Development of New Processes for Control of Internal Deformation and Internal Stress in Hot Free Forging of Heavy Ingots*

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Synopsis

For developing an optimum free forging process to close and consolidate internal cavities in heavy ingots by direct forging alone, internal deformation and internal stress were investigated with Plasticine models. First, a method to simulate the material behavior with the existence of a large temperature gradient was established. The forging processes used were the followings;

- 1) the conventional process which uses symmetrical upper and lower anvils
- 2) a process called the FM process in which the upper anvil is of the usual type but the lower anvil is flat and larger than the dimension of the material to be forged
- 3) a process called the FML process—where the lower anvil is the same as that of the FM process and the upper anvil is smaller than the dimension of the material to be forged
- 4) the so-called JTS forging process which uses the same combination of anvils as that of the FML process and is carried out with a large temperature gradient in the material.

Among these processes, the conventional process can effectively cause a large deformation rate at the center and the use of wide anvils in any process is also effective for a large deformation even without a temperature gradient in the material. For attaining compressive stress, that is, a higher hydrostatic stress at the center, it is effective even without a temperature gradient to raise the value of the parameter w/h (w : width of anvil, h : height of forging material) or to carry out unsymmetrical reductions such as that in the FM process and the FML process. A tri-axial compressive stress state is considered to be effective for closing and consolidating the central cavities.

I. Introduction

In recent years, the size of ingots has become remarkably large in keeping up with an increase in the size of such forgings as rotor shafts for generators and steam turbines or ultra-heavy forged slabs to be rolled into thick plates for nuclear reactor pressure vessels. This increase in ingot size tends to result in a greater size of cavities referred to as loose structures,¹⁾ segregation and grain size. On the other hand, in large free forging process, it is often impossible to perform sufficient upsetting process or to give large forging ratio to ingots owing to the limitation of press load and size of products. Consequently, it is important to develop forging processes for improvement of internal soundness and cost reduction by solid forging alone with limited press capacity.

There are various experimental results, theoretical investigations and proposals of special processes available for forging of heavy ingots. However, the present techniques of the large free forging are based on the experiences of the practical operations rather than

theoretical and quantitative knowledges.

For example, the “JTS forging process” is intended to consolidate the loose structure, making use of a large temperature gradient between the surface zone and the center zone which forms during the cooling of a large material. But the effect of anvil arrangement and a temperature gradient in this forging process is not entirely evident.

On the other hand, the FM forging process mentioned in detail below has the benefit of being Free from Mannesmann effect. The tensile stress formed at the center (Mannesmann effect) in the case of symmetrical reduction of the upper and lower sides of the plate is avoided by employing unsymmetrical reduction in this process that leads to increasing the hydrostatic pressure at the center which tends to close and consolidate the loose structures effectively. With these points as background, and in order to find the stress-strain relationship and forging conditions necessary for effectively closing and consolidating the cavities under the restrictions encountered in practical manufacturing, the authors clarified the characteristics of internal deformation (strain) and internal stress in the conventional process and the foregoing FM, FML and JTS forging processes by using Plasticine models.

II. Experimental Procedure

1. Model Sample

White Plasticine was used as a normal forging material having no internal temperature gradient. Figure 1 shows the shape and size of model for material having a temperature gradient. In order to simulate the temperature gradient of about 300 °C which is formed when a large forging material is cool-

Fig. 1. Shape and dimension of Plasticine model for simulating material with a large temperature gradient.

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ed,²⁾ white Plasticine with high deformation resistance was used for the outer shell of the model and black Plasticine containing vaseline and having about one third the deformation resistance of the white one was used for the inner core.³⁾

2. Forging Process and Parameter w/h

Figure 2 shows forging processes used in the experiment. The conventional process is a usual method which uses symmetrical upper and lower anvils. An unsymmetrical reduction is carried out in a process called the FM process by using a usual upper anvil and a lower flat anvil which is larger than the material to be forged. A process called the FML process uses the same lower anvil as in the FM process, and an upper anvil whose width (w_2) is smaller than that of the material. The so-called JTS forging process²⁾ uses the same combination of anvils as the FML process and is carried out under a large temperature gradient in the material. The FML process was derived from the FM process so as to lower the press load of the FM process.

The four values 0.3; 0.4; 0.6; and 0.95 were adopted for the parameter w/h (w : width of the anvil, h : height of the material) in the conventional process and the FM process. The values $w_1/h=0.5$, $w_2/h=0.67$ (I) and $w_1/h=1.4$, $w_2/h=0.63$ (II) (cf. Fig. 2 (c)) were chosen for the FML process and the JTS forging process.

3. Measurement of Internal Deformation

The reduction rate (or reduction in height) and the deformation rate (or ratio) are defined as follows:

Reduction rate $r = (h - h')/h \times 100$

where, h , h' : height of the material before and after reduction.

Deformation rate $e = (t - t')/t \times 100$

where, t , t' : thickness of each layer before and after reduction.

The deformation rate in the direction of reduction was measured at each layer under the center of anvil after forging with reduction rate between 5 % and 20 %.

4. Measurement of Internal Stress and Load

The internal stress components in the ' x ', ' y ' and ' z ' directions were measured at specific locations

Fig. 2. Forging processes used in the experiment.

($1/4 h$, $1/2 h$, $3/4 h$) by a small sensor ($\phi 6 \text{ mm} \times t 0.6 \text{ mm}$) embedded in the Plasticine model as shown in Fig. 3. Simultaneous with these measurements, the load for reduction was measured by the Amsler type universal tester.

III. Experimental Results and Discussion^{3,4)}

1. Distribution of Deformation Rate and the Factors of Importance

1. Influence of Reduction Rate

Figure 4 shows the influence of reduction rate on the distribution of deformation rate in the conventional process. For example, in the case of $w/h=0.3$ the increase in reduction rate ' r ' from 5 to 20 % leads to an increase in deformation rate in each position but does not result in a change in the distribution pattern of deformation rate. The case of $w/h=0.6$ has also the same tendency as that of $w/h=0.3$.

In the same way, Figs. 5 and 6 show the influence of reduction rate on the distribution of deformation

Fig. 3. Locations and directions of stress sensor.

Fig. 4. Influence of reduction in height ' r ' on distribution of internal deformation ratio ' e ' in the conventional process.

rate in the FM process under uniform temperature condition and in the JTS forging process respectively. In all the cases the trend is the same as in the conventional process.

2. Influence of Parameter w/h

The influence of parameter w/h on the distribution of the deformation rate ' e ' in the conventional

process is shown in Fig. 7. The distribution of deformation rate between the upper and lower anvils is comparatively uniform for smaller w/h values but peaks sharply at the center with larger w/h values.

The distribution in the FM process is shown in Fig. 8. Irrespective of a temperature gradient, when w/h increases, the position of maximum deformation rate shifts from the outer shell in the reduction side (near $1/4 h$) to the center core and therefore the distribution of deformation rate becomes symmetrical. As w/h increases, the deformation rate becomes larger at the center.

Fig. 5. Influence of reduction in height ' r ' on distribution of internal deformation ratio ' e ' in the specimen with uniform temperature in the FM process.

Fig. 6. Influence of reduction in height ' r ' on distribution of internal deformation ratio ' e ' in the JTS forging process.

Fig. 7. Influence of parameter w/h on distribution of internal deformation ratio ' e ' in the conventional process.

Fig. 8. Influence of parameter w/h on distribution of internal deformation ratio ' e ' in the FM process.

3. Influence of Temperature Distribution

The influence of temperature distribution can be seen by comparing (a) with (b) in Fig. 8. In the smaller w/h (≤ 0.4), a temperature gradient causes the shift of the position of maximum deformation rate to the central region and the deformation rate at the center becomes large. But, in the larger w/h (≥ 0.6), the maximum deformation rate is present approximately at the center and is about 50 % irrespective of a temperature gradient. The temperature gradient is consequently of no effect in this case.

4. Influence of Forging Process

Figure 9 shows the influence of each forging process on the distribution of deformation rate. In the small w/h ($=0.3$) value, the deformation rate at the center in each forging process is almost the same. But, in the large w/h ($=0.6$) value, the deformation rate in the conventional process alone is large and the deformation rate in the other processes is almost the same.

The distribution of deformation rate in the JTS forging process which is carried out with a large temperature gradient in the material is almost the same as that in the FM process with a uniform temperature. Consequently, the internal deformation in the JTS forging process is considered attributable to the same unsymmetry of the geometrical arrangement between the material and the anvils as in the FM and FML

processes rather than the effect of a temperature gradient.

2. Deformation Rate at the Center

Due to the existence of loose structures particularly at the center of ingots, the deformation rate at the center is of the utmost importance. Figure 10 shows the influence of parameter w/h on deformation rate at the center in the three forging processes (reduction in height 20 %). The deformation rate at the center in the conventional process and in the FM process with a uniform temperature becomes nearly constant for w/h values larger than 0.6. The deformation rate in the conventional process is higher than that in the FM process for all w/h values. The deformation rate in the FM process with a temperature gradient becomes nearly constant for w/h values larger than 0.4 and the saturation value is the same as that with a uniform temperature.

It was found from the results mentioned above that in order to increase the deformation rate at the center, the conventional process among the three forging processes and the increase in w/h value rather than a temperature gradient are effective. But it is not evident from the present experiments alone if the large deformation rate is directly effective for closing and consolidation of loose structures. Therefore, it is necessary to investigate in detail, taking into account the below mentioned internal stress.

3. Distribution of Internal Stress

Figure 11 shows the internal stress at each location in the conventional process.

(1) In the case of $w/h=0.3$, the stresses at the center ($1/2 h$) in the 'x' and 'z' directions are tensions referred to as "Mannesmann effect" and the stress at the center in the 'y' direction is compression and is lower than that at $1/4 h$, $3/4 h$.

(2) In the case of $w/h=0.6$, the stress at the center in the 'x' direction is also tension, the stress in the 'y' direction is compression and is higher than that in the case of $w/h=0.3$ and the stress in the 'z' direction is converted into compression. The stresses at $1/4 h$, $3/4 h$ in the three directions are almost the same as those in the case of $w/h=0.3$.

Fig. 9. Influence of forging process on distribution of internal deformation ratio 'e'.

Fig. 10. Influence of parameter w/h on internal deformation ratio 'e' at the center in three forging processes (reduction in height 20 %).

Fig. 11. Internal stress at each location in the conventional process (uniform temperature).

Fig. 12. Internal stress at each location in the FM process (uniform temperature).

Figure 12 shows the stresses in the FM process.

(1) In the case of $w/h=0.3$, the compressive stresses at 1/4 h tend to be the highest in all three directions and those at 3/4 h to be the lowest, and therefore the stress values depend considerably on the positions. The tensile stresses exist only slightly at 1/2 h and 3/4 h in the 'x' direction.

(2) In the case of $w/h=0.6$, in the same way, the stresses at 1/4 h are the highest in all the directions and those at 3/4 h are the lowest. The tensile stress is caused only slightly at 3/4 h in the 'x' direction. As a result, the stresses at the center are compression in all three directions. The stress in the 'y' direction is the highest and the stresses in the 'x' and 'z' directions are nearly equal.

From the above-mentioned results, it can be seen that an unsymmetrical anvil arrangement as in the FM process causes the unsymmetrical distribution of the internal stresses. However, the high tensile stress such as in the conventional process does not occur at the center but the compressive stresses are readily obtained.

4. Stresses at the Center in the Three Directions and Factors Affecting Them

1. Influence of Parameter w/h

Figure 13 shows the influence of parameter w/h on stress component in three directions at the center.

(1) In the case of the conventional process, the

Fig. 13. Influence of parameter w/h on stress component in each direction at the center (uniform temperature).

Fig. 14. Influence of forging process on stress component in each direction at the center (uniform temperature).

stresses in the 'x' direction are tension for $w/h \leq 0.6$ and converted to compression for $w/h=0.95$ in all the reductions in height. The stresses in the 'y' direction are compression for all w/h values and tend to be higher compression for larger w/h . Those in the 'z' direction are tension for $w/h \leq 0.4$ and converted to compression for $w/h=0.6$.

(2) In the case of the FM process, the tensile stress occurs only slightly for $w/h=0.3$ in the 'x' direction but the stresses in the 'x' direction are converted to compression for $w/h \geq 0.4$. The stresses in the 'y' direction increase with an increase in w/h value but the differences in the stress values for the different w/h values are small. The stresses in the 'z' direction are compression even for $w/h=0.3$.

2. Influence of Forging Process

Figure 14 shows the influence of forging process on stress component in each direction at the center.

(1) In the case of $w/h=0.3$, the tensile stress occurs in the 'x' direction in both the conventional and the FM processes while the stress in the conventional process is considerably higher. The stresses in the 'y' direction are compression in both the processes but the compressive stress in the FM process is larger. Special attention should be paid to the fact that the stress in the 'z' direction is compression in the FM process but is tension in the conventional process.

(2) In (b), besides the stresses in the conventional and the FM processes for $w/h=0.6$, those in the FML processes I and II are also shown. The stress in the

' x ' direction is tension in the conventional process only. The stresses in the ' y ' direction are compression in any process, and the compressive stress in the FML process I is the largest and that in the conventional process is the smallest. The stress in the ' z ' direction is tension in the FML process II alone. The compressive stresses in the FML process I are the largest in all three directions.

3. Influence of Temperature Distribution

Figure 15 shows the influence of temperature distribution on stress component in the ' x ' direction which tends to be tension. The conventional process and the FM process for $w/h=0.3$ and the former process for $w/h=0.6$ produce the tensile stress with a uniform temperature but they tend to produce compressive stress in the presence of a temperature gradient. However, the FM process for $w/h=0.6$ and the FML process I produce the compressive stress irrespective of temperature distribution. Consequently, the formation of the compressive stress in the JTS forging process is considered to be more strongly affected by an unsymmetrical geometrical arrangement between the material and the anvils than by the effect of temperature gradient.

5. Characteristics of the Stress State at the Center

Figure 16 shows types of characteristic stress state at the center in each forging process. As the value of w/h is raised from 0.3 to 0.6, the stress state is converted from uni-axial to bi-axial compression in the conventional process, while from bi-axial to tri-axial compression in the FM process. Accordingly, a higher hydrostatic compressive stress is more readily attained by the FM process than the conventional one and by raising the ratio w/h .

It is necessary to investigate in further detail what stress state is effective for closing and consolidation of the cavities. The forging process which forms the tensile stress may cause to open the once closed cavities by alternate reductions in two mutually perpendicular directions. It is considered to be necessary at least to obtain the state in which the tensile stress does not occur at the center, that is, the tri-axial compressive stress state.

IV. Conclusion

In order to develop the forging processes which effectively close and consolidate the loose structures in large ingots, the internal deformation and the internal stress in hot free forging were investigated and the following conclusions were made.

(1) The internal deformation is more strongly affected by the geometrical factors such as the parameter w/h and anvil arrangement rather than by a temperature distribution in the material.

Fig. 15. Influence of temperature distribution on stress component in the ' x ' direction at the center.

Fig. 16. Types of characteristic stress state at the center.

(2) The conventional process for $w/h=0.95$, the FM process for $w/h \geq 0.4$ and the FML process I may produce the tri-axial compressive stress state at the center, that is, a higher hydrostatic component even without a temperature gradient in the material.

Hereafter, it is considered to be necessary to investigate in more detail the relationship between the deformation of cavities and both the internal deformation and the internal stress.

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