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Effect of Wire Gauge, Web Speed, and Coating Solids on Leveling of Streaks in Rod Coating

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EFFECT OF WIRE GAUGE, WEB SPEED, AND COATING SOLIDS ON LEVELING OF STREAKS IN ROD COATING

by

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The behavior of coatings and their study is becoming more important in proportion to additional use of coated paper. Good coating is key to enhance print quality. Blade coating is quite common, but rod coating is coming back for the advantages it has over blade coating. The process of rod coating is simpler and maintenance is easier. Coatings at low solids can be applied with ease and the impurities are washed away by rod rotation. The surface profile of coating is a potential concern, due to streaks in the machine direction. If the coating is immobilized before the streaks heal, these streaks become coating defects. These defects are often referred to as 'rod streaks' and are partly caused by the interaction of wire and hydrodynamic forces.

Wire-wound rods were developed to apply coatings more uniformly than it was done with smooth rods. The problem of streaks still exists. A ribbing pattern also develops. There are several factors that cause these problems. The coating solids and speed play an important role in this process. This study was done to see the effects of speed and coating solids on surface formation in terms of peaks and valleys generated at three different speeds and solids levels. The ribbing effect was also analyzed.

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CHAPTER I

INTRODUCTION

Coated paper use is expanding rapidly. Consumer demand and digital printing require a paper substrate of excellent optical and surface characteristics. Specialty coated papers are also used for photography. The quality of coated paper is measured mainly by its gloss, ink holdout, and ability to form a sharp printed image. The solid areas in an image form an important aspect of coated paper. The halftone images also require a very high degree of smoothness and demand better quality. Coated paperboard is printed for use in packing numerous products for foods, like cereal, and cookies. The quality of printing and images greatly depend on the quality of coating. The latex and plastic pigment have contributed to gloss and ink-hold-out. They have also allowed the use of high solids and increased drying rates for coatings.

The problem of smooth surface profile development still remains a concern. Freshly applied coatings may have micro-pores and streaks in the machine direction. These streaks level out depending on various factors. If the coating is immobilized before they heal, these streaks become matter of concern. Coating streaks have been a long-standing problem and their cause still needs to be explored. The nature of coating, the method of application, base-stock, and several other factors may be suspect.

Wire-wound metering rods have been used for more than 75 years to apply liquids to flexible materials. They are now also being used for less flexible paperboard and paper. They were the first tools used to control coating thickness across the full width of a moving web. They are used in a wide range of applications including the manufacture of tapes, labels, office products, flexible packaging, paper and paperboard (1).

The first rods were made of ordinary carbon steel, wrapped with music wire. Today's metering rods use precision-ground core rods made of stainless steel, which are tightly wound with polished stainless steel wire at high speeds, on custom designed winding machines. According to Booth (1), these metering rods can control coating thickness accurately within 0.0001 inch (0.003mm). Mechanically grooved rods are also being used.

Wire rods have been used in the adhesive and coatings industries for many years. Such coaters boast low cost equipment and excellent coat weight versatility as major advantages. A disadvantage has been the quality of the coating due to defect lines in the coating running in the machine direction. These defect lines are often referred to as 'rod streaks'. The assumption is that the defects are caused by the wire wrap on the rod or the contact of particulate matter in the coating with the rod. It can be shown, however, that these defects are more closely related to the 'ribbing' type of defect seen in roll coating.

The rod coater came from the Mayer Coating process. In 1905, Charles W. Mayer founded the Mayer Coating Machine company in Rochester, New York. The firm made equipment for manufacture of carbon and wax papers, two new and growing industries. These machines used “equalizer bars” or “doctor rods”, the fore-runners of today’s precision metering rods. The rods were made of carbon steel wound with different sizes of music wire (1).Coaters of carbon and wax papers found that they could easily change the thickness of their coatings by switching rods, so they began ordering rods with different wire sizes (1).

Stainless steel rods are resistant to wear. This development has helped wider use of rod-coating, but current high opacity coating materials are abrasive and the wear of metering rods results in a steady loss of coat weight (2). Ribbing problems may occur and hydrodynamic forces may cause loss of coat weight control at high speeds.

In case of rod coating, the wire wrap also disrupts uniform film formation. It can be seen that even without defects, the rod coating has some pattern from the wire. The defects begin at a single point where the disruption reaches a critical level (3). The critical level is reached when the defect is too large to be contained in the wire pattern.

Wire wound rod coating is probably one of the least complex methods for the application of adhesives or other coatings. An excess of material is applied to the web by roll applicator and then the web is drawn over a steel rod wrapped with wire of a specific gauge as shown in Figure 1. This rod meters the amount of material to remain on the web. The amount of material may be adjusted easily by changing the gauge of the wire wrapped on the rod (Figure 2). A large diameter wire allows more material to remain on the web. The simplicity of this coating method allows for low equipment

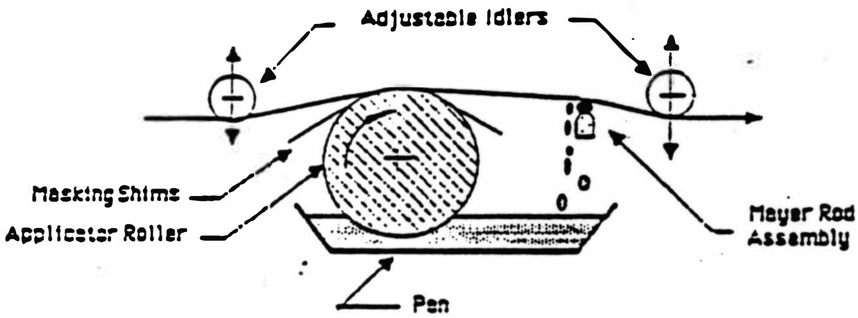

Figure 1. Mayer Rod Coater (1) .

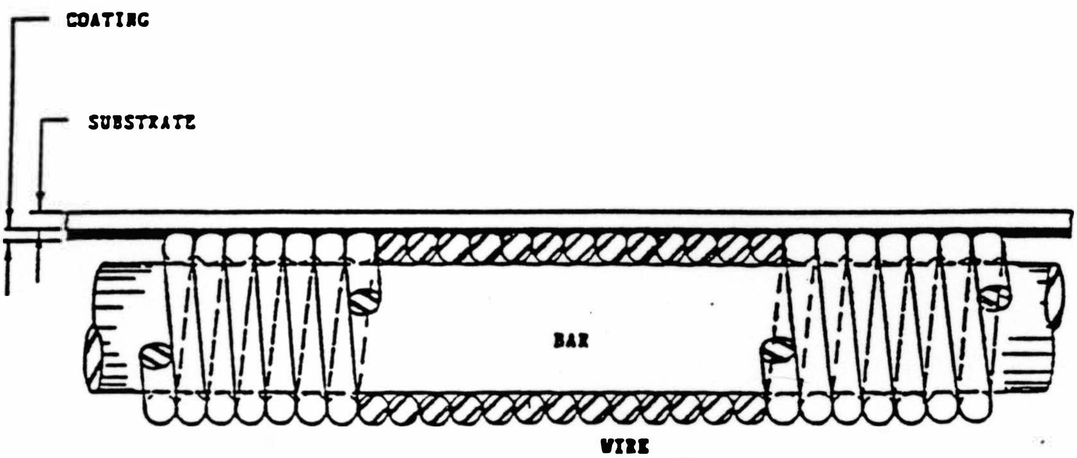

Figure 2. Wire-wound Rod (1) .

costs, easy clean up, quick production changes, and great versatility in the coating to be used. It can be used to apply adhesives or coatings to paper, paperboard, plastic films, and textiles.

The rod coater is used to apply starches, waxes, latexes, and polyvinylidene chloride coatings to paper. Clay coating is one of the most important areas for rod applicators. Wire-wound rods as shown in Figure 2 are used for high grade waxing paper,carbon, and hectrographic paper.Some of the other rod coaters are shown in Figure 3 and Figure 4. The web is moved by a hold-down roll to the applicator roll as shown in Figure 3. The angle of wrap varies from five degrees to twenty degrees to ensure adequate coating pickup. In some designs, the applicator roll is brought in contact with the web by pneumatic pressure as in Figure 4.

The method is not without drawbacks. For example the viscosity range to be used on a rod coater is limited. As the viscosity rises, the metering effectiveness of the rod diminishes. The rod coater also does not deal with dimensional inconsistencies in the web. Another problem area in rod coating is the appearance of coating defects. These usually appear as streaks (3).

Despite the problems of streaks and ribbing, rod coaters have proved to be effective replacement for air knife and blade coaters. For heavier coat weights, coarse surfaces, and wet on wet coating, rod coating has appeared to be more convenient. The debris can lodge under blades and cause many problems. This problem can be reduced substantially by use of rod coaters. Thin coatings can be easily applied with wire wound rods, knurled rolls, and gravure and microgravure rolls at relatively high

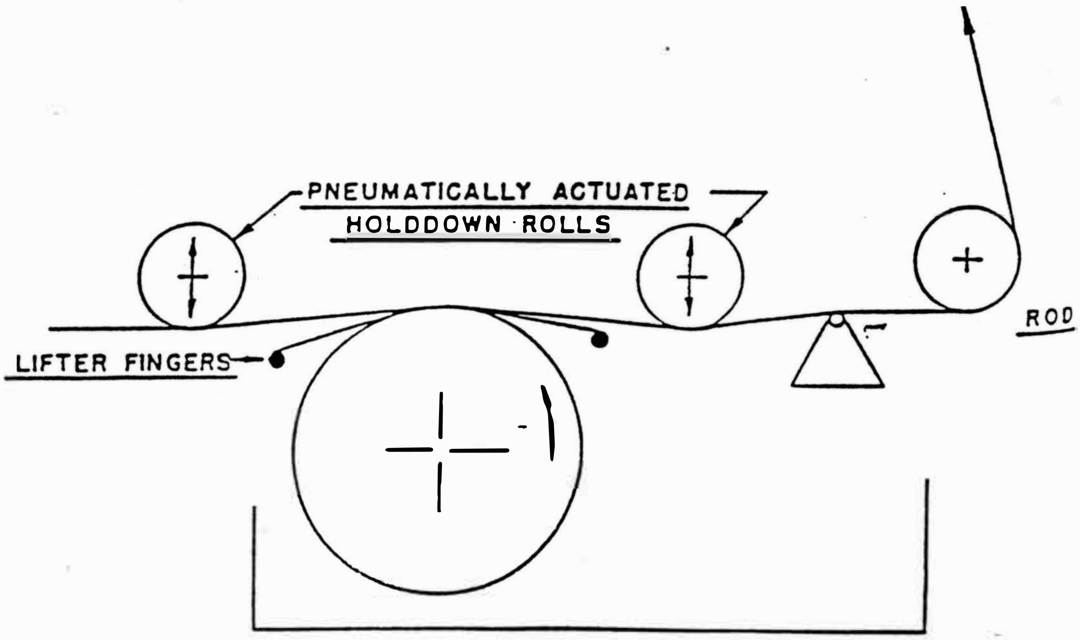

Figure 3. Rod Coater With Hold-down Rolls (2).

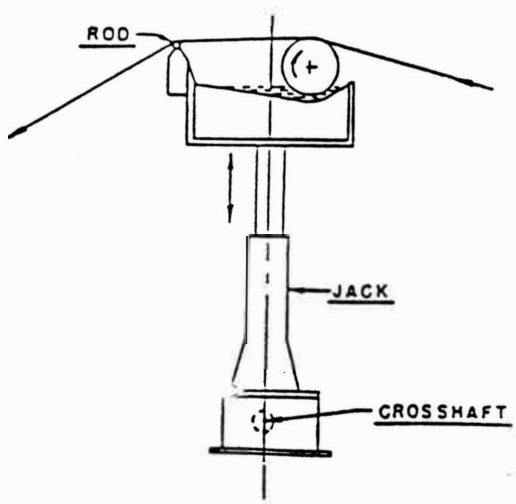

Figure 4. Rod Coater With Pneumatic Roll Applicator (2).

speeds. As compared to smooth rolls, patterned rolls are more effective in metering and ,hence, coat weight control (5).

The development of new less abrasive pigments and synthetic binders that allow higher solids has had favorable effect on the use of rod coaters.

The use of a backing roll against the rod expanded the use of the rod coater. Any inconsistency in the web or tension profile across the web will not seriously affect the coating quality.

Many such coaters are in operation today including the Vari-Bar, the ISO-Bar, the Flex-Bar and others.In addition to this explosion of rod coaters, wire wound rods have been used greatly to apply a heavy coat weight as primary coat, and in some cases on secondary fiber machines (1).

CHAPTER II

REVIEW OF LITERATURE

There are many reasons for defects appearing on the surface being coated. Some of them are process related and may occur in blade, rod, size, or air knife coating due to similar mechanisms.

Some mechanisms in blade coating and rod coating are similar while others vary. The behavior of substrate mostly depends on surface energy, moisture content, micro and macro structure regardless of method of coating used. The nip width, the direction and intensity of hydrodynamic forces vary with the process used. While in the same process, variation in parameters changes the quality of coating in terms of surface profile and coat weight.

As streaks have been a major problem in rod coating, several studies were done to explore the reasons for these streaks. It has been argued that film split, the hydrodynamic forces under the nip and non-Newtonian flow of coating might cause ribbing and streaks. Hull (3) did a study to see the formation of streaks at the meniscus as the film split. Quick immobilization of coating due to properties of substrate or coating formulation may give the streaks less time to heal.

In his study, Engstrom (4) proved that substrate and pressure in the nip changed the quality of coating. Wire-wound rods transfer coating according to wire-gauge and rod-size. Hanumanthu (5) studied coat-weight and coating quality using wire-wound rods and knurled rolls. Ribbing and rod-streaks are closely related phenomena. In the most serious cases, ribbing changes to spattering, streaks, or other coating imperfections and irregularities depending on how the extra coating deposits on paper. Carvalho (6) explored the non-Newtonian effects on the ribbing instability. Bousfield (4) in his work studied leveling of systematically produced coating defects. The web speed, the wire-gauge, and change in percentage solids are important parameters in the coating process and a change in any of them may affect the quality of coating. Some related studies were found in the literature that explain some of the mechanisms involved in rod coating and occurrence of related problems. No study was found in the literature on leveling of coatings for wire wound rods in relation to any of the conditions that are thought to be reason for coating defects, namely: (a) coating solids and rheology, (b) substrates at different level of absorption and caliper, and (c) web speed and angle.

Defects Related to Wire Wound Rod Coating

In his study Hull (3) agrees that even in smooth coating wire marks can be seen but, he rejects the general idea that coating defects are caused by roll patterns or wire. He believed that these defects were caused by particulate matter in the coating during metering. The same idea is supported by the concept of extensional viscosity used by Carvalho et al. (6) to explain the ribbing phenomena.

In the study by Hull (3), the web used was a 2 mil transparent polyester film. Rod number, web tension, rodspeed and direction, applicator roll direction and speed and angle of web wrap were control variables. Photographs of the menisci obtained are presented in Figure 5, 6, 7, and 8.

The white band at the top is the coating applied by applicator roll. The short vertical black lines are wire wraps of the rod. The series of downward pointing white arcs are the menisci formed by the adhesive at the line of separation between the web and the rod. The very white vertical lines across the center of the photo are merely the intense reflection of the photoflash off the metal of the rod. Menisci and coating defects reveal that coating defects appear as meniscus peaks that correspond to spaces between the wires rather than the wire peaks themselves (3). Explaining the exact frequency of the defect, which is obvious from photos, Hull (3) states that if the defect is smaller than the distance between wire wraps, the disruption from the rod will wipe out the defect. The effect of the rod continues even if the defect is larger than the distance between wire wraps. The rod tends to disrupt the edges of the defect and restore some order. This disruption from the wire becomes the determining factor in the character of the coating on either side of the defect. In this way, the defect is always channeled to be contained between wire wraps. If the defect is large enough, the defect can encompass the span of three wire wraps rather than two. Hull (3) hyphothesized that these defects are caused by the same factors that cause ribbing in roll coating.

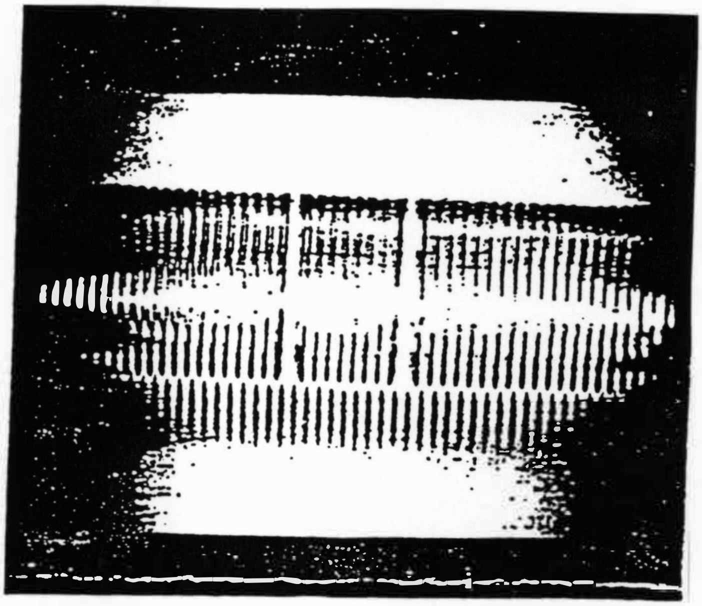

Figure 5. Wire-wound Rod Coating Meniscus (3).

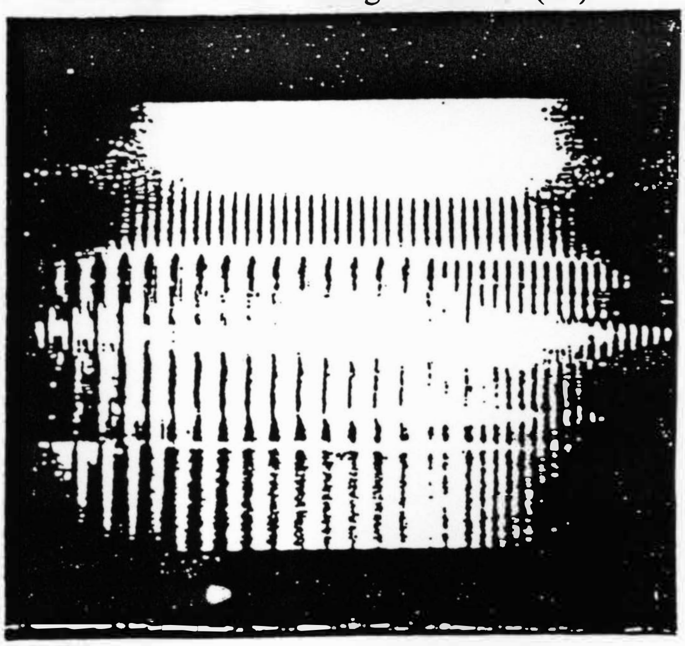

Figure 6. Wire-wound Rod Coating Meniscus (3).

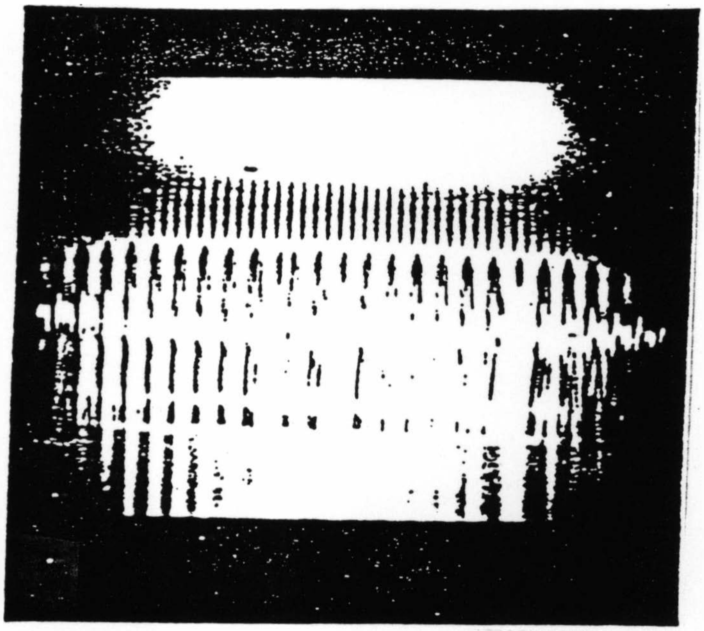

Figure 7. Wire-wound Rod Coating Meniscus (3).

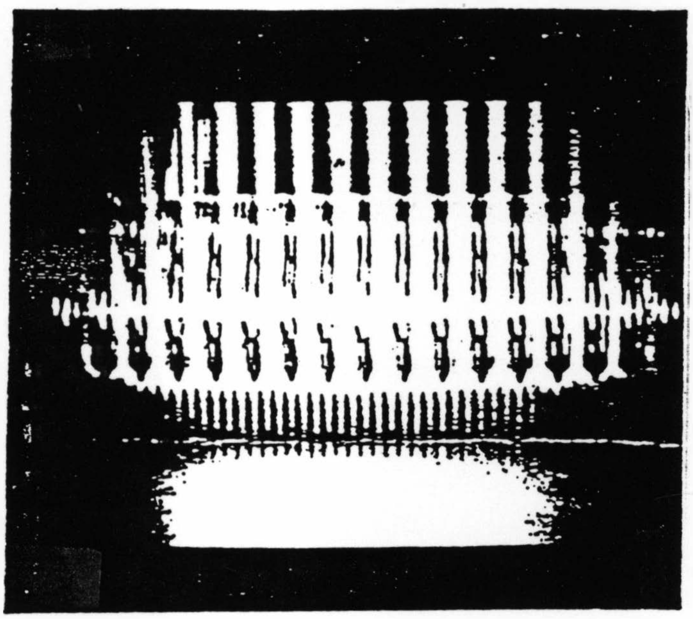

Figure 8. Wire-wound Rod Coating Meniscus (3).

Forming and Consolidation of Coating

Kahila and Eklund have suggested that the coating layer is formed by filling the compressed surface volume of the base paper under the nip, in blade coating.Turai, Kuzmak, and Pranckh and Scriven have a different view. Their opinion is that the coating layer is formed by a fluid flow between the blade tip and base paper. Although compressive forces on the paper are much lower in rod coating, across the rod we may have both conditions occurring (7).

Engstrom also suggested that the forming of the coat layer, regardless of coat weight, is a fluid flow process rather than a void-filling process. This fluid flow continues even after the coating layer is applied (7).

Once coating is applied to the substrate, under gravitational and other forces the coating starts moving from peaks to valleys and this process is normally referred to as leveling. The time for this leveling, though very important, is short and this leveling process stops when the coating is exposed to heat. The amount of solids at the point when leveling stops, is termed as immobilization solids.

'Immobilization solids' is an elusive quantity to measure. A large research effort has dealt with measuring the rate of dehydration on the occurrence of immobilization solids; these are reviewed by Lepoture and Herbert and co-workers . The rate of water sorption into the base sheet has been studied by Eklund and Salminen, Engstrom and Rigdahl, and others (4).The point at which the coating cannot flow is characterized as the immobilization point. As water is removed from the coating layer either due to sorption into the base sheet or due to evaporation, regions of the coating cannot flow, but other regions have the potential to flow. Only when the entire coating layer reaches the solids volume fraction which corresponds to high viscosities is the total coating layer immobilized (5).

The above discussion suggests that percentage solids, coating rheology, and water-retention of coating may affect the leveling before immobilization which will be extended with low solids, higher coat weight, high water-retention and favorable rheology of coating (low viscosity).

Coating With Patterned Rolls and Rods

Roll coaters perform the four basic functions of coating: to feed, meter, distribute, and apply a liquid film onto a continuous substrate, by using a system of counter- and/or co-rotating rolls (Benjamin et al. 1991, 1992).Common configurations of roll coaters have from two to six rolls to accomplish these coating functions and in most cases one or more rolls are equipped with a soft rubber cover.In any of these smooth roll coating configurations, the hard roll can be replaced by a patterned roll. A smooth metering rod held against a tensioned web can equivalently be replaced by a wire-wound (Mayer) rod. The main advantage of using patterned rolls over smooth ones is that the metering function is achieved by the volume of the wire diameter, rather than the gap between smooth rolls (5).

The main issues in roll coating are: (a) mean coated thickness and its dependence on gap (positive clearance),(b) nip (interference) between rolls,(c) speed differential of roll surfaces, (d) direction of rotation of rolls with respect to each other, (e) gap variations from roll misalignment and roll run-out, (f) pressure profile developed between the rolls and the resulting roll separating forces, and (g) coating instabilities like ribbing, film breakdown, rivulet formation,and other aspects of coating quality.

The same fundamental issues relate to patterned roll coating as well. Some issues, however, are unique to patterned roll coating. Not only is the mean coating thickness a concern, but also the cross-web coating profile imparted by the pattern. Pressure distribution developed is three-dimensional and cross-web gradients drive cross-web flow that may lead to flow rearrangement (5). Mean coated thickness delivered by a metering rod depends on the cross-section available for flow per unit length of rod. The viscocapillary lubrication model of wire-wound rod metering predicts, for several different cross-web profiles, that mean coating thickness is always between 60 and 70% of this cross-sectional area between the rod and the web. When the gap between the rod surface and the web is much smaller than the rod diameter and the wire diameter or groove depth, the cross section available is called the ***volume factor*** of the patterned rod (5). Experiments by Hanumanthu (5) indicate that the mean coating thickness, as a fraction of the volume factor of a wire-wound rod, predicted by this approximate theory exceeds measured ones by less than 10%. The agreement between theoretical and experimental curves improves as gap and wire diameter become smaller.

In his study, Hanumanthu (5) showed that metered thickness did not depend on roll speed, liquid viscosity or surface tension, i.e., it was independent of the capillary number,Ca. (Ca ≡ viscosity × roll speed/surface tension); it depends on wire diameter alone. However, at a higher speed, the lift created by the rejected liquid is sufficient to widen the set gap and coating thickness rises.

According to Orchard (5) at low speeds, the leveling rate is directly proportional to mean thickness and surface tension and inversely proportional to viscosity and rib spacing.

$$\boxed{\text{Leveling rate} \propto \frac{\text{mean thickness}^3 \times \text{surface tension}}{\text{viscosity} \times \text{rib spacing}^4}}$$

At higher speeds this relation does not hold. In this formula, the rate of water absorption by the web is ignored.

Ribbing in Wire Wound Rod Coating

Roll coating is widely used to apply a thin liquid layer to a continuous, flexible substrate or web. If the roll speed is too high, the profile at the film split meniscus is often wavy in the transverse direction. This type of instability, or rather the three-dimensional flow to which it may lead, is commonly called *ribbing* as shown in Figure 9 and 10. It can limit the speed of the process if a smooth film is required as a final product. Many paper making and coating operations involve film splitting between rolls and thus, are susceptible to this type of instability.

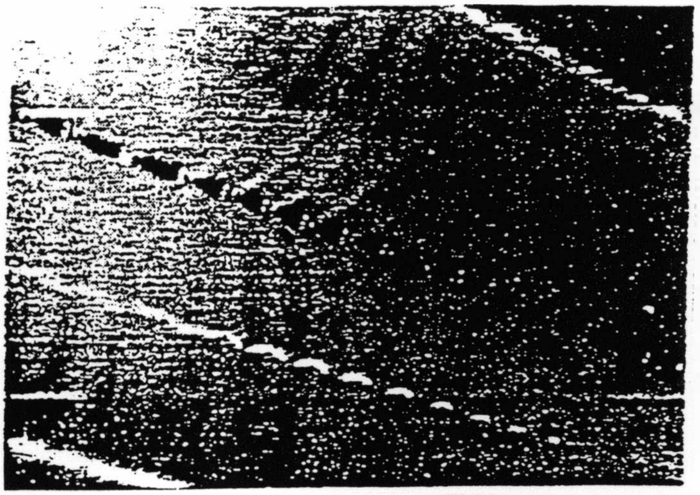

Figure 9. Ribbing Instability in a Forward Roll Coating Gap With Newtonian Liquid (6).

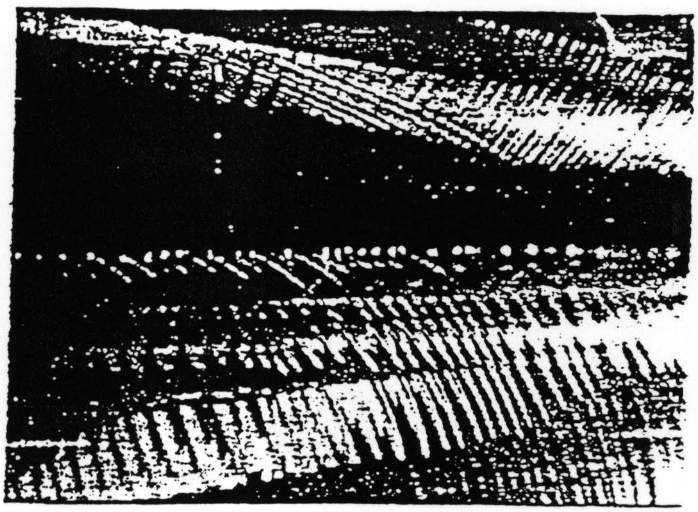

Figure 10. Ribbing Instability in a Forward Roll Coating Gap With Polymeric Solution (poly-acrylamide in Water) (6).

The instability of the splitting of a Newtonian liquid layer, or film, as it exits from between two rotating rolls or spreaders has been extensively studied. The onset of visible ribbing in symmetric film splitting (i.e. counter-rotating rolls of identical diameter and speeds) was the subject of experiments by Pitts & Greiller, Mill & Smith, Greener et al., Benkreira et al. and Coyle et al. (6).

The tendency of surface tension to smooth a perturbed meniscus opposes the destabilizing tendency of viscosity induced pressure perturbation. A critical value of the ratio between these two forces, i.e. the capillary number $Ca \equiv \mu V/\sigma$ marks the onset of meniscus nonuniformity. Here μ is the liquid viscosity, σ its surface tension and V is the mean roll speed. In practice, coating solutions often contain polymers. The rheological properties may markedly alter the performance of a coater. At extreme conditions, the ribs may grow and form filaments that eventually break in such a way as to form small drops, a phenomenon known as spatter or misting.The first analyses of non-Newtonian effects in roll-coating flows were restricted to shear-thinning behavior and simple power-law models. Greener demonstrated that a shear-thinning liquid is always more stable than a Newtonian liquid when the basis of comparison is equal viscosities at a nominal gap shear rate of $\dot{\gamma} = V/H_0$, where v is the mean roll speed and H_0 is the half-gap width. Coyle showed by solving the equations of linear stability theory by Galerkin's method that the flow stability of Newtonian liquid is approximately the same as that of shear-thinning liquid of equal viscosity at a nominal shear rate of $\dot{\gamma} = V/2H_0$ (6).

Onset of Ribbing

Due to excessive interaction of forces involved and exaggerated difference in intensity of forces at higher speeds, the ribbing instability common in roll coating (Mill and South, Pitts and Greillor, Pearson, Cafe) sets in. The downweb ribs start off spaced wider than the wire spacing, but get closer as roll speed rises further.At even higher speeds, the still narrowing rib spacing ends up matching the wire spacing, and then the ribs are steadied by the wire windings. The rib frequency does not change further. So a distinct advantage of coating with wire wound rods is in their steadying the ribs at high speeds. The appearance of unsteady ribs at high roll speeds has been observed by Carvalho et al. In wire-wound rod coating, the appearance of the ribs at spacing different from wire spacing has also been observed (5).

Bauman et al. experimentally tested the effect of certain polymer additives on the ribbing instability. They observed that the critical speed at which ribbing first appeared was smaller than in the case of a Newtonian liquid. They advanced a simple argument about the effect of liquid elasticity on the stability of the flow. They concluded that the Non-Newtonian normal stress destabilizes the flow (6).

Glass like Carvalho also related ribbing to the extensional viscosity. He was working on the behavior of trade paints. His main conclusion was that paints with high apparent extensional viscosity produced extremely large and stable filaments. He argued that the more stable the filaments, the greater the spatter, because the filaments elongate more and are farther from the roll when they break.However, he was unable to correlate quantitatively the extent of spattering with the data available on apparent extensional viscosity (6).

Extensional Stress and Mechanisms of Ribbing

Fernando and Glass found that the greater the apparent extensional viscosity, as measured by fiber-section technique, the longer the filament in their experiments and greater the misting in certain applications.

The ribbing problem, origin of streaks, and other related problems are attributed to the stress component along, across, and perpendicular to the streamlines. All stress components vanish in outflow region, because the velocity distribution approaches plug flow.

"As expected at the symmetry plane, the shear stress is zero.The region of high shear across streamlines is close to the roll surfaces and peak at the plane of minimum clearance. It is noteworthy that just upstream and downstream of the plane, the shear stress is zero across the whole gap; moreover at these same locations, the extensional stress field (stress along the web - stress perpendicular to the web) reach a local maximum (upstream) and minimum (downstream). These portions are at the maximum and the minimum of the pressure along the gap; at them the pressure gradient is zero and the velocity profile is therefore constant. The maximum extensional stress occurs at the free surface, just downstream of the stagnation point. The shear stress vanishes across streamlines at the film split region. However, no component of stress tension, intrinsic or otherwise, can be used to decompose the state of stress suffered by a liquid particle into shear and extension contributions. For example, in a strictly elongation flow which is irrotational, across the streamline stress does not vanish although the particles do not suffer shear deformation (6)".

Extensional Rheology of Polymers

The addition of small amounts of high molecular weight polymer to a lower molecular weight solvent can dramatically affect its shear and extensional rheology. The rheology is strongly influenced by the polymer conformation in solution, in particular by whether it is coiled or rod-like (in extreme cases) in the presence of solvent.

Effect of Extensional Thickening and Extensional Thinning on Ribbing

Polyethylene oxide (PEO) is an immensely flexible coil in water, whereas xanthan gum is semi-rigid.Aqueous solutions of both demonstrate shear thinning behavior. PEO is extensional thickening and xanthan is extensional thinning. The extensional thickening of PEO solutions has been attributed to the presence of entanglements. Extensional thinning in the case of xanthan is thought to be due to the alignment of rod-like molecules with the flow (6).

In their study Carvalho et al. (5) used 0.5 weight percent solution of PEO (molecular weight 5 million gram per mole) in water and 0.05 weight percent of xanthan (molecular weight 2 million gram per mole) in 50/50 (by volume) glycerin/water. This gave steady shear viscosity for both solutions (6).

A stationary plexiglass plate and a roll 20.3 cm in diameter and approximately 30.5 cm in length was used. The roll could be adjusted horizontally to change the gap. The image of separation line on the plate was viewed through the transparent plexiglas plate and was recorded with a camera placed behind it.

"The gap between the roll and the plate was varied from 100 to 400 μm. At each gap setting, the speed was raised in increments of 1 RPM until the separation line displayed a perceptible distortion that was approximately periodic along its length. This speed was taken to be the critical capillary number (6)." They found out that as the gap widened, the critical velocity increased, and a uniform film could be obtained at a much faster speed.

At the gaps, that were studied, PEO solutions had the smallest capillary number for the onset of ribbing. The reason cited by the author is that the actual viscosity of this solution in the film split region was larger than the value used in the definition of capillary number, due to the extensional thickening character of the solution. Xanthan solution, in spite of its extensional thinning behavior, had lower critical capillary number than that of Newtonian liquid(glycerin/water solution). The elastic character of the liquid might have contributed to the early onset of ribbing. The wavelength of ribbing pattern for PEO was smaller than that of Xanthan.

The Leveling of Coating Defects

In relaxation of coating after application both surface tension and the viscoelasticity of coating materials play an important role.The physical shape of pigments as well as active groups of additives like CMC affect rheology that affects leveling. The coating materials show not only shear thickening or shear thinning ; they also exhibit a great amount of viscoelasticity. It can have pronounced effect on the behavior of colors in terms of rheology and its consideration is very important to predict the properties of final coating. Viscoelasticity of dried coatings can play an improtant role in determining the supercalendering parameters to achieve optimum gloss, surface profile and ink hold-out (8). It has also been shown that the magnitude of the elastic parameters of the colors is related to the presence of the water-soluble polymers, e.g. starch or carboxymethyl cellulose (CMC) in the liquid phase of the colors (1,4,5). Since coating colors are viscoelastic materials, they are expected to exhibit a pronounced creep deformation under load and also stress relaxation when subjected to a constan strain (8).

The irregularities or streaks are usually visible in wet coating that disappear before coating is immobilized. Some of them, usually the coarser ones, do not flow out sufficiently to disappear completely and they remain as severe quality defects in the dry coating layer. It is possible that the elimination of such blade or rod streaks is dependent on the relationship between the viscoelastic flow rate of the colors and the immobilization rate, determined by the dewatering and the drying of the wet coating layer.

The study by Adelfson et al. (8) showed that leveling time was substantially reduced when 2 parts CMC per 100 parts of $CaCO_3$ or clay was used. They concluded that the viscoelasticity may have a strong influence on such an important technical problem as the elimination of streaks. They admitted though, that dewatering and the drying rate are also of prime importance.

Substrate and Leveling

The leveling is also affected by water-retention capability of coating. The substrate is another important factor in absorption of liquid and consequent immobilization of coating which then affects the leveling of streaks in coating.

As noted by Salminen (9), the physical entrapment of coating into paper originates from capillary pressure. In the absence of external pressure, the transport of coating into the web is the balance between the capillary pressure and the viscous drag of coating. The dynamic character of the capillary pressure is often dependent on the molecular processes ahead of the liquid front. Therefore, the capillary transport rate is strongly influenced by the liquid temperature, dynamic surface tension of the liquid, and the surface tension of the solid phase. The capillary transport rate is also influenced by the viscosity of the liquid and the moisture content of the paper, although their effect is not especially significant. However, calendering was found to be an inefficient method of regulating water transport under no external pressure.

Diffusion is probably the most important transport mechanism in hydrophobic (sized) paper qualities under no external pressure. Water transport rate in hydrophobic papers is therefore reduced by absorbed moisture.

External pressure, on the other hand, accentuates the importance of the structural properties of the paper and the viscous properties of the liquid. Water transport under high external pressure can therefore be effectively controlled by the degree of calendering, the liquid temperature, and the degree of sizing. However, the surface tension of the liquid phase and the moisture content of the paper have only minor influence on water transport under high external pressure.

Keunings and Boustead present a linear analysis and a two-dimensional finite element solution for the leveling of a viscoelastic film. Large polymer relaxation times were found to retard the rate of film leveling compared to the equivalent Newtonian case. The effect of thixotropy and yield stress on the rate of leveling is not well quantified in the literature (4).

According to Bousfield (4) as the irregularity levels, water is typically absorbed into base sheet and evaporated from the surface. Both of these processes cause a filter cake to form. If the coating is a suspension with significantly large particles the Brownian motion of the particles is small. The loss of water due to evaporation may cause a high concentration of starch or other additives at the gas-liquid interface. This high concentration will increase the viscosity of the coating in this region and may slow down the evaporation rate.

Surface tension tends to minimize the surface area of any liquid. Therefore, on a planar surface, surface tension creates a high pressure region under the thick coating layer and a low pressure region under the thin layer. This pressure difference drives the liquid from the thick to thin regions.

Obviously leveling of coating depends on substrate properties, coating formulation and related properties, and hydrodynamic forces that are related to speed, nip, and liquid dynamics.

CHAPTER III

STATEMENT OF THE PROBLEM

The uniformity of the coating layers is critical in determining the quality of the final paper coating. Irregularities in coating thickness which are too large can cause problems during supercalendering, winding and printing. Microscopic irregularities can result in low gloss coatings (5). The surface tension, coating rheology, water flow into the base sheet, process conditions, and drying, all interact to determine the final surface quality.

In rod coating, the leveling of coating defects and irregularities is important in obtaining high quality coated surfaces (6). The streaks labeled as rod marks or wire marks have to heal before the coating is immobilized. There are a number of factors involved:

1. Material Variables: (a) the substrate, (b) rheological properties of coating, (c) water retention of coating, and (d) hydrodynamic forces.

2. Process Conditions: (a) wire and rod sizes, (b) the speed and angle of web (in-going nip and outgoing nip), (c) deformity of backing roll, (d) force applied against backing roll, and (e) the rod speed and direction of rotation.

The object of this study was to measure the effect of coating solids and speed of the web on the leveling of coating in terms of the surface profile.

Coating solids change the rheological and hydrodynamic forces. The web speed changes retention time under nip and the hydrodynamic and centrifugal forces. The wire-gauge changes the coat weight and as a result the behavior of pigment immobilization and the amount of available liquid for healing is changed.

There are some related problems of ribbing, splashing, and loss of coat weight control. The occurrence of these problems at different coating solids and machine speeds was also observed.

CHAPTER IV

OBJECTIVES OF THE STUDY

When coating is applied to the substrate, a new surface is formed by coating particles. Variable conditions generate different surfaces. The effect of the following variables was studied on the surface formation and ribbing patterns generated when coatings were applied using wire-wound rod: (a) web speed, and (b) coating solids.

To meet the above mentioned objectives, the following variables were measured: (a) surface roughness as peaks and valleys, (b) the wavelengths and amplitudes of dominating ribbing patterns, (c) wavelength and amplitude variation in dominant curves, (d) resulting ribbing patterns, and (e) coat weight under various speeds and solids.

CHAPTER V

EXPERIMENTAL DESIGN AND PROCEDURE

Three different coatings were applied to a hydrophilic polyester film at three speeds.

The coating colors were prepared using the formulation in Table 1 at 64%, 62%, and 60 % solids.

Table 1

Coating Formulation (Dry Basis)

Clay #1 (D.B.Cote)	80 parts
TiO_2	20 parts
Latex	16 parts
Lubricant (calcium stearate)	0.85 parts
Water retention aid	1.6 parts
pH	8

The latex used was Dow 620 and water retention aid used was Alco gum(L-29). Both Brookfield and Hercules high shear viscosities were measured. The particulars are given in Table 2.

Table 2

Brookfield and High Shear Viscosity of Coating

Coating Solids	Brookfield Viscosity (cP)	Spindle	RPM	Hercules High Shear Viscosity (cP)	Bob	RPM
60 %	648	#5	100	30.7	E	4400
62 %	848			39.6		
64 %	1200			55.2		

The solids and speeds referred to in the following pages are as described in Table 3.

Table 3

Speeds and Solids

Level	Speed (ft. / min)	Solids
Low	1500	60%
Medium	2200	62%
High	3000	64%
Drying Delay Distance		2 meters
Rod Rotation	200 rpm in counter roll direction	

A preliminary study was done to determine the parameters for final study. The above parameters were changed based on the coating results. Extreme conditions were determined through variation in the above parameters to ensure full coverage.

The coatings at low, medium, and high solids levels were applied to the surface-treated polyester clear film (Hoechst Celanese) at low, medium, and high speeds. Thus nine coated films were generated using all nine possible combinations of coatings and speeds.

The coating was applied using a wire-wound rod of 0.5 inch diameter with a wire gauge of 0.012 inches. The thickness of polyester film was 0.03 inches. A Cylinderical Laboratory Coater (CLC) was used to apply the coatings.

Surface Characterization

Surfanalyzer System 2000 stylus profilometer was used to chracterize the surface of these nine coating combinations.A cut-off value 0.03 inches was used . In this case, only those irregularities that had a wavelength of less than 0.03 inches were included. The stylus traversed back and forth a span of 0.35 inches at a speed of 0.01 inches/sec over the sample. The stylus generated electrical signals that were stored by computer in a file at a rate of ten signals/sec. In this way about 700 data points were generated for each sample characterize the surface profile.

Statistical analysis was then carried out on the surface profile data. Frequency distribution was used to determine the range and frequency of surface peaks and valleys. Fourier transform was used to characterize the dominant wavelengths of the surface profile.

Surfanalyzer System 2000

The Surfanalyzer® System 2000 (Federal Product Corporation, Rhode Island) is a stylus profilometer system that measures, computes, displays and records linear profile and surface texture characteristics. It can be used in production, inspection, quality control and research laboratories in a wide variety of industries.

The stylus profilometer consists of three basic components: (1) a probe, (2) a precision line drive, and (3) a controller. The controller includes a dual channel recorder, linear drive controls, digital displays and space for three plug-in modules.

The controller converts the analog signal to a digital display. Roughness or profile options can be selected and be displayed as microinches or micrometers. The analog out put can be directed to an external port for storage and processing. Six plug-in modules can be used for different functions such as roughness average, auto level, bearing length and bearing area curve.

CHAPTER VI

RESULTS AND DISCUSSION

Roughness

There are numerous factors involved in the process of coating a surface. Two critical factors are coating solids and speed. The effect of hydrodynamic forces, though crucial, is not well understood in the rod coating process.

Throughout this discussion, it is arbitrarily assumed that peaks and valleys less than 5 microns contribute minimal roughness to the surface . These arbitrary values can be chosen higher or lower, based on the final application of paper. For some printing methods a substrate surface with low peaks and valleys may be needed to satisfactorily transfer the ink. So the tolerance for peaks and valleys may be narrower.

Unlike blade coating, the surface generated by the wire-wound rods (normally known as Mayer rods) is marred by peaks and valleys dependent on leveling behavior. Among other factors, the speed of the web and the coating solids are major contributors to the ribbing and leveling behavior.

The purpose of this study was to explore and understand the effect of web speed and coating solids on surface formation. The intent was to use the highest possible speed to see its effect on generation of a coated surface. It was determined in the preliminary study that only a narrow window for solids variation was possible for the range of speeds selected.

The solids were used at three levels; (1) 60 % , (2) 62 % , and (3) 64 % and are referred to as low , medium , and high solids throughout the discussion of results. Each solids level was run at 1500 feet per minute , 2200 feet per minute , and 3000 feet per minute and are referred to as low , medium , and high speed throughout the discussion of results.

Frequency Distribution

Any surface can be characterized in two ways. The local irregularities are termed as roughness. This is immediate change from point to point on the surface in terms of depths and heights. This is shown in Figure 11. The gradual change, as well as local irregularities, in the same direction over a wider range on the surface is termed profile. This is explained in Figure 12. A glass slide can have low surface roughness but its profile can have plateaus and wide valleys.

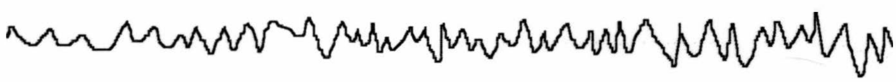

Figure 11. Roughness (Irregularities in a Surface).

This experiment was intended to study those local irregularities. The frequency distribution of these irregularities is shown in Table 4. These frequencies were divided

Figure 12. Profile (Irregularities and Skewness).

into seven intervals. Each interval represents the magnitude of a peak or a valley in the surface. The column under each interval shows the number of peaks and valleys that fall in that interval. The sum of these peaks and valleys is given in a separate column. In column eleven are listed the peaks and valleys that are less than one micron in magnitude. This was arbitrarily assumed that peaks and valleys less than one micron are so small that their contribution to roughness is minimal. The greater the number of peaks and valleys less than one micron, the smoother the sample.

Table 4 shows that there were no peaks and valleys equal to or greater than six microns at low speed regardless of amount of solids. The peaks and valleys less than one micron are more than 73 % of a total of about 3200 data points observed at all three solids' levels for low speed. All the frequencies increase when the speed is increased except the for the interval with values less than one micron, which decreases. These frequencies can be used as a rough measure of smoothness. The difference in these frequencies can be interpreted as increase or decrease in roughness. If the frequency in this interval decreases while all the other frequencies in higher intervals increase, it is considered a reduction in smoothness or increase in roughness. These terms are used interchangeably throughout this discussion.

Table 4

Frequency Distribution for Peaks and Valleys (in microns)

		Interval Heights of Peaks and Valleys (microns)									
Solids	Speed	>10	$6<X \le 10$	$5<X \le 6$	$3<X \le 5$	$2<X \le 3$	$1<X \le 2$	$1 \le X \ge 0$	Total	%<1	% Difference
L	L	0	0	2	4	19	103	3112	3240	99.4	25.5
L	M	3	131	95	257	365	760	1629	3240	73.9	26.4
L	H	6	41	59	535	684	945	670	3240	47.5	
M	L	0	0	2	3	35	395	2805	3240	90.4	64.5
M	M	11	230	135	735	614	715	761	3201	25.9	6.5
M	H	318	497	205	630	419	493	641	3203	32.4	
H	L	0	0	3	20	136	702	2379	3240	89.2	3.7
H	M	8	267	144	465	364	476	1516	3240	85.51	50.3
H	H	260	342	183	587	482	623	763	3240	35.21	

L = Low; M = Medium; H = High; Low Solids = 60 % ; Medium Solids = 62 % ; High Solids = 64 %. Low Speed = 1500 ft./min ;Medium Speed = 2200 ft./min ; High Speed = 3000 ft./min.

Out of 3240 data points observed at low speed 96.0 %, 86.6%, and 73.4% readings for low solids, medium solids, and high solids, respectively, were less than one micron. The decrease in these percentages can be interpreted as loss in smoothness . There was a 9.4 % loss of smoothness from low solids to medium solids at low speed -(96.0 % - 86.6 %). There was a 13.2 % loss of smoothness when changing from medium solids to high solids (86.6 % - 73.4 %). On the other hand there was a loss of 45.8% and 62.9% smoothness at low and medium solids, respectively, when changing from low speed to medium speed. This indicates that solids have quite a low effect as compared to speed. There were two more important observations at medium and high solid levels.

1. At medium solids level, when speed was changed from low to medium, there was a 62.9% loss of smoothness, but the change from medium to high speed resulted only in a 3.5 % decrease in smoothness.

2. There was a comparatively lower loss in smoothness when speed was changed from low to medium at high solids level - a loss of only 26.6%. However when speed was changed from medium to high there was an additional 23.3 % loss.

These observations suggest the following :

1. If the acceptable range for coat weight variation is wider, opposed to as in the case of light weight coated paper (LWC), an increase in solids at higher speeds may contribute to a smoother surface.

2. If the surface smoothness deteriorates with an increase in speed, a higher solids level may reverse the results.

The above observations are based on this study. The coating formulations, the application methods, drying speed, and the direction of web in relation to the gravitational pull , are also a few other factors that may change the process and consequently affect the final outcome.

The above results do not indicate or predict the behavior of coating when solids are increased further but they do indicate that to find a reversion point is possible for certain solids and speed.

It is a common observation that at low speeds, smoother coated surfaces are produced and at the higher speeds, spitting, whiskers and misting cause defects in coated surfaces. Spitting and whiskers were not observed because they are chronic in most cases and it takes a steady flow of coating for an extended period of time to observe them. Misting is an instantaneous phenomenon and can occur any moment depending on the hydrodynamic forces. Misting was observed at medium speed but because of the location of pond, and web direction, the free flow of coating during shutter opening and closing flooded the observations stripe that was placed for this purpose. Other efforts were inconclusive.

As mentioned previously, at all solids levels, more than 70% of the roughness values were less than one micron at low speed. Low solids provided the best results at all speed levels. There was a steady increase in roughness with an increase in speed. At medium solids there was an increase of 62.9 % in roughness when changing from low to medium speed while at high solids under the same conditions there was an increase of 26.6 % in roughness. When the speed was changed from medium to high, at medium solids there was an increase of only 3.5% in roughness while at high solids it was 23.3%

As mentioned before, at low speed, no peaks or valleys are greater than 6 microns regardless of solids content of the coating. At high speed and low solids level, there are only 6 peaks or valleys greater than 10 microns. The number of peaks and valleys greater than 10 microns is 318 and 260 for medium and high solids levels for the same speed (high) respectively. This is more than 40 % increase. These peaks and valleys of the highest magnitude contribute to the substantial increase in roughness. This tendency is more pronounced at high speed when solids level is increased from low to medium rather than medium to high.

Smoother surfaces will result if both the solids and speeds are kept low. Solids higher than 60 % produced peaks and valleys, greater than 10 microns, 40 to 50 times more when speed was raised to 2200 ft. / min. or higher.

All the frequencies greater than 5 microns increase in number at medium solids and high speed as compared to those at high solids and high speed. Since larger peaks and valleys obviously contribute more to the roughness, it can be concluded that at high speed, medium solids produced rougher surface as compared to that produced at high solids and high speed.

There were some more important observations. At all solids levels the number of peaks and valleys decreased as their magnitude increased. At medium and high speed, the number of peaks and valleys dropped gradually as they increased in magnitude as compared to those produced at low speed. If we traverse through

Table 4 along rows showing number of peaks and valleys for all solids, we reach a column where the difference between corresponding values for speed and solids is smallest. This balancing point can help to choose the best combination suited for a particular application. Only the values on the left hand would determine the acceptable roughness level. For example, if we compare medium speed frequencies for low and medium solids, the least difference is 40 - (135 - 95) at the interval where peaks and valleys lie between 5 and 6 microns. This happens in the interval where peaks and valleys are greater than 6 microns at medium solids and medium speed are 241 (230+11). For low solids this number is 135. If these extra 106 peaks and valleys (241-135) can be tolerated, then it will be more efficient to use medium speed. A table constructed in this way gives more predictable choices for particular needs. This also indicates that a new balance can be achieved with change in solids and speed within a particular application. Based on the formulations of the coatings, an upper and lower limit of speeds and solids has to be determined. To get an acceptable coverage, a random selection of coatings and speed is not a feasible choice. Once these limits are determined, then based on the importance of speed, coat weight or solids ,a more useful combination can be devised depending on the results for a particular application.

The peaks and valleys less than one micron were 86.6 % at medium solids and low speed. When the speed was changed to high, this amount was 20.2 %. Thus the total decrease in peaks and valleys less than one micron was 66.4 % (86.6 % -20.2 %) when the speed was changed from low to high at medium solids level . A similar decrease was 49.9 % at high solids (73.4 % - 23.5 %). This decrease was more evenly divided at high solids level. The decrease from low to medium speed was 26.6 % and from medium to high speed it was 23.3 %. While in case of medium solids, from low speed to medium speed the decrease was 62.9 and 3.5 % for change from medium to high speed.

This indicates two patterns of behavior:

1. The increase of roughness was sharp in the beginning but it leveled off as the speed was increased under the same conditions.

2. The pattern of variation was not uniform for different solids levels when the speed was changed.

At all solids levels, when the speed was changed to medium or high, there was a shift of frequencies to the left in Table 4. All these shifts to the left were the result of reduction in the interval of frequencies less than one micron. This shift to the left was larger at high speed for all the runs as compared to that at medium speed. The higher the shift to the left, the higher the roughness. This indicates increase in roughness with increasing speed.

There was another important observation. The maximum number of peaks and valleys greater than six microns occurred at medium solids and high speed. There were 318 peaks and valleys greater than 10 microns and 497 greater than six microns and less than 10 microns. They make 25.4 % of a total of 3203 peaks and valleys. This indicates that less than 74.7 % peaks and valleys for all runs are less than six microns in magnitude. The second highest number of peaks and valleys greater than six microns appeared when high solids were run at high speed. They were 602 in number (342+260).They make 18.6 % of 3240 total data points observed.

Table 5 represents average magnitude of peaks and valleys for each of five scans on the same coated surface for each combination of speed and solids. These averages were calculated based on more than six hundred readings for each scan by stylus profilometer. The average of these averages and standard deviation are presented in the last two columns.

At all solids levels the roughness increased with increased speed. At constant speed, the change in solids produced similar results. The roughness increased with increased solids except for two instances. When solids were changed from medium to high at medium speed, the roughness decreased. The same was the observation when at high speed the solids were changed from medium to high.

Table 6 was constructed in an effort to eliminate variation in the same run. Frequencies of one scan were chosen out of a total of five scans for each of nine combinations of speeds and solids. The basis for this choice was the maximum magnitude of peaks and valleys. The sample with lowest maximum was chosen. The percentages were calculated based on the total frequencies less than five microns. This was again arbitrarily assumed that the frequencies less than five microns were a measure of smoothness. The larger the frequencies, the smoother the sample.

At low speed and low solids, 99.4 % of peaks and valleys had a magnitude less than one micron, while at high solids and high speed it was reduced to 35.2 %. At low solids level when speed was changed from low to medium, the peaks and valleys

Table 5

Absolute Roughness Average (microns)

Solid	Speed	Samples 1	2	3	4	5	Average	Std. Dev.
L	L	0.354	0.232	0.385	0.463	0.329	0.352	0.084
	M	1.855	0.779	0.785	3.687	0.965	1.614	1.24
	H	2.050	2.270	2.396	1.312	1.665	1.938	0.45
M	L	0.470	0.641	0.547	0.523	0.545	0.545	0.062
	M	2.220	2.210	3.952	3.052	3.313	2.950	0.75
	H	2.273	5.352	2.489	5.824	4.120	4.012	1.62
H	L	0.805	0.673	0.966	0.592	0.685	0.744	0.14
	M	0.594	0.561	2.086	3.684	3.658	2.120	1.55
	H	3.796	4.787	2.941	4.583	1.659	3.553	1.28

L = Low; M = Medium; H = High

Table 6

Frequency Distribution of Roughness
Solids vs Speed

		Low Solids		Medium Solids		High Solids	
	Amplitude	Frequency	%*	Frequency	%*	Frequency	%*
Low Speed	≥3	0	0	0	0	0	0
	≥2	0	0	1	0.1	3	0.5
	≥1	4	0.6	61	9.4	125	19.2
	≥0	644	99.4	586	90.4	578	89.2
Med. Speed	≥3	9	1.4	115	17.7	4	0.6
	≥2	35	5.4	189	29.2	5	0.8
	≥1	125	19.3	126	19.4	85	13.1
	≥0	479	73.9	168	25.9	554	85.5
High Speed	≥3	49	7.6	112	17.3	90	13.9
	≥2	91	14.0	101	15.6	75	11.6
	≥1	198	30.5	145	22.4	237	36.6
	≥0	308	47.5	210	32.4	228	35.2

* % of count of the roughness readings <5 microns

Low Speed = 1500 ft./min.;Medium Speed = 2200 ft./min.;High Speed = 3000 ft./min.

less than one micron were reduced from 99.4 % to 73.9 %. At medium solids when speed was changed from low to medium , the percentage was reduced from 90.4 % to 25.9 %. In the first case there was a decrease of 25.5 % while in the later case it was 64.5 %. The change of solids showed quite a significant effect. This decrease was because of the peaks and valleys shifted to intervals of higher magnitude. The larger the decrease in this interval, the larger the surface roughness. The degree of change is non-uniform when changing solids or speeds from one level to another. So it is difficult to predict the behavior of a coating in a precise way when solids or speed are changed.

There was another important observation. For all solids and all speed levels in this study, 74.8% of the values for peaks and valleys were below six microns. The magnitude of peaks and valleys exceeded six microns at all solids levels when they were run at medium or high speed as shown in Table 4.

Fourier Analysis Results and Discussion

If data has any cyclic trends, data points can be related to a series of sine and cosine curves, by Fourier transform. Poly Software International software for Fourier transform gives the frequency and actual amplitude of the curves. Ribbing patterns emerge due to interaction of the substrate surface characteristics, the hydrodynamic forces generated by the web speed and the application rod in the coating process. Ribbing at macro level causes print problems while at the micro level the printing defects can not be detected by the bare eye. Fourier transform is a helpful tool to determine the dominant wavelength of the surface profile.

Table 7 was constructed to see the relation between the wire thickness (the diameter of wire) and the highest amplitude and wavelength of the sine wave generated by the wire under different speeds and solids. Out of five samples, one sample was picked up at random for each of nine combinations to see this relation. The predominant wavelength is 109 % of the wire diameter at low speed for low and high solids.

Table 7

Fourier Transform Analysis, Dominant Wavelength and Amplitude Compared to Wire Wavelength and Amplitude

Solids	Speed	Wavelength (microns)	Amplitude (microns)	% of Wire Wavelength	% of Wire Amplitude
Low	Low	667	0.0466	218	0.03
	Medium	612	3.1434	200	2.06
	High	773	1.8411	254	1.21
Medium	Low	798	0.1305	262	0.09
	Medium	906	1.0594	298	0.70
	High	1288	2.4137	422	1.58
High	Low	671	0.3747	220	0.25
	Medium	470	0.0699	154	0.05
	High	1631	12.7140	536	8.34

This indicates that at low speeds the wire produces these so called wire marks. Ripples are the wavelike fluid collections between the application rod and the web.

The ripples are generated in part by hydrodynamic forces and wire. They appear as thick bands of coating on the web. At low speed, both at low and high solids the ripple effect is minimum. Ripple effect results in amplified roughness patterns and coating streaks. Ripples are amplified when they merge under higher forces. At medium speed and low solids the wavelength is the same as the wire-diameter.

The wavelength of predominant sine wave at medium speed and medium solids is 906 microns that is almost twice as much as that of high solids at medium speed, which measures only 470 microns. One way to interpret this is that the available fraction of liquid allows horizontal mobility of coating particles under the forces in that direction. But at high speed and medium solids, the wavelength is 1288 microns while it is 1631 microns in case of high speed and high solids which is 126.6 % of the wavelength for medium solids and high speed - (1631 / 1288 * 100). The above argument does not hold in this case.

With increased speed at the same solids level, the wavelength of predominant sine curve increased. It shows that at higher speeds the wavelengths cause wider ribbing patterns. There were two exceptions. At low and high solids, the wavelength decreased with speed increasing from low to medium. A decrease in wavelength contributes to increased roughness. It can be observed that both speed and wire size play an important role in ribbing pattern and as a result surface formation.

Table 8 represents the average wavelengths and average amplitude of sine waves for all nine combinations. As in Table 7, the wavelength shows increase with

Table 8

Fourier Transform Analysis, Average Wavelength and Amplitude of Surface Compared to Wire Wavelength and Amplitude

Solids	Speed	Wavelength (microns)	Amplitude	% of Wire Wavelength	% of Wire Amplitude
Low	Low	551	0.0378	181	0.02
	Mediu	880	2.5710	289	1.69
	High	872	1.6520	286	1.08
Mediu	Low	397	0.1130	130	0.07
	Mediu	1124	5.0800	369	3.33
	High	1163	14.3700	382	9.43
High	Low	443	0.2540	145	0.17
	Mediu	801	6.3700	263	4.18
	High	1235	11.5000	405	7.55

Wire Wavelength = 304.8 microns; Wire Amplitude = 152.4 microns

increased speed for all solids levels. The highest amplitude is for medium solids and high speed. The next highest amplitude is for high solids and high speed.

The scatter graph of Fourier transform, where amplitude is shown against the wavelength for all three solids levels, is presented in Figure 13, 14, and 15. The wavelengths are in close vicinity of each other for low and medium solids for all speeds. Wavelengths are shifted to the right for medium solids at all speeds .

Tables 9, 10, and 11 show the magnitude of the highest amplitude and its wavelength for the five scans of each of the nine coated surfaces and their average magnitudes.

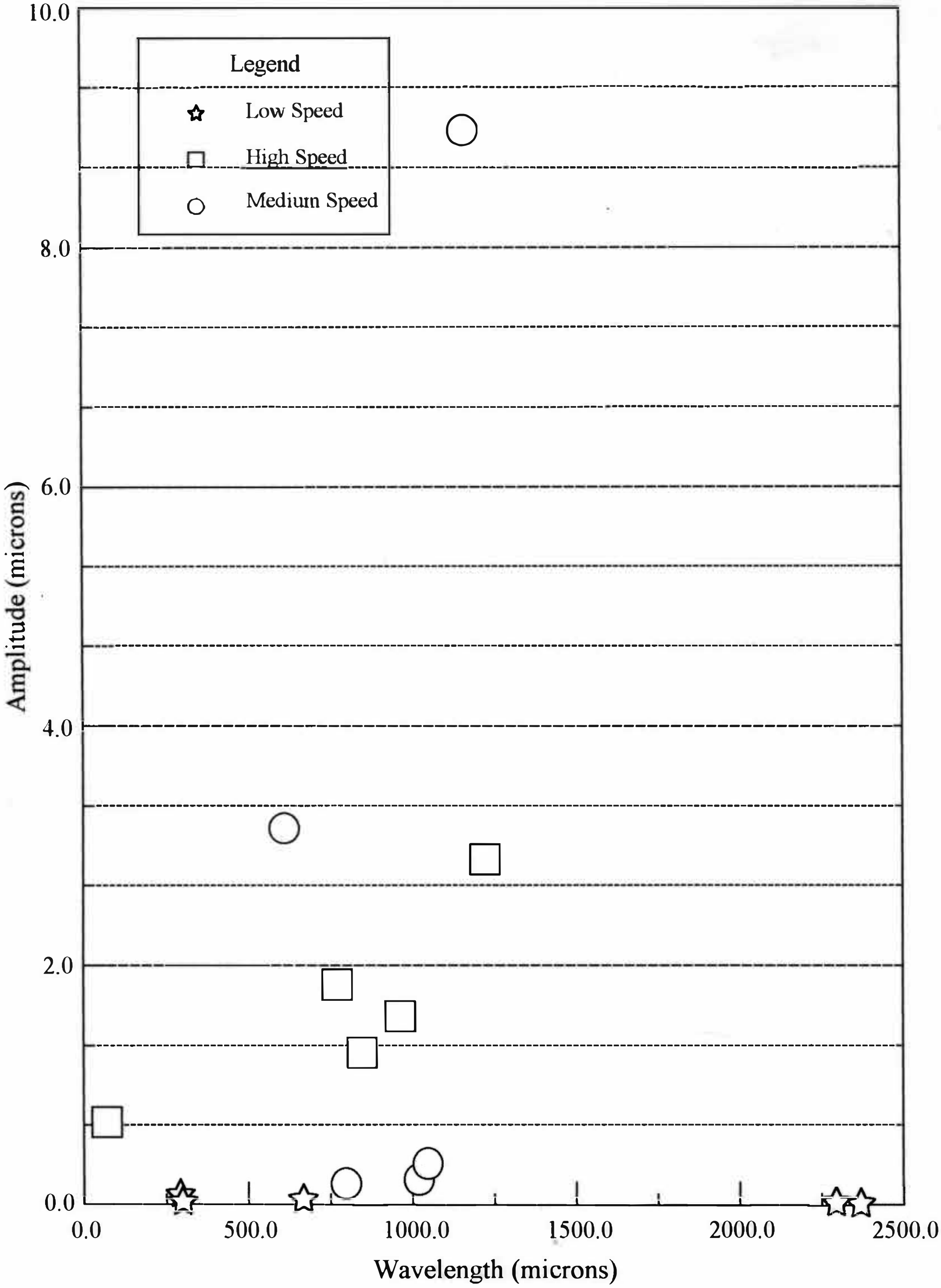

Figure 13. Fourier Transform Amplitude and Wavelength at Low Solids.

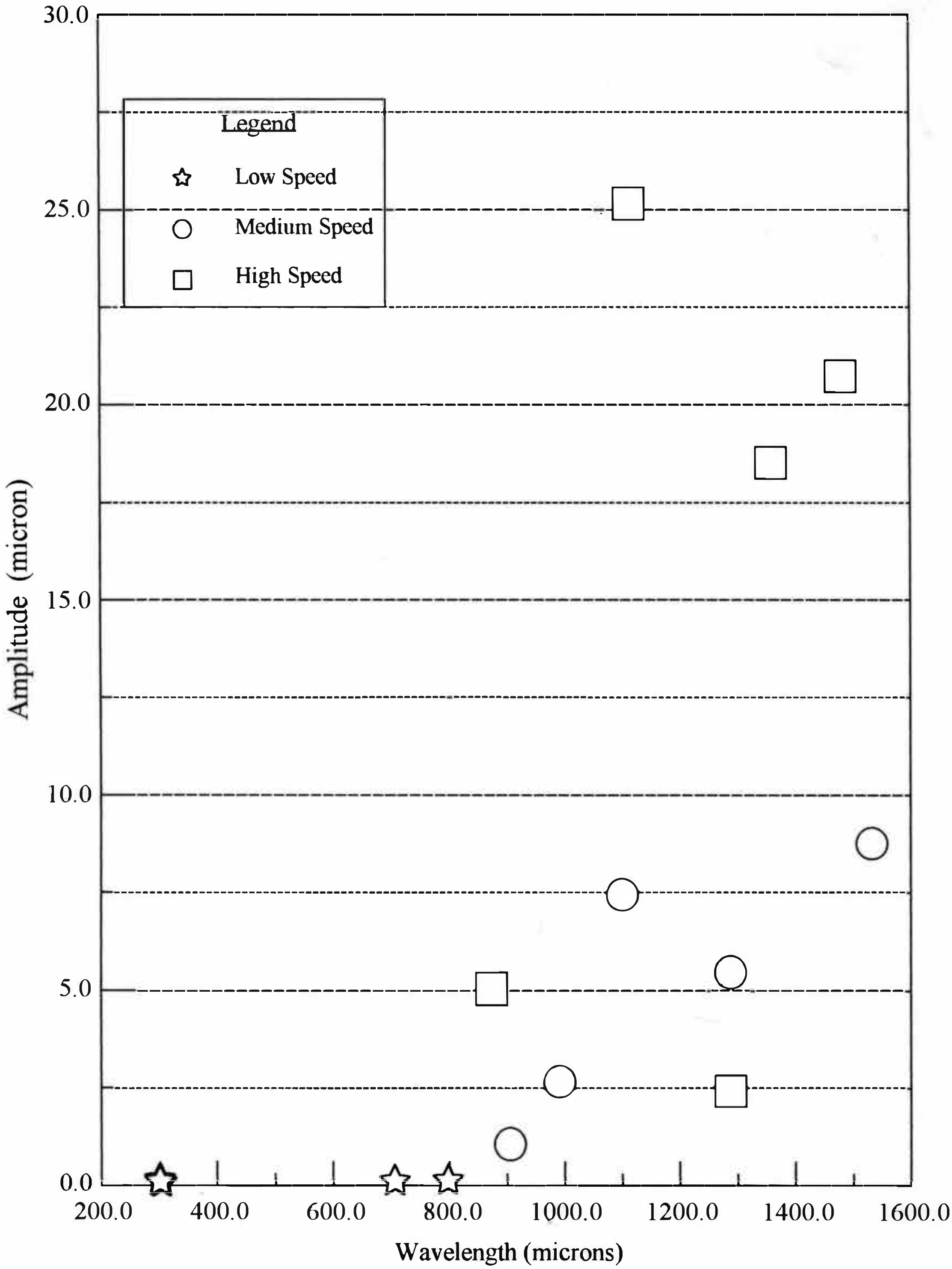

Figure 14. Fourier Transform Amplitude and Wavelength at Medium Solids.

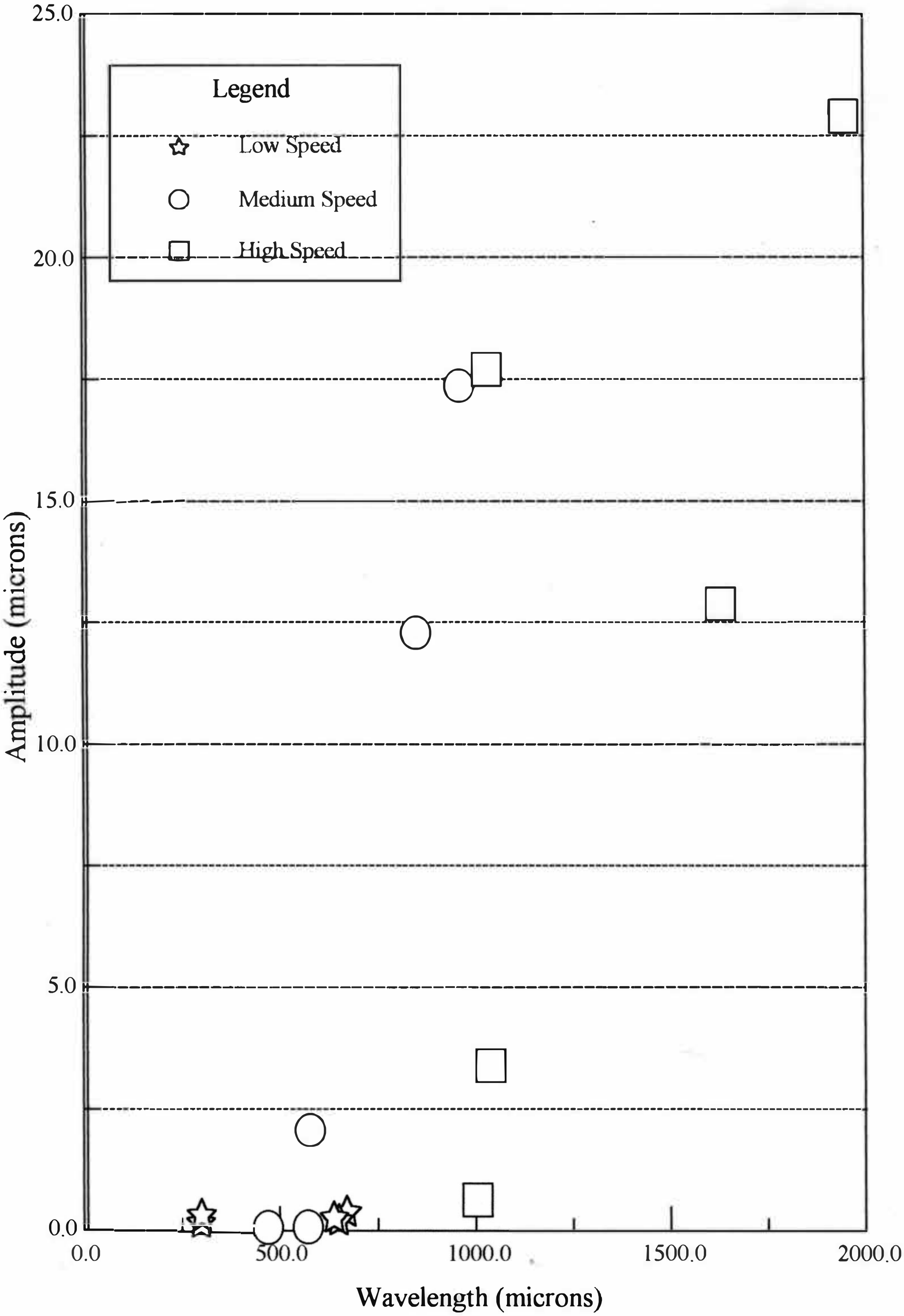

Figure 15. Fourier Transform Amplitude and Wavelength at High Solids.

Table 9

Fourier Transform Analysis, Wavelengths
and Amplitudes (microns)
Low Solids

Sample	Low Speed		Medium Speed		High Speed	
	Wavelength	Amplitude	Wavelength	Amplitude	Wavelength	Amplitude
1	667	0.04666	612	3.143	773	1.841
2	2368	0.009	1020	0.213	965	1.575
3	2294	0.022	798	0.176	1224	2.88
4	294	0.086	1165	8.98	71	0.69
5	301	0.0254	1047	0.342	850	1.272
Avg.	1185	0.0837	928	2.57	904	1.65
SD	1057	0.03	221	3.8	202	0.81

Table 10

Fourier Transform Analysis, Wavelengths
and Amplitudes (microns)
Medium Solids

Sample	Low Speed		Medium Speed		High Speed	
	Wavelength	Amplitude	Wavelength	Amplitude	Wavelength	Amplitude
1	798	0.131	906	1.059	1288	2.414
2	706	0.11	992	2.661	1480	20.727
3	304	0.071	1533	8.764	874	5.052
4	301	0.154	1288	5.473	1115	25.16
5	301	0.101	1101	7.44	1359	18.52
Avg.	482	0.113	1164	5.0794	1223	14.37
SD	249	0.031	251	3.21	236	10.048

Table 11

Fourier Transform Analysis, Wavelengths
and Amplitudes (microns)
High Solids

Sample	Low Speed		Medium Speed		High Speed	
	Wavelength	Amplitude	Wavelength	Amplitude	Wavelength	Amplitude
1	671	0.377	470	0.0699	1631	12.882
2	650	0.202	572	0.0784	1034	17.695
3	638	0.263	578	2.063	1040	3.398
4	298	0.153	964	17.361	1950	22.885
5	300	0.313	850	12.281	1005	0.624
Avg.	511	0.262	715	6.37	1332	11.496
SD	194	0.088	230	7.962	434	9.405

The amplitude increased both with increase of solids or speed. There were two exceptions. The average amplitude at low solids and medium speed is 2.57 microns. The amplitude decreased to 1.65 microns when speed was changed from medium to high at low solids level. The other exception was when changing from medium solids to high solids at high speed. The amplitude decreased from 14.37 to 11.50.

Surface Regularity

The stylus profilometer gives much more detailed information about the surface patterns as compared to any other roughness measuring device. The surface generated by a Mayer rod consists of peaks and valleys. If these peaks and valleys resemble a single sine wave, then this surface can be classified as a regular surface which has peaks and valleys equally wide , deep and high.

This can happen when a stabilized flow of coating is taking place and all the forces have stabilized to generate a surface like a sine wave, termed here as 'regular surface'.The following discussion is based on the roughness graphs and their Fourier transforms which are represented in Figures 16 - 28. They give the visual details of the features of the different surfaces generated at different solids and speed levels.The facts can be observed by looking at the related roughness and Fourier transform graphs.

The fewer the peaks in a Fourier transform graph, the fewer the irregularities in a surface roughness pattern. A regular surface was generated at low solids and medium speed . Figure 13 and 14 show this phenomenon. This is the surface that has a micro ribbing pattern equal to the wire diameter with minimal disturbance. The wavelength is the same as for the wire diameter. Another regular surface was generated using high speed at low solids level (Figure 15,16).There is only one dominant amplitude, as shown in Figure 16. There are other amplitudes but their effect is minimal. That can be easily detected by looking at Figure 15. An equilibrium is established in all forces involved.

At low solids and low speed, the surface has too many peaks and valleys (Fig. 11). The Fourier transform also shows many small amplitudes which disturb the main sine waves. The result is a very irregular surface, although it is smoother than the surfaces mentioned above.

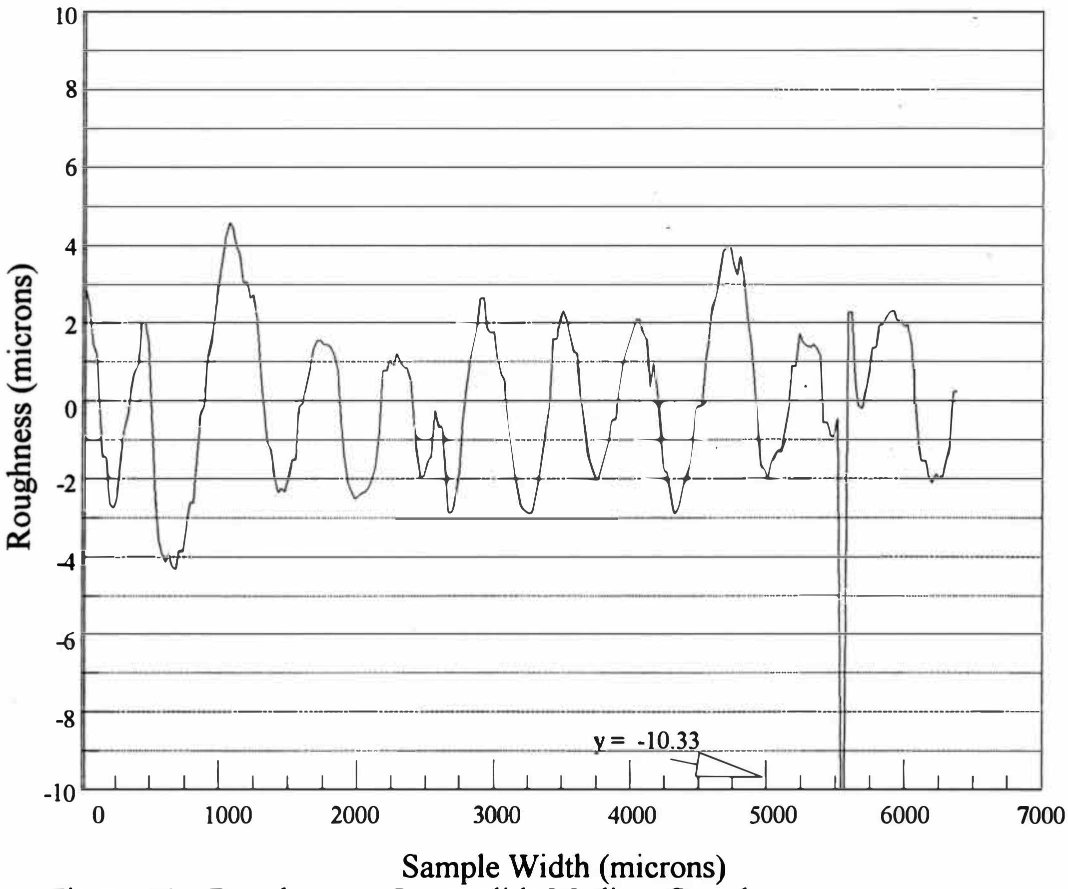

Figure 16. Roughness at Low solids,Medium Speed.

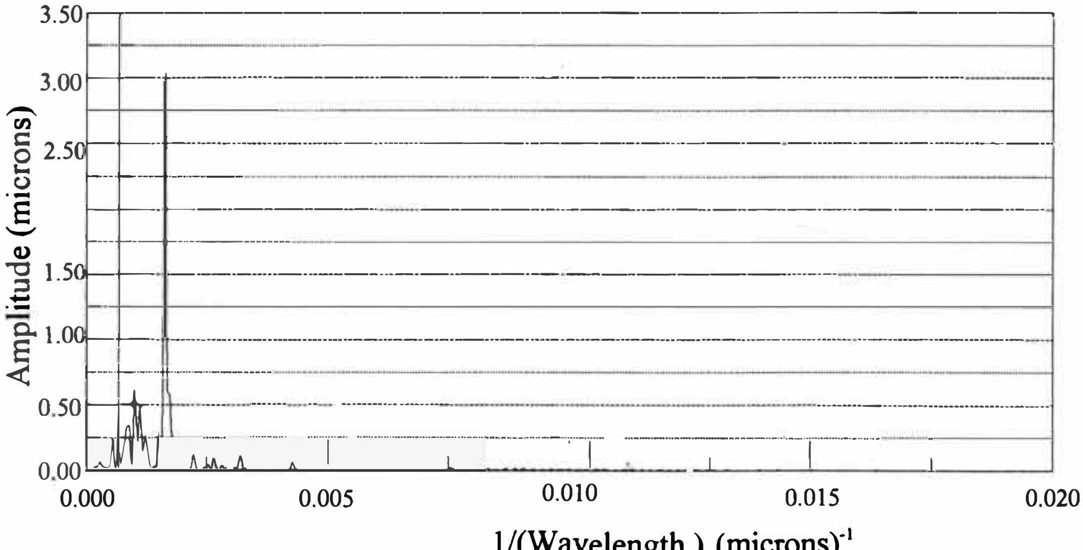

Figure 17. Fourier Transform for Roughness Data at Low Solids, Medium Speed.

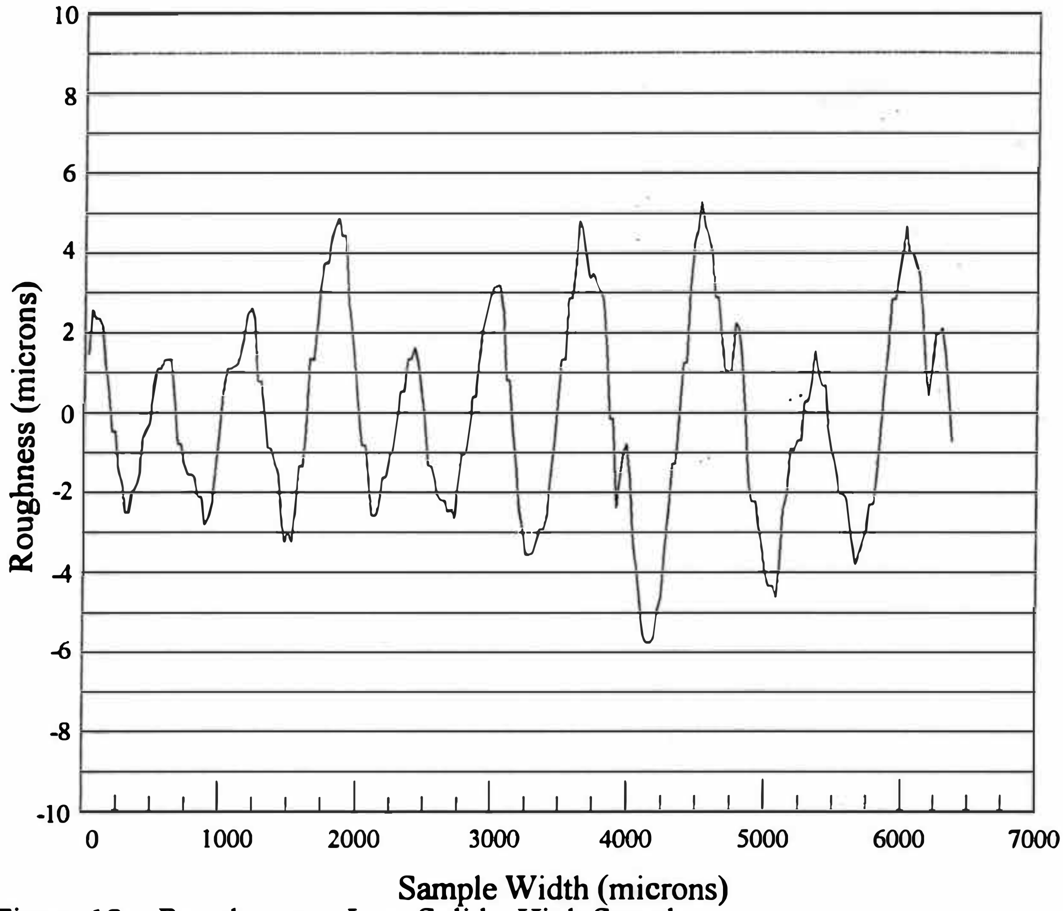

Figure 18. Roughness at Low Solids, High Speed.

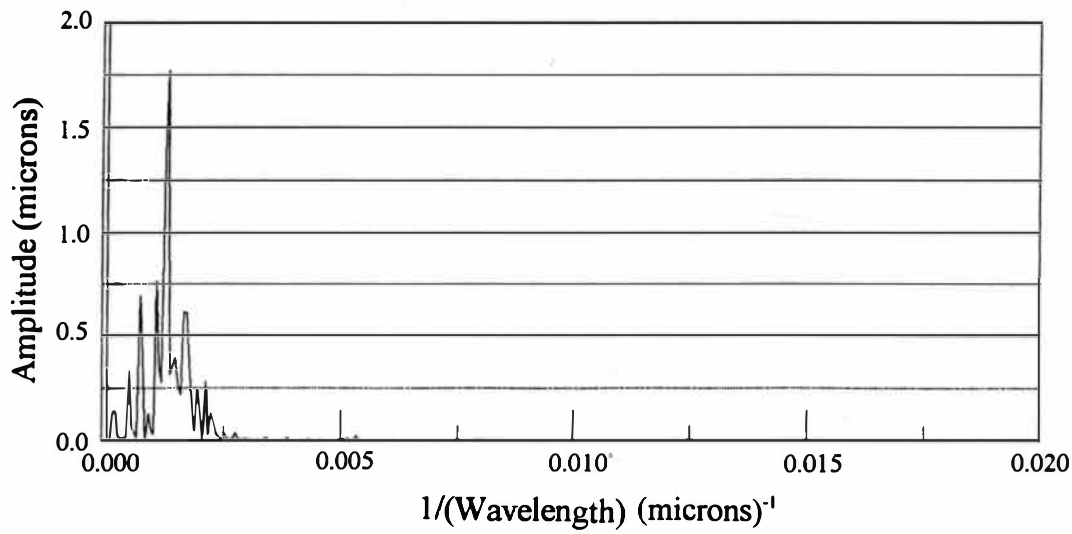

Figure 19. Fourier Transform for Roughness Data at Low Solids, High Speed.

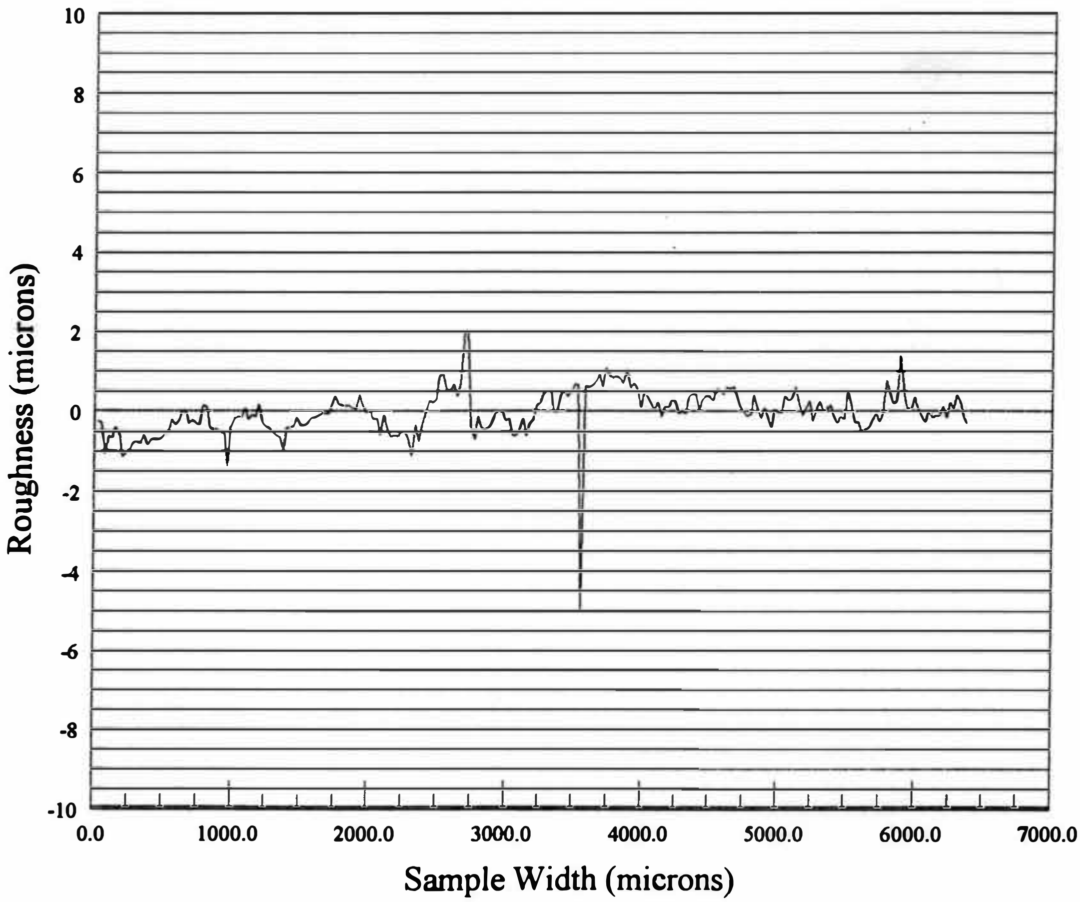

Figure 20. Roughness at Low Solids,Low Speed.

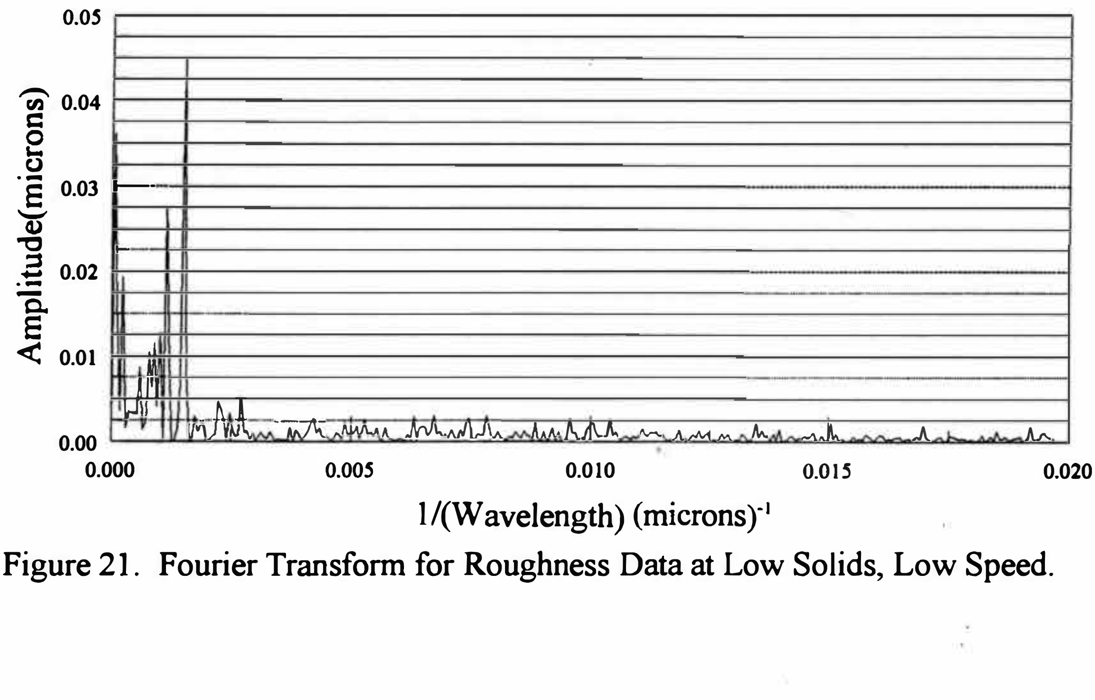

Figure 21. Fourier Transform for Roughness Data at Low Solids, Low Speed.

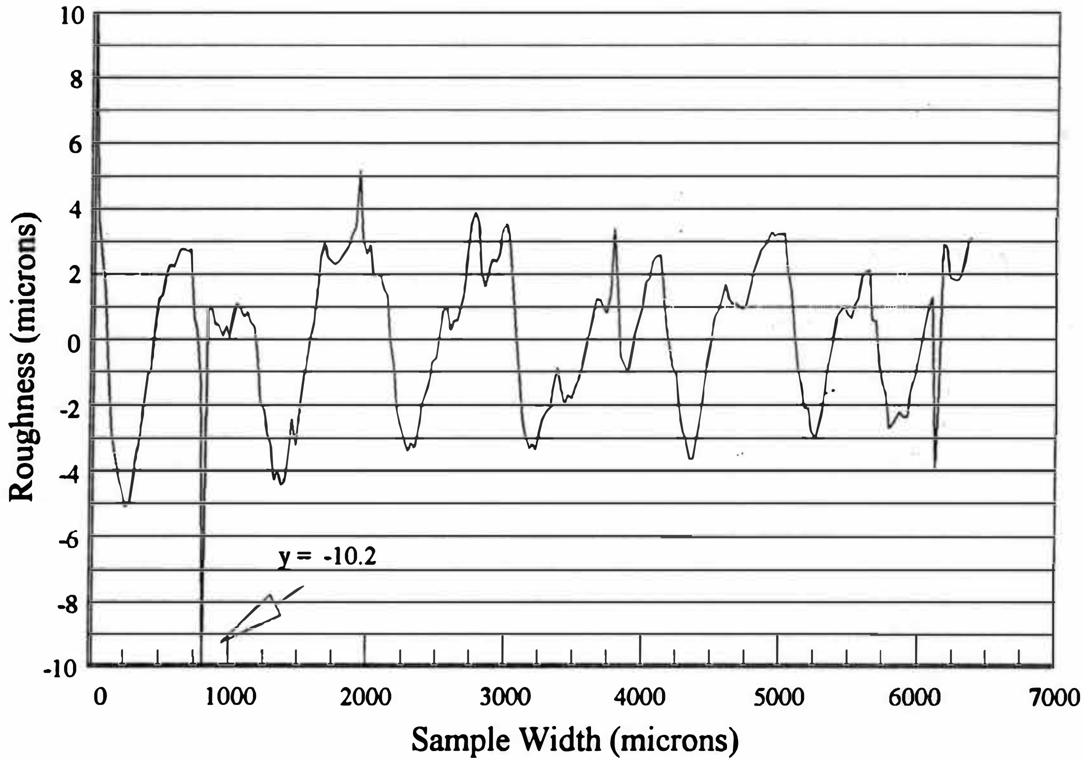

Figure 22. Roughness at Medium Solids, Medium Speed.

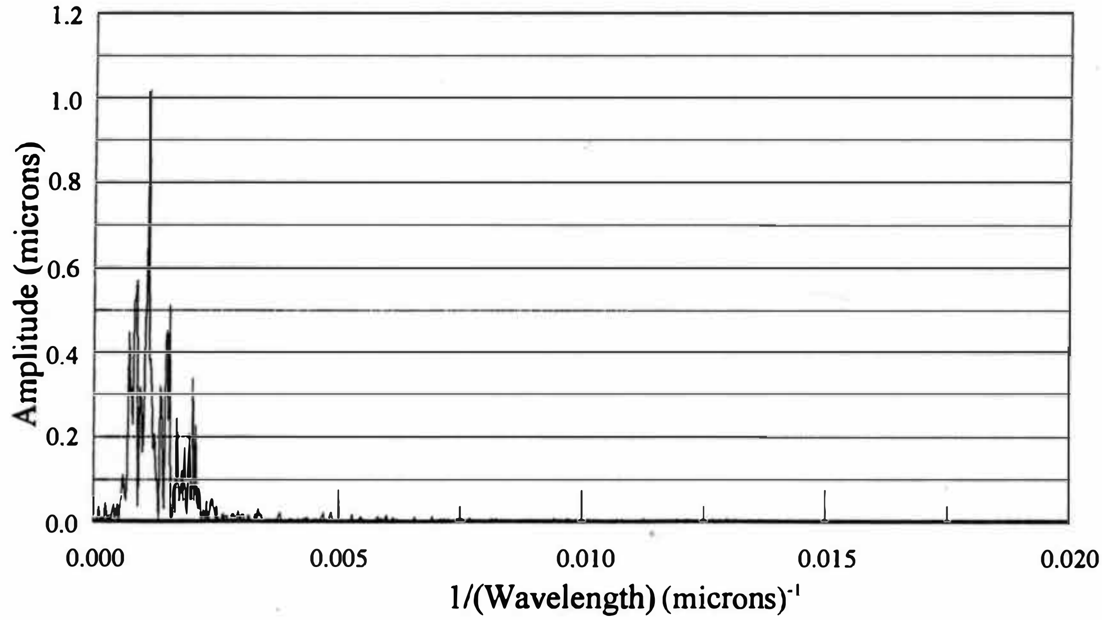

Figure 23. Fourier Transform for Roughness Data at Medium Solids, Medium Speed.

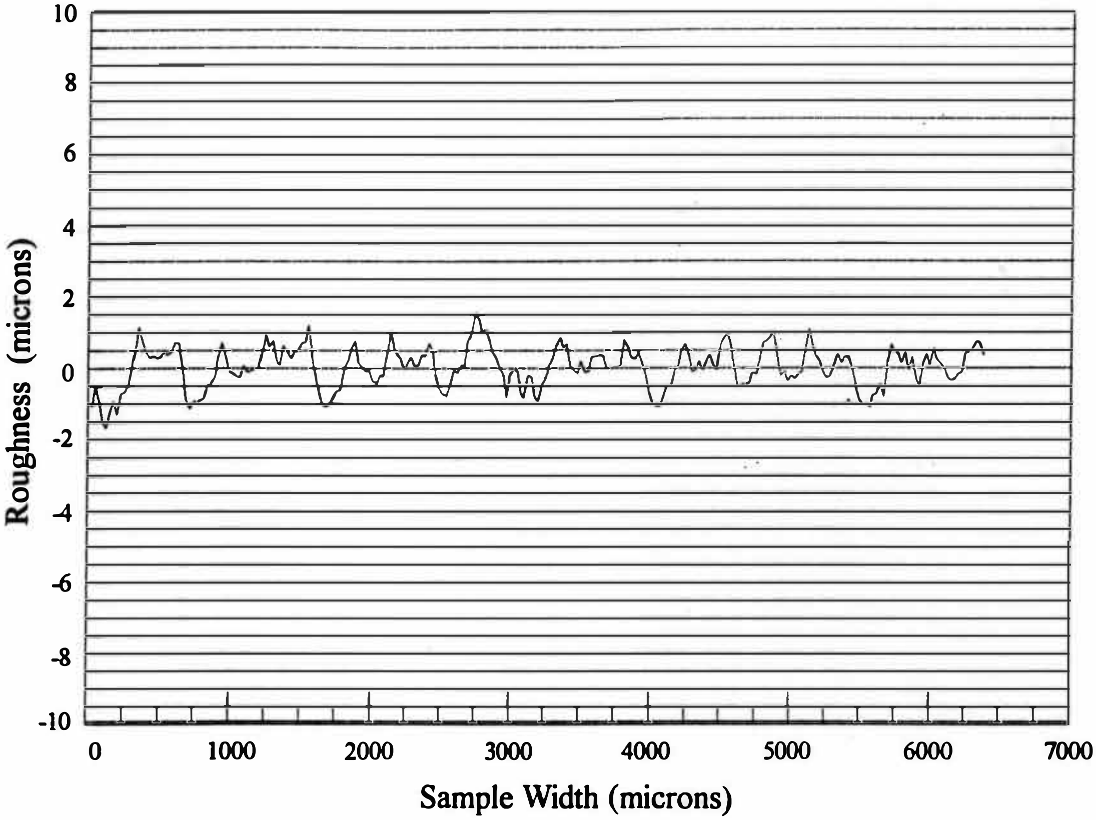

Figure 24. Roughness at Medium Solids, Low Speed.

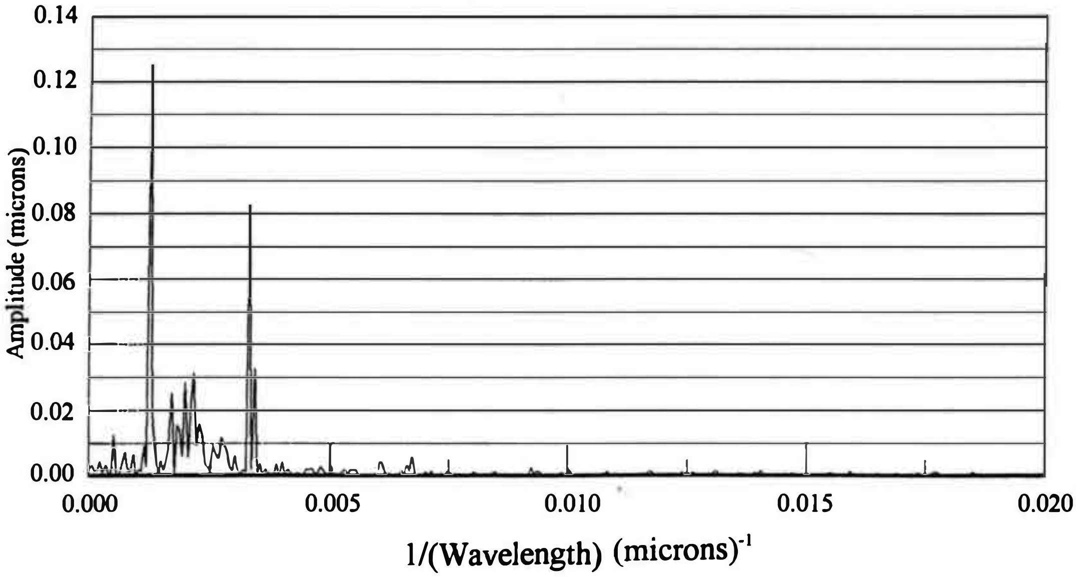

Figure 25. Fourier Transform for Roughness Data at Medium Solids, Low Speed.

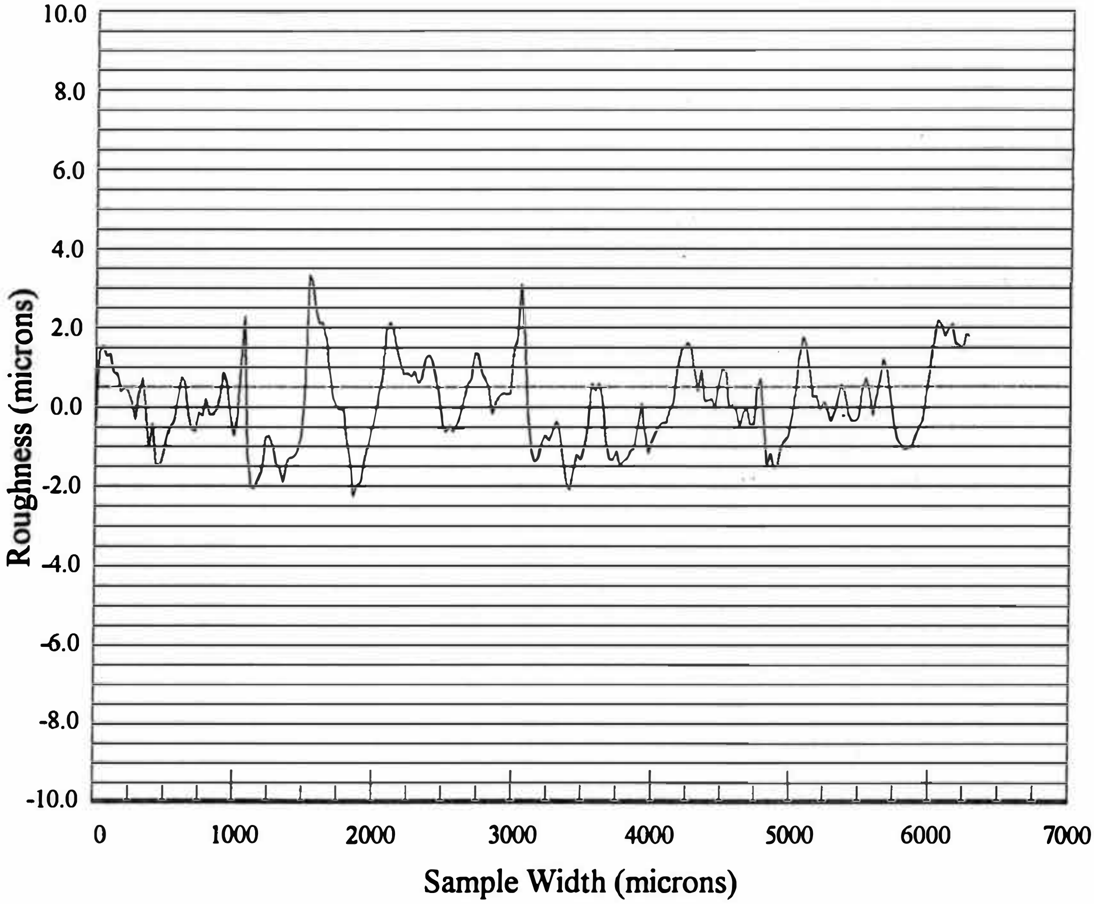

Figure 26. Roughness at High Solids, Low Speed.

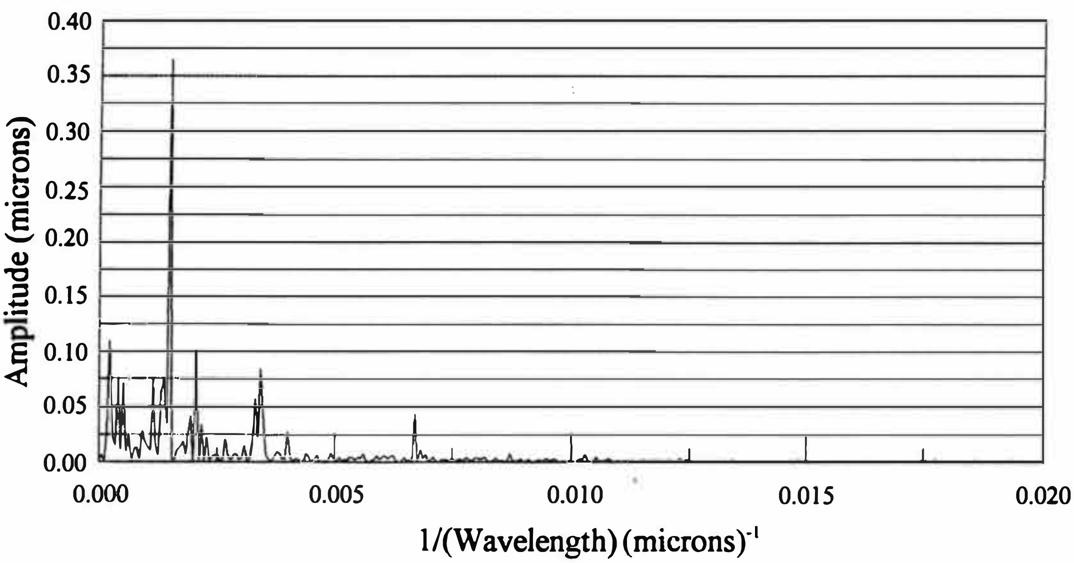

Figure 27. Fourier Transform for Roughness Data at High Solids, Low Speed.

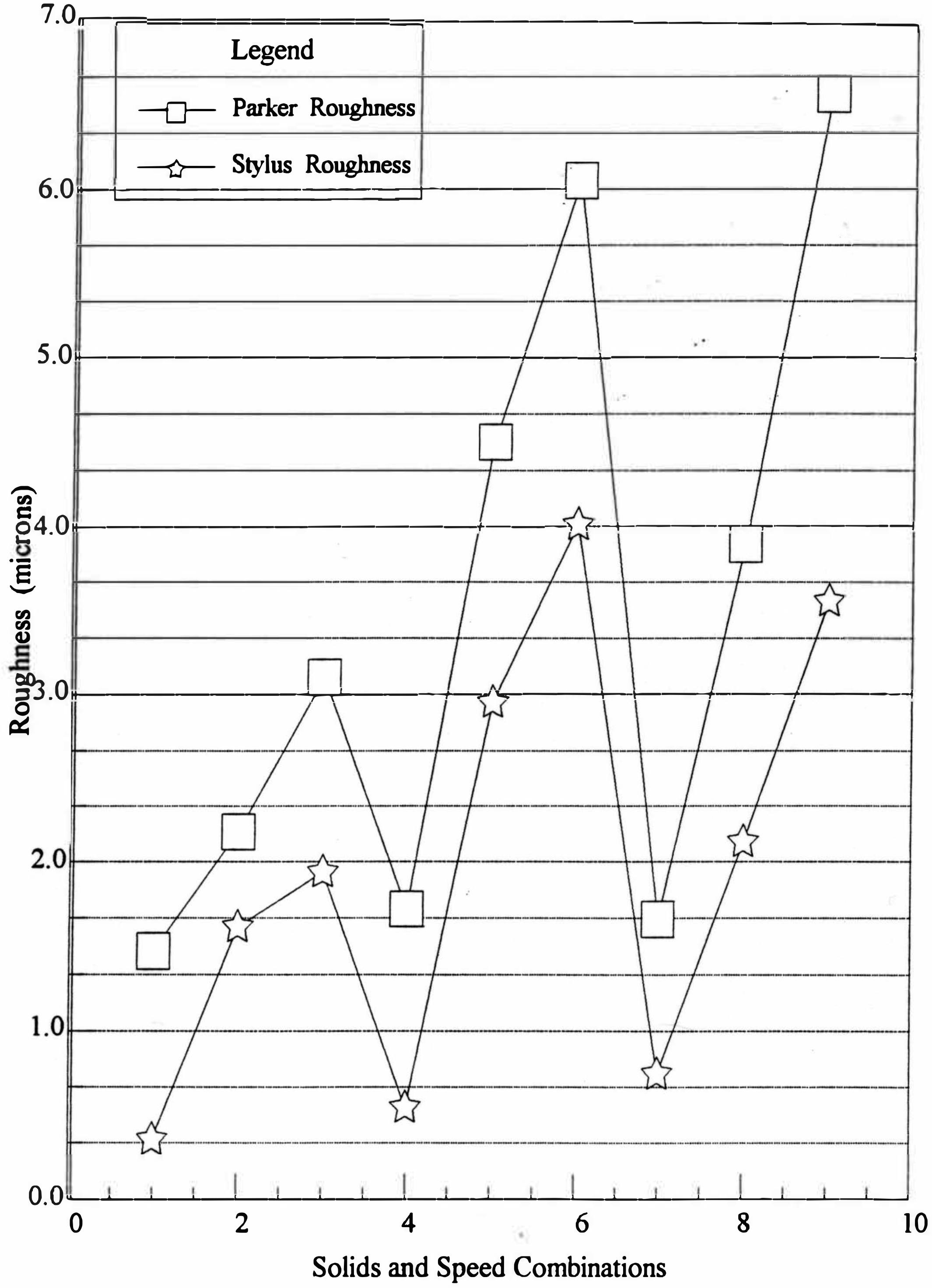

Figure 28. Stylus and Parker Roughness.

At medium solids and medium speed, though disturbed, the surface as a whole is regular (Fig. 19).

As in Figure 11, the magnitude of peaks and valleys is approximately 0.5 microns with few exceptions when low solids and low speed were used. These peaks and valleys generally reached 2 microns in magnitude when low solids were run at medium speed. At high speed, more peaks and valleys reached 4 microns, but the general pattern was still 2 microns.

A general observation is that roughness increased sharply when speed was changed from low to medium, but this increase in roughness was reduced when changing from medium to high speed.

As shown in Figure 17, roughness is around one micron when medium solids are run at low speed. The roughness doubled when solids were changed from low to medium. The roughness increased four times when the speed was changed from low to medium at low solids level. This again shows the significant effect of speed on roughness.

The roughness was generally three microns, as in Figure 19, when the medium solids were run at medium speed but it was 2 microns when low solids were run at medium speed.

As in Figure 23, the roughness is generally 2 microns at low speed and high solids that is four times the roughness at low solids and low speed. So in accordance with this observation, the high solids content contributed to increased roughness.

At medium and high solids, the roughness reached 10 microns at high speed, which in some cases was five times the roughness at medium speed.

Coat Weight and Parker Print Surf Roughness

Table 12 shows the coat weight for all nine combinations, the thickness of the wet coating and Parker roughness. The roughness average and standard deviation are based on 10 readings for each of the nine samples.

Table 12

Coat Weight, Wet Volume Thickness, and Parker Print Surf Roughness

Solids	Speed	Coat Weight (g/M2)	Wet Vol. Thickness (microns)	Parker Roughness (microns)	
				Average	SD
Low	Low	18.4	16	1.47	0.13
	Medium	41.81	36	2.18	0.56
	High	50.48	44	3.10	0.71
Medium	Low	17.18	14	1.72	0.22
	Medium	79.09	66	4.50	0.77
	High	83.56	70	6.05	1.28
High	Low	31.03	26	1.66	0.13
	Medium	71.48	59	3.89	1.10
	High	129.98	107	6.56	2.06

It is observed from Table 12 that coat weight increases both with increase in solids and increase in speed and so does the roughness. Both speed and solids seem to have significant effect.

Parker Print Surf Roughness confirms the findings that resulted from comparison of peaks and valleys. This is apparent in Figure 28. Figur 29 shows incresed roughness but Figure 30 shows only one major amplitude.At the same solids level, the roughness increased with increase in speed. These results suggest that a compromise of roughness and coat weight is possible depending on the choice of speed and solids level, but the upper and lower limits of solids for a certain speed are not very wide. The coating rheology, the hydrodynamic forces, and other factors such as coat weight restrictions render it impssible to change solids over a wide range. The same is true for speed, when the solids are constant. So the combination of solids, speed, and coat weight can be optimized based on the importance of one of the factors mentioned above. If coat weight is critical, then solids and speed can be determined within a range.The coat weight at low speed for low and medium solids was the same. There was a minor increase in roughness.

Change in Roughness

Table 13 is derived from Table 5 . The average roughness for low solids and low speed is 0.352 microns and at this speed (low) when solids were changed from low to medium, the roughness reached 0.545 microns.This is an increase of 54.8 % — (0.545-0.352) / 0.352. Table 14 and Table 15 are constructed from Table 13. All the

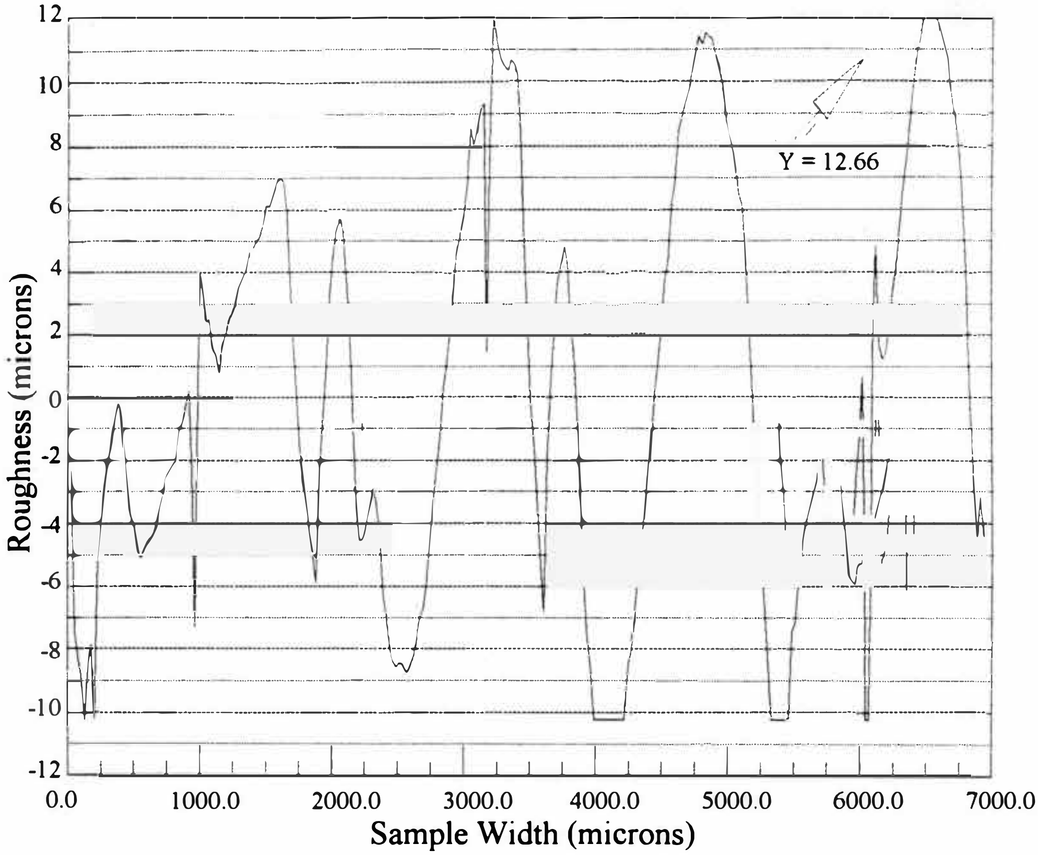

Figure 29. Roughness at Medium Solids, High Speed.

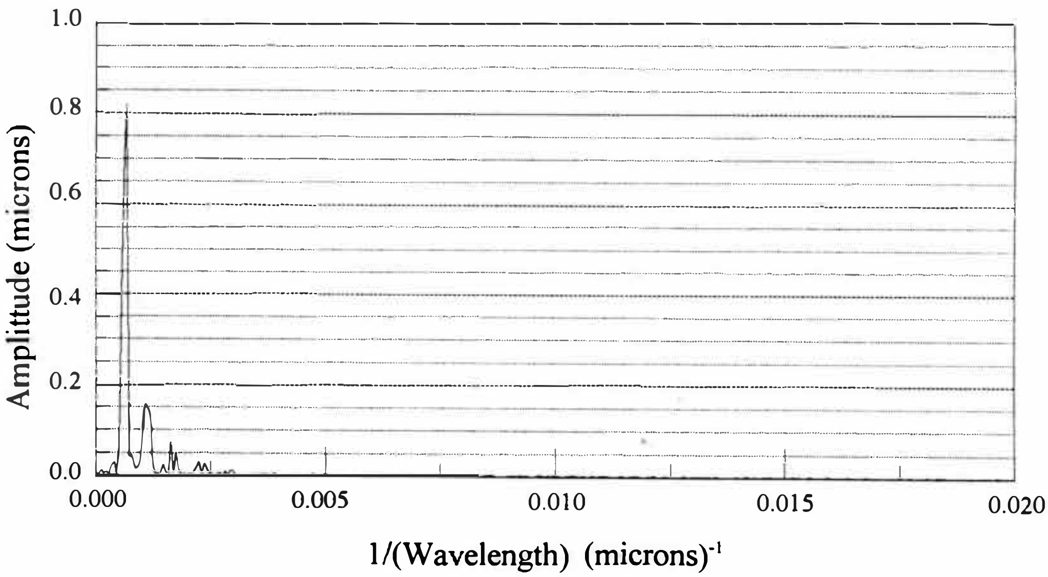

Figure 30. Fourier Transform for Roughness Data at Medium Solids, High Speed.

values in the last column of Tables 14, and 15 were calculated the same way. The following discussion was based on Tables 13, 14, and 15.

The roughness of the coated surface increases with increased speed, regardless of amount of solids. As in Table 13 the roughness was at its lowest level when low solids (60 %) in the coating were used at low speed (1500 ft./ min.). The average roughness was 0.35 microns that also includes the noise factor in the signal.

Table 13

Average Roughness (Microns)

	Low Speed	Medium Speed	High Speed
Low Solids	0.352	1.614	1.938
Medium Solids	0.545	2.950	4.011
High Solids	0.744	2.117	3.550

Table 14

Roughness Change With Solids Change

Speed	Solids Change		Percent Change
	From	To	
Low	Low	Medium	54.7
	Medium	High	36.4
Medium	Low	Medium	82.7
	Medium	High	-28.2
High	Low	Medium	106.9
	Medium	High	-11.0

When the solids were increased in the coating, so did the roughness. For medium and high speed, the roughness decreased from 2.9 microns to 2.12 microns,and from 4.01 microns to 3.55 microns, respectively, when solids were changed from medium to high.

At all speed levels, when solids were changed from low to medium, the roughness increased 55 % at low speed, 83 % at medium speed, and 107 % at high speed. It was roughly a 25 % increase at each higher level of speed. When the solids were changed from medium (62 %) to high (64 %) at low speed, the roughness increased by 36.4 %. But at medium (2200 ft./min.) and high speed (3000 ft./min.), the roughness decreased by 28.2 % and 11 % respectively when solids were increased.

As seen from Table 15, the highest increase in roughness (441 %) appeared when the speed was raised from low to medium at medium solids level. The next highest increase (357.9 %) occurred at low solids when speed was raised from low to medium.But when speed was changed form medium to high, the increase in roughness was comparatively small. This increase was 20 % at low solids, 36 % at medium solids, and 68 % at high solids.

The coatings were dried at high heat to keep the post healing at its minimum. The major part of the surface formation occurred during the application of solids and passage through the nip.

During these short periods, there were substantial changes. Major components of nip forces are parallel or perpendicular to the rod inside the pond.

Table 15

Roughness Change With Speed Change

Solids	Speed Change		Percent Change
	From	To	
Low	Low	Medium	357.9
	Medium	High	20.1
Medium	Low	Medium	440.9
	Medium	High	36.0
High	Low	Medium	184.6
	Medium	High	67.7

Thixotropy and anisotropy also play their role. Some of the mechanical energy is transformed into heat. All these things happened at the same time and it is difficult to theorize the observed behavior.

When the solids were increased and consequently there was less fluid available for movement of coating particles, the roughness decreased. Unfortunately, coat weight increased with increased speed. It made isolation of the roughness effects from effect of coat weight increase impossible. It also can be seen that decrease in roughness at medium speed was only 28.2 % as the solids were changed from medium to high.

At high speed, when solids were changed from medium to high, the decrease in roughness was 11.0 % as compared to 28.2 % decrease at medium speed. It also confirms that speed is a significant factor to change the qualities of a coated surface.

The Figures 30 through 34 represent the rest of the surface profiles and the Fourier transforms of the coated surfaces generated for the combinations of coating solids and speeds that were not reffered to in the discussion of results.

A Theoretical Explanation of Surface Formation

The desired final product of the coating process is the formation of a uniform and high quality surface. This process involved is very complex and not well understood.

The coatings are viscoelastic materials. This elastic behavior causes extension of solids before permanent deformation under shear stress. This extensional movement is not linear and there is an instantaneous velocity ingredient at each tiny time interval in clockwise or anti-clockwise direction, with a continuous change in direction.

In case of wire-wound rod coating, the non-extensional flow is also important. Hull (3) believes that all the surface phenomena are caused by cross directional flow. The irregularities and ribbing are attributed to this cross directional flow.

The observed surface characteristics vary considerably under the nine combinations of speeds and solids used in this study. The following discussion explains the possible mechanism responsible for this surface variation. The Cylindrical Laboratory Coater is in principal a puddle coater. The following explanation is related to this design.

The surface roughness increased with increased speed or solids. When speed is increased, the speed of fluid in contact with substrate is increased. As the immediate

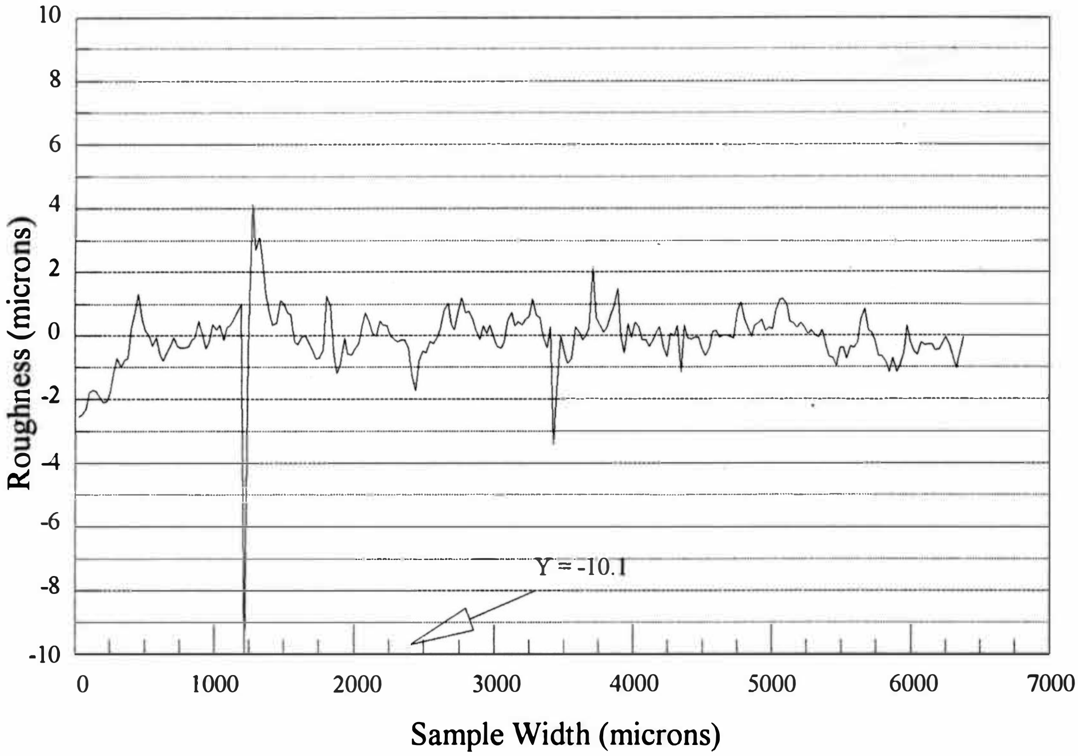

Figure 31. Roughness at High Solids , Medium Speed.

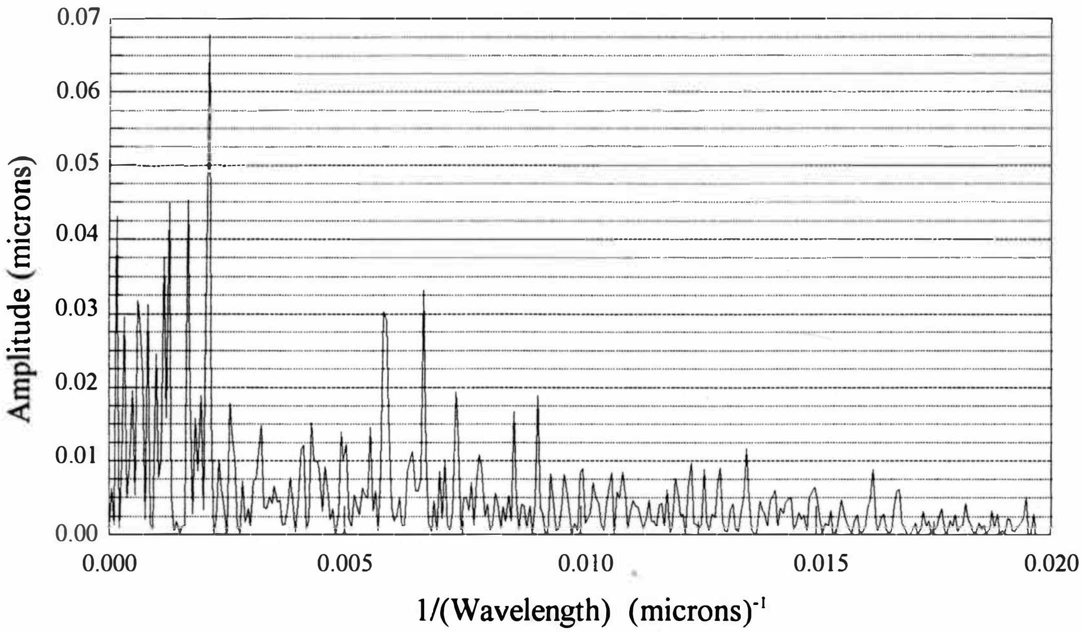

Figure 32. Fourier Transform for Roughness Data at High Solids, Medium Speed.

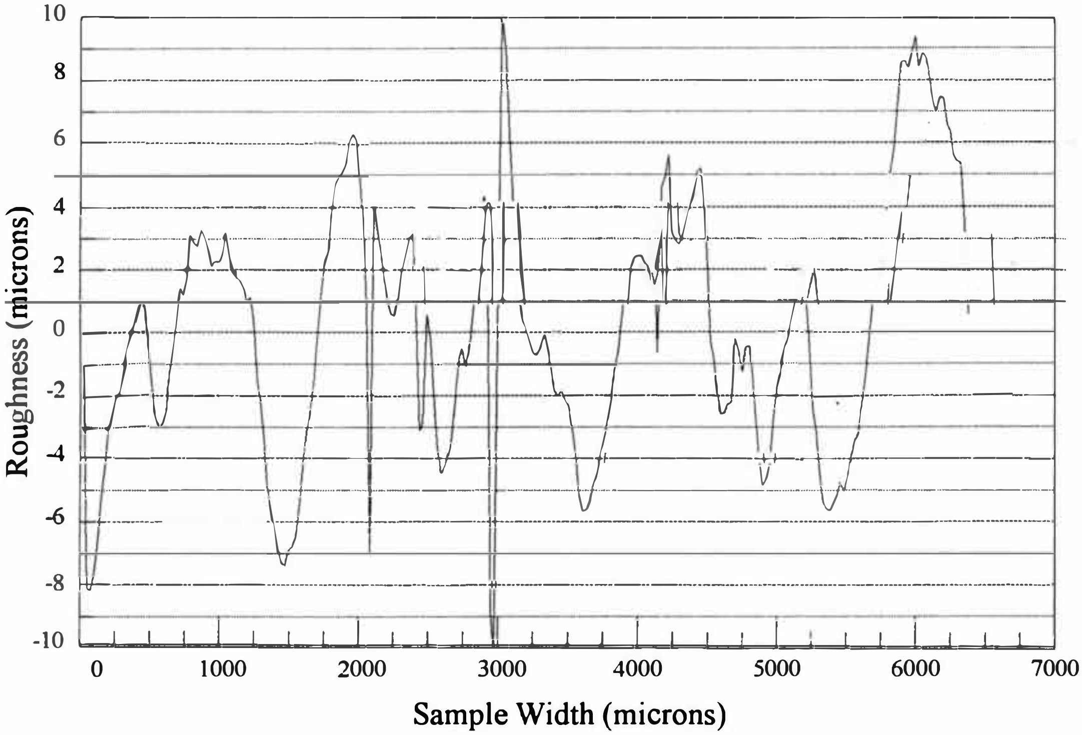

Figure 33. Roughness at High Solids , High Speed.

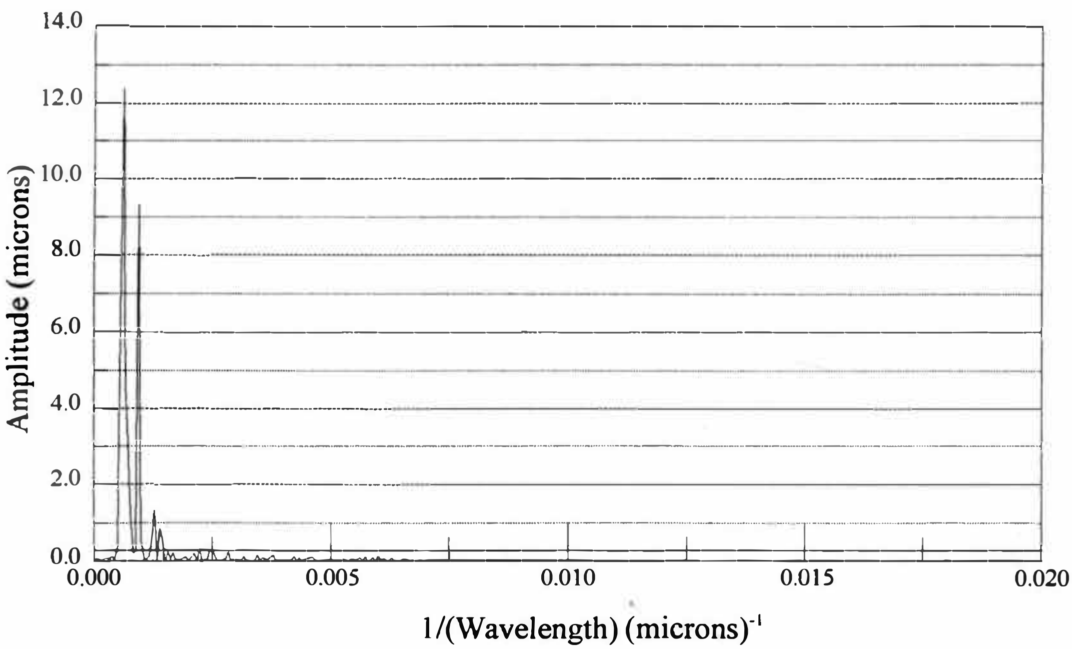

Figure 34. Fourier Transform for Roughness Data at High Solids, High Speed.

layer next to the web starts moving, the next layer and consequently the layer next in succession moves towards the nip. This generates a greater hydrodynamic force under the rod that may either force more fluid through the gaps between the wire or lift the rod and increase bulk flow under it. The excess coating flows in all directions, but some of these reverse currents are stronger in the direction where resistance is the least.

As shown in Figure 35, the highest resistance to the backward flow (a) is in the direction adjacent to the incoming substrate along the backing roll. The excess liquid flow is vertical to the backing roll. This flow is circular in motion. It flows down with the web, then away from the the web in the bottom of the pond (b) and to the surface, towards the web and down again as an immediate layer in contact with the web or as a layer in succession.

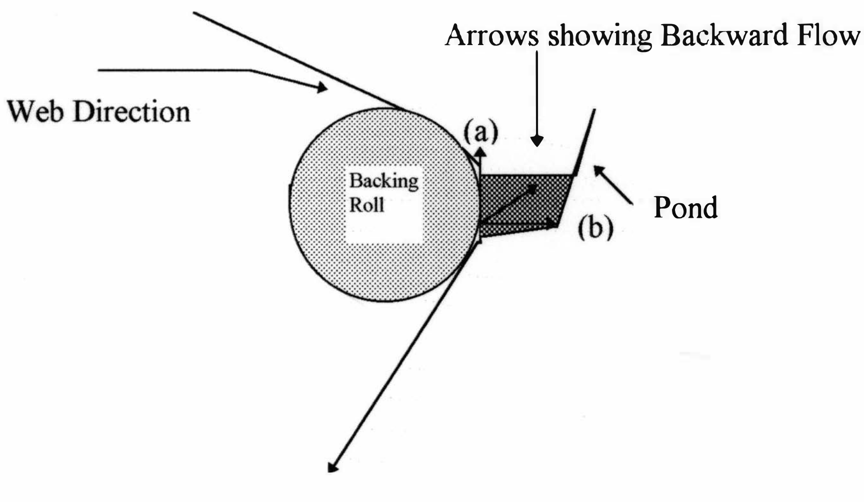

Figure 35. Backward Flow in the Coating Process.

Another flow is across the web in both directions. This flow originates at different points at the nip and under hydrodynamic forces develops a steady pattern of waves. The perpendicular flow away from the web may have a part in giving regular pattern to this cross-directional flow.

The amount of fluid and the amount of coating passing under the nip is not uniform. This extra amount is laid on the surface of substrate as a wavy pattern, and in most cases, this pattern is quite regular when the flow stabilizes. Some of the sine waves under Fourier transform showed a regular pattern in this study though the duration of the flow was short. In actual coating situation these patterns are regular and hence the name ribbing.

The Fourier analysis of data, in this study, shows that the wavelength of the sine curves increased with increased speed. With increased speed the velocity of cross-directional flow is increased, so the rib pattern widens with emergence of large fluid waves.

The local irregularities created in the surface may be due to the dilatant behavior, the viscoelasticity, and the extensional flow of coatings. The particle size and shape, the amount of fluid and the particle charge also contribute to the local irregularities that finally appear as peaks and valleys in the coated surface. These peaks and valleys along with micro ribbing are termed as roughness.

With increased speed, these irregularities are accentuated and cause a rougher surface. Most of the healing takes place before the coatings reach the immobilization solids level. This healing is mainly due to elastic behavior of coatings and the surface tension. These forces are less effective when the amount of fluid is reduced by increasing the solids level. So, when the solids are increased, the roughness is increased. The final surface is therefore a function of both the ribbing and leveling behavior, which were not isolated in this work.

CHAPTER VII

CONCLUSIONS

The following were observed in this study:

1. The surface roughness increased when either coating speed or the coating solids were increased.

2. The speed had more profound effect on surface roughness as compared to that of coating solids content.

3. The relation between surface roughness and speed is nonlinear.

4. With increased solids content the coat weight of a coated surface increases.

5. Lower speeds produce the lowest surface roughness regardless of solids level.

6. At certain speed and solids combination,the coated surface displays a regular pattern. The combination varies with change of solids or speed.The surface resembles a single sine wave. If any of the speed or solids are changed beyond a limit, this pattern is broken.

7. Under Fourier transform analysis, the average wavelength of the dominant curve increased with increased speed for medium and high solids, but decreased for low solids.

8. The average amplitude of the dominant curve increased with increased speed at all solids levels.

9. Visually the coated surfaces varied from very smooth to very rough. The peaks and valleys ranged from less than a micron to 16 microns.

CHAPTER VIII

SUGGESTIONS FOR FUTURE WORK

Three solids levels and three speeds were used in this study. More small steps in intervals of speed and solids will generate more data and the level of validity can be increased.

A continuous coater can provide enough time for the interacting forces, in the coating process, to stabilize and give more reliable results. The time span, for a coating formulation to be applied to the substrate on a Cylindrical Laboratory Coater, is very short. This study can be repeated using a continuous coater and paper instead of polyester film that was used in this study.

There was only one formulation that was used in this study. A change in formulation can help to determine the combination that performs better under high speed for a desired coat weight.

If coating solids and speed are predetermined, then the coat weight becomes a dependent variable. A study can be done in which speed or coating solids are varied to achieve constant coat weight. This will help in isolating the coat weight effect and help determine the effect of solids or speed alone on the surface formation in the coating process.

In this study maximum heat was applied to immobilize the coating solids as soon as possible. A study can be done to change the drying intensity and determine the effect of heat transfer to the coated surface.

The wire gauge may also interact with the solids or speed. This can be studied by using speed or solids as constant variable. The interaction of wire, solids and speed may provide optimum conditions for a specific formulation. The effect of wire can be isolated by keeping both solids and speed constant. These studies may enhance the understanding of surface formation in the coating process.

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