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Importance and role of grain size in free surface cracking prediction of heavy forgings

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ABSTRACT

The importance and role of grain size in predicting surface cracking of heavy forgings were investigated. 18Mn18Cr0.5N steel specimens with four different grain sizes were tensioned between 900 and 1100 °C at a strain rate of 0.1 s^{-1}. The nucleation sites and crack morphology were analyzed through electron backscatter diffraction analysis, and the fracture morphology was examined using scanning electron microscopy. The nucleation sites were independent of the grain size, and cracks primarily formed at grain boundaries and triple junctions between grains with high Taylor factors. Grains with lower Taylor factors inhibited crack propagation. Strain was found to mainly concentrate near the grain boundaries; thus, a material with a larger grain size cracks more easily because there are fewer grain boundaries. Fine grains can be easily rotated to a lower Taylor factor to further inhibit cracking. The fracture morphology transformed from a brittle to ductile type with a lowering of grain size. At lower temperature, small dimples on the fracture surfaces of specimens with smaller grain sizes were left by single parent grains and the dimple edge was the grain edge. At higher temperature, dimples formed through void coalescence and the dimple edge was the tearing edge. Finally, the relationship between the reduction in area, grain size, and deformation temperature was obtained.

1. Introduction

Free surface cracking occurs on surface undergoing free expansion due to compressive loads on contact surfaces between the tools and the workpiece [1]. This problem usually arises during the hot forming process of heavy forgings [2]. Once a free surface crack appears, the forging process should be paused and the crack removed. As a result, the hot working process is discontinuous and controlling the microstructure of the metal is difficult. In serious cases, the development of surface cracks results in termination of the forging process. Therefore, a defect-free surface is a prime requirement for the formation of valuable heavy forgings, such as 18Mn18Cr0.5N steel retaining rings [3], 316LN steel main pipes [4], and 8%Cr steel rollers [5]. However, it is difficult to propose a proper forging process through the trial manufacturing of heavy forgings because this is expensive and time consuming. If a free surface cracking criterion for heavy forgings can be established, the cracking behavior could be predicted conveniently, which would have important industrial implications.

Many valuable studies have been conducted on the cracking and fracture criteria for steels during the hot forming process. Lin et al. [6] reported that the fracture strain of 42CrMo steel is highly dependent upon temperature and strain rate at elevated temperature. A ductile damage model was established by combining the normalized Cockroft–Latham ductile damage model, strain rate, and temperature. Physical tests and numerical simulations indicated that this criterion was capable of predicting the fracture behaviors of 42CrMo steel during hot forging. Duan et al. [7] observed the damage evolution process of 316LN nuclear power main pipe steel during hot tension and established a relationship between the critical damage value, temperature, and strain rate by regression analysis. He et al. [8] analyzed the fracture behavior of 30Cr2Ni4MoV ultra-super-critical rotor steel and proposed a model by combining the Oyane's criterion and the effective strain as a function of the temperature and strain rate. Xia et al. [9] investigated the hot deformation behavior of 3Cr20Ni10W2 steel. A varying ductile fracture criterion characterized by a function of strain rate and temperature was defined. This criterion may be useful for predicting the fracture moment and position of 3Cr20Ni10W2 steel during hot forming. Most of these criteria were established by combining traditional criteria for cold forming and the deformation conditions.

Free surface cracking of heavy forgings is affected by a larger number of factors [3,10]. In addition to the deformation temperature and strain rate, grain size is an important factor that needs to

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be taken into account [11]. During the long preheating process, the surface layer grains are larger than the inner grains. Furthermore, the grain size at different surface sites varies because of the complex deformation process. The cracking behavior of heavy forgings is different from that of small- and medium-sized forgings.

The effect of grain size on dynamic recrystallization (DRX) behavior [12–17], hot ductility [11], and performances [18–22] has previously been reported. However, limited information is available on the effect of grain size on the fracture mechanism and free surface cracking prediction for heavy forgings, and on detailed relationship between the grain size and hot ductility. In this study, 18Mn18Cr0.5N steel specimens with four different initial grain sizes were tensioned. The nucleation sites and crack characteristics were observed and the fracture morphology examined. The main objective of this study is to reveal the importance and role of grain size in free surface cracking prediction for heavy forgings.

2. Experimental procedure

18Mn18Cr0.5N steel was melted in a vacuum induction furnace. After electroslag remelting, its chemical composition is shown in Table 1. Slabs were cut from the ingot and rolled at 1000 °C. The total strain in rolling was approximately 1.6. The rolled slabs were heat treated at different temperatures for different times to obtain a range of grain sizes. The grain size was measured using the line intercept method [23]. The rolled slabs were held at 1100 °C for 5 min, resulting in a microstructure with an average grain size of 28 μm. To obtain a larger grain size, the slabs were held at 1100 °C for 20 min, resulting in the formation of coarse grains (51 μm). After being held at 1100 °C for 2 h and at 1200 °C for 3 h, specimens with grain sizes of 106 and 177 μm were obtained, respectively.

Hot tensile specimens (Ø6 × 120 mm) were cut parallel to the rolling direction. Hot tensile tests were conducted on a Gleeble-3500 thermal/mechanical simulator. The specimens were preheated at a rate of 10 °C s^{-1} to 900–1100 °C. Thereafter, tensile tests were performed at 0.1 s^{-1}. The specimens were then deformed to a strain of 0.3–0.8. A gage length of 12 mm was used to determine the strain. Some specimens were tensioned to fracture, whereas others were not. The fracture surfaces were examined by scanning electron microscopy using a Hitachi S4800 instrument.

Unbroken specimens were sectioned parallel to the direction of tension. The observation area was situated in the center of the specimen in the necking region and the specimens were prepared as per ASTM E3 [24]. The sectioned specimen was ground using 100–1200 grit SiC paper followed by polishing with 3-, 1-, and 0.5-μm oil-based diamond slurries. Final polishing was carried out using a chemo-mechanical slurry with colloidal silica (0.02 μm) to achieve relatively flat surfaces free from damage caused during the previous mechanical polishing steps. The microstructures were observed using electron backscatter diffraction (EBSD) analysis with TSL-OIM-Analysis software. The spatial resolution was 0.15–3 μm and the misorientation detection limit was 1°. The crystal orientation maps displayed high-angle grain boundaries (misorientation ≥15°, shown as black lines) and twin boundaries (shown as white lines).

The grain boundary profile and differences in crystallographic orientation of the specimens after the hot tensile tests were plotted as inverse pole figure (IPF) maps, kernel average misorientation (KAM) maps, and Taylor factor maps. The KAM is a parameter indicative of the dislocation density. A Taylor factor is a geometric factor that describes the propensity of a crystal to slip (or not slip) based on the orientation of the crystal relative to the sample reference frame.

Table 1
Chemical composition of 18Mn18Cr0.5N steel.

Elements	C	Mn	Cr	N	Si	P	S	Al	Fe
wt%	0.11	18.46	18.5	0.54	0.71	0.02	0.01	0.01	Bal.

3. Results

3.1. Crack morphology

Fig. 1 shows the IPF maps of non-deformed specimens with different grain sizes. For each condition, all grains are equiaxial with random orientation.

Fig. 2 shows the results for the specimen tensioned at 900 °C to a strain of 0.3 with an initial grain size of 177 μm. In the SEM image shown in Fig. 2a, several small cracks with different orientations are apparent, as indicated by the arrows. For clarity, the cracks are shaded black in the corresponding IPF, KAM, and Taylor factor maps. In the IPF map (Fig. 2b), it can be seen that the elongation of grains is not obvious. Cracks mainly appear at grain boundaries and triple junctions and slip bands exist in some grains. In the KAM map (Fig. 2c), the lowest and highest dislocation density areas are marked in blue and red, respectively. It can be seen that the deformation is not uniform on the grain size scale. Although the strain is high in several grains, the deformation is mainly concentrated near grain boundaries. Fig. 2d shows the Taylor factor map. It is interesting to note that cracks arise mainly between grains with large Taylor factors. The larger the Taylor factor, the "harder" the grain. Cracks will form between "harder" grains, for which slip is less likely to occur.

Because the hot ductility increases with decreasing grain size, the strain is larger in specimens with finer grains. Fig. 3 shows the results for the specimen deformed at 900 °C to a strain of 0.45 with an initial grain size of 106 μm. It should be noted that the magnification is higher in this case than in Fig. 2. In the SEM image (Fig. 3a), fine cracks are apparent, as indicated by the arrows. It can also be observed that the parent grains are elongated to a small extent. Cracks are also mainly distributed at the grain boundaries and triple junctions (Fig. 3b). High KAM values appear near the grain boundaries (Fig. 3c). From Fig. 3d it can be seen that most of the cracks are between grains with large Taylor factors, which is similar to the case in Fig. 2d. In Figs.2 and 3, there are almost no newly formed cracks parallel to the tensile direction.

Fig. 4 shows the results for the specimen deformed at 900 °C to a strain of 0.55 with an initial grain size of 51 μm. Two cracks can be seen to have propagated nearly parallel to the direction of tension (indicated by red arrows). The elongation content of the grains is larger because of the larger bulk strain (Fig. 4b). The strain distribution (Fig. 4c) is more uniform than those in Figs. 2 and 3. As was the case for the specimens with larger grain sizes, cracks also appeared between grains with large Taylor factors (Fig. 4d). When a crack meets a grain with a lower Taylor factor, its propagation stops, which is quite a remarkable result.

Fig. 5 shows the results for the specimen tensioned at 900 °C to a strain of 0.55 with an initial grain size of 28 μm. Many finer cracks are apparent in the SEM image (Fig. 5a). Some cracks can be seen to have propagated parallel to the direction of tension (indicated by red arrows). From the IPF map (Fig. 5b), it can be seen that the newly formed DRX grains are located around elongated parent grains. The KAM values are low in these DRX grains (Fig. 5c).