The Frictional Mechanism on Surface of Metals Plastically Deformed*

(3rd Report, Effects of the Bulk Plastic

Deformation on the Frictional Shear Stress)

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Using the two-dimensional drawing-type friction testing machine reported in the 2nd report, the experiments on aluminium sheets have been first carried out. The following have been concluded. (1) The frictional shear stress τ_f on the blank-holder surface is proportional to a real contact pressure p_r in every lubricant. This is similar to that obtained on the sheet metal drawing and the U-bending reported previously. After all it has been concluded that τ_f is not influenced by the plastic deformation but by p_r only, on the frictional surface where the apparent surface area does not increase. (2) The values of τ_f on the die surface are always larger than those on the blank-holder surface. It has been found newly that τ_f is influenced by an increase of the apparent surface area besides p_r , on the die surface. (3) Variations of τ_f on both the blank-holder and the die surface correspond consistently to variations of the appearance of the frictional surfaces. (4) Consequently, it has been concluded that the bulk plastic deformation influences mainly the frictional mechanism through an increase of apparent surface area.

2. Experimental conditions

1. Introduction

In these investigations, changes in surface of metals being plastically deformed have been classified into three components as described in the 1st report⁽¹⁾. To make clear effects of these factors on the frictional mechanism, a two-dimensional drawing-type friction testing machine has been designed and made. It has been confirmed in the previous report⁽²⁾ that the frictional and the normal forces on both the die and blank-holder surfaces can be measured precisely, simultaneously and without mutual interference during the process by this apparatus. As the result of some preliminary tests, it has been found that the frictional coefficient on the die surface is larger than that on the blank-holder surface.

In this report, in order to examine the effects of the bulk plastic deformation on the frictional mechanism, the experiments are carried out on aluminium sheets, changing the reduction in area and lubricants systematically. And, the frictional characteristics are compared between the die surface and the blank-holder surface.

The two-dimensional drawing-type friction testing machine reported previously⁽²⁾ is used, by which the frictional and normal forces on the die and blank-holder surfaces and the drawing force are measured simultaneously and continuously during the process. Working conditions are similar to those shown in Table 1 of the previous report⁽²⁾. The experiments are carried out using the reductions of 3, 8 and 11 %, because the limited reduction in area has been about 11 ~12 % under these experimental conditions. A normal load on the blank-holder surface before drawing is constant 20 kg as a standard. The die semi-angle is 10° and the drawing speed at the die exit is constant 0.6 mm/s.

To examine effects of lubricants systematically, 7 kinds of paraffin base oils, whose viscosity are within a range of 1.63 cSt(P01)~4600 cSt(St) as shown in Table 1, are used. Table 1 shows the viscosity, the chemical composition and so on. Refining process of these mineral oils is similar to that shown in the previous report⁽³⁾.

3. Comparison of the frictional coefficient between the die surface and the blank-holder surface

Figures 1, 2 and 3 show variations of the frictional coefficient μ on the die surface during the process in the case of the reduction being 3, 8 and 11 %, respectively. The case of being dry in Figure 1 presents a friction test carried out under condition where surfaces of test piece and tool were degreased with benzen and dried. In every case of the reduction as shown in Figures

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1, 2 and 3, the frictional coefficients μ of the low viscous oils P01~P3 are approximately constant throughout the stage of the processing, and the value of μ is about 0.80~1.05. The frictional coefficients μ of the high viscous oils Br and St become approximately constant after the stage of about 10 mm in the case of the small reduction 3 %, and the stage comes later with an increasing reduction, as shown in Figs. 2 and 3. Furthermore, the steady values of μ increase with an increasing reduction. For example, μ of Stock oil rises notably from 0.1 to 0.6 as the reduction increases from 3 % to 11 %. This tendency is observed also in the case of P4. Moreover, in the case of P4, the frictional coefficients wave up and down with a period of the process 10~15 mm as observed in Figures 2 and 3. This waving phenomenon has appeared always in the case where the value of μ is about 0.7~0.8 even with other lubricants, for example a naphthene base oil or a liquid paraffin blended with additives. As shown at the right hand in Figures 2 and 3, a bulging of metal appears at the die entrance in the case of P01 and P2 whose frictional coefficients μ are higher than 0.7~0.8, while the bulging does not appear in the case of Br and St whose μ is lower than 0.7~0.8. Therefore, the waving phenomenon of P4 seems to have appeared due to the unsteady lubrication conditions occurring at the boundary of the

bulging. Thus, it has been found that the steady values of μ on the die surface increase with an increasing reduction in the cases of the high viscous oils such as P4~St.

Figure 4 shows variations of μ on the blank-holder surface during the process in the case of the reduction 11 %. The values of μ in the case of $r = 3$ and 8 % also are similar to this figure. It is found from this figure that the frictional coefficients of all the lubricants are approximately constant during the process. And, they are relatively lower than the frictional coefficients of the die surface shown in Figures 1~3, respectively.

Figures 5 and 6 show relations between the steady values of μ and viscosity of lubricants in both cases of the die surface and the blank-holder surface. In both cases of Figures 5 and 6, the frictional coefficient decreases monotonously with an increase of the viscosity. In the case of the die surface shown in Figure 5, the frictional coefficients of the lower viscous lubricants than P3 are scarcely influenced by the reduction, while the frictional

Table 1 Properties of paraffin base oil

	P01	P 1	P 2	P 3	p 4	Bright-stock Br	Stock-oil St
Viscosity	20 °C	1.63	6.45	19.6	83.0	326	2150
	37.8	1.24	3.98	10.4	33.7	112.2	549.6
	98.9	0.65	1.42	2.6	5.3	11.5	32.2
Sulfur	wt %	0.02	0.02	0.01	0.10	0.13	0.20
Ring	CA %	7.1	10.7	3.2	0.0	1.5	3.6
analysis*	CN %	32.3	31.5	27.7	36.8	31.3	30.6
	CP %	60.6	57.8	69.1	63.2	67.2	65.8
Mean molecular weight		175	203	298	399	529	699
							787

* n-d-M method

Fig.1 Variation of frictional coefficient on the die surface during the process ($r = 3$ %)

Fig.3 Variation of frictional coefficient on the die surface during the process ($r = 11$ %)

Fig.2 Variation of frictional coefficient on the die surface during the process ($r = 8$ %)

Fig.4 Variation of frictional coefficient on the blank-holder surface during the process ($r=11$ %)

coefficient μ of the higher viscous lubricants than P3 increases with an increasing reduction. The higher the viscosity of the lubricant, the more remarkable becomes the difference of μ due to the reduction. On the other hand, in the case of the blank-holder surface, the value of μ approximately full on one curve independently of the reduction. After all, it has been found that only the frictional coefficient on the die surface has been influenced by the reduction. So, in the following chapter, it will be examined based on the frictional shear stress and the appearance of the frictional surface by what the above effect is brought about.

4. An examination on the frictional shear stress

To evaluate the frictional shear stress τ_f , the contact mechanisms at a tool-work interface are examined. Figure 7 (a) shows an appearance of the frictional surface of the die side metal. It is confirmed from a semi-microscopic observation of the frictional surface as shown in Figures 12 and 13 later that the whole apparent contact region i.e. white region in Figure 7 (a) presents approximate conditions of boundary lubrication, namely the contact ratio R is approximately 100 % under the experimental conditions. Figure 7 (b) shows an appearance of the frictional surface of the blank-holder side metal. Plastic deformation occurs mainly near the die surface because of a relatively small reduction, and so the apparent contact region appears near the die surface. It is confirmed in this case also that the contact ratio R is approximately 100 % in the whole apparent contact region. To measure the contact area on the die and the blank-holder surface, the contact region of metal is magnified using a projector, and profile of the contact region is copied on a tracing paper. Then, this area is measured by a planimeter. The frictional shear stress τ_f is obtained by dividing the frictional force by the contact area measured.

Figure 8 shows relations between the frictional shear stress τ_f and the viscosity of the lubricants. In this figure, solid signs show values on the die surface and blank signs show values on the blank-holder surface. Number in parenthesis () presents mean contact pressure p_r in the region of the boundary lubrication (this is called hereafter real contact pressure), and number in a brackets [] presents the contact area A_r mm². Comparing the cases of lower viscous oils than P4 with the cases of higher viscous oils than P4, the contact area A_r on the die surface is relatively large, and the real contact pressure p_r is relatively small. This is due to the bulging deformation. A similar phenomenon appears also on the blank-holder sur-

Fig. 5 Relation between frictional coefficient and viscosity on die surface

Fig. 6 Relation between frictional coefficient and viscosity on the blank-holder surface

Fig. 7 Appearance of contact surface of metal

Fig. 8 Relation between frictional shear stress and viscosity

face. This is due to a spreading of the plastically deformed region produced by the bulging on the die surface.

Figure 8 shows that the frictional shear stress τ_f on the die surface is larger remarkably than that on the blank-holder surface all over the range of viscosities. The frictional shear stress τ_f on the die surface is influenced by the reduction and the effect reserves at the viscosity of P4, while τ_f on the blank-holder surface is scarcely influenced by reduction. The effect of the reduction is most prominent in the case of St. Subsequently, it will be examined by what rules the above variation of frictional shear stress are governed.

Referring to the results of the 1st report, it is considered that the frictional shear stress τ_f is dominated mainly by two factors, i.e., the real contact pressure p_r and the quantity of bulk plastic deformation (for example, reduction in area). So, the result shown in Figure 8 is rearranged in terms of the real contact pressure p_r . Figure 9 shows the results. In this case also, solid and blank signs show values of the die and the blank-holder surface respectively. This figure shows a proportional relation between τ_f and p_r on the blank-holder surface and a branch line on the die surface along which τ_f increases unusually with an increasing reduction, in every lubricant. But, as the measured range of p_r on the blank-holder surface is different from that of the die surface, comparison of the τ_f - p_r relations in both cases is difficult. So, the following experiments on the blank-holder surface are added to match the range of p_r measured in both cases. To increase p_r on the blank-holder, an asperity of truncated wedge as shown in Figure 10 has been machined on the blank-holder surface of the metal. The semi-angle of the wedge is about 80° , the width of the plateau is about 1 mm and its surface is asrolled. Figure 11 shows the result in the cases of the low viscous oil P01 and the high viscous oil St. In this figure, signs X show values in the case where the reduction is zero.

The following are found obviously from Figures 9 and 11. On the blank-holder surface, the frictional shear stress τ_f is approximately proportional to real contact pressure p_r in every lubricant, and the proportional coefficient i.e. the frictional coefficient lowers with an increasing lubricant viscosity. Furthermore, the values in the case without the bulk plastic deformation also are plotted on the same relation of τ_f - p_r . A chain line added in the figure shows the result of Figure 14 in the 1st report⁽¹⁾ where a naphthene base oil N3 was used as a lubricant. After all it is concluded that the proportional relation between the frictional shear stress τ_f and the real contact pressure p_r holds in all the cases of the blank-holder surface in the sheet metal drawing, the U-bending and the two-dimensional drawing. Moreover, this relation is recognized in the case of a disc-slender type friction testing machine⁽⁴⁾.

On the other hand, τ_f on the die surface is larger than τ_f on the blank-holder surface and presents a different relation τ_f - p_r from that on the blank-holder surface. It has a positive correlation with p_r in the case of the low viscous oils P01~P3, but a negative correlation becomes stronger as the lubricant viscosity increases with P4 $\rightarrow$ Br $\rightarrow$ St.

Thus, the difference of the frictional shear stress between the blank-holder and the die surface has been clearly distinguished. This difference may be presumed to be due to an increase of the apparent surface area. In the following, it will be examined by what mechanisms such results have been brought about.

Fig. 9 Relation between frictional shear stress and real contact pressure (I)

Fig. 10 Shape of asperity manufactured on blank-holder surface

Fig. 11 Relation between frictional shear stress and real contact pressure (II)

5. The effects of the real contact pressure and the plastic deformation on the frictional shear stress

When the real contact pressure p_r or the apparent contact area increases under the condition of boundary lubrication, the following variations are considered to occur in frictional condition.

- (1) An increase of shearing resistance due to a thinning of lubricants film.
- (2) An increase of adhesion area due to break-down of lubricants film.
- (3) An increase of metal region ploughed by asperity of tool or adhesion layer.

It is likely that on the actual frictional surface, the above factors influence simultaneously τ_f and its increasing ratio. For example, if the effect of the factor (1) is prominent, an appearance of frictional surface will not deteriorate so much and an increase of τ_f will be relatively slight. On the other hand, if effects of the factors (2) and (3) are prominent, an appearance of frictional surface will be deteriorated by an increase of scars due to adhesion and ploughing, and increase of τ_f will be intensified. Thus, comparing the τ_f - p_r relation in Figure 11 with an appearance of the frictional surface in Figures 12 and 13, correspondence between them may be recognized.

Figures 12 (a) and 13 (b) show an appearance of the frictional surface on the blank-holder side of metal in both cases of

P01 where an increase of τ_f is large and of St where an increase of τ_f is small. Fig. 12 (a) shows the case of $r = 8\%$, $p_r = 3.1 \text{ kg/mm}^2$ and $\tau_f = 2.3 \text{ kg/mm}^2$. Figure 13 (a) shows the case of $r = 11\%$, $p_r = 5.7 \text{ kg/mm}^2$ and $\tau_f = 0.8 \text{ kg/mm}^2$. The photographs (1) and (2) in both figures show the same surface taken through a microscope with different magnifications, and the photograph (3) shows an optical interference fringe. In the case of P01, some scars of adhesion and disturbance of the optical interference fringe may be observed, that is, the appearance of frictional surface is inferior. On the other hand, in the case of St, the appearance of frictional surface is relatively smooth although many streaks may be observed on the sliding direction. This difference of the appearance reflects on the increasing rate of τ_f with p_r .

An appearance of the frictional surface on the die side of metal may be observed as follows. Figure 12 (b) shows the case of P01, $r = 8\%$, $p_r = 8.8 \text{ kg/mm}^2$ and $\tau_f = 8.2 \text{ kg/mm}^2$. Comparing this with the case of Figure 12 (a), scars of adhesion increase remarkably, and so the values of τ_f are considered to be subjected to the above factors (2) and (3). Figure 13 (b), (c) and (d) shows the cases of $r = 3, 8$ and 11% respectively. Comparing Figure 13 (b) with (a), streaks in the sliding direction increase slightly. With an increase of reduction from (c) to (d), the deterioration

Fig. 12 Appearance of frictional surface of metal in case of applying P01 as lubricant

Fig. 13 Appearance of frictional surface of metal in case of applying St as lubricant

of the frictional surface appearance starts from the surface at the die exit independently of a decrease of p_r . This deteriorated region occupies 70 ~ 80 % of the apparent contact area. Thus, it is concluded that the branch of the τ_f - p_r relation in Figure 11 appears due to the surface deterioration produced by an increase of the reduction i.e. that of the apparent surface area.

An appearance of the die tool surface after friction tests is shown in Figure 14. Figure 14 (a) and (b) show the case of $r = 8\%$, lubricated with PO1 and St respectively, and they correspond to the frictional surface of metal shown in Figure 12 (b) and Figure 13 (c) respectively. In the case of PO1 in Figure 14 (a), a remarkable adhesion of aluminium may be observed. Therefore, it is understandable that friction occurs actually between this adhesion layer and the metal i.e. between the same metals and so a severe frictional condition appears on the interface. In the case of St in Figure 14 (b), a remarkable adhesion of metal appears near the exit of die surface. This corresponds to the above deteriorated region on the frictional surface of metal. As explained above, it is confirmed that the appearances of the frictional surfaces are deteriorated by a break down of lubricants film and an adhesion on the tool-metal interface, which are produced by an increase of the apparent surface area accompanied with the

bulk plastic deformation. An appearance of the frictional surface in the case of Br is similar to that in the case of St. In the case of P_4 , τ_f is approximately constant along a branch shown in Figure 9, and an appearance of the frictional surface also scarcely changes along that. This seems due to the fact that as the effect of p_r on τ_f is enhanced with a lowering of the viscosity of lubricant used, the deterioration due to the increase of the reduction is offset with an accompanying improvement due to the decrease of p_r . Thus, in the case of PO1, the effect of an increase of the apparent surface area lowers relatively and the proportional relation holds between τ_f and p_r . Thus, it can be concluded that the frictional shear stress is increased by an increase of the apparent surface area during the bulk plastic deformation as well as the increase of the real contact pressure.

Taking into consideration the above results, a friction testing machine, by which the effect of an increase of the apparent surface is measurable besides the real contact pressure, is essential to test a performance of lubricant for the deformation processing.

6. Conclusions

Using a two-dimensional drawing-type friction testing machine, the effects of the bulk plastic deformation on the fric-

Fig. 14 Appearance of die tool surface after frictional tests

tional mechanism have been investigated using an aluminium sheet. The following have been concluded within the limits of this experiment.

(1) By examining the correlation between the frictional shear stress τ_f and the real contact pressure p_r , a difference of the frictional shear stress between the blank-holder surface and the die surface could be clearly understood. That is, on the blank-holder surface, a proportional relation holds between τ_f and p_r independently of the presence of the bulk plastic deformation in every lubricant. The increasing rate of τ_f due to p_r becomes smaller with an increase of lubricant viscosity. This relation holds all the same in the cases of the blank-holder surface in the sheet metal drawing and U-bending. After all, τ_f depends on only p_r independently of the presence of the bulk plastic deformation in the case without an increase of the apparent surface area.

(2) Meanwhile τ_f on the die surface is always larger than that on the blank-holder surface and shows a different relation from the proportional relation of τ_f - p_r . After all, the dependence of τ_f on the increase of apparent surface area has been recognized besides the dependence on p_r . Both effects appear overlapping each other in practice. In the case of low viscous oils P01 ~ P3, the effects of the increase of the reduction lower relatively because the dependence of τ_f on p_r becomes large. Thus, a positive correlation between τ_f and p_r appears. On the other hand, with an increase of the viscosity from P4 to St, the dependence of τ_f on p_r lowers. Therefore, the effect of the bulk plastic deformation is relatively enhanced, and its increase raises the value of τ_f regardless of an accompanying decrease of p_r . As the result, a negative correlation between τ_f and p_r appears.

(3) The value of τ_f corresponds closely with a variation in appearance of the frictional metal surface on both the blank-

holder and the die. For example, in the case of the low viscous oil P01 where an increasing rate of τ_f due to p_r is relatively large, remarkable scars by adhesion and ploughing are observed. With an increase of p_r , the deterioration such as this becomes striking and an increasing rate of τ_f also becomes larger. On the other hand, in the case of the viscous oil St where an increasing rate of τ_f by p_r is relatively small, hardly any scar by adhesion and ploughing appears even if p_r increases. But, in the case where τ_f increases with an increase of the apparent surface area, a deterioration due to adhesion and ploughing can be observed.

(4) From the results described above, it has been concluded that the effects of the bulk plastic deformation on the frictional mechanism appear through the increase of the apparent surface area.

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