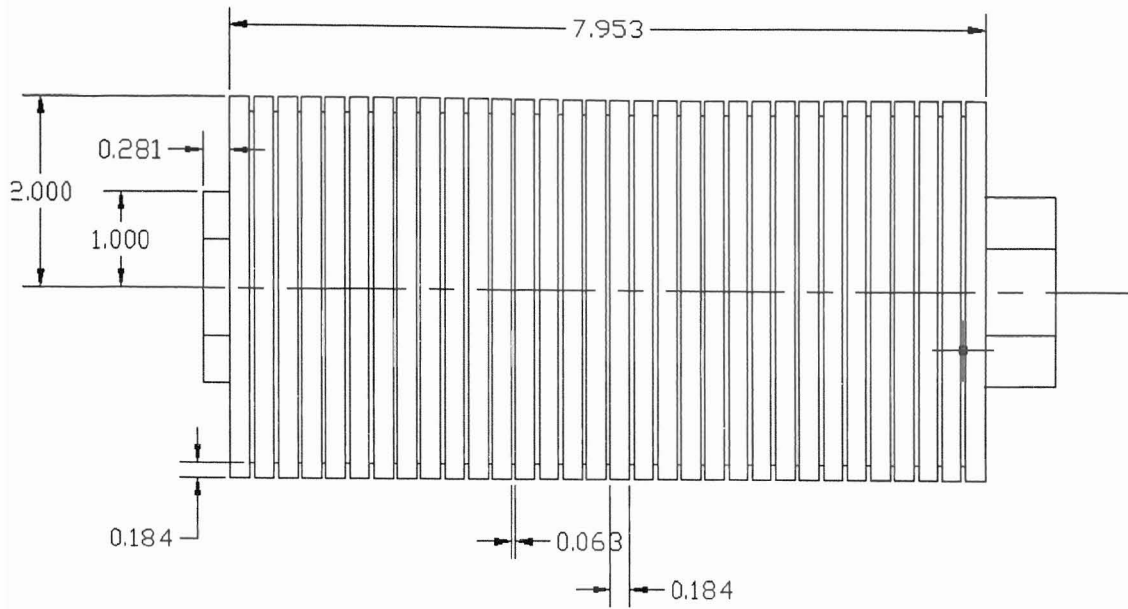


Figure 3.2: Front View of Grooved Rubber Roller G with all dimensions in inches

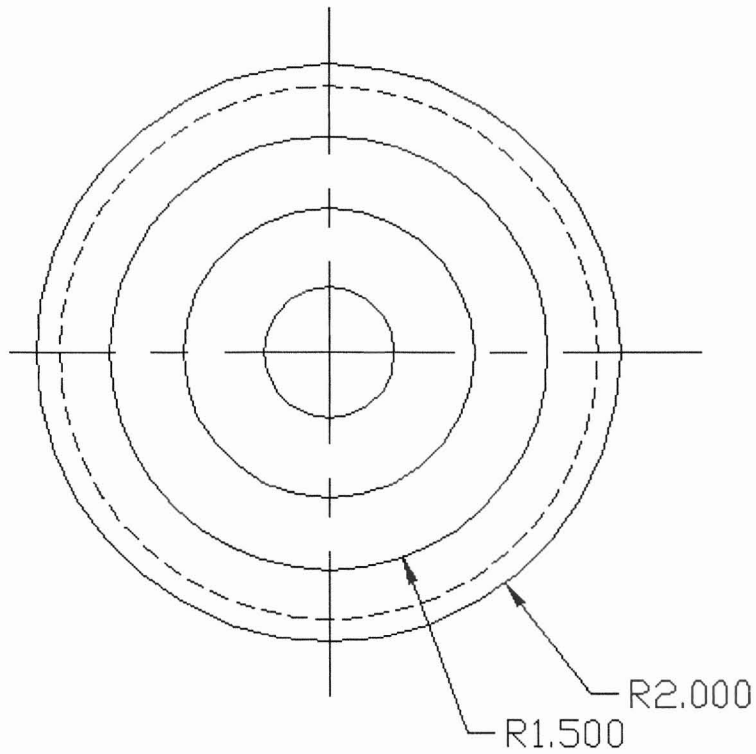


Figure 3.3: Right Side View of Roller G showing the radial thickness of rubber in inches

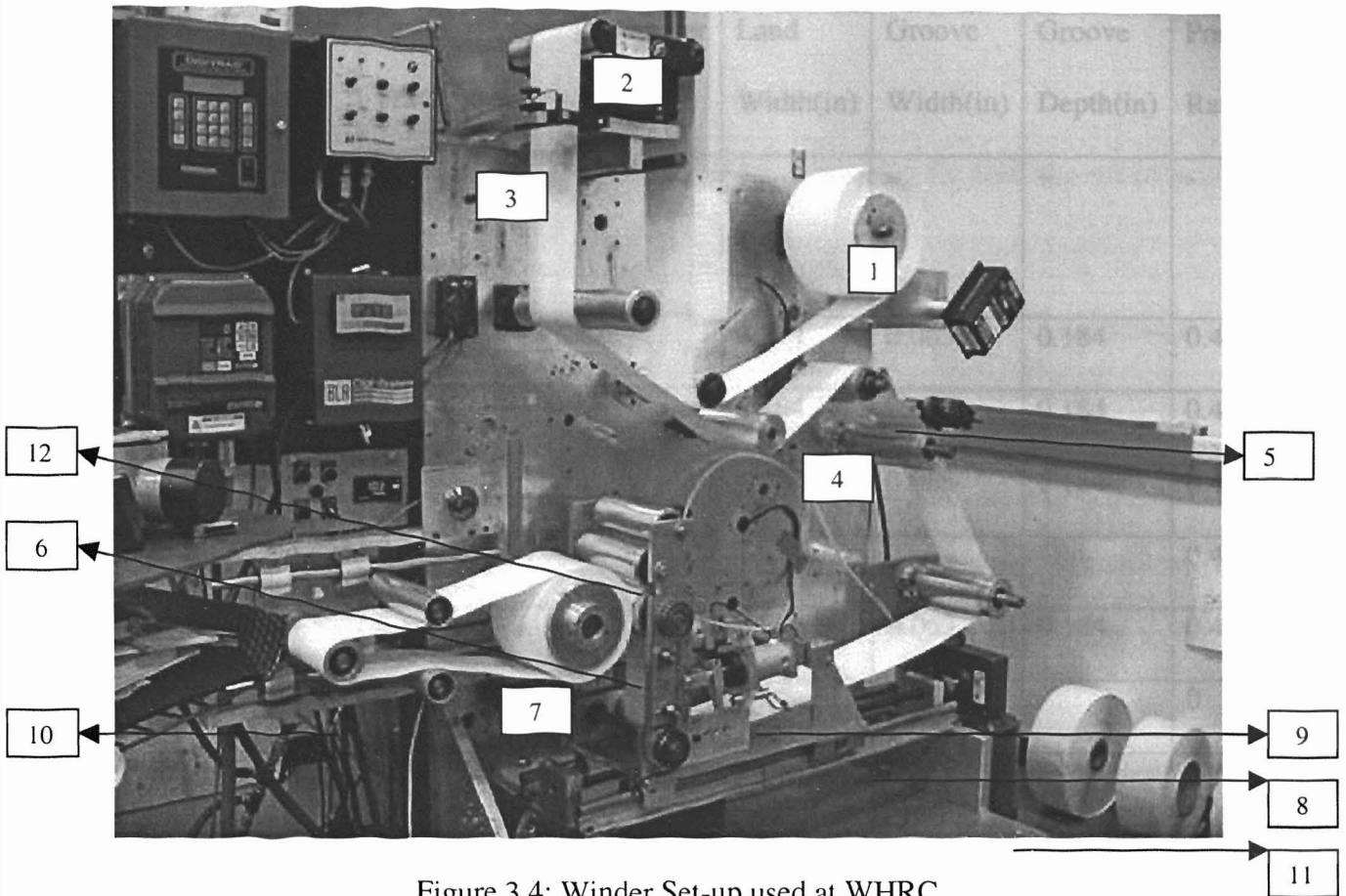


Figure 3.4: Winder Set-up used at WHRC

**Legends:**

- |  |                           |
|--|---------------------------|
| 1. Unwind Station                            | 7. Winding Station        |
| 2. Web Lateral Motion Guide                  | 8. Linear Guide ways      |
| 3. Infra red sensor for lateral motion guide | 9. Air Cylinder           |
| 4. Web Line Tension Feedback Roller          | 10. WOT Roller            |
| 5. Speed Comparator                          | 11. Stepper Motor         |
| 6. Nip Roller                                | 12. 45° Wrap Angle Set-up |



Nip Roll	O.D. (in)	Cover Thickness(in)	Durometer Shore A	Land Width(in)	Groove Width(in)	Groove Depth(in)	Poisson's Ratio
Rigid Aluminum Roll	4	-	-	-	-	-	-
Roll A	4	0.36	86	0.184	0.063	0.184	0.46
Roll B	4	0.49	55	0.184	0.063	0.184	0.46
Roll C	4	0.307	55	0.184	0.063	0.184	0.46
Roll F	4	0.5	62	-	-	-	0.46
Roll G	4	0.5	62	0.184	0.063	0.184	0.46
Roll H	4	0.5	12	-	-	-	0
Roll I	4	0.5	30	-	-	-	0.46

Table 3.1 Details of Different Rollers used for measuring WOT in WHRC Winder

**Angle of Wrap Adjustment:** Kaya's[3] results showed that an increase in WOT required a high nip load and a sufficient wrap of the web about the nip prior to the web being wound onto the winding roll. In the present research, two wrap angles were possible, 180° and 45°. The 180° wrap angle was obtained with the old Winding Machine Set-up. For the 45° wrap angle, two new idle rollers were mounted on top on the existing nip rollers to give a 45° wrap angle. The figure A-7 shows the winder with a wrap angle of 180° of web around the web and Figure A-8 shows us the modification made to the previous winder to achieve a 45° wrap angle of web.

### 3.2 Modulus of Rubber Covered Rollers:

The modulus of a rubber covered roller is estimated by the equation given below by Good[13].

$$E_{rr} = 26.54 * e^{0.0524*(hardness)} \quad \text{Equation 3.1}$$

where  $E_{rr}$  is Modulus of Rubber in psi

Hardness = IRHD Number = Durometer Shore A

He obtained this equation from the curve fit of experimentally measured modulus versus IRHD data for several different types of rubber. In this experiment Rubber Rolls of 86,55, 62,30 and 12 Durometer Shore A were used and their modulus are given in the table 3.2.

Nip Roll	Durometer Shore A	Modulus of Rubber(psi)
Roll A	86	2404
Roll B	55	474
Roll C	55	474
Roll F	62	684
Roll G	62	684
Roll H	12	50
Roll I	30	128

Table 3.2 Value of  $E_{rr}$  for Nip Rollers Used during Experiment

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Roll I	30	128

Table 3.2 Value of  $E_{rr}$  for Nip Rollers Used during Experiment

### 3.3 Web Thickness and Width:

The thickness of all the web materials were measured using a micrometer. A stack of 10 layers of web was prepared and the thickness of the web was measured at six different points along the width of the web. The thickness of each layer of web was thus calculated from the average values of these trials. Care was taken not to allow any air entrainment between the web while measuring the web thickness. This was done by sliding the webs, to remove air entrainment when stacked for thickness measurement. Also the web was held in a flat position to give accurate results. The width, which is very crucial in finding the pounds per inch of web line tension or nip load, was also measured and it is documented along with thickness in table 3.3.

Web Material	MFC	FCP	LWC	NEWS	SC
Thickness (in)	0.00260	0.00337	0.00167	0.00295	0.00185
Width (in)	6	6	6	6	5.4

Table 3.3 Thickness and Width of Various Web Materials

Where LWC is Light Weight Coated paper

MFC is Machine Finished Coated paper

NEWS is Newsprint

FCP is Fine Coat Paper

SC is Super Calendared

### **3.4 Web Materials Used and their Applications:**

The five paper grades used in this research were LWC, MFC, NEWS, FCP and SC. In this section the paper grades and their commercial applications are described.

**LWC:** Light Weight Coated paper delivers brightness, shade, opacity and cleanliness. It prints with a high gloss and excellent fidelity at lighter basis weights. This paper is used in magazines, catalogs and brochures where its light weight for postage is crucial.

**MFC:** The machine finish coated paper has one side rough and other side printable. This paper is mainly used in business forms. It is also used in tag stocks, hand peel label and catalogs.

**NEWS:** The main use for newsprint is newspapers, with smaller amounts being used for magazines, inserts, comics and general commercial printing. In some places, newsprint serves as a cheap general purpose printing paper like exercise books. Standard newsprint is printed mainly by offset and letterpress, but flexography is also increasing. It has less glossiness and brightness compared with other paper grades.

**FCP:** The fine coated paper is designed for applications like ink-jet printers, as it provides an economic alternative, which is especially suited to CAD type applications and graphic type images. It is also used in company brochures and stock reports. The FCP has a white glossy look and is the thickest of the paper grades used here.

**SC:** The super calendared paper has high sheen and smoothness. It is excellent for use in die-cutting applications. It has good strength and high apparent density. It is widely used in manufacturing tapes, labels and magazines.

### 3.5 In-Plane Modulus( $E_t$ ) Test:

A web 50-ft in length and 6” in width was constrained at one end by taping to the floor while the other end was attached to a 6” wide metal strip, with a hole in the middle to apply pull force using hand force gauge. On the metal strip side, a clean sheet of paper was taped to the floor adjacent to the web and the end of web was marked on this sheet. The web was pulled slowly and gradually for different pulling forces and the corresponding deflections were marked on the clean sheet of paper. The stress-strain graph was plotted and the value of in-plane modulus estimated from the slope of the curve. Tests were repeated thrice and average values of the modulus were recorded as the in-plane modulus of the web. The In-plane moduli of various web materials used are given in the table 3.3. An example plot of a stress-strain curve for newsprint is shown in Figure 3.

Web	LWC	MFC	NEWS	FCP	SC
$E_t$ (psi)	804680	830000	584050	909570	1145700

Table 3.4 Results of In-Plane Modulus Tests for Various Web Materials

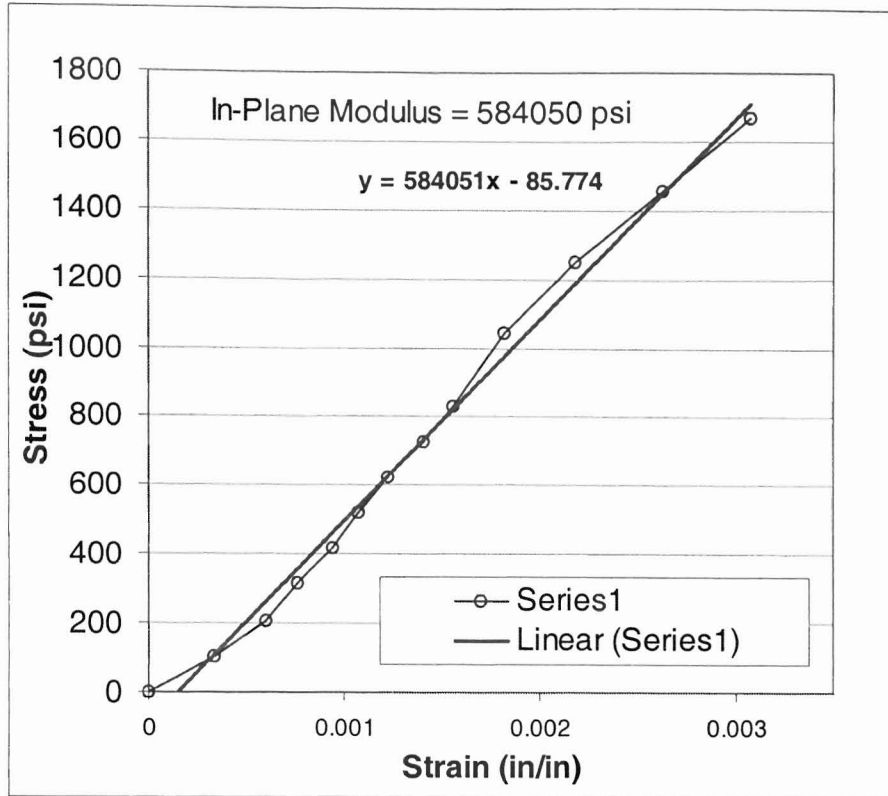


Figure 3.5: Stress-strain curve for Newsprint for in-plane modulus test.

### 3.6 Radial Modulus( $E_r$ ) Test:

The radial modulus( $E_r$ ) is another input parameter needed to study the pressure distribution inside the wound roll, using the mathematical models like Hakiel's[3]. Web samples were cut 6" by 6" and stacked 2" high. This stack was loaded on the Instron Material Testing Machine having platens of square cross section of  $7 \times 7(\text{in}^2)$ . The LabVIEW program controlled the application of load to the web stack from 0 to 200-psi pressure. The program recorded the pressure and strain values. The radial modulus and

pressure is given as input to MS Excel spreadsheet. The predicted pressure is obtained from Pfeiffer's Equation show in equation 3.2

$$P = K_1(e^{(K_2 \epsilon)} - 1) \tag{Equation (3.2)}$$

Web	$K_1$ psi	$K_2$
LWC	0.166	55.43
MFC	0.195	59.73
NEWS	1.803	27.49
FCP	0.397	182.57
SCA	0.5	77.129

Table 3.5: Coefficients of K1 and K2 in Pfeiffer's Equation

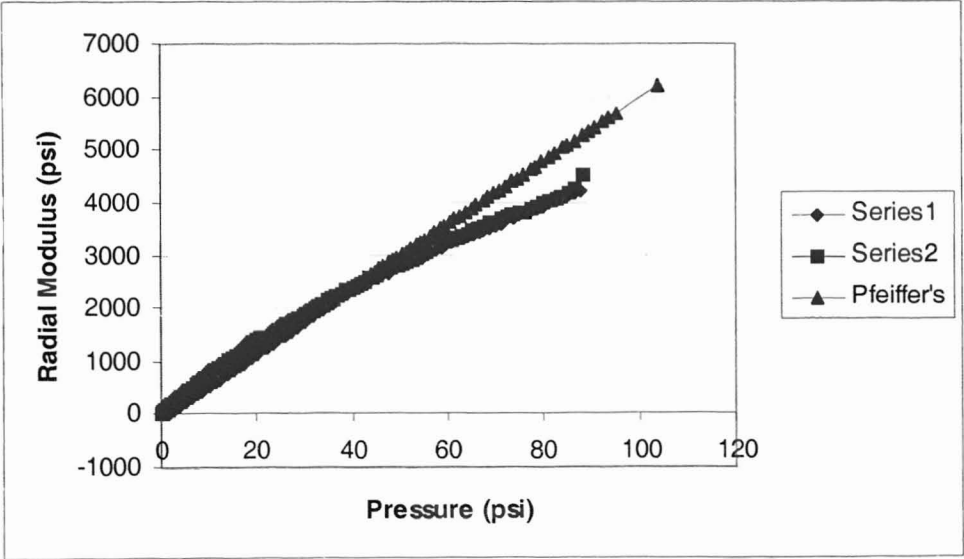


Figure 3.6: Radial Modulus of Elasticity for LWC



The absolute difference between the measured pressure, and predicted pressure is measured as error. The total error is obtained and minimized by iterating on  $K_1$  and  $K_2$  simultaneously. The Solver in MS Excel program is used to find  $K_1$  and  $K_2$ . The radial modulus of web is obtained from the equation

$$E_r = K_2(P + K_1) \quad \text{Equation (3.3)}$$

A plot of Radial Modulus of LWC and pressure is shown in Figure 3.4

### 3.7 Friction Tests:

The coefficient of friction between the different web materials over different rollers was measured in addition to web to web friction. The 4 inch aluminum roller was fixed at both ends, using bench vises as shown in Figure 3.4 and a piece of the web was wrapped around and a known weight of 10 pounds was hung from one end. The other end was attached to a force gauge.

The frictional force was measured by pulling at constant velocity about the roller. The tests were repeated thrice and averaged to find the kinetic coefficient of friction between the web and aluminum roller. The web to web friction was measured using the same setup by wrapping a layer of web around the roller and then repeating the test described above. The friction coefficients were determined using capstan expression. The results of the friction tests are summarized in the table 3.5. The capstan equation, which is used to find coefficient of friction, is given in equation 3.4

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad \text{Equation (3.4)}$$

where  $T_1$  and  $T_2$  are loads,  $\mu$  is coefficient of friction and  $\theta$  is Wrap Angle

Web	Rigid Aluminum Roll	Roll A	Roll B	Roll C	Roll F	Roll G	Web to Web
LWC	0.59	0.53	0.82	0.63	0.66	0.64	0.34
MFC	0.35	0.51	0.87	0.67	0.67	0.65	0.33
NEWS	0.22	0.49	0.75	0.91	0.64	0.67	0.16
FCP	0.38	0.51	0.34	0.35	0.49	0.46	.36
SCA	0.27	0.49	0.56	0.78	0.54	0.66	0.34

Table 3.6: Coefficient of Friction of Various webs on Different Rollers and web

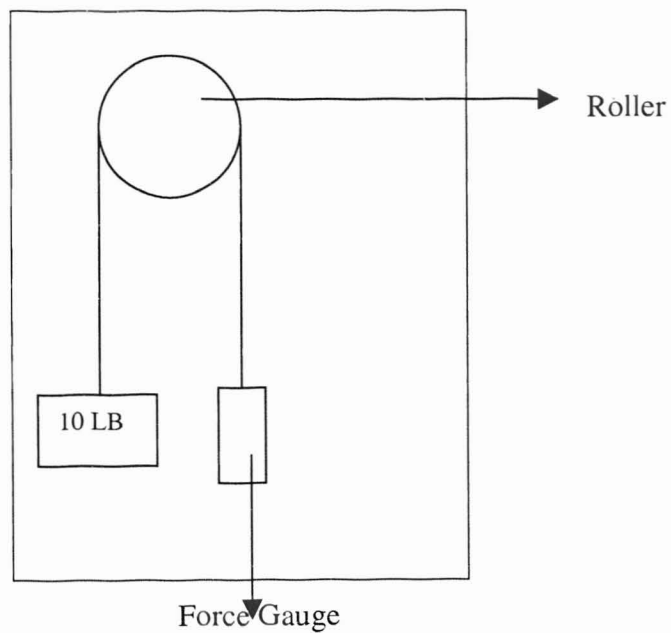


Figure 3.7 Friction Measurement Test

## CHAPTER 4

### EXPERIMENTAL RESULTS AND DISCUSSION

#### **4.1 Wound-on-Tension dependency on Wound Roll Radius and Nip Load Sequence:**

The WOT was measured by a two stage testing process in which WOT was directly observed using the WOT load cells in one stage and inferring WOT from pull-tab measurements in another case. In this thesis WOT was measured using the Interfering Method using the load cells.

In the sets of experiments done so far with the seven different type of nip covers and various web types, the value of WOT values were independent on the wound roll radius, so the value of the WOT was averaged for each nip load.

The WOT appeared to be independent of wound roll radius, while nip load was held constant, an example of which is shown in Figure 4.1. The nip load was increased during experiments performed with the urethane foam covered roller (Roll H). This was done because the behavior of Roll H was just the opposite of the other rolls as nip load increased the WOT decreased, as shown in Figure 4.2. The nip load was always decreased from highest value say 33.3 to 25 to 16.7 to 8.3 pli. This was done to prevent internal roll slippage during winding which can lead to erroneous WOT measurement.

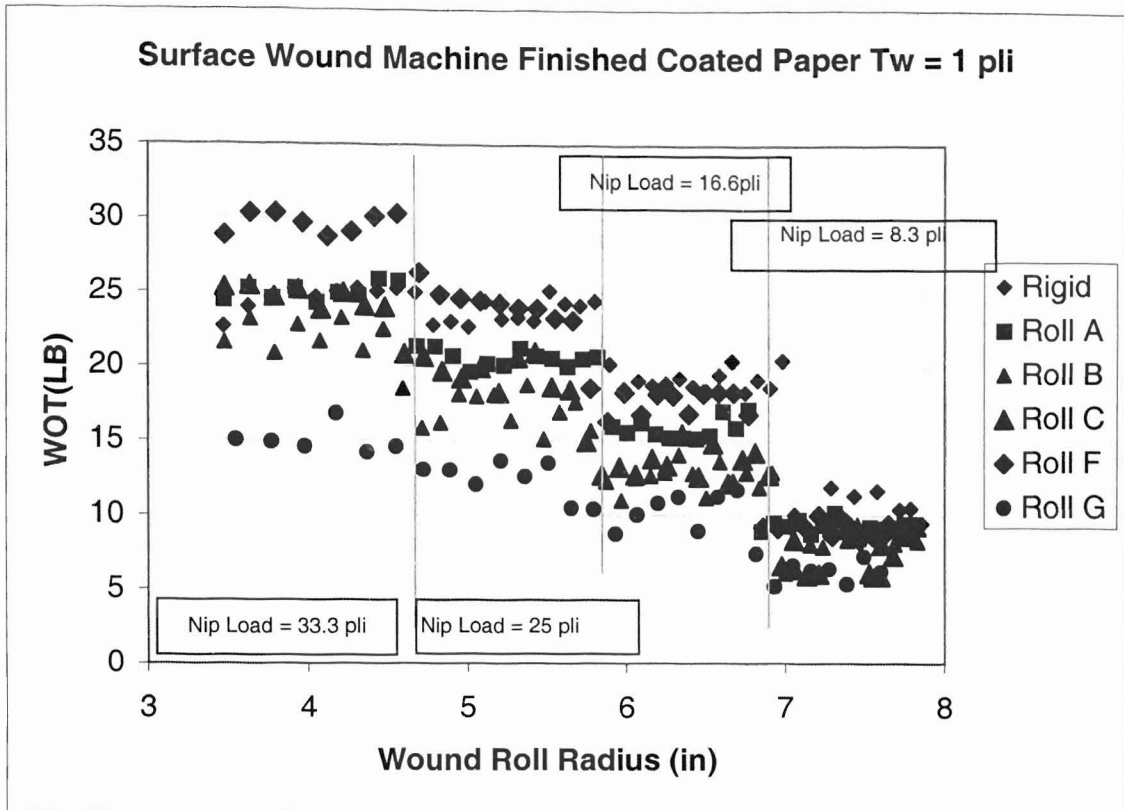


Figure 4.1 Effect of Wound Roll Radius on WOT for Surface Wound MFC Paper with Different Rollers

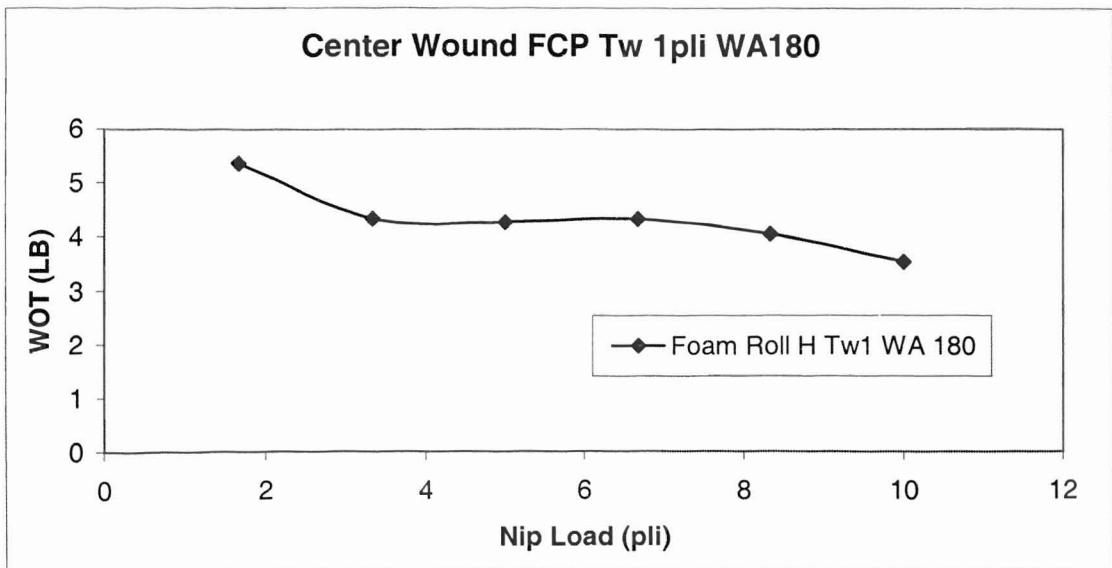


Figure 4.2 Center Wound FCP showing the Decreasing WOT with Increasing Nip Load

Figure 4.3 is the error bar plot for surface wound LWC at 1 pli web line tension for four nip load sequence. From the plot we can say 95% confidence level and the tests are highly repeatable. Another plot for surface wound MFC at 1 pli web line tension is given the Figure A.9. This plot also gives 95% confidence level.

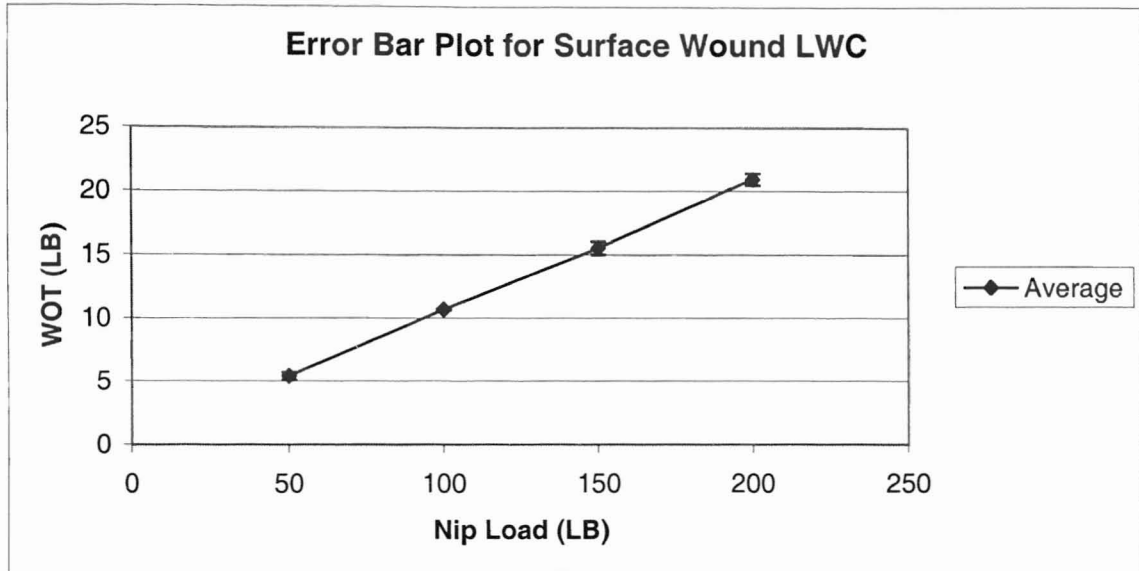


Figure 4.3 Error Bar Plot for Surface Wound LWC with 95% Confidence level.

#### 4.2 Angle of Wrap Dependency:

The effect of angle of wrap of the web about the nip roller on WOT was studied with the various rolls including rigid aluminum and solid rubber rollers. The wrap angles used in these experiments were  $180^\circ$  and  $45^\circ$ . The first set of results are shown in Figure 4.4 and are for the machine finished coated paper which was surface wound at Web Line Tension of 1 pli with the rigid roll and roll F at  $180^\circ$  and  $45^\circ$ . From the results, it is shown that the WOT values are dependent on wrap angle of both the rigid and un-grooved rubber cover(roll F). It is seen from the plot that the value of WOT is

lower for lower wrap angle  $45^\circ$  than for the higher wrap angle  $180^\circ$ , for the same winding and nip roll conditions. The effect of wrap angle is seen more at higher nip loads than at lower nip loads in these test results.

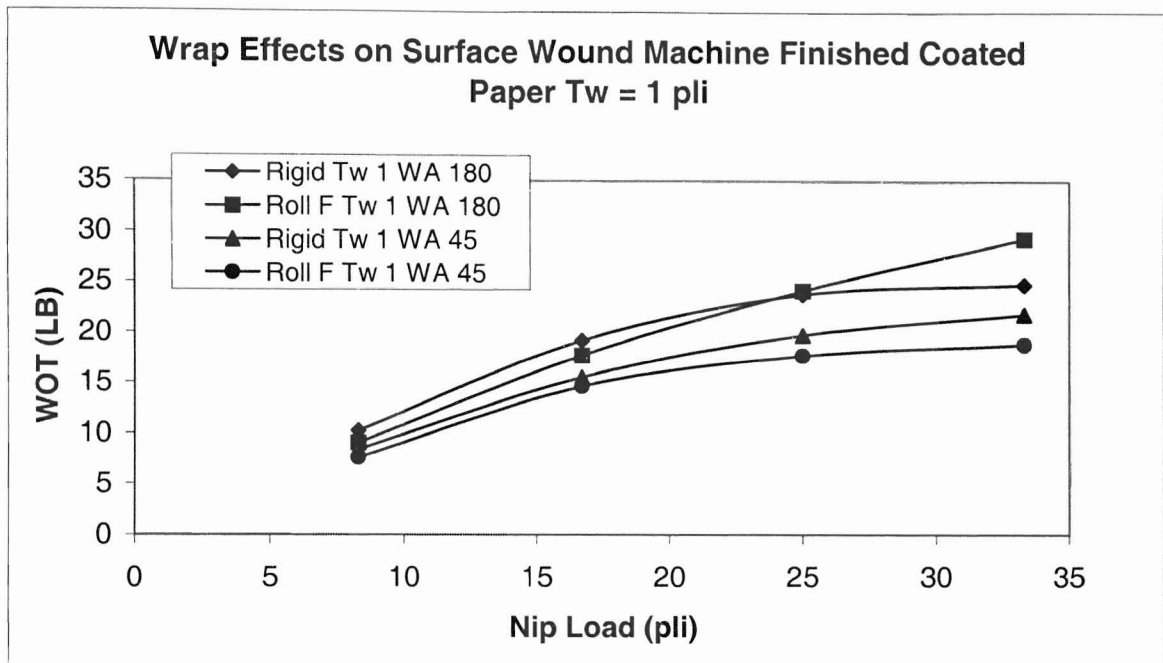


Figure 4.4 Wrap Effects on Surface Wound Machine Finished Coated Paper at  $T_w = 1 \text{ pli}$

The same rollers were tested for wrap angle dependency for same surface winding conditions and rollers but for a higher web line tension of 3 pli. The results are shown in the Figure 4.5. From the plots, WOT is seen to have dependence of wrap angle, but now the WOT dependence on Wrap Angle is less. Again, this plot shows the wrap angle has larger effect at higher nip loads

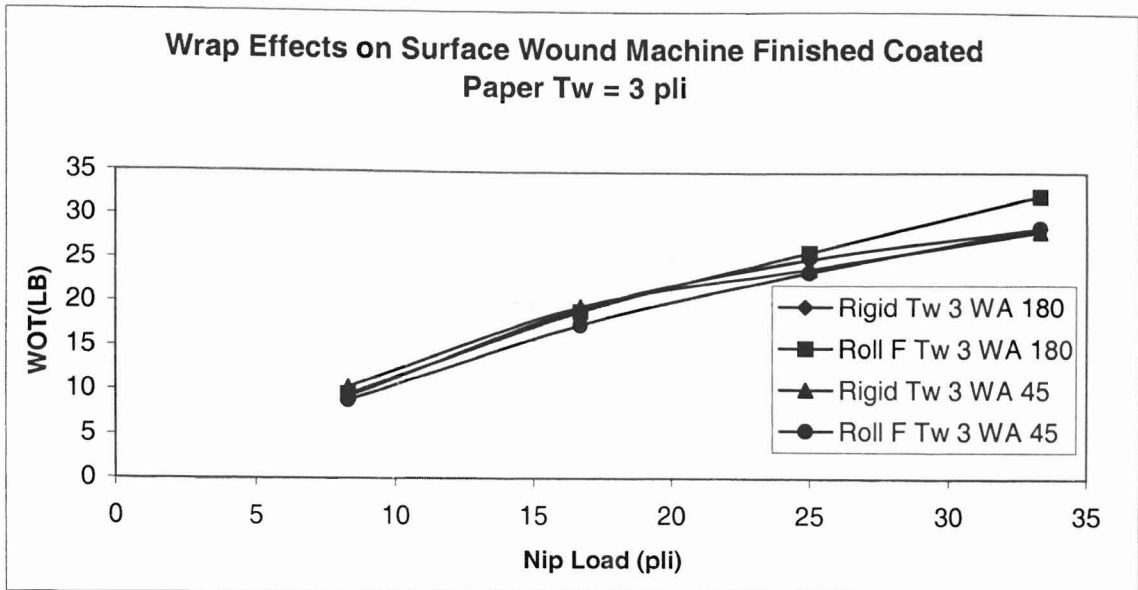


Figure 4.5 Wrap Effects on Surface Wound Machine Finished Coated Paper at  $T_w = 3$  pli

Figure 4.6 shows the results for MFC paper center wound at 3 pli web line tension, with a rigid, un-grooved roller(Roll F) and grooved roller(Roll G). The value of WOT is lower for lower wrap angle and higher for higher wrap angle throughout the nip load sequence. The most significant impact of wrap angle on WOT was noted for the un-grooved rubber roller. It appears the paper speeds up with the rubber cover in the contact zone, which requires the web on the nip roller to slide, which results in frictional forces which increase the WOT. The increased angle of wrap generates additional friction forces and hence higher WOT. If the difference is significant, this is interesting because Kaya's[3] work was all surface winding.

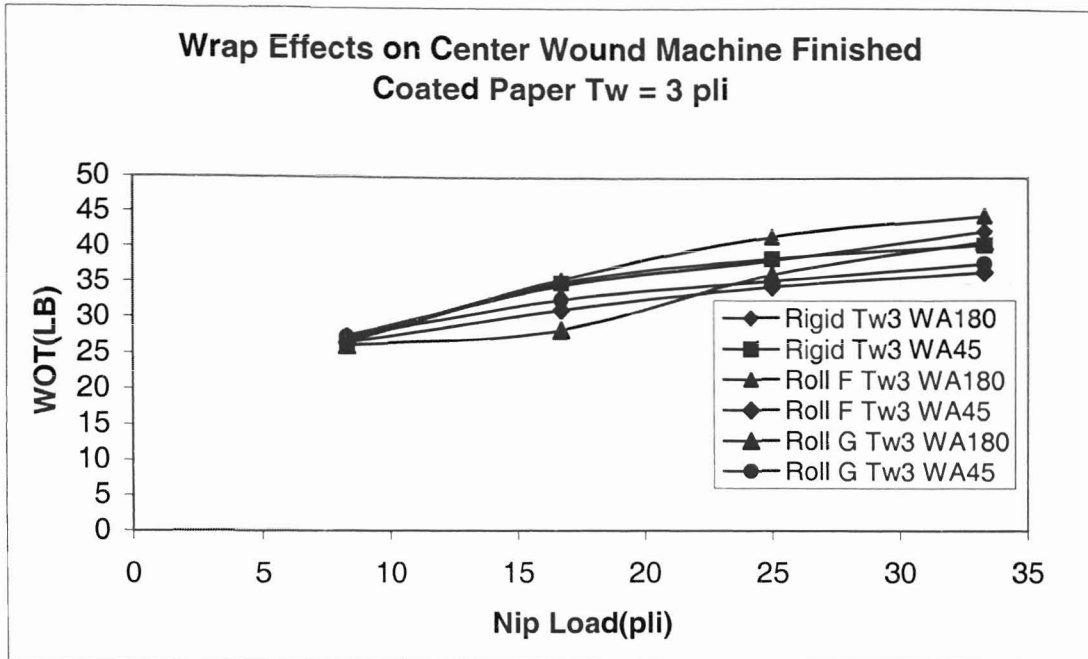


Figure 4.6 Wrap Effects on Center Wound Machine Finished Coated Paper at

$$T_w = 3 \text{ pli}$$

The rigid roller was used to study the effect of wrap angle during center winding at different web line tensions. The rigid roller was run with machine finished coated paper for two web line tensions 1 and 3 pli, and two wrap angles  $180^\circ$  and  $45^\circ$ . The results are shown in Figure 4.6, It was found that wrap angle had no impact on WOT, when center winding with rigid rollers. This agreed with the previous research work of Kaya[3]. He found that the aluminum roller exhibited no effect of wrap angle on WOT at any nip load.



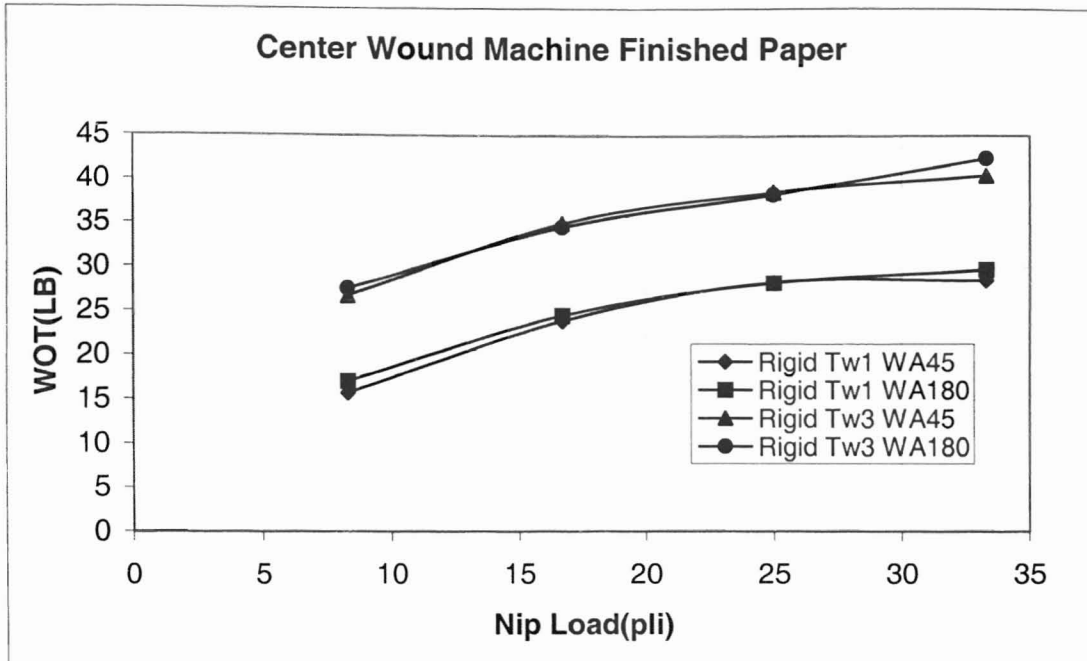


Figure 4.7 Wrap Effects on Center Wound Machine Finished Coated Paper for Rigid Aluminum Roller

Results of center wound machine finished coated paper at both 1 and 3 pli web line tensions with  $45^\circ$  and  $180^\circ$  wrap angle are shown in Figure 4.8. Note from the plot that for 1 pli web line tension, the WOT values are the same for rigid and rubber covered roller (Roll F) at lower nip loads of 8.3 and 16.7 pli. at higher nip loads of 25 and 33.3 pli, the rubber covered roller produces higher WOT compared with the rigid aluminum roller. The same behavior is observed with 3 pli web tension where the WOT values are high at higher nip loads for Roll F when compared to the rigid Aluminum roller. The WOT values were lower for lower wrap angle  $45^\circ$  and higher for higher wrap angle  $180^\circ$  at all nip loads. This behavior is seen even at higher web line tension of 3 pli.

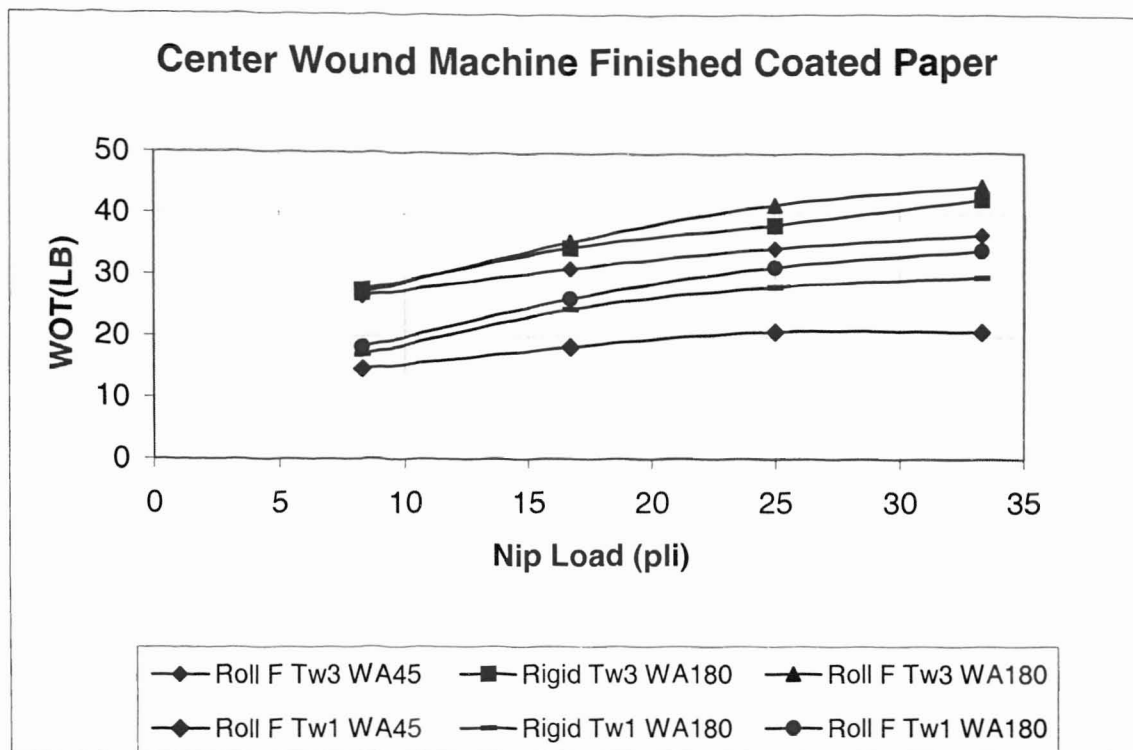


Figure 4.8 Variation of WOT at High Nip Loads for Rubber Covered Roll F with Rigid Aluminum Roll and at Different Wrap Angles 180° and 45° during Center Winding.

**4.3 Web Material Effects:** The impact of these rubber covered rollers on WOT was studied for several web materials. While winding them in surface winding at 1 pli web line tension, the materials (including MFC, LWC, SC and News) produced a WOT behavior which was consistent for web materials. For all the curves in Figure 4.9, for a given material, the value of WOT is almost same for both rigid aluminum roll and un-grooved rubber roller (Roll F) at low nip loads of 8.3 and 16.7 pli. This is seen for all materials. At higher nip loads, the Roll F produces a higher WOT when compared with the Rigid Aluminum Nip Roll for all the web materials. This provides evidence that this WOT behavior occurs for several web materials.

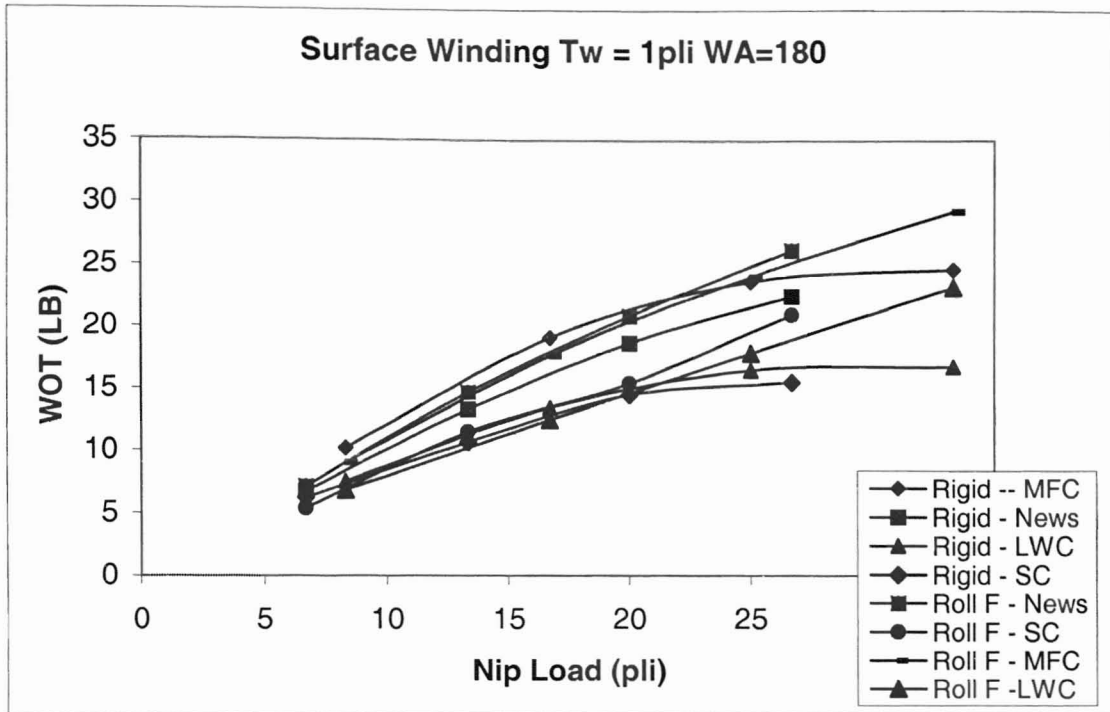


Figure 4.9 Surface Wound Results for 4 Paper Grades for Rigid Aluminum Roll and Un-Grooved Rubber Roll ( Roll F ) at 1 pli Web Line Tension and 180° wrap angle

Web line tension and nip load can be very high in the real time factory conditions. To study a high web line tension and nip load with center wound nip rollers, like rigid aluminum and un-grooved rubber roll(Roll F ), materials such as machine finished coated paper and fine coated paper were required, as they had high breaking strengths. Tests were run at 180° wrap angle and 3 pli web line tension. The FCP results shown in Figure 4.10 are superimposing well and the MFC results are similar. At high web tensions and perhaps high web/rubber friction coefficients, the rubber cover has little impact on WOT.

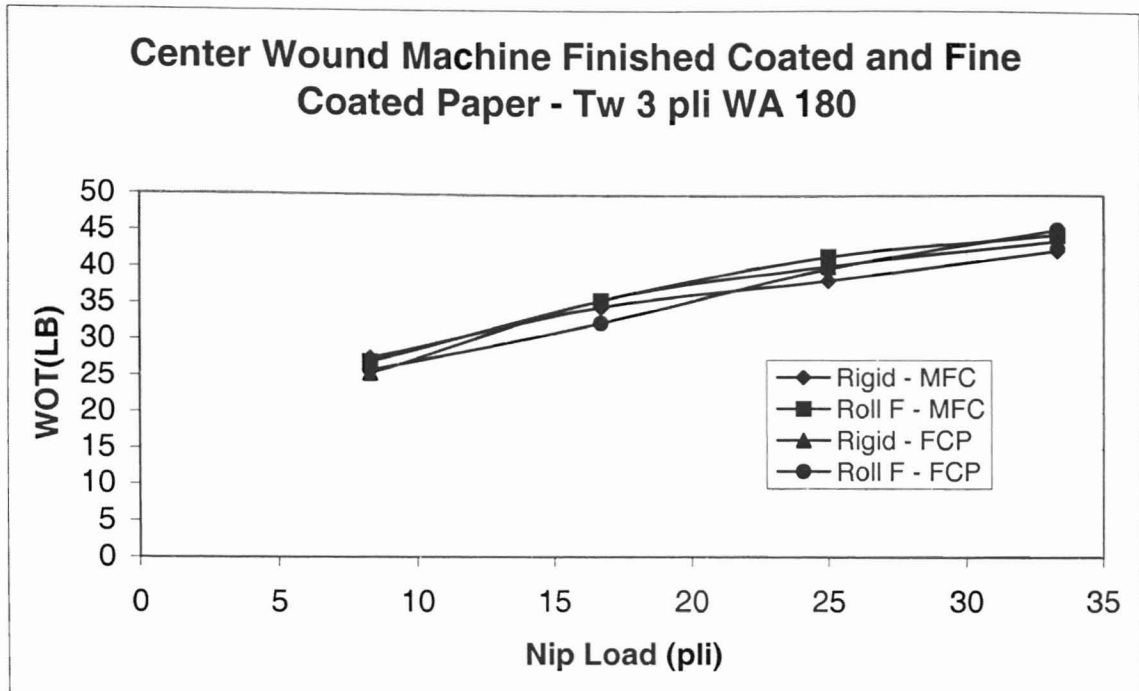


Figure 4.10 Variation of WOT at High Nip Loads for Center Wound MFC and FCP at 3 pli Web Line Tension and 180° Wrap Angle

**4.4 Impact of Grooves, Cover Thickness and Hardness:** Kaya[3] reported in his research work that at high nip loads, the WOT was higher at higher nip loads for the 4” 30 Durometer Rubber Covered Roller than with 4” Rigid Aluminum Roller, for surface winding. Similar behavior was seen in the experiments done in this research with rubber covered rolls with no grooves.

The experiments and results of the grooved rubber covers and solid rubber covers for surface wound MFC at 1 pli Web Line Tension and 180° wrap angle are shown in Figure 4.11. In the plot, the un-grooved roller (Roll F) produces higher WOT at higher

nip loads. Whereas, the grooved rollers A, B, C and G are producing lower WOT at all nip loads when compared with both Rigid Aluminum roller and Un-grooved Rubber Roller. The dimensions and properties are given in Table 3.1. In Table 3.1, note that Roll A is the grooved roller with highest hardness and it is seen as giving the WOT highest among the grooved rollers for all nip loads.

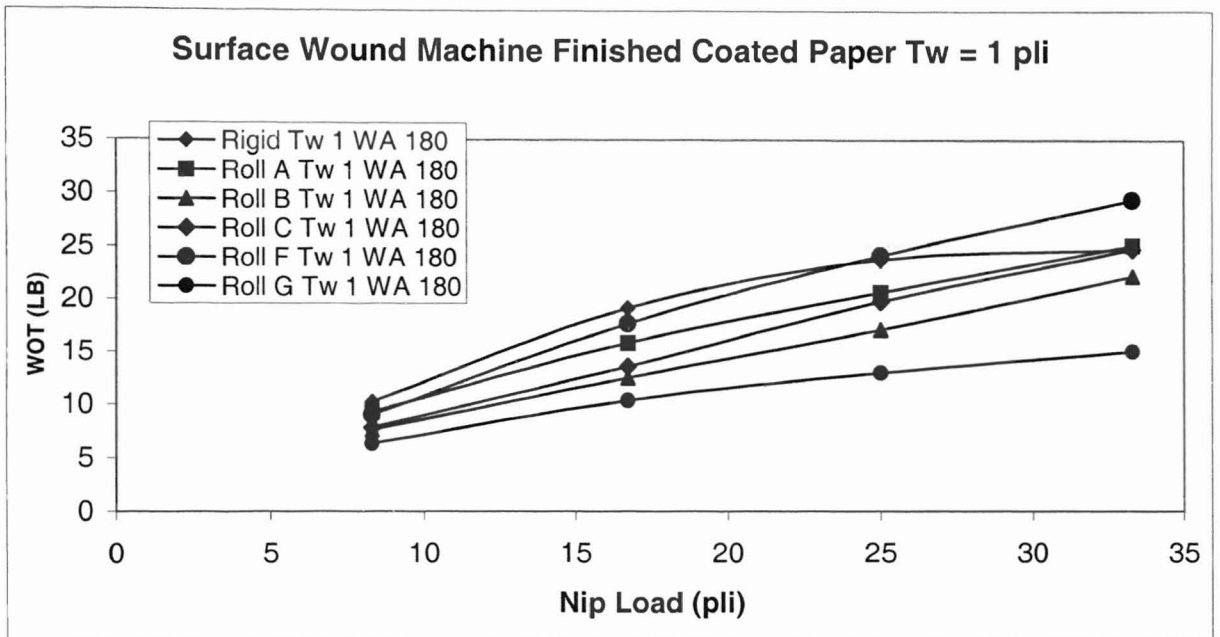


Figure 4.11 Variation of WOT for Surface Wound MFC at 1 pli Web Line Tension and

180° Wrap Angle

The only difference between the Roll B and Roll C is that the rubber thickness of Roll B is higher than Roll C, and every other property like hardness and dimensions of land width and groove width are the same. Roll B yields lower WOT at all nip loads when compared with Roll C. Thus, the thickness of the grooved rubber roll also

influences the WOT value. The Rolls F and G are the ones with same hardness and G is the grooved roller, and F is one without grooves. From the plot of WOT values from Figure 4.11 it is clear that Roll G yields lower WOT values when compared with Rigid Roll or the Un-grooved Roll F at all nip loads.

The grooved rubber covers were then studied at a higher web line tension of 3 pli for surface winding. The results from these set of experiments were consistent with WOT behavior at 1 pli web line tension. From the plots in Figure 4.12, it is shown that the grooved rollers yield lower WOT values for almost all nip loads and at higher nip loads the grooved rollers yield lower WOT than the un-grooved rubber roller.

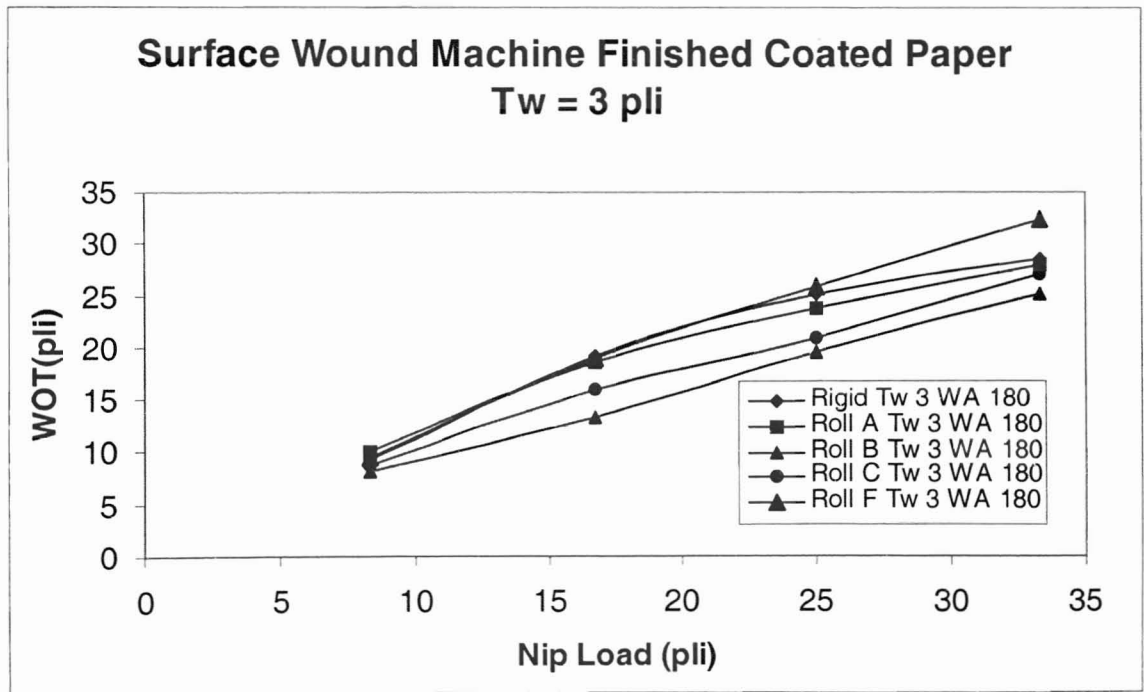


Figure 4.12 Variation of WOT for Surface Wound MFC at 3 pli Web Line Tension and

180° Wrap Angle

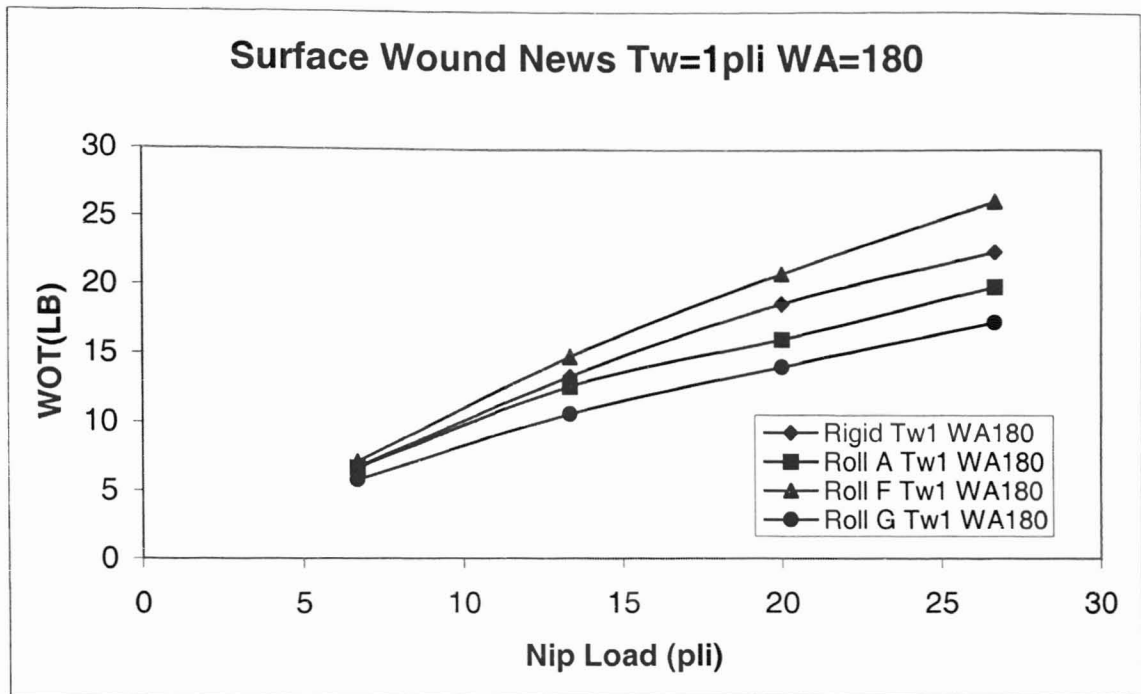


Figure 4.14 Variation of WOT for Surface Wound News at 1 pli Web Line Tension and 180° Wrap Angle

**4.5 Study of Foam Roller on WOT Behavior:** A material with low Poisson's ratio (Polyurethane Foam) was used as a rubber cover to see the effect on the WOT. While center winding with Foam Roller H at 1 pli web line tension and wrap angle of 180°, the WOT was found to decrease with increasing nip load. The plot is shown in the Figure 4.15 and in these experiments the nip load increased during the test. The highest WOT was observed with lowest nip load. This was done to eradicate the slippage of wound roll and interference of slippage on WOT measurements. The results shown in Figure 4.15

may be quite useful for webs which must be wound with a nip to disclude entrained air but where low WOT is required to prevent defects.

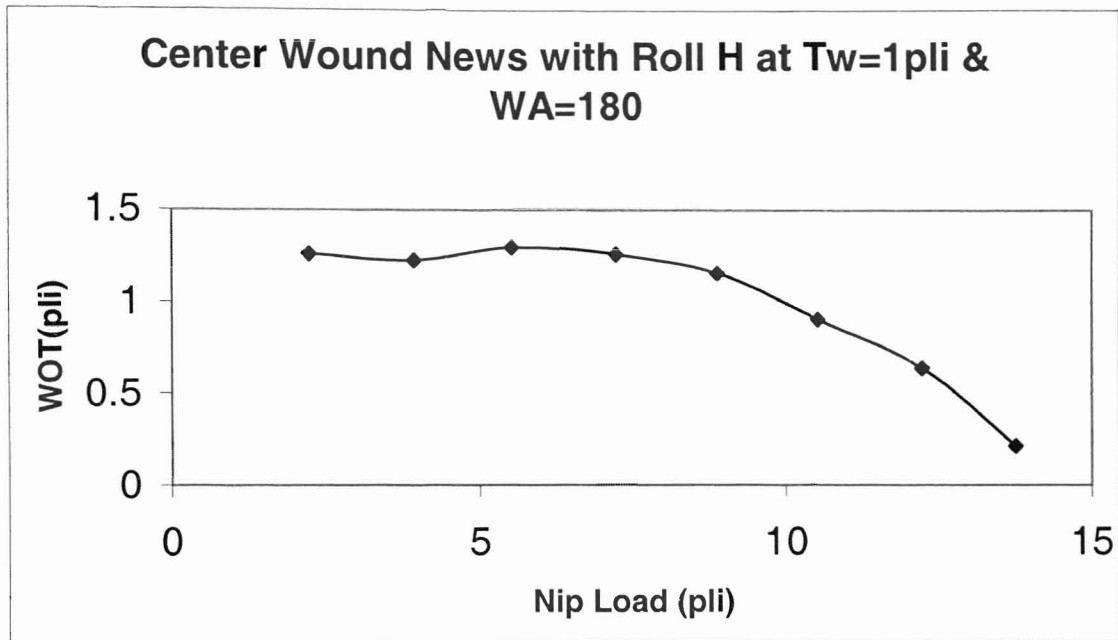


Figure 4.15 WOT Plot for Foam Roller H for Center Wound News at 1 pli Web Line Tension and Wrap Angle  $180^{\circ}$ .

The cover of Roll H was quite soft (Shore A 12) and was a urethane foam rubber and Roll I was a urethane rubber with a 30 Shore A. Results of winding tests with these rollers and the rigid roller are shown in the Figure 4.16. It appears Poisson's ratio of the nip roller is quite important in determining the WOT.



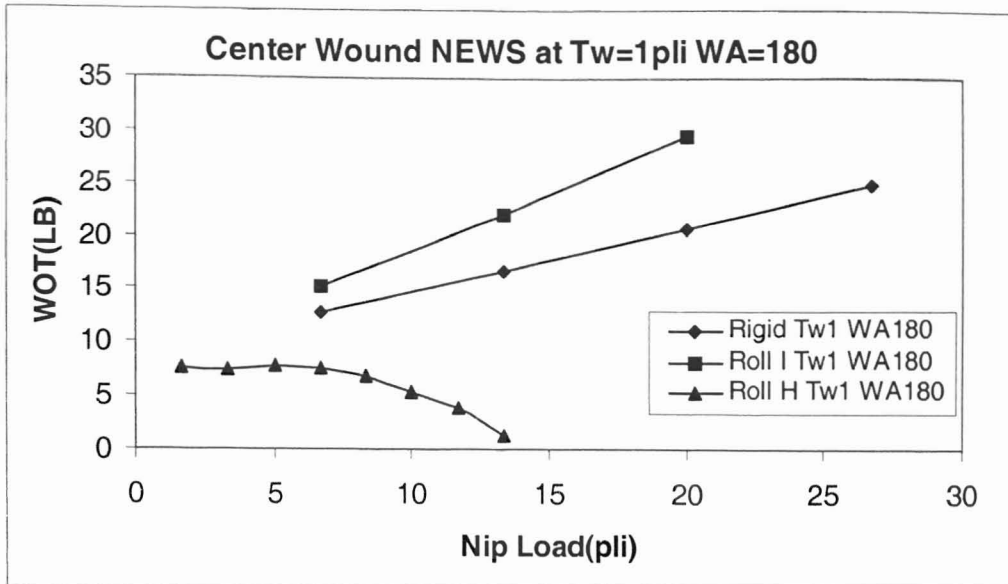


Figure 4.16 WOT Plot for Center Wound News at 1 pli Web Line Tension and Wrap Angle  $180^{\circ}$ .

**4.6 Discussion:** In this research work it was found that at high nip loads the solid rubber covered nip rollers produce higher WOT than for similar solid aluminum rollers, whereas the grooved rubber rollers produced WOT lower than the solid aluminum roller. Also, a study of foam seems to be interesting as they have the very different behavior of decreasing WOT with increasing nip load.

In this work, the grooved rubber covers were studied for their effect on WOT and Rubber covers with voids(Urethane Foam) were also studied. From the results it is seen that grooved rollers of high durometer produce WOT comparable to rigid rollers. Grooving of low durometer covers appears to successfully prevent the velocity increase of the rubber in the contact zone. Poisson's ratio of the cover appears to be quite important in determining WOT behavior as a function of nip load. For the

rubber foam cover WOT was nearly independent of nip load from 0-7 pli after which the WOT declined.

## CHAPTER 5

### CONCLUSIONS & OBSERVATIONS FOR DESIGN

#### 5.1 CONCLUSIONS:

Conclusions have been drawn from the experiments done with various rollers and web materials at different running conditions. They are:

1. At high nip loads solid rubber covers can produce WOT higher than that produced by a rigid roller. This behavior confirms the postulate of Kaya[3] given in his research work.
2. Also this higher WOT is achieved by using high wrap angles of the web around the rubber covered nip rollers. Low wrap angle produced the same or less WOT than that produced by rigid nip roll. Kaya[3] too observed that the higher wrap angle combined with high nip load produced higher WOT.
3. The increased web line tension decreases the amount of WOT that can be gained by using solid rubber cover.
4. Grooved Rubber Nip Rollers can produce WOT less than the Rigid Nip roll at all nip loads. Grooved rollers of high durometer produce WOT comparable to rigid rollers. Grooving of low durometer covers appears to successfully prevent the velocity increase of the rubber in the contact zone.
5. Grooved roll cover of higher thickness can produce lower WOT when compared with grooved roll cover of same durometer.

6. Grooved roll cover of higher durometer can produce higher WOT when compared with grooved roll cover of same thickness.
7. Poisson's ratio of the cover appears to be quite important in determining WOT behavior as a function of nip load. The urethane rubber foam cover has a Poisson's ratio close to zero and the WOT was nearly independent of nip load from 0-7 pli after which the WOT declined.

## **5.2 OBSERVATIONS FOR DESIGN:**

Nip rolls are often grooved to provide vents for entrained air. This study shows grooving rubber rolls can significantly decrease the WOT. If both venting and high WOT are desired. The width of the rubber between grooved should be set high enough to achieve plane strain conditions. If low WOT is desired a urethane foam roller should be considered.

## **FUTURE WORK**

The control of WOT has often been a big problem in Web Handling Industry, so the usage of rubber rollers and grooved rollers can be helpful in deciding the WOT so that nip rollers can be designed based on the need. and this capability can be incorporated in the WINDER to analyze soft roll covers.

The study of low Poisson's ratio covers gives us new interesting behavior and this can be extended with studying more covers of low Poisson's ratio with varying hardness levels and structure of grooved rolls can be studied more to know the impact of land width of the grooves on WOT.

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## **APPENDIX A**



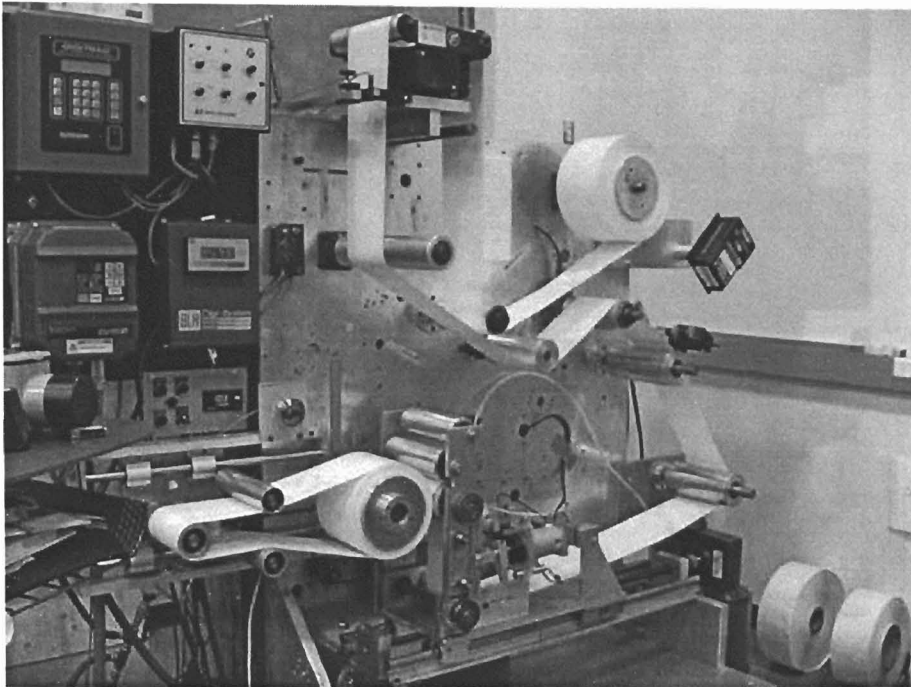


Figure A-1: WOTM Machine at WHRC

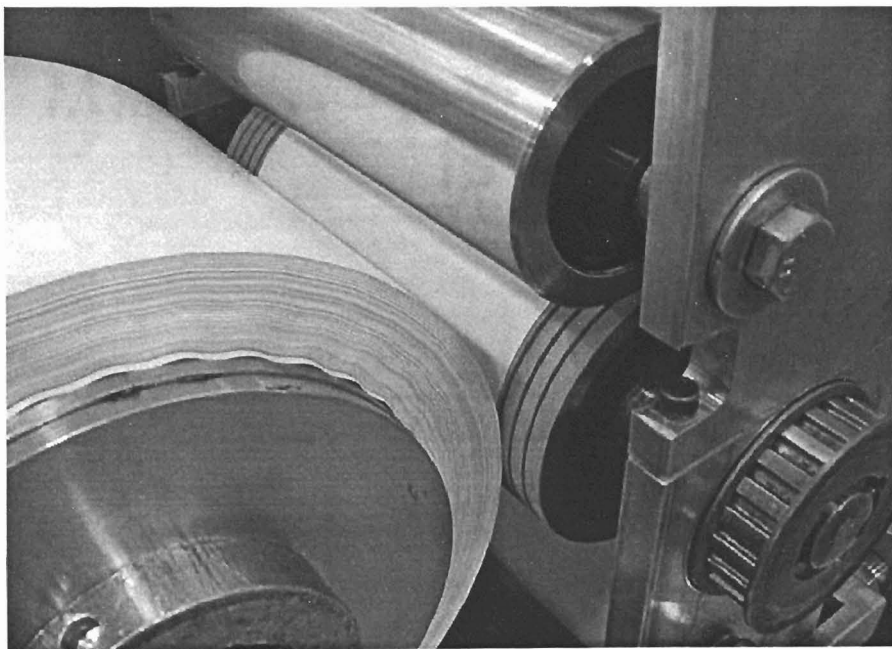


Figure A-2: WOT Experiment with Grooved Rubber Roller B and Wound Roll

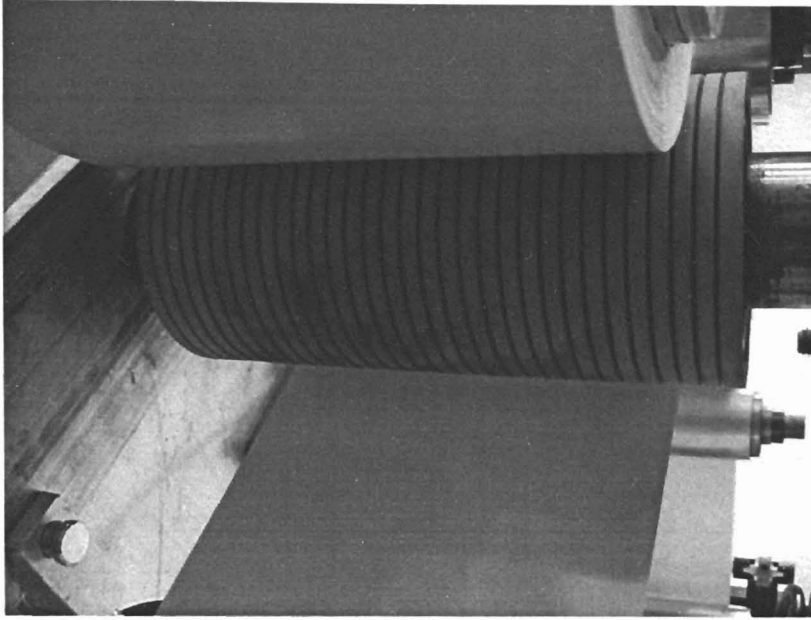


Figure A-3: Another View of WOT Experiment with Grooved Rubber Roller B

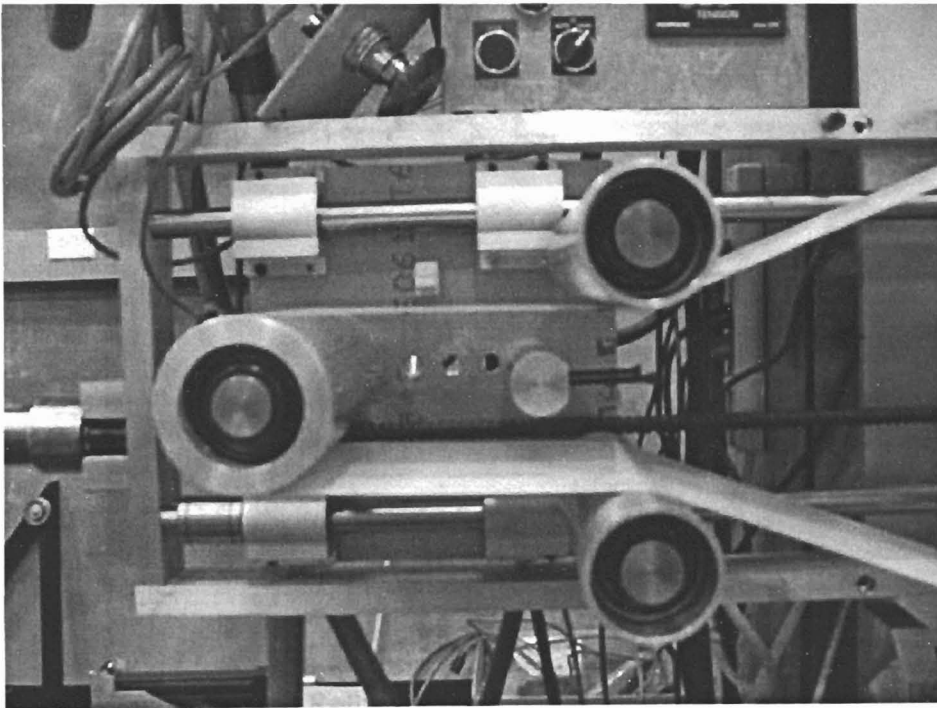


Figure A-4: WOT Measurement Set-up at WHRC

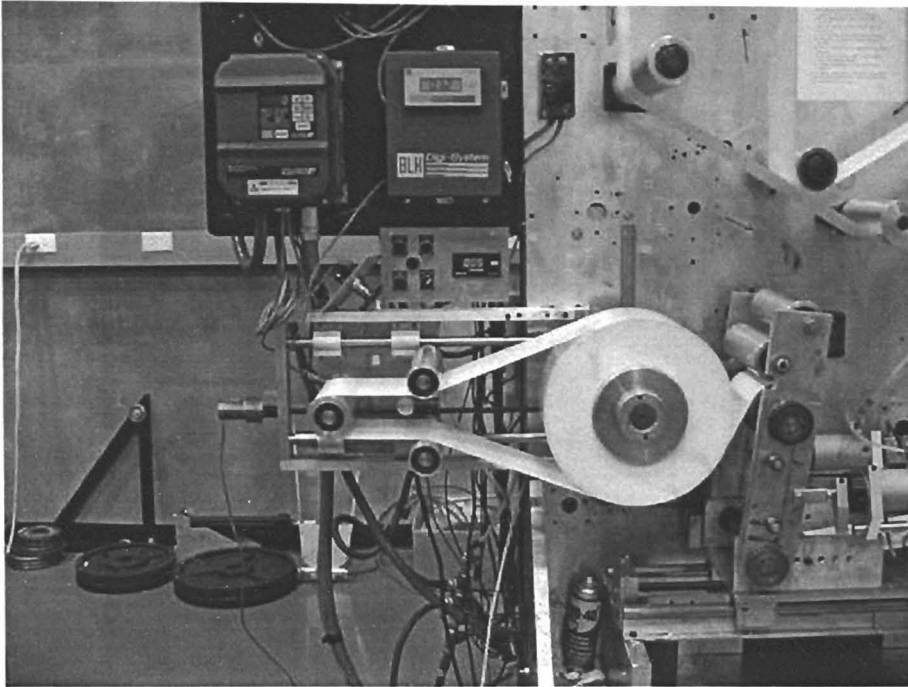


Figure A-5: Another View of WOT Measurement with Wound Roll Set-up at WHRC

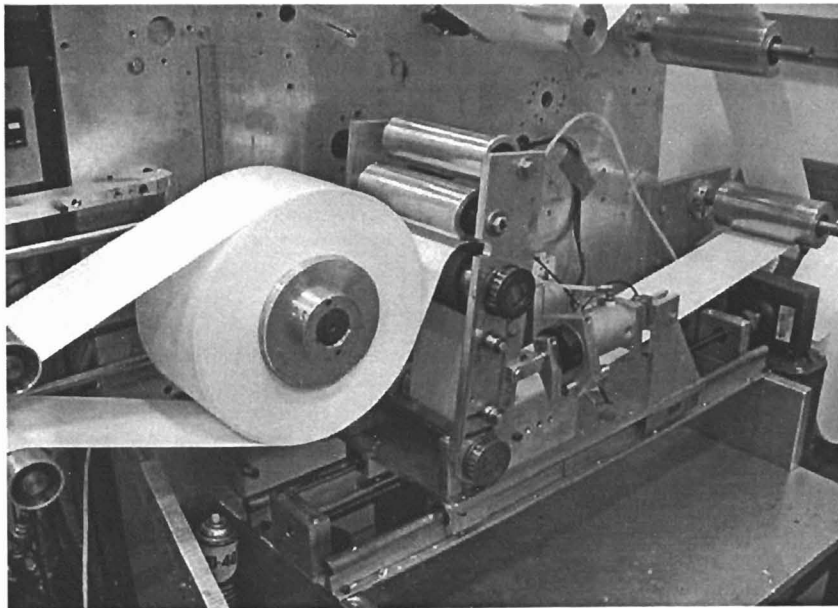


Figure A-6: View of Wound Roll with Wrap Angle and Nip Loading Set-up at WHRC

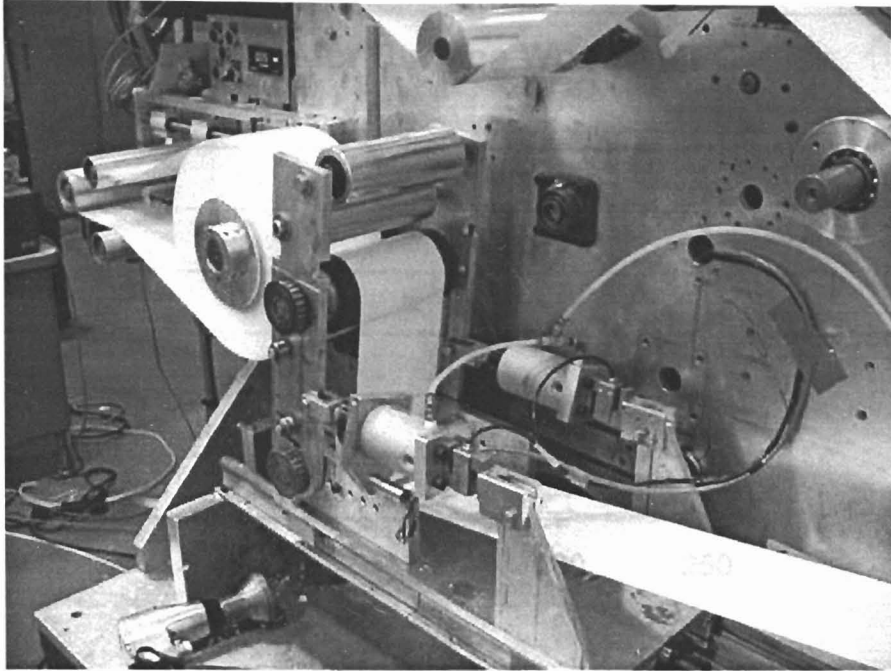


Figure A-7: Wrap Angle at  $180^\circ$  in WHRC Set-up

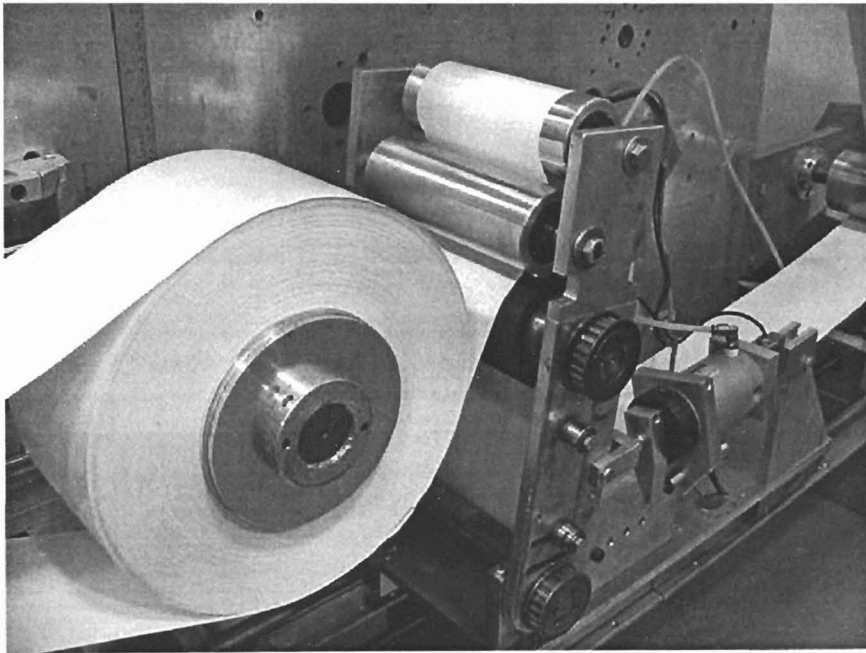


Figure A-8: Wrap Angle at  $45^\circ$  in WHRC Set-up

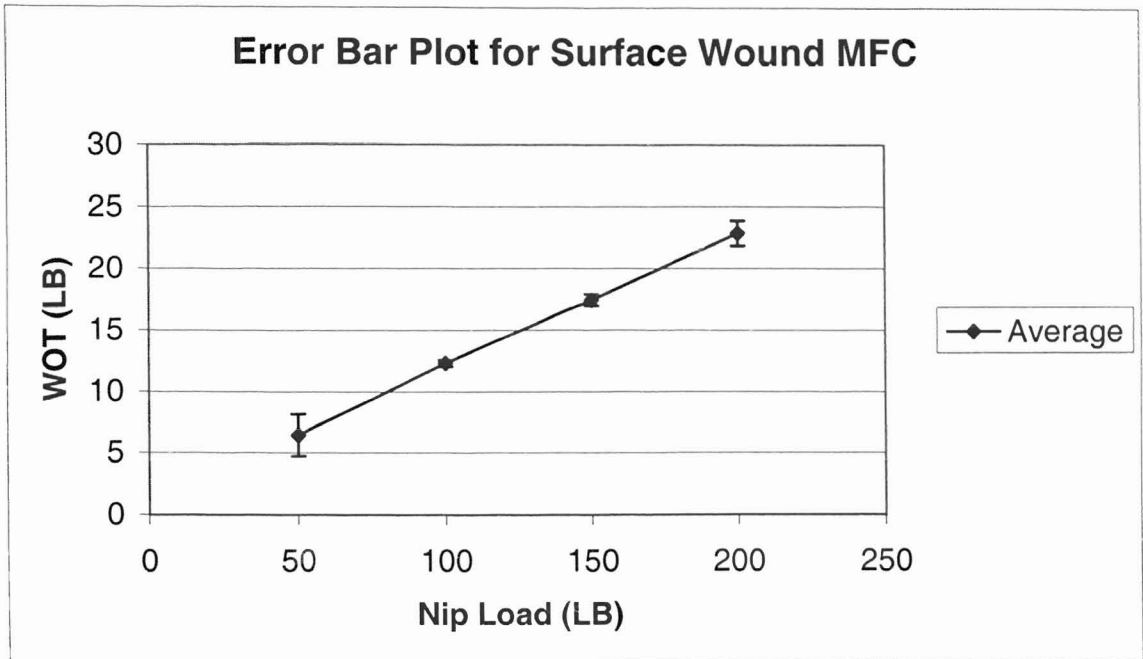


Figure A-9: Error Bar Plot for Surface Wound MFC with 95% Confidence Level

## VITA

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