Flow Activation Volume and Lubricity of Polymer-blended Oil as a Rolling Fluid

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Light mineral oil was blended with methacrylate polymers to suitable viscosities for cold rolling of steel. The flow activation volume of the blended oils was measured and investigated in comparison with frictional characteristics under sliding-rolling conditions. The performance of the oils was also examined with a laboratory mill up to 2,000 m/min with good results.

1. Introduction

It is well known that fatty oil, especially palm oil, is one of the best lubricants for cold rolling of steel to produce thin plates. This superior performance is considered to be due to the oiliness of the free fatty acid in the oil. However, the effectiveness of the fatty acid is not so clear-cut, if judged from the following instances. Carbon steel was rolled under the conditions of single pass and reduction of 16.5% with a paraffinic mineral oil lubricant and the same containing 1% stearic acid¹⁾. Their coefficients of friction were found to be 0.080 and 0.075, respectively, showing a very small difference as compared with the results 0.18 and 0.10 for the above mentioned two lubricants, obtained with a conventional boundary lubricity tester such as friction pendulum.

This fact suggests the importance of thin oil film lubrication in steel rolling. One of the aims of this study was to investigate the role of viscosity in cold rolling of steel. As a parameter of high-pressure viscosity, the flow activation volume was measured by Eyring's theory for several lubricants, and its relation to lubricity in sliding rolling friction was examined. Another aim was to develop a fluid suitable for rolling utilizing the guiding principle of activation volume. A polymer-blended oil was tested with a laboratory mill which was operated at rolling speeds up to 2,000 m/min.

2. Measurement of Flow Activation Volume

2.1 Test Oils

Two groups of oils were investigated. One group was polymer-blended oils, and the other was representative rolling fluids. Their viscosities were in the same range—about 120 cSt at 25.0 °C.

Polymethacrylates of stearyl (S), tridecanoyl (T), and lauryl (L) alcohols were used. These polymer esters were blended with a light paraffinic mineral base oil (viscosity : 5.4 cSt at 25 °C, 3.1 cSt at 50 °C). They are listed in **Table 1**, where SL, for example, indicates a methacrylate polymer consisting of both stearyl and lauryl esters, and SL8/ST2 means a mixture of SL polymer (80%) and ST polymer (20%). The average molecular weight of the polymer was different for each case, higher in oil No. 2 than in oil No. 1. As a reference oil, oil No. 6 was prepared by blending the light mineral oil with paraffinic bright stock (viscosity : 123.8 cSt at 25 °C).

Another group included a vegetable oil (oil No. 7) and a synthetic ester (oil No. 8), pentaerythritol tetraoleate (viscosity : 120.7 cSt at 25 °C). The vegetable oil was a blend of castor oil and olive oil in a weight ratio of 3 to 7 (viscosity : 117.3 cSt at 25 °C).

2.2 High Pressure Viscosity and Density

As has been reported previously²⁾, to obtain flow activation volume, it is necessary in the present study to measure both viscosity and density at high pressure—300 atm. The activation volume,

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Table 1 Polymer-blended Oils

Oil No.	Polymer	Blend (%)	Viscosity (cSt, 25°C)
1	SL	21	120.7
2	SL	13	125.9
3	L	71	114.5
4	SL8/ST2	15	121.3
5	ST	21	118.6

Table 2 Viscosity and Density

Oil	η_1	ρ_1	η_{300}	ρ_{300}
1	100.4	0.8322	164.7	0.8465
2	103.0	0.8215	166.0	0.8392
3	99.74	0.8883	181.0	0.9064
4	100.3	0.8372	161.9	0.8389
5	98.41	0.8298	161.3	0.8416
6	104.9	0.8475	199.4	0.8640
7	108.3	0.9227	175.1	0.9342
8	110.8	0.9195	171.6	0.9331

$\Delta V^\ddagger$, is calculated from the following equation :

$$\Delta V^\ddagger = RT \frac{\ln \nu_1 - \ln \nu_{300}}{p_1 - p_{300}} \quad \nu = \frac{\eta}{\rho}$$

where R is the gas constant, T absolute temperature, ν kinematic viscosity, p pressure, η viscosity, and ρ density. Subscripts 1 and 300 mean 1 and 300 atm, respectively. Viscosity was measure with a rolling-ball viscometer and density with a piezo-meter, both at $25.0 \pm 0.1^\circ\text{C}$ within $\pm 1\%$ accuracy. The results are summarized in **Table 2**, where viscosity and density are given in cP and g/cm^3 , respectively.

2.3 Calculated Activation Volume

From the above equation, $\Delta V^\ddagger$ can readily be calculated, and the results are shown in **Table 3**. The smallest value is for pentaerythrytol ester and the largest for the mineral oil. Oils No. 1 and No. 2 are blends of the same type of polymers but differing in the amount blended and degree of polymerization. However, the $\Delta V^\ddagger$ values are nearly equal, suggesting a mechanism of segment flow at the molecular level.

Table 3 Flow Activation Volume

Oil	$\Delta V^\ddagger$ (cm^3/mol)
1 PSLMA 21	38.5
2 PSLMA 13	37.2
3 PLMA	46.6
4 PSLMA/PSTMA	37.4
5 PSTMA	38.7
6 Mineral Oil	50.8
7 Vegetable Oil	37.8
9 Synthetic Ester	34.6

3. Measurement of Lubricity in Sliding-Rolling

3.1 Friction Device

The friction device used was similar to the SAE friction machine. Two bearing-steel rings were made of high chromium bearing steel, in identical shape of 4 cm in diameter, 12 mm in width, and the face curved with a radius of 60 cm. They could be rotated separately, and were pressed together with a spring. Oil was supplied through an oil-containing sponge lightly contacting with

Fig. 1 Rolling-Sliding Friction Machine

the two rotating rings. A schematic drawing of the device is given in **Fig. 1**.

Friction was measured electronically from the phase shift between the rotating shaft and its driving shaft both of which were connected with a torsion bar.

3.2 Friction Measurement

Details of measuring procedures are described elsewhere³⁾. In short, prior to the measurement, run-in was made with a light load but at pre-determined sliding-rolling, and then the applied load was increased up to the desired level. Steady friction was observed after 2 or 3 min. After the test, the friction trace was examined to ascertain that no seizure had occurred under the testing conditions.

Conditions for measurements were fixed at a rolling speed of 27 m/min for one ring and 87 m/min for the other that resulted in a sliding speed of 1 m/sec. The applied load was usually 150 kg which corresponded to the average contact pressure of 64 kg/mm^2 . Measurements were made at room temperature.

The results of friction coefficient, f , are shown in **Table 4** for the polymer-blended oils and the bright stock blended oil; the oils are arranged in order of increasing $\Delta V^\ddagger$.

From this table, oil No. 5 seemed best among the polymer-blended oils. This oil was compared with a vegetable oil and a synthetic ester under a severer condition of 200 kg load (82 kg/mm^2). The results in **Table 5** indicate that oil

Table 4 Lubricity f Blended Oils

Oil	f
2 PSLMA 13	0.071
4 PSLMA/PSTMA	0.073
1 PSLMA 21	0.070
5 PSTMA	0.067
3 PLMA	0.086
6 Bright Stock	0.083

Table 5 Comparison of Rolling Oils

Oil	f (150 kg)	f (300 kg)
Vegetable Oil	0.067	0.067~0.069
Synthetic Ester	0.064	0.064~0.065
PSTMA 21% Oil	0.067~0.068	0.026~0.067

No. 5 is almost equivalent to these rolling fluids.

4. Relation between Lubricity and Flow Activation Volume

As mentioned in the introduction, there may be a hydrodynamic oil film at friction contact in the sliding-rolling experiment, and a relation between f and $\Delta V^\ddagger$ may exist. In Fig. 2, f is plotted against $\Delta V^\ddagger$ for all the fluids examined. It is evident that increasing $\Delta V^\ddagger$ results in increasing f ; in other words, larger viscosity at higher pressure makes traction greater. This relation may hold, with certain limitations, that viscosities of the oils are at the same level.

Fig. 2 Relation between f and $\Delta V^\ddagger$

5. Laboratory Mill Test

5.1 Rolling Performance

A high-speed laboratory test mill constructed by Nippon Steel Corporation was used. The working roll was bright finish, 400 mm in diameter, and 100 mm in width.

Oil No. 5, the best polymer-blended oil, and palm oil were tested. A $1.8 \times 50 \times 100$ mm sheet of low carbon steel was cold rolled at a reduction of 20% and at various speeds from 250 to 1,000 m/min. The oil was applied as a precoated thin film on the test steel specimen in various thicknesses of 0.2, 0.5, 1.0, and 2.0 g/m^2 . The necessary load was measured and shown in Fig. 3, where the abscissa is the amount of the coated.

When only a smaller amount of oil was applied, the roll load was larger with polymer-blended oil, but when a sufficient amount was applied, it was almost the same as that of palm oil. Interestingly, the load is smaller at 1,000 m/min

△ : polymer, 625 m/min; ▲ : palm, 625 m/min
○ : polymer, 1,000 m/min; ● : palm, 1,000 m/min

Fig. 3 Roll Load and Oil Amount

than at 625 m/min. This may be due to a higher temperature rise, that reduces the viscosity of the oil at rolling contact, and/or due to a thicker hydrodynamic oil film which reduces both the shear rate and probable metallic contact.

5.2 Oil Film Thickness

Oil film thickness between the roll and strip was measured at higher rolling speeds. Low-carbon steel strip of 1.0 mm thickness was cold rolled at various speeds at 30°C and the reduction was 20%. The oils examined were oil No. 5 and a commercial rolling fluid. The oil tested was not precoated on the whole surface but only on the square area of 30×33 mm, the front side of which was perpendicular to the rolling direction as shown in Fig. 4. The weight of the precoated oil was measured. After rolling, the square shape was deformed and spread into a bullet-shaped area which was measured, and the mean thickness of the oil was calculated by dividing the amount of oil by the bullet-shaped area. The results are shown in Fig. 5.

The behavior of the two tested oils was quite different from each other. The thickness of the commercial fluid increased at lower speeds and

Fig. 4 Film Thickness Measurement

Fig. 5 Oil Film Thickness after Rolling

was almost constant at speeds higher than 250 m/min. In contrast, the thickness of oil No. 5 increased linearly up to 2,000 m/min.

According to a simple hydrodynamic theory, the oil thickness should be proportional to the rolling velocity, provided that viscosity and shape of the solid elements are unchanged. However, the observed behavior of the commercial fluid is normal in rolling practice, and it is explained by such factors as temperature rise, viscosity decrease, and so forth at higher speeds. The behavior of the polymer-blended oil is rather strange. The

reason may be rheological, but at present no adequate explanation can be given.

6. Conclusion

In the development of rolling oils, a series of polymer-blended, thin mineral oil type fluids were studied from the theoretical standpoint of flow activation volume and they were also examined by use of a high-speed laboratory mill. A poly-stearyl-tridecanoyl-methacrylate blended low viscosity paraffinic oil was found promising in the sense that the rolling performance was comparable to that of palm oil. The strange behavior of increasing oil thickness with higher rolling speed was, indeed, favorable. Practical application tests of polymerblended oils on an industrial scale are now in progress.

References

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要 旨

圧延油用高分子混合油の流動活性化体積と潤滑性

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鉄鋼薄板の冷間圧延油として油脂が良好な性能を示すことは周知であるが、その理由として上げられる遊離脂肪酸の油性は、純パラフィン油と脂肪酸添加パラフィン油の実験ミルでの性能にほとんど差がないことから、必ずしも十分でなく、油膜潤滑の可能性が強い。そこで数種の油について高圧粘性の指標である流動活性化体積 ΔV_K を測り、ころがり-すべり試験機による摩擦係数 f との関連を求め、その結果良好な性能を示した高分子混合油については、2,000 m/min の高速運転圧延試験を行い、圧延荷重、油膜厚について油脂同等あるいはそれ以上の性能をもつことを明らかにした。

高分子はメタクリレートでアルコールはステアシル、トリデカノイル、ラウリルの純あるいは2成分エステルであり、分子量も異なるものを低粘度パラフィン油に13~21% 混合して試油とした。対比のため植物油脂、ペンタエリスリトールエステル、パラフィン油とブライトストックの混合油も試験した。粘

度は25°C で120 cSt に調製してある (Tables 1, 2)。

ΔV_K は常法²⁾ によって求めた (Table 3)。ころがり-すべり試験機はSAEマシン類似のもので³⁾、2円筒 (ベアリング鋼、径4 cm、面曲率60 cm) のころがり速度は27および87 m/min、すべり速度1 m/sec、接触荷重は150 kg (64 kg/mm²) および200 kg (82 kg/mm²) であり、給油はパッドで行った。 f は0.064 から0.086 の間に入り、大体 ΔV_K と直線関係にあり、 ΔV_K が小さい程 f は小さい (Tables 4, 5, Fig. 2)。高分子混合油の中の最良のものは油脂に劣らず、高速試験圧延機でバーム油との性能比較を行った。1.8 mm の軟鋼板を圧延速度625 および1,000 m/min で油塗布量を0.2~2.0 g/m² に変えて圧下率20% のときの圧延荷重を測った結果、1,000 m/min では十分給油すると高分子混合油はバーム油と同等であることが判った (Fig. 3)。また同試験機でロールと鋼板にはさまれる油膜厚を測ったところ (Fig. 4)、市販圧延油は250 m/min まで増大しそれ以上では一定となるのに、高分子混合油は高速ほど厚くなった (Fig. 5)。この現象のレオロジック的説明はまだできないが、高分子混合油は有望であり実験テストが計画されている。

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