SUMMARY

Four kinds of solid lubricant were tested in order to examine the frictional characteristics by the friction testing apparatus developed by the author. In order to investigate lubrication behavior of solid lubricants in forming processes, FEM simulations for the upsetting and the forward extrusion process have been carried out under a constant value of the friction coefficient and a constant value of yield stress of solid lubricant. Some experimental forming tests were tried using some solid lubricants. It has been confirmed that the solid lubricants can lubricate successfully without a metal to metal contact when \( \mu_D \) at the interface between tool and solid lubricant is relatively low and \( \mu_M \) at the interface between work piece and solid lubricant is relatively high. On the other hand, the metal to metal contact occurs easily, when \( \mu_D \) is relatively high and \( \mu_M \) is relatively low.

Key words: tribology, upsetting, forward extrusion, solid lubricant, FEM simulation

1 INTRODUCTION

A few researchers have investigated theoretically the lubrication mechanisms of the solid lubricants in metal forming processes [1-3]. Wilson et al. [1] have proposed a simple analytical model concerning with a breakdown of solid lubricants in upsetting process of rectangular work metal. Moreover, Johnson et al. [2, 3] have proposed a theory of entrapment of solid lubricant in a hydrostatic extrusion. However, it was difficult to simulate completely deformation of solid lubricants at the interface between tool and work metal.

In the present paper, four kinds of solid lubricant were tested in order to examine the frictional characteristics by the friction testing apparatus. In order to investigate lubrication behaviour of solid lubricants in upsetting and forward extrusion processes, FEM simulations for the forming processes of cylindrical billet have been carried out and some experimental tests were tried using some kinds of solid lubricants.

2 FRICTIONAL CHARACTERISTICS OF SOLID POWDER LUBRICANT

Figure 2: Friction coefficients of solid lubricants with the punch pressure

Figure 2 shows the friction coefficients \( \mu \) of solid lubricants with the punch pressure \( p \). Each value of \( \mu \) for solid lubricants is approximately constant; 0.01 - 0.02 for PTFE, 0.03 - 0.04 for UHMEPE, 0.04 - 0.06 for MoS\(_2\), and 0.08-0.12 for graphite. But, the value of \( \mu = 0.08 - 0.12 \) for UHMWPE using the rough surface anvil of \( R_y = 0.5 \) \( \mu \) is very higher than that for smooth surface anvil of \( R_y = 0.1 \) \( \mu \).
3 FEM SIMULATION CONDITIONS IN UPSETTING AND EXTRUSION

Figure 3 and 4 show the FEM simulation models for upsetting and forward extrusion of cylindrical billets. The billet in Figure 3 is 21mm in diameter and 7mm in height and the billet in Figure 4 is 20 mm in diameter and 10mm in height. The true stress $\sigma$ and true strain $\varepsilon$ relationship of the billets is expressed as the Holloman expression $\sigma = 100 \varepsilon^{0.15 \text{ MPa}}$. The solid lubricant is applied with 0.05, 0.1, and 0.2 mm in thickness. The yield stress of solid lubricant is assumed to be constant 20 MPa. Coulomb’s friction law $\mu = \text{constant}$ is adopted as a frictional boundary condition along the interface between tool and lubricant, and billet and lubricant. The friction coefficient $\mu_D$ between tool and lubricant and the friction coefficient $\mu_M$ between billet and lubricant are changed within a range from 0.01 to 0.30. However, the friction coefficient $\mu_{DM}$ is assumed to be constant 0.3 when a metal to metal contact between tool and billet occurs.

The FEM numerical simulations are carried out by using the rigid-plastic finite element code DEFORM2 [4]. The FEM simulations are carried out as an isothermal, axisymmetric problem applying four nodes, square formed elements. The number of elements used in the billet is about 800 and the number of elements used in the solid lubricant is about 700. The maximum upsetting amount is 4.2 mm, namely $Re = 60\%$ of the reduction in height. The number of calculation steps is 200.

4 LUBRICATION BEHAVIOR OF SOLID LUBRICANTS IN UPSETTING

Figure 5 shows some results of flow pattern of the billet and the lubricant by FEM simulation where the high friction coefficient $\mu_M = 0.15$ at the interface between billet and lubricant and the low friction coefficient $\mu_D = 0.05$ between tool and lubricant were assumed. The solid lubricant film thickness can be reduced with the progress of the upsetting and particularly at the peripheral region of the billet, but the minimum thickness of the solid lubricant at the most outer position is still about 5 $\mu$m even at the reduction in height of $Re = 60\%$. It has been confirmed that a metal to metal contact between tool and billet doesn’t occur in the case of high friction on billet and low friction on die.

![Figure 6: Variations of thickness distribution of solid lubricant film during upsetting ($\mu_M = 0.15$, $\mu_D = 0.10$)](image)

Figure 6 shows the variations of the thickness distribution of the solid lubricant film during the upsetting process the lubricant by FEM simulation when the high friction coefficient $\mu_M = 0.15$ and the medium friction coefficient $\mu_D = 0.10$. The solid lubricant film thickness can be reduced with the progress of the upsetting and particularly at the peripheral region of the billet. The minimum thickness of the solid lubricant at the most outer position is less than 1 $\mu$m at the reduction in height of $Re = 24\%$. It has been assumed that a metal to metal contact between tool and billet occurs when the thickness of solid lubricant is less than 1 $\mu$m. The area of the metal to metal contact is enlarged with the progress of reduction in height larger than $Re = 24\%$.

Figure 7 shows the variation of the metal to metal contact area with the friction coefficient $\mu_D$ on the tool at the constant high friction $\mu_M = 0.15$ on the billet. When $\mu_D$ is less than 0.05, the metal to metal contact doesn’t occur. However, the critical reduction in height $Re_{cr}$ when the metal to metal contact initiates is being reduced and the metal to metal contact area is being enlarged according as the friction coefficient $\mu_D$ is larger than 0.1.
Figure 7: Variations of thickness distribution of solid lubricant film during upsetting [$\mu_M = 0.15$]

Figure 8 shows the variation of the critical reduction in height ($R_{eff}$) by the friction coefficients $\mu_D$ and $\mu_M$. When $\mu_M$ is higher than 0.10 and $\mu_D$ is lower than 0.10, the critical reduction in height ($R_{eff}$) is larger than 60%. Therefore, it will be important to select the friction conditions of the higher friction coefficient of $\mu_M$ and the lower friction coefficient of $\mu_D$ in order to restrain the metal to metal contact between tool and billet. The critical reduction in height ($R_{eff}$) is reduced with the decreasing of $\mu_M$ and the increasing of $\mu_D$. It will be difficult to restrain any metal to metal contacts between tool and billet in these cases, because ($R_{eff}$) is lower than 27% when $\mu_M$ is lower than 0.05.

Figure 8: Variation of critical reduction in height ($R_{eff}$) by friction coefficients $\mu_D$ and $\mu_M$

Figure 9: Some examples of work upset until 60 percent by smooth surface dies

Some experimental tests were carried out to verify the lubrication behavior of solid lubricants obtained by FEM Simulations. The billet is a circular blank made of commercially pure aluminum A1050. The surface roughness of the billet is about 4-5 $\mu$m in maximum height roughness $R_z$. The tools are a set of flat dies made of a tool steel alloy, and the maximum height surface roughness $R_z$ is a smooth one of 0.1 $\mu$m or a rough one of 1.8 $\mu$m. All the solid film lubricants were applied with the equivalent thickness of 0.1 mm.

Figure 9: Some examples of work upset until 60 percent by smooth surface dies

(a) UHMWPE  (b) MoS$_2$

Figure 10: Experimental plots on diagram showing metal to metal contact area by FEM [$\mu_M = 0.05$]

Figure 9 shows some examples of the billet upset until $R_{eff} = 60\%$ by the smooth surface dies of $R_z = 0.1\mu$m. All the solid lubricants can follow the surface enlargement of the billet. Figure 10 shows that the outer radius of solid lubricant film in the experimental tests is plotted close to the low friction line $\mu_D = 0.01$ on the diagram showing the metal to metal contact area obtained by FEM simulations with the constant friction coefficient $\mu_M = 0.05$.

Figure 11: Surface of billet and tool during upsetting by rough surface dies of $R_z = 1.8\mu$m with PTFE

Figure 11 shows some examples of the billet upset until $R_{eff} = 60\%$ by the rough surface dies of $R_z = 1.8\mu$m. The solid lubricant PTFE can’t almost follow the surface enlargement of the billet because of the high friction on the die surface. Figure 10 shows that the experimental points are plotted close to the high friction line $\mu_D = 0.15$.

Therefore it has been confirmed that the lubricant behaviour of solid lubricant can be simulated reasonably by FEM simulations of the upsetting.

5 LUBRICATION BEHAVIOR OF SOLID LUBRICANT IN FORWARD EXTRUSION

Figure 12 shows some results of flow pattern of the billet and the lubricant by FEM simulation where the high friction coefficient $\mu_M = 0.15$ at the interface between billet and lubricant and the low friction coefficient $\mu_D = 0.01$ between tool and lubricant. The solid lubricant film thickness can be reduced with punch stroke $S$ and particularly at the tip of the billet, but the minimum thickness of the solid lubricant is still about 5 $\mu$m even at the punch stroke $S = 10$ mm. It has been confirmed that a metal to metal contact between tool and billet doesn’t occur in the case of high friction on billet and low friction on die.

Figure 12: Experimental plots on diagram showing metal to metal contact area by FEM [$\mu_M = 0.05$]

Figure 10: Experimental plots on diagram showing metal to metal contact area by FEM [$\mu_M = 0.05$]
Figure 12: Some results of flow pattern of billet and lubricant of forward extrusion \([\mu_M = 0.15, \mu_D = 0.01]\)

Figure 13 shows the variations of the thickness distribution of the solid lubricant film by FEM simulation where the high friction \(\mu_M = 0.15\) and the medium low friction coefficient \(\mu_D = 0.05\). The solid lubricant film thickness can be reduced at the tip of the billet with the punch stroke \(S\) and the minimum is less than 1 \(\mu\)m at \(S = 2\) mm. It has been confirmed in this case that the critical punch stroke \(S_c\) is 2 mm.

![Figure 13: Thickness distribution of solid lubricant with punch stroke in forward extrusion, \([\mu_M=0.15, \mu_D=0.05]\)](image)

Some experimental tests were carried out to verify the lubrication behaviour of solid lubricants. The billet is a cylindrical billet of 20 mm in diameter and 15 mm in thickness made of commercially pure aluminum A1050. The surface roughness of the billets are 2.7 \(\mu\)m and 57.5 \(\mu\)m in maximum height roughness \(R_y\). The die is made of a cemented carbide alloy, and the surface roughness \(R_y\) is a smooth one of 0.1 \(\mu\)m. The solid film lubricants MoS\(_2\) were applied with the equivalent thickness of about 0.1 mm.

![Figure 15: Friction surface appearance of billets until \(S = 8.5\) mm](image)

Figure 15 (a) and (b) shows the billets upset until \(S = 8.5\) mm. The solid lubricant can follow the surface enlargement of the billet of \(R_y = 57.5\) \(\mu\)m as shown in (a), while the lubricant failure occurs remarkably at the billet of \(R_y = 2.7\) \(\mu\)m.

6 CONCLUSIONS

FEM simulations for the upsetting and forward extrusion of cylindrical billets have been carried out under the friction coefficient \(\mu = \) constant and the constant yield stress. Some experimental tests of upsetting and forward extrusion processes were tried using some kinds of solid lubricants. As a result, the following conclusions were obtained.

In the upsetting and the forward extrusion processes, the solid lubricants can lubricate successfully without a metal to metal contact when \(\mu_D\) at the interface between the tool and the solid lubricant is relatively low and \(\mu_M\) at the interface between the billet and the solid lubricant is relatively high. On the other hand, the metal to metal contact occurs at the peripheral regions of the billet in the upsetting or at the tip of the billet in the forward extrusion, when \(\mu_D\) is relatively high and \(\mu_M\) is relatively low.

REFERENCES