An Experimental Research on the Lubrication in Cold Rolling

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For investigating the lubrication mechanism in the cold rolling, the mild steel sheets of different thicknesses were rolled with lubricants of various viscosities. The coefficients of friction were caluculated by the ordinary method (the load method, the forward slip method) and the modified load method proposed by one of the authors. And the conception of "equivalent oil-film thickness of the hydrodynamic effect" was applied to analyse the experimental results.

1. Introduction

The lubricants for the cold strip rolling have various aims. First of all, it is to control the relative magnitude of the coefficient of friction to the angle of bite. Excessive friction increases the rolling load and decreases the efficiency of the process. On the other hand, the process does not proceed, if the coefficient of friction is reduced below a certain lower limiting value. That is, the efficiency of the process is rised by reducing the coefficient of fricton to the lower limiting value, which is about one half of the bite angle, with a suitable lubrication. Secondly, it is to obtain a good surfase finish of the product. In addition to these, the prevention of the wear and the cooling of the roll may be performed by the lubrication in practice. In order to obtain a reasonable guide available for adjusting these effects of the lubrication, many investigations$^{1)\sim4)}$ have been done.

The factors which concern the friction in cold rolling are lubricant (the physical and the chemical properties), material (the mechanical and metallurgical properties), surface roughness of roll and strip, conditions of the process (roll diameter, strip thickness, reduction and rolling speed) and so on. And some qualitative relationships between the friction and these factors have been already presented. For examples, the more viscous oil shows the lower friction. A fat shows lower friction than a mineral oil. The smoother roll brings the lower friction. Friction decreases with increasing the roll speed, and so on.

Some of these results may be understood by considering how the volume of the lubricant carried in the interface of the roll and strip is influenced by the above mentioned factors. Oil enters the roll bite as chemically and physically adsorbed layers, by being trapped mechanically in small pits of the surfaces of roll and strip, and by being pumped by a hydrodynamic pressure exerted on the oil at the entrance. A complete theoretical analysis of the three means is impossible at this date. Regarding the hydrodynamic effect, however, it is expected that oil quantity dragged in the roll bite increases in proportion to the following parameter;

$$t_d=\frac{\eta(U_0+U_1)}{\alpha p_1} \quad \cdots\cdots(1)$$

where t_d was termed an equivalent oil-film thickness of the hydrodynamic effect by one of the authors$^{5)}$, and η is viscosity of lubricant, U_0 peripheral speed of roll, U_1 entry speed of strip, α angle of bite and p_1 yield stress of strip in plane strain. And, it was shown that oil quantity dragged in the roll bite increases with the value of t_d, and the larger the t_d the smaller the coefficient of friction in rolling of aluminum$^{5),6)}$.

However, the friction sometimes depends primarilly on some other factors rather than the parameter t_d especially in rolling of steel where the roll pressure, which a lubricant undergoes, becomes much higher than in rolling of aluminum. The primary aim of this paper is to point out distinctive phenomena in the lubrication of steel rolling.

On the other hand, since there takes place considerable roll flattening in the cold rolling of thin steel strip, it becomes difficult that the geometry of the contact of roll and strip can be predicted accurately from the rolling data. For example, it was presented$^{7)\sim9)}$ that the actual length of the contact arc is larger than the predicted from Hitchcock's formula. This fact brings a serious problem that the coefficients of friction calculated by the ordinary methods may be unrealistic. W. L. Roberts$^{8)}$ presented a simple mathematical model of cold rolling which allows to estimate the coefficient of friction. This paper also presents a method of determining the coefficient of friction which may be hardly affected by the errors included in both the estimated length of contact arc and the yield stress of material.

2. Experimental Procedure

2-1 Rolling Mill

For the present purpose of the experiment, a laboratory two-high mill with 100 mm diam. 130mm face rolls of high carbon chrome steel was employed. Roll speed was constant at 39.6 rev/min, corresponding to 12.5 m/min. The surface roughness of the roll is shown in Fig.1.

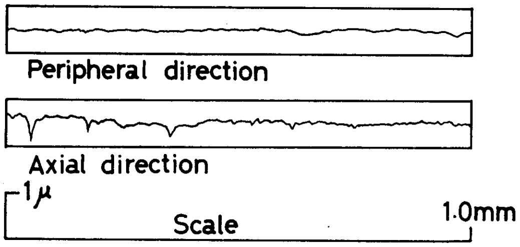

Fig. 1 Surface roughness curves of the roll.

2-2 Materials and Lubricants

The strip materials were mild steel finished bright and the dimensions of specimens were as follows; nominal thicknesses were 0.3, 0.5 and 1.0mm, the width 50mm and the length 400mm. Figure 2. shows the yield stress curves of these specimens which were obtained by tensile test. The surface roughness curves of the specimens are shown in Fig.3.

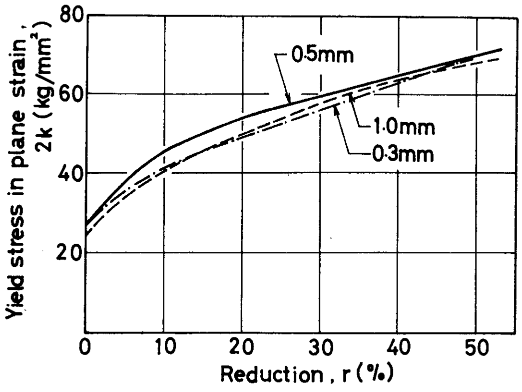

Fig. 2 Yield stress curves of the materials used.

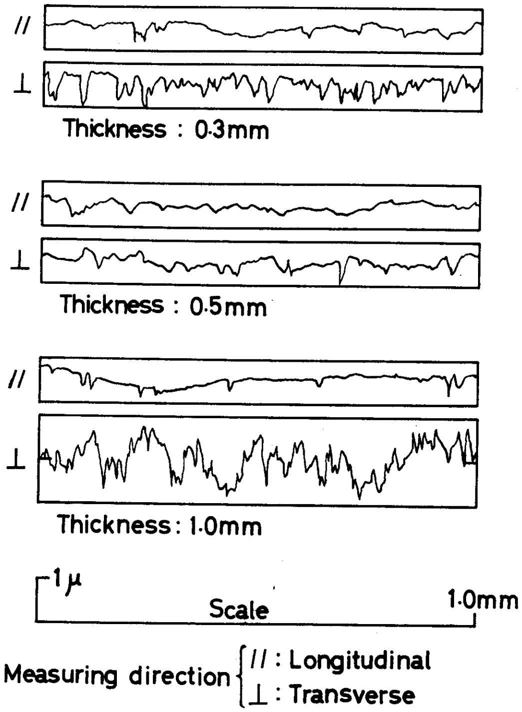

Fig. 3 Surface roughness curves of the materials used.

The lubricants were mineral and vegetable oils of various viscosities as shown in Table.1. In the experiment, 0.3 and 1.0mm specimens were rolled at the room temperature of 18℃ and 0.5mm specimens at 31℃.

2-3 Measurement of Roll Force

In order to measure the rolling load, the minute elastic strain of load measuring cells was detected by electrical-resistance strain gauges. The load cells were located under each mill screw.

The mean roll pressure p_m was calculated from the measured rolling load by using the

Table. 1 Viscosity of lubricants used.

Lubricant	Viscosity cS	
	18℃	31℃
Spindle oil ♯60		12
Turbine oil ♯90	94	47
Turbine oil ♯180	243	
Motor oil ♯40		230
Cylinder oil ♯90	5770	1310
Coconut oil		40
Rapeseed oil	88	52
Castor oil	1180	450

following equations.

$$p_m = P/(w \cdot L') \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(2)$$

where P: total rolling load, kg

w: width of specimen, mm

L': length of contact arc, mm.

L' was calculated from Hitchcock's formula, that is,

$$L' = \sqrt{R' \cdot \varDelta h} = \sqrt{R\left(1 + c\frac{P}{w \cdot \varDelta h}\right)\varDelta h} \quad \cdots\cdots(3)$$

where R: roll radius, mm

R': flattened roll radius, mm

$\varDelta h$: draft, mm

c: elastic roll constant, 2.2×10^{-4} mm^2/kg.

2-4 Measurement of Forward Slip

Forward slip δ is defined as $\delta = (U_2 - U_0)/U_0$, where U_0 is peripheral speed of roll and U_2 exit speed of strip. Forward slip was determined by the method of measuring the distance ℓ mm of impressions left on the surface of the rolled strip by the lines scratched on the roll surface at intervals of 100 mm. Then, δ was calculated by $\delta = (\ell - 100)/100$.

2-5 Measurement of Surface Roughness

In order to estimate how much amount of lubricant was carried into the contact arc, the surface roughness of rolled sheets was measured by using a "TALY-SURE" instrument in this experiment.

2-6 Estimation of Coefficient of Friction

In order to evaluate the coefficient of frictionμ, Fig.4 obtained from Bland-Ford theory was used. However, the length of the contact arc L' and the mean yield stress of material $2\bar{k}$ during rolling are not expected to be determined so accurately that the load method gives a reasonably acceptable value of coefficient of friction. So, the authors attempted to reduce the influences of the two quantities by the following procedure[10].

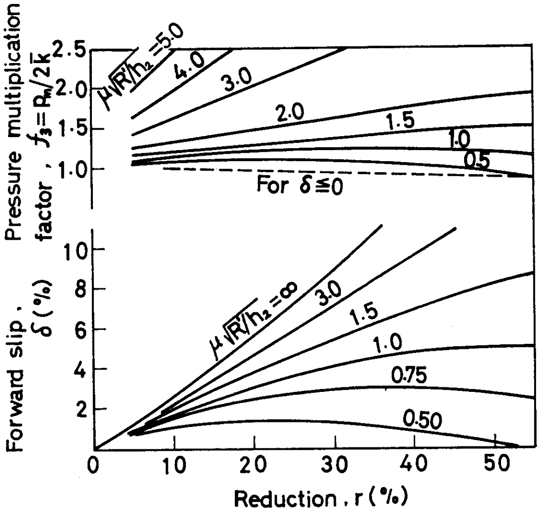

Fig. 4 Theoretical relationships used for calculating coefficients of friction (Bland-Ford theory).

According to the rolling theory, when the coefficient of friction μ attains to a certain lower limiting value and consequently the forward slip becomes zero or slightly negative, the mean roll pressure p_m and the pressure multiplication factor f_3 in Fig. 4 reach also minimum values. In the experiment, the rolling condition of $\delta \leqq 0$ was previously realized by using appropriate lubricants, thus the lower limiting value of p_m (i. e. $p_{m(\delta \leqq 0)}$) was determined. Then, the mean yield stress of the material $2\bar{k}$ during rolling was calculated back so that the experimental value of $p_{m(\delta \leqq 0)}$ became equal to the theoretical one. That is, $2\bar{k}$ during rolling was determined by dividing $p_{m(\delta \leqq 0)}$ by the lower limit of f_3 (i. e. f_{3cr}). Therefore,

$$2\bar{k} = p_{m(\delta \leqq 0)}/f_{3cr} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

where, f_{3cr} is given from the rolling theory as shown in Table. 2. For the ordinary cases of $\delta > 0$, μ was calculated by substituting the experimental value of p_m and the previously determined $2\bar{k}$ into the following equation.

$$f_3 = p_m/2\bar{k} = p_m \cdot f_{3cr}/p_{m(\delta \leqq 0)} \cdots\cdots\cdots\cdots\cdots\cdots(5)$$

Then, μ was evaluated from f_3 using Fig.4.

In the following, μ which was obtained by

Table. 2 The limiting vaues of pressure multiplication factor f_{3cr} (Bland-Ford theory).

r(%)	10	20	30	40	50	60
f_{3cr}	0.984	0.963	0.941	0.917	0.887	0.851

this modified load method is denoted as μ'_L, μ by the ordinary load method μ_L and μ by the forward slip method μ_F.

3. Experimental Results

3-1 Mean Roll Pressure and Forward Slip

In Fig.5, the relation between reduction and mean roll pressure p_m is shown for various lubricants in rolling of mild steel of 0.5mm thickness. p_m increases with reduction and the rate of increase is larger in less viscous oil.

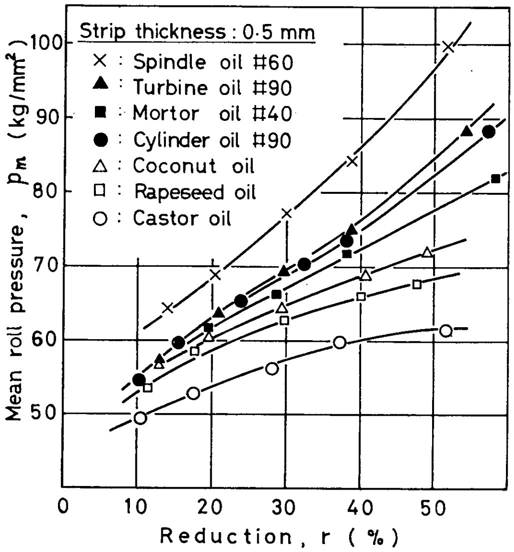

Fig. 5 Measured mean roll pressure.

One of the reasons is the workhardening of the material. Another is the increase in the friction loss with reduction due to the increase of the length of contact arc and the decrease of the mean thickness of the material in the roll bite. Furthermore there is also a possibility that oil quantity carried into the contact arc decreased with increase in reduction and therefore the coefficient of friction μ increased, because the bite angle α in Eq. (1) increases with reduction.

Generally, as oil quantity carried between the contact surfaces increases with viscosity of oil as predicted by the parameter t_d, coefficient of friction and consequently p_m are expected to decrease with increase in viscosity. Comparing mineral oils in Fig. 5, p_m decreases with increase in viscosity. Cylinder oil ♯90 (the viscosity is 1300 cS), however, showed higher values of p_m rather than motor oil ♯40 (230 cS). Regarding the oil quantity, following results were obtained from the measurements of surface roughness. That is, the surface of strip rolled with cylinder oil ♯90 were so entirely dull and mat that almost continuous oil films appeared to have existed in the roll bite at low reductions. And, the authors think the reasons of the unexpected high value of p_m in cylinder oil ♯90 as follows; the resistance due to the viscosity in the areas lubricated hydro-statically or dynamically becomes not to be negligible in comparison with the boundary frictional force exerted on the true contact areas, and, the pressure created hydrodynamically by the two approaching surfaces of roll and strip at the entrance becomes not to be negligible to the measured rolling load.

Comparing fatty oils in Fig. 5, the higher the viscosity of oil the lower the p_m is. And coconut oil and rapeseed oil, in spite of the lower viscosities than motor oil ♯40, showed lower values of p_m than motor oil ♯40. As the result, the mineral and fatty oils formed obviously the different groups each other. This result may be attributed to the well known fact that a fatty oil gives lower coefficient of friction than a mineral oil, if the amount of each oil between the contact surfaces are equal. That is, a fat forms the thin lubricating film which does not easily brake down, and consequently appears to give lower friction than a mineral oil under high pressure as in rolling.

Furthermore, as shown later where oil quantity is estimated by measuring the surface roughness of rolled sheets, it was found that more oil quantity could enter the roll bite in fatty oils than in mineral oils of same viscosities. This fact may also contribute to the remarkable difference between mineral and fatty oil inFig.5.

Figure 6 shows the relation between forward slip δ and reduction. δ also tends to

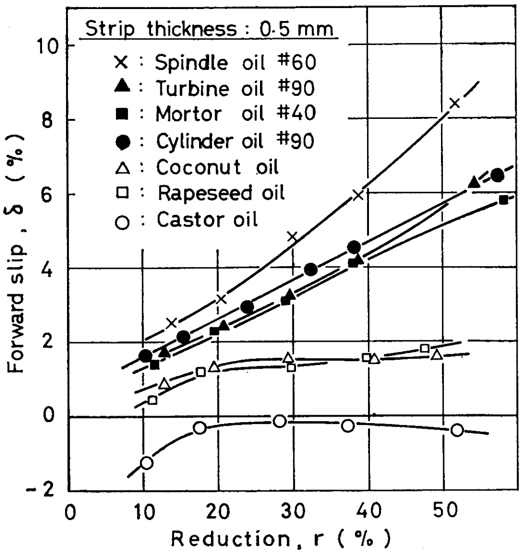

Fig. 6 Measured forward slip.

increase with reduction in the same manner as p_m and in most cases the lubricants which showed high p_m showed also high δ as predicted from the rolling theory. But the differences between turbine oil ♯90 and motor oil ♯40 or coconut oil and rapeseed oil are not so clear in δ as in p_m. Futhermore, cylinder oil ♯90 showed high values of δ in spite of the most oil quantity being dragged in the roll bite as previously noted.

The somewhat erratic behaviors of δ appear to suggest that the distribution of μ along the contact arc may be differed by lubricants. In fact, it is considered that firstly the distribution of oil quantity in unit area along the contact arc is not constant, and it decreases from the entry toward the exit, and secondly the effect of a lubricant on the friction varies with the pressure, the relative speed of the roll and material and the temperature which are not constant along the contact arc. Thirdly, the shape of the contact arc is not precisely a circular arc, as reported by D. R. Bland[11] that the main feature of contact arc is the depression in the region of peak pressure and the compensating greater curvature at the both ends. Since forward slip δ is determined as $\delta=(h_n-h_2)/h_2$ (where h_2 is exit thickness and h_n thickness at the neutral point), δ may vary according to the pressure distribution even if the neutral point located at the same angular distance from the vertical line. These reasons, which are not ascertained enough at this date, appears to have brought the disagreement of the orders in p_m and in δ.

Now, it is noted in Fig. 6 that δ became slightly negative with castor oil. It is obvious that the lower limiting values of μ, which are about one half of the bite angles, were attained.

3-2 Coefficient of Friction

The calculated results of μ_L and μ_F from p_m and δ by the ordinary methods are shown in Fig.7.

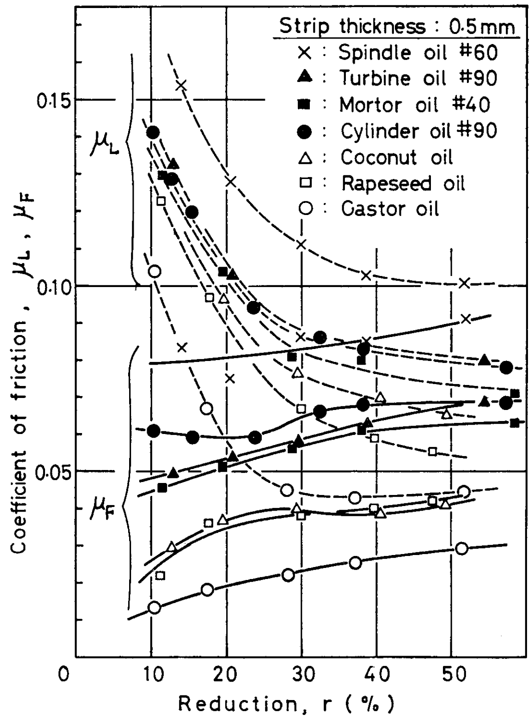

Fig. 7 Comparison of the coefficients of friction calculated by the load method (μ_L) and forward slip method (μ_F).

There appeared considerable difference between μ_L and μ_F. That is, μ_L decreased remarkably with increase in reduction and μ_F rather increased slightly with reduction. The result of much higher values of μ_L than μ_F especially at low reduction may be attributed to that the mean yield stress of the material during rolling and the actual length of contact arc become larger than the estimated value from the static tensile test and the estimated from Eq. (3) respectively.

On the other hand, although the forward slip method resulted appropriate values of μ, μ_F did not show the differences of lubricants so clearly as p_m.

In order to obtain more reasonably acceptable values of μ, the modified load method was employed. The result is shown in Fig.8,

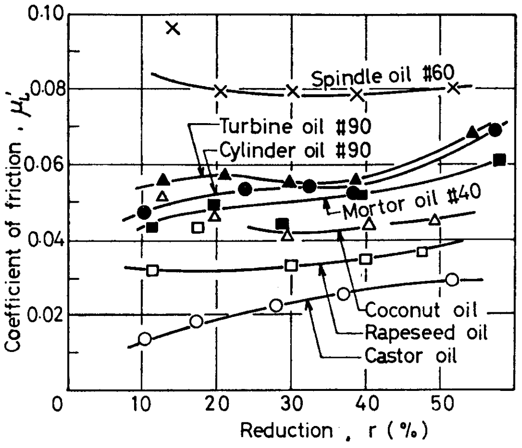

Fig. 8 Caluculated values of coefficient of friction by the modified load method (μ'_L).

in which μ'_L for castor oil is essentially equal to μ_F in Fig. 7, because δ were slightly negative for castor oil and the critical condition just bofore the occurence of skidding were realized. μ'_L increases gradually with reduction as in μ_F. And, μ'_L can discriminate the difference between the lubricants as p_m. Therefore, the values of μ'_L are thought to be available for discussion of the lubrication mechanism.

Figure 9 shows the effect of strip thickness on the friction. It was expected that the thinner strip shows the lower coefficient of friction, because the bite angle α in Eq. (1) is reduced and consequently the more oil will enter the roll bite in rolling of the thinner strip. In mineral oils, however, such influences of strip thickness and consequently of oil quantity were hardly found except an extremely viscous oil (cylinder oil #90), and these oils showed almost same values of μ'_L at severe reductions in spite of different oil quantities. On the other hand, the effect of strip thickness was remarkable in fatty oils as expected and as reported[5,6] on rolling of aluminum using mineral oils. And, the increase of μ'_L with reduction is also attributed to the decrease in oil quantity with increase in reduction.

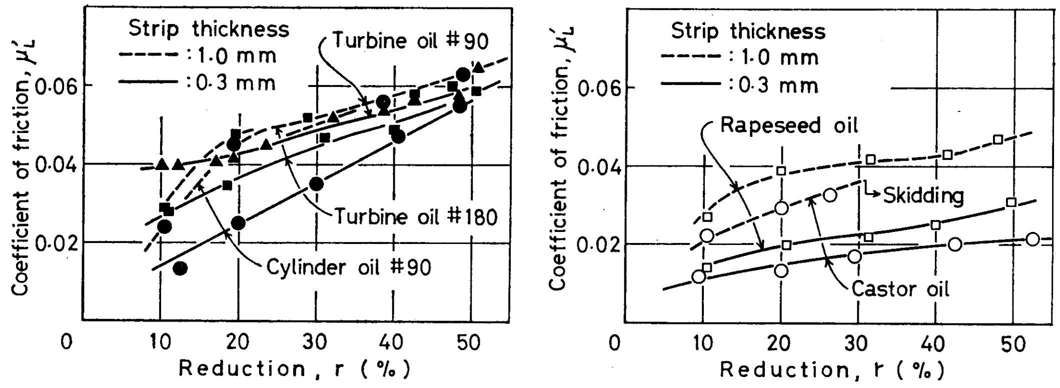

Fig. 9 Fffect of strip thickness on coefficient of friction.

From these results, it is concluded that when fatty oils are used, oil quantity between the contact surfaces has primary infuence on the ratio of true contact area to the total area and accordingly on the friction in the roll bite even under such high pressure as in rolling of steel, when mineral oils are used, however, oil quantity has no longer primary effect on the friction, though the reason can not be explained at this date.

3-3 Surface Texture of Rolled Sheets

The lubricating condition in the roll bite can be infered not only from the measurements of the roll pressure and the forward slip during rolling, but also from the appearance of the strip surface after rolling. The surface roughness is expected to increase with increasing oil quantity brought in the roll bite, and if so much oil entered the roll bite that a completely continuous oil film was formed, the surface roughness of the rolled sheet would become as larse as that of the elongated specimen in a tensile test to the same strain. Since t_d is a parameter which may predict the more or less of oil quantity at the roll entry as stated before, the surface roughness of the rolled sheet will be related to the oil quantity at the roll exit, that is, to $t_d(1-r)$ where r is reduction.

The surface roughness and the values of $t_d(1-r)$ are shown in Fig. 10. The surface roughness curves in rolling direction for turbine oil ♯90 are fairly smooth, and those perpendicular to rolling direction appear to be replicas of the roll surface. This shows that little oil was carried into the contact arc. The surface roughness curve for rapeseed oil has some pits at low reduction, but the area occupied by the pits decreases and the projections due to the impression of the roll surface increase with increasing reduction. For castor oil the pits, which were filled with oil during rolling are numerous, and it is suggested that oil quantity carried into the contact arc was more than the other oils.

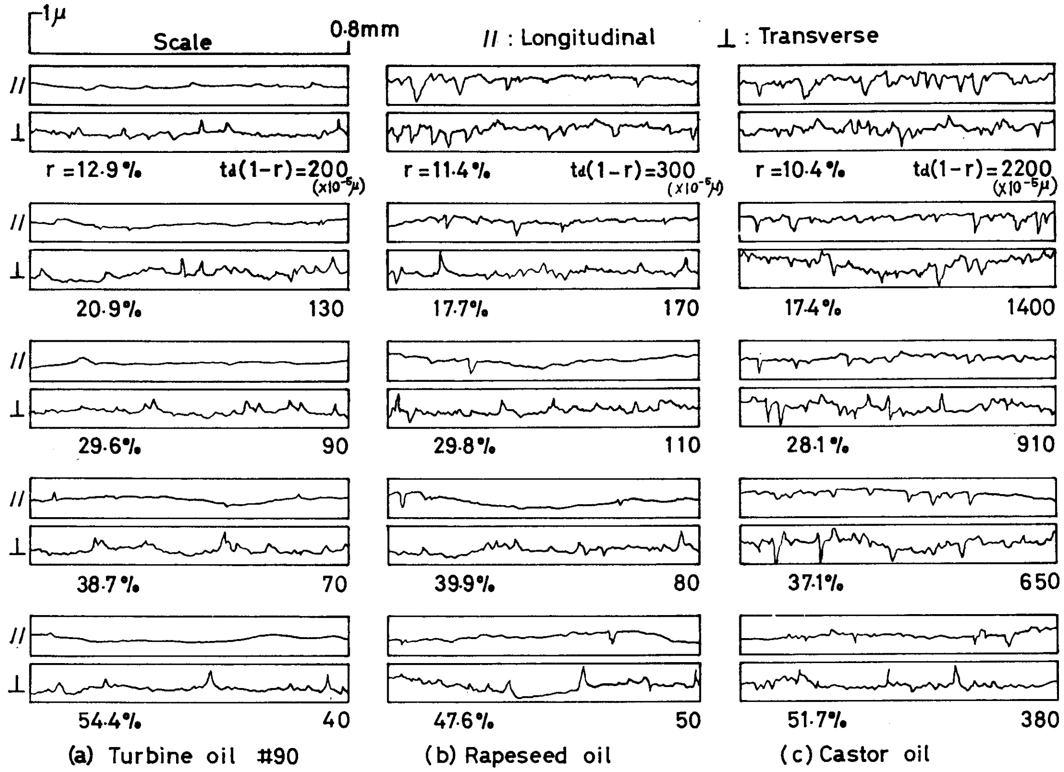

Fig. 10 Surface roughness and the calculated oil-film thickness at exit, $t_d(1\text{-}r)$.

The surface roughness represented by maximum height H_{max} in rolling direction was plotted against reduction for each lubricants in Fig. 11. H_{max} reachs maximum at 22% reduction for cylinder oil, then decreases with increasing reduction as predicted from $t_d(1-r)$. Below the critical reduction, it is suggested that the oil was dragged in the roll bite so much that the hydraulic lubrication film could not be broken by the free "getting rough" of the surface due to the plastic deformation. Although H_{max} and therefore oil quantity increased with viscosity in most cases, comparing fatty oil with mineral oil, the former seemed to enter the roll bite more easily than the latter. For examples, motor oil ♯40 (the vicosity is 230 cS) and rapeseed oil (52 cS) showed almost same H_{max} in Fig.11, and less oil entered the roll bite when turbine oil ♯90 (47 cS) was used than rapeseed oil as shown in Fig. 10. That is, oil quantity carried into the contact arc, which had been regarded to depend primarilly on the physical property of oil,

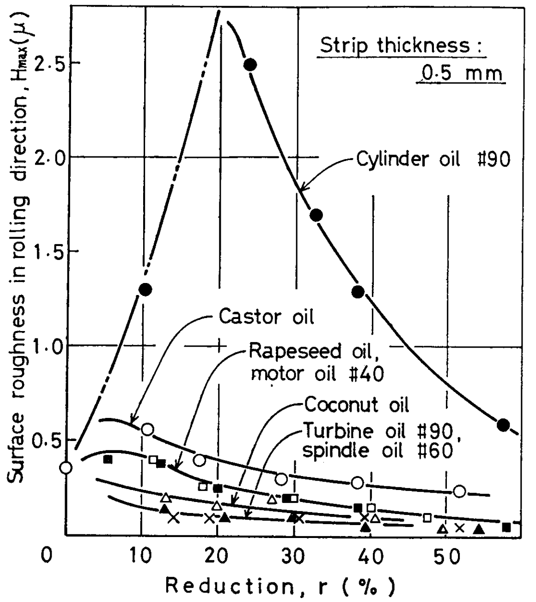

Fig. 11 Surface roughness H_{max} of the strip after rolling.

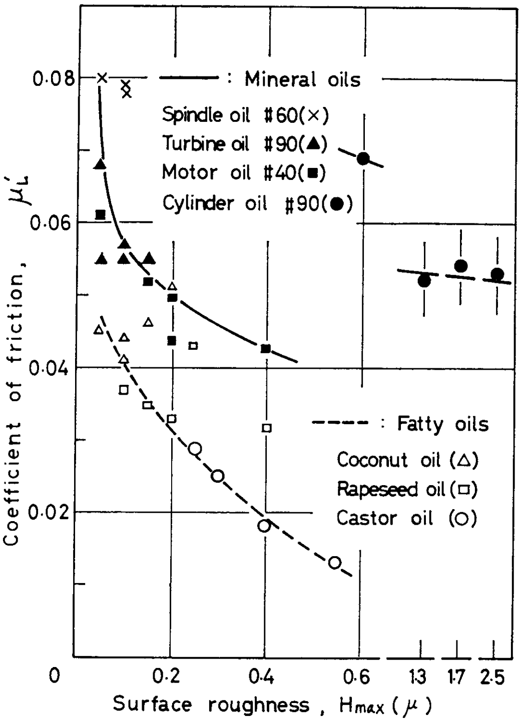

Fig. 12 Relationship between coefficient of friction and surface roughness H_{max} in rolling direction.

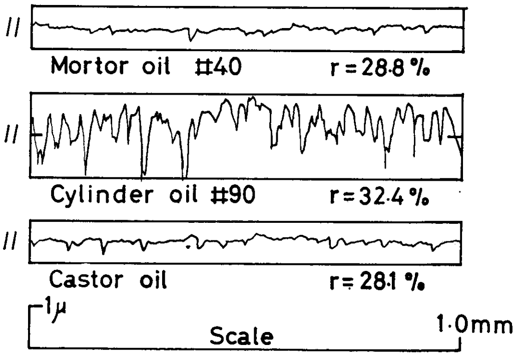

Fig. 13 Surface roughness curves showing different lubricating conditions.

appeared to vary also with the chemical one.

Next, the relation between the oil quantity and the coefficient of friction was investigated. In the previous report[5], it was shown that there existed a good correspondence between the mean equivalent oil-film thickness on the contact arc $t_d(1-2r/3)$ (where r is reduction) and μ_F in rolling of aluminum with mineral oils. But as it was recognized that oil quantities are different between mineral oil and fatty oil even if t_d are equal as stated above, for simplicity the coefficient of friction μ'_L was plotted against H_{max} in stead of $t_d(1-2r/3)$ in Fig.12. Obviously, two groups are formed by the fatty oils and the mineral oils except for cylinder oil ♯90, and fatty oil gives lower friction than mineral oil. And, cylinder oil ♯90 showed relatively high μ'_L in spite of its plentiful oil quantity as shown in Fig. 13. In fact, there appeared many sharp projections due to the free 'getting rough' of the surface in cylinder oil ♯90, therefore considerable areas in the contact arc are thought to be suffered the hydraulic lubrication. While for motor oil ♯40 and castor oil, there appears considerable areas flattened by the roll and suffered the boundary lubrication. Thus, the lubricating condition is very different between cylinder oil ♯90 and the other oils. And the viscosity of cylinder oil ♯90 seemed to become so high under such high presssure as in rolling of steel that the viscosity had a direct influence on the friction.

Fig. 14 shows the surface roughness being influenced by strip thickness. The surface roughness is obviously larger in 0.3mm than in 1.0mm, though the difference is not so clear in less viscous oils. Therefore, it may be recognized that oil enters the roll bite more easily in rolling of thinner strip, and

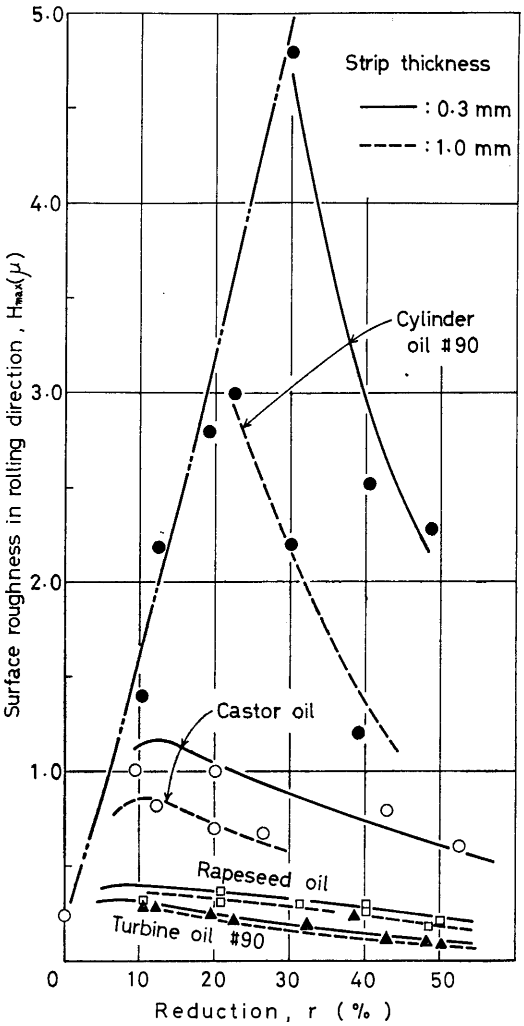

Fig. 14 Effect of strip thickness on surface roughness.

there is a possibility that the friction is reduced correspondingly.

3-4 Mean Yield Stress during Rolling

For reference, the estimated values of the mean yield stress in the roll bite are shown in Fig.15.

The estimated value from tensile test is smaller than the reduced one from Eq. (4) using the rolling data, and the difference is larger in the thinner strip probably according to the higher strain rate during rolling.

4. Conclusions

As the result of the present investigation, the following conclusions were obtained;

(1) It was ascertained that the modified load method is available for estimating the coefficient of fricton in the roll bite.

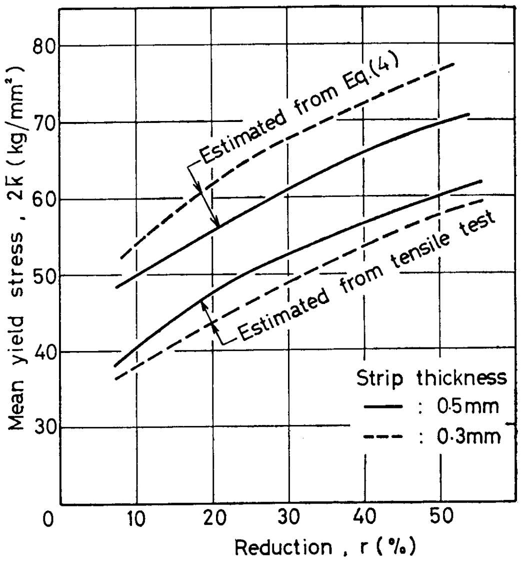

Fig. 15 Estimated values of mean yield stress during rolling.

(2) The larger the parameter t_d, the more oil enters the roll bite in most cases, fatty oil, however, seemed to enter more easily than mineral oil probably according to the stronger affinity to the metal surfaces.

(3) In rolling of steel, the more viscous fatty oil showed the lower coefficient of friction as expected from the parameter t_d, however, the dependence of coefficient of friction on viscosity and consequently on oil quantity was not so clear in mineral oils.

(4) An extremely viscous mineral oil appeared to form almost continuous oil-film between the contact surfaces at low reductions, and yet resulting the required friction for maintaining the strip in the roll bite.

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