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Effects of grain size on the microstructures and mechanical properties of 304 austenitic steel processed by torsional deformation

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ABSTRACT

In this paper, two grain sized 304 austenitic steel rods (coarse-grained steel with an average grain size of ~20 μm and ultra-coarse-grained steel with an average grain size of ~1 mm) were treated by pre-torsional deformation. Gradient microstructures with "dislocations → stacking faults → nanotwins" along the radial direction were formed in the ultra-coarse-grained specimen, and this type of gradient microstructures is beneficial to the mechanical properties. The results also showed that grain size affects the onset of twinning. Under the same strain the onset of twinning in the ultra-coarse-grained specimen was postponed compared to the coarse-grained specimen, and the postponed onset of twinning further affected the martensite transformation. This work showed that applying pre-torsional treatment on large grain sized structural materials is beneficial to the overall mechanical properties.

1. Introduction

High strength and excellent ductility are two vital targets for most structural materials, while the strength and ductility are generally a contradictory pair (Ritchie, 2011). Metals possessing gradient microstructures have recently attracted great attention due to their remarkable ability to produce a superior combination of strength and ductility (Fang et al., 2011; Wu et al., 2014a, 2014b). Until now, the gradient structures mainly include: (1) grain size gradient (Fang et al., 2011; Wu et al., 2014a,b; Zhang et al., 2003; Moering et al., 2016, 2015), (2) gradient grains with embedded twins (Wang et al., 2012, 2013) and (3) gradient of twin density (Wei et al., 2014). The most common and well studied gradient structure is grain size gradient structure (Fang et al., 2011; Wu et al., 2014a,b; Zhang et al., 2003; Moering et al., 2016, 2015), which often consists of nanocrystalline or ultrafine grains at the surface and coarse grains in the interior of a sample, and the grain size gradually transforms from nano-scale to micro-scale from the surface to the interior. The well-known strategies to introduce gradient structures include surface mechanical attrition treatment (SMAT) (Wu et al., 2016; Lu and Lu, 2004; Wang et al., 2006), surface mechanical grinding treatment (SMGT) (Fang et al., 2011; Li et al., 2008) and pre-torsional treatment (Wei et al., 2014; Guo et al., 2016; Wu et al., 2017). The SMAT and SMGT techniques are convenient for systematic investigations of gradient structures due to the gradients in strain, strain rate, hardness, grain size and hardening mechanisms throughout the deformed layer, and the gradient structures synthesized by SMAT and SMGT are relatively well characterized (Zhang et al., 2003; Lu and Lu, 2004; Tao et al., 2002; Wu et al., 2005, 2016; Zhou et al., 2008). On the other hand, the pre-torsional treatment with only pure shear strain does not induce any change in the shape and size of the sample, and the gradient strain along the radial direction leads to the gradient microstructures along the radial direction (Wei et al., 2014; Guo et al., 2016; Wu et al., 2017). However, the investigation on the effects of pre-torsional treatment on the microstructure and mechanical properties of metals is still limited. In this work, pre-torsional treatment was applied on a 304 austenitic steel to introducing gradient structure, in order to obtain high strength and good ductility simultaneously.

It is widely known that grain size is an important factor affecting the deformation mechanism of materials (Ni et al., 2011; Tian et al., 2015; El-Danaf et al., 1999; Gutierrez-Urrutia and Raabe, 2012; Zhu et al., 2012; Meyers et al., 2001). Ni et al. (2011) indicated that the grain size can affect the competition between twinning and detwinning in nanocrystalline metals. The effects of grain size on the microstructures and mechanical properties of many materials (Ni-Fe alloy (Ni et al., 2011), Cu alloy (Tian et al., 2015), steel (El-Danaf et al., 1999) et al.), ranging from nano-scale to micron-scale, were widely studied. However, it should be noted that the effect of grain size on the microstructures and mechanical properties of materials with the grain size being upper to millimeter was rarely reported. In addition, phase transformation might occur during the plastic deformation in some metals and affects significantly the mechanical properties (Zhao et al., 2017; Yang et al., 2014; Wu et al., 2005). For example, the γ → α' transformation in 304

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stainless steel can be induced by plastic deformation under various conditions of strain and strain rate at room temperature (Zhang et al., 2003; Murr et al., 1982; Shin et al., 2001; Cheng et al., 2008; Osman et al., 2017), while grain size effect on the phase transformation was also rarely studied. In this study, 304 austenite steels with two different grain sizes of ~20 μm and ~1 mm were chosen as the starting materials for torsional treatment. The grain size effect on the microstructural evolution and mechanical properties of 304 austenite steel after pre-torsional treatment were systematically investigated.

2. Experimental

The 304 austenitic steel was bought from the market with an average grain size of ~20 μm. Electrical discharge machine was used to fabricate the dumb-bell-shaped coarse-grained (CG) 304 austenitic steel specimens with the gauge length of 20 mm. To prepare the ultra-coarse-grained (UCG) 304 austenitic steel specimens, the dumb-bell-shaped specimens were heat treated at 1273 K for 10 h under high vacuum condition, followed by cooling in the water. The heat treated UCG 304 austenitic steel has an average grain size of ~1 mm. Torsional treatments were conducted using an MTS model 858 Mini Bionix II axial/torsional system with an angular loading rate of 1 revolution per minute (rpm) with the torsional degree of 45°, 90° and 180°, respectively. The tensile experiments were conducted using an Instron 3369 testing system with a tensile rate of $\sim 10^{-5}\ s^{-1}$. The EBSD analysis was performed using an FEI Quanta FEG 250 field emission gun scanning electron microscope (FEG-SEM) equipped with electron backscattering diffraction (EBSD, EDAX TSL). Samples for TEM investigation were prepared by twin-jet polishing technique with an electrolyte of perchloric acid (7%) and ethyl alcohol (93%) at a temperature of 243 K. Dual beam focused ion beam/scanning electron microscope (FIB/SEM, FEI 600i) method was used to prepared the TEM specimens of some special positions. TEM observation was carried out using a JEOL 2100F TEM operated at 200 kV. It should be noted that some grains with the size of tens of micrometers can be observed in the UCG specimens, but the proportion of the millimeter sized grains is significant larger than that of the grains with tens of micrometers. So the TEM observation for UCG specimens is choosing the millimeter sized grains.

3. Results

Fig. 1a and b shows the EBSD images of the CG and UCG specimens,

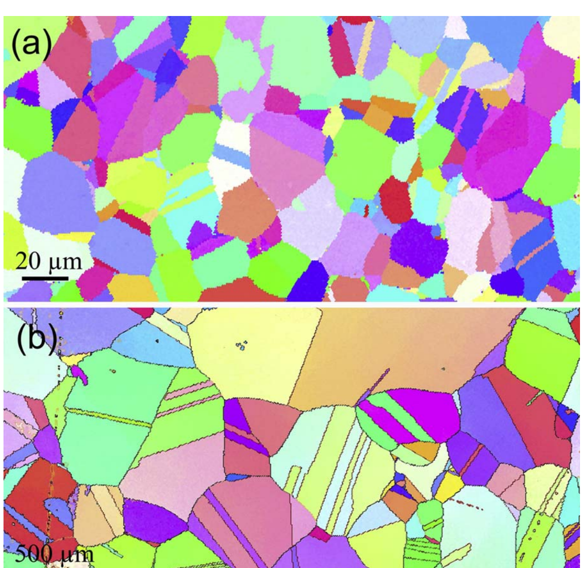

Fig. 1. The EBSD images of (a) CG and (b) UCG specimens before pre-torsional treatment.

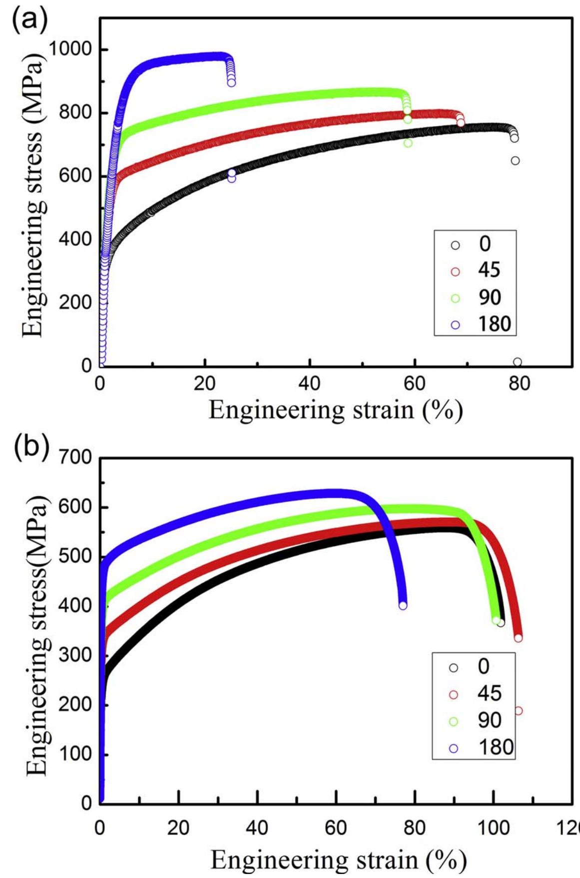

Fig. 2. The strain-stress curves before and after pre-torsional deformation of (a) CG and (b) UCG specimens.

respectively, before pre-torsional deformation. It can be seen that the initial average grain sizes of the CG and UCG specimens are ~20 μm and ~1 mm, respectively. Some twins were observed in the CG specimen, while a lot of annealing twins can be observed in the UCG specimen.

Fig. 2a and b shows the stress-strain curves of the pre-torsionally treated CG and UCG 304 austenitic steels, respectively. It can be seen from Fig. 2a that the CG 304 austenitic steel shows an obvious strength-ductility trade-off after pre-torsional treatment. The yield strength increases from ~390 MPa to ~970 MPa, while the engineering strain decreases from ~80% to ~25% after pre-torsional treatment for 180°. It can be seen from Fig. 2b that the pre-torsional treatment for 45° and 90° improves the strength and retains the ductility of the UCG 304 austenitic steel. With further increasing the pre-torsional degree to 180°, the yield strength further increases with the sacrifice of the ductility.

Fig. 3 shows the microstructural evolution of the CG (Fig. 3a–c) and UCG (Fig. 3d–f) specimens after pre-torsional treatment for 90°, where r/R indicates the position for TEM observation (R is the radius of the cross section of the specimen, r is the radius of the observed position). Fig. 3a–c shows the TEM images of the pre-torsionally treated CG specimen. In the region r/R ≈ 0 (see Fig. 3a), dislocations and stacking faults can be observed. In the region r/R ≈ 0.5 (see Fig. 3b), a high density of the stacking faults and nantwins can be observed. In the region r/R ≈ 1 (see Fig. 3c), the grains are refined to "strip-like" pattern and filled with nanotwins. It can be seen from Fig. 3d that dislocation pile-ups and planar slip dominate the microstructures in the region r/R ≈ 0 (central region in the specimen) in the UCG specimen. In the region r/R ≈ 0.5 (see Fig. 3e), a large number of the stacking faults and some dislocations can be observed, while the dislocation density is relatively low compared to that in the region r/R ≈ 0. In the