Research on Precision Die Forging Utilizing Divided Flow
(First report, Theoretical analysis of processes utilizing flow relief-axis and relief-hole)

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In the conventional closed die forging, working loads increase rapidly at the stroke end and a complete filling up of materials into die cavity is impossible. A new precision forging process is proposed in this research. A flow relief-hole is prepared in the middle of the die or a specimen to reduce working loads by causing an inward material flow by forming a relief-axis or by shrinking the diameter of the relief-hole in this process. The reduction of working loads enlarges the depression and causes a preferable outward material flow to occur, which contributes to the complete filling up.

In this report, the filling up behavior in a barrelled disk specimen will be analyzed theoretically by the upper bound theory and possibility of decreasing working loads will be made clear.

Forming, Cold precision forging, Flow relief-axis and relief-hole
Theoretical analysis.

1. Introduction

In a die forging, the way of complete filling up of materials into die cavity is regarded most important for improving the dimensional accuracy of forged products. Nevertheless, few researches have taken up this subject in detail. This is considered due to the following view. The complete filling up through the conventional closed die forging process causes the fractional reduction in area of materials to reach unity at the stroke end. This requires an infinitely large working load naturally and it makes the complete filling up impossible, as was pointed out by H. Suzuki.(3)

If the working load required for the complete filling up can be reduced by any special device, the dimensional accuracy of forged products will be improved remarkably and availability of the die forging will increase much more.

Recently, one of the authors has succeeded in realizing a precision die forging of ‘spur gear with boss’, which has been considered difficult in general, by means of the simultaneous working of the parts of gear and boss.(4) The principle of this new method is as follows. In the working step of the part of tooth form, the material flow is somehow divided into an inward flow (as a centripetal one) and an outward one (as a centrifugal one). This divided flow prevents an increase of the fractional reduction in area and that of the working load, and reduces the pressure on the tools used. The complete filling up is thus considered possible.

If the above-mentioned is true and correct, the process utilizing this divided flow has to be duly valued and estimated with a view to improving the dimensional accuracy of forged products, because realizing the divided flow is considered possible in various other cases as well.

This research aims to confirm availability of the die forging process utilizing the divided flow and establish the theoretical and experimental grounds for its wider application.

Now, for the purpose of realizing the divided flow, the principle of the flow relief-axis,(5) which has been used for the die forging, can be regarded as a useful means for obtaining a similar effect. A new method on another principle, moreover, can be suggested, which might be called ‘principle of flow relief-hole’.

In this report, the principles of the relief-axis and the relief-hole are taken up and possibility of the processes utilizing these principles is examined with careful attention to the filling up of materials into the corner of die cavity at the stroke end. Here, a barrelled disk specimen is adopted as the basic means for applying these processes and the filling up behavior is analyzed theoretically by the upper bound theory. These attempts are expected to be useful to determine availability of the die forging process utilizing the divided flow.

2. Calculation of dissipation rate of total energy required for filling up

This report deals with the processes shown in Fig.1. One of them utilizes the principle of the flow relief-axis, which has the flow relief-holes in the middle of a parallel die set above and below, where the material is designed to flow into the
die cavities (called 'the process R.A.' hereafter). The other utilizes the principle of the flow relief-hole proposed newly in this report, which has the flow relief-hole in the material, contrary to the former with that in the dies, where the diameter of the relief-hole is designed to shrink (called 'the process R.H.' hereafter).

A barreled disk specimen is taken up with the intention of examining the filling up behavior of the material at the stroke end of these processes and analyzed by assuming as follows.

(a) The height of the specimen is small enough and the whole material is deformed. In this case, the analysis suffices only with the upper half zone of the specimen.

(b) The material profile shown as A in Fig. 1 is linear, and has constant slope throughout the working.

Figure 1, furthermore, shows the dimensions of every part of the material deformed during the working. In this figure, \( r_a \) denotes the radius position of the flow divide—that is, at this point, the material starts to flow in two directions—outwards and inwards separately. Five kinds of material flow patterns shown in Fig. 2 can be produced according to the variation of \( r_a \), because the position of \( r_a \) is unknown generally. Especially, the patterns turn into ten kinds when the types A and B are adopted in the process R.A.

H. Kudo (19) induced various upper bound solutions in die forging and extrusion by originating kinematically admissible velocity fields where a parallel and a triangle velocity block are combined with each other, assuming that the material is a perfect plastic solid which is subjected to von Mises’s yield condition and Lévy-von Mises’s stress-strain equation. This theory is used here, too. In this case, the upper bound solution is induced by calculating the dissipation rate of the total energy in every flow pattern and by minimizing the obtained rates, where cylindrical co-ordinates with the symmetrical axis of \( Z \) is used and \( u, v, \) and \( \dot{r} \) denote the velocity components in the directions of \( r \) and \( Z \) respectively and furthermore, \( \dot{r} \) is assumed independent only on the function of \( r \).

2.1 The patterns Ia, Ib and I

Figure 3 shows the admissible velocity fields assumed in the patterns Ia and Ib, in the process R.A., where the zone I is a rigid one descending with the velocity of \( \dot{V}_o \), each of the zones 2, 3, and 4 a plastic deformation one and the zone 5 a stationary rigid one. The depressing velocity of the die is given as \( \dot{V}_o \). Either zone 2 or 3 does not exist in the pattern I because of the process R.H. used in this case.

The following equations can be induced as the velocity components of each zone under condition of the constant volume and the boundary velocities, in zone 2: 

\[ \dot{v} = 0, \quad \dot{u} = \dot{V}_o \quad \text{---(1)} \]

in zone 3: 

\[ \dot{u} = \frac{\dot{r}}{2k} \dot{r}, \quad \dot{v} = \frac{\dot{r}}{2k} \dot{r} \]

in zone 4 (in the pattern Ia)

\[ \dot{u} = \frac{r}{2k} \dot{r}, \quad \dot{v} = \frac{r}{2k} \dot{r} \quad \text{---(2)} \]

in zone 5 (in the pattern Ib)

\[ \dot{u} = \frac{r}{2k} \dot{r} + \frac{\dot{r}}{2k} \dot{r}, \quad \dot{v} = \frac{r}{2k} \dot{r} \quad \text{---(2)} \]

where \( \dot{V}_o \) denotes the horizontal velocity on the boundary plane of \( \beta \) and \( \dot{V}_o = \frac{r}{2k} \dot{r} \) exist.
in zone (2): \( \dot{\omega} = -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \) and \( \dot{\varphi} = -\frac{r}{r_r} \dot{\varphi} + \frac{m}{2r_r} \dot{\varphi} \) and \( \dot{\varphi} = \frac{r}{r_r} \dot{\varphi} + \frac{m}{2r_r} \dot{\varphi} \) (4)

and in zone (5): \( \dot{\omega} = 0 \) (5)

The equivalent strain rate \( \dot{e}_e \) in each zone and the relative slipping velocity \( \dot{\delta}_h \) (as the discontinuous one) on each boundary plane \( \partial F \) can be induced from Eq. (1) to Eq. (5), too.

The dissipation rate \( S \) of the total energy can be calculated from the relation \( S = \gamma \frac{\int f_s \, dV}{\int f_s \, dV} \)

and is assumed constant on the same plane for the usual simple analysis. Assuming that the mathematical integration is complicated and not easy to calculate, H. Kudo tried to make a convenient approximation for substitution of the integral part. A similar way to this approach is taken up here, too.

The following equations of \( S \) are induced according to the above-mentioned, where \( f_{S} = f_{S} + f_{S} \) and \( f_{S} \) is replaced for \( f_{S} \),

in the pattern I: \( \dot{e}_e = \frac{\dot{V}_V}{\sqrt{3}} \left[ -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right] + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) \) (6)

in the pattern II: \( \dot{e}_e = \frac{\dot{V}_V}{\sqrt{3}} \left[ -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right] + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) \) (7)

in the pattern III: \( \dot{e}_e = \frac{\dot{V}_V}{\sqrt{3}} \left[ -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right] + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) \) (8)

where \( \dot{V}_V = \frac{r}{r_F} \dot{\omega} - \frac{1}{r_r} \dot{\varphi} \), and \( \dot{\omega} = r \dot{\varphi} \) exist, and furthermore, only when \( k = 0 \) holds, the term \( \frac{r}{r_F} \dot{\omega} \) in Eq. (8) is negligible.

Figure 4 shows the admissible velocity fields assumed in the patterns IIIa and IIIb, where the zone (2) is a rigid one ascending with the velocity of \( V_0 \), each of the zones (2), (3) and (4) a plastic deformation one and the zone (5) a stationary rigid one. Either zone (2) or (3) does not exist in the pattern III.

The velocity component of the zones (1) and (6) can be obtained by replacing \( \dot{V}_V \) for \( \dot{V}_V \), each of the zones (2), (3) and (4) can be induced as \( \dot{V}_V = \frac{r}{r_F} \dot{\omega} - \frac{1}{r_r} \dot{\varphi} \), \( \dot{\omega} = r \dot{\varphi} \), \( \dot{\varphi} = \frac{r}{r_r} \dot{\varphi} \) and \( \dot{\varphi} = \frac{m}{2r_r} \dot{\varphi} \) (in the zone (2)).

The equations of \( \dot{e}_e \) are induced in the same way as mentioned in the section 2.1.2, where \( f_{S} = f_{S} + f_{S} \) is replaced for \( f_{S} \),

in the pattern IIIa: \( \dot{e}_e = \frac{\dot{V}_V}{\sqrt{3}} \left[ -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right] + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) \) (9)

in the pattern IIIb: \( \dot{e}_e = \frac{\dot{V}_V}{\sqrt{3}} \left[ -r + \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right] + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) + \frac{\dot{V}_V}{\sqrt{3}} \left( \frac{r}{r_F} \dot{\omega} + \frac{2m}{r_r} \dot{\varphi} \right) \) (10)

where \( \dot{V}_V \) exists and only when \( k = 0 \) holds, the term \( \frac{r}{r_F} \dot{\omega} \) in Eq. (11) is negligible.

Here, \( \dot{V}_V \) shown in these equations is fixed from the relation \( \dot{e}_e / \dot{V}_V = m \). These flow patterns conceived in this section can not be expected to appear in case the relation of \( \dot{e}_e / \dot{V}_V \) not does hold.

2.3 The patterns IIIa, IIIb and III and the patterns IVa, IVb and IV
The following equations of \( \dot{E} \) are induced easily, because these patterns can be considered special cases in Eq. (6) to Eq. (11), in the pattern II: \( E_{II} = (E_{II} + \alpha_{II} + \beta_{II}) \), in the pattern III: \( E_{III} = (E_{III} + \alpha_{III} + \beta_{III}) \), in the pattern IV: \( E_{IV} = (E_{IV} + \alpha_{IV} + \beta_{IV}) \), in the pattern V: \( E_{V} = (E_{V} + \alpha_{V} + \beta_{V}) \), in the pattern VI: \( E_{VI} = (E_{VI} + \alpha_{VI} + \beta_{VI}) \), in the pattern VII: \( E_{VII} = (E_{VII} + \alpha_{VII} + \beta_{VII}) \). The equations of \( \dot{E} \) in the patterns VIII, IX, and VII are examined by minimizing the upper bound solution, too. However, these flow patterns can not be expected to appear, because the minimum rate is confirmed to agree with the rate of Eqs. (12) and (13).

The equations of \( \dot{E} \) in the conventional closed-die forging process (called the process C.D.) hereafter can be induced easily by replacing zero for \( r_{s}^2 \), \( V_{s}^2 \) for \( V_{o} \) and zero for \( a \) in Eqs. (6), (7), (9), (10), (11), (12), and (13).

2.4 Numerical calculation

Equations (7), (8), (10), (11), (12), and (13) are used in the process R.A., and Eqs. (6), (9), (12), and (13) are used in the process R.H. The upper bound solution \( \dot{E}_{III} \) is induced successively by minimizing \( \dot{E} \) of each equation of the material depressed very 0.5% of the working stroke. The position of \( r_{o} \) can be considered to change as the depression increases, but here, the position is assumed to remain unchanged within the range of 0.5% in depression. The new dimensions of the material in the next deformation step are fixed on this assumption under condition of the constant volume.

The fractional upper bound working load \( P/Y \) and the mean working pressure \( P/Y \) can be induced by using the relations \( \dot{E}_{III} = (V_{o}^2 - V_{r}^2) \), \( \dot{E}_{III} = (V_{o}^2 - V_{r}^2) \), and \( \dot{E}_{III} = (V_{o}^2 - V_{r}^2) \), respectively.

The percentage \( \delta \) of the filled up volume is defined here as \( (V_{o} - V)/V_{o} \times 100 \% \) for the purpose of examining the filling up behavior of the material into die cavity, where \( V_{o} \) is the volume fixed by the initial dimensions of the specimen: \( V_{o} = (r_{r}^2 - r_{l}^2) \), and \( V \) is the unfilled up volume of the material throughout the working. The following values are used in this report as an example of the initial dimensions of the specimen: \( r_{r} = 80 \text{mm}, r_{l} = 28 \text{mm}, r_{e} = 5 \text{mm}, r_{m} = 0 \text{mm}, r_{n} = 0 \text{mm}, \) and \( k = 0 \text{mm}. \) These are quoted from the former report to convenience sake.

3. Calculation results and considerations

Figure 5 shows the radial position \( 2r_{R} \) of the flow divide, where \( D_{IO} \) is the initial diameter of the relief-axis or the relief-hole, \( f \) the mean friction factor between the material and the die and \( \delta \) the percentage of the filled up volume. \( 2r_{R} \) changes according as \( f \) increases in Fig. 5 and gets more smooth as \( D_{IO} \) increases. The value \( 2r_{R} \) comes between the outside diameter \( 2r_{O} \) and the inside diameter \( 2r_{I} \) of the material: \( 2r_{R} < 2r_{R} < 2r_{O} \). The processes R.A. and R.H., therefore, can be expected to cause a divided flow in materials.

Figures 6 and 7 show the fractional upper bound working load \( P/Y \) and the material flow pattern appearing with an increase of \( \delta \), where \( D_{IO} = 0 \text{mm} \) means the process C.D. \( P/Y \) in each of the processes R.A. and R.H. gets lowered; usually compared with that in the process C.D. in Figs. 6 and 7. This appears usually independently of variations of \( f \) and its lowering tendency grows remarkable as \( D_{IO} \) or \( \delta \) increases. These processes, therefore, can be expected to be more useful than the process C.D. for reducing the working loads.

Next, the material flow patterns are observed carefully.

In the process C.D., the filling up is performed through only a single centrifugal flow.

In the process R.A., the material flow appears as only a single centrifugal one (the pattern \( P_{A} \) or \( P_{B} \) ) at first, then turns into a divided one (the pattern \( P_{C} \), and at last, becomes a single centripetal one (the pattern \( P_{a} \)) as \( \delta \) increases gradually. The pattern \( P_{B} \) or \( P_{b} \) appears occasionally according to variations of \( D_{IO} \) or \( f \), too. The zone realizing the pattern \( P_{a} \) is enlarged more as \( f \) increases.

In the process R.H., the material flow appears as only a divided one (the pattern \( P_{III} \) ) under small values of \( D_{IO} \) and this appears usually independently of variations of \( \delta \). However, the material flow comes to appear as a single centripetal one (the pattern \( P_{V} \) ) as \( D_{IO} \) gets larger; and occasionally, the pattern \( P_{III} \) appears under larger values of \( \delta \), too. The zone realizing the pattern \( P_{III} \) is enlarged more as \( f \) increases just as in the process R.A. But, the diameter of the relief-hole is shrunk under the depression in this process and there can be imagined a risk that the hole may be closed up completely. Following this, the material flow turns into a single centrifugal one under the depression and this process comes to

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Fig.5 Variation of the radial position of flow divide (where \( f : 0.677 \) holds or no lubricant is used.)

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be equal to the process C.D. Moreover, the filling up by only a single centrifugal flow can be considered a passive one, where the unfilled zone diminishes naturally under the depression, and is not an active one through the component of a centrifugal material flow. This calls for attention.

From the above, the material flows in the processes R.A. and R.H. can not be considered so simple as that in the process C.D., but the divided flow can be realized under fairly wide conditions.

Figure 8 shows the fractional mean working pressure $P/Y$, where $D_{LO}:D_{mm}$ means the process C.D. Here, the variation of $P/Y$ is examined with regard to occurrence of the material flow.

In the process R.A., $P/Y$ gets lower than that in the process C.D. when $\delta$ is larger or $D_{LO}$ is smaller—that is, when the filling up is promoted by the divided flow as shown in Fig. 8(a). Moreover, $P/Y$ gets much lower as $\delta$ increases much more—that is, as the filling up is promoted by a single centrifugal flow. This filling up, however, is a passive one as mentioned above.

In the process R.H., the filling up through the divided flow starts with a small value of $\delta$ as shown in Fig. 8(b). A decrease of $P/Y$, therefore, can be expected from appearance of a divided flow. $P/Y$ gets lowered more remarkably as $\delta$ increases in Fig. 8(b), but it is enlarged rapidly as the relief-hole is shrunk through the depression and approaches its complete closure.

But, $P/Y$ gets lowered in the same way as in the process R.A. while a passive filling up proceeds, and it decreases monotonously as $D_{LO}$ increases. The tendencies mentioned above are confirmed to appear usually independently of variations of $f$.

From the above, it follows that if a divided flow can be realized, the process utilizing this flow will be available for the purpose of decreasing working pressures. This is thought to be very important from the viewpoint of maintenance of tool-life, too.

Then, the characteristics of the processes R.A. and R.H. are confirmed by comparing them with each other. The former has been used in actual production fields $P/Y$, but the latter is proposed anew in this report.

Figure 8 shows each fractional mean working pressure $P/Y$ required for the percentage $\delta$ of the filled up volume, where $\delta$ is supposed to be 87 or 94% and $D_{LO}$ denotes the initial diameter of the relief-axis or the relief-hole.

In the process R.A., $P/Y$ gets only a little lower than that in the process C.D. (shown as $D_{LO}:D_{mm}$) when $\delta$ is set equal to 87%, but it gets lowered much more when $\delta$ is changed to 94%. This process, therefore,
comes to be available evidently. Here, \( D_{lo} \) minimizing \( F/Y \) exists usually for each value of \( \delta \) and this value of \( D_{lo} \) gets larger as \( f \) increases. This must be noted as the optimum diameter of the relief-axis, because it minimizes the working pressure.

In the process R.H., the optimum diameter of the relief-hole corresponding to the former does not exist and \( F/Y \) gets lower monotonously as \( D_{lo} \) increases. This appears usually independently of variations of \( \delta \). \( F/Y \) in this process, therefore, can be made continuously lower than that in the process R.A. The process R.H., therefore, is expected to be more preferable than the process R.A. This means that the former is proved to be more effective than the latter in applying die forging utilizing the divided flow.

Working pressures are generally considered enlarged as friction coefficients of lubricants used increase, but this way of thinking does not seem usually valid as shown in Fig. 9(b). Here, influence of \( f \) on \( F/Y \) in each process is examined carefully. Figure 10 shows the case in the process R.A., where \( f \) is supposed to be zero or 0.3 or 0.577 and \( D_{lo} \) is set equal to \( 8 \) or 16mm. \( F/Y \) grows larger monotonously as \( f \) increases in Fig. 10. This is weakened more by larger values of \( D_{lo} \).

Figure 11 shows the case in the process R.H., where \( D_{lo} \) is set equal to \( 8 \) or 16mm. \( F/Y \) grows larger as \( f \) increases while \( \delta \) is smaller, but this tendency begins to decline gradually and disappears as \( \delta \) gets larger than a certain value, and a reverse tendency comes to appear anew. This reversal occurs earlier as \( D_{lo} \) gets smaller.

Figure 12 shows the diameter \( Dp \) of a deformed relief-hole and the worked height \( 2h \) of the material during the depression in

\[ F/Y \]

(a) When the value of \( \delta \) gets up to 87%

(b) When the value of \( \delta \) gets up to 84%

Fig. 9 Fractional mean working pressure \( F/Y \) required for percentage \( \delta \) of filled up volume

Fig. 10 Fractional mean working pressure \( F/Y \) in the process R.A.

Fig. 11 Fractional mean working pressure \( F/Y \) in the process R.H.
the process R.H., where $D_{10}$ is set at $a_{mp}$. The following relations can be expected to hold in comparing Fig. 12 with Fig. 11. The difference in $2q_{1}$ is not perceived so distinctly with variations of $f$ while $\delta$ is smaller, and this gives rise to the relation that $F/N$ gets enlarged as $f$ increases. Its difference gets remarkable with variations of $f$ while $\delta$ is larger and this gives rise to the relation that $F/N$ gets lowered as $f$ increases. In other words, an increase of $f$ can be considered to promote an increase of the friction force, and at the same time, to suppress a decrease of $2q_{1}$. In case the latter is more effective than the former, the reversal shown in Fig. 11(b) can be easily expected. The increase of $f$, moreover, makes $2h$ larger. This causes the reversal to appear earlier. Therefore, influence of the friction on working pressures is supposed to be somewhat different in each of the processes.

The height $2h$ of flange portion of the products in these processes is examined next. Figure 13 shows the height $2h$ when $\delta$ reaches to 94%. $2h$ in the process R.A. is usually larger than that in the process R.H. in Fig. 13—that is, the former enables $\delta$ to be reached earlier than the latter does. Variation of $F/N$ can be found to correspond to that of $2h$ by comparing Fig. 13 with Fig. 8(b). In other words, the larger decrease of $F/N$ in the process R.H. can be considered to be obtained through smaller values of $2h$ or through the loss of the material height. Moreover, $2h$ gets larger as $f$ increases. The height of products finally obtained is important for saving materials. The process R.A., therefore, is expected to be more effective for this purpose than the process R.H.

Then, in case these processes are considered applicable to the working of such products as gear etc. and the materials are expected to flow actively into the parts of even tooth form, a single centrifugal flow alone has no effect, but an active flow with centrifugal components is required. This means that the divided flow needs to be rationalized.

Figure 14 shows the marginal percentage $\delta$ of the filled up volume preserving the divided flow. $\delta$ in the process R.H. is larger than that in the process R.A. in Fig. 14. Moreover, the zone preserving the divided flow gets larger as $f$ increases. The former, therefore, can be expected to be more useful than the latter from this viewpoint, too.

4. Conclusions

In view of the former success in the precision die forging of ‘spur gear with boss’, the die forging process utilizing a divided flow may be expected to be available and useful. In order to examine this, the principles of the flow relief-axis and the relief-hole are taken up and the filling up behavior in a barreled disk specimen is analyzed theoretically by means of the upper bound theory. Based on the results of the analysis and the calculation, the following conclusions are drawn:

(1). The processes utilizing the relief-axis principle and the relief-hole one realize a divided flow and save more of the working load and the pressure required for the filling up of the material, than the process without these principles. This, therefore, makes the process utilizing the divided flow more preferable for the precision die forging.

(2). The reduction of the working pressure can be expected only in the case of realizing the divided flow or the single centrifugal flow. The process with the relief-axis principle has an opti-
mum diameter minimizing the working pressure. The process with the relief-hole principle has no optimum diameter and the working pressure is reduced monotonously to less value than that in the former as the initial diameter of the relief-hole gets larger. This suggests that the process with the relief-hole is more useful than that with the relief-axis for reducing working pressures. The latter, however, gives larger thickness to the product than the former, which suggests that the latter will be more effective for saving materials.

(3). The process with the relief-hole can make the marginal filling up ratio enabling the divided flow larger than that with the relief-axis. This means that the former is more useful than the latter for the working of products which have various projections around the outside.

(4). The influence of friction on the filling up behavior in each of the processes is almost the same, but occasionally, different under conditions of the relief-hole getting near to its closure.

References