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Research on the Material Flow in Sunken Forging Dies*

(1st Report, Geometry of Deformation in the H-Shaped Section)

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The dimensional factors which affect the die filling are examined and reported in this paper. A plasticine is used as a model material and the square grid technique is employed to measure the displacement. The components having H-shaped sections are tested as one of the typical geometries under a plane strain condition.

It has been proved that an overall forging process is divided into five stages according to the mode of deformation which occurs in the regions joining the rim and the web where the mode appears to change markedly during the process.

The sequence of these deformation modes is so important for improving the die-filling that it provides an approach to the optimum design of the die and to an estimation of the optimum volume of material. The dimensional factor which relates closely to this sequence is the ratio of flash width to height.

1. Introduction

In the field of metal working process, die-forging is regarded as one of the important methods to produce many engineering components. However, general designing principle of forgings and the forging-dies utilized have not yet been established consistently so that the determination of forging parameters still relies much on empirical methods^{(1)~(3)}.

Recently a high-velocity forging in hot state has been introduced by many practical staffs in order to forge metals of either poor forgeability or of high flow strength. In this kind of forging processes, it becomes essential in design problem how to choose such die and billet dimensions as to suit the dimensions of a finished component which satisfy the requirements of strength.

In specifying these forging parameters, it is necessary to understand the material flow in a die in order to prevent forging defects such as the overlap, the cold shut, the extrusion defect, the flow-through defect and so on.

When the specialities of closed-die-forging processes are considered, it will be easy to see that the material flow is in an unsteady state and is closely

connected with particular geometry of the forging. Therefore, it has been a difficult matter to treat of the material flow consistently^{(4)~(13)}.

In view of the material flow, the die impressions may be said to consist of the horizontal and vertical passages† which are connected with fillets†† having different functions for the flow. In a forging process the blank material laid on a relevant portion of the die cavity is forcedly pressed out to fill in those passages.

Under a condition of axial symmetry the material is thus forced to flow centrifugally or centripetally and then to part into several directions taken by the passages. In order to control this material flow, it might be needed to observe the flow or to trace the displacement of material during the process.

In the present investigation, two-dimensional model forging-dies are utilized to produce components of model plastic material having an H-shaped section. As a result, it has been proved that some typical deformation modes successively occur in this kind of unsteady process and that an approach to the forging design can be found through consideration of this sequence of deformation modes.

2. Model material

It is very difficult to use practical metal in hot state in order to observe continuously the material

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† There may be an inclined passage⁽¹²⁾ according to the position of the parting-line.

†† As will be mentioned in the later report, they are specified by the "flow-through fillet" and the "shedding fillet".

flow in the die. Up to this time, therefore, many investigators have used model materials such as lead⁽¹⁴⁾⁽¹⁵⁾, tellur-lead⁽¹⁶⁾, mixture of waxes or plasticine^{(17)~(18)} for this purpose.

In this experiment, a plasticine was used as a model material under the condition of exactly controlled temperature and speed. The stress-strain curves of plasticine obtained by uniaxial compression at three different testing temperatures are shown in Fig. 1. The flow stress shows a strong temperature dependence. At low temperature there is a sharp bend similar to that of a hardened metal or an ideally plastic metal. At high temperature, however, the tendency of the curve is similar to that of an annealed metal.

3. Scope, purpose and preparation of the experiment

This paper purports:

- (1) to find out several kinds of typical deformation modes and to confirm critical conditions for the change of these deformation modes to occur and
- (2) to clarify the influence of the geometry of

Fig. 1 Stress-strain curve of a plasticine under uniaxial compression

Fig. 2 Oblique view of a half of the lower die and a plasticine blank

die and material on the critical conditions.

Figure 2 shows an oblique view of a half of the lower model die and a plasticine blank. This die is composed of sharp cornered blocks whose surfaces are finished smoothly by grinding until a surface roughness of $R_{\max}=1.6 \mu\text{m}$ is obtained. As will be seen, this model-die is different from practical die-form in the neglect of corner radii and drafts. However, it was expected that prototypes of the material flow could be observed in this type of die. As the die and the blank are able to be divided into halves in x -direction, the material flow in xy -plane could be easily observed by deformation of the grid which had previously been printed on the sectional xy -plane of the blank material. The distorted grid was successively photographed during the process.

For previously forming plasticine into a blank shape and performing the experimental deformation process, a 10 ton universal testing machine was utilized under a constant temperature. Figure 3 shows a photograph of the die assembly, whose diagram is shown in below.

① Die-set ② Constraining plate for plain strain
③ Upper-die ④ Lower-die

Fig. 3 Photograph and diagram of the die assembly

4. Parameters representing geometry of the forging

In order to specify the geometry encountered in die forging, some specific values or the ratios of dimensions should be mentioned. In this paper, the authors like to propose as parameters to be employed for representing the sectional shape of the die the width ratio of the rim and the web-half A/B , the ratio of the web thickness to the web width H/B and that of the rim height to its width $J/A = (J/B)/(A/B)$, the web width $2B$ being given as a referring dimensional scale.

For a process where the material flows over flash lands, width of the flash land W should be also taken into account. See Fig. 4(a).

Once the above mentioned parameters for the die have been given, volume of the blank material may be so determined as to fill just the closed cavity of the dies without any excess or deficiency, which will be written in areal notation as below.

$$F_{i0} = 4(AJ + BH) = 4B^2((A/B)^2(J/A) + H/B)$$

This may be said to be the necessary minimum area of the vertical section (or the volume) of the blank.

For a condition of die-filling in which the die engravings are filled up and the flashes having a thickness of $2t$ take place, sectional area of the forging after trimming may be written as

$$F_i = 4((AJ + BH) + t(A + B))$$

In this case, if the material of $4f$ (in areal measure) flows through the flash lands to the gutters, the volume of the blank to be prepared must be

$$F_a = 4((AJ + BH) + t(A + B + W) + f)$$

And, F_a must be equal to the rectangular area of the blank $4h_0b_0$. See Fig. 2.

In order to specify the cross-section of the blank, it will be necessary to give the ratio h_0/b_0 ,

b_0/B and the scale dimension B . In the process, when the web thickness is reduced to $2h$, the possible half-thickness of the flash will be given by $t = h - H$, to that the width-height ratio of the flash may be $w/2t$ or simply w/t . See Fig. 4(b).

Utilizing the parameters specified above, the following induced parameters can be written.

$$\text{Percentage of surplus material } \phi = (F_a - F_i)/F_i = (F_a/F_i) - 1,$$

$$\text{efficacious material } Y = F_i/F_a = 1/(1 + \phi) \text{ and}$$

$$\text{degree of die closure } \delta_e = (h_0 - h)/(h_0 - H) = 1 - t/(h_0 - H).$$

Fig. 4 Shape parameters of closed-die forging

Table 1 Values of the experimental variables

Shape parameters in the die					
	Width ratio of the rim and the web A/B	Height-width ratio of the web H/B	Height-width ratio of the rim J/A	Web width $2B$ mm	Flash-land width W mm
Fundamental value	0.6	0.3	1.5	50	30
Altered value		0.1, 0.2			10.5, 5.5, 1.2
Shape parameters of blank					
Group	Percentage of surplus material %, $\phi_0 = (F_a/F_{i0}) - 1$	Height-width ratio, h_0/b_0	Width ratio of blank and the web, b_0/B ($2B=50$ mm)	Remarks	
I	about 26	0.451	1.60	Standard	
		0.534	1.40	Altered	
		0.731	1.20	"	
		1.054	1.00	"	
II	6.8	0.350	1.60	Altered	
	16.2	0.381	1.60	"	
	26.4	0.415	1.60	Standard	
	36.1	0.446	1.60	Altered	
	44.2	0.472	1.60	"	

5. Typified modes of deformation

In order to specify the experimental conditions, still some apriori grants would be required for defining the values of forging parameters mentioned above.

In this investigation, aiming at a finished component which is composed of the web and the rim having equal and uniform thicknesses, A/B of 0.6 has been chosen as a fundamental ratio and $A/H=(A/B)/(H/B)=0.6/0.3=2$ so that A/H is fixed at 2.

Table 1 gives the values of the variables in the test. In this test, the tools having the ratios and dimensions of $A/B=0.6$, $H/B=0.3$, $J/A=1.5$, $2B=50$ mm and $W=30$ mm were regarded as those of the

fundamental form. See Table 1 above.

At first, 4 kinds of blanks listed in Table 1-group II were formed by the tools of fundamental dimensions. Photographs in Fig. 5 show the states of distortion of the square grid originally printed on the sectional plane.

It is observed that when the width of blank material $2b_0$ is smaller than $2(A+B)$, the deformation of material in early stage of the process is similar to that of simple upsetting of a slab between parallel anvils. So, it might be said that the flow peculiar to this kind of die forging could not take place until the material reaches the entrance of flash lands. Hence, in the beginning the observation was confined

Fig. 5 Comparison of the states of distorted grid pattern at nearly the same degree of die closure where blanks listed in Table 1-II have been shaped by fundamental tools lubricated by vaseline

Fig. 6 Photograph: distorted grid patterns at 5-typical stages of the process and diagram: schematic representation of these modes

to the case when the blank width $2b_0$ equals to $2(A+B)$, and this condition is shown in (a) of Fig. 5. In this case, the detailed deformation patterns in a process are shown in Fig. 6. The right hand halves of the figures show the distorted grids and the left hand halves illustrate their deformation schemes. In the left half illustrations, the square grids represent the region where the deformation has not taken place, the inclined solid lines represent the portions of high strain rate, the dotted regions correspond to the plastic zones and the white regions to the rigid zones which translate under these relevant configurations.

As will be seen in Fig. (i)~(v), throughout a process, the deformation pattern of material between the web faces (region 1 1'2'2') is similar to that of the plane strain indentation of flat anvils into a rectangular blank.

The condition is somewhat peculiar in the region of rims and in the joining region because the sunken depth H of the web affects the flow. See Fig. 4(a). In fact, the region 578 in Fig. 6(i) is able to move upward along the side wall 45 as if it were a chip in cutting with a shear plane 57. In the bud of flash portion 56, a similar deformation is observed according to the scraping action of the flash land. As the filling of the rim goes on, shear plane 57 changes its direction to 52. Consequently, material in the rim and the joining region can move as a rigid body as shown in Fig. 6(ii). In these two stages the material constituting the rim rises according to a mechanism like chip removal in the cutting and so the material in the joining region can move as a rigid body. Therefore, these stages may be referred to as the "cutting stage".

After this stage, as the ratio of the flash w/t increases, the deformation comes up to a stage where the material in the joining region can not move without plastic deformation. In this process the material in the rim rises as if it were a rigid body floating on the plastic mass. This deformation mode appears when free surface of the rim does not reach the depth end and the ratio w/t is kept within a limited value. In this stage the filling velocity of

the rims seems to be enhanced by the brake-action of the flash, so it may be referred to as the "brake-boosting stage".

When the thickness of the flash t becomes less and its length w larger so that the ratio w/t exceeds a critical value which is defined by friction of the flash-land, a neutral line (or region) of material flow takes place near the entrance of the flash and a part of the material begins to flow reversely into the joining region. As a result of this reverse flow, the filling-in action of the rims is so accelerated that this stage may be referred to as the "reverse-boosting stage".

After the rim tip touches the depth end of the die, corners of the rim cavity are filled up gradually with the adjacent material. In accordance with this filling up of the cavity corners the reverse flow from the flash becomes depressed and finally, all of the surplus material comes to be extruded out through the flash-land to the gutter by the squeezing action which takes place in the web and the joining regions. See Fig. 6(iv) and (v). This final stage may be called "upset-extrusion stage".

Summing up the above, in a compound flow which occurs during the die forging process there can be noticed four distinguished types of deformation modes i.e. "cutting" "brake-boosting", "reverse-boosting" and "upset-extrusion". These deformation modes are identified by the symbols I, II_a, II_b and III respectively in Fig. 6. Hereafter, the critical moments in the process when the deformation mode changes will be referred to as follows:

The critical point C; deformation mode changes

from I to II_a,

the critical point R; deformation mode changes

from II_a to II_b,

the critical point F; deformation mode changes

from II_b to III.

And the supposed ultimate state when flash height $2t$ becomes zero will be denoted by U .

By experiment where the tools of the fundamental form are used, the authors will explain below how the occurrence of these critical stages is affected by a change in the volume of surplus material.

6. Horizontal displacement of material along the parting line

Assuming that the die engraving is symmetric about its parting line, characteristics of the material flow will be clarified by tracing the displacement of material on the symmetric plane or the parting plane. On the sectional plane of the blanks shown in Fig. 7 (above), numbers from 1 to 27 are given to the constant-spaced grid points on the parting line, being counted from center to out side. Curves in Fig. 7 show plots of the horizontal displacement u_x of each point in re-

lation to the die stroke s . The broken lines and the chain lines correspond to the points which occupy central and outside regions respectively. They seem to increase monotonously with the die stroke. The intermediate points from 14 to 27, represented by full lines, seem to make the most extensive displacement until a certain earlier point of the process. See point C in Fig. 7. This means that until this point, the material between these numbers has moved translationally as a rigid body. However, this single solid line begins to part off after C. This means that plastic deformation occurs in the material belonging to this joining region. According to a bifurcation of curves at C the deformation mode changes from I to II_a at this point.

The maximum point R of curve 21 shows that an inverse flow from the flash to the joining region starts. And so, this maximum corresponds to nothing but the critical point R. Since the slope of all these curves represents horizontal velocity, when a curve changes its slope abruptly, a sudden change in the direction of flow should be thought to have occurred somewhere. As will be seen in the curve 21, at point F the process comes under this change, so it should be thought that the belonging material starts an intense outward flow at this point. The point F is

Fig. 7 Diagram of the horizontal displacement of elements on the parting line

thus called the critical point for upset-extrusion.

As stated above, it has been found that the critical points C, R and F can be defined clearly by tracing the horizontal displacement of particular elements on the parting line. Therefore, in the following, examinations on the material flow will be done based on the displacement curves like those represented by solid lines in Fig. 7.

7. Effect of surplus material and the height-width ratio of blank on occurrence of the change of modes

The blanks listed in group II of Table 1 have a common width of $2b_0=80$ mm, and have different heights or volumes. The horizontal displacement curves for these blanks are shown in Fig. 8. Though the critical points seem to come earlier with a decrease in the surplus material, this will not be the case when the filling-up point F disappears because of lack of the blank material. On the other hand, if critical points R and C disappear before filling-up because of much surplus material, the boosting effect of the flash will not be available, and this leads to an excess of forming energy because of an increase in the rate of process after the point F.

Figure 9 shows a diagram in which critical points for the case mentioned above are plotted. If a defined percentage of surplus material is imagined in Fig. 9, it will be possible to draw a parallel line to the abscissa, and by doing so, the moment at which the deformation mode changes can be predicted knowing the intersection of this line and each critical line. The section length of this line between F- and U-lines corresponds to the flash height taken when the die cavity has just filled up. The minimum allowable surplus material can be estimated as about 3% by reading the ordinate of the point at which the curve

F and the line U intersect.

Blanks listed in Table 1, group I, have the same volume but different shape-ratios. When they are deformed by the fundamental tools, the simple up-setting stage increases with an increase of the blank height. This circumstance is seen in (b), (c) and (d) of Fig. 5. Therefore, in a tall blank the critical point comes later and thus a reverse flow from the flash to the joining region will become difficult to occur because the rim tip can touch the depth end of the die before development of the flash. The diagram of critical points for this case is shown in Fig. 10. The abscissa in Fig. 10 is dimensionless flash height t/B instead of $s/2B$ in Fig. 9. The curve $j=J+t$ may be considered to be a kind of critical line which means that, on this line, the tip of the rim just touches the depth end surface of the die. If the process is observed on the basis of t/B , inclined tendencies of the critical lines C and R show much differences according to the shape ratio of the blank even when the volume is constant. In a very tall blank, the critical point F comes slightly earlier than in a dwarf one.

Fig. 9 Diagram of the critical points (For the standard die) Attendant figures of the plotted curves show $w/2t$'s assumed at the critical points

Fig. 8 Horizontal displacement curves (Effect of surplus material)

8. Effect of the dimensional parameters of the die on occurrence of the critical points

It might be supposed that the die dimensions H , J and W among shape parameters of the die will certainly affect the material flow. Since percentage of the surplus material ϕ_0 becomes different by alteration of H or J , it would be necessary to take this change into account in discussing the effect of these parameters on the critical point. H is the depth of a web-face which should be nearly equal to the final web thickness. Therefore, H is supposed to control the stroke duration of the cutting stage and thus to affect the degree of deformation. To ascertain this, blanks listed in Table I-II were shaped by the tools having $H/B=0.1$, and as a result, the diagram of critical point has been obtained as shown in Fig. 11.

Comparing this result with Fig. 9, it will be realized that critical points come later when H/B is

small. Thus, in this case, more material flows out into flash for the same amount of die closure.

The width of the flash land appears to have an effect of primary importance on the material flow in the joining region. So, in Figs. 9 and 11, the values of the width-height ratio of the flash w/t which are assumed to take place at the critical points have been indicated by figures along the plotted curves. It seems that when the flash-land width W is sufficiently large for the deformation mode to change during a process, w/t values must exist within the following limited ranges:

$w/t=0.8\sim 1.3$ for the critical point C,

$w/t=2.8\sim 3.2$ for the critical point R.

For occurrence of the critical points, w/t can be said to be an effective factor whenever in a process the mode of flow changes. Therefore, if W is defined within certain limits, the occurrence of critical points may be adjusted. To ascertain this, the standard blanks ($b_0=A+B$, $h_0/b_0=0.451$) have been shaped by the dies whose W is altered as shown in Table 1.

Figure 12 shows the horizontal displacement diagram in this experiment. It may be realized that the horizontal velocity of material on the parting line

Fig. 10 Diagram of the critical points (Effect of the height-width ratio of blank)

Fig. 11 Diagram of the critical points (For the die having $H/B=0.1$). Attendant figures of the plotted curves show w/t 's assumed at the critical points

Fig. 12 Horizontal displacement curves (Effect of alteration of flash land width)

cannot tend downward during a process in the case of the smallest W . This result tells that the mode changes of deformation at C and R have been brought about by slip resistance of the flash land. It follows from this that if W is so small that, during a process, the value of W/t cannot come under the range of values mentioned above, an enhancement of die-filling by the flash land resistance will not occur.

9. Filling-up of the rim (Das Steigen)

Material of the grid spaces numbered from 17 to 27 is situated below the rim-cavity at first. See Fig. 5(a) or Fig. 7. In the process, the free surface toward the cavity being numbered 0 to 10 in Fig. 7 (above) rises for the most part keeping itself free until it touches the depth end of the die as will be seen in Fig. 13(a) and (b).

In Fig. 13' (above), stages of die closure are specified by numbers from 0 to 9 and the corresponding outlines of the free surface are shown by repeated lines. Small arrows in the figure indicate the corresponding positions of the material points at these stages. [i.e. in (a) 0→5 and in (b) 1→6]. The difference between (a) and (b) comes from that of lubrication conditions.

Diagrams in Fig. 13 (below) show the vertical

and horizontal displacements of the points on the free surface of the rim. [As stated, numbers 0 to 10 are designated from the outermost grid point. See Fig. 7 (above).] These curves, being almost parallel with each other, show that shape of the free surface does not change markedly during a process. It follows from this that the deformation of the free surface almost settles after a certain initial stage.

The differences which are observable between (a) and (b) can be explained by slip-line field applicable to the cutting stage which will be referred to elsewhere. For other details see the figure.

10. Sequence diagram of material flow in the die

In the material flow treated so far, the dimensions A and B have been kept constant but other parameters varied so as to clarify the conditions when the deformation mode changes. In the diagrams of critical points as shown in Figs. 8, 9 and 10, however, it will be difficult to understand the development of deformations in various portions of die-passage at the same time. For the sake of the simultaneous knowledge of the change of various parameters during the process, the sequence diagrams for a forging process as shown in Fig. 14, 15 and 16 are proposed. In these figures,

Fig. 13 Filling of the rim

the parameters respected are width-height ratio of the flash w/t , sectional area of the flash $F_f/4B^2=wt/B^2$ or $(Wt+f)/B^2$, height-width ratio of the rim j/A and the specific web thickness h/B .

Figure 14 shows a sequence diagram in which

$H/B=0.3$, $A/B=0.6$, $W/B=1.2$, $h_0b_0/B^2=1.056$
Fig. 14 Sequence diagram of material flow (Lubricated by vaseline. Constant volume of blank. Fundamental tools)

blanks listed in Table 1-I are shaped by the tools of the fundamental form. The abscissa represents h/B instead of die stroke for the convenience of comparison of various blank heights. In this figure, it should be noted that the critical point C comes at a stage when the value w/t reaches about 1 and the critical point R comes at w/t of about 3. The curve wt/B^2 shows a maximum or an inflection at the critical point R. The curve j/A shows somewhat severe undulation due to characteristics of this value. At its minimum the material is supposed to reach the entrance of the flash land when the variable 'a' becomes just equal to the rim width A. Meanwhile at its maximum, the material of the rim tip reaches the depth end of the die. Since the critical point F should come a little after this maximum, the tendency of the curve j/A or j/a may be said to give a key to finding the point F.

Figure 15 shows a sequence diagram where standard blanks are shaped by the dies whose flash land width W is altered. As will be supposed, the critical point C comes at the time when the value of w/t reaches about 1. Meanwhile, it has been proved that, to define the point R, one should have recourse to the maximum point of wt/B^2 . For a value of $W/B=0.048$ critical conditions C and R could not happen.

The sequence diagram for various dies whose step heights H 's are different is shown in Fig. 16. It will be noticed in the figure that the critical points C and R, and accordingly, the tendencies of parameters

$h_0/B=0.66$, $b_0/B=1.6$, $H/B=0.3$, $A/B=0.6$
Fig. 15 Sequence diagram of material flow (Lubricated by vaseline. Standard blank. Alteration of flash land width) In the curves $F_f/4$ and j/A , a double dots-dash-line nearly lies on the broken line

$A/B=0.6$, $W/B=1.2$, $J/B=0.9$, $h_0b_0/B^2=1.056$, $b_0/B=1.6$
Fig. 16 Sequence diagram of material flow (Lubricated by vaseline. Standard blank. Alteration of the sunken depth of the web)

w/t , $F_f/4B^2$ and j/A are strongly affected by the change of step height H . Therefore, it might be stated that step height H is one of the most important among the parameters which control the die-filling.

In any diagram, w/B^2 should increase rapidly after the critical point F.

11. Conclusions

Plasticine model material has been deformed by the two dimensional model dies containing an H-shaped section. On the basis of this experiment, process of die-filling and flow pattern of material have been clarified fully. The results obtained are summarized as follows:

1) Material flow in rim-formation can be classified into several typified modes of deformation corresponding to the geometrical conditions which are given by die passages and filling-in material, and in the process, there appear these deformation modes in sequence. The typical modes which were noticed in this experiment are "cutting", "brake-boosting", "reverse-boosting" and "upset-extrusion". Individual deformation characteristics of them and their sequence have been clarified fully in order to improve the die-filling and to find an approach to the optimum design.

2) The dimensional factor which relates closely to this sequence is the ratio of flash width to height w/t . In this experiment, when this ratio w/t exceeds 3, filling of the rim is strongly boosted due to the inverse flow from flash to the die cavity. Therefore, flash land width W must have a length enough to satisfy this condition in the vicinity of the final stage.

3) A sequence diagram of the forging process has been proposed to know the effects of various forging parameters on die filling simultaneously. And,

an approach to the optimum design of the die and to the estimation of the optimum volume of material has been shown.

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Discussion

H. KUDO (Yokohama University):

(1) Isn't there any inconsistency in the two expressions on the occurrence of the brake-boosting mode, which are "as the ratio of the flash w/t increases" and "the ratio w/t is kept within a limited value"? Furthermore, it is obscure whether the term "boosting" has been used only as a similitude or to express something which has a positive driving force.

Finally, will it not be necessary to clarify the difference in the deformation between a plane strain and an axial symmetry? For example, it is thought that the brake-boosting stage may disappear under the condition of an axial symmetry because of the expanding phenomena in flash similar to the expanding

flow in a ring upsetting.

H. TAKAHASHI (Tohoku University):

(2) Although Fig. 1 shows the effect of the testing temperature on the stress-strain curve of plasticine, what would be the flow curves of plasticine under the constant temperature but different strain rate?

(3) It would be desirable to show how to choose the shaping velocity for this experiment and to what degree the testing temperature has varied during a process.

(4) How does strain-rate variations throughout the die affect the deformation patterns?

(5) In an experimental research on the closed

die forging⁽²⁰⁾ formerly conducted by the discussor it has been noticed that the material in the rim-cavity rotated before filling-up to form the rim. Was not this phenomenon observed in this experiment, especially at small H/B ?

(6) It is believed that the rim width A of the die affects the material flow in the die. How do the authors think about this point?

S. TAKAHASHI (Hitachi Ltd.):

(7) Although it is stated that plasticine may be used as a model material for an annealed metal, it had been experienced by the discussor that the behavior of plasticine at high temperature seemed to be similar to that of sand but not to that of the annealed metal.

It is believed that this similarity in flow curve will come from the effect of frictional condition on the platen or other factors which change during upsetting.

(8) According to the experiment of the die forging now being conducted by the discussor, even hardened aluminium does not behave like plasticine especially in the manner of die-filling. Did the authors confirm the similarity in large scale deformation between metal and plasticine?

(9) As mentioned above, it will be misleading about an actual forging to make a quantitative estimation on the basis of the results obtained by plasticine without consideration of the difference in the frictional conditions. (It is thought that limitation of application of these results should be shown.)

Author's closure

(1) First, the relation between the value w/t and the deformation modes will be explained. As seen in Fig. 10, while the ratio w/t does not reach about 1, the frictional resistance of the flash land will not be enough for the material in the joining region to give a wholly plastic deformation. So, during that stage of cutting the material in the joining region moves as a rigid body. However, after the ratio w/t exceeds unity, the frictional resistance of the flash-land forces the material in to the joining region to deform plastically. As a result, the out-flowing velocity of material into flash decreases according to this brake action of the flash and the filling velocity of the rim will be enhanced by this. We have called it "boosting stage" because this brake action contributes to an increase of the filling velocity.

This boosting effect of the flash increases with an increase in w/t . However, if w/t is kept within the range between 1 and 3, the material can still flow out into flash. So, we have called this deformation mode the "brake-boosting". Furthermore, when w/t exceeds 3 and the brake action of the flash intensifies,

a part of the material in the flash comes to flow reversely into the joining region. Thus, as the filling-in of the rim is accelerated, we have referred to this stage as the "reverse-boosting".

Next, we also have examined the material flow in a die of axial symmetry and have obtained interesting results. Although we are going to refer to it in detail elsewhere, it has been clarified that the five typical modes of deformation can be distinguished also under the condition of axial symmetry. However, as it is pointed out, the effect of the flash on the brake action will certainly diminish because the material in the flash is apt to flow outward like a material in a ring upsetting between smooth platens. But, it has been proved by the upper bound method that this centrifugal-flow effect is negligibly small in comparison with the brake action of the flash due to the frictional shear stress, which is assumed to be equal to $0.5k$ ($\sim 0.25k$) in this experiment. Therefore, it might be imagined that in an axi-symmetric condition the brake-boosting stage will also appear where the brake-action of the flash can have a certain effect on the filling-in action of the rim.

About questions (2) and (3). In a model material such as plasticine whose flow stress sensitively depends on temperature the characteristic of the flow stress curve might be affected by the variation of strain rate. Figure 1 appended shows one of the examples of the stress-strain curve of plasticine obtained by uniaxial compression at two different strain rates i.e. 0.002/sec and 0.02/sec.

The difference of flow stress at $\epsilon=0.25$ attains even approximately 0.25 kg/cm^2 . Furthermore the tendency of worksoftening seems to appear at $\dot{\epsilon}=$

Append.-Fig. 1 Stress-strain curve of a plasticine (Effect of strain rate)

0.02/sec. Therefore, the experiments have been carried out at a strain rate below $\dot{\epsilon}=0.003/\text{sec}$ at which work-softening begins to appear. All the tests are carried out at a constant temperature of adjustment in a range of $20 \pm 1^\circ\text{C}$.

About the questions (4) and (8). It will be necessary to consider that the deformation pattern is governed by the variation of strain rate. However, the authors would like to suggest the following experimental fact. Plasticine has been utilized in an experiment relating to the shearing mechanism and in one relating to the squeezing mechanism of a surface asperity model. By comparing the result with those of the hardened aluminium (JIS A-1100), it has been clarified that the deformation zone and the distribution of strain rates are also similar in both the plasticine and the metal.

(5) In our experiment, it has been also observed that the material in the rim slightly rotates like a chip removed in the cutting. However, as will be seen in Fig. 13, at a larger H/A and at a rather small B/h , this rotational movement is so slight that it is unnecessary to propose another new deformation mode. But in the case of $H/B=0$ and a small h/B , the rim is shaped with its rotation in the cutting stage I_a so that a cave which develops inside of the rim leads to overlap defects. Therefore, in the case where the boosting stage is not available, it will be necessary to suppress this material flow in the rim.

(6) Although we have treated in the report the deformation that is similar to neither pure extrusion nor pure piercing, the critical points of the deformation will be affected by the ratio A/B as the discussor pointed out. For example, at a small value of A/B , the volume of material out-flowing from the web part is relatively large in comparison with the volume of the rim cavity. Therefore, the filling velocity of the rim increases and the critical stage when the deformation mode I_a changes to I_b occurs earlier with a decrease in A/B . On the other hand, the critical points C and R come in later stages because the boosting action under the rim becomes hard to

utilize with an increase of h/A . At a small A/B the flash land width W should be large enough to utilize the advantage of the boosting stage.

At a large A/B the state is just the reverse of the above.

(7) The tendency of the stress-strain curve of plasticine obtained by compression test below 20°C was similar to that of a hardened metal, while at high temperature (25.5°C) it was similar to an annealed metal.

Although in our experience the deformation pattern and its load characteristic obtained by plasticine below 20°C seems to be similar to that of a hardened metal, there is a problem whether plasticine at high temperature behaves like an annealed metal or not. But this similarity does not seem to originate from the effect of variation in frictional coefficient during a process.

This research has aimed at the material flow of a hardened metal or an ideally plastic metal which is supposed to be exercised by a hot state forging.

(9) In order to generalize the characteristics of the material flow based on the experimental results the frictional condition on the die surface should be considered. In this report all tests except Fig. 13(b) have been carried out under the condition of lubrication with white vaseline. Therefore, assuming that the frictional shear stress on the surface of the die impression τ_G is nearly equal to zero except in the vicinity of the entrance of the flash land, and that the frictional shear stress on the flash land τ_F is nearly equal to 0.5 k, the load characteristics in the typified mode of deformation and their critical points obtained by experiment can be estimated consistently by means of the upper bound theory. However, whatever value τ_F may have, the conclusion will not be changed because the critical points for the change of the deformation mode result mainly from the brake action of the flash.

The purpose of this report is essentially to find the prototypes of the compound flow in the die and to clarify the sequence of these deformation modes.