Staggered Anvil and Rotation Processes for Refining and Homogenizing Centimeter-Scale Grains during FM Forging of Superheavy Ingots

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Typically, the microstructure of superheavy ingots weighing more than 300 tons consists of centimeter-scale grains. In this study, a forging method for refining and homogenizing such grain structure is proposed on the basis of modeling and simulation results. After a superheavy ingot has been subjected to a single deformation process during FM forging, different areas of the ingot exhibit variations in the degree of deformation and microstructure. The critical value of the equivalent strain for obtaining a fine-grained structure (~30 µm) was calculated to be 0.16; on the basis of this, the staggered anvil process was designed in order to improve the deformation uniformity in the meridian plane of heavy forgings. Given that traditional rotation processes usually result in inhomogeneous deformation distributions in the cross-sections of heavy forgings, the quantitative relationship between the rotation angle and the reduction ratio was determined. This was done with the view of improving the rotation process to solve the problem of uneven deformation distribution close to the surfaces of heavy forgings. Using the improved rotation process should ensure a uniform microstructure across the entire cross-section.

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Keywords: heavy forgings, coarse grains, forging process, staggered anvil process, rotation process

1. Introduction

During the casting process, defects such as shrinkages, pores, non-metallic inclusions and segregation inevitably exist in heavy ingots due to solidification characteristic. Specifically, such defects become increasingly problematic as the weight and size of the heavy ingots increase to an ultralarge scale. For example, our previous study had confirmed the grain structure of superheavy 30Cr2Ni4MoV steel ingots weighing more than 300 tons by dissection and metallographic analysis, which was found to comprise centimeter-scale columnar grains, equiaxed grains, and dendrites.1,2) This material is commonly used to fabricate low-pressure rotors for 1000 and 1400 MW advanced passive pressurized water reactors in China. Given that the mechanical properties of heavy forgings are directly attributable to their micro-structure, they can only be deemed suitable for use if the coarse grain structure of the steel can be suitably refined during forging.3–5) Furthermore, the dynamic recrystallization (DRX) behavior of 30Cr2Ni4MoV steel indicates that the final grain structure is closely related to deformation.6–8) Therefore, it is a major technical challenge to ensure that a uniform deformation and microstructure distribution are formed in heavy forgings.

Typically, forming and modification are the two main effects of forging process on the plastic forming of ingots, i.e., the obtainment of the final shape and size required for heavy forgings, but also the refinement of coarse grains and the elimination of metallurgical defects. At present, as the mature forging processes, the Free from Mannesmann (FM) forging, Japan Tefeno Shikano (JTS) forging, Asymmetric V-shaped Octagon (AVO) forging and Wide Die Heavy Blow Forging (WHF) are normally employed to fabricate heavy low-pressure rotors in China, among which FM forging is most commonly used. Based on the traditional forging process with top and bottom flat anvils, FM forging replaces the bottom flat anvil with a platform to generate a greater friction between the ingot and the platform, further resulting in an asymmetric deformation distribution in the ingot. The tensile stress in the ingot is therefore transferred from the center of the ingot to a region close to the platform, significantly improving the compaction of the center of heavy forgings. Extensive studies have shown that the anvil width ratio should be set as 0.6 with a reduction ratio ranging from 14% to 20% during FM forging to ensure a fine and compact internal quality formed in the heavy forging.3–11) However, our thermal simulation showed that after a single deformation was performed during the FM forging process, the specimen certainly exhibited an uneven deformation and microstructure distribution in either the cross-section or the meridian plane, which is considered detrimental to the mechanical properties of processed steels. Therefore, rational staggered anvil and rotation processes should be designed to improve the deformation and microstructure uniformity in heavy forgings.

2. Experimental Procedure, Simulation and Modeling

2.1 Experimental procedure

A 30Cr2Ni4MoV steel that is used in the commercial fabrication of rotors was selected for this study, with details of its composition given in Table 1. Cylindrical specimens were machined from this alloy to a diameter of 30 mm and a height of 45 mm, a size which was considered to contain a sufficient number of coarse grains for analysis. These specimens were pre-treated by heating to 900, 1000, 1100 or 1200°C and holding for 15 min, and were then FM forged with a reduction ratio of 15% and anvil width ratio of 0.6 to ensure complete DRX and to prevent an axial tensile stress.

Table 1 Composition of 30Cr2Ni4MoV steel (mass%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
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<td>0.01</td>
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<td>0.003</td>
<td>1.72</td>
<td>0.41</td>
<td>3.63</td>
<td>0.11</td>
</tr>
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</table>

*Corresponding author, E-mail: maqxdme@mail.tsinghua.edu.cn
from being generated.1,6,8) All the hot-deformed specimens were immediately quenched in water to retain the grain boundaries of the austenitized grains. Next, they were etched with a C6H12N2O7-H2O solution for metallographic observations after being cut along the longitudinal direction and polished mechanically.

2.2 Simulation and modeling
The material model of the 30Cr2Ni4MoV steel was constructed using Deform-3D, with the flow stress being expressed as $\sigma = \sigma(\dot{\varepsilon}, \dot{\varepsilon}, T)$.6,12) The boundary conditions were simplified and took into account only the heat transferred and the interfacial friction. For example, the environmental temperature was set as 20°C, while the coefficients of heat convection and transfer between the ingot, the environment, and the anvil were set as 0.02 W/(m²·K) and 11 W/(m²·K), respectively. A shear friction model with a friction coefficient of 0.7 was selected to describe the interaction between the ingot, the anvil, and the platform. A three-dimensional model of the ingot was constructed with a height of 4500 mm and a diameter of 3000 mm. The other conditions were the same as those for the thermal simulation.

The specimens used for modeling were machined from forged pure lead; the coordinate grid method was used to calculate the strain after plastic deformation.13) The experimental procedure was as follows. First, a lead specimen, which had a height of 60 mm and diameter of 45 mm, was cut along the meridian plane. Next, square grids with a length of 2 mm were depicted over the entire meridian plane of the specimen. The two separated halves of the specimen were then bonded with Wood’s metal. The bonded specimen was then FM forged using a universal material testing machine. Finally, the deformed specimen was cut again along the previously bonded meridian plane. The changes in the grids were scanned during the post-forging process.

The finite element model of the FM forging process is shown in Fig. 1(a), and the distribution of the grids used for modeling after plastic deformation is presented in Fig. 1(b).

3. Result and Discussion

3.1 Uneven deformation and microstructure distribution during FM forging
It can be seen from the specimen deformed at 900°C that after a steel specimen has been subjected to a single deformation process during FM forging, it exhibits an uneven deformation distribution in either the cross-section or the meridian plane, as shown in Fig. 2; here, region I represents the rigid region, whereas regions II and III are the large-deformation region and the low-deformation region, respectively. Although each region has undergone a similar change in temperature, there is a disparity among the grain structures of regions I, II, and III, owing to the difference in their degrees of deformation, as shown by the metallographic images in Fig. 2. In terms of grain morphology and size, region I has a larger average grain size (~120 µm), with a nonuniform number of sites being occupied by the small-sized and large-sized grains. This can be explained by the fact that there is almost no deformation of the rigid region (region I). Therefore, it does not undergo DRX. Hence, the original coarse, as-cast grains are crushed because of the austenite transformation but do not undergo refinement. Region II is located in the large-deformation zone, which has a fine and uniform grain structure with an average grain size of 30 µm after forging, illustrating that the degree of deformation in this region is sufficient to induce complete DRX. The microstructure of region III is characterized by large-sized grains surrounded by a number of fine grains, as the degree of deformation of this region is near the critical strain level at which DRX is initiated. At this level, dynamically recrystallized grains nucleate preferentially at the grain boundaries of the original grains. After the steel specimens have been forged, their mechanical properties are expected to have a uniform distribution. However, different areas of the specimens exhibit variations in the degree of deformation and microstructure after the individual specimen is subjected to a single deformation process during FM forging. Staggered anvil and rotation processes should therefore be employed during FM forging in order to improve the performance of the thus-produced heavy forgings and to ensure that they meet industry requirements.

3.2 Critical value of the equivalent strain for a fine-grained structure (~30 µm)
To display the simulation and modeling results, a plane coordinate system was established along the meridian plane of the ingot, as show in Fig. 3. The center of the ingot was selected to be the origin of coordinate system. The coordinates of the four points intersected by the axial and radial lines of the ingot passing through the origin with the ingot boundaries were (0, 0.5), (0, −0.5), (−0.5, 0), and (0.5, 0).
The distributions of the equivalent strain along the $x$- and $y$-axes after forging at a reduction ratio of 15% are shown in Fig. 4. The magnitudes of the equivalent strains in I, II, and III, which corresponded to the three regions in Fig. 2, differed markedly, illustrating that the uneven distribution of deformation was caused by the single deformation process employed for FM forging. Moreover, the coordinate interval covered by region II shows that a large deformation zone is formed deep in the center area of the ingot, indicating that FM forging results in the formation of uniform and fine grains at the center of the ingot as well as the grain structure seen in region II. However, the realization of such microstructure over a larger area in heavy forgings is dependent on the rational design of the staggered anvil and rotation processes of FM forging method. In order to determine the relationship between the magnitude of the equivalent strain experienced and the formation of a fine microstructure, we propose a weighted coefficient. The weighted average of the equivalent strain can then be calculated using eq. (1):

$$
\varepsilon_{\text{AVG}} = \frac{\sum_{i=10}^{10} a_i \varepsilon_{0.05i}}{\sum_{i=10}^{10} a_i}
$$

(1)

Fig. 2 Uneven deformation and microstructure distribution in the specimen subjected to a single deformation process during FM forging.

Fig. 3 Schematic for the plane coordinate system established along the meridian plane of the ingot.

The distributions of the equivalent strain along the $x$- and $y$-axes after forging at a reduction ratio of 15% are shown in Fig. 4. The magnitudes of the equivalent strains in I, II, and III, which corresponded to the three regions in Fig. 2,
where $\bar{\varepsilon}$ is the weighted average, $\varepsilon_{0.05i}$ ($i = 0, \pm 1, \pm 2, \ldots, \pm 10$) is the magnitude of the equivalent strain, whose $x$ coordinate is $0.05i$, and $a_i$ is the weighted coefficient, given that the settings and the magnitude of the equivalent strain obtained by simulation and modeling are shown in Table 2. The $\bar{\varepsilon}$ values calculated on the basis of the simulation and modeling results were 0.15 and 0.16, respectively; thus, the values were almost similar. Therefore, it can be concluded that the magnitude of the equivalent strain needed to ensure a fine microstructure ($\leq 30 \mu m$) in 30Cr2Ni4MoV steel is 0.16 or higher.

### Table 2: Magnitude of the equivalent strain along x-axis obtained by simulation and modeling.

<table>
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<tr>
<th>$i$</th>
<th>$x$ coordinate</th>
<th>$a_i$</th>
<th>$\varepsilon_{0.05}$ simulation</th>
<th>$\varepsilon_{0.05}$ modeling</th>
<th>$i$</th>
<th>$x$ coordinate</th>
<th>$a_i$</th>
<th>$\varepsilon_{0.05}$ simulation</th>
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### 3.3 Improved staggered anvil and rotation processes

The staggered anvil coefficient, $\delta$, is defined as follows:

$$\delta = \frac{\Delta W}{W}$$

where $W$ is the anvil width and $\Delta W$ is the overlap width of the anvil during two adjacent deformations (see Fig. 3). The adjacent deformation fields can overlap and further aid the generation of a uniformly distributed equivalent strain in the meridian plane of heavy forgings for a rational $\delta$. Figure 5(a) shows the distribution of the equivalent strain in the meridian plane of an ingot after it had been subjected to two adjacent deformations at a reduction ratio of 15% under different $\delta$ values. It can be seen from the distribution of the equivalent strain along the $x$-axis that the magnitude of the equivalent strain in the bulk of the ingot interior had reached the critical value 0.16, resulting in a fine-grained structure. However, as $\delta$ was increased, the uniformity of the equivalent strain distribution decreased. This was manifested in the increase in the standard deviation ($\sigma$) of the equivalent strain. Further, large $\delta$ values mean lower forging efficiency. Although the equivalent strain is usually distributed more uniformly under the $\delta$ of 0.0, both the simulation and modeling results show that defect on the surface of the ingot can form between the two adjacent anvils, as shown by the dashed circle in Fig. 5(b). Thus, the above-mentioned comparison and analysis suggest that the staggering anvil coefficient, $\delta$, should be approximately 0.3 in order to ensure a uniform distribution of the equivalent strain in the meridian plane of heavy forgings.

The traditional rotation process includes rotation by 90° and 180° (see the illustrations in Fig. 6). Both of these steps inevitably result in inhomogeneous deformation in the cross-sections of heavy forgings, with the areas closer to the outer surface exhibiting a more inhomogeneous deformation distribution, as can be seen from the simulation results in Fig. 6. A few small deformation regions are formed along with rigid regions (dashed circle), because of the friction between the anvil and the ingot; here, the magnitude of the...
equivalent strain is very different from the critical value of 0.16. These regions finally left at the edges and corners of the cross-section. The coarse grains present in these regions cannot be refined by DRX and thus differ significantly from the refined grains in the large-deformation regions, adversely affecting the mechanical properties of heavy forgings. A simple comparison of the 90°- and 180°-rotation steps shows that deformation distribution is a little more uniform in the later case, as can be seen from the standard deviation ($\sigma$) of the equivalent strain corresponding to the two rotation processes.

After the single-deformation process during FM forging, two large deformation regions (solid circle) and one small-deformation region (dashed circle) form in the area under the anvil. The angle, $\theta$, between the two intersecting lines connecting the large-deformation regions and the center of the cross-section of the ingot is defined as the divergence angle (see Fig. 7). The superposition of the small- and large-deformation regions generated by low and high deformations, respectively, takes place, preventing uneven deformation in the cross-section of heavy forgings, when a rational rotation process is adopted. Thus, the ingot should theoretically be rotated by an angle of $\theta/2$ before the next deformation. The relationship between the rotation angle and the reduction ratio can be expressed quantitatively on the basis of the simulation results, as shown in Fig. 8 and eq. (3):

$$\theta/2 = 1.37143\Delta H + 4.83334$$

where $\Delta H$ stands for the reduction ratio. The correlation coefficient used for data fitting was 0.97. The experimental results demonstrated that a reduction ratio of 15% is sufficient to induce complete DRX during the forging of 30Cr2Ni4MoV steel. During the rotation process, a single
deformation can be performed with a reduction ratio of 8%, because the pressure is applied symmetrically.

Using eq. (3), the divergence angle, $\theta$, corresponding to a reduction ratio of 8% was calculated to be approximately 30°. Thus, the rotation angle was set to 15° and the rotational frequency was set to 24 throughout the forging process. Based on the actual production, the traditional 180° rotation process (see the illustration in Fig. 6(b)) was employed in every four deformations such as the 1st thru 4th deformations, 5th thru 8th deformations, 9th thru 12th deformations, 13th thru 16th deformations, 17th thru 20th deformations, and 21th thru 24th deformations. Moreover, when the 4th, 8th, 12th, 16th, and 20th deformation was finished, the ingot had to be rotated by 15° before the next deformation, as shown in Fig. 9(a). Such rotation process was designed with a view of the superposition of the small-deformation regions and the large-deformation regions generated by subsequent deformations. However, during the simulation, it was found that when the fifth deformation was about to begin, after the specimen has been rotated by 15°, the contact points between the ingot and the anvil and those between the ingot and the platform were not in the same vertical line. This resulted in the ingot becoming unstable under the vertical pressure, as shown in Fig. 10. The high rotational frequency and the instability of the theoretical rotation process make it unsuitable for practical use, and the process needs to be improved.

After the 1st thru 4th deformations, the large-deformation regions (solid circle) and small-deformation regions (dashed circle) under the anvil are distributed with a $\theta$ of 30°, as shown in Fig. 11(a). When the 5th deformation is performed, in order to prevent the ingot from becoming unstable, the rotation angle should be set as 45°.

After the 5th thru 8th deformations have been made, the newly formed large- and small-deformation regions will also be distributed with a $\theta$ of 30°, as shown in Fig. 11(b). The
first eight deformations, eventually result in the formation of sixteen large-deformation regions and eight small-deformation regions, and the angle between two intersecting lines connecting two adjacent small-deformation regions and the center of the cross-section of the ingot will be 45°, as shown in Fig. 11(c). Assuming symmetric deformation, the rotation angle should be adjusted to 22.5° when the 9th deformation is about to begin. Meanwhile, to ensure the superposition of the previously produced small-deformation regions and the large-deformation regions generated by subsequent deformations, the reduction ratio should be adjusted to make the divergence angle, $\theta$, 45°. The corresponding reduction ratio will be approximately 12%, as calculated using eq. (3). Thus, after the 9th to 16th deformations, another eight large- and small-deformation regions will form, as shown in Fig. 11(d). They can be superposed with the deformation regions in Fig. 11(c) to eliminate the adverse effects of the small-deformation regions on deformation uniformity in the cross-section, as shown in Fig. 11(e). The rotational frequency of the improved process will reduce to 16. Details of the improved rotation process are shown in Fig. 9(b).

The improved rotation process was also simulated. The distributions of the equivalent strain corresponding to Fig. 11(a) and (c) were produced by the 1st thru 4th deformations and 1st thru 8th deformations, respectively, as shown in Fig. 12; these reflected the accuracy and feasibility of the design of the rotation process, which was based on the divergence angle. The final distribution of the equivalent strain and the hydrostatic pressure resulting from the improved rotation process is shown in Fig. 13. Compared to the deformation uniformity of the traditional rotation processes, the deformation uniformity resulting from the improved process was significantly higher, with the standard deviation ($\sigma$) of the equivalent strain significantly decreasing to 0.0176 and magnitude of the equivalent strain reaching the critical value (0.16) for forming fine grains; this was
particularly true for the deformation distribution in the areas close to the surface. Moreover, the stress in the interior of the ingot was compressive, which is more conducive to the elimination of casting defects, such as shrinkages and loose. Thus, using the improved rotation process should result in dense forging products with a uniform, fine-grained structure as well as uniform internal quality.

4. Conclusions

In this study, in order to refine and homogenize centimeter-scale grains ubiquitously existing in superheavy ingots during FM forging, we determined a method for optimizing the refinement process. The main conclusions of the study are as follows:

(1) When a steel specimen has been subjected to a single deformation process during FM forging, it certainly exhibits an uneven deformation distribution in either the cross-section or the meridian plane, further leading to the disparity among microstructures. The uneven deformation and microstructure distribution should be improved by rational staggering anvil and rotation processes.

(2) Through simulation and modeling, the critical value of the equivalent strain for generating a fine-grained structure ($\leq 30 \mu m$) was found to be 0.16. To ensure deformation uniformity and the formation of a fine-grained structure in the meridian plane of heavy forgings, the staggering anvil coefficient, $\delta$, should be approximately 0.3.

(3) The quantitative relationship between the rotation angle and the reduction ratio was determined. Further, on the basis of this relationship, the traditional rotation process was improved to solve the problem of uneven deformation distribution in the cross-sections of heavy forgings, particularly in the areas close to the surface.

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