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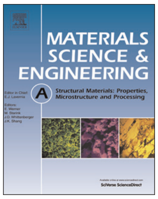

Comparison of strength–ductility combinations between nanotwinned austenite and martensite–austenite stainless steels

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ABSTRACT

Two types of austenitic stainless steel samples were prepared by means of dynamic plastic deformation followed by annealing: nanotwinned austenitic grains embedded in recrystallized austenite matrix and martensitic/austenitic duplex microstructures. Annealing at 923 K induced martensitic reversion while most nanotwinned grains are stable. An enhanced strength–ductility combination is observed in the annealed nanotwinned samples which exhibit a uniform elongation of ~21% and a yield strength of ~900 MPa, in contrast to a uniform elongation of ~12% with comparable strength in the martensitic/austenitic samples.

1. Introduction

Martensitic transformation and deformation twinning are two major competing mechanisms in plastic deformation of an AISI 304 austenitic stainless steel (SS). Strain-induced martensitic transformation (SIMT) dominates plastic deformation of cold-worked 304 SS at room temperature or below [1–5]. For example, martensite constitutes beyond 50% in volume for 304 SS under cold rolling at room temperature [1,2], and even as high as 80–100 vol% in the steel deformed by means of severe plastic deformation (SPD) techniques [3,4]. Introduction of a large amount of martensites can significantly enhance strength to a level of 1.4 GPa [5].

Recently, a novel strategy is proposed for strengthening austenitic steels by introducing nanotwinned austenite (nt-γ) grains which contain multiple twins with twin boundaries (TB) spaced in the nanometer regime [6–9]. These nt-γ grains are strong, ductile and elastically homogenous with the matrix. Moreover, they can co-deform homogeneously in conjunction with the surrounding matrix without generating notable strain localization near their interfaces at some tensile strains of ~5% [10]. Therefore, the nanotwinned austenitic steels exhibited an excellent combination of strength and ductility.

In the present work, a single phase nanotwinned/recrystallized duplex microstructured austenitic 304 samples (hereafter referred to as nanotwinned austenite 304 SS) and a dual phase martensitic/austenitic 304 samples (hereafter referred to as martensite–austenite 304 SS) were synthesized by means of dynamic plastic deformation followed by subsequent thermal annealing, respectively. The objective of this work is to compare the mechanical properties between these two types of samples.

2. Experimental

A commercial AISI 304 stainless steel with a composition of Fe–18.46Cr–8.28Ni–0.012Mo–0.049C–0.42Si–1.64Mn–0.003S–0.021P (wt%) is used in this work. The as-received samples were annealed at 1473 K for 2 h followed by air cooling to obtain fully austenitic coarse grains (averagely ~140 μm). The cylindrical samples were processed by using dynamic plastic deformation (DPD) at 77 K (liquid nitrogen temperature, LNT) and 423 K (Warm) to various strains, respectively. The DPD set up and processing parameters are described elsewhere [11]. Microstructure characterization was performed by using a FEI Nova NanoSEM 430 microscope and a transmission electron microscope (TEM) JEOL 2010 operated at 200 kV, respectively. Uniaxial tensile tests were performed on an Instron 5848 Micro-Tester system with a strain rate of 5×10^{-3} at room temperature. A contactless MTS LX 300 Laser extensometer was used to measure strain in the sample gage upon loading. The tensile specimens were cut into a dog-bone shape with a gage section of $5 \times 1 \times 0.5$ mm^3.

3. Results

3.1. Microstructure of the as-deformed martensite–austenite 304 SS

During the LNT-DPD process, plastic deformation of the sample is dominated by SIMT. Quantitative XRD analyses indicated that

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the LNT-DPD 304 sample (with $\varepsilon=0.3$) is composed of 80 vol% α'-martensite mixed with 7 vol% ε-martensite and 13 vol% residual austenite. As shown in Fig. 1a, the original austenite grain boundaries are still clearly identified. Numerous parallel strips are observed inside these grains, some of which are intersected with each other. TEM observations revealed that a few parallel strips with sharp boundaries are ε-martensite/austenite lamellae (see the selected area electron diffraction, SAED pattern). The ε-martensites are very fine and only several nanometers of thickness. And some α'-martensites nuclei formed inside the ε-martensite lamellae (circled in Fig. 1b). Alternatively, most of the other strips are α'-martensites which present regular-shaped blocks and are aligned as long laths, as shown in Fig. 1c. Statistical TEM measurements indicate that the average size of the α'-martenistes is ~100 nm. Only a few ε-martensites are survived in the α'-martensites region, as arrowed in Fig. 1c.

3.2. *Microstructure of the as-deformed nanotwinned austenite 304 SS*

Warm-DPD processing results in formation of multiple deformation twins in 304 samples. Specifically, XRD analyses indicated that the Warm-DPD 304 sample (with $\varepsilon=1.0$) is composed of only a single austenite phase without any martensite. The microstructure of this sample also contains a lot of parallel strips, as shown in Fig. 2a. These strips are proved to be high density nanoscale twins by TEM observations (Fig. 2b). Most nanotwins are parallel to each other in the form of bundles which are referred as to nt-γ grains. The nt-γ grains are quite large with sizes ranging from several micrometers to ~140 μm, constituting ~58% in volume by statistical TEM measurements. The twin/matrix (T/M) lamellae thickness is very thin, varying in a range from a few to 95 nm, with an average value of ~10 nm. High density dislocations exist at the TBs and inside the lamellae. In addition to the nt-γ grains, the remained microstructure is massive dislocation structures in the form of tangles, walls and cells (Fig. 2c), as usually observed in the deformed 304 SS [1].

3.3. *Microstructure of the annealed martensite–austenite 304 SS*

Subsequent isothermal annealing at 923 K resulted in massive martensitic reversion of the martensite–austenite 304 SS. XRD analyses indicated that the volume fraction of the α'-martensite dramatically dropped to ~17 vol% and the ε-martensite could not be detected in the martensite–austenite 304 SS annealed for 1 h. As shown in Fig. 3a, the parallel strips were inconsecutive and their boundaries were blurred. EBSD orientation maps of the austenitic phase (Fig. 3b) indicated that most of these strips were long austenite laths, which originated from the martensitic reversion. Most austenitic grains are very small, with sizes of only hundreds of nanometers.

3.4. *Microstructure of the annealed nanotwinned austenite 304 SS*

However, for the nanotwinned austenite 304 SS under the same annealing conditions, early recrystallization (SRX) is induced in the deformed structures, forming a hierarchical microstructure consisting of nt-γ grains mixed with SRX grains and dislocation

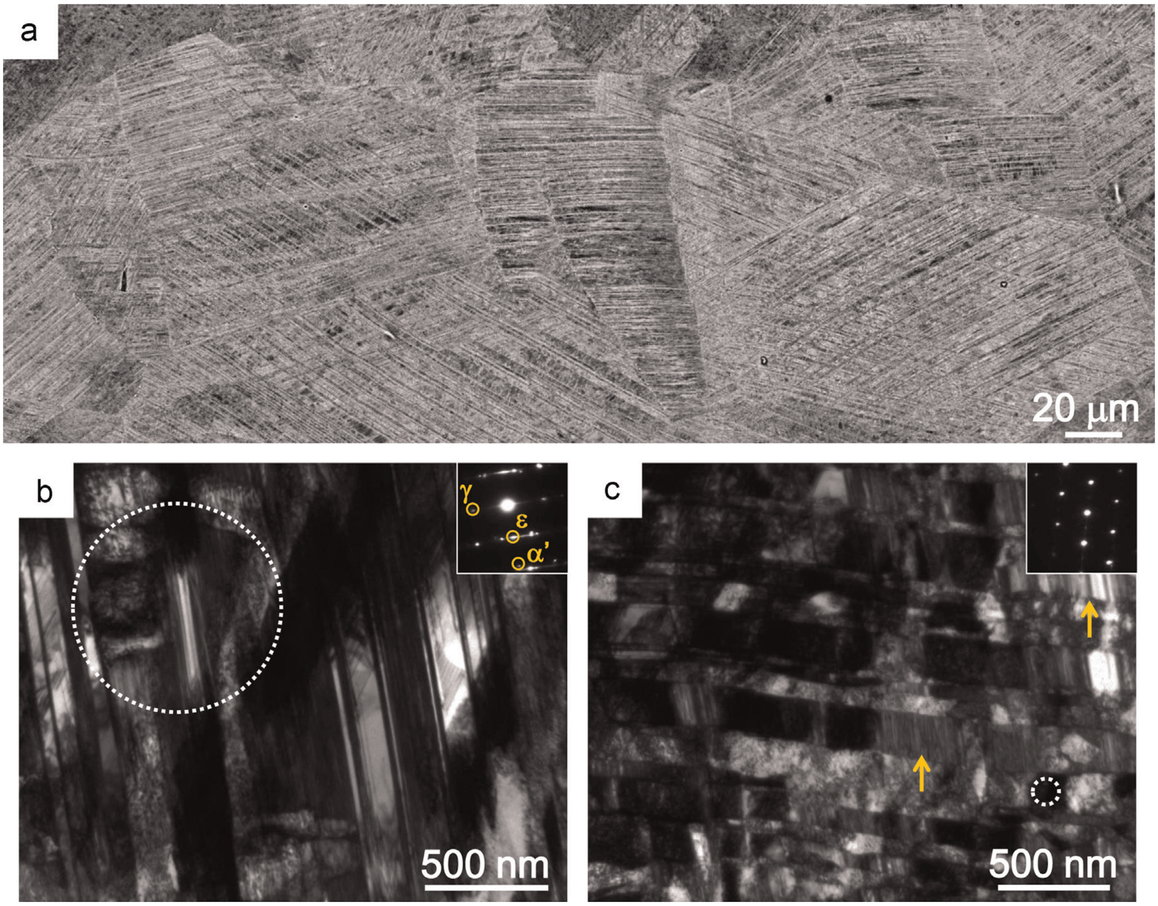

Fig. 1. Typical cross-sectional microstructures of the martensite–austenite 304 sample: (a) SEM-ECC image; TEM images of the: (b) austenite/ε-martensite lamellae and (c) linearly arranged α'-martensites. Insets show the corresponding selected area electron diffraction (SAED) patterns (circle). The arrows in (c) indicate the residual ε-martensites.