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Dynamic recrystallization behavior of centimeter-scale grains during the forging process of superheavy ingots

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Typically, the microstructure of superheavy ingots consists of centimeter-scale grains. In this study, the dynamic recrystallization (DRX) behavior of such grains during forging was investigated. It was found that the centimeter-scale grains are refined by DRX mechanisms to various degrees, depending on the temperature. When forging is performed at 900°C, the nucleation mechanisms of DRX at 900°C are assisted by discontinuous dynamic recrystallization (DDRX) as well as the formation and development of subgrains, whose developing sub-boundaries divide the individual original grains into several fine grains. However, as the temperature increased to 1000°C, the final grain size increases significantly. The nucleation of DRX is manifested mainly as DDRX, but is also accompanied by twinning within the interiors of the original grains, contributing to the formation of new grains by means of transformation into grains with high-angle boundaries or nucleation through superposition.

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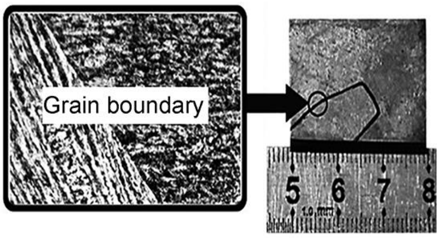
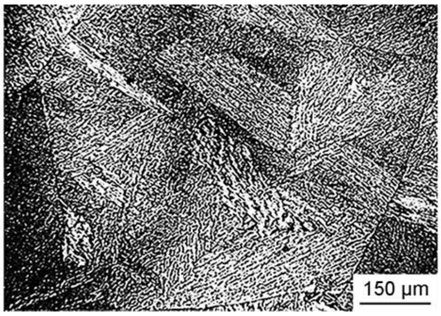
Keywords: Heavy forgings, Coarse grains, DRX

1. Introduction

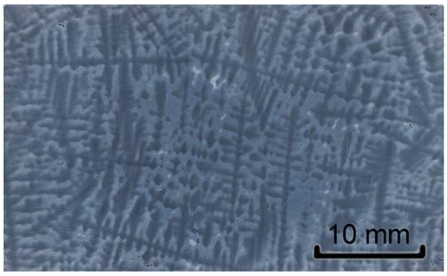
Although casting ingots are normally used as the initial blanks for heavy forgings, defects in such ingots, such as pores, shrinkages, and nonmetallic inclusions, become increasingly problematic as the weight of the ingots increases. The 30Cr2Ni4MoV steel (American grade: 3.5%NiCrMoV) is the material commonly used to fabricate low-pressure rotors in China. The heaviest ingots currently used to create low-pressure rotors for 1000 and 1400 MW advanced passive pressurized water reactors have weights of 500 and 715 tons, respectively. Further, products such as the largest low-pressure rotor in the world for nuclear steam turbines have been manufactured successfully with a weight of 300 tons and a cross sectional diameter of more than 3 m. In a previous study, we had investigated the microstructure of superheavy ingots by sectioning a 380-ton ingot, which was found to comprise centimeter-scale columnar grains, equiaxed grains, and dendrites (Fig. 1). This structure is considered detrimental to the mechanical properties of processed steels. Therefore, it is a major technical challenge to ensure that a uniform microstructure and deformation distribution are formed in heavy forgings after plastic deformation. In this study, we explored the refinement and DRX mechanism of such grains of superheavy ingots during forging.



(a) Columnar grain



(b) Equiaxed grain



(c) Dendrites

Fig. 1. Centimeter-scale grains.

2. Experimental

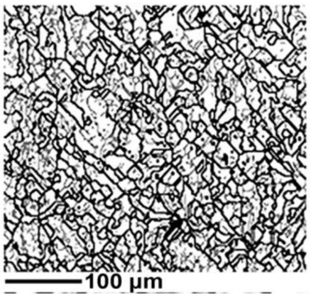
A commercial 30Cr2Ni4MoV rotor steel consisting of (in wt pct) 0.28 C, 0.02 Mn, 0.01 Si, 0.003 P, 0.003 S, 1.72 Cr, 0.41 Mo, 3.63 Ni, 0.11 V, and balance Fe was used in this study. Cylindrical specimens with a diameter of 30 mm and height of 45 mm were machined such that they contained a sufficient number of coarse grains.

In order to investigate the refinement and DRX mechanism of centimeter-scale grains during the forging process, these specimens were pretreated by being heated to 900, 1000, 1100, or 1200°C and being held at the respective temperature for 15 min. They were then forged at a reduction ratio of 15% and anvil width ratio of 0.6 to ensure complete DRX and to prevent an axial tensile stress from being generated [1-3]. 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 $C_6H_3N_3O_7$-H_2O solution after being cut along the longitudinal direction and polished mechanically. A few samples were subjected to electron back scattering diffraction (EBSD) analysis to reveal the nucleation mechanisms of DRX; these samples were prepared from the deformed specimens and were electrolytically polished in a 10%$HClO_4$+90%C_2H_6O solution. Further, a few of the samples were mechanically polished with a 0.3 μm paste and then double-jet electro-polished with a 7%$HClO_4$+93%C_2H_6O solution for use for transmission electron microscopy (TEM) observations. The electrolytic voltage and current were controlled to approximately 25 V and 0.08 A, respectively.

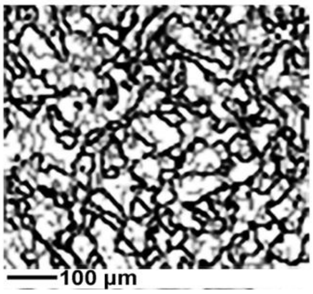
3. Results and discussion

3.1 DDRX nucleation mechanism

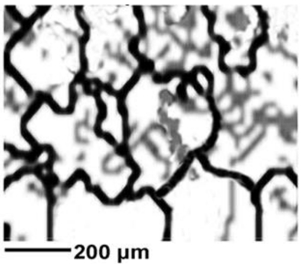
The phenomenon of DRX can be grouped into discontinuous dynamic recrystallization (DDRX) and continuous dynamic recrystallization (CDRX). DDRX is characterized by the migration of high-angle grain boundary, while CDRX involves the formation of subgrains and the rotation of these subgrains to form new grains by the absorption of dislocations, which leads to limited boundary migration and grain growth [4]. The conditions for the occurrence of these two types of DRX are closely associated with the temperature. EBSD maps illustrating the microstructures of the samples deformed at different temperatures are shown in Fig. 2. In these EBSD maps, the high-angle boundaries (>15°) are represented by bold black lines, whereas the low-angle grain boundaries (3–15°) are shown by thin black lines. It can be seen that the migration of the original high-angle grain boundaries induced by strain results in the bulging of the boundaries to varying degrees at each tested temperature. The higher the temperature, the more obvious the bulging of the grain boundaries; this was particularly the case for forging at 1200°C, which resulted in significantly serrated grain boundaries, as can be seen in the OM image of the microstructure in Fig. 3. Miura et al. have proposed that a number of nucleation steps are involved in DDRX [5-7]. During the early hot-deformation stage, grain-boundary shearing leads to the evolution of serrated boundaries. As the strain increases, the degree of misorientation of the dislocation sub-boundaries because of grain rotation increases gradually, resulting in the evolution of mid-angle sub-boundaries into high-angle sub-boundaries and the development of inhomogeneous local strain gradients along the boundaries. Consequently, the strain-induced sub-boundaries change to high-angle boundaries owing to the separation of the bulging part of the grains from the parent grains. This can be seen from the TEM illustration in Fig. 3 and is in keeping with the nucleation steps mentioned above. It can therefore be surmised that the nucleation mechanism of DRX during the forging of 30Cr2Ni4MoV steel includes DDRX.



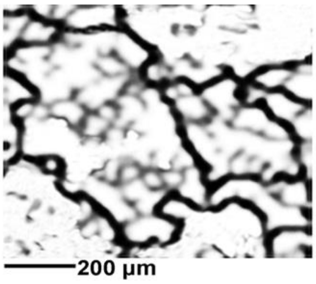
(a) 900°C



(b) 1000°C



(c) 1100°C



(d) 1200°C

Fig. 2. EBSD maps illustrating the microstructures after deformation at different temperatures.

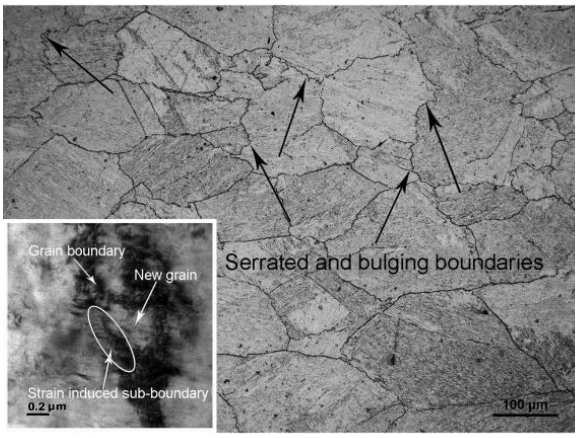
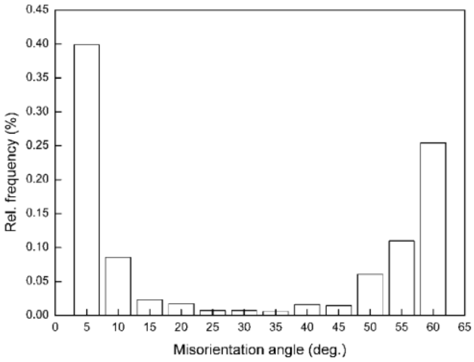


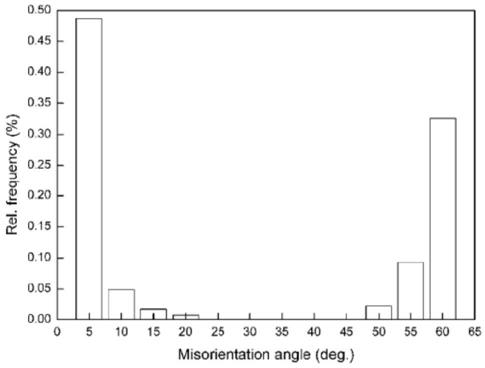
Fig. 3. OM and TEM images of the serrated grain boundaries formed at 1200°C.

3.2 Formation and development of subgrains at 900°C

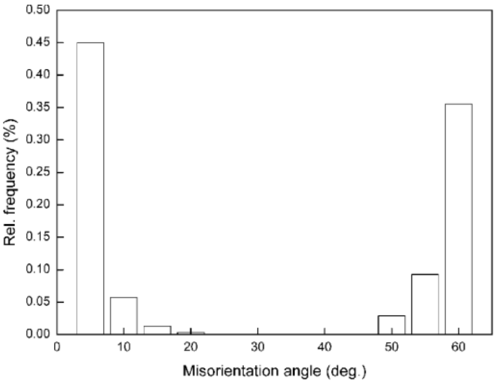
Fig. 2 also shows that low-angle subgrains form near the original grain boundaries and that a few high-angle boundaries exist in the interiors of the original grains, implying that CDRX occurs during hot deformation. When considered with the misorientation angle distributions in Fig. 4, it can be concluded that the DRX phenomenon that occurs at the tested temperatures is associated with the formation of low-angle boundaries. In particular, the relative number of subgrains with misorientation angles of 10–15° is higher at 900°C than at any other temperature. TEM analysis of the sample deformed at 900°C showed that a few developing subgrains formed within the original grain (see Fig. 5) and that these subgrains exhibited continuous growth along a specific direction until they subdivided the individual original grains into fine grains. The division of the original grains into smaller parts resulted from the variations in the local crystallographic orientations of the grains, owing to the strain incompatibilities between neighboring deformed grains. These subdivided parts gradually develop into new grains, and their boundaries can act as additional nucleation sites in the interiors of the original grains at higher strains [8].



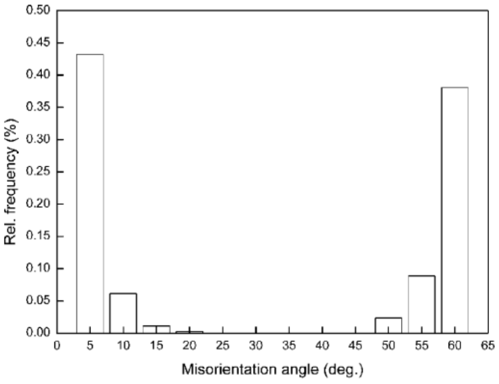
(a) 900℃



(b) 1000℃



(c) 1100℃



(d) 1200℃

Fig. 4. Misorientation angle distributions in the samples deformed at different temperatures.

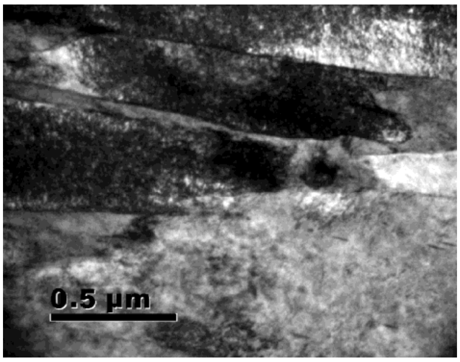
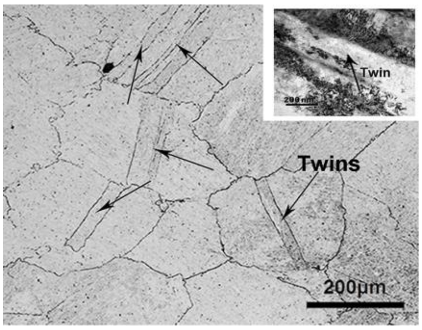


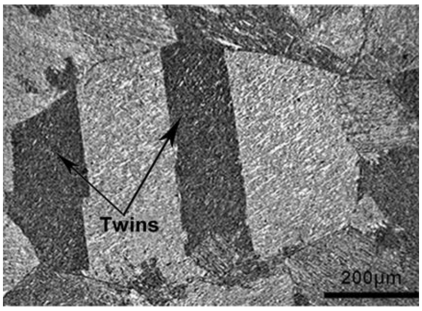
Fig. 5. TEM image of the developing subgrains at 900°C.

3.3 Twinning at 1100°C and 1200°C

It has been reported that twinning plays an important role during the nucleation process of DRX in materials with low stacking-fault energies [9-10]. It can been seen from Fig. 4 that the misorientation angle distribution of the high-angle segment exhibits a clear peak at an angle of approximately 60°; this peak corresponds to twin boundaries. Further, the peak value (approximately 0.35) corresponding to 1100°C and 1200°C is larger than for 900°C and 1000°C, implying that twin boundaries probably participate in the DRX nucleation of 30Cr2Ni4MoV steel at 1100°C and 1200°C. Further observations of the microstructure of the steel after forging at 1100°C and 1200°C confirmed that numerous twins were produced within the original grains, as shown in Fig. 6. It was seen in Fig. 3 that 30Cr2Ni4MoV steel exhibits high grain-boundary mobility during hot plastic deformation. The nucleation of the twins, owing to the higher grain-boundary mobility, was operated by the dissociation of an initial migrating grain boundary into an immobile coherent twin part, a mobile incoherent twin segment, and a low-angle boundary [11]. Subsequently, the twin boundaries transformed into random high-angle boundaries, owing to interactions between the mobile dislocations and the twin boundaries [8]. Furthermore, new grains can be generated by the superposition of the two twins, as shown in Fig. 7a [12-13]. A deformation twin is generated along *x* direction. As the strain increases, another twin is produced near the former one along *y* direction, and the two are superposed. The extent of superposition tends to increase with an increase in the degree of deformation, and a crystal nucleus is formed eventually. Fig. 7b shows that although superposition staggered by two twins along different directions certainly exists in 30Cr2Ni4MoV steel, new grains do not yet form, as the degree of deformation is not sufficiently high. However, nucleation owing to twinning makes little contribution to the refinement of the original grains. The final microstructure is characterized by coarse grains mainly caused by grain growth.

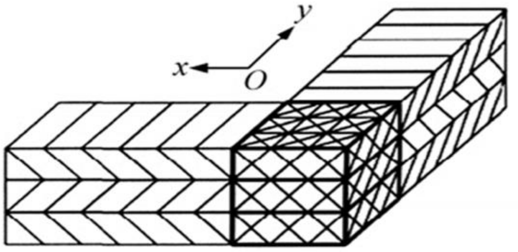


(a) 1100°C

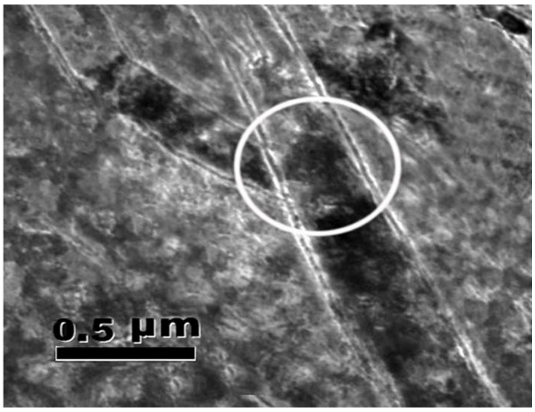


(b) 1200°C

Fig. 6. OM and TEM images of the twins formed at temperatures higher than 1000°C.



(a) Schematic for the nucleation by the superposition of the two twins



(b) TEM image of the superposition staggered by two twins in 30Cr2Ni4MoV steel

Fig. 7. New grains generated by the superposition of the two twins.

4. Conclusions

DDRX plays a predominant role in the DRX of 30Cr2Ni4MoV steel containing a centimeter-scale grain structure. Moreover, when forging is performed at 900°C, subgrains are likely to form within the original grains and eventually subdivide the original grains, resulting in the refinement of the microstructure. These subgrain boundaries also provide additional nucleation sites in the interiors of the original grains at higher strains. During deformation at 1100°C and 1200°C, twinning takes place in the original grains. The deformation twins are not only transformed into grains with high-angle boundaries, but are conducive to nucleation through superposition as well.

Acknowledgements

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