The Effect of Deformation Speed on Friction and Lubrication in Cold Forging*

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The effects of deformation speed upon friction coefficient in the cold forging condition are investigated. The ring-shaped specimens of a number of metals are compressed in a high speed hammer (impact speed=10 m/sec) and in a hydraulic testing machine (0.1 mm/sec). The friction coefficient of copper in the unlubricated condition decreases with an increasing deformation speed. Some of the solid lubricants show the speed dependence of friction coefficient. Significant effects of speed are seen in the liquid lubricants, especially in case of the high friction metals such as 18-8 stainless steel and titanium. The frictional properties of liquid lubricants are related with the lubrication mechanism due to hydrodynamic effect. The effects of additives, viscosity of lubricant, size of specimen, and hardness of specimen material upon the speed dependence of friction coefficient are also investigated.

1. Introduction

Lubrication and friction in metal forming processes are the main factors affecting the load required, wear of the die, and workability. But the mechanism of friction between die and billet had been unclear because the pressure was extremely high. Recent studies on lubrication and friction have suggested that lubricant, being trapped between the die and the billet, supports the load, and keeps frictional force low in the forming condition. Because the trapping of liquid lubricant depends mainly on the hydrodynamic effect of the lubricant, the influence of deformation speed upon friction appears in respective processes.

Ram speed of a press or a forging hammer is much higher than that of a quasistatic testing machine, and the speed tends to be increased. Besides there are developed high energy rate formings, which include forging with a high speed hammer driven by high pressure gas, explosive forming, electrospark forming and magnetic forming. Their forming speeds are higher than the speed of an ordinary forming machine. The characteristics of friction under

high speed sliding may be different from those under low speed in cases of solid lubricant and dry friction as well as in case of liquid lubricant. In the present work, friction coefficients are measured for high and low speed compressions at room temperature in order to examine the effect of deformation speed on the friction and lubrication characteristics.

2. Examples of speed dependence of friction

Figure 1 shows load-stroke curves for extrusion of pure aluminium in a hydraulic press and in a high speed hammer at room temperature⁽¹⁾. The lubricant used is a mixture of mineral oil

Fig. 1 Extrusion load against punch stroke under low and high speed extrusions for pure aluminium. The die angle is 90° and the lubricant is a mixture of mineral oil and molybdenum disulphide⁽¹⁾

* Received 19th May, 1969.

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and molybdenum disulphide. The extrusion pressure in the high speed hammer is lower than that in the press though the flow stress of the metal increases with deformation speed. This decrease in extrusion pressure with speed depends on the decrease in friction due to hydrodynamic effect.

The hardness distributions of products made by compacting copper powders are shown in Fig. 2⁽²⁾. They are compacted in the press and in the hammer. The distribution of hardness is the result of uneven distribution of pressure caused by friction between the compaction die and the product. The distribution of the high speed compaction is more uniform than that of the low speed compaction. This suggests that the friction coefficient decreases with deformation speed also in the unlubricated condition.

3. Experimental method

Because it is difficult to measure the dynamic load accurately, the methods for determination of friction coefficient by means of load measurement are not adequate in case of high speed compression. In this study, compression tests are carried out on a flat ring-shaped specimen, where the friction coefficient is related to the change in inside radius as suggested by Kunogi⁽³⁾.

The specimen materials used in this investigation are lead, pure aluminium, 52S aluminium

(5%Mg), pure copper, titanium, α -brass, zircalloy, medium carbon steel S35C and 18-8 stainless steel SUS27. Their Vickers hardnesses are listed in Table 1. Among these materials, medium carbon steel, 18-8 stainless steel and 52S aluminium are used for many purposes, and the others are used only for the testing of the effect of hardness.

The initial shape of the specimen is: height: inside diameter: outside diameter=1: 1.5: 3, and the specimens of 10 mm H, 15 mm I.D. and 30mm O.D. are used except for the testing of size effect.

As listed in Table 2, the lubricants used are mineral oils with different viscosities, solid lubricants, and additives.

In order to get the same lubricating condition on the lower and the upper surfaces of a speci-

Table 1 Specimen materials

Material	Vickers hardness (200 g)
Pb	5
Al	34
52SA1	60
Cu	90
Ti	124
7-3 Brass	173
Zircalloy	180
Mild steel (0.35%C)	197
18-8 stainless steel	316

Numbers in the figure indicate Vickers hardness

Fig. 2 Hardness distribution of compacted copper powder formed under high and low speed compressions in the unlubricated condition (Average density: 93.3%)

men, the specimen is supported about 1 mm above the lower platen by an adhesive cellophane tape.

The platens are of hardened tool steel SKD 11 (JIS), and they are abraded with Emery paper 01 by hand and cleaned with acetone before each compression.

High speed tests are carried out in a high speed hammer giving an impact speed of about 10 m/sec. A special apparatus is made to control the amount of deformation in the hammer as shown in Fig. 3. Deformation of the specimen stops when the upper platen strikes against the stopper and then the dummy specimen is deformed to absorb the rest of hammer energy.

Low speed tests are carried out in a hydraulic compression testing machine giving an average speed of 0.1 mm/sec. The ratio of speeds in both machines is 10^5 to 1.

4. Measurement of friction coefficient

As mentioned above, friction coefficient is determined by measuring the inside diameter of the specimen after compression. Some theoretical⁽³⁾⁽⁴⁾ and experimental studies^{(5)~(7)} concerning the ring compression have been reported. If the friction coefficient μ is equal to zero, the

ring deforms in the same way as simple compression of a solid disc. With an increasing of μ , the rate of outward expansion of the hole becomes lower, and if μ exceeds a critical value the inside diameter decreases because of the strong frictional restriction. In this study, an analysis of the deformation is done after Kunogi⁽³⁾, and friction coefficient is determined by comparing experimental results with the analytical results.

Consider a ring specimen having at an instant an inside radius r_i , an outside radius r_o , and a height h , and assume that barrelling does not take place. Radial stress σ_r , axial stress σ_z , and hoop stress σ_θ can be related using von Mises yield condition, Lévy-Mises incremental theory of strain, the condition of compatibility of strain, and the condition of volume constancy. At a radius r ,

$$\sigma_r - \sigma_\theta = \frac{2}{3} \sigma_0 \frac{(r_c/r)^2}{\sqrt{1 + (1/3)(r_c/r)^4}} \quad \dots\dots\dots (1)$$

$$\sigma_z = \sigma_r - \sigma_0 \frac{1 + (1/3)(r_c/r)^2}{\sqrt{1 + (1/3)(r_c/r)^4}} \quad \dots\dots\dots (2)$$

where σ_0 is flow stress and r_c is critical radius as material outside r_c flows outwards and inside r_c flows inwards.

The equations of radial equilibrium are,

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} - \frac{2\mu\sigma_z}{z} = 0 \quad (r_c \geq r \geq r_i) \quad \dots\dots\dots (3)_1$$

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} + \frac{2\mu\sigma_z}{z} = 0 \quad (r_c \leq r \leq r_o) \quad \dots\dots\dots (3)_2$$

Because the frictional stress $(-\mu\sigma_z)$ can not exceed the shear flow stress of the material $(\sigma_0/\sqrt{3})$, the following equations are used instead of Eq. (3):

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} + \frac{2}{\sqrt{3}} \frac{\sigma_0}{z} = 0 \quad (r_c \geq r \geq r_i) \quad \dots\dots\dots (4)_1$$

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} - \frac{2}{\sqrt{3}} \frac{\sigma_0}{z} = 0 \quad (r_c \leq r \leq r_o) \quad \dots\dots\dots (4)_2$$

If r_c is a known value, these equations can be solved by adopting the boundary conditions that $\sigma_r = 0$ at $r = r_i$ [for Eq. (3)₁ or (4)₁] and at $r = r_o$ [Eq. (3)₂ or (4)₂]. Because r_c is unknown yet, trial and error method is applied using a digital computer, i.e. the calculation is repeated until finding a correct value of r_c , which satisfies the condition that σ_r is continuous at r_c when r_c exists between r_i and r_o , or zero at both boundaries of $r = r_o$ and $r = r_i$ when r_c is smaller than r_i .

The geometrical change of the ring by small amount of compressive deformation (1%) is calculated using the value of r_c , and the final shape of the specimen is decided by adding geometrical changes due to each 1% deformation.

Table 2 Lubricants and additives

	Lubricant	Remarks
Liquid	Spindle oil	11 cSt
	Turbine oil	42 cSt
	Mobile oil	130 cSt
	Cylinder oil	360 cSt
Solid	Teflon sheet	0.55 mm
	Lead sheet	0.1 mm
	Phosphate coating +Stearic soap	For steel
	Molybdenum disulphide	
	Graphite	Diameter 20 μ m
Additive	Stearic acid	
	Stearic chrolide	
	Newpole LB625	
	10% I ₂ +90% Diphenyl- Diphenylether

Fig. 3 Deformation controlling apparatus in the high speed hammer

Some examples of the calculated position of r_c and the pressure distributions are given in Fig. 4 for the initial state of compression of the ring specimen having the above-mentioned shape. With an increasing friction coefficient, r_c becomes more distant from the centre and the maximum pressure higher.

The change in inside radius as a function of the amount of deformation is given in Fig. 5 assuming that the friction coefficient is constant throughout the deformation. The friction coefficients in the actual compression are determined by plotting the measured inside radius on this figure.

The inside radius of a compressed specimen is measured at the end surface with a projector. In case of high friction coefficient, the inside surface of a specimen becomes barrelled and the error of the obtained value can not be neglected.

Fig. 4 Contact pressure distribution and position of r_c for the various values of μ

Fig. 5 Change in inside radius with increasing amounts of deformation for various values of μ

But the inside radius does not change and no barrelling occurs at $\mu \approx 0.1$ as shown in Fig. 5, and barrelling of inside surface can be neglected when μ is smaller than 0.1. Because the measured values of μ tend to become close to or less than 0.1 when lubricant is used, it is thought that the error is slight in most of the cases. Even if the friction coefficient is high, qualitative comparison is valid.

5. Experimental result

(a) Dry friction

Figure 6 shows the relation between the inside radius and the amount of deformation for copper specimens compressed without lubricant. The measured points tend to lie on the line of $\mu = 0.18$ under high speed compression, and $\mu = 0.25$ under low speed compression. The friction coefficient decreases with deformation speed. This is the same tendency as suggested by the result for the metallic powder compaction (Fig. 2).

The reason for the decreasing of friction coefficient under high speed compression is considered to be that the flow stress of the material near the interface decreases because of the temperature rise due to friction. In case of the 52 S aluminium, however, no speed effect is seen on the friction coefficient, where μ is 0.3 under high and low speed compressions. The difference between two materials may depend on the sensitiveness of flow stress to temperature or on the difference in the amount of temperature rise.

(b) Solid soap on phosphate coating

The treatment of phosphate coating which

Fig. 6 Relation between inside radius and amount of deformation for copper, showing the effect of deformation speed in unlubricated condition

subsequently partially reacted with solid soap (stearic soap) is widely adopted in the cold forging of steels. Experiments are carried out on the mild steel and the results are given in Fig. 7. The measured points tend to lie on the line of $\mu=0.04$ under high speed compression, and $\mu=0.06$ under low speed. In both cases, the friction coefficients are low enough and the surface appearances of the deformed metals are good.

(c) Mobile oil

The results for the mobile oil are given in Fig. 8 for compression of the mild steel. It is worth to note that μ is nearly equal to zero at

Fig. 7 Relation between inside radius and amount of deformation for the mild steel, showing the effect of deformation speed when solid soap on phosphate coating is used as lubricant

Fig. 8 Relation between inside radius and amount of deformation for the mild steel, showing the effect of deformation speed when mobile oil is used as lubricant

the early stage of high speed compression. The reason for this low friction coefficient is that a thick lubricant film is trapped at the onset of compression. The coefficient tends to increase with an increasing amount of deformation. Because the inside radius is affected by the history of μ up to the present strain, it is impossible to measure the history by this method in which μ is assumed constant throughout the deformation.

Also under low speed compression, μ increases with an increasing strain. This is due to increasing of the fraction or true contact area with strain as reported previously⁽⁶⁾⁽⁹⁾.

(d) Comparison of lubricants

In Fig. 9 is shown the comparison between μ under high speed compression and μ under low speed for the liquid and the solid lubricants. The specimen material is mild steel and the measurements are carried out after 40% deformation. The measured values of μ are considered to be the average up to the amount of deformation.

Under low speed compression, the solid lubricants such as Teflon sheet, molybdenum disulphide, lead sheet and stearic soap on the phosphate coating show low values of μ (≈ 0.06), and the liquid lubricants comparatively high ($\mu=0.09\sim 0.12$). On the other hand, under high speed compression the values of μ for the liquid lubricants are very low. No change in μ is seen for Teflon, MoS_2 and Pb, and slight changes for stearic soap and powdered graphite.

The friction coefficient of solid lubricant is

Fig. 9 Comparison of friction coefficient between under high speed compression and low speed compression for the various lubricants. The specimen material is the mild steel and the amount of deformation is 40 %

determined by the ratio of the shear stress of the lubricant to the flow stress of the billet. Therefore the effect of the deforming speed on μ appears when the ratio changes with speed, i.e. the speed dependence of the shear stress differs from that of the flow stress. The effect of deformation speed on μ is not remarkable, because shear stress of a solid lubricants and flow stress of a metal are generally insensitive to deformation speed.

The comparisons are also made for the 18-8 stainless steel as shown in Fig. 10, in which the amount of deformation is 30%. Because the surface condition of 18-8 stainless steel is inactive, the friction coefficient is quite high ($\mu \approx 0.18$) under low speed compression with liquid lubricant. The coefficient remarkably decreases with an increasing deformation speed. As for the solid lubricants, the effect of speed is not so marked, i.e. no changes in friction coefficient are seen for solid soap on phosphate coating, Teflon sheet and lead sheet, and small changes for MoS_2 and powdered graphite.

(e) Additives

In order to examine the effect of additives, specimens of mild steel and 18-8 stainless steel are compressed with liquid lubricant containing the additives listed in Table 2. I_2 additive (10% $\text{I}_2 + 90\%$ diphenyl-diphenylether) has been proposed by R.W. Robert et al.⁽¹¹⁾ for cutting of 18-8 stainless steel. The main composition of Newpole L.B. is polyoxi-propeneglycol-monoether. The respective lubricants contain as much as 5% of these additives in the mobile oil. In Fig. 11 are

shown comparisons between μ under high speed and μ under low speed. The amount of deformation is 40% for mild steel and 30% for 18-8 stainless steel. In case of mild steel, stearic acid and stearic chrolide are effective under low speed compression, but none of the additives are effective under high speed compression. When stearic acid is used, μ under high speed compression is higher than μ under low speed compression, although hydrodynamic effect exists. From this, it is thought that the chemical reaction of the lubricant with the specimen material can hardly take place under high speed compression.

For 18-8 stainless steel, all of the additives are effective under low speed compression, and the effect of stearic chrolide is remarkable. On the other hand, under high speed compression, only slight effects of the additives are seen.

6. Discussion

In the former report⁽¹⁰⁾, it is theoretically analyzed that a thick lubricant film is hydrodynamically trapped as shown schematically in Fig. 12. The film is thickest at the centre and direct contact between the tool and the specimen takes place only at the periphery. The thickness h_0 at the centre is affected by the specimen radius R , the compressive speed V , the viscosity of the lubricant η and the flow stress σ_0 of the material, and is written in the following form:

$$h_0 = \sqrt[3]{\frac{\eta V R^2}{3\sigma_0}} \quad (5)$$

Examples of dished surfaces are shown in Fig. 13

Fig. 10 Comparison of friction coefficient between under high speed compression and low speed compression for the various lubricants. The specimen material is the 18-8 stainless steel and the amount of deformation is 30%

Fig. 11 Comparison of friction coefficient between under high speed compression and low speed compression when the lubricants containing the additives are used. The amount of deformation is 40% for the mild steel and 30% for the 18-8 stainless steel

for the specimens compressed in a high speed hammer. The central portion of the surface is depressed to 0.05~0.5 mm, and this shows that much lubricant was entrapped. Comparison between Eq. (5) and the measured values is made in Fig. 14 for pure aluminium specimens of different diameters and for lubricants of different viscosities. Because the experimental results agree well with the theory, it is clear that the lubricating mechanism depends on hydrodynamic effect.

The hydrodynamic effect is also seen under low speed compression. The lubricant film thickness under low speed compression is affected by the viscosity and the loading rate as shown in Fig. 15.

Because the fraction of true contact area is generally smaller in the thicker lubricant film, it can be attributed to the hydrodynamic effect that the friction coefficient is very low under high speed compression in case of the liquid lubricant.

According to Vogelpohl⁽¹²⁾, the friction coefficient μ is affected by the fraction β of the true contact area, the friction coefficient μ_1 of the true contact area and μ_2 of the area where the tool and the material are separated by the

Fig. 12 Schematic illustration of the trapping of liquid lubricant under high speed compression

Fig. 13 Examples of the depressed surface of the specimen compressed in a high speed hammer⁽¹⁰⁾

lubricant, and is written in the following form:

$$\mu = \mu_1\beta + \mu_2(1-\beta) \quad \dots\dots\dots(6)$$

As frictional force of the separated area depends on the viscous resistance of the lubricant in case of liquid, μ_2 may not be negligible under high speed compression. Let us estimate the value of μ_2 in the present experiment. Suppose a liquid film having a thickness h and viscosity η is trapped between a stationary flat tool and a specimen moving with a speed V . Referring to these experimental conditions, let us assume that $h=0.01$ mm, $\eta=500$ cP, $V=10$ m/sec and the contact pressure $p=50$ kg/mm². Then

$$\mu_2 = \eta \frac{V}{h p} = \frac{0.05}{50} = 0.001$$

It can be concluded that μ_2 is neglected even in high speed compression with a liquid lubricant having an ordinary viscosity. Then Eq. (6) is written as follows for liquid lubricant:

$$\mu = \mu_1\beta \quad \dots\dots\dots(7)$$

Fig. 14 Comparison of the depth of the surface between calculation and experiment

Fig. 15 Effect of viscosity of lubricant on lubricant film thickness⁽⁹⁾

(a) Effect of viscosity

In order to examine the effect of viscosity on the friction coefficient, specimens of 52 S aluminium are compressed using water and mineral oils of different viscosities as lubricant. The results are plotted against viscosity as shown in Fig. 16. Measurements are carried out after 50% deformation under high and low speed compressions. Because water has slight chemical reaction tendency with the metal as mineral oils, it is thought that the figure indicates the predominant effect of viscosity. Under both high and low speed compressions, μ tends to decrease with an increasing viscosity as expected from Eq. (5).

Measurements of β are also carried out on these specimens deformed under high speed compression, and the results are given in Fig. 17. With an increasing viscosity, β tends to increase as expected from the measurement of μ . As shown in Fig. 12 the contact between the tool

Fig. 16 Relation between friction coefficient and viscosity of lubricant, showing the effect of deformation speed when the 52S aluminium specimens are compressed with water and the mineral oils as lubricant. The amount of deformation is 50%

Fig. 17 Relation between fraction of true contact area and viscosity of lubricant when the 52S aluminium specimens are deformed with water and the mineral oils as lubricant under high speed compression. The amount of deformation is 50%

and the specimen occurs only at the periphery in case of the cylindrical specimen. But in case of ring-shaped specimen, the specimen contacts at both outside and inside zones, and the outside contact zone is wider than the inside zone.

(b) Effect of specimen size

Specimens of outside diameters varying from 10 to 40 mm are compressed in order to examine the size effect. The specimens are of 52 S aluminium and are compressed to 50% using mobile oil as lubricant. The results are given in Fig. 18. Under low speed compression, μ decreases monotonously with specimen size, but only slight effect is seen under high speed compression, where μ is nearly constant for the diameters from 20 to 40 mm.

(c) Effect of hardness

The friction coefficients of the materials listed in Table 1 are measured under high and low speed compressions. The specimens having an initial outside diameter of 30 mm are deformed

Fig. 18 Relation between friction coefficient and outside diameter of specimen, showing the effect of deformation speed when the 52S aluminium specimens are compressed with mobile oil as lubricant. The amount of deformation is 50%

Fig. 19 Relation between friction coefficient and hardness of specimen material when the specimens of various metals are deformed under high and low speed compressions with mobile oil as lubricant. The amount of deformation is 30%

to 30% using mobile oil as lubricant. Results are plotted against hardness as shown in Fig. 19. Under low speed compression, the friction coefficients for titanium, zircalloy, and 18-8 stainless steel are high and those for mild steel and α -brass are low. No direct relation between μ and hardness is found under low speed compression. Under high speed compression, the friction coefficients are nearly constant ($\mu \approx 0.05$) or slightly increase with an increasing hardness. As the film thickness decreases with an increasing hardness as indicated by Eq. (5), β may increase with an increasing hardness of the specimen material, and μ increases with an increasing hardness.

Judging from this result and from Fig. 11, which indicates that the additives are not effective to reduce the friction coefficient under high speed compression, the value of μ_1 is not sensitive to chemical properties of lubricant and of the specimen material under high speed compression. It is thought that an effective adsorption layer is not formed because the period of deformation is too short.

7. Conclusions

In order to examine the effect of deformation speed on the friction coefficient in cold forging condition, ring-shaped specimens are compressed in a high speed hammer (impact speed=10m/sec) and in a hydraulic testing machine (0.1mm/sec). Friction coefficients are determined by measuring the change in inside diameter of the specimen, and the following results are obtained:

(1) The friction coefficient of copper in the unlubricated condition decreases with deformation speed. This decrease in μ is considered to be caused by the temperature rise of the contact zone due to the frictional heat.

(2) The decrease in μ under high speed

compression is also seen in some of the solid lubricants.

(3) The liquid lubricants show significant effect to decrease μ under high speed compression owing to the hydrodynamic effect. Especially, the effects are remarkable for the high friction metals such as titanium, zircalloy, and 18-8 stainless steel.

(4) The additives are not effective under high speed compression, although they are effective under low speed.

(5) Effects of viscosity and specimen size are seen in case of liquid lubricant under high and low speed compressions.

(6) Under high speed compression μ is constant regardless of specimen material or slightly increases with an increasing hardness of the material in case of liquid lubricant, although no direct relation between μ and hardness is seen under low speed compression.

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