# THE EFFECTS OF NIP AND WOUND ROLL DIAMETER ON WOUND-ON-TENSION IN SURFACE WOUND PRODUCTION SIZE ROLLS

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# THE EFFECTS OF NIP AND WOUND ROLL DIAMETER ON WOUND-ON-TENSION IN SURFACE WOUND PRODUCTION SIZE ROLLS

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# NOMENCLATURE

| | |
|---|---|
| $T_w$ | Winding Tension (pli) |
| WHRC | Web Handling Research Center |
| $\mu$ | Coefficient of Friction |
| $\mu_{st}$ | Static Coefficient of Friction |
| $\mu_k$ | Kinetic Coefficient of Friction |
| $\mu_{k\ w/w}$ | Web to Web Kinetic Coefficient of Friction |
| $\mu_{k\ a/w}$ | Aluminum to Web Kinetic Coefficient of Friction |
| N | Nip Load (pli) |
| h | Web Thickness (in) |
| WOT | Wound-on-Tension (pli) |
| WIT | Wound-in-Tension (pli) |
| NIT | Nip Induced Tension (pli) |
| $E_r$ | Radial Modulus (psi) |
| $E_t$ | Tangential Modulus (psi) |
| C.O.F. | Coefficient of friction |
| WLT | Web Line Tension |
| $K_1$ | Offset and Scale Factor |
| $K_2$ | Basic Spring Constant of the Material |
| PLI | Pounds per linear inch |

# CHAPTER 1

# INTRODUCTION

A web is a continuous, flexible strip of material such as paper, plastic film, metal foil, textile, and non-woven material. Webs are stored at least on an intermediate basis in wound rolls. The wound roll form is the most efficient and opportune storage format for automated manufacturing processes. Web handling is the science involving the mechanics and dynamics of transporting webs from unwind stations, through process machinery to rewind stations.

Winding is an integral operation in almost every web handling process. During the course of a web becoming a final converted product, it may be unwound and rewound several times depending upon the number of web processes that must be performed. Winding exerts stresses and curvatures upon webs, which can often degrade the web quality. Winding parameters include drum torque, nip load, web tension, web properties, machine and operating parameters can affect the stress patterns within a roll. Wound roll defects can often be cast in terms of stresses. Thus, the ability to predict stresses and roll defects helps to forecast the quality of wound roll. This project has put efforts to understand the effect of nip load, web tension, nip and wound roll size on the wound roll stresses in production size surface wound rolls. During the last few decades, a number of the theoretical models have been developed for center winding, and the experimental results have confirmed the validity of those models. Winding with an impinged nip is common for high speed winding machines as it helps to reduce air entrapment.

Winding with an impinged nip is common when it is necessary to wind higher stress levels into the wound rolls. Papers published by Pfeiffer [1-3] in 1960's & 1970's have proved to be a landmark in the field of web handling to understand the effect of nip rollers on stresses in wound rolls. Pfeiffer [3] proved that the nip is responsible for a strain-inducing mechanism, which increases the sheet tension beyond the web line tension on the outgoing side of the nip. This extra tension induced beyond the web tension is known as Nip Induced Tension (NIT) and is influenced by nip force, drum diameter, and web properties. Pfeiffer [3] found that more NIT was produced at constant nip load when smaller diameters were used.

Previous researchers at the Web Handling Research Center (WHRC) [4-8] have focused on the nip rollers ranging from 2 to 10 inches in diameter and wound rolls of a maximum diameter of about 10 inches. Depending upon the winder type, it is known that the NIT combines with some portion of the web tension, just upstream of the winder, to produce the Wound-On-Tension (WOT). The WOT is tension in the outer layer of the winding roll. Hartwig [7] has shown that there is some influence of nip roll diameter on WOT, but little or no influence of wound roll diameter over the range he was able to study with his setup. This research focuses specifically on how WOT is affected by nip and wound roll diameter. The ranges of the nip and wound roll diameter in this study, approach the ranges of diameters used in the web industry.

# CHAPTER 2

# LITERATURE REVIEW

Webs are wound into rolls by two winding methods, center winding and surface winding. Center winding can be of two types, either with an impinging nip roller or without a nip roller. In both cases, the torque is applied to the center of the winding core. In surface winding, the wound roll is free to rotate and the winding torque is applied to the nip roller. In center winding, winding at very low nip loads is possible. Surface winding requires a minimum nip load to prevent stalling of the winder. In some cases, substantial amounts of winding torque are applied to the winding roll and the nip roller, which is known as combination winding.

Several winding models exist to predict the internal pressures in wound rolls based on different assumptions of material properties. Pfeiffer [2] is considered as pioneer in this field. He explored about wound roll stresses through experimental analysis. Before this only operator skills like club striking etc. were used to infer in-roll stresses. He observed that the rolls wound with a lay-on or nip roller were found to be much harder than the rolls wound without a nip roller.

Pfeiffer [3] was the first to explain that the rolling nip is a strain inducing mechanism, which increases the web tension beyond the web line tension on the outgoing side of the nip. His first quantitative data showed that the NIT was dependent on nip force, nip diameter, and web properties. The NIT was found to vary empirically as inverse square root of the drum diameter from his experiments on nip rollers ranging in diameter from 3" to 10". He didn't extrapolate the result to large nip diameters due to the small amount of data taken. The NIT was also found to be approximately proportional to nip load to the 2/3 power. NIT was found to be directly proportional to the number of sheets between the nip roller and plate. The photomicrographs taken from the side of the nip/stack interface by Pfeiffer showed that the instant center of rotation did not lie at the surface of the interface, rather it was located several layers beneath the interface. The layers above the instant center would travel in the direction of the rolling nip, while layers below the instant center would move in the opposite direction. These tests were performed by rolling loaded nip rollers across stacks of web. Thus, it is not clear if these findings relate directly to wound rolls.

Rand and Erickson [9] extended the work of Pfeiffer [2,3]. They used experimental stress analysis, including destructive and nondestructive tests. They glued strain gauges to the paper webs, which provided continuous information about the stress in the web during the entire winding process.

Pfeiffer [1] proved that nip force was responsible for increasing the wound-on-tension beyond the magnitude of web tension. He developed a specialized winder, which is shown in Figure 2-1. It is to be noted that Pfeiffer coined the acronym WIT for Wound-In-Tension and WOT for Wound-Off-Tension. But later on, WOT (Wound-On-Tension) was used in spite of WIT in OSU. Therefore, now onwards this thesis will refer to WOT to what Pfeiffer referred as WIT.

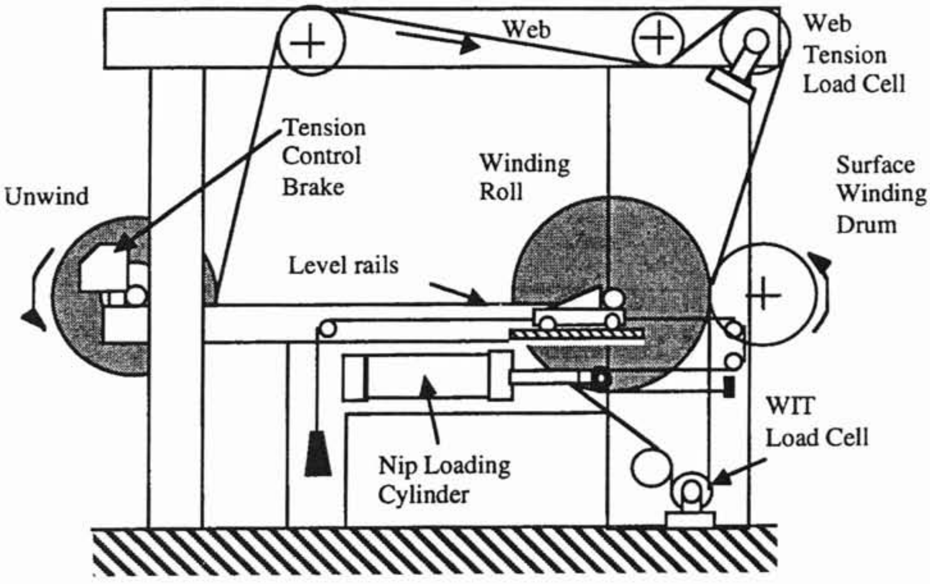

**Figure 2-1: Pfeiffer's Winder Configuration.**

This winder measured the wound-on-tension by peeling off the outer layer of the web after it contacted the winding roll and directed it to the load cell, before directing the web back to the wound roll. The load cells were used to measure the tension of the outer layer after it had passed under the nip roller. He developed an empirical equation by curve fitting from the experimental data:

$$\text{WOT} = \frac{1}{B}\ln\left(\frac{N+A}{A}\right) + \frac{TN}{C+DN} \qquad \textbf{Equation 2-1}$$

where N= nip load (pli) and T= web line tension (pli).

The coefficients A-D are his coefficients for WOT, F is the coefficient of friction. His original data and the curve fit equations agree with each other within 1%. The coefficients A, B, C, D may be affected by nip or wound roll diameter, but this was not studied by Pfeiffer. The coefficients A-D for $62 g/m^2$ coated and supercalendered paper which were obtained through curve fits are as follows:

A=4.75 (pli) B=0.736(1/pli) C=7.14 pli
D=1.34 F=0.311

Pfeiffer's winder stalled at lower nip loads, so he knew that his WOT was limited by the C.O.F. between the winding nip and the wound roll. He never measured the C.O.F., he just assumed the limiting slope of his WOT measurements was the static C.O.F. Since he never measured the C.O.F., he did not know if this was a static or kinetic C.O.F. He observed that at low nip loads, the frictional forces needed to drive the wound roll became less, which caused stalling. This is also shown in Figure 2-2. The lower left hand corner of the WOT vs. nip force graph represents a region, where the normal force of the nip is not sufficient enough to slippage. Therefore, he deduced the following expression after conducting experiments on three different materials.

$$WOT \leq \mu_{st} N \quad \textbf{Equation 2-2}$$

where $\mu_{st}$ = static coefficient of friction, N = Nip Load (pli)

It should be noted this expression applies only to surface winders, which was Pfeiffer's focus in this study. This expression implies that the WOT cannot exceed the friction force between outer layer and the winding drum or nip of a surface winder. It is clear from graph that WOT increases with increase in nip load. The zero pli web line tension curve shows the absolute minimum value of WOT, although it is impossible to run WOT experiments at such a low web tension.

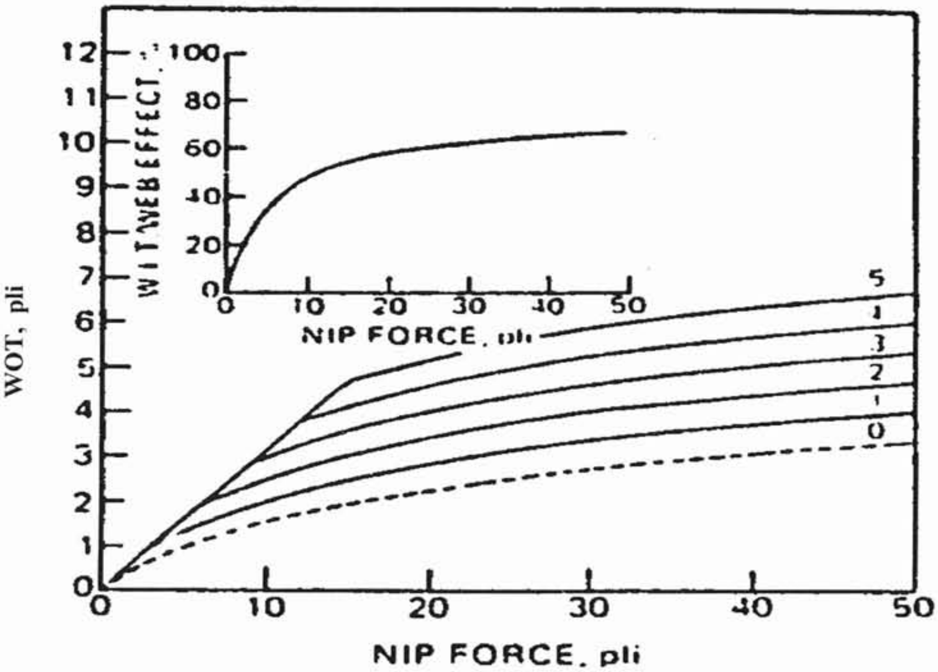

Figure 2-2: Pfeiffer's WOT Curves.

Good and Wu [10] continued the work after Pfeiffer [3] on the mechanism of NIT in wound rolls and drew certain conclusions based on their experimental and finite element analysis. They found that the mechanism responsible for NIT is an elongating machine direction strain in outer layer of the web. This occurs because of compressive Hertzian-like contact stresses, which exist through the depth of the web beneath the nip roller. They also determined that NIT couldn't exceed the product of the nip load and kinetic coefficient of friction between outer wrap & the wrap beneath it.

As earlier wound roll models applied only to the pure center winding, Good et al [11] in 1994 published a paper in which they incorporated new boundary conditions to the earlier wound roll models to consider the effect of an undriven nip roller. Verification was accomplished by winding pressure sensors into rolls wound under center winding conditions with fixed nip load and web tension. A winding model was used in the form of Hakiel [20] in which the WOT was iterated until the predicted and measured pressures agreed. After winding rolls at several web tensions and nip loads, it was found that:

$$WOT_{\text{center winding with nip}}=\{T_w\}+(\mu_k.N)/h \qquad \textbf{Equation 2-3}$$

where N = Nip Load (lb), $\mu_k$ = kinetic coefficient of friction, Tw = Web Line Tension (pli), h = thickness of the web (in.).

Raphael [6] conducted an empirical study on surface wound rolls, which was focused on the interlayer pressure of surface wound rolls. The nip load was applied through a pneumatic cylinder. The winding conditions are shown in Table 2-1. A 6" wide roll was used for the study.

| Nip Diameter (in.) | Nip Load (pli) | Web Line Tension (lb.) | Material |
|---|---|---|---|
| 3,4,5 | 4,6,8 | 4.2,5,5.3,6,6.7,7.7,9.5 | Newsprint |

**Table 2-1: Raphael's Winding Conditions**

It was concluded from his experimental analysis that under surface winding conditions, WOT is only a factor of nip force and does not depend on web tension.

Raphael also stated that the increase in WOT is due to advancing of the first layer over the second layer, resulting in rejection of web material back into the incoming web span prior to the winder. He stated that this problem is observed only in case of surface winding and not in case of center winding with an undriven nip roller.

In 1992, Markum [5] examined NIT for center and surface winding using a specially constructed circular nip mechanics test bed. His winding conditions are given in Table 2-2. He stated that NIT is a function of nip load and the C.O.F. for center winding with a nip roller. Markum found that the NIT does not depend on the nip roller diameter in case of center winding with a lay-on or nip roller and surface winding for nip roller diameter ranging from 2" to 8". This is in contradiction to Pfeiffer's study, where he rolled nip rollers over stacks of web. Markum found that the NIT is a function of C.O.F., nip load, machine rolling resistance and a percentage of web tension in case of surface winding. Since slippage occurred most of the time, he recommended that the kinetic coeff. of friction to be used in calculating NIT. This supports the results of Good [11]. He stated that the web in front of the nip is displaced in the direction of nip roller and this causes the web immediately before the nip roller to leesen the tension, which is supporting the findings of Rand and Erickson [9]. This effect can be seen in the most drastic conditions in the form of a lateral bubble just before the point of contact of web and nip roller.

| Nip Diameter (in.) | Nip Load (lb.) | Web Line Tension | Web Material |
|---|---|---|---|
| 2,4,6,8 | 2,4,6,8 | Unknown | Newsprint |

**Table 2-2: Markum's Winding Conditions**

Cai [13] studied the effect of nip roll compliancy upon center and surface winding. The winding conditions are shown in Table 2-3. A pull-tab, thin piece of steel feeler gauge encased by a piece of brass shim stock, was used to measure the interlayer radial pressure. The pull-tabs were inserted at various radial distances while winding a roll. Each pull-tab was tested after the roll was wound to produce discrete profiles of radial pressure as a function of radius in wound roll. After the roll pressure was found, WOT was estimated using winding software such as WINDER developed at Oklahoma State University. He concluded, that the compliancy of nip rollers had no substantial effect on wound roll stresses in nip winding. He also stated, "The nip induced tension 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." His conclusion was similar to that of Markum [5], who said that the WOT in surface winding is the sum of NIT and some part of web line tension. He stated that NIT has been found to be same for both center and surface winding. He proved experimentally that NIT is dependent only on nip load and the kinetic coefficient of friction between web and web. He concluded that the friction coefficient can play much more important role than roll compliancy in determining WOT. A few years later, Cai's work was found to be limited when Kaya [14] found that nip cover compliancy affects WOT when nip load and angle of wrap of web around nip roller are high.

| **Nip Diameter (in.)** | **Nip Load (pli)** | **Nip Compliance** | **$T_w$ (pli)** | **Material** |
|---|---|---|---|---|
| 5 | 6 | Shore A (37,46,53) | 1.4 | Bond Paper |

**Table 2-3: Cai's Winding Conditions**

Steves [4] studied the effect of nip load on WOT in surface winding. The winding conditions are shown in Table 2-4.

| Nip Dia. (in.) | Nip Loads (pli) | $T_w$ (pli) | Material Wound |
|---|---|---|---|
| 2.5 | 2,3.33,4,5,6,8,10 | 0.5, 1, 1.5,2, 2.5 | Newsprint |
| 6 | 3.33,6.67,10,15,20,26.67,33.33 | 0.67,1,1.33,2.67 | Newsprint |
| 8 | 3.33,6.67,10 | 0.67,1.33,2,2.67 | Newsprint |

**Table 2-4: Steves's Winding Conditions**

A similar method was used to estimate the WOT as reported in the review of Cai [13]'s work. It was found that the WOT equation 2-4 is valid at low nip loads. At high nip loads, WOT was found to be less than that calculated by equation 2-4. It was found to be similar with Pfeiffer [1]. At nip loads higher than 10 pli, there is no interlayer slippage showing that WOT is lesser than that given by equation 2-4.

$$WOT= (\mu_k N)/h$$ **Equation 2-4**

where N=Nip Load, h=Web Caliper, $\mu_k$ is the kinetic coefficient of friction.

Kaya [14] worked mainly on a 4" O.D. aluminum nip roller and the diameter of roll he wound was about 10". A 6" wide roll was used for the study. He concluded that based upon surface winding WOT tests, only some portion of the web tension contributed to WOT at high nip loads. This is in agreement with the work done by other researchers [5,7,16]. He also stated, "Wrap angle has little or no effect on WOT for aluminum nip rollers regardless of the applied nip load." It was also found that in case of surface winding, the WOT continuously increases as the wound roll gets bigger and bigger. His experiments showed an increase of about 2.5 lb in wound-on-tension from start to end of the roll.

Good et al [16] have done a thorough study on the methods, which can be used to predict the structure of wound rolls. Their experimental set up is shown in Figure 2-3. The Wound-On-Tension Measurement (WOTM) is a nondestructive type of measurement, which makes it perfect for the laboratory and manufacturing environment. This concept has to be partially credited to Pfeiffer et al. To measure WOT, we measure the tension in the outermost layer by pulling away the web from the nip roller that is in contact with core of the roll and passing it over the rollers where load cells have been mounted before returning it to be the winding roll. Good et al [16] found that WOT is in fact an interfering method and these values can be corrected to yield true values which were inferred from pull-tabs. It was proved that there is a friction loss in the WOT due to extracting the outer layer, which can be corrected by the following band brake expression:

$$WOT_{measured} = \frac{WOT}{e^{\mu_{ww}\phi}} \qquad \textbf{Equation 2-5}$$

where, $\mu_{ww}$ is the kinetic coefficient of friction between web layers and $\phi$ is the angle of wrap between the nip and the point at which the web is extracted for the WOT measurement. If there is no slippage between the layers at the point where the web is extracted:

$$\mathrm{WOT}_{\mathrm{measured}} = \mathrm{WOT}$$

Thus, it is difficult to know when the WOTM method is an interfering method.

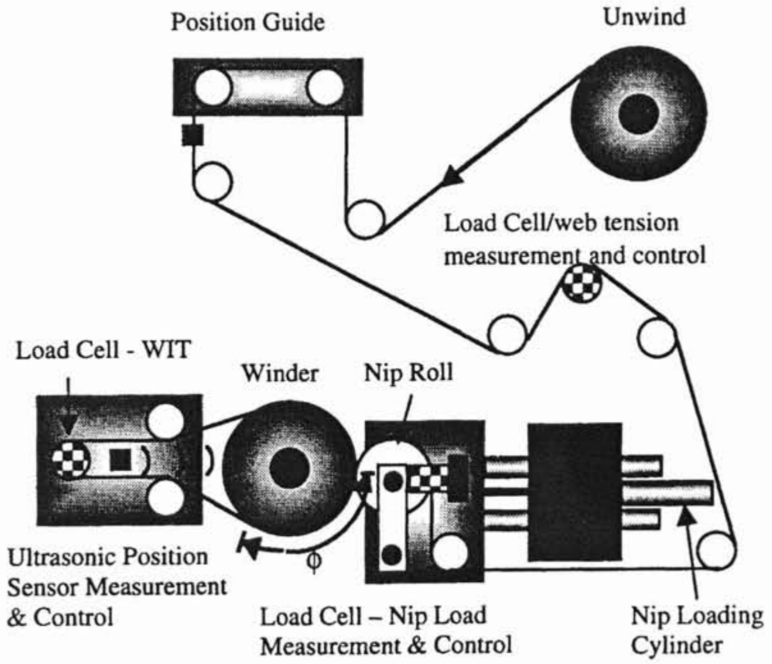

**Figure 2-3: WHRC WOT Apparatus.**

Good et al [16] stated that the NIT appears to be independent of the average radial modulus of the wound roll. He showed that NIT is the same whether there is center or surface winding. It was also found that NIT appears to bear no-relation with the pressures that develop due to winding within the wound roll. He told that WOT with an undriven nip seems to be directly a function of web tension and less a function of nip load, in the case of center winding. This statement supported the work of previous researchers. He represented WOT through the following equation:

$$WOT_{surface\_winding} = NIT \qquad 0 \leq \text{Nip Load} \leq 10.0 \text{ pli} \qquad \textbf{Equation 2-6}$$

$$WOT_{surface\_winding} = NIT + \left( \frac{T_W}{e^{\mu_{wn}\beta}} \frac{N}{C} \right) \quad 10.0 \le \text{Nip Load} \le 33.3 \text{ pli} \qquad \textbf{Equation 2-7}$$

in which, $\beta$ represents the angle of wrap about the nip roll (180 degrees), $\mu_{wn}$ represents the kinetic coefficient of friction between the web and the nip roll, $T_w$ is the web line tension, C is a constant, and N is the nip load.

Good [18] has stated, "The NIT appears to be independent of web tension." He presented figures of experimental data where the WOT changed little with wound roll radius. He found that WOT is dependent on nip load. He observed that WOT is proportional to nip load as per equations 2-8 and 2-9 at low nip loads but the slope decays with increasing nip load. In center winding, WOT is directly a function of web tension at all nip loads. In surface winding, WOT is independent of web tension at low nip loads, but exhibits some dependency at high loads.

$$WOT_{center\ winding} = T_W + \mu_{k\ w/w} P \qquad \textbf{Equation 2-8}$$

$$WOT_{surface\ winding} = \mu_{k\ w/w} P \qquad \textbf{Equation 2-9}$$

where P is the nip load per unit width of web.

He stated that "WIT does not exhibit much dependency if any on wound roll radius" in the case of center and surface winding. This statement has been supported by Santhanakrishnan [17], who stated that "In the sets of experiments done so far with seven different type of nip covers and various web types, the value of WOT values were

independent of wound roll radius, so the value of the WOT was averaged for each nip load".

Balaji [8] did a study on the WOT measurement method in surface winding condition on a low modulus material Tyvek®[1] at WHRC. His winding conditions are shown in Table 2-5. He concluded, "The WOT in surface winding process appears to be a function of nip load and web tension for Tyvek webs." Steves [4], Kaya [14], Good [16] concluded that WOT is independent of web tension in case of surface winding below nip load of 10 pli for winding high modulus material like newsprint. Balaji [8] found the slope of WOT-Nip Load graph to be less than the kinetic coefficient of friction. Previous researchers [4,7,15] concluded that at low nip loads, the slope of WOT-Nip Load graph is proportional to the web/web kinetic coefficient of friction.

| **Nip Dia. (in.)** | **Web Tension (pli)** | **Nip Load** | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | 0.5 | 4 | 8 | 16 | 24 | 32 | 40 |
| 6 | 1.0 | - | 8 | 16 | 24 | 32 | 40 |
| 6 | 1.5 | - | - | 16 | 24 | 32 | 40 |

**Table 2-5: Balaji's Winding Conditions**

### ***Objectives of this Research***

Previous researchers [4-7,13,14,16] in this area, who have studied the effect of nip and wound roll diameter on wound-on-tension, have worked on very limited ranges of nip and wound roll diameter. Thus, the objective of this research is to explore the effect of nip and wound roll diameter on WOT on a production scale surface winder.

# CHAPTER 3

## EXPERIMENTAL SETUP

### 3.1: Winding Machine Description:

This winder is composed of components, which previously served as a circular nip mechanics test bed, which was designed by Markum [9] for use in his research. Markum at WHRC more recently reassembled these components in the form of a surface winder with interchangeable winding drums of 6", 30" and 60" diameters (Refer Fig. 3-1 and 3-2).

The unwind station consists of an expanding core shaft which engages the roll which is to be unwound. The web tension between the unwind stand and the winder is controlled by a magnetic particle brake (MAGPOWR Model HDB50VDC90) on the unwind core shaft. The web tension is sensed by passing the web over an idler roll that is supported by two load cells (MAGPOWR CL 150). The angle of wrap of the web about this idler is maintained constant by adjacent idlers upstream and downstream. The signal from the load cells is input to a Digital tension Readout and Control System (MAGPOWR DIGITRAC2). This control system provides current to the magnetic particle brake as required, to maintain a user defined tension level. The stability factors in DIGITRAC tension controller can be adjusted after the start of the winding experiment to achieve better stability of the web line tension.

The web is then passed through a FIFE Model OPG-LRA web guide and an infrared gate sensor controlled by FIFE A-9 Signal Processor to control the lateral position of the web in the machine. The web then enters the winder. It first passes over the nip roller which is driven with an AC Motor (Reliance Electric Duty Master 2HP 1750RPM) that is controlled with a Reliance Electric GV 3000/SE-Sensorless Enhanced AC Drive. The nip roller, web and wound roll are all in contact, so that when the web exits the nip roll it passes onto the winding roll. The web is then extracted from the wound roll where it passes on to an idler roller, an idler roller on load cells (MAGPOWR CL 150), and another idler. These load cells sense the Wound-On-Tension (WOT) level. The idler rollers preceding and following the WOT rollers were placed such as to maintain a 180° angle of wrap of the web around the WOT roller. This is important as the output of the WOT load cells would vary with constant WOT if the angle of wrap was allowed to vary. The web then passes back to the surface of the winding roll and is wound into that roll. The winding roll sets upon linear ways and the nip load between the nip roller and the winding roll is controlled through cables, pulleys and a hanger where various amounts of dead weights can be hung.

Data from the load cells were collected with a data acquisition system. The data acquired consists of the web tension measured between the unwind and rewind stands, and the $WOT_{measurement.}$ The load cell signals are acquired by a National Instruments Data Acquisition Card (Model: NI 80MIO-16-E), which resides in the back panel of a personal computer. A LabVIEW® program controls the rate of acquisition and stores the data to a file. The nip load was inferred from the stack of dead weights applied. There can be dynamic components of nip load due to Out-Of-Round winding rolls. The winding velocity was low in these tests and thus the dynamic nip loads should have been small. The photograph of surface winder is shown below [Figure 3-1] with various components labeled and the schematic diagram is shown in the following page [Figure 3-2].

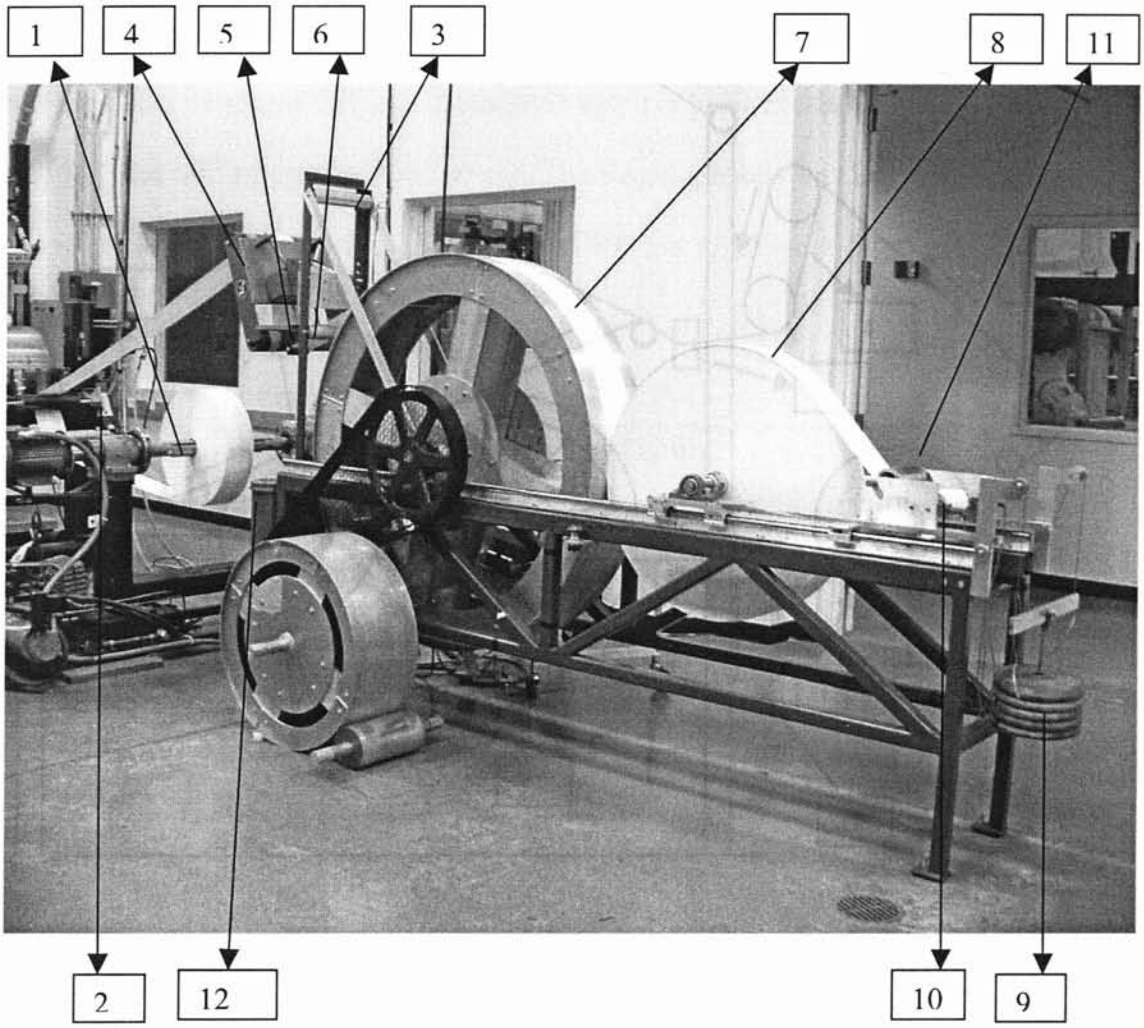

Figure 3-1: Surface Winder Set Up at WHRC.

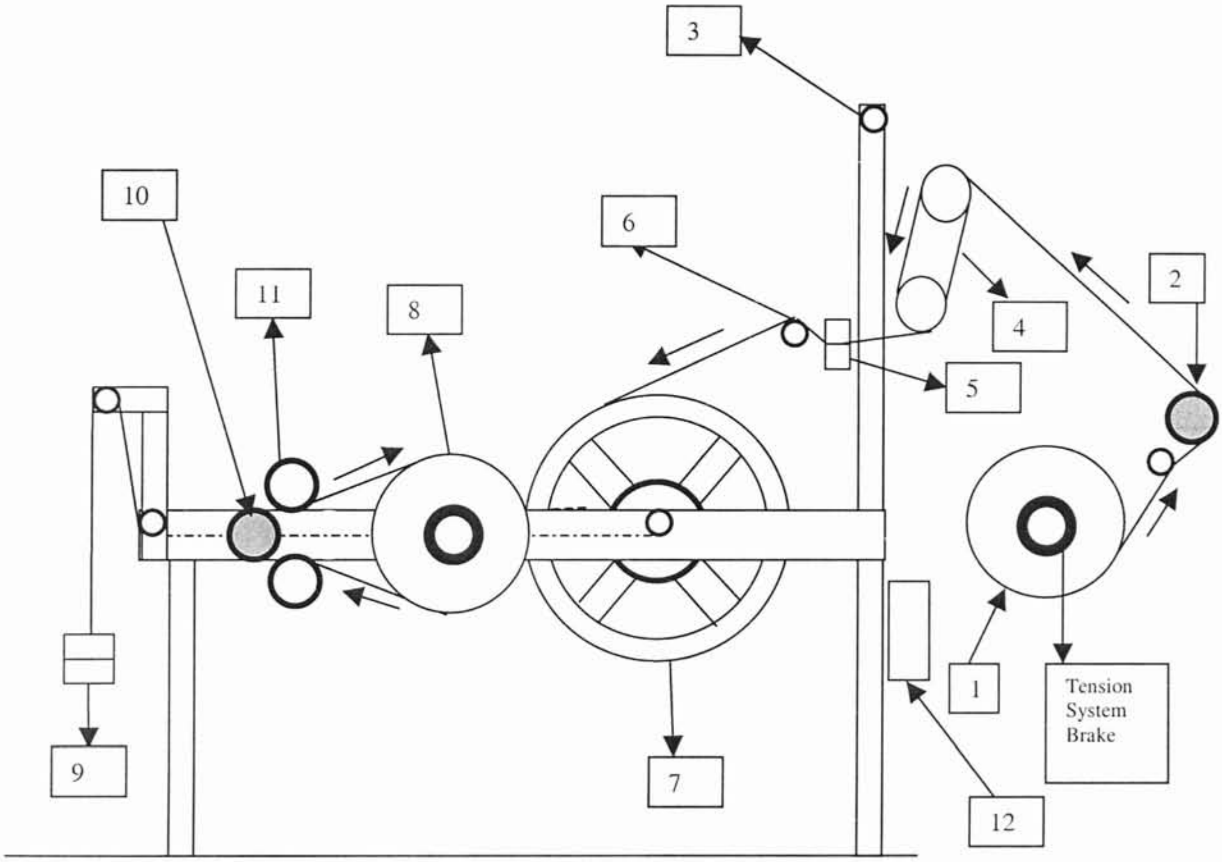

**Figure 3-2: Schematic diagram of the Surface Winder Set Up at WHRC.**

**Legend :**

1. Unwinding roll station with magnetic particle brake.
2. Web line tension load cell.
3. Idler roller.
4. FIFE Lateral Web Guide.
5. FIFE Infrared Gate.
6. Idler aluminum roller.
7. Al Nip Roller (6", 30", 60").
8. Winding roll station.
9. Dead weights (Nip Loads).
10. Wound on Tension Load Cells.
11. Idler roller.
12. An AC Motor (Reliance Electric Duty Master 2HP 1750RPM)

### 3.2: Winding Conditions:

The winding conditions were set after winding rolls at different tensions and nip loads. After this exploratory set of tests were completed, a final operating parameter range for Fine Coated Paper (FCP) was determined and it is presented in Tables 3-1, 3-2, 3-3 for 6", 30" and 60" nip rollers respectively. The winding speed was kept 154 ft/min in all the experiments. The wrap angles for 30" and 60" nip roller were 47.53 and 57.68 degree respectively.

| **Web Ten.(pli)** | **Nip Load (pli)** | | | | |
|---|---|---|---|---|---|
| 1.0 | 10 | 15 | 20 | 26.3 | 33.3 |
| 1.5 | 10 | 15 | 20 | 26.3 | 33.3 |
| 2.0 | 10 | 15 | 20 | 26.3 | 33.3 |

**Table 3-1: Operability range for 6" nip roller.**

| **Web Tension (pli)** | **Nip Load(pli)** | | |
|---|---|---|---|
| 1.0 | 10 | 15 | 20 |
| 1.5 | 10 | 15 | 20 |
| 2.0 | 10 | 15 | 20 |

**Table 3-2: Operability range for 30" nip roller.**

| Web Ten.(pli) | Nip Load (pli) | | | | |
|---|---|---|---|---|---|
| 1.0 | 10 | 15 | 20 | 26.3 | 33.3 |
| 1.5 | 10 | 15 | 20 | 26.3 | 33.3 |
| 2.0 | 10 | 15 | 20 | 26.3 | |

**Table 3-3: Operability range for 60" nip roller.**

A set of preliminary tests was conducted on newsprint and the winder operating parameters are shown in Table 3-4.

| Nip Diameter (in.) | Nip Load (pli) | Web Line Tension (pli) | Material |
|---|---|---|---|
| 60 | 10,15,20,33.3 | 2 | Newsprint |

**Table 3-4: Operability range for different winding tensions and nip loads.**

Figure 3-3 shows the variation of a typical web tension with respect to wound roll radius. This graph depicts the results of the experiment run at 20 pli nip load, 2 pli web line tension and 6" nip roller. This graph shows several data points, as the web line tension data was retrieved at less than one-second interval, and therefore several data points could be averaged. This particular graph has 32053 points; from these many points, a good average can be produced fairly accurately. In this run, web tension was found to be fluctuating between 1.5 pli and 2.5 pli for most of the time. With the help of "average" function in Excel Software, this fluctuation was filtered out. The average and standard deviation of this graph have been found to be 2.02 pli and 0.38 pli respectively.

The machine was run at the best possible tension control. Source of nonuniform web tension were uneven wound roll, problems in alignment of the roll, and other unknown reasons.

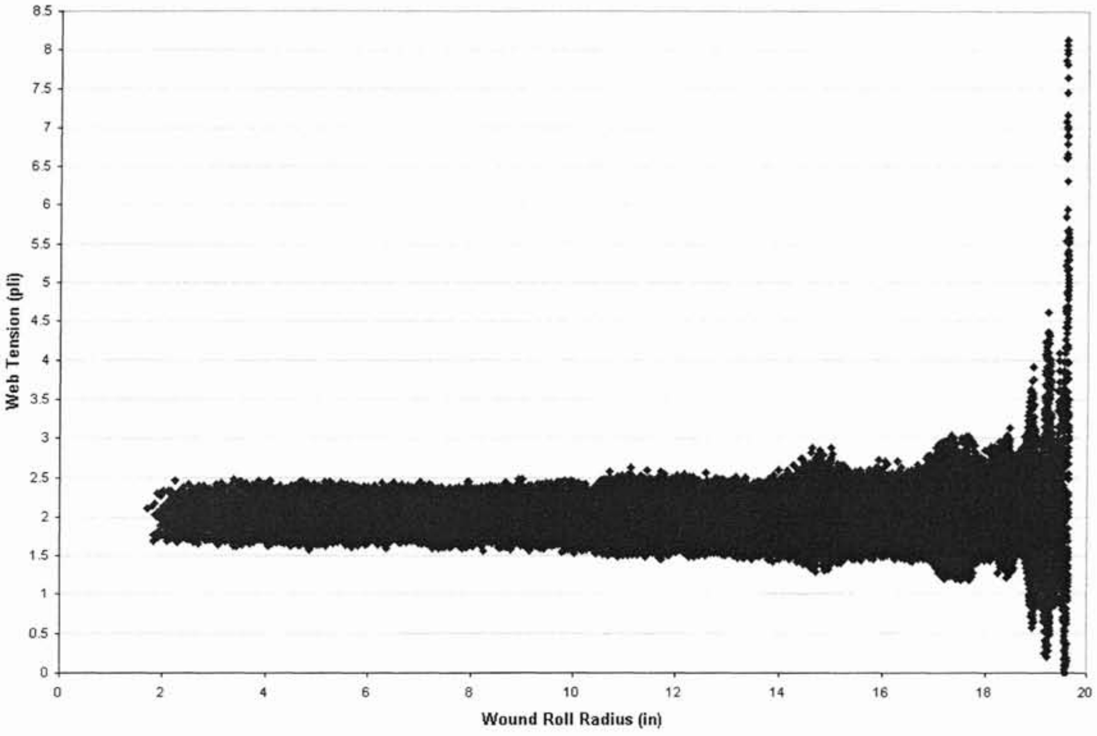

**Figure 3-3: Variation of Web line Tension with radius at a set value of 2.0 pli.**

### 3.3. Repeatability:

Each graph in this section shows 2 sets of the experiments. Each set is showing the results of two graphs at same winding conditions to check repeatability. Suppose the average of one experiment in a set is $W_1$ and the other one is $W_2$. The difference between two experiments at same winding conditions has been calculated as percentage of $(W_2 - W_1)/W_1$.

The first set in figure 3-4 shows experiments at 10 pli nip load and 1 pli web tension at 60" nip roller, it shows a difference of 4.07%. The other set of experiments at

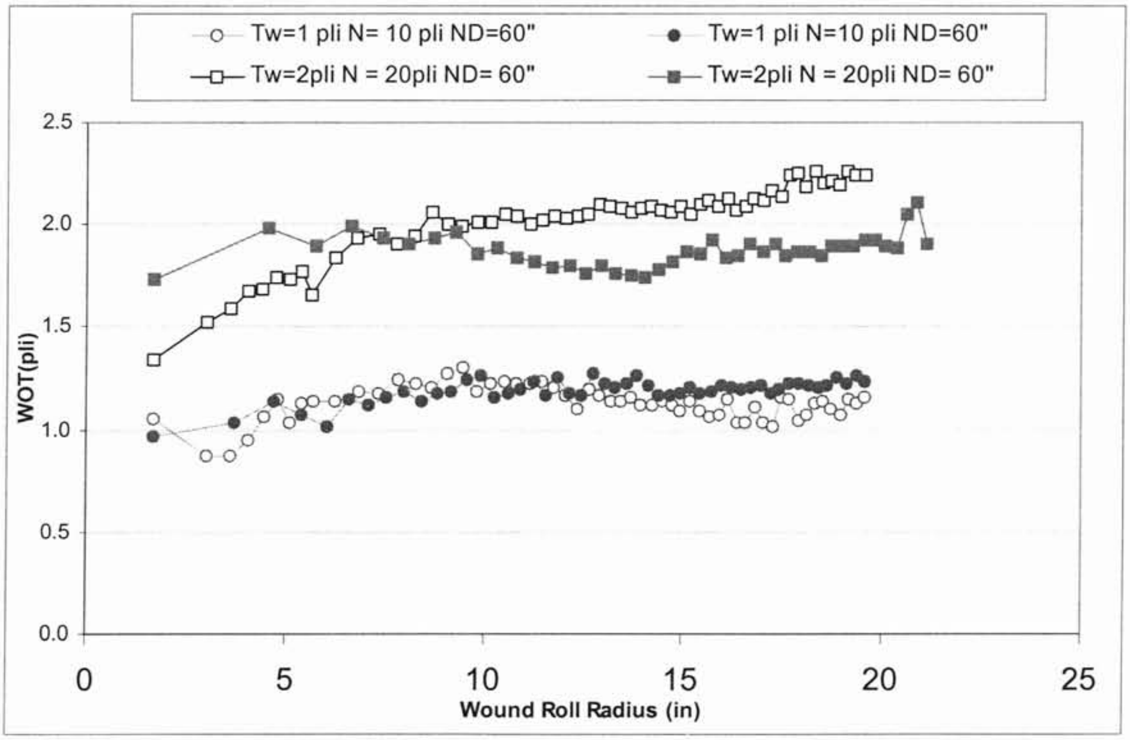

**Figure 3-4: Repeatability of the two sets of experiments at two different winding at 60"nip roller.**

20 pli nip load and 2 pli web tension at 60" nip roller shows a difference of 7.3% in average WOT between two experiments.

Figure 3-5 shows the two sets of experiments. The first set of experiment at 20 pli nip load and 2 pli web tension for 30" nip roller is showing a difference of 4.6%. The other set of experiments at 10 pli nip load and 2 pli web tension for 60" nip roller is showing a difference of 16%.

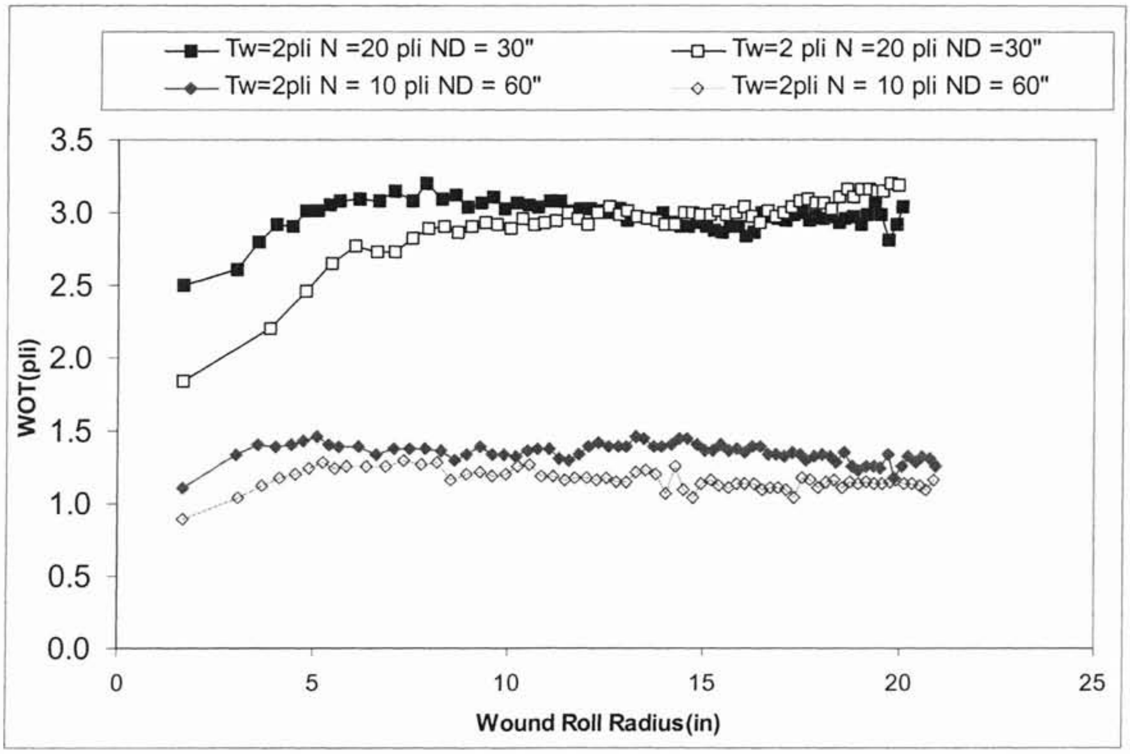

**Figure 3-5: Repeatability of the two sets of experiments at two different winding.**

### 3.4: Material Properties:

Knowledge about the material properties is necessary to the scope of this study. The results of this research will be valuable to those attempting to model the effect of nip roller and wound roll diameter on WOT. The measured parameters were web thickness, kinetic coefficient of friction between web and web and between web and aluminum, radial modulus, and the tangential modulus.

#### 3.4.1 Web Thickness and Width:

A stack of 10 layers was prepared and the thickness of the web was measured along six different points along the width with a micrometer. The thickness of each layer of the web was calculated from the average values of these trials. Care was taken not to allow any air entrainment between the web layers while measuring the web thickness. The width, which is very crucial for further calculations, is documented along with thickness in Table 3-5.

| **Web Material** | **FCP** | **NEWS** |
|---|---|---|
| Thickness (in) | 0.0037 | 0.00295 |
| Width (in) | 6 | 6 |

**Table 3-5: Thickness and Width of Web Materials.**

### 3.4.2 Radial Modulus ($E_r$):

The radial modulus $E_r$ is required to model the pressure distribution inside the wound roll using mathematical models like Hakiel's [12]. The web samples were cut in 6" by 6" coupons and stacked 2" high. The stack was loaded on the Instron Material testing machine. An existing LabVIEW® program controlled the application of pressure to the web stack from zero to 100 psi. The program was set to record the pressure and corresponding strain values. The pressure versus strain characteristics of webs in radial direction is typically non-linear in nature.

There are different methods of obtaining radial modulus using the pressure and strain data. The details about the method used in this study and other methods can be found in the work of Balaji [8]. A polynomial curve fit was used as shown in Fig 3-4 using the Trend line function in Excel software to finally arrive at the radial modulus equation given in Equation 3-1 for Fine Coasted Paper (FCP).

$$E_r = 0.0166\sigma_r^3 - 2.5067\sigma_r^2 + 229.44\sigma_r + 48.207 \qquad \textbf{Equation 3-1}$$

where $\sigma_r$ was the radial pressure in the stack in units of psi.

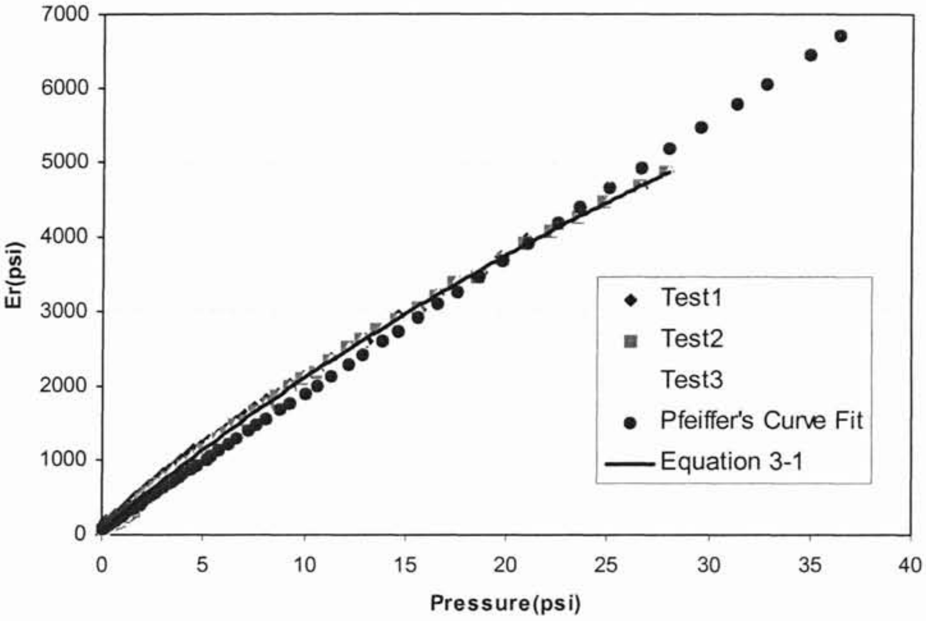

**Figure 3-4: Radial modulus of Elasticity for Fine Coated Paper (FCP).**

The coefficients $K_1$ and $K_2$ in Pfeiffer's [21] expression for pressure vs. strain, and for modulus vs. pressure given in equations 3-2, 3-3, 3-4 were determined using the Solver package in MS Excel software. The error between the experimental pressure vs. strain data and estimates using the Pfeiffer's equation was minimized to yield the least error while varying $K_1$ and $K_2$ values. Those $K_1$ and $K_2$ values, which resulted in the least error, are recorded in Table 3-6.

$$P = K_1\left(e^{K_2\varepsilon} - 1\right)$$ **Equation 3-2**

$$E_r = \frac{dP}{d\varepsilon} = K_1 K_2 e^{K_2\varepsilon}$$ **Equation 3-3**

$$E_r = K_2(K_1 + P)$$ **Equation 3-4**

| Web | $K_1$ (psi) | $K_2$ |
|---|---|---|
| FCP | 0.397 | 182.57 |
| NEWS | 1.803 | 27.49 |

**Table 3-6: Coefficients $K_1$ and $K_2$ in Pfeiffer's equation**

### 3.4.3: In-Plane Modulus ($E_t$):

The procedure to conduct this experiment has been covered in full detail by Balaji [8]. An example of the plot of the stress-strain curve for FCP is shown in Figure 3-5.

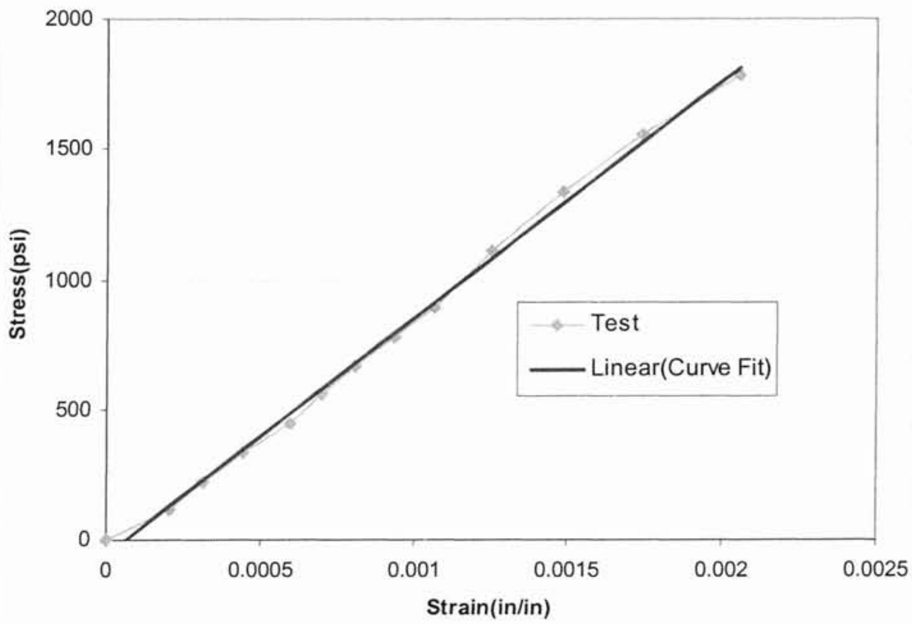

**Figure 3-5: Stress-strain curve for Fine Coated Paper (FCP) for in-plane modulus**

The following equation 3-5 was obtained after using the Trend line function in Excel software for Fine Coasted Paper (FCP). The in-plane modulus of various web materials used is given in the Table 3-7.

$$\sigma_t = 909565\ \varepsilon_t - 60.496$$ **Equation 3-5**

where $\sigma_r$ was the tangential stress in units of psi and $\varepsilon_t$ are tangential strain.

| **Web** | **NEWS** | **FCP** |
|---|---|---|
| $E_t$ (psi) | 584050 | 909565 |

**Table 3-7: Results of In-plane Modulus test for Web Materials.**

### 3.4.4: Friction Tests:

In this study, friction tests were performed to determine the kinetic coefficient of friction between web to web and web to aluminum core. The three aluminum rollers of 6", 30" and 60" were fixed at both ends, while running the experiment. A strip of web was wrapped around the roller and a known weight was hung from one end and the other end was attached to a force gauge as shown in Figure 3-6. The frictional force was measured while pulling the web at constant velocity about the roller.

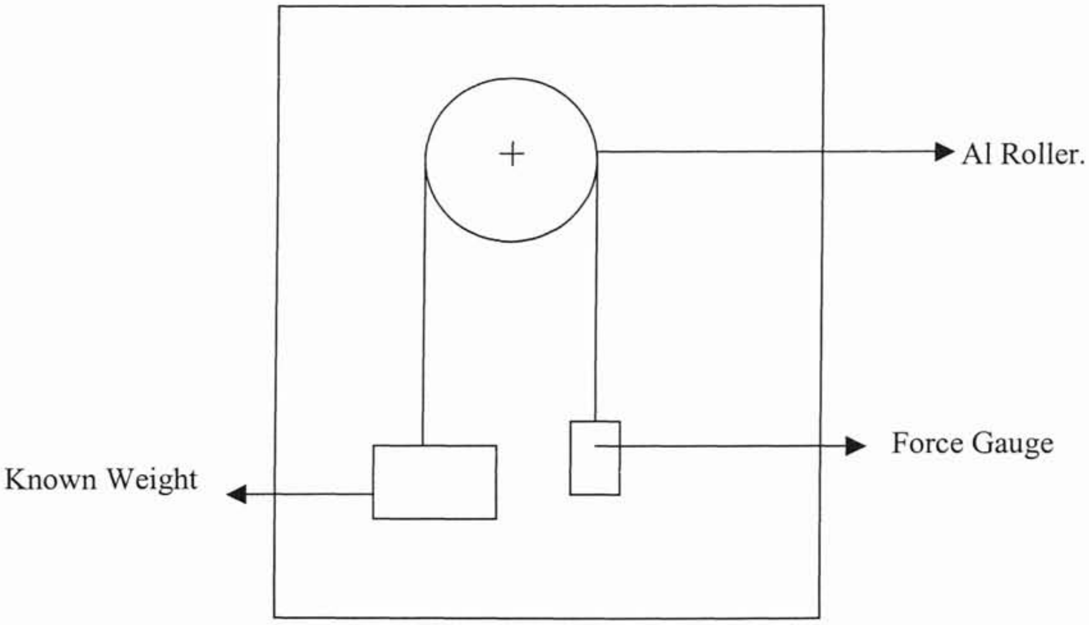

**Figure 3-6: Demonstration of the Friction Measurement Test.**

The tests were repeated thrice and averaged to find the kinetic coefficient of friction between the web and aluminum roller. The same setup was used even for measuring the frictional force between web and web, except that a layer of web was wrapped around the 6” diameter roller and not allowed to slip. The values calculated for 3 Aluminum nip rollers are different, which can be attributed to error in conducting friction tests. The kinetic coefficient of friction was determined using the capstan expression and results of the friction tests are summarized in Table 3-8. The Capstan expression, which is used to find the coefficient of friction, is given in equation 3-6.

$$\frac{T_1}{T_2} = e^{\mu\beta} \qquad \textbf{Equation 3-6}$$

where $T_1$ and $T_2$ are loads, $\mu$ is coefficient of friction and $\beta$ is angle of wrap.

| **Web** | **Roller 60”** | **Roller 30”** | **Roller 6”** | **Web to Web** |
|---|---|---|---|---|
| FCP | 0.38 | 0.38 | 0.35 | 0.39 |
| NEWS | 0.428 | - | - | 0.35 |

**Table 3-8: Coefficients of friction.**

# CHAPTER 4

# RESULTS AND DISCUSSION

This chapter reports the results of the surface winding experiments, which were described in Chapter 3, Experimental Setup.

The first results, which will be presented, will examine the effect of the diameter of the nip roller (sometimes called a drum). Results will be grouped such that, the only winder variables will be nip diameter and web tension, with nip load held constant. The bulk of the results shown were obtained by surface winding Fine Coated Paper (FCP). This is a heavy glossy finished paper often used for printing brochures, stock reports etc.

## 4.1: Wound-On-Tension Behavior for Fine Coated Paper (FCP):

The first results shown in the figure 4-1 are for a constant nip load of 10 pli. The trends which first appear are that both the nip diameter and the web tension affect the WOT.

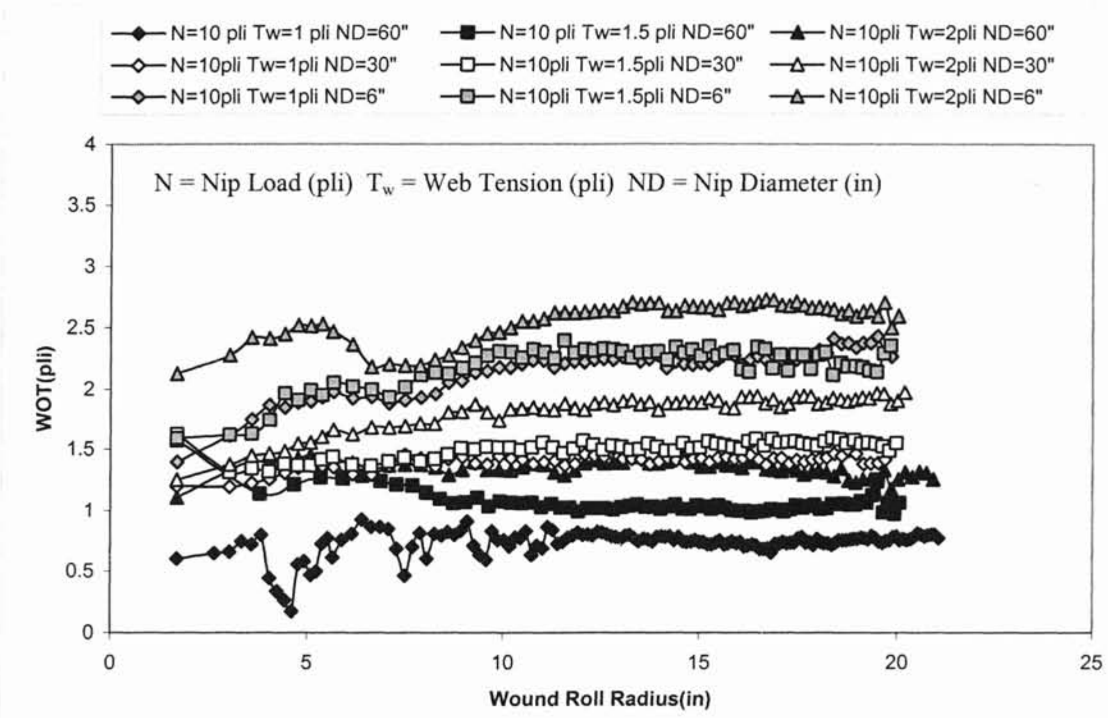

**Figure 4-1: WOT Data for surface winding FCP at 10 pli nip load.**

It can be observed from Figure 4-1 that the WOT data for a 10 pli nip load and 1 pli web tension and a 60" nip roller has a sudden drop in WOT at certain points. This happened because the machine had to be stopped as there was some problem with machine alignment resulting in a poorly wound roll.

Next, the nip load is increased to 15 pli and the results are shown in Figure 4-2. Again, both the nip diameter and web tension appear to affect WOT. Also, there appears to be a consistent dependence on wound roll radius as the roll begins to wind. At low winding radii, the WOT increases with the wound roll radius. At higher wound roll radii, the dependence is less clear with several test cases showing little or no dependence, whilst others show positive or negative slopes in WOT with respect to wound roll radius. When comparing to the 10 pli nip load data shown in Figure 4-1, the WOT data for the 15 pli nip load is typically higher with the exception of the data shown taken with the 60" nip diameter.

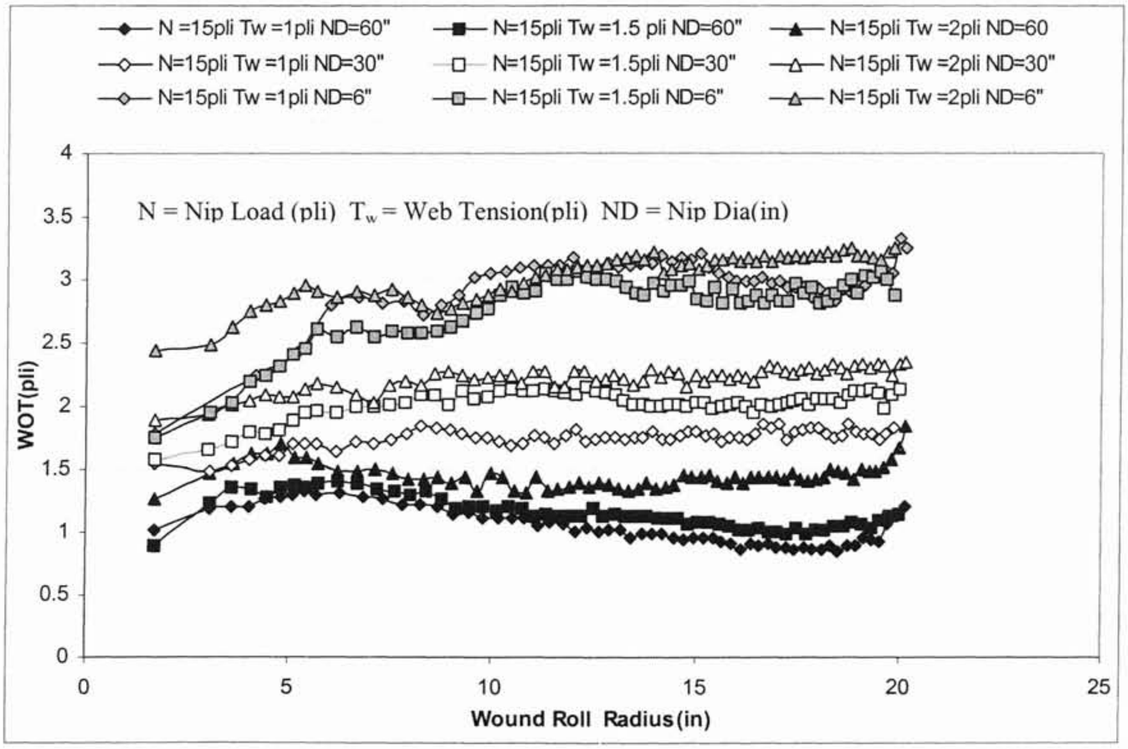

**Figure 4-2: WOT Data for surface winding FCP at 15 pli nip load.**

The nip load was increased to 20 pli and the results are shown in Figure 4-3. Although the WOT levels increased above those recorded at nip loads of 10 pli (Fig. 4-1) and 15 pli (Fig.4-2), the trend of the data is similar.

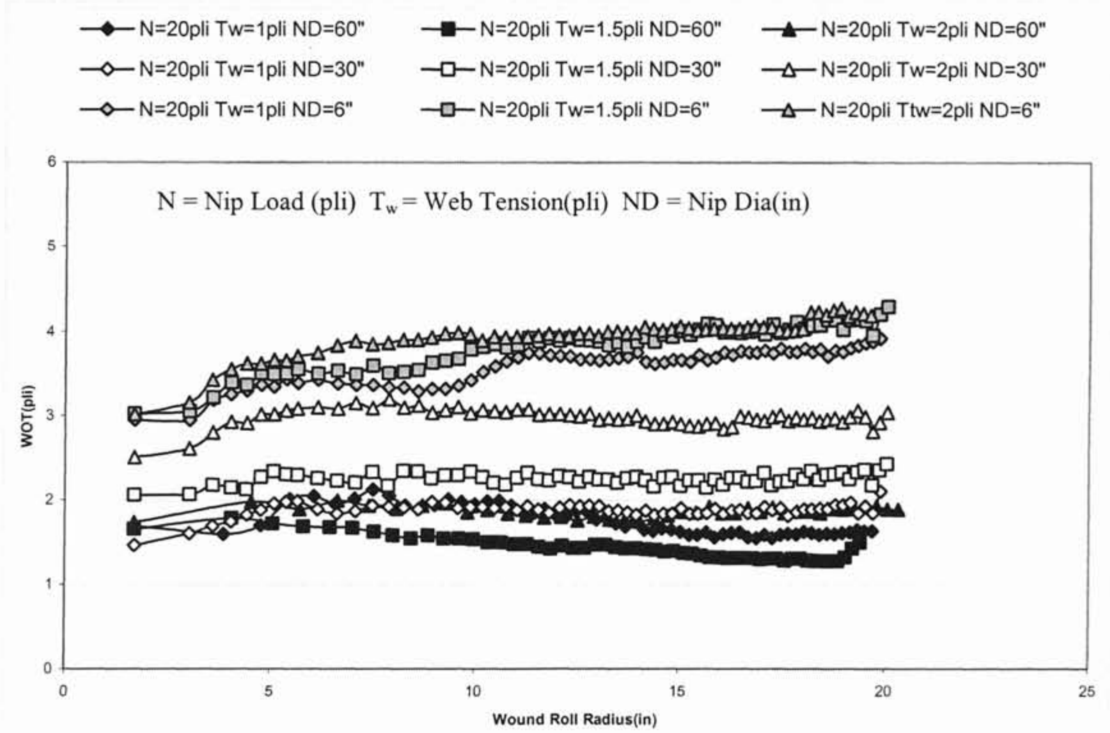

**Figure 4-3: WOT Data for surface winding FCP at 20 pli nip load.**

Nip Loads can be very high in production environments. Some tests were conducted at nip loads as high as 26.3 pli and 33.3 pli, to study the behavior of WOT, the results of which are shown in Fig. 4-4 and 4-5. The following figures do not have any WOT curves for the 30" nip diameter. Figure 4-4 shows the WOT levels increased above those recorded in previous figures (Fig. 4-1, Fig 4-2, Fig.4-3); the trend of the data is similar.

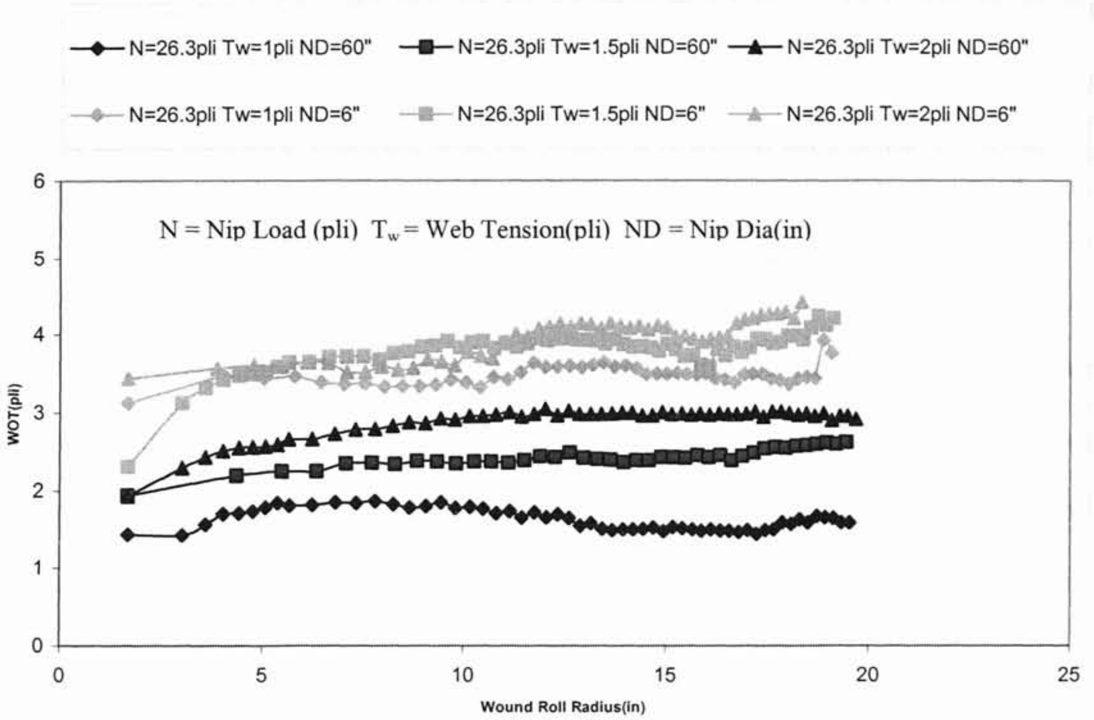

Figure 4-4: WOT Data for surface winding FCP at 26.3 pli nip load.

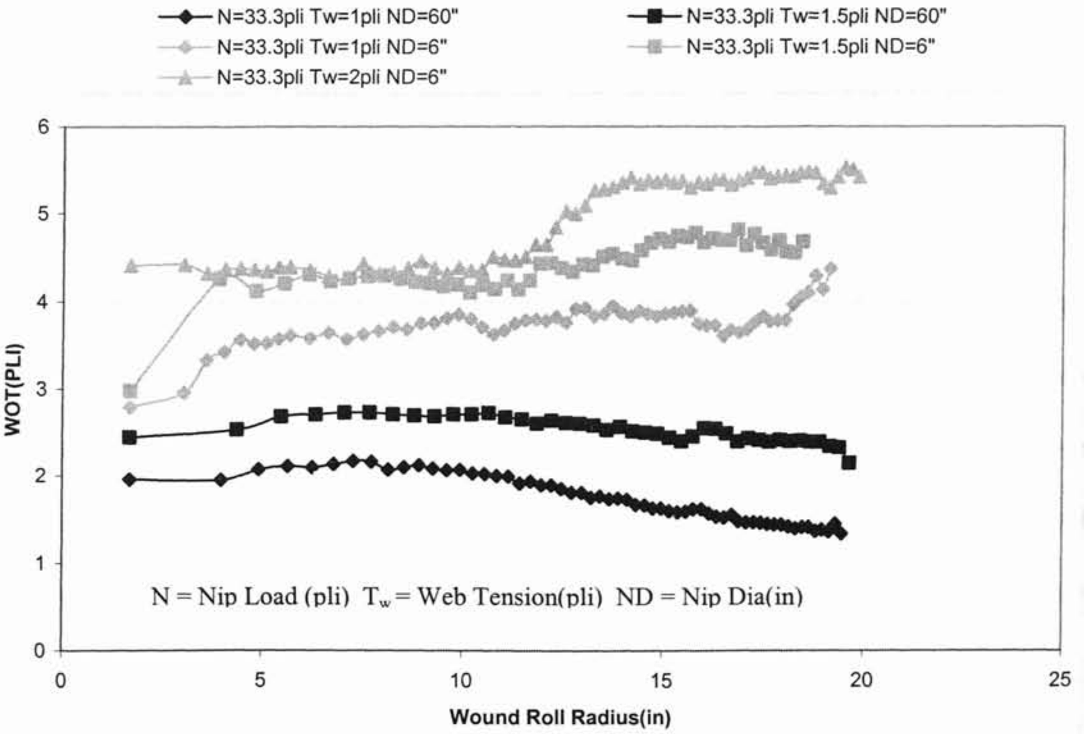

Figure 4-5: Data for surface winding FCP at 33.3 pli nip load.

From the figures 4-1 through 4-5 presented in this section, it has been found that all the four variables: nip load, web line tension, nip and wound roll diameter affect the WOT. It should be noted, however, that nip diameter increases by a factor of 10 with nip load and web tension increasing only by a factor of 3.3 and 2 respectively.

It has been found that in most of the cases, as the wound roll radius increases, there is an increase in WOT. Some cases are even reporting an increase of 80% increase in WOT as roll ends. On the average from Fig 4-1 to 4-5, it has been found that WOT increases by 28% from start to end of roll. So, it can be said that wound roll radius is a factor affecting WOT.

Kaya [14] worked mainly on 4" O.D. aluminum nip roller and the diameter of roll he wound was about 10". He found that the slope of WOT curve with respect to wound roll radius is positive. Earlier, it was stated that Kaya [14] reported 2.5 lb (0.42 pli) increase in WOT over a wound roll radius range of 1.7" to 5.3". Based on the average slopes witnessed in the data shown in Figure 4-1 through 4-5, there was an increase of 2.02 lb (0.34 pli) over a limited range of wound roll radius. It appears that this research yielded comparable results. Another observation is that, based on the average data shown in Figure 4-1 through 4-5 for 6" nip roller, there was an increase of 3.24 lb (0.54 pli) over a limited range of wound roll radius. Comparing it with Kaya's work, who wound with 4" nip roller, the average increase in the WOT over limited range of wound roll diameter is more in this study.

It is observed that some of the WOT curves are having a steep rise in slope with respect to wound roll radius at start of winding the roll. It is can be probably attributed to poor control of web tension in the start.

### 4.2: Effect of Nip Load on Wound-on-Tension:

In this section, the WOT for a particular test has been averaged with respect to wound roll radius. This allows the effects of web tension, nip load, and nip diameter on WOT to be studied further.

First the effect of nip load on WOT will be studied, the results are shown in Figure 4-6.

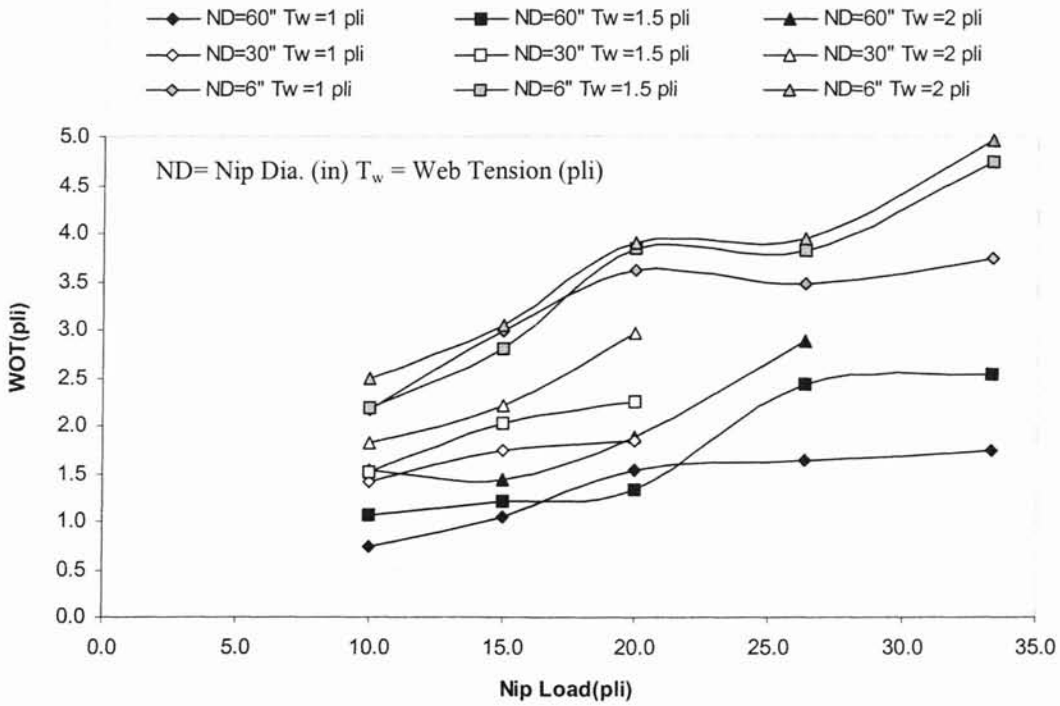

**Figure 4-6: The effect of Nip Load on average WOT.**

Each curve represents a group of winding experiments, which had nip diameter and web tension in common. The number of points on the curve shows the number of experiments carried out on that particular nip roller and web line tension. Some points are missing, as the experiments at those particular winding conditions could not be carried out due to problems with machine alignment.

It can be inferred from Figure 4-6 that with increase in nip load, there is a corresponding increase in WOT. This confirms the work of previous researchers [8,14,16-18] at WHRC. The average slope of all curves in Figure 4-6 is 0.06, which is substantially less than $\mu_{k\ w/w}$ of 0.39 of FCP. This conclusion supports the work of Balaji [8]. He has shown that the average slope of WOT curves in his study was 0.07 as compared to the $\mu_{k\ w/w}$ value of 0.2 of Tyvek.

Pfeiffer [3] has shown that by doubling the nip load, wound-on-tension becomes 1.59 times and by tripling the nip load under same winding conditions, wound-on-tension increases further to 2.08 times the base value of 1pli. This study has shown that by doubling the nip load, wound-on-tension becomes 1.56 times and by making nip load 3.3 times under same winding conditions, wound-on-tension increases further to 2.2 times. It appears this study has yielded comparable results.

Pfeiffer [1], Balaji [8], Kaya [14], and Santhanakrishnan [17] have shown that WOT approaches zero as nip load approaches zero for surface winding. This behavior was not observed in this study, which can be probably attributed to the poor control of web tension. Hartwig [7] also found that WOT did not approach zero as nip load approached zero, in his study conducted over 4" and 10" nip rollers. Good [16,18] and Pfeiffer [1] showed at low nip loads that web tension had little or no impact on WOT, but this study certainly shows the effects of web line tension on WOT at low nip loads. At high nip loads, other researchers [1,16] have shown that web tension has substantial effect on WOT. This study seems to support this finding typically at lower web tensions.

At high nip load and low web tension, the WOT shows little dependency on nip load; while at high nip loads and high web tension cases, WOT seems to show much greater dependency on nip load. The average slope of Fig. 4-6 is 0.06, which shows that it is substantially less than kinetic coefficient of friction for FCP. This confirms the work of Balaji [8].

### 4.3 Effect of Web Tension on Wound-on-Tension:

The impact of web tension on average WOT is shown in Fig. 4-7. Each curve represents winding experiments, which have nip diameter and nip load in common.

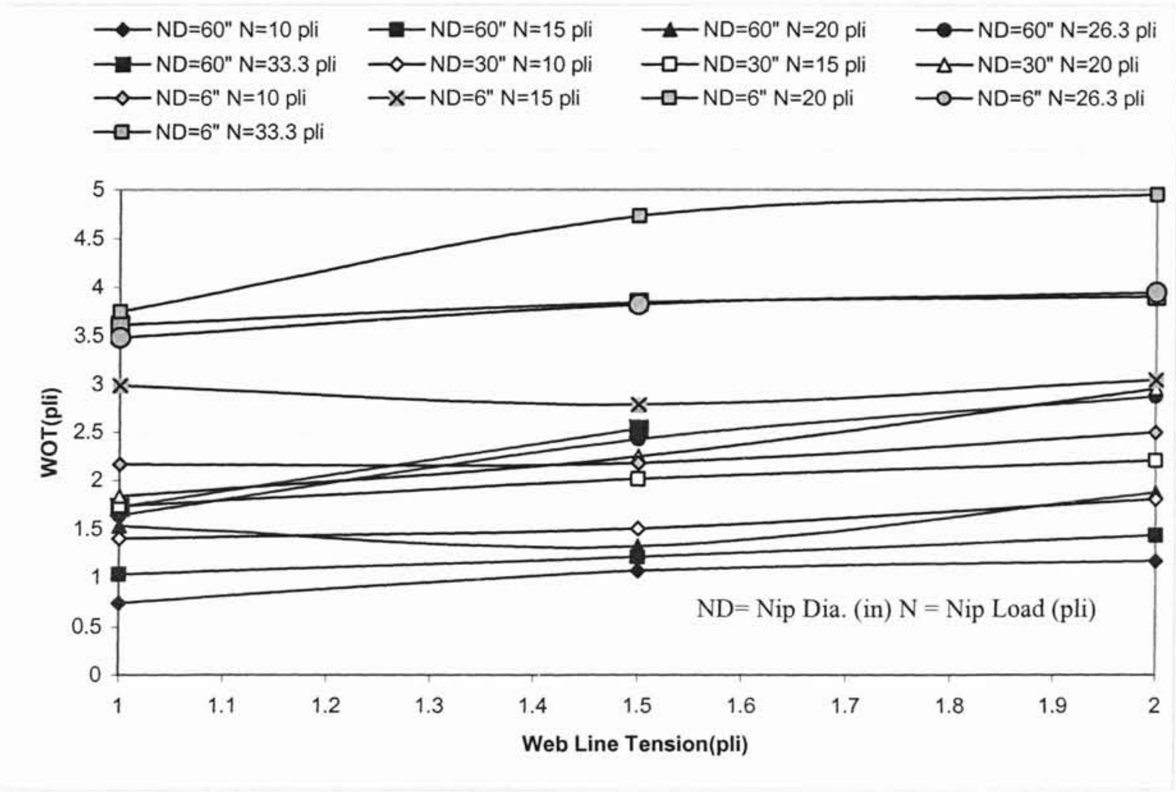

**Figure 4-7: The effect of Web Tension on average WOT.**

It can be inferred from the Figure 4-7, that with increase in web line tension for a particular nip roller and nip load, there is a corresponding increase in WOT. This has confirmed the work done by pervious researchers [5,7,14]. Previous researchers [5,7,14] at WHRC have found that unlike center winding, only some part of web tension contributes to the WOT, in case of surface winding. This study shows it to be true; even in case of production size surface wound rolls. Raphael [6] has stated that the WOT is only a factor of nip load and does not depend on web tension, which was probably true for the range of nip load and web material he used. Therefore, the following 3 tables for 60", 30" and 6" nip rollers respectively contain average and standard variation for web line tension and wound-on-tension for each experiment, whose average value of WOT has been plotted. The plots of the ratio of WLT standard deviation to WLT average vs. ratio of WOT standard deviation to WOT average are shown in Figures 4-8, 4-9 and 4-10 for 60", 30" and 6" respectively.

| **Nip Load-Web Tension (pli-pli)** | **Standard Deviation of WLT (pli)** | **Average WLT (pli)** | **Standard Deviation of WOT (pli)** | **Average WOT (pli)** |
|---|---|---|---|---|
| 33.3-1.5 | 0.11 | 1.50 | 0.23 | 2.53 |
| 33.3-1.0 | 0.10 | 1.0 | 0.34 | 1.73 |
| 26.3-2.0 | 0.11 | 2.01 | 0.35 | 2.88 |
| 26.3-1.5 | 0.12 | 1.50 | 0.43 | 2.42 |
| 26.3-1.0 | 0.09 | 1.00 | 0.35 | 1.64 |
| 20.0-2.0 | 0.34 | 2.08 | 0.21 | 1.88 |
| 20.0-1.5 | 0.34 | 1.55 | 0.21 | 1.43 |
| 20.0-1.0 | 0.09 | 0.99 | 0.41 | 1.75 |
| 15.0-2.0 | 0.36 | 2.09 | 0.21 | 1.44 |
| 15.0-1.5 | 0.24 | 1.57 | 0.30 | 1.15 |
| 15.0-1.0 | 0.33 | 1.07 | 1.04 | 0.29 |
| 10.0-2.0 | 0.31 | 2.05 | 0.17 | 1.33 |
| 10.0-1.5 | 0.51 | 1.65 | 0.14 | 1.07 |
| 10.0-1.0 | 0.49 | 0.95 | 0.15 | 0.76 |

**Table 4-1: Standard Deviation and Average of WLT and WOT for each Experiment for 60" nip roller.**

| Nip Load-Web Tension (pli-pli) | Standard Deviation of WLT (pli) | Average WLT (pli) | Standard Deviation of WOT (pli) | Average WOT (pli) |
|---|---|---|---|---|
| 20.0-2.0 | 0.26 | 2.03 | 0.25 | 2.98 |
| 20.0-1.5 | 0.11 | 1.51 | 0.36 | 2.24 |
| 20.0-1.0 | 0.19 | 1.00 | 0.22 | 1.88 |
| 15.0-2.0 | 0.23 | 2.02 | 0.300 | 2.22 |
| 15.0-1.5 | 0.21 | 1.51 | 0.14 | 2.02 |
| 15.0-1.0 | 0.22 | 1.01 | 0.30 | 1.74 |
| 10.0-2.0 | 0.21 | 2.02 | 0.31 | 1.81 |
| 10.0-1.5 | 0.17 | 1.51 | 0.19 | 1.51 |
| 10.0-1.0 | 0.21 | 1.01 | 0.09 | 1.4 |

**Table 4-2: Standard Deviation and Average of WLT and WOT for each Experiment for 30" nip roller.**

| Nip Load-Web Tension (pli-pli) | Standard Deviation of WLT (pli) | Average WLT (pli) | Standard Deviation of WOT (pli) | Average WOT (pli) |
|---|---|---|---|---|
| 33.3-2.0 | 0.44 | 2.05 | 0.44 | 4.96 |
| 33.3-1.5 | 0.47 | 1.62 | 0.37 | 4.43 |
| 33.3-1.0 | 0.50 | 1.13 | 0.28 | 3.74 |
| 26.3-2.0 | 0.42 | 2.10 | 0.33 | 3.94 |
| 26.3-1.5 | 0.53 | 1.61 | 0.36 | 3.82 |
| 26.3-1.0 | 0.58 | 1.16 | 0.26 | 3.48 |
| 20.0-2.0 | 0.38 | 2.02 | 0.24 | 3.94 |
| 20.0-1.5 | 0.46 | 1.54 | 0.44 | 3.84 |
| 20.0-1.0 | 0.56 | 1.10 | 0.25 | 3.61 |
| 15.0-2.0 | 0.43 | 2.05 | 0.25 | 3.04 |
| 15.0-1.5 | 0.50 | 1.59 | 0.57 | 2.79 |
| 15.0-1.0 | 0.53 | 1.10 | 0.79 | 2.98 |
| 10.0-2.0 | 0.50 | 2.08 | 0.20 | 2.32 |
| 10.0-1.5 | 0.46 | 1.57 | 0.64 | 2.18 |
| 10.0-1.0 | 0.51 | 1.11 | 0.30 | 2.16 |

**Table 4-3: Standard Deviation and Average of WLT and WOT for each Experiment for 6" nip roller.**

The diagonal lines in Figures 4-8,4-9 and 4-10 show that how many points are lying on, above or below that diagonal line and henceforth, demonstrate the correlation between independent variable and dependent variable.

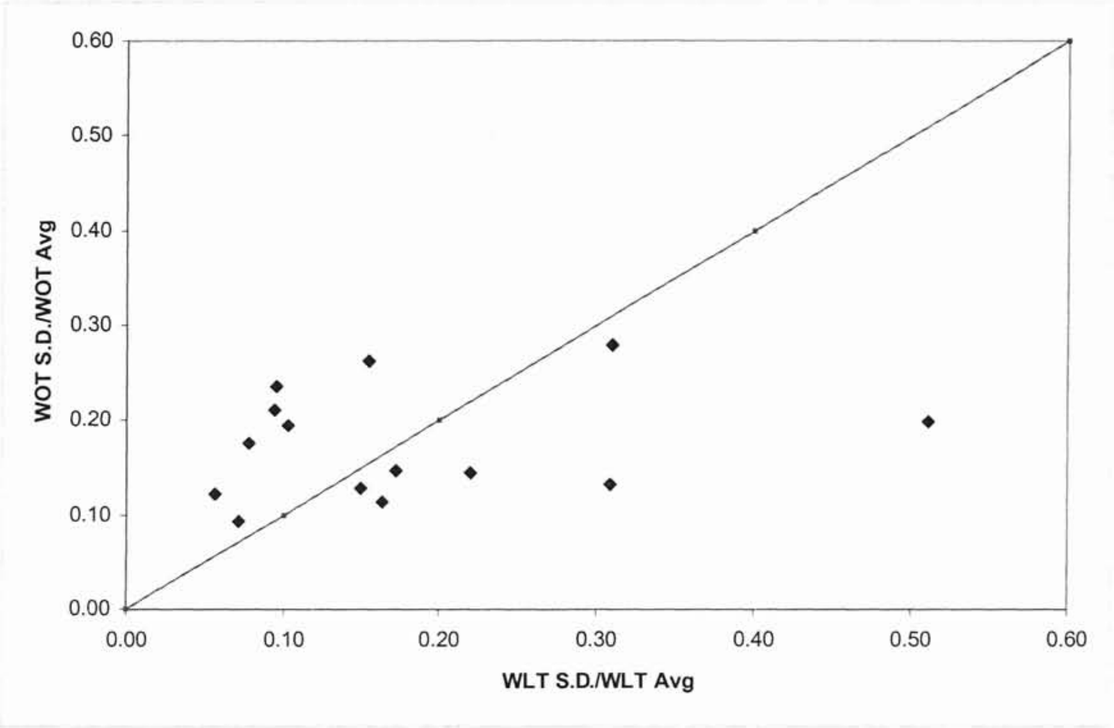

**Figure 4-8: Variation of WOT Std. Dev./WOT Avg. Vs. WLT Std. Dev. / WLT Avg. for 60" Nip Diameter.**

Some of the experiments in Fig 4-8 are very close to the diagonal line, showing that WOT is strongly correlated with variation in WLT, while others are quite much above or below the diagonal line, hence showing little correlation. It is difficult to say if it is following any pattern.

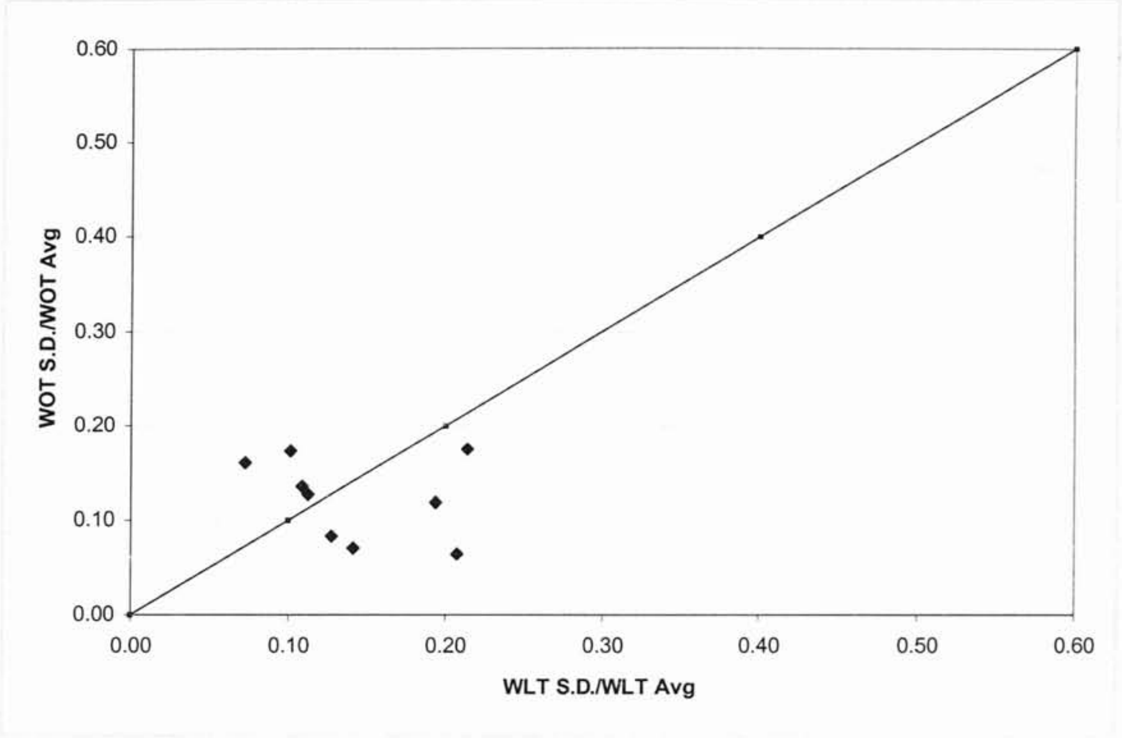

**Figure 4-9: Variation of WOT Std. Dev./WOT Avg. Vs. WLT Std. Dev. / WLT Avg. for 30" Nip Diameter.**

Most of the experiments in Fig 4-9 are pretty close to the diagonal line showing that variation in WOT is strongly correlated with variation in WLT.

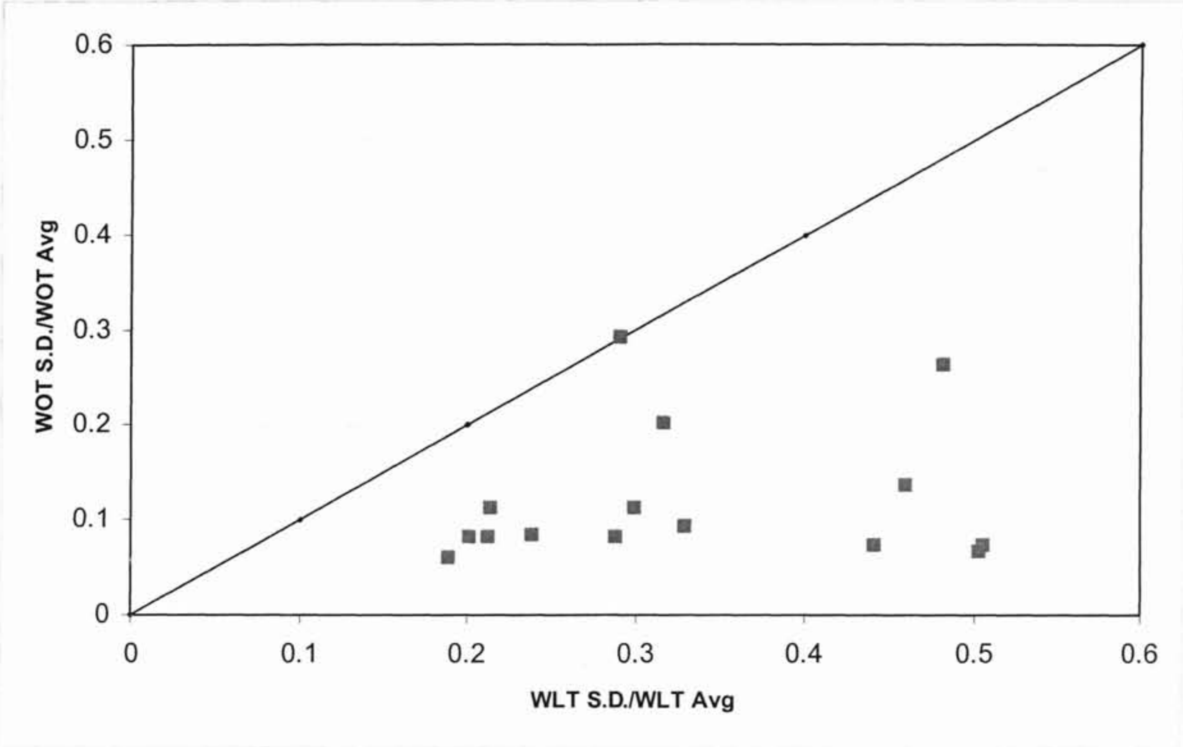

**Figure 4-10: Variation of WOT Std. Dev./WOT Avg. Vs. WLT Std. Dev. / WLT Avg. for 6" Nip Diameter.**

Most experiments in Figure 4-10 are lying below the diagonal line showing that WLT variation is always more than WOT variation and hence it shows little correlation as compared to Figures 4-8 and 4-9. From Figures 4-8 and 4-9, it can be concluded that for 30" and 60" nip roller, the variation in WLT is definitely affecting the variation in WOT, but it seems that there are other factors which are also causing variation in WOT.

From the three graphs (Figures 4-8,4-9 and 4-10) plotted to study the variation of WOT vs. variation of WLT, it can concluded that variation of WLT is causing variation in WOT, but certainly other unknown factors are also playing role to cause variation in WOT.

### 4.4 Effect of Nip Roller Size on Wound-on-Tension:

The effect of nip roller diameter on average WOT is shown in Figure 4-8. Each curve in this figure represents a group of winding experiments, which had both nip load and web tension in common. It is clear from the figure, that the nip diameter has an effect on WOT and for the same winding conditions, smaller nip roller will produce more WOT.

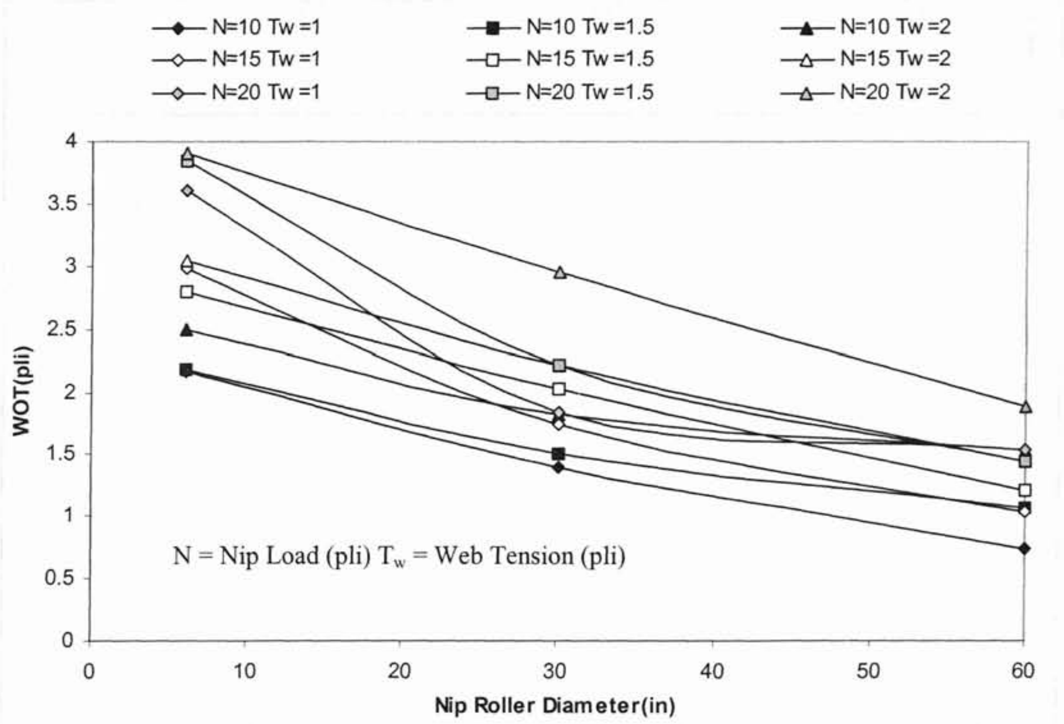

**Figure 4-11: The effect of Nip Roll Diameter on average WOT.**

This study confirms the work of Hartwig [7], who stated that "The difference in WOT and web line tension is a function of the nip load and the diameter of the nip roller." The slope of WOT vs. nip roll diameter in his study was 0.10, in which nip roller diameter was ranging from 4 to 10 inches. This study has lesser slope than what has been found in Hartwig's study.

This study also supports the work of Frye [21], who stated "The small diameter drums produce more wound in tension than the large diameter drums." Frye [21] used nip diameters ranging from about 10-100 inches in his study to see that how much wound-in-tension can be decreased by increasing the size of nip roller. He also found that "There seems to be a limit where any increase in drum diameter (above 30-40 in.) produced no further improvement in the reduction of wound-in-tension." In this study conducted over nip diameters ranging from 6 to 60 inches, there is a sharp decrease in WOT with increase in nip diameter.

Pfeiffer [3] has shown that when the size of the drum is doubled by keeping nip load constant, the wound-on-tension in the rewound roll decreases from a baseline tension of 1 pli to 0.707 pli and if the drum size is tripled, the WOT reduces further to 0.577 pli. In this study, when the size of drum is made 5 times by keeping nip load constant, the wound-on-tension in the rewound roll decreases by 34% and if the drum size is made 10 times, the WOT reduces by 56%. It appears this study has yielded comparable results.

### 4.5: Relative Sensitivity of Input Parameters on WOT:

The average slopes of the Figures 4-6, 4-7 and 4-8 are 0.06, 0.65 and 0.03 respectively. These values indicate that the order in which three parameters affect WOT with highest one first are web tension, nip load, and nip diameter respectively. There are physical limits that confine the ranges of these sensitivities. The break strength of the web will be the upper limit at which sensitivities have validity.

### 4.6: Wound-On-Tension Behavior for Newsprint:

Preliminary studies have been conducted on newsprint to see how a material with relatively low modulus and low coefficient of friction will behave. The WOT, in this case, has been found to change with respect to wound roll radius at all nip loads and it increases more sharply at high nip loads. Figure 4-12 shows the sudden drops of WOT at certain points across the diameter as the machine was stopped to make J-lines. This figure shows that nip load has an effect on WOT and it increases with an increase in nip load.

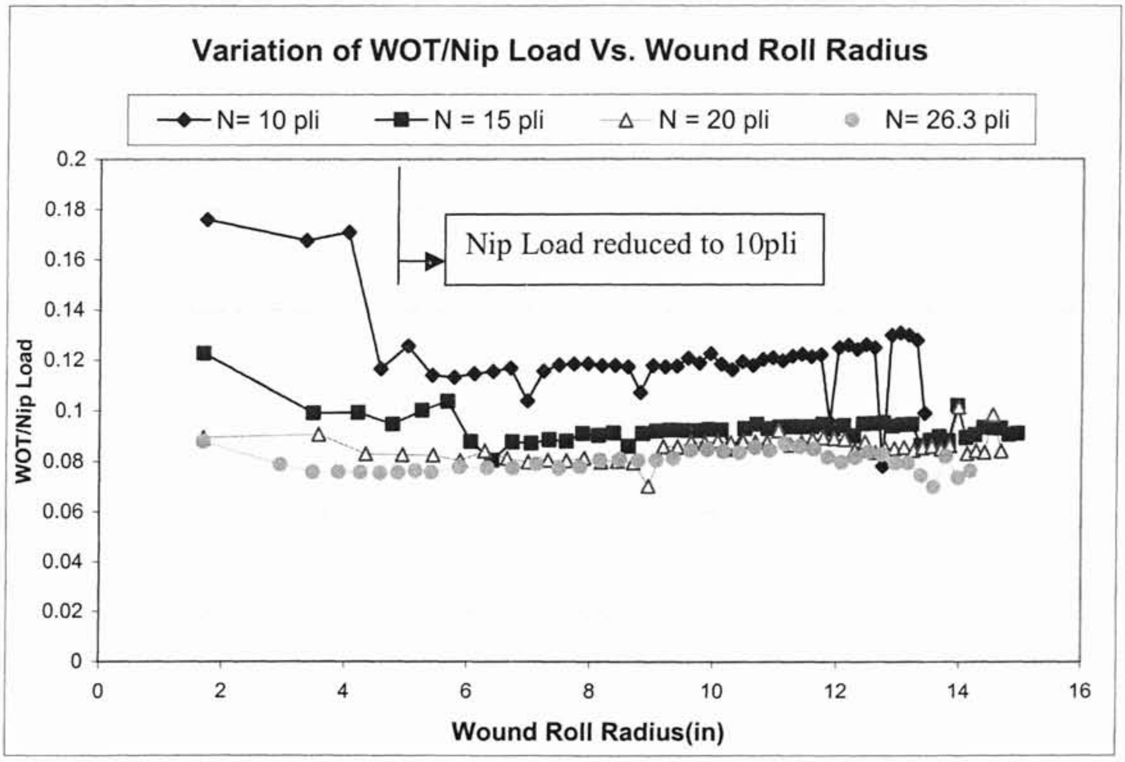

**Figure 4-12: The effect of Wound Roll Radius on WOT for Newsprint wound, with a 60" nip diameter and a web tension of 2pli.**

While winding newsprint rolls at low web tensions, it has been observed that the rewound roll was very soft and loose. So, the experiments on newsprint have been conducted only at high web line tension, i.e., 2pli. Given the variability in the experiments, by comparing experiments at same nip load and web tension conditions for 60" nip roller, WOT's are found to be comparable for FCP and newsprint. Newsprint rolls were found to be soft as compared to FCP at the same winding conditions. Therefore, it can be inferred that newsprint rolls had less pressure inside as compared to FCP. Thus, if 2pli web tension rolls were not acceptable, newsprint would have to be wound with smaller diameter nip rolls.

### 4.7: Interlayer Slippage:

Interlayer slippage, which occurred during winding, was detected with the help of radial lines scribed on the wound roll. In surface winding, slippage is of "loosening" kind, as opposed to the clinching effect in center winding. Most of the slippage occurs in the vicinity of the location of the nip. The radial line scribed on the edge of the roll had started to curve in the direction of the loosening side of the wound roll and gave the radial line a familiar hook or curving popularly known as "J-Line". The winder was stopped about 6-7 times to scribe radial line on the roll at about equal interval of time. The straight portion of the J-Line lies towards the core region while the curved portion of the J-Line is towards the periphery of the roll with the curve of the J-line pointing towards a loosening direction of the wind. The figures from B-1 to B-3 attached in Appendix B are for newsprint and B-4 is for FCP. Newsprint experiments show that angle of J-lines increases with an increase in nip load. This indicates that it is a nip-induced slippage. This supports the work of Vaidyanathan [23]. From the comparison of the J-line experiments for newsprint and FCP at same winding conditions, the angle of J-line was lower for FCP as compared to newsprint. This may be attributed to the difference in C.O.F.. Even though the J-lines for News are dramatic, they represent very little tension change in the web. For instance, Figure B-1 might be having ½" of J-line movement over a thousand feet of web length. Therefore, it can said that these J-lines are not causing much change in WOT.

### 4.8: Discussion:

Frye [21] has documented that there are about 21 winder and web variables, which can affect the roll structure. This research work has focused on studying the effect of four parameters: wound roll diameter, nip diameter, nip load and, web tension.

Figures 4-6 and 4-7 show that the WOT, in case of production scale surface winder, seems to be dependent on nip load and web line tension. This confirms the work of previous researchers [5,8,13].

Hartwig [7] has stated that the difference in web line tension and wound-on-tension is function of the nip load and the diameter of the nip roller. This study appears to support this finding.

Pfeiffer [20] has stated, " The web tension is seen to have proportionately less effect than the nip." Pfeiffer [3] has stated that WOT is heavily dependent on nip load and drum diameter. This study has shown that the order in which WOT is dependent on three parameters with the highest one first are web tension, nip load, and nip diameter respectively. Therefore, this study does not seem to support the findings of Pfeiffer [3,20], probably because of poor control of web tension.

# CHAPTER 5

# CONCLUSIONS AND FUTURE WORK

## 5.1: CONCLUSIONS:

The following conclusions apply specifically to the web materials studied over the range of conditions tested (Sections 3.3.1 through 3.3.4 and Tables 3-1 through 3-3).

- This study shows that the nip diameter is a modifying factor determining the roll structure of surface wound production size rolls as per Figure 4-11. Hartwig [7], Lucas [21], and Frye [22] have reported similar findings. WOT was found to increase 100% over the range of nip diameters studied, refer to Figure 4-11.

- This study has shown that on the average, WOT increases by 28% from start to end of roll (Figures 4-1 through 4-5). So, it can be said that Wound roll radius is a factor in determining the roll structure of surface wound production size rolls. In comparison to the nip diameter, it appears that wound roll radius is less important in determining the level of WOT by as much as a factor of three. This configuration is based on winder configurations in which wound roll radius and hence wound roll weight does not effect nip load.

- Previous researchers [5,7,14] have observed that unlike center winding, only some portion of the web line tension is added to the WOT in surface winding. The results in this study appear to support this finding as per Figure 4-7. At high nip loads, other researchers [1,16] have shown that web tension has substantial effect on WOT. This study seems to support this finding typically at lower web tensions as per Figure 4-6.

- It has been found that with increase in the nip load, there is a corresponding increase in WOT as per Figure 4-6, which confirms the work of previous researchers at OSU [4,8,16-18] and other investigators [1,3]. The average slope of the WOT curves in Fig 4-6 is substantially less than kinetic coefficient of friction for FCP. This is in confirmation with what has been found by Balaji [8].

- Kaya [14] worked mainly on 4" O.D. aluminum nip roller and the diameter of roll he wound was about 10". He found that the slope of WOT curve with respect to wound roll radius is positive. Earlier it was stated that Kaya [14] reported 2.5 lb (0.42 pli) increase in WOT over a wound roll radius range of 1.7" to 5.3". Based on the average slopes witnessed in the data shown in Figure 4-1 through 4-5, there was an increase of 2.02 lb (0.34 pli) over limited range of wound roll radius. It appears that this research yielded comparable results.

## 5.2: FUTURE WORK

- ✓ To check whether WOT is an interfering method or not in case of production scale surface winder.
- ✓ To use nip rollers of diameter more than 60 inches, to see whether there is further decrease in WOT or not as has been reported by Frye [21] in his work.
- ✓ To conduct more experiments on materials exhibiting different material properties and see how material properties affect the wound roll structure in case of production scale surface winder.
- ✓ To modify existing wound roll models to incorporate the effect of nip and wound roll diameter, so that roll structure of a wound roll can be predicted more accurately.
- ✓ To consider the environmental effects as it can change the COF and hence, WOT in a particular experiment.

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# APPENDIX A

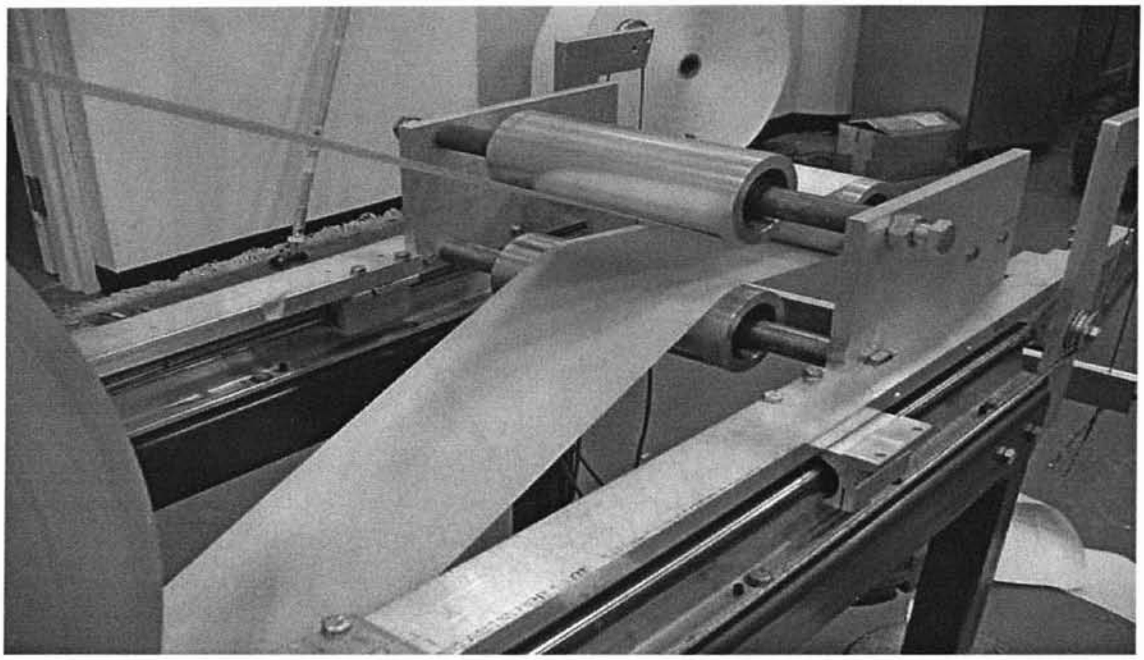

Figure A-1: WOT measurement setup at WHRC.

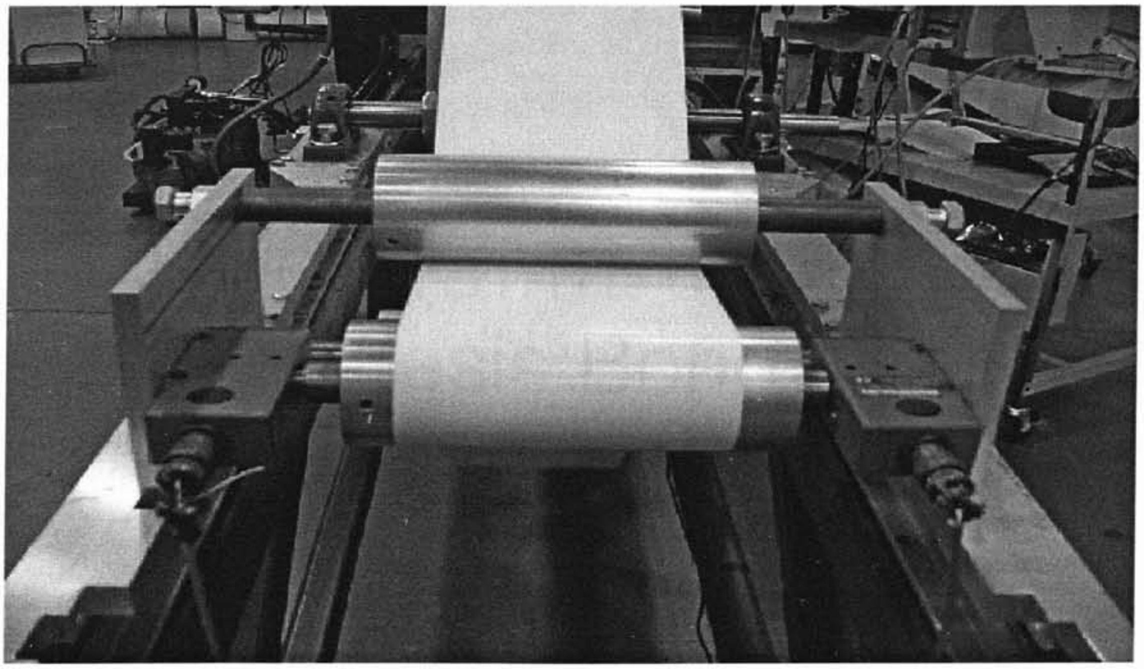

Figure A-2: Another view of WOT measurement setup at WHRC.

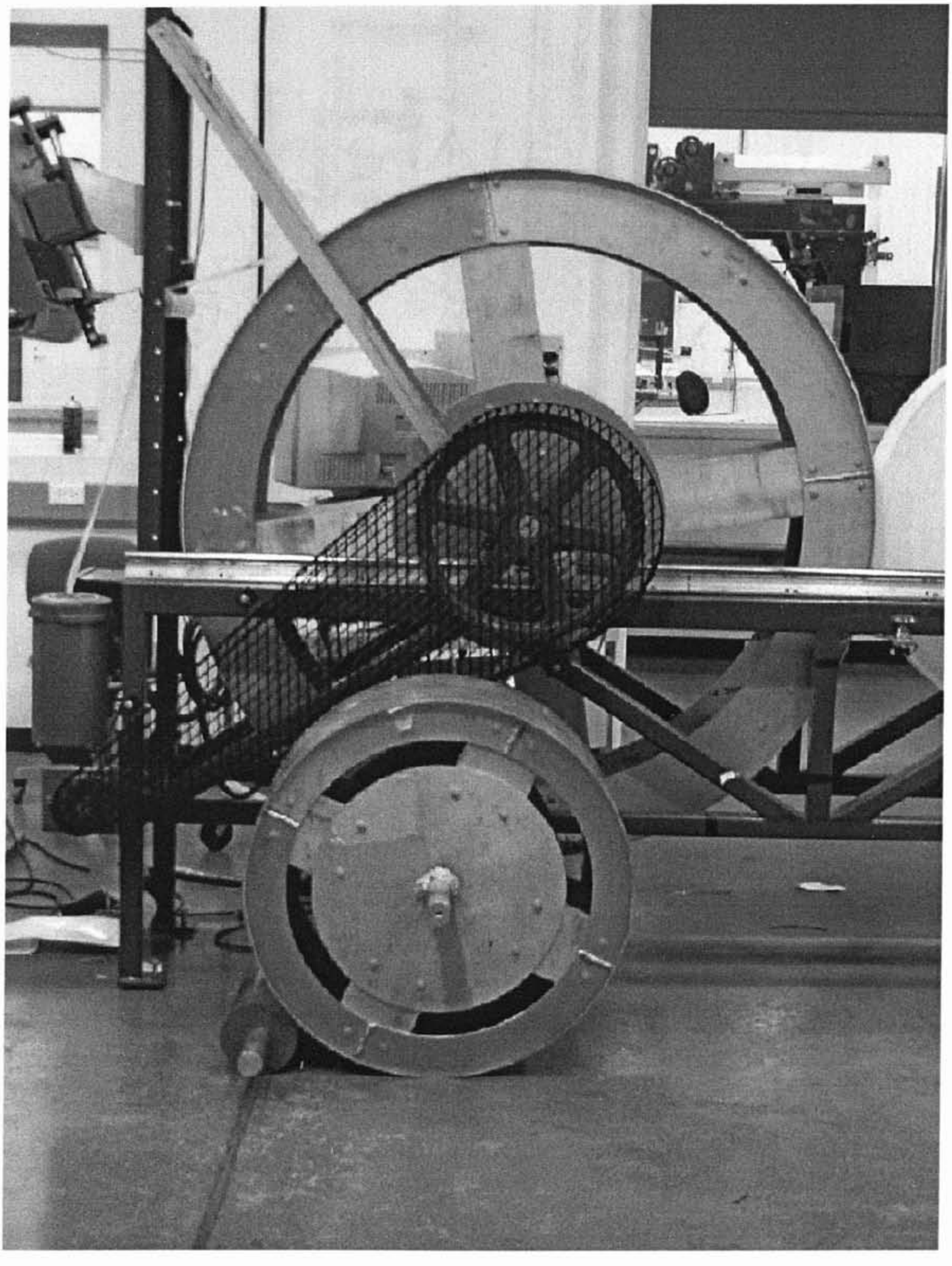

Figure A-3: Three nip rollers of diameters 6”, 30” and 60” used in this study.

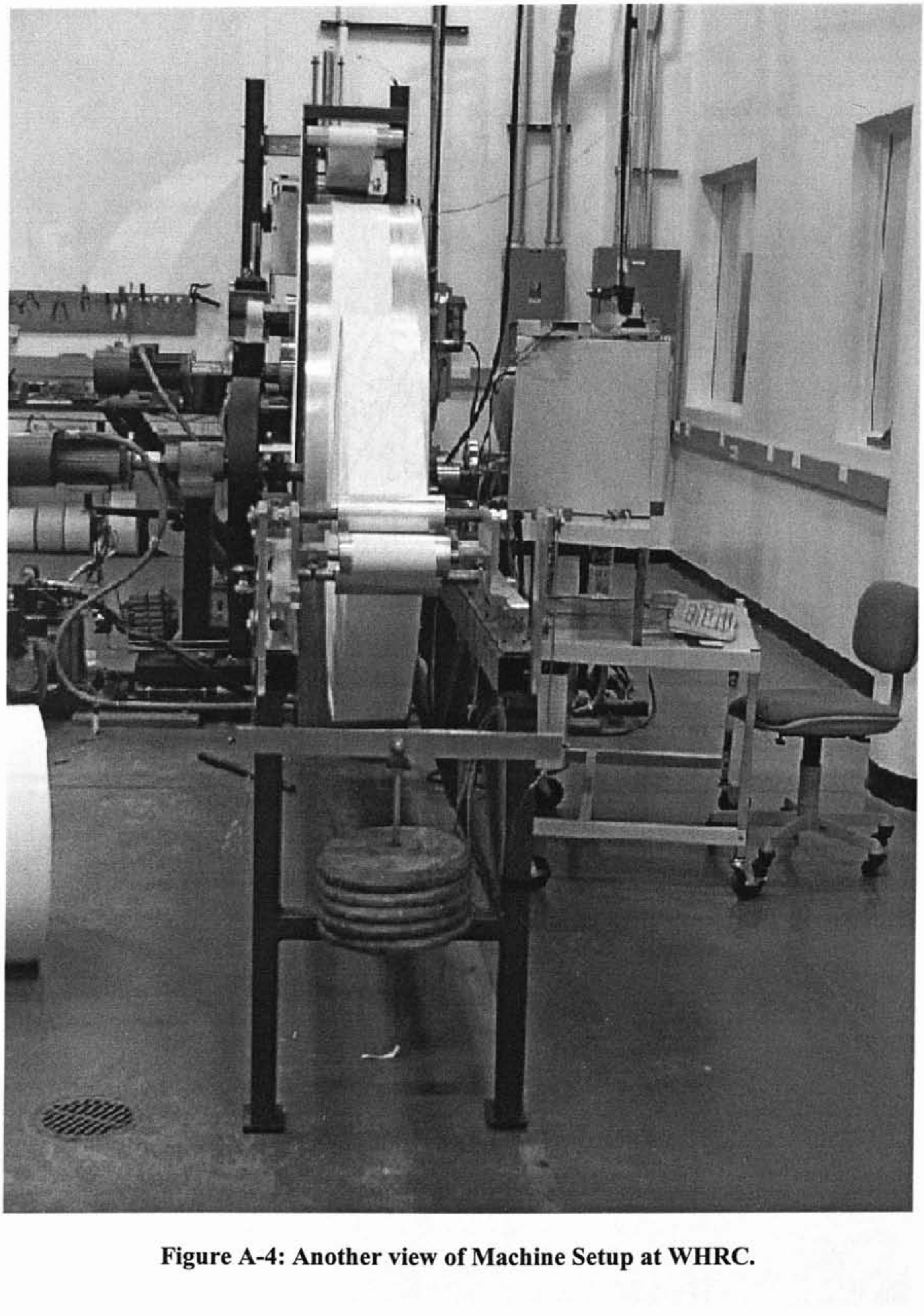

Figure A-4: Another view of Machine Setup at WHRC.

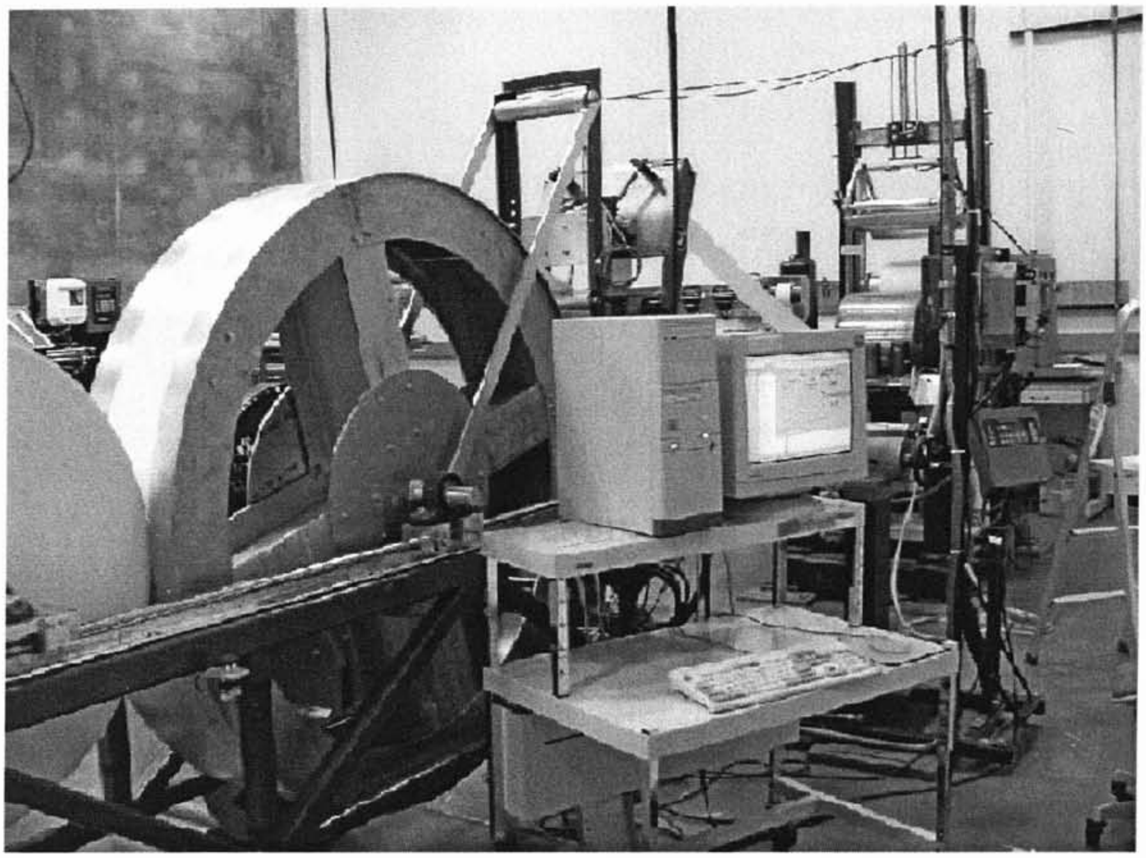

Figure A-5: Data Acquisition system of the machine at WHRC.

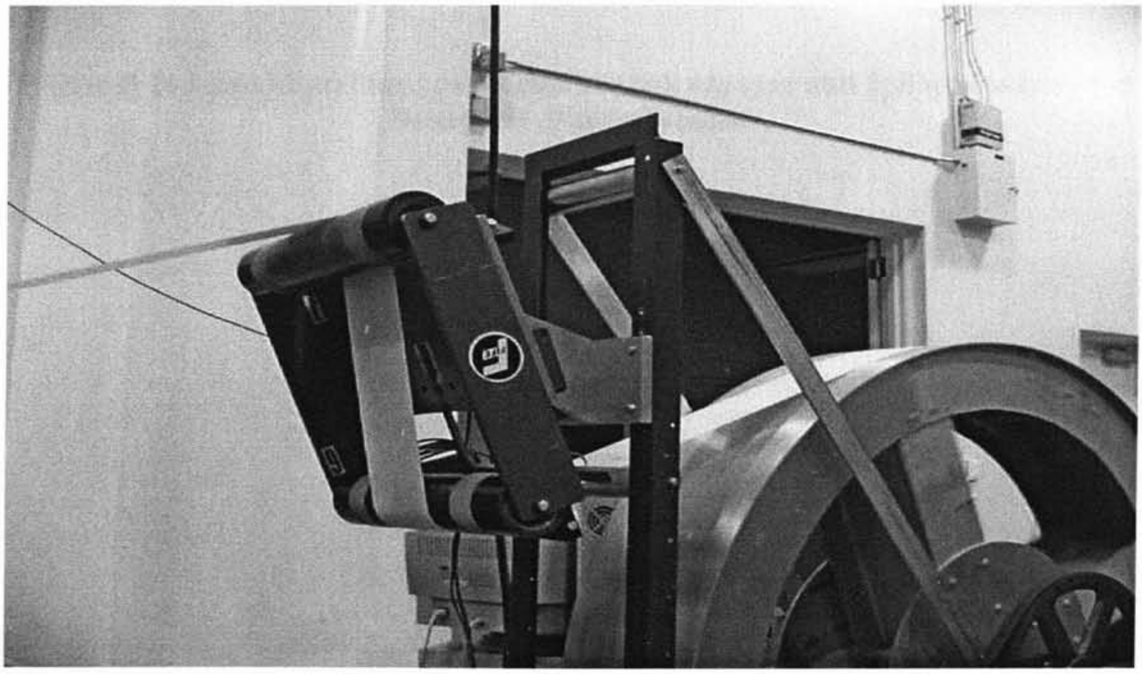

Figure A-6: FIFE Displacement guide at WHRC.

# APPENDIX B

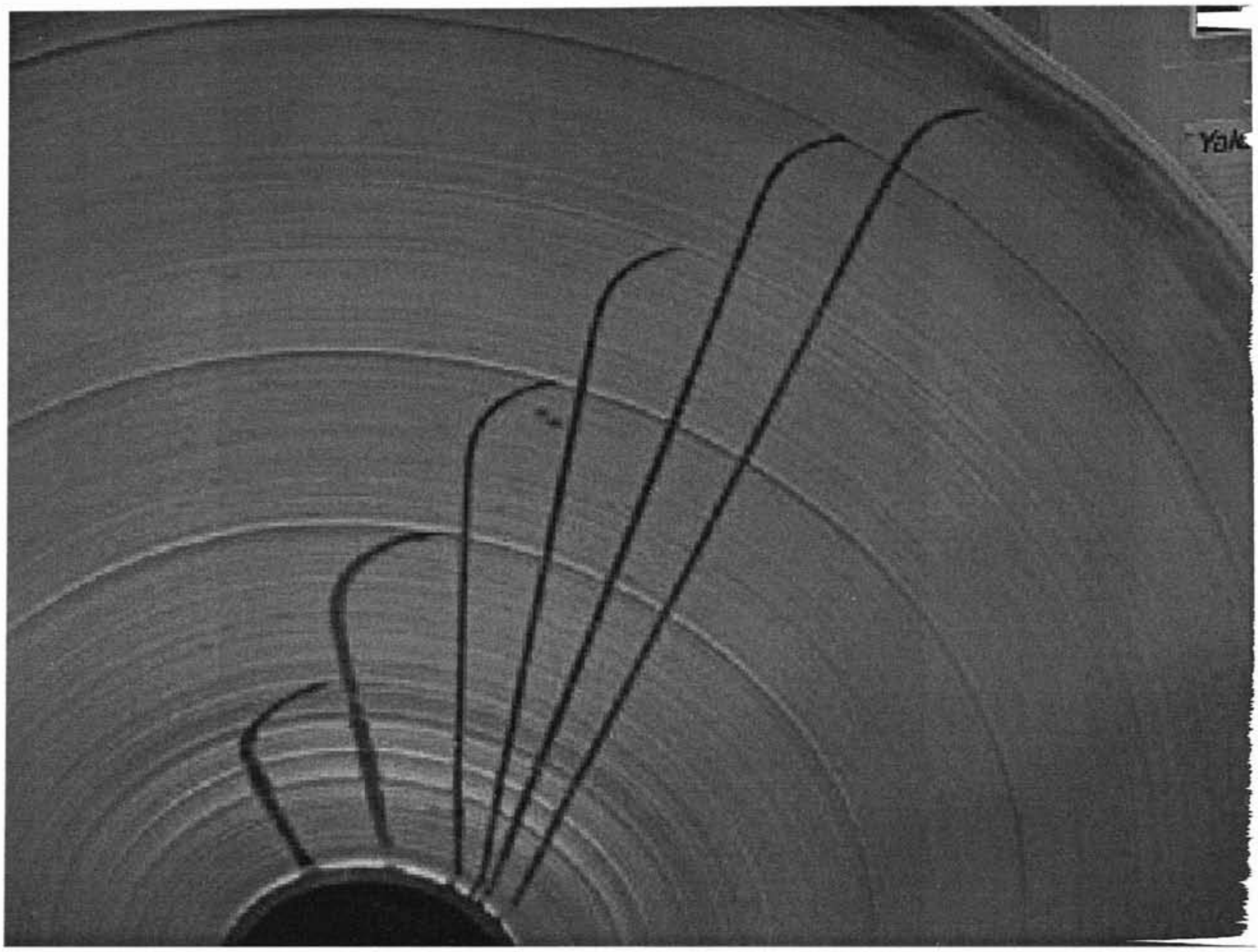

Figure B-1: J-line Experiment conducted at 10pli nip load and 2pli web tension for Newsprint at 60” nip roller.

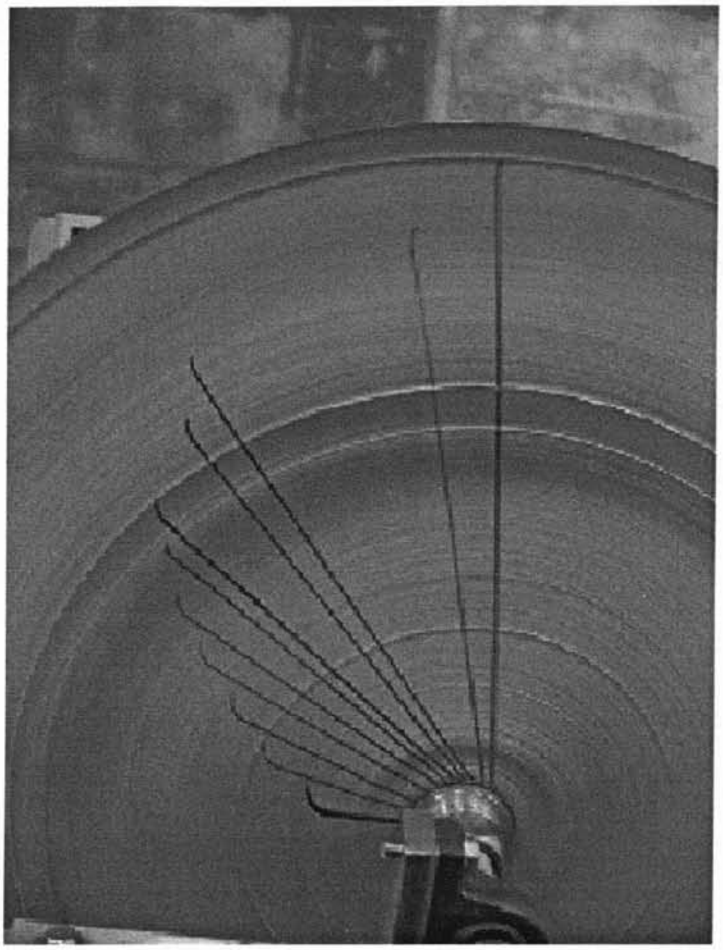

**Figure B-2: J-line Experiment conducted at 15pli nip load and 2pli web tension for Newsprint at 60" nip roller.**

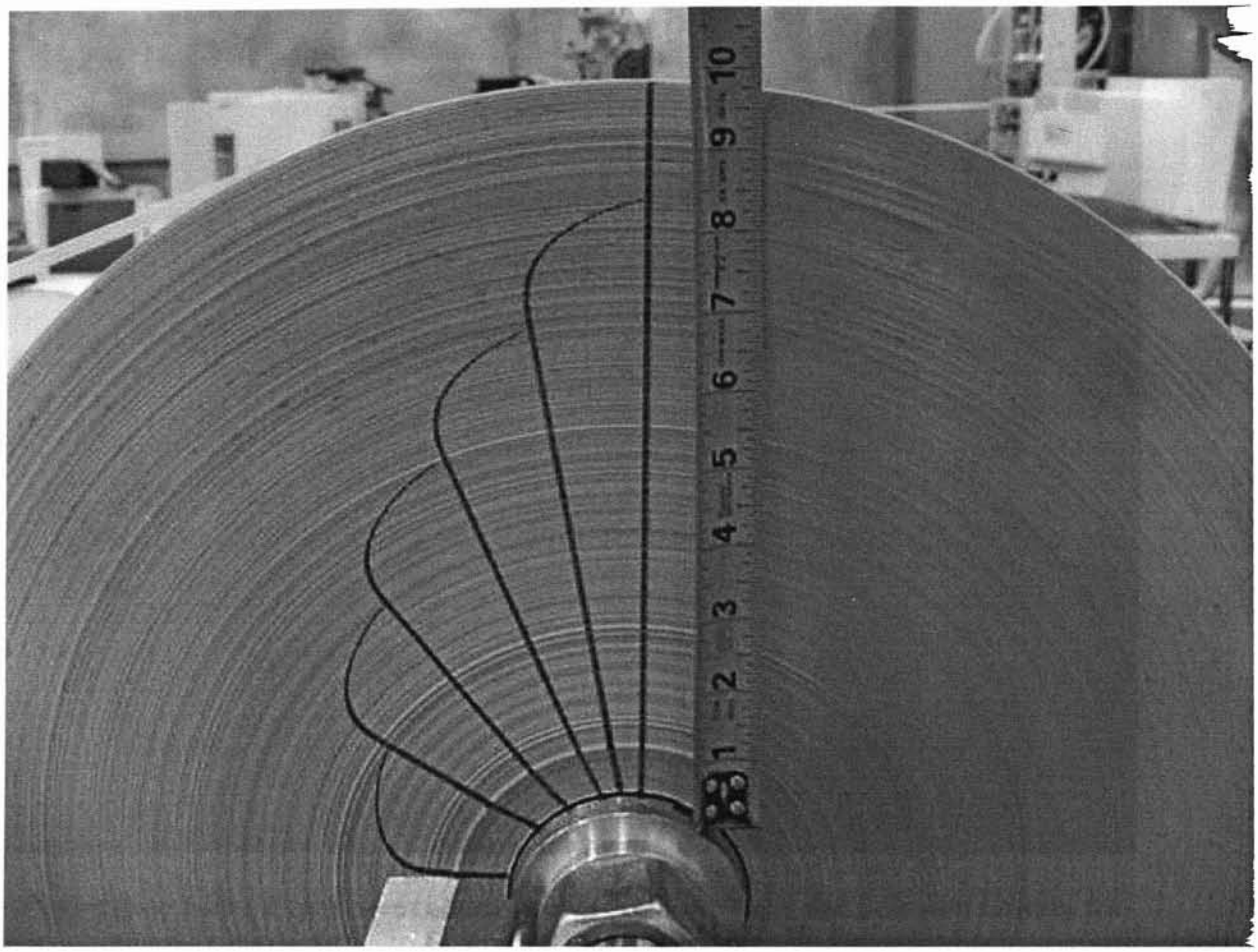

**Figure B-3: J-line Experiment conducted at 20pli nip load and 2pli web tension for Newsprint at 60" nip roller.**

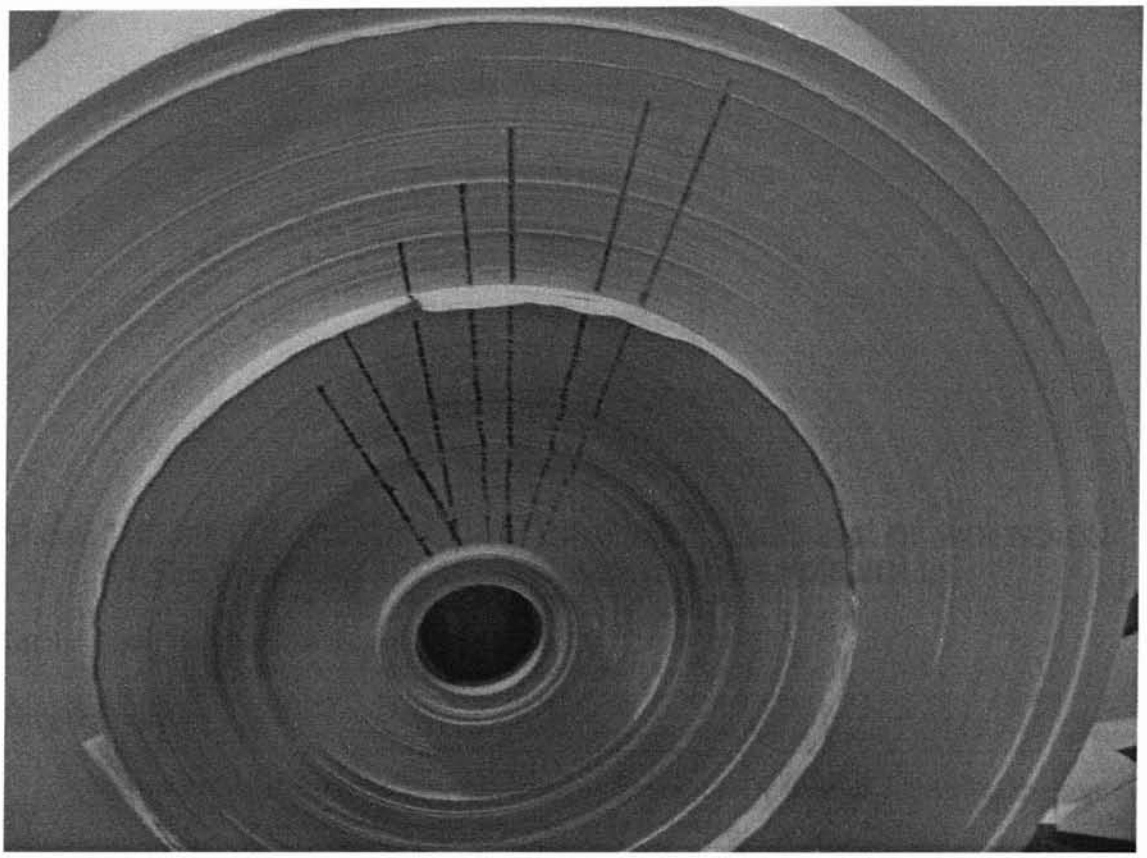

**Figure B-4: J-line Experiment conducted at 10pli nip load and 2pli web tension for FCP at 60" nip roller.**

# VITA

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