

THE EFFECT OF FORWARD SLIP ON
THE SURFACE FINISH OF COLD
ROLLED ALUMINUM

BY

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TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
LIST OF FIGURES.	iv
LIST OF TABLES	v
NOMENCLATURE	vi
INTRODUCTION	1
LITERATURE REVIEW.	4
EXPERIMENTAL EQUIPMENT AND PROCEDURE	8
RESULTS.	14
DISCUSSION	25
CONCLUSIONS.	31
RECOMMENDATIONS.	33
REFERENCES	34
APPENDIX A. Forward Slip Calculations	36
APPENDIX B. Theoretical Calculation of Relative Slip. . .	37
VITA	41
ABSTRACT	

LIST OF FIGURES

No.	Page
1. Schematic drawing of the rolling process.	2
2. Strip guide and timing mechanism.	9
3. Lubrication applicators	11
4. Effect of rolling and the groove produced by the Talysurf stylus	20
5. Comparison of kerosene and oil samples rolled at low speed with rough rolls, 200 x magnification	21
6. Comparison of low and high speed samples rolled with kerosene and smooth rolls, 346 x magnification.	22
7. Comparison of low and high speed samples rolled with oil and smooth rolls, 346 x magnification	23
8. Scanning electron micrographs of rough roll samples, 950 x magnification	24
9. Role contact geometry	38

LIST OF TABLES

No.	Page
1. Experimental variables and samples reduced for analysis	15
2. Forward slip calculations.	16
3. Relative slip lengths.	17
4. Roll and sample roughness.	19
5. Discussion Summary	29

NOMENCLATURE

A1	Aluminum
C	Limit of integration
D	Total contact distance
FS	Forward slip
H	Strip thickness at neutral axis
H_1	Inlet strip thickness
H_2	Exit strip thickness
H^1	Penetration depth of roll into strip
HP	Hydrodynamic pitting
N_A	Neutral axis
PT	Photo transistor
R	Roll radius
S	Contact distance with respect to the neutral axis
SEM	Scanning electron microscope
SL	Slip length
V	Strip velocity at neutral axis
V_1	Inlet strip velocity
V_2	Exit strip velocity
V_R	Roll velocity
y	Total contact angle
z	Contact angle to the neutral axis

INTRODUCTION

The surface finish of cold-rolled aluminum (Al) is a critical marketing factor. The aesthetics of a product are directly influenced by the visual appearance and mechanical applications require a specific roughness for designed performance. Sheet Al is formed with a rolling mill where the percent reduction, lubricant, roll roughness, and roll speed determine the surface finish. Forward slip (FS) occurs when the strip velocity exceeds the roll velocity due to the elongation of the strip. This research was performed to determine the effect FS has on the surface finish of cold-rolled Al.

FS is used as an indication of rolling performance. The production rate is directly related to FS since FS increases as the strip velocity exceeds the roll velocity; note the equation below and Fig. 1.

$$FS = (V_2 - V_R) / V_R$$

At zero or negative FS the lubricated roll is going faster than the strip and the strip can slide transversely across the roll. This condition, called mill instability, can damage the strip and the mill if the strip touches the side of the mill. Finally, FS varies directly with rolling friction. An increase in friction necessitates an increase in power to maintain the mill speed (10). The optimal FS is a trade off between high production, and an increase in the power requirement. If the surface finish also

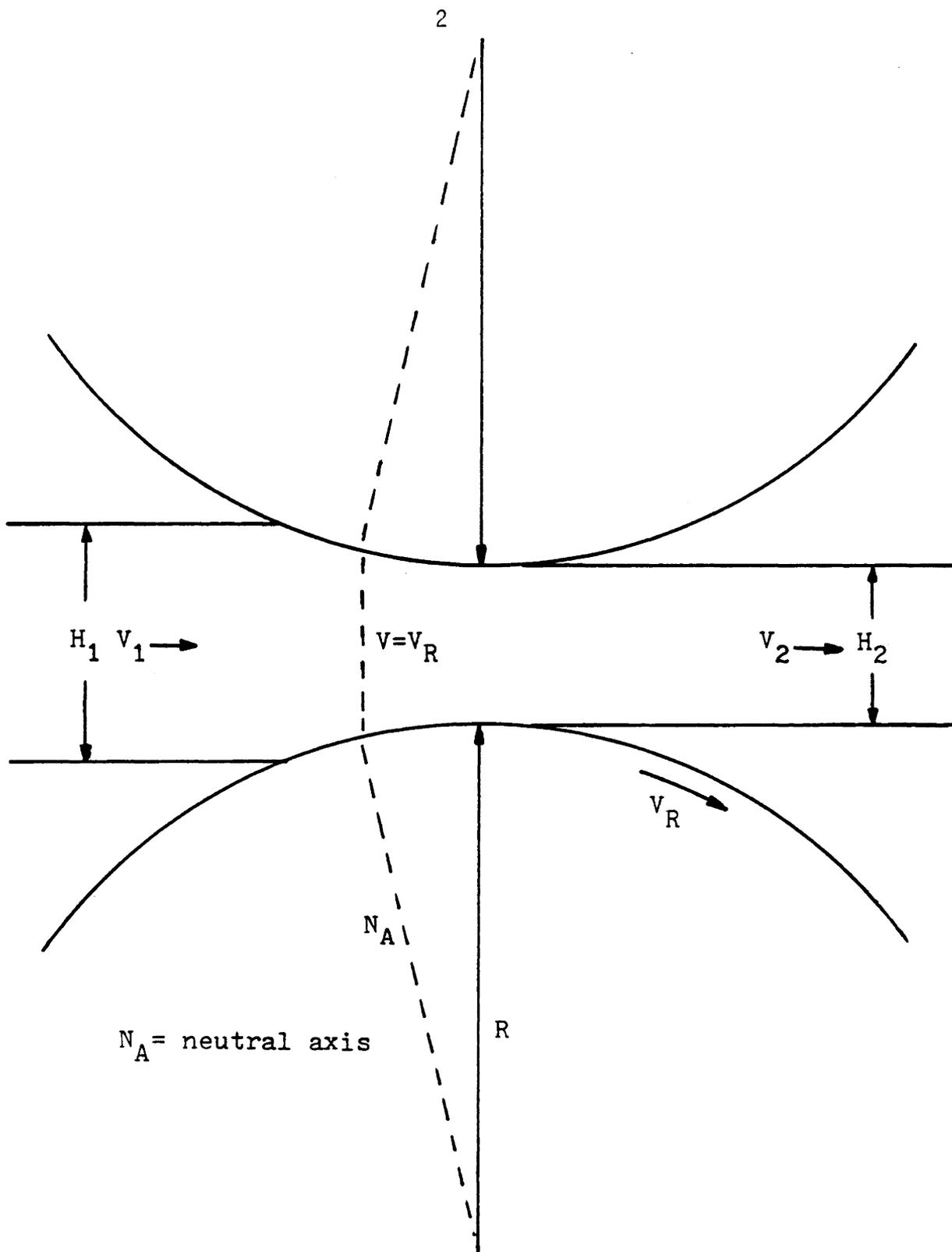


Figure 1. Schematic drawing of the rolling process.

changes with FS then the optimal FS would be a function of three variables.

The surface finish of cold-rolled Al was studied at Virginia Polytechnic Institute prior to this investigation, by P. M. Sandy (1). He concluded that the strip surface roughness conformed to the roll surface roughness with increasing reduction and was independent of rolling speed. Mr. Sandy's first recommendation for continued research was the study of FS; therefore, based on his work and a study of the literature, this investigator chose to examine the effect of FS on surface finish.

To aid in this examination, two apparatus were built--the first to measure FS, and the second to lubricate the rolls. The FS was varied by using different roll speeds and lubricants of different viscosities. Samples were rolled and the surface finish analyzed using various profilemetric and optical techniques. The sample surface finish was then characterized to determine the change produced by varying the FS for a given reduction.

LITERATURE REVIEW

A description of a typical rolling mill opens this review followed by a discussion of surface finish analysis and rolling research.

Rolling is the process of plastically deforming metal into sheets. A rolling mill consists of two work rolls, through which the strip is reduced, an uncoiler and a windup reel. The uncoiler feeds the strip under back tension while the windup reel coils the reduced strip under front tension. Lubrication is supplied to the roll bite to cool the rolls, lower frictional resistance, and reduce wear. The percent reduction, front and back tension, lubricant viscosity, and composition, roll roughness, and velocity can all be varied to produce a desired product. The area of strip and roll contact is the roll bite. The dynamics of the roll bite and the resulting products are the subject of rolling research (2).

The surface finish of rolled metal is characterized by visual appearance and surface topography. Sandy (1) examined 11 surface characterization parameters to determine which were good indicators of surface changes. All samples were rolled at different speeds and reductions were then analyzed using a stylus profile meter and two computers. He found that five parameters of the height distribution were good indicators of surface change and that roughness was independent of velocity. Quiney (3) examined the performance of two stylus and one optical interference profile meters. The stylus

instruments scratched a groove in brass and Al which seriously distorted the profile. Interferometric roughness measurements were found to be accurate when compared to a known standard. The stylus method could not accurately measure the surface roughness but could marginally determine the relative roughness. He concluded that stylus methods are inaccurate on metals with a Rockwell hardness less than C-66 and relative measurements were inaccurate on soft metals, unless differences of over 40 microinches were examined. Surface damage by a stylus was also examined by Guerrero (4), who reported that pressures up to 26,000 PSI can be produced with a stylus and recommended the scanning electron microscope (SEM) as an alternative. The specular and diffuse reflectance of laser light has been used to study surface roughness by various researchers. Tanner (5) and Clarke (6) concluded that laser scanning analysis can accurately measure surface roughness and has a future as an industrial tool. Deka (7) used a computer to analyze the statistics of reflected laser light and measured the correlation length of rough surfaces using the speckle produced by two different wavelengths.

The effect of lubricant viscosity and composition in rolling has been examined by several researchers (8 - 16). All but two of these researchers used FS as a measure of mill performance. Mill performance was analyzed in terms of either rolling stability or rolling effects such as friction and surface finish. Kondo (8) determined that an increase in front tension, roll roughness,

and roll diameter would increase FS while an increase in roll speed, sheet thickness, and lubricant viscosity would decrease FS. Rolling friction was calculated and was found to vary directly with FS. Reid and Schey (9), performed an experiment similar to Kondo's with emphasis on determining the onset of negative FS and mill instability. SEM photographs showed hydrodynamic pitting occurred with increasing reduction and negative FS indicating hydrodynamic lubrication. They concluded that the onset of negative FS could not be predicted using any of the known theories. Schey (10, 11) had previously conducted two experiments in which he analyzed the effect that combinations of Al alloy, lubrication viscosity, and additives had on rolling torque and FS. He concluded that rolling friction was primarily due to local asperity welding and that FS increased with increasing reduction. Sargent and Stawson (12) used the Sommerfeld number, a "dimensionless ratio of the product of velocity and viscosity to pressure", to measure the energy used in rolling. They found this number correlated well with known performance when FS was used as a measure of velocity and constrained yield stress as a measure of pressure.

Drumgold (13) studied the effect of lubricant viscosity on the reduction of Al foil. He found that reduction increased with increasing viscosity except at low viscosities where it decreased. He could not explain this phenomenon but suggested that polar additives might be more easily aligned in the less viscous, smaller

molecule oil. A dull surface finish was produced when more viscous oils were used.

Finally, Tsao (14, 15, 16) published three papers in which he presented a "Mixed Lubrication Model" which modelled the conditions in the rolling bite. This model incorporated all of the rolling parameters already mentioned and determined the friction, pressure distribution, and FS. The calculated results were in agreement with experimental results.

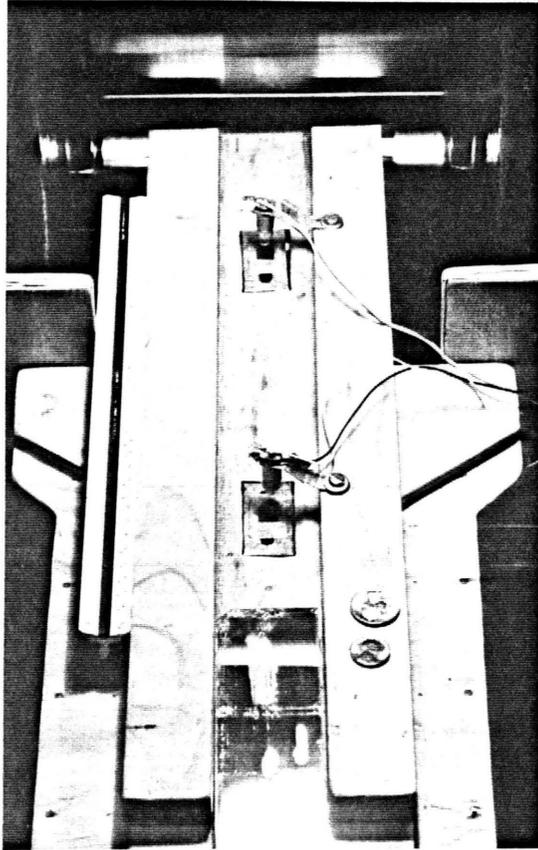
Three additional papers were reviewed in which surface finish was studied with respect to rolling factors. Ratnager (17) examined the effect viscosity had on the surface finish of Al. Low viscosity lubricants caused individual crystals to deform at grain boundaries and slip within the boundaries. Viscous lubricants formed hydrodynamic pockets as well as the deformation noted for low viscosities. Tripathi (18) studied the pickup film which forms on rolls during rolling. He concluded that at low velocities the pickup was due to mechanical shearing action. At high velocities the pickup was due to a combination of mechanical shearing and the formation of a polymeric film at the sheared faces. The film coating was also influenced by the roll and strip surface finish, temperature and the rate of cooling. Thompson (19) examined the surface finish of rolled Al under various conditions. He concluded that the strip surface finish was strongly dependent on FS and the roll finish. The surface finish of the strip was dependent on the roll roughness and independent of the initial strip finish after a sufficient reduction.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

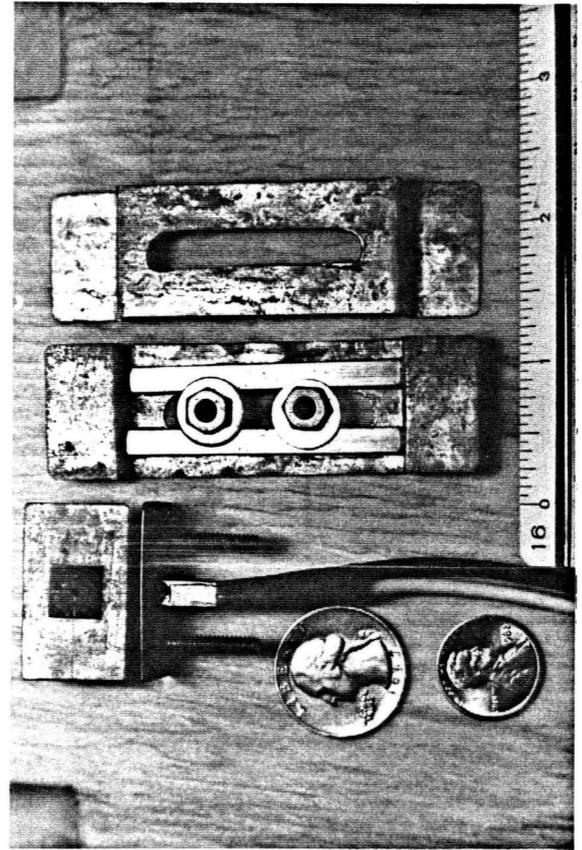
Mill Description

Strips of Al sheet 508 mm x 50.8 mm x 1.63 mm thick were rolled on a Starrat model TA-215 laboratory rolling mill. The mill was equipped with two vanadium alloy steel rolls 127 mm in diameter and 197 mm wide. Variable reduction was achieved with a worm gear screwdown system adjusted with a handwheel. The roll velocity was regulated with a four speed transmission connected to a fixed speed electric motor. The mill weighed 3000 pounds, incorporated needle bearings on the rolls, and produced little vibration.

FS was measured by determining the strip and roll velocity. A wooden guide platform was mounted on the mill face to support the strip timing system and to minimize strip feed variations. Two HEP P003 Motorola photo transistors (PT) were fixed to the bottom of the guide platform to time the strip speed. The PT were illuminated with 1.5 volt DC lights located 5 mm above the platform surface. They were mounted such that their separation distance could be adjusted to ± 0.1 mm accuracy. The PT, initially shielded from the light by the strip, emitted a signal pulse upon illumination as the strip was pulled into the mill (see Fig. 2). The PT signals were used to trigger an HP 5327A 55MHZ timer/counter. The strips were timed to ± 0.0001 sec.



1) Strip guide and timer



2) PT slide and mounting

Figure 2. Strip guide and timing mechanism.

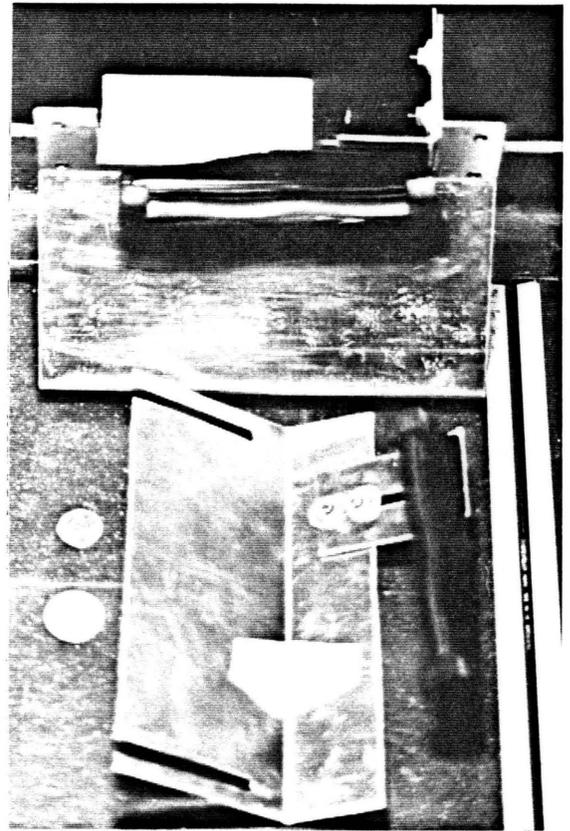
The roll speed was measured with a PT triggered by reflected light. A 6.35 mm x 336.6 mm Al foil strip was divided into 53 alternating light and dark rectangular segment pairs with black paper. The strip was taped to the roll drive shaft and a DC light was mounted with the PT such that a periodic electric signal was produced when the shaft turned. An HP 5300 timer/counter was used to measure the periodic signal with an accuracy of ± 0.5 periods/sec.

Lubrication was applied to the rolls from reservoirs on each roll surface. A rubber wiper blade was mounted to rub against the roll and form a dam with foam rubber sides (see Fig. 3). The wiper blades could be positioned in all directions such that a uniformly thick film of lubricant was applied to the rolls. The reservoirs were filled manually from laboratory squirt bottles.

The unalloyed H16 tempered Al strips were sheared from 508 mm x 254 mm plates. The plates were finished with a bright and a mat side. The strips were rolled bright side up with the forward right hand corner cut off. The two lubricants used in the experiment, kerosene plus five percent butyl stearate additive and 10 W40 oil, had viscosities of one and five centipoises, respectively. This difference in viscosities was used to generate a range of FS. Four reductions--16.4, 34.4, 50.0, and 59.4 percent--were rolled with each lubricant at velocity of 304.8 mm/sec. Samples were also rolled at 1473 mm/sec and 304.8 mm/sec. using polished rolls, which are described later.



1) Lubrication reservoirs



2) Top and bottom lubricators

Figure 3. The lubrication applicators.

Test Procedure

The lubricant reservoirs were filled while the rolls were turning. A strip was placed in the guide and moved back and forth to trigger the timer, check its operation, and charge the PT NPN junction. The roll gap was set, the timer reset, and the strip gently pushed into the rollers. The roll frequency was observed during the reduction and found to be invariant. The reduced strip thickness was measured with a one inch Starett micrometer. Each sample was identified by a number on a piece of masking tape affixed to the strip surface. The strip time, mill frequency, strip number, and strip thickness were recorded for each sample. The strips were laid on newspaper before being wrapped in paper or cloth and stored. At the conclusion of one series of reductions, the kerosene was wiped off, replaced with oil, and the experiment repeated. The initial reductions were chosen to correspond to graduations on the handwheel. Afterwards, they were obtained through trial with as many as 30 samples reduced to obtain the four required. The thickness tolerance was ± 0.025 mm. At the completion of the oil reduction, the rolls were cleaned with kerosene and the experiment repeated at the higher velocity. The experiment was run over two days separated by six months. It was then repeated in one day. The rolls were polished with 400 grit emery cloth at the end of the six month period, prior to continuing the experiment. The polished rolls were smoother than the original rolls and thus another analysis variable was introduced, rough and smooth rolls.

Sample Analysis

A Talysurf four profile meter was used to produce amplified profiles of the strip surfaces with a chart recorder. These profiles were analyzed and compared to examine the effect of FS. The Talysurf was connected to a Tektronix 4051 minicomputer-Zonic digital memory combination which digitized the profile, stored the data, and linked to an IBM 360/370 mainframe computer. A computer program was used to statistically analyze profiles taken from the oil and kerosene lubricated strips at two reductions. The samples were then studied with various optical microscopes. The SEM was used to examine and photograph the prominent differences observed in the strips. Speckle patterns were produced with a laser and studied for specular and diffuse reflectance variations. Finally, a Leitz Orthoplan microscope was used to photograph the strips. The photograph negatives were magnified with a print enlarged and the images were characterized for surface finish differences.

RESULTS

Table 1 on the following page shows the combinations of variables with which samples were rolled. The FS values for the samples were calculated using the equations below and appear in Table 2. An explanation of the calculation derivation is presented in Appendix A.

$$FS = \left[\frac{1.52}{(\text{strip time}) (\text{exit thickness})} - 1 \right] \text{ Low Speed}$$
$$FS = \left[\frac{0.40}{(\text{strip time}) (\text{exit thickness})} - 1 \right] \text{ High Speed}$$

The relative slip between the strip and roll, not to be confused with FS, was calculated hypothetically and is introduced here. The roll moves faster than the strip up to the neutral axis of no relative motion, as shown in Fig. 1. The strip then moves faster than the roll as it is squeezed out. FS is the velocity difference between the exiting strip and the roll, whereas, the relative slip is the distance the roll moves with respect to the strip, because of this velocity difference. The relative slip lengths were calculated to compare with the surface scratches on the samples and are presented in Table 3. A detailed explanation of the calculation procedure appears in Appendix B.

The roll roughness before and after polishing and the sample roughness for each reduction were measured with the Talysurf

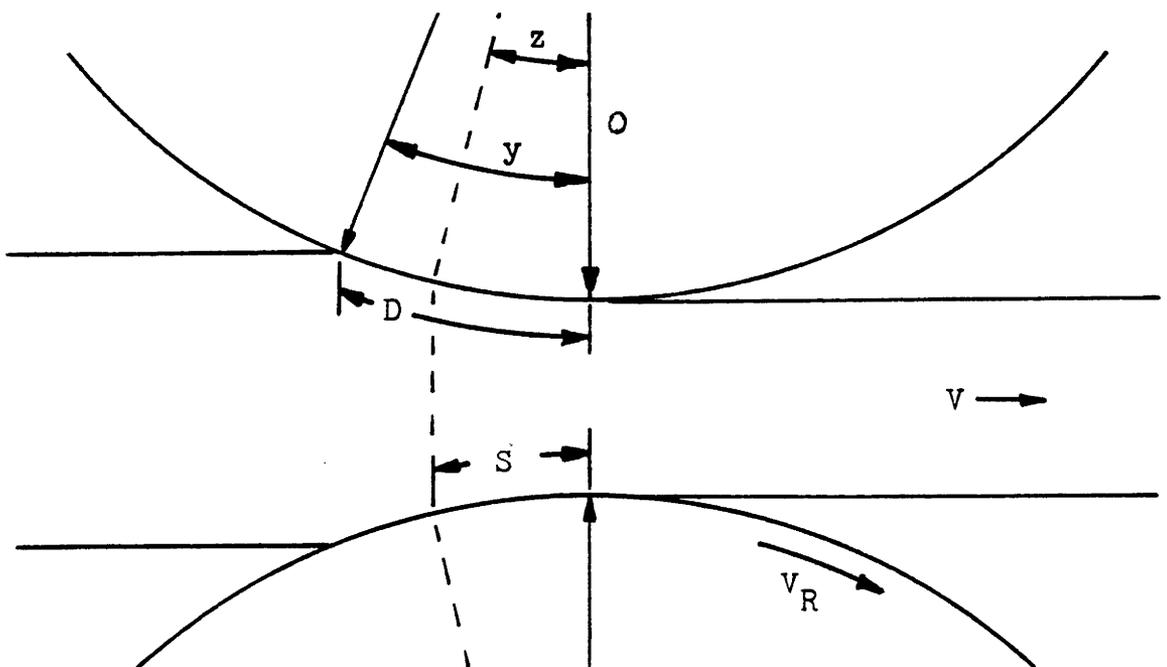
Table 2. Forward Slip Calculations

		<u>FORWARD SLIP PERCENT</u>					
		<u>Rough</u>			<u>Smooth</u>		
		<u>Kerosene</u>		<u>Oil</u>	<u>Kerosene</u>		<u>Oil</u>
Reduction Percent	Roll:						
	Lubricant:						
	Speed:	<u>Low</u>	<u>Low</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
16.4		3.3	2.4	1.4	1.95	0.42	-0.44
34.4		6.5	3.16	2.8	3.3	0.02	-2.6
50		12.2	3.73	11.1	5.0	2.68	
59		15.57	4.4	21.46	10.99	10.34	

Table 3. Relative Slip Lengths for Rough Rolls at Low Speed

Reduction Percent	Contact Length mm		Slip Length mm*	
	S	D	0-z(Exit)	z-y(Entree)
<u>Kerosene</u>				
16.4	2.39	5.83	-0.053	0.206
34.4	2.97	8.46	-0.130	0.785
50	3.56	10.19	-0.287	1.49
59.4	3.62	11.10	-0.363	2.121
<u>Oil</u>				
16.4	2.03	5.83	-0.030	0.234
34.4	2.07	8.46	-0.051	0.950
50	1.96	10.19	-0.048	1.933
59	1.93	11.10	-0.053	2.72

* The slip for the arc length defined by the angle 0-z or z-y.



four profile meter and are the subject of Table 4.* The Talysurf was also used to examine the samples for FS differences. The Talysurf was unable to distinguish details which are visually apparent (see Fig. 4), thus, optical techniques were utilized. The pictures in Figs. 5 through 8 show these details.

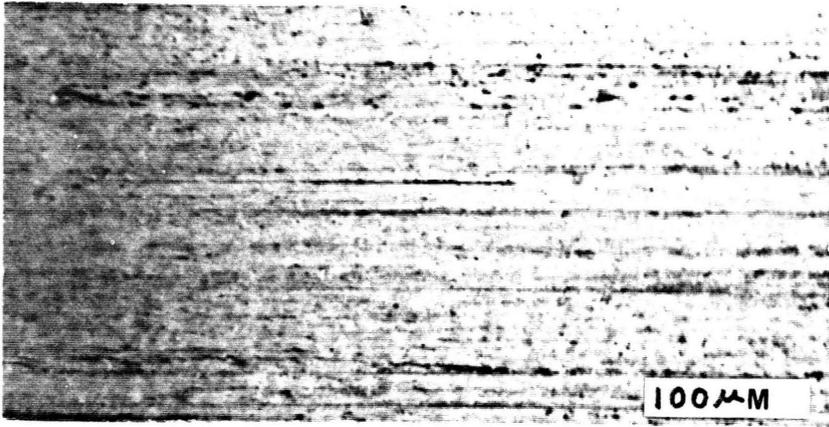
Figure 4 shows an unrolled and rolled sample for comparison and the groove made by the Talysurf stylus. The lines in the pictures are surface ridges formed as the sample conformed to the roll grind grooves. The six pictures in Fig. 5 represent all of the samples reduced with the rough rolls. The 50 percent reduction samples were similar to the 59 percent reduction samples and were therefore not photographed. The samples are arranged so the reader can compare the effect of lubricant on surface finish for a given reduction. Pictures of the samples rolled with the polished rolls appear in Figs. 6 and 7. These samples were rolled at high and low speed and are displayed to compare the effect of rolling velocity. The photographs of the smooth roll samples are 1.73 times more magnified than the rough roll samples. Two cameras, with different magnification, were used to take the sets of pictures. SEM photos appear in Fig. 8 to show the fine detail which distinguishes the samples.

* These measurements were made by Sandy (1) except for the polished roll.

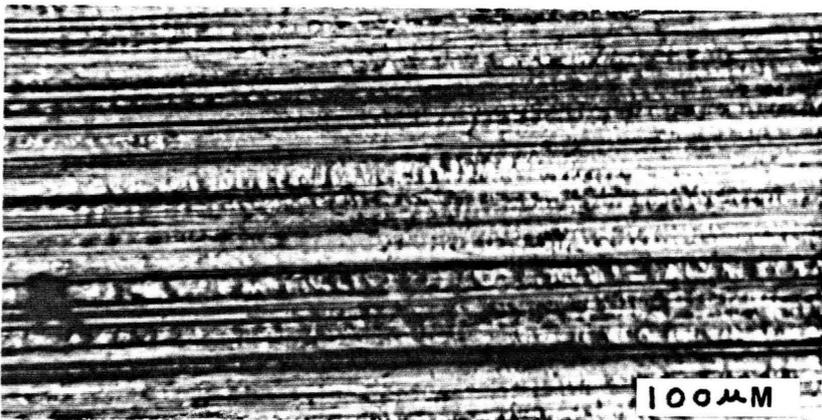
Table 4. Roll and Sample Roughness

<u>Arithmetic Average Roughness, Microns</u>	
Original, (rough rolls)	0.5
Polished, (smooth rolls)	0.4
Sample Reduction Percent	
0.0	0.0574 [#]
16.4	0.45
34.4	0.5
50.0	0.5
59.4	0.5

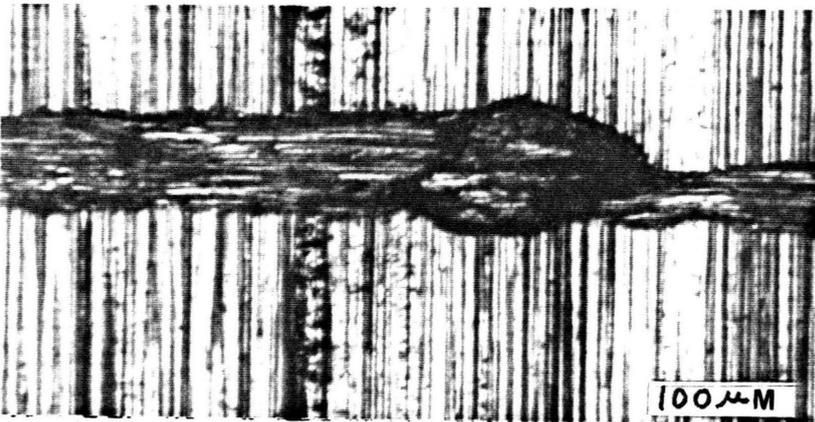
#, These sample roughness values were taken from P. Sandy's thesis (1).
 The samples were rolled with kerosene plus 15 percent butyl stearate
 All the measurements were made with the Talysurf four profile meter.



1) Unrolled sample

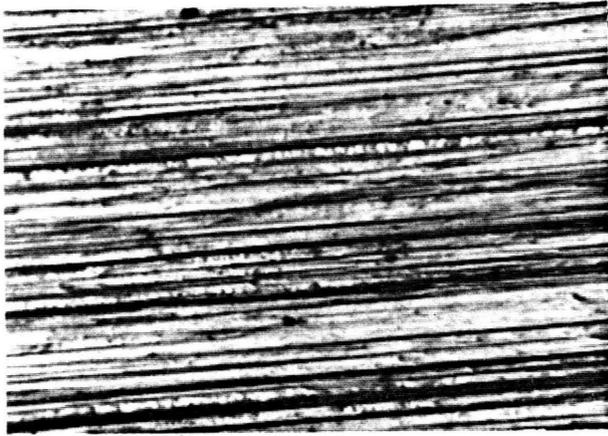


2) Rolled sample, 34% reduction

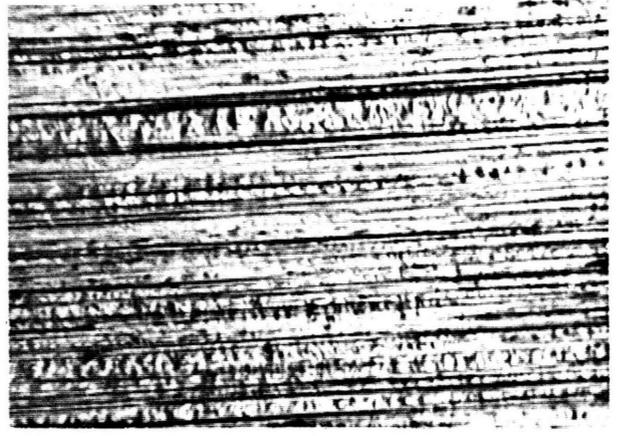


3) Talysurf trace scratch

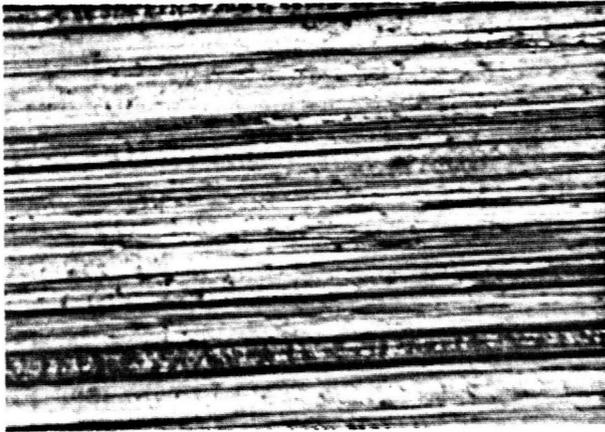
Figure 4. Effect of rolling and the groove produced by the Talysurf stylus.



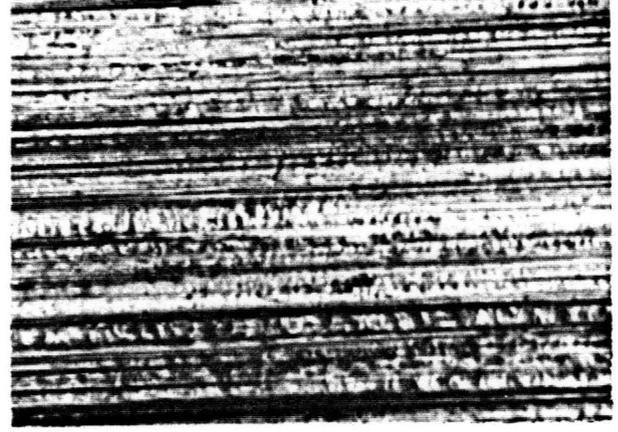
1) Kerosene, 16% reduction



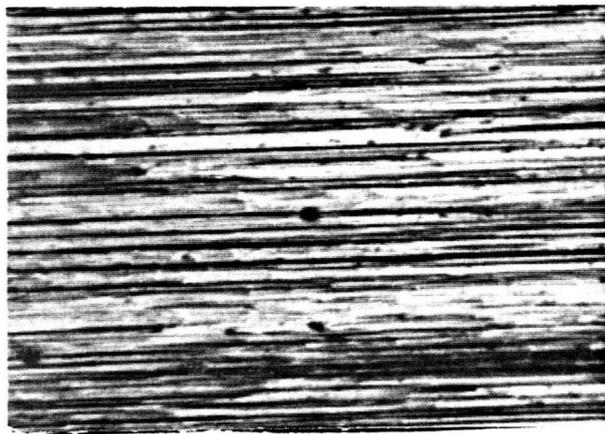
4) Oil, 16% reduction



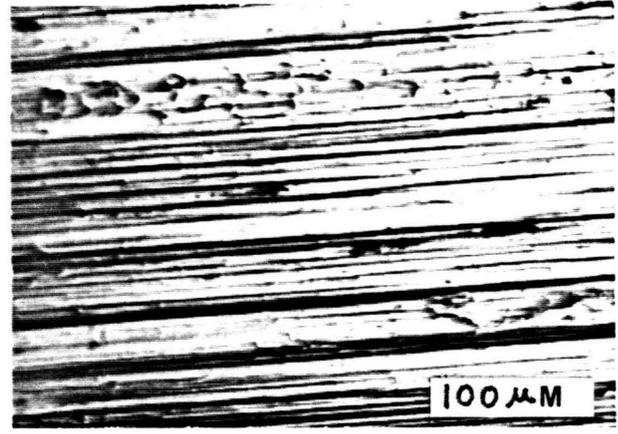
2) Kerosene, 34% reduction



5) Oil, 34% reduction

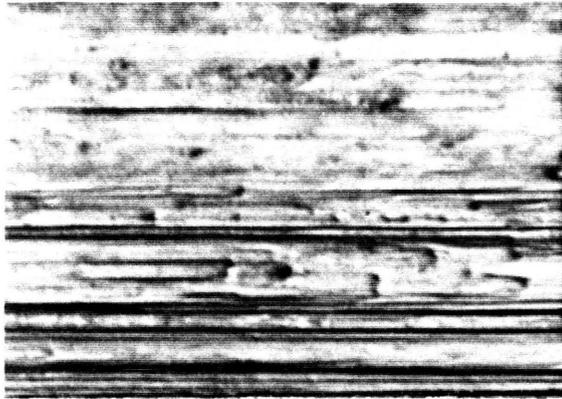


3) Kerosene, 59% reduction



6) Oil, 59% reduction

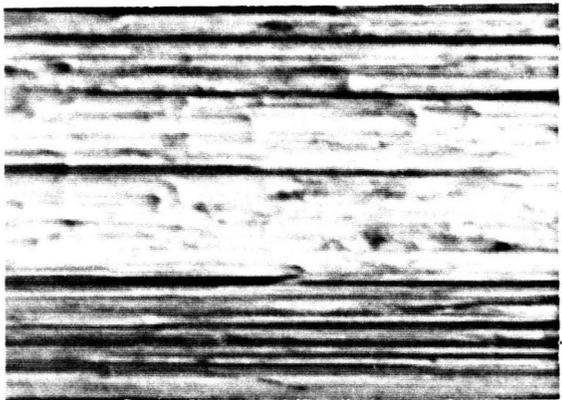
Figure 5. Comparison of kerosene and oil samples rolled at low speed with rough rolls, 200 x magnification.



1) Low speed, 16% reduction



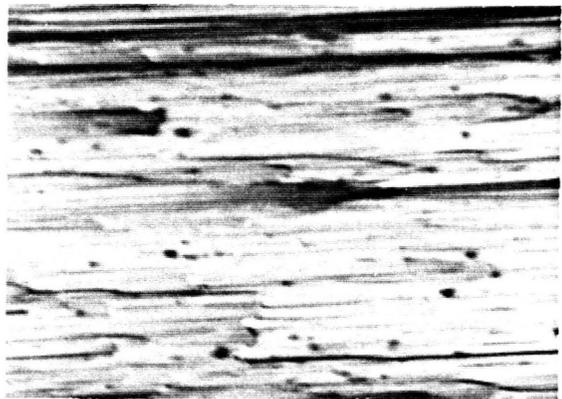
4) High speed, 16% reduction



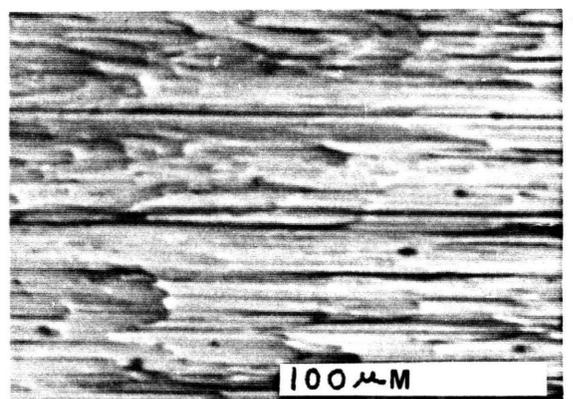
2) Low speed, 34% reduction



5) High speed, 34% reduction



3) Low speed, 59% reduction



6) High speed, 59% reduction

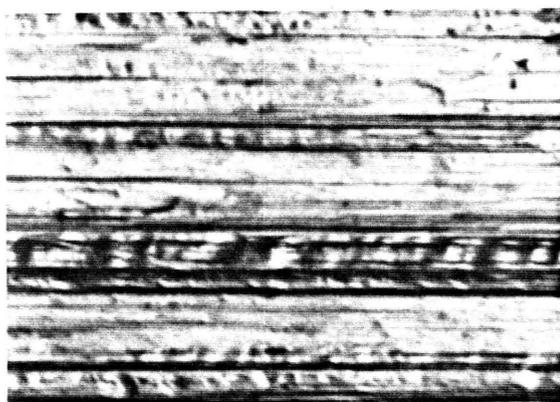
Figure 6. Comparison of low and high speed samples rolled with kerosene and smooth rolls, 346 x magnification.



1) Low speed, 16% reduction



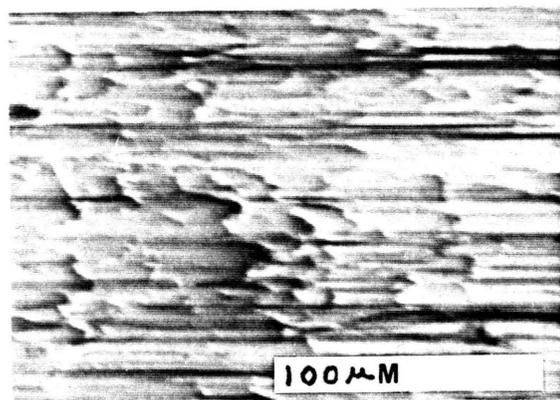
4) High speed, 16% reduction



2) Low speed, 34% reduction

This picture was overexposed.

The sample was similar to above with more hydropitting.



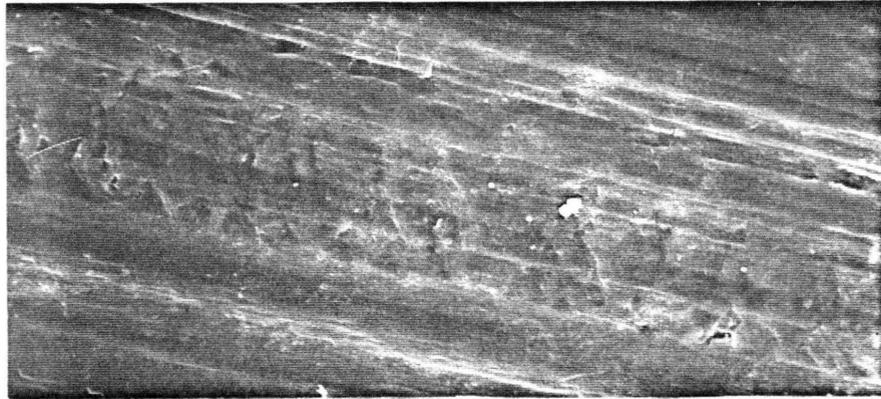
3) Low speed, 59% reduction

5) High speed, 34% reduction

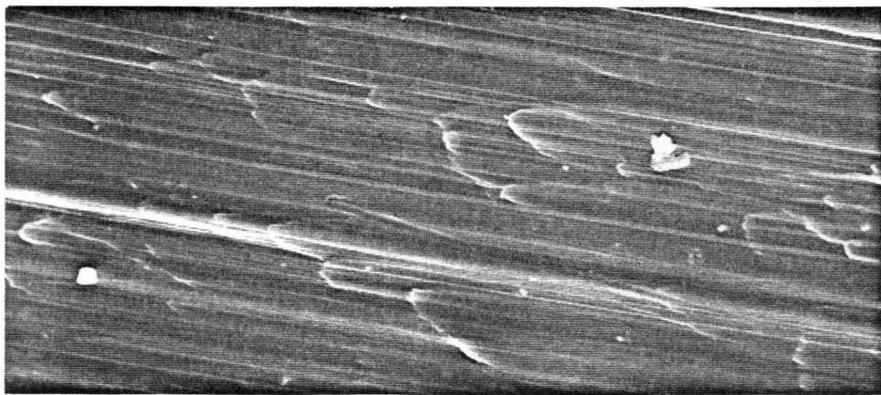
The mill was unable to grip the sample at any reduction above 42% at high speed with oil lubricant.

6) High speed, 59% reduction

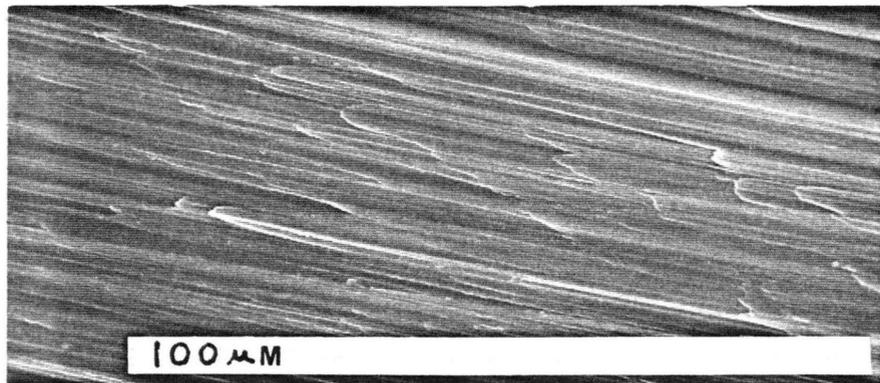
Figure 7. Comparison of low and high speed samples rolled with oil and smooth rolls, 346 x magnification.



1) Oil, 34% reduction, hydropitting



2) Oil, 59% reduction, FS marks



3) Kerosene, 59% reduction, FS marks

Figure 8. Scanning electron micrographs of rough roll samples, 950 x magnification.

DISCUSSION

The first attempt to analyze the sample surface finish was made with the Talysurf four profilemeter. Numerous traces were taken of the original rough roll samples at all reductions. The traces showed no difference attributable to FS. A computer program was used to analyze digitized profiles but the results showed no significant differences. The samples then were examined visually, by eye, and found to have a grainy pattern which was darker with increasing reduction and oil lubrication. This effect was studied with various light microscopes and finally an SEM, but no quantitative results could be drawn. A laser was used to produce speckle patterns but neither the diffuse nor the specular reflectance patterns revealed discernable differences. At this point the author located a Leitze Orthoplane microscope with a low angle of incident reflectance. The photographs presented in Figs. 4 to 7 were made with this microscope and clearly show the surface characteristics which differentiate the sample.

The first two photos of Fig. 4 show the marked difference between a rolled and unrolled sample. The rolls were much rougher than the unrolled samples. Samples measured by Sandy (1) had an arithmetic average roughness of 0.574 versus 0.5 microns respectively as shown in Table 4. The rolled sample, picture two of Fig. 4, exhibits some of the features characterized in this thesis. The dark spots were formed by hydropitting (HP), trapped lubricant

forming depressions under pressure. The dark lines are ridges formed as the smooth sample conformed to the grinding grooves in the roll. The light colored bands are valleys on the sample surface. Photograph three, of Fig. 4, shows the groove formed when the Talysurf stylus traced across the sample. This groove was observed on all of the samples tested with the Talysurf and was about 100 microns wide. The HP was smaller than 10 microns and the sample surface grooves varied from 5 to 30 microns in width.

The measurements made by Sandy (1), Table 4, are questionable due to the destructive nature of the Talysurf stylus, Fig. 4 and Quiney (3). They are included for a relative comparison with respect to the effects of roll roughness and reduction. The strip speed varied with each sample for a given reduction; thus, the FS values in Table 2 represent average values. The measured FS values, Table 2, are in accordance with previous experiments (8, 10, 15). Reid (9) produced negative FS by using viscous lubricants and high speeds.

Figure 5 is a comparison of samples rolled with oil and kerosene at low speed with the original, rough rolls. The first striking difference observed was the degree of HP, black spots, on the oil lubricated samples. This was not observed on the kerosene lubricated samples. The HP was concentrated in the grooves bordered by the ridges. The amount of HP decreased with increasing reduction for the kerosene lubricated samples but increased with increasing reduction for the oil lubricated samples, except at high reductions. At 59 percent reduction, HP did not

occur, but a wavy line pattern was observed. Thompson (19) attributed these lines to FS, thus, for lack of another explanation this practice is followed here. The FS marks had a white leading edge, center of the mark, and resembled the water marks on beach sand. These marks are apparent in photograph six and also photograph three as white spots with black central dots. The FS marks in picture six vary between 10 and 20 microns in width and ten to thirty microns in length. The marks are about one half as large in photograph three.

The photographs in Figs. 6 and 7, polished roll samples, are 1.73 times more magnified than the pictures in Fig. 5. The smooth roll samples had flat valleys twice as wide as the rough roll samples. These valleys were usually covered with FS marks. Figure 6 is a comparison of high and low speed kerosene lubricated samples. The high speed samples had about three times the amount of FS marks as the low speed samples. The marks were the same size for a given reduction and ranged from 30 microns at 16.4 percent reduction to 60 microns at 59 percent reduction. The magnitude of FS marks in Fig. 6 did not correlate well with the FS values of Table 2. The calculated FS values were only slightly higher for the high speed versus the low speed samples at 16.4 and 34.4 percent reduction; and, the high speed value was about half the low speed value at 59 percent reduction. One would not expect this difference if only FS was responsible for the marks. A small degree of HP occurred at low reductions but none at 59 percent reduction.

The oil samples, Fig. 7, were markedly different from the kerosene samples, Fig. 6. The high speed samples were covered with HP and had no FS marks. This extreme HP was in agreement with the results of Reid (9) who noted that gross HP occurred with negative FS. The degree of HP increased with reduction for both the low and high speed samples except at 59 percent reduction, for the low speed, where no HP occurred. The low speed samples had small FS marks at 16 percent reduction, no FS marks at 34 percent reduction, and five times the FS marks at 59 percent reduction as the kerosene samples in Fig. 7. The FS marks appear to be smeared Al with small ridges forming the leading edge. The SEM photographs in Fig. 9 show the marks more clearly.

HP can be seen in the first picture of Fig. 4 as the tiny black spots and general waviness. The oil FS marks were about twice as wide as the kerosene FS marks, photographs two and three, and no HP was present on either sample. This effect also occurred for the smooth roll samples. The kerosene FS marks are more tapered in appearance than the oil FS marks. A summary of these observations is presented in Table 5 to help the reader compare the effects caused by each variable.

The rough rolls and oil lubrication produced more HP. This was noted in previous research (9, 17, 19) and can be easily explained. HP is caused by trapped lubricant. The rough rolls formed deep grooves in the samples which trapped the lubricant. Oil was easier to trap because it is more viscous; both effects

caused HP. At high reduction the roll pressure is highest and one would expect more HP but none was observed; instead, FS marks occurred. The FS marks might have been caused by the lubricant flowing across the surface under pressure. Finally, the FS marks are of the same order of magnitude in length as the predicted exit slip lengths for the oil reductions, 0.01 mm. All of the other predicted slip lengths are one order of magnitude greater than the FS mark lengths. The FS marks point opposite to the direction of rolling indicating that they were caused by exit relative slip.

CONCLUSIONS

These experiments were conducted to determine the effect of FS on the surface finish of rolled Al. The appearance of the samples was found to be dependent on a combination of HP, FS, and the conformance of the surface to the roll grind grooves. Sandy (1) found that sample roughness conformed to roll roughness with increasing reduction. The following effects were observed in the present study.

The oil lubricated samples had more HP than the kerosene lubricated samples and more FS marks at high reduction. High speed rolling produced more HP and FS marks than low speed rolling. Increasing reduction produced more HP with oil lubricant but less HP with kerosene lubricant. FS marks occurred at 59 percent reduction for all the samples but no HP was produced. The rough rolls produced more HP and the smooth rolls more FS marks. The Taly-surf four profilometer cut a groove across the sample ten times wider than the surface details; thus, it was unable to reproduce the surface profile for analysis. The observed FS lengths were of the same order of magnitude as the exit slip lengths predicted for oil reductions. This indicates that relative slip might have caused the FS marks observed on the samples.

The absence of HP and the presence of FS marks on particular surfaces indicated that a hydraulic effect might have been responsible for the FS marks. This occurred in four cases. The

smooth rolls produced FS marks at low reductions unobserved for the rough rolls. High speed samples had more FS marks than low speed samples when rolled with smooth rolls and kerosene. FS marks occurred at 59 percent in all cases; and, oil lubricant produced more FS marks than kerosene at high reductions. In each of these cases a pressure increase paralleled the occurrence or proliferation of FS marks (12, 13, 17). For HP to occur a pressure gradient had to exist on the sample surface with pits forming at high pressure areas. At high reduction the surface did not show HP indicating that uniform high pressure, probably exceeding the Al yield stress, existed. The FS marks would then have resulted as localized high pressure lubricant flowed across the surface to equalize the film pressure.

RECOMMENDATIONS

Five percent of this work was spent recognizing the surface finish variable, FS. The remaining 95 percent, trying to quantitatively characterize this variable's effect. The first two ideas suggested herein pertain specifically to FS, the remaining to aid in surface finish analysis. A pattern could be inscribed on the roll or strip which should smear during rolling and indicate the effect of FS and rolling deformation. Front tension would increase FS and could be included as a variable in future work.

An interferometer would be of assistance in analyzing the surface topography of soft materials. A profilometer with less tracking force and a damped stylus pickup arm would be useful. A laser profilometer capable of electronically characterizing the surface finish would be an asset. A high quality direct reflecting microscope such as the Leitze Orthoplane and a photography lab would be a primary tool for surface studies.

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APPENDIX A

Forward Slip Calculation

The method used for empirically calculating FS is described below. The total strip volume is assumed to remain constant during rolling or,

$$H_1 V_1 = H_2 V_2$$

where H = thickness, V = velocity, 1 = inlet, and 2 = exit. This relationship is shown in Fig. 1. FS is calculated as,

$$(V_2 - V_R) / V_R$$

where V_R is the roll velocity. From the above relationship,

$$V_2 = \frac{H_1}{H_2} V_1 \quad \text{and,} \quad FS = \left(\frac{V_1}{V_R} \frac{H_1}{H_2} - 1 \right).$$

The roll velocity was determined by measuring the strip velocity as zero reduction. This velocity was used for the calculations since the roll velocity was invariant for all reductions. The roll velocity was 217.1 mm/sec. at low speed and 819 mm/sec. at high speed. The initial thickness was 1.63 mm and V_1 was determined as 203.2 mm/strip time (sec), thus:

$$FS = \left[\frac{1.52}{(\text{strip time}) (H_2)} - 1 \right] \quad \text{Low Speed}$$

$$FS = \left[\frac{0.40}{(\text{strip time}) (H_2)} - 1 \right] \quad \text{High Speed}$$

APPENDIX B

Theoretical Calculation of Relative Slip

The object of this analysis was to estimate the relative slip lengths involved in rolling and then to correlate the strip scratches with these lengths. An explanation of how the relative slip was calculated is presented below. Four assumptions were made.

- 1) Ignore elastic deformation
- 2) Ignore film thickness.
- 3) Assume no sliding at the neutral axis and $z = 0$ at $FS = 0$.
- 4) The actual strip surface velocity in the roll bite is tangent to the roll surface. The axial velocity parallel to the strip surface is used in these calculations. A maximum velocity error of 0.07 percent results at 59 percent reduction at the bite entrance.

The roll contact geometry is presented first, in accordance with the sketch on the following page, Fig. 9.

Fundamental Trigonometry

$$D = R y$$

$$S = R z$$

y, z in radius

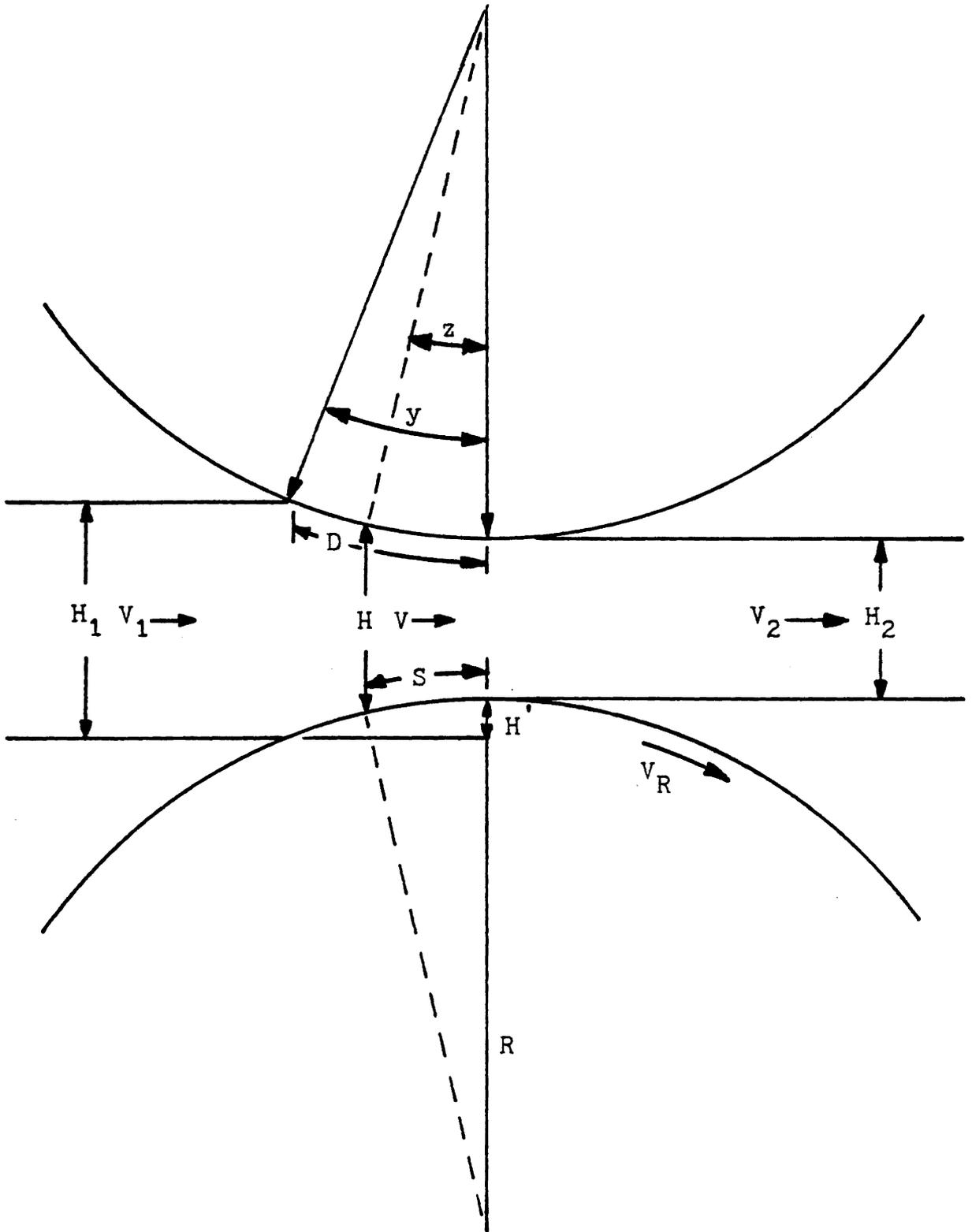


Figure 9. Role contact geometry.

D = total contact distance

y = total contact angle

z = angle from strip exit point to the neutral point

S = contact distance from strip exit point to the neutral point

$$y = \cos^{-1} \left(\frac{R - H^1}{R} \right) \quad H^1 = \left(\frac{H - H_2}{2} \right)$$

$V_1 H_1 = V_2 H_2 = VH$, continuity of volume in rolling,
combining these relationships

$$D = R \left[\cos^{-1} \frac{1}{R} \left(R - \left(\frac{H_1 - H_2}{2} \right) \right) \right]$$

since z occurs at the neutral axis then

$$V_R = V,$$

$$H^1 = \frac{V_1}{V_R} \frac{H_1 - H_2}{2}, \text{ and}$$

$$S = R \left[\cos^{-1} \left(\frac{R - \left(\frac{V_1}{V_R} \frac{H_1 - H_2}{2} \right)}{R} \right) \right].$$

Finally, this equation relates FS to the slip contact distance S.

$$S = R \left[\cos^{-1} \left(1 - \frac{H_2}{2R} (FS) \right) \right]$$

These equations allow one to calculate the total contact distance D and the contact distance with respect to the neutral axis S. The relative slip calculations are based on these equations.

The roll and strip move relative to one another except at the neutral axis. The relative velocity is integrated with respect

to time, thus calculating distance.

$(V_R - V)$ = relative velocity dt - differential time

$$SL = \text{relative slip length} = \int (V_R - V) dt$$

$$dt = \frac{ds}{V_R} \quad ds = R(dz) \quad dt = \frac{R(dz)}{V_R}$$

$$SL = \int (V_R - V) \frac{R}{V_R} dz$$

$$SL = \int \frac{R}{V_R} \left(V_R - \frac{V_1 H_1}{2R(1 - \cos z) + H_2} \right) dz$$

This integral was solved using a solution from the Handbook of Chemistry and Physics (20),

$$\int \frac{dx}{a + b \cos x} = \frac{2}{\sqrt{a^2 - b^2}} \frac{\tan^{-1} \sqrt{\frac{a^2 - b^2}{a + b}} \tan \frac{1}{2} x}{a + b}$$

where, $dx = dz$ $a = (2R + H_2)$

$b = -2R$ and $\cos x = \cos z$

Thus,

$$SL = (Rz) \frac{c_2}{c_1} - \frac{R}{V_R} V_1 H_1 \left[\frac{2}{\sqrt{(2R + H_2)^2 - (-2R)^2}} \frac{\tan^{-1} \sqrt{\frac{(2R + H_2)^2 - (-2R)^2}{(2R + H_2) - 2R}} \tan^2(z/2)}{(2R + H_2) - 2R} \right] \frac{c_2}{c_1}$$

The slip lengths for the rough rolls were calculated using this equation and the solutions are tabulated in the results section.

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THE EFFECT OF FORWARD SLIP ON
THE SURFACE FINISH OF COLD
ROLLED ALUMINUM

by

David H. Domermuth

(ABSTRACT)

Forward slip (FS), the percent difference between the roll velocity and the strip exit velocity, was achieved by altering four variables: reduction, rolling speed, lubricant viscosity, and roll roughness. A two-high laboratory mill was used to roll strips of unalloyed, H-18 temper aluminum. An SEM and a Leitze Orthoplane microscope were used to examine the strip surface.

A grainy pattern, which varied with the rolling condition, was observed on the sample surface. The grainy pattern resulted from three effects: grooves imprinted by the rolls, black spots identified as hydropitting (HP), and horseshoe shaped marks which were attributed to FS. These effects were studied and the following conclusions drawn. Higher viscosity, high speed, and rough rolls produced more HP. Increasing reduction produced HP with the viscous lubricant, oil, but less HP with kerosene. No HP was observed at 59 percent reduction but FS marks occurred and were more prevalent with oil than kerosene. The smooth rolls produced more FS marks than the rough rolls. Two postulates were presented to explain the pattern of these effects.

First, the FS mark lengths were of the same order of magnitude as one set of theoretically calculated relative slip lengths; indicating, that FS was responsible for the marks. Second, the absence of HP and presence of FS marks, in particular cases, indicated that a hydraulic effect was responsible for the FS marks. The FS marks would have been created as localized high pressure lubricant flowed across the surface to equalize the film pressure.