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Effect of Lubricants on Compressive Deformation*

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Synopsis

The compression test was carried out with aluminium, copper, mild steel and stainless steel at 100, 200, 300, 400°C and room temperature by making use of various kinds of lubricant. The results obtained are as follows:

(1) It is necessary to take account of the elastic strain of the testing machine for the calculation of the friction coefficient from the load-strain curve of the compression testing.

(2) In comparing both friction coefficients of rolling and of compression with each other, there is a tendency that the rolling shows a smaller friction coefficient than in the compression. This is considered to be due to the difference in the amount of friction length.

(3) In the compression test with the mineral oils of various viscosities, the friction coefficient decreases with a slight increase of viscosity in the case of the viscosity below 100 Redwood sec at 50°C. However, at the viscosity above 100 Red Wood sec at 50°C, it is little changed by the variety of viscosity.

(4) The order of lubricating effects is variant with the variety of lubricants, but the palm oil or beef-tallow oil shows a lower friction coefficient at room temperature and paste oil containing MoS_2, stearic acid sopa or paraffine chrolide shows good lubricating effects at high temperatures.

I. Introduction

In melting metals, such a technique as Reviation melting method[1] has been developed in laboratories, by which metals are melted without contact with the pot, that is, one need not take into consideration the reaction between metal and pot while working. This is a success as a laboratory work, but there is no method at present by which metal can be deformed without tool, and accordingly, friction and the lubrication are of great importance in engineering practice of all metal workings.

There has been a great deal of investigation[2] into the mechanism of friction and lubrication in the case where two metals merely contact with each other and slide, and the results have been applied to industries with much benefit. On the other hand, there are few reports concerning friction and lubrication in metal working.

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* The **120lst** report of the Research Institute for Iron, Steel and Other Metals. Reported in Japanese in the Journal of the Japan Institute of Metals, **28** (1964), 228.

** Daido Chemical Industry Co., Osaka.

(1) T. Saito, Bull. Japan Inst. Metals, **2** (1963), 8.

(2) F.P. Bouden and D. Tabor, *The Friction and Lubrication of Solids*, Oxford (1954).

The friction and the lubrication in metal deformation are much complicated, which may be due to the following circumstances:

(1) In general, total resistance to deformation of metal is in the range from thousands to tens of thousands of kg/cm^2, so that a very high load is required for metal working.

(2) Heat developed during metal working elevates the temperature of worked materials by scores to hundreds of degrees, and accordingly, in cold working, the actual conditions may be different from those at a given temperature.

(3) Although the surface of metal is usually covered by thin film composed of oxide or hydroxide, during metal deformation fresh metal atoms will come out on the surface due to increasing area of contact. Therefore, the effect of lubricant may become different from the initial condition.

For these reasons, it is insufficient to estimate the lubricant for metal working only with usual friction tester, and at present their evaluation depends chiefly on practical test at factory. Such methods, however, require much labor, and their results are hardly reproducible; therefore, a simple method for this purpose will be desirable.

The effects of various lubricants on rolling process have been investigated and an evaluation method has been devised(3). It has been found that the coefficient of friction calculated from the relation between stress and strain in the compression of cylindrical specimen is much useful to evaluate lubricant. The present study was carried out to discuss the following matters in connection with the compression of cylindrical specimen described above:

(1) The point to be considered in calculating the coefficient of friction from compression test of the cylindrical specimen.
(2) The relation between the coefficient of friction in the compression of cylindrical specimen and that in the rolling.
(3) The effect of various lubricants on the compression of cylindrical specimens of aluminium, copper, mild steel and 18–8 stainless steel at room and high temperatures.

II. Method of testing

1. Lubricant

The lubricants used were, as shown in Table 1, mineral oil having various viscosities, fats and fatty oils, alcohols, metallic soaps, solid lubricants, and extreme pressure lubricants.

2. Specimens

The specimens 10 mm in diameter and 4mm in height are shown in Table 2. If the ratio of the diameter to the height is too small, the evaluation of lubricants will be difficult due to little frictional influence, while if it is too large, an appreci-

(3) E. Tanaka, T. Yoshida and T. Fukuda, J. Japan Soc. Technology Plasticity, **1** (1960), 3.

ably large load will be required for compression; so the above-mentioned size was adopted from these considerations.

Table 1. Lubricants used in the experiment.

No.	Lubricant	Specific gravity 15/4°C	Flash point °C	Viscosity (R. W)		Value of 4 ball test		Coefficient of friction (pendulum)	Sulfer value (%)
				30°C	50°C	Pressure (kg/cm²)	Coefficient of friction		
1	3# Solvent oil	0.847	108	35.2	32.1	3.0	0.115	0.28	0.10
2	3# Spindle 〃	0.880	140	52.2	39.5	3.0	0.120	0.25	0.10
3	60# Spindle 〃	0.851	148	66.1	45.4	3.0	0.122	0.19	0.77
4	120# Machine 〃	0.914	198	295.0	112.4	3.0	0.093	0.17	1.02
5	90# Turbine 〃	0.883	196	228.4	94.6	3.0	0.086	0.17	0.18
6	140# Turbine 〃	0.932	206	411.0	144.2	3.5	0.098	0.17	0.75
7	40# Motor 〃	0.945	228	2309.0	532.0	6.0	0.104	0.125	1.41

Type	No.	Lubricant	Type	No.	Lubricant
Fat & Fatty oil	8	Palm oil	Base lubricant + Additive	20	No. 17+Graphite 10% (wt)
	9	Castor 〃		21	〃 PbO_2 〃
	10	Rape seed 〃		22	No. 7+Graphite 〃
	11	Sperm whale 〃		23	〃 PbO_2 〃
	12	Lanolin 〃		24	〃 Al Stearate 〃
	13	Tallow 〃		25	〃 Pb 〃
Fatty acid & alcohol	14	Oleic acid	Others	26	MOS_2
	15	Stearic 〃		27	Paraffine chlorid
	16	Oleyl alcohol		28	Nil
Soap	17	Stearic acid soap			
	18	Tallow 〃			
	19	Palm 〃			

Table 2. Metals used in the experiment.

Material	Dia. × Height	Annealing condition
99.7% Al	10 mm × 4 mm	370°C × 1 hour
99.98 Tough pitch copper	〃	500 〃
0.13 C Mild steel	〃	800 〃
18-8 Stainless steel	9.5 mm × 4 mm	900 〃

3. Compression test at room temperature

The schematic diagram of compressing tool is shown in Fig. 1. The die surface was after grinding polished with emery paper, and the specimen surface was finished also with emery. In each run the surfaces of die and specimen were cleaned with benzene and alcohol, dried, lubricated and set on for the test. Compressing machine was the universal tester of 50-ton capacity, which was electrically controlled. Rum speed capable of automatic control was set at 0.5 mm/sec. Compression was always carried out up to the total reduction of 60%, but the lubrication was done in two ways: in one way oil was supplied only once at the beginning of the test, and in the other the supply was repeated every 10% reduction. Load-strain curve was recorded automatically on a paper 250×200 mm² in size.

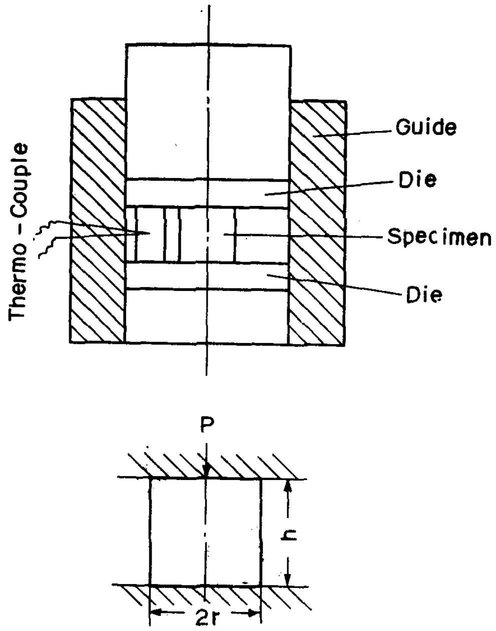


Fig. 1. Apparatus for the compression test.

4. Compression test above room temperature

These tests were performed with the same tools as the above by using a vertical electric furnace at 100, 200, 300 and 400°C. The specimen lubricated was heated at a given temperature for about 10 minutes, and then compressed.

At hot working machine of 30-ton capacity having an electronic controlling system was used and the load-strain curve was recorded on the same paper as described above.

III. Calibration of elastic strain due to testing machine

In calculating the coefficient of friction from the load-strain curv ... strain produced by the apparatus must be removed completely. The amount of strain recorded contains elastic strains of the machine, tool and specimen together with the plastic strain of specimen. When the specimen is of such low height as in the present case, the load-plastic strain curve calibrated by elastic strain must be used.

The calibration curve in Fig. 2 was determined by compressing the specimen having various diameters within the load range of elastic strain value.

In Figs. 3 (a) and (b) are shown the examples of mild steel specimen by using spindle oil 3, in which 1 and 1' refer respectively to calibrated curve by the above method and uncalibrated (recorded) one at the reduction of one step, and 2 and 2' to those at six steps.

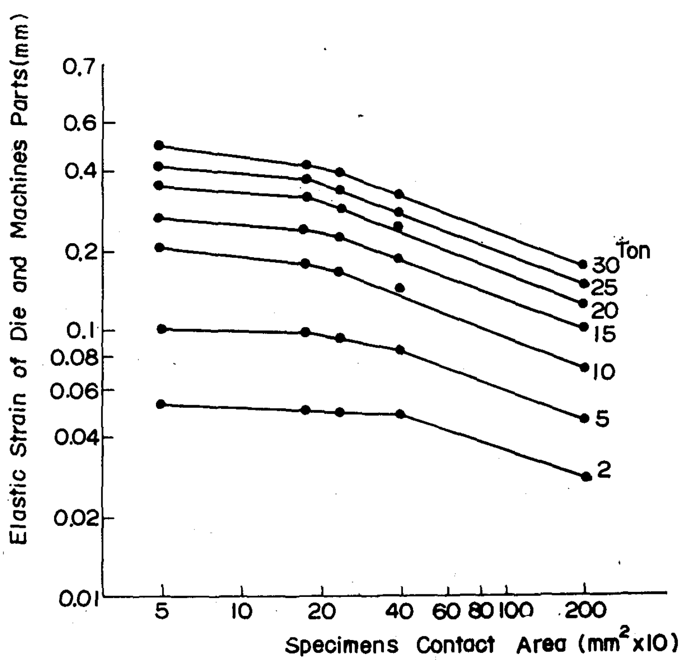


Fig. 2. Relation of elastic strain of tool & machine and contact area of test pieces.

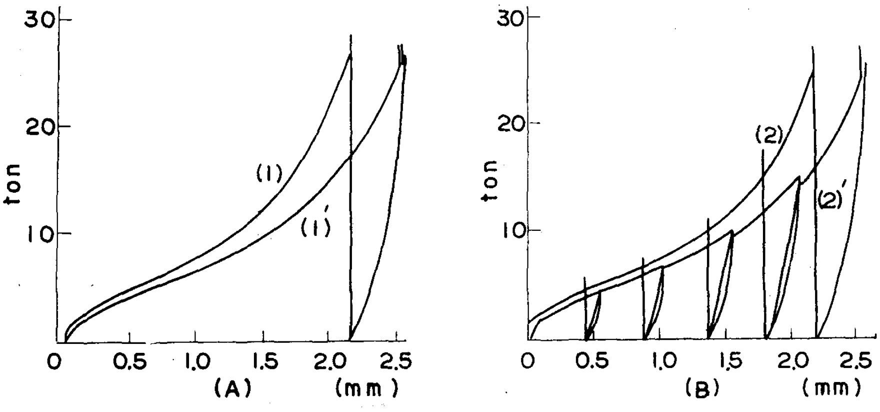


Fig. 3. Load-strain curve.
(A) Compressed in one step. (B) Compressed in 5 steps.
Lubricant: 3# spindle. Material; Mild steel.
(1′), (2′); Recorded curves
(1), (2); Corrected curves for elastic strain of machine's parts.

IV. Calculation of the coefficient of friction

Siebel's equation(4) was used: let p be the compressive stress expressed in kg/mm^2, k_f the resistance to deformation in kg/mm^2, r the radius, h the height of specimen in mm, and μ the coefficient of friction, then

$$p = k_f\left(1 + \frac{2\mu r}{3h}\right),$$

(4) E. Siebel, Stahl und Eisen, **43** (1923), 1295.

or by rewriting

$$\mu=\left(\frac{p}{k_f}-1\right)\frac{3h}{2r}.$$

k_f was determined by compressing the specimen ($h/2r=1.5$) using palm oil, beef tallow and paste containing molybdenum disulphide as lubricants.

V. Results and discussion

1. The relation between the frequency of oil supply and the coefficient of friction of lubricants

Fig. 4 shows the relation between the coefficient of friction and the compressive stress in repeated compression test with castor-oil as lubricant. The step numbers in the figure correspond to the frequency of oil supply during the total reduction of 60%. The coefficient of friction in each stress decreased gradually with the increase of supplying number, but the supply of more than three times had little effect on it. In this figure, the curve marked with "rolling" indicates the coefficient of friction of practical cold-rolling obtained previously(3), and comparing them with each other it is seen that the coefficient of friction in multi-oil supply considerably approximates that of cold-rolling.

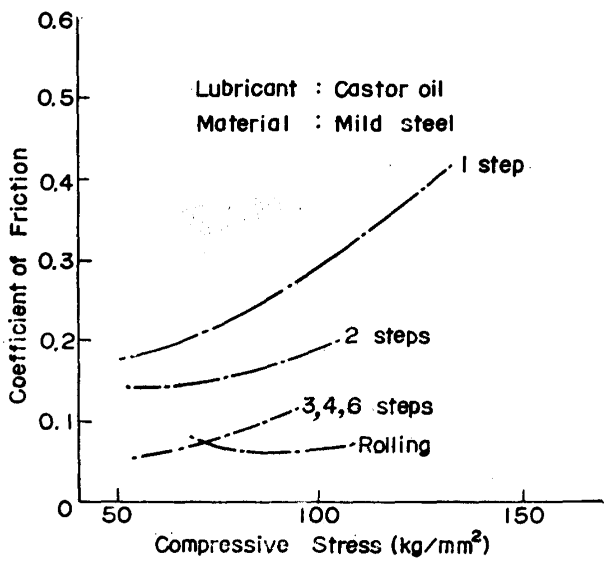


Fig. 4. Relation of friction coefficient and supplying quant. of oil in compressing.

In Fig. 5 is given the results obtained with various lubricants, which shows that the larger the number of times of oil supply is, the less the coefficient of friction is in any lubricants even in the same compression strain.

It has been found previously(3) that to evaluate the effect of various lubricants for rolling process, the compression test of cylindrical specimen is convenient, and that the relative values of friction coefficient are similar to those of rolling, though their absolute values were fairly different. It was found in the present experiment that even in the compression test the coefficient of friction became nearly equal to that of rolling with the increase in the number of oil supply.

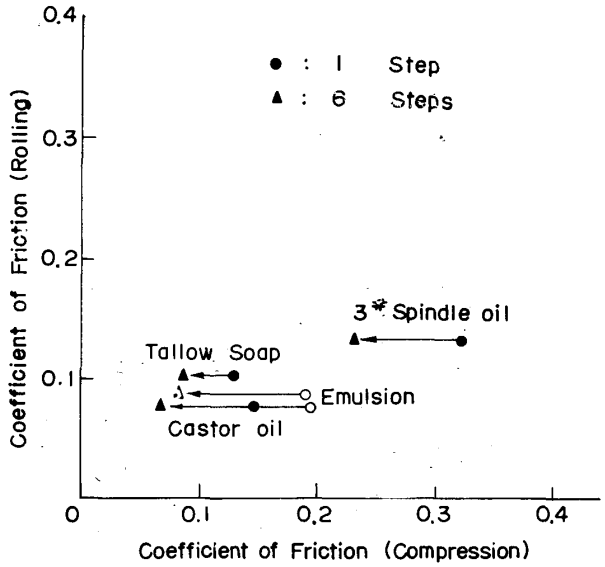
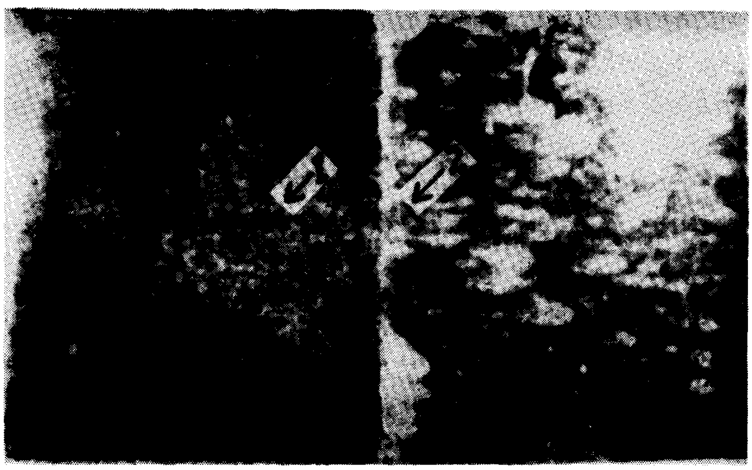
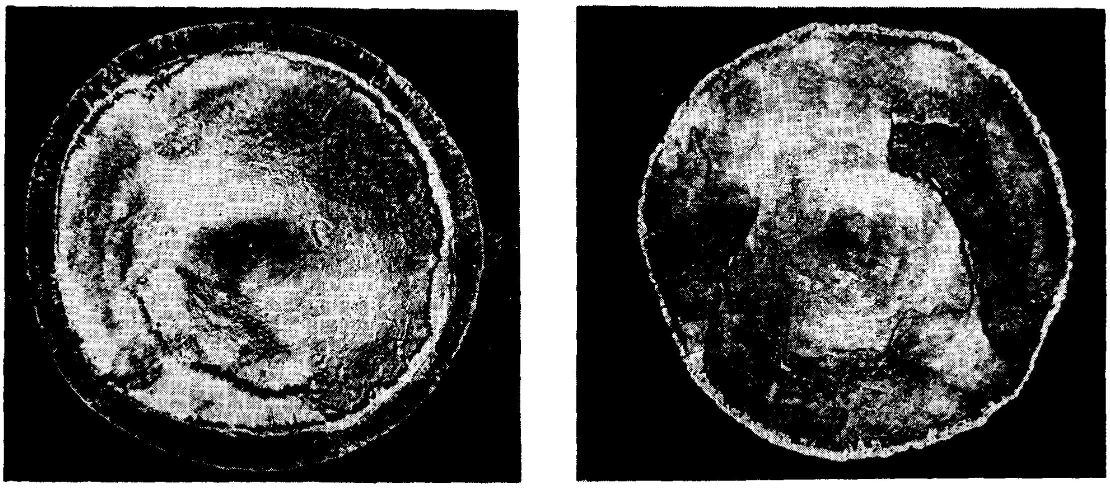


Fig. 5. Relation of friction coefficient in rolling and compressing.

Phot. 1 shows the metal surface of the roll bite observed when the rotation of roll was suddenly ceased. It seemes likely that palm oil as lubricant permeates into the roll bite (the white dapple parts shown by arrow in Phot. 1). Thus, the lubricant permeates into the roll bite and lubricates the roll and the plate during rolling, but the contact length of them is shorter than that in the compression, which seems to be the cause of the difference in the absolute value between the one-step reduction and the rolling. It may be considered, therefore, that the coeffiicent of friction in the compression test comes nearly to that in the rolling with the increase in the frequency of oil supply.



Phot. 1. Surface appearance of roll bite.
Lubricant; Palm oil. Material; Mild steel



(A) Compressed in one step. (B) Compressed in 5 steps.

Phot. 2. Surface appearance of compressed aluminium lubricated with machine oil.

The view of the surface of compressed aluminium specimen with 120 machine oil is shown in Phot. 2, the left one being that after the one-step reduction and the right being that after the six-step reduction. The left shows a higher friction coefficient than that in the right. In the left the side-face of cylindrical specimen before compression (arrow part) appears on the compressed surface, but scarcely in the right.

Therefore, it is clear that it is necessary to increase the frequency of oil supply in compression test in comparing the absolute value of the friction coefficient at the time of compressing with that of the rolling.

2. Effect of the lubricants on compression at room temperature

The test described above was performed to compare the friction coefficients of rolling and compression with each other, but in the case of lubricant, the one-step reduction method might be sufficient, and so all friction coefficients discussed below were determined by this method.

Fig. 6 shows the relations between the coefficient of friction and the compressive stress obtained with aluminium, copper, mild steel and stainless steel specimens by using minerals with different viscosities. As shown in the figure, the coefficient of friction had generally a tendency to increase with the increase in compressing pressure in any material. These tendencies were especially remarkable in aluminium and in mild steel. In copper, such a tendency was less remarkable and the coefficient of friction was fairly low as a whole. In stainless steel, though the coefficient of friction was fairly high, it had little tendency to become high with the increase in the compressing pressure. These properties considerably agreed with those observed in the welding condition of specimen. Thus, in aluminium and mild steel the welding took place on the surfaces of the tool and the specimen. but in copper any welding hardly appeared even if it was unlubricated. In the case of stainless steel little welding was observed in spite of high friction coefficient.

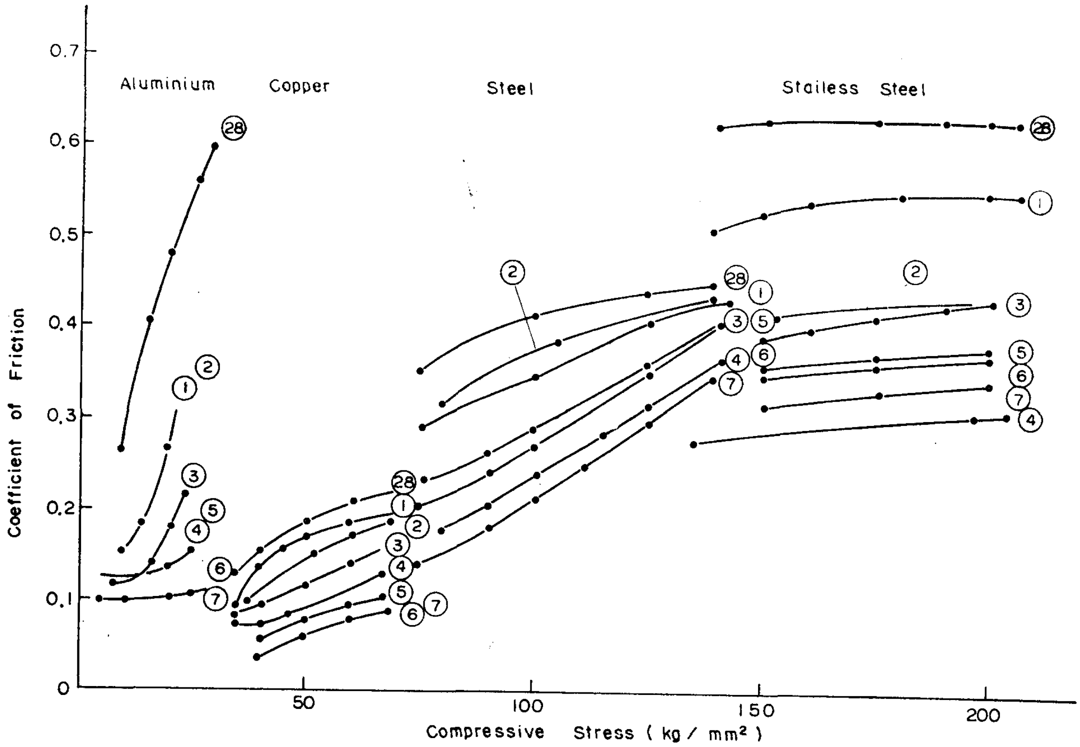


Fig. 6. Relation of friction coefficient and compressive stress on various lubricating condition in compressing.

In general, the coefficient of friction had a tendency to decrease with increasing viscosity, except mild steel and stainless steel, in which the coefficient of friction obtained with 120 machine oil was slightly lower than that with more viscous oil than it. This may be due to the effect of sulphur or other impurities contained in the oil, as shown in Table 1.

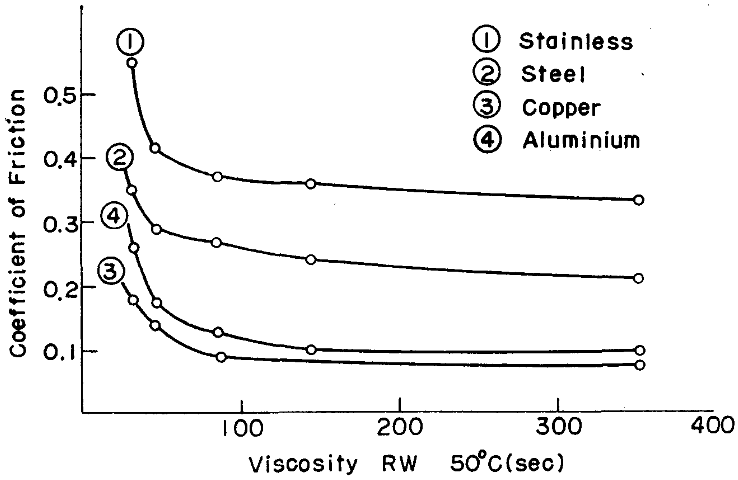


Fig. 7. Relation of friction coefficient and viscosity of mineral oil.

Fig. 7 shows the relation between the viscosity and the coefficient of friction of mineral oil. In any material, the coefficient of friction decreased considerably with a slight increase in viscosity in Red Wood at 50°C, at below 100 sec, while it was little affected by the viscosity above 100 sec.

Fig. 8 shows the results when fat, fatty acid and alchol were used as lubricant. In contrast with the cases of mineral oils shown in Fig. 6, the friction coefficients were low in these materials, except a few cases. These are classified into two groups: One is a fluid at room temperature, for example, rape-seed oil, castor-oil, sperm whale oil, oleic acid and oleyl alcohol, and the other is a paste or a solid at room temperature, for example, palm oil, beef tallow, lanoline and stearic acid. Those with extremely low friction coefficients fall within the latter. In such cases the contact of tool with specimen takes place only at the circumference of the specimen, and most part of the specimen may be deformed through lubricating film.

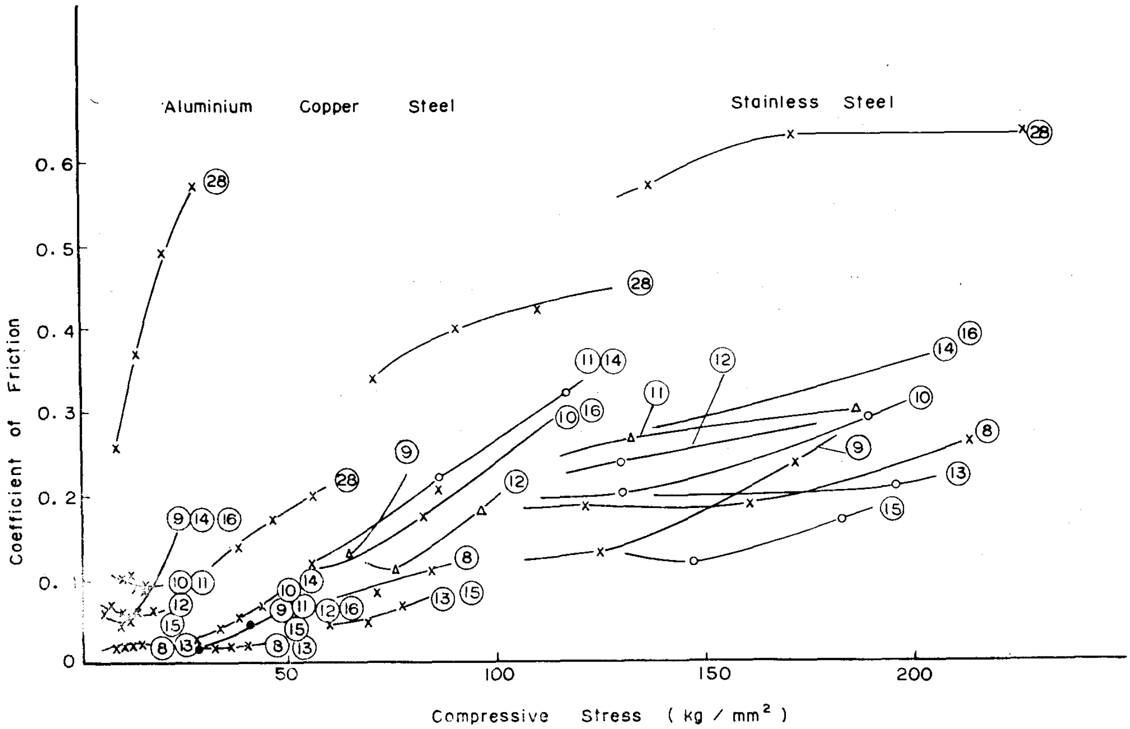


Fig. 8. Relation of friction coefficient and compressive stress on various lubricating condition in compressing.

Fig. 9 shows the results obtained from the experiments with fats, kalium soap of fatty acid, mineral oils containing solid lubricants or metallic soap, chlorinated paraffine and paste oil containing molybdenum disulphide. Even if the same lubricant was used, the order of friction coefficient was different with different materials. The paste oil containing molybdenum disulphide tended to have the lowest friction coefficient, followed by the kalium soap of fatty acid and mixed oil containing aluminium stearate, and the oil containing graphite or lead dioxide was comparatively high in the friction coefficient. On the other hand, chlorinated paraffine as an extreme pressure additive had a poor lubricity at room temperature, which was similar to that of turbine oil. It is not clear yet why kalium soap of stearic acid gives a high friction coefficient in compressing mild steel.

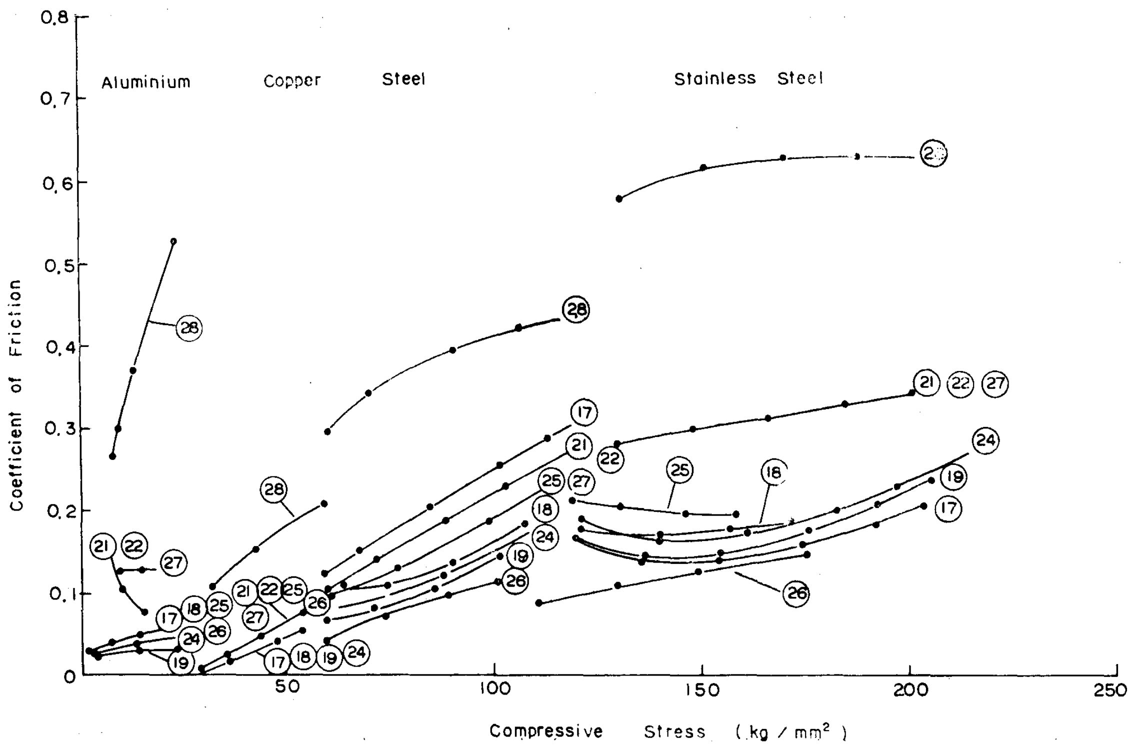


Fig. 9. Relation of friction coefficient and compressive stress on various lubricating condition in compressing.

3. Effect of lubricants in the compression at high temperatures

Even in cold working, the temperature[5] of specimen rises by several tens to several hundred degrees, and so the properties of lubricants at high temperatures must be examined.

Fig. 10 shows the coefficient of friction in compressing aluminium at high temperatures. The coefficient of friction at 100°C was hardly different from that at room temperature. However, at 200°C it increased, but slightly decreased at 300°C. At 400°C it increased again, at which the friction coefficient showed an irregular curve without a steady relation with stress. The paste containing molybdenum disulphide showed a good lubricity below 300°C, while at 400°C the friction coefficient increased suddenly. 40 motor oil had poorer lubricity than other lubricants, but by addition of various additives, the coefficient of friction may decrease considerably. Palm oil and lanoline were fairly high in friction coefficient at 200°C, but gave a low value at 300C. In chlorinated paraffine the welding took place on the surface, and especially at 300° and 400°C the friction coefficient was remarkably high.

Fig. 11 shows the result obtained from the examination of copper. As in the

(5) A. Pomp, *The Manufacture Properties of Steel Wire,* The Wire Industry Ltd., 1954.

case shown in Fig. 6, the coefficient of friction at room temperature was generally lower than other materials, but increased rapidly with the rise of temperature, and as in the case of aluminium shown in Fig. 10, its curve became irregular at 400°C. The effectiveness of lubricants was fairly different from that in the case of aluminium.

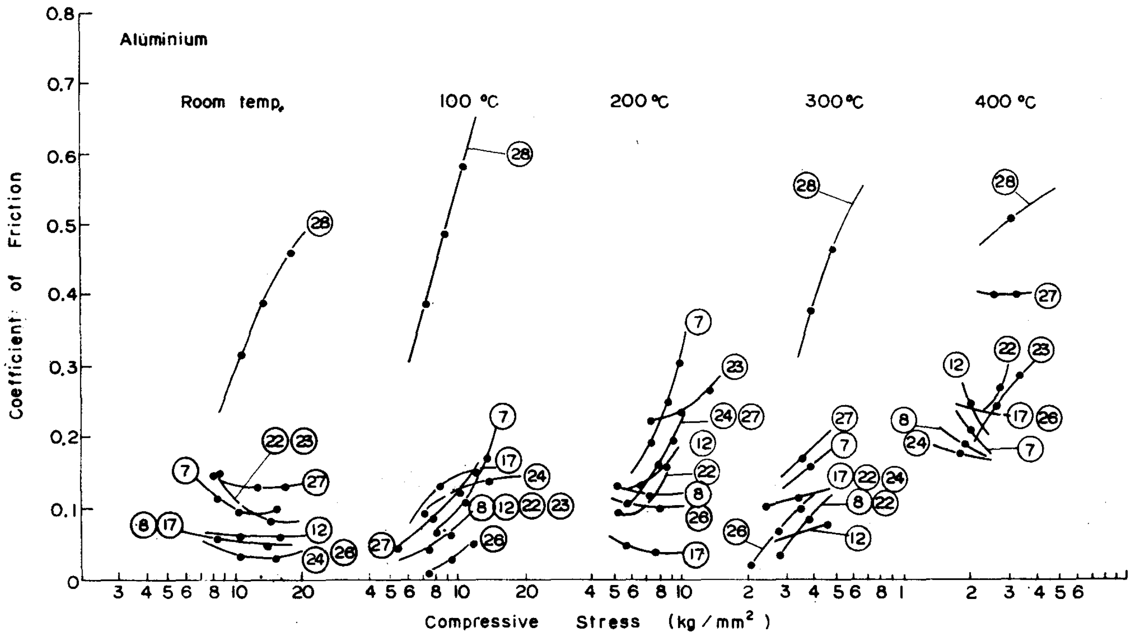


Fig. 10. Effect of lubricants on various temperature in compression tests of aluminium.

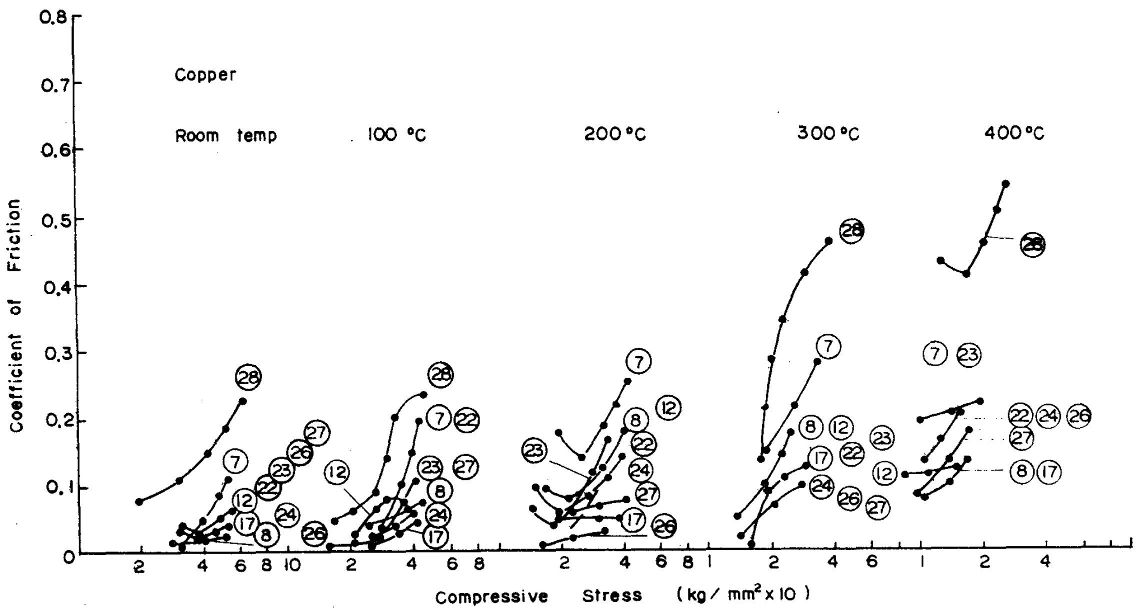


Fig. 11. Effect of lubricants on various temperature in compression tests of copper.

For example, chlorinated paraffine showed comparatively high friction coefficient at any temperature in aluminium, but showed a good lubricity in copper only at high temperatures.

In Figs. 12 and 13 are shown the results obtained in the examinations of mild steel and stainless steel. Although their absolute values were, as a whole, considerably different from each other, they showed higher values at 100°C or 200°C than at room temperature, and at 300°C or 400°C they had a tendency to approach that at room temperature again. Molybdenum disulphide showed the lowest friction coefficient below 300°C, while chlorinated paraffine had good lubricity at 200, 300 and 400°C. In this case, stearic acid soap gave the lowest friction coefficient at 200, 300 and 400°C like molybdenum disulphide.

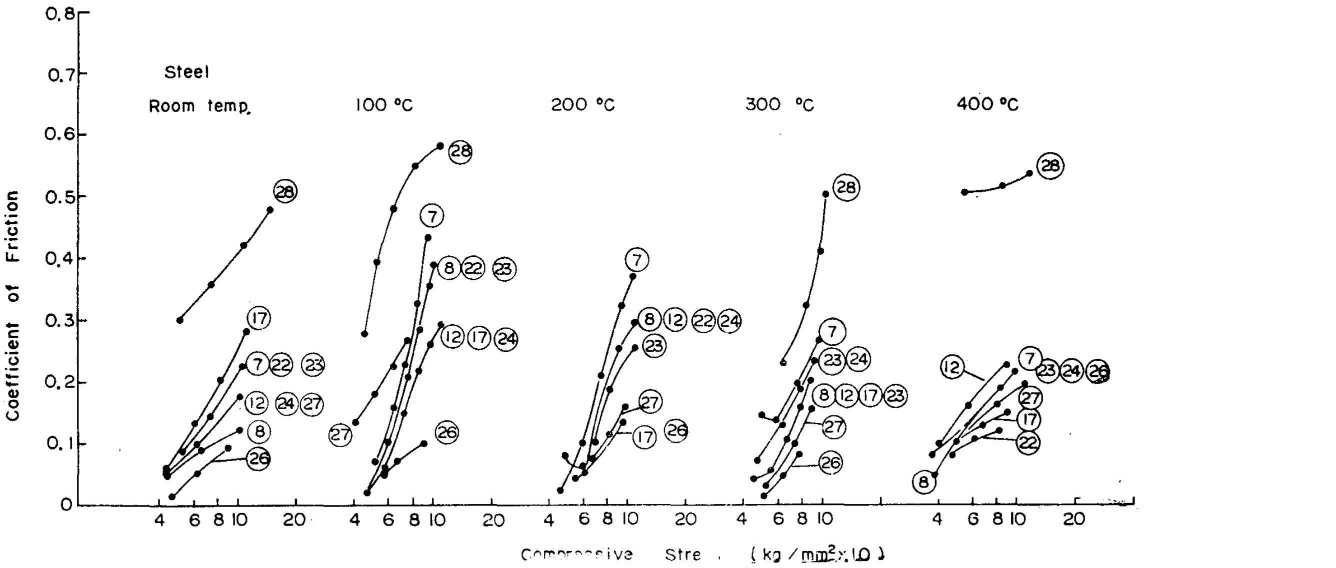


Fig. 12. Effect of lubricant on various temperature in compression tests of mild steel.

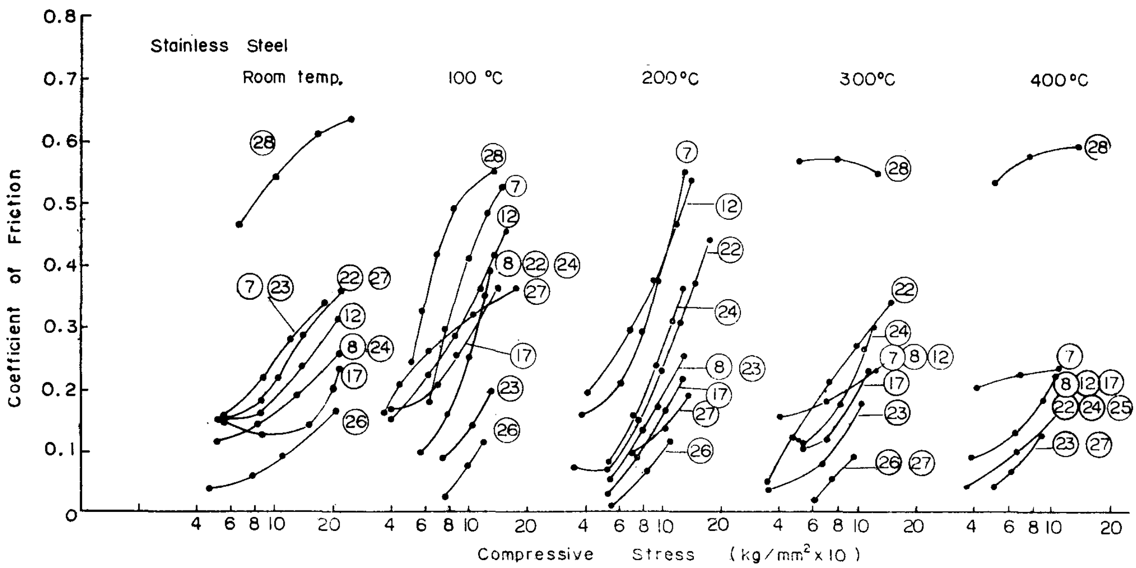


Fig. 13. Effect of lubricants on various temperature in compression tests of stainless steel.

In Fig. 14 is summarized the influences of these lubricants on various materials. As seen in the figure, in aluminium and copper, the friction coefficient has a tendency to increase as the temperature rises, while in mild steel and stainless steel it shows the maximum value at 100°C or 200°C and then decreases as the temperature rises to 300°C or 400°C, reaching nearly the value at room temperature.

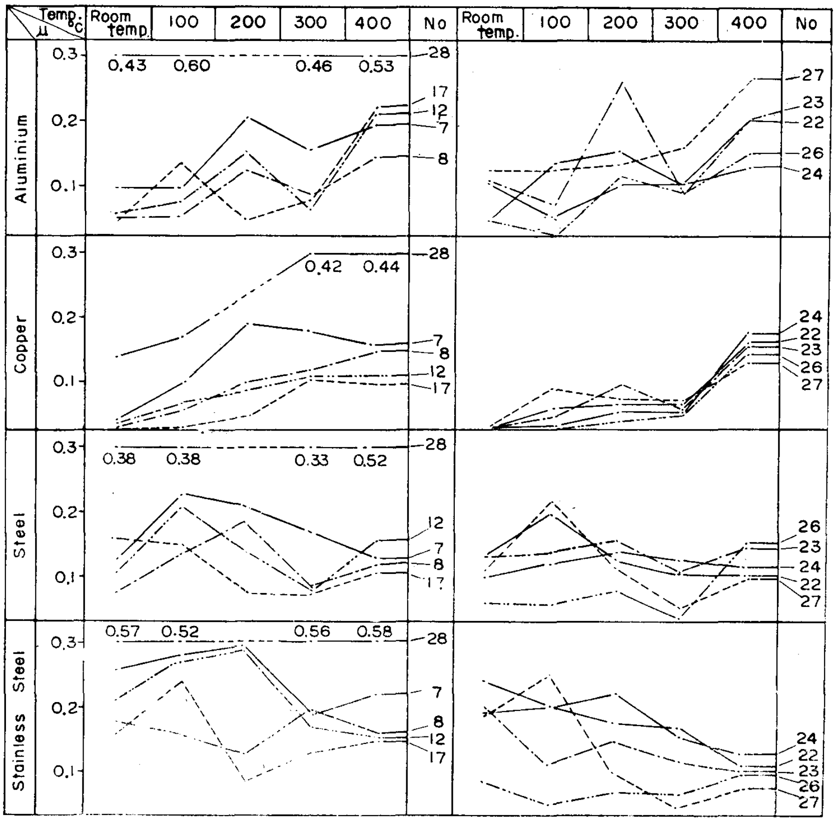


Fig. 14. Relation of friction coefficient and temperature on various lubricating condition in compressing.

In most cases various lubricants manifested various effects with the kinds of material worked. In particular, at high temperatures, various characteristics were observable with the kinds of lubricant or of material utilized, and for physical adsorption or chemical reaction between them. For example, the friction coefficient of chlorinated paraffine as an extreme pressure additive was low in aluminium at room temperature, but it increased rapidly with the rise of temperature, while in copper it showed a similar value in the temperature range from room temperature to 200°C, but at 300 and 400°C, it increased again. In mild steel and stainless steel, it was comparatively high at room temperature or at 100°C, but decreased considerably with the rise of temperature.

The above results suggest that the characteristics of lubricating film produced by chlorinated paraffine are influenced by materials. Although molybdenum disulphide as a solid lubricant may be considered to act physically, it shows high friction coefficient at 400°C, because at this temperature it solidifies as sand by losing original characteristics. Mineral oils containing lead dioxide, graphite or metallic soap showed a very good lubricity. Stearic acid soap showed a low friction coefficient at 200 and 300°C in any material. This may be due to its thin solid film.

Summary

The present examinations lead to the following conclusions:

(1) The elastic strain of the test apparatus must be taken into account in the calculation of the coefficient of friction from load-strain curve in a compressive deformation.

(2) The coefficient of friction in the compression test is nearly equal in the relative value, but fairly high in the absolute value as compared with that in the rolling. Both values can be made quite equal to each other by increasing the frequency of oil supply in the compression test. This may arise from the difference in the relative contact length of the tool with the material.

(3) By making use of mineral oils having various viscosities, the coefficient of friction is changeable by a slight difference in viscosity at 50°C in Red Wood under 100 sec, and above 100 sec, the change is comparatively small.

(4) The order of effect of lubricants is changeable by the kinds of material. At room temperature, palm oil, beef tallow and lanoline show a low friction coefficient, and at high temperatures, paste oil containing molybdenum disulphide, kalium soap of stearic acid and chlorinated paraffine show a considerably low value. (Chlorinated paraffine has a poor lubricity in aluminium.)

(5) In aluminium and copper, the friction coefficient of most lubricants increases with the rise of temperature, while in steel and stainless steel, it increases up to 100°C or 200°C, but decreases inversely at 300°C or 400°C.

These may be caused by the viscosity and the adsorption of the lubricants, the reaction between lubricants and materials, polimerizations and decompositions of the lubricants, and by other factors. Further investigations are desirable in this field.

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