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Enhanced fatigue damage resistance of nanotwinned austenitic grains in a nanotwinned stainless steel

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ABSTRACT

The fatigue damage behavior of a novel nanotwinned stainless steel consisting of nanotwinned austenitic grains, nanograins and dislocation structures was investigated. It is found that the nanotwinned grains can effectively suppress the generation of persistent-slip-bands-like shear bands and nucleation of fatigue cracks in comparison with the other two deformed regions. Such better fatigue damage resistance of nanotwinned grains is mainly ascribed to the higher microstructural stability of them without obviously structural coarsening.

Grain refinement is an effective strategy to enhance the tensile strength and the fatigue property of materials. However, for some nanocrystalline and ultrafined metals and alloys produced by severe plastic deformation [1–3], it is found that the fatigue strength can be considerably improved in the high stress amplitude range, but the fatigue limit increases slightly or even remains essentially unchanged in comparison with that of coarse-grained (CG) counterparts. Such phenomenon is mainly correlated with their cyclic softening and strain localization, which originate from the microstructural instability due to grain coarsening and shear banding during the cyclic deformation [1,4]. Hence, improving microstructural stability plays a crucial role in reducing fatigue damage and achieving the comprehensive fatigue strength of materials.

Recent investigations [5,6] suggested that reducing the purity of elemental metals or alloying (such as adding Al to Cu) could stabilize the microstructure and suppress cyclic softening during cyclic deformation, thereby decreasing the fatigue damage and enhancing the fatigue limit. Besides that, it was recently discovered that nanotwinned metals produced by electro-deposition exhibited an excellent microstructural stability during cyclic deformation while maintaining an ultrahigh strength comparable to that of nanocrystalline metals [7,8]. Pan et al. [7] found that the majority of nanotwins within polycrystalline columnar-grained Cu were quite stable without notably thickening during cyclic deformation. These nanotwins can sustain some plastic strains in terms of the "zigzag" slip bands stemming from the activation of threading dislocations in the twin lamellae to release the stress/strain concentration, thereby retarding fatigue crack initiation and enhancing the fatigue limit.

Based on the nanotwin strengthening and stabilizing characteristics, we recently synthesized a novel nanotwinned AISI 316L austenitic stainless steel, i.e. introducing high density nanoscale twins into coarse grains (referred to as *nt*-γ grains) by means of dynamic plastic deformation (DPD) [9–11]. The mixed microstructure is mainly composed of *nt*-γ grains and severely deformed non-nanotwinned regions including dislocation structures and nanograins (hereafter referred to as DS/NG regions). The object of this work is to compare the fatigue damage resistance and microstructural stability between the *nt*-γ grains and the DS/NG regions in this nanotwinned 316L.

A commercial AISI 316L stainless steel with a composition of Fe-16.11Cr-10.00Ni-2.01Mo-1.43Mn-0.38Si-0.039P-0.012S-0.011C (wt%) is used in this work. The commercial steels were annealed at 1473 K for 1 h followed by water quenching to obtain a uniform austenitic structure with an average grain size of 65 μm (CG samples). Cylindrical CG samples with a diameter of 24 mm and a height of 10 mm were subjected to DPD treatments to a strain of 0.8 at room temperature (as-DPD- $\varepsilon = 0.8$). Details about the DPD facility set-up and processing parameters can be found in Ref. [10].

Uniaxial tensile tests with an initial rate of $5 \times 10^{-3}\ s^{-1}$ were performed on an Instron 5848 microtester system equipped with a contactless MTS LX 300 laser extensometer to measure the gauge ($5 \times 1 \times 0.5\ mm^3$) strain upon loading. The symmetrical push-pull (stress ratio $R = -1$) fatigue tests were performed on an Instron E3000 under the stress-control mode with a frequency of 20 Hz. Fatigue specimens were cut into a plate-type dog-bone shape with a gauge section of $5 \times 2.2 \times 2\ mm^3$. Microstructures were

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characterized by a scanning electron microscope (SEM) FEI Nova NanoSEM 430 with electron channeling contrast (ECC) imaging, and by a transmission electron microscope (TEM) JEOL 2010 operated at 200 kV.

After the DPD to $\varepsilon = 0.8$, high density nanoscale deformation twins were introduced into many coarse grains in 316L samples. As shown in Fig. 1a, these rhombic blocks (outlined) containing numerous parallel strips (i.e. nanoscale deformation twins by TEM observations (Fig. 1b)) are *nt*-γ grains. Most *nt*-γ grains, with sizes ranging from several micrometers to 100 μm, originate from the "cutting" of well-developed shear bands through the nanotwinned original coarse grains. Statistical TEM measurements indicate that these *nt*-γ grains constitute ~56% in volume and the average thickness is ~22 nm for the twin/matrix (T/M) lamellae. The other remained regions surrounding *nt*-γ grains are severely deformed non-nanotwin components consisting of dislocation structures and nano-sized grains (DS/NG regions). The dislocation structures are typical dislocation tangles, walls and cells (Fig. 1c), which are not uncommon in severely deformed metals and alloys [12,13]. Note that, as shown the dot line in Fig. 1a, some prior austenitic grain boundaries (PAGBs) are still clear due to the modest DPD strains.

The yield strength of as-DPD nanotwinned samples is as high as ~1186 MPa, as shown in Fig. 1d, nearly three times higher than that of CG samples. But the samples exhibit a very limited tensile ductility (with elongation to failure of ~9%) without obvious uniform elongation. Such mechanical property characteristic is commonly observed in many typical nanostructured samples after severe plastic deformation (SPD) [14,15].

After the stress-controlled fatigue tests, as shown the Wöhler S-N curves in Fig. 1e, both the fatigue life and the fatigue stress of as-DPD nanotwinned samples are much improved in comparison with that of CG samples. The fatigue limit (σ_f, i.e. the strength at a cycling lifetime $\geq 10^7$) increases to 425 ± 25 MPa, two folds of that of the CG samples. Such elevated fatigue strength might be mainly contributed to the pronounced increment of tensile strength (σ_{UTS}). Additionally, the fatigue ratio (i.e. σ_f/σ_{UTS}) is about ~0.35 ± 0.2, which is nearly identical to that in ECAPed 316L stainless steels [14].

To compare the fatigue damage resistance degree between the *nt*-γ grains and DS/NG regions, the surface morphologies of the as-fatigued nanotwinned 316L samples at the high $\sigma_a = 600$ MPa were investigated by SEM-ECC observations. As shown in Fig. 2a–c, surface damage in terms of stripped shear bands (SBs) developed both in *nt*-γ grains and DS/NG regions. Most SBs were approximately parallel accompanied by protrusions/intrusions, analogous to persistent slip bands (PSB) in single crystal copper, which were recognized as PSB-like SBs in nanostructured metals and alloys [4,5,16]. In *nt*-γ grains, most SBs are along twin boundaries (TBs) or intersect with TBs, extending over several to dozens of micrometers. Note that some intersected SBs are interrupted by TBs, as shown in Fig. 2b, confined into several twin/matrix (T/M) lamellae without obvious protrusions. While many small island-like regions containing PSB-like SBs distribute in the DS/NG regions surrounding *nt*-γ grains or PAGBs. These SBs are much more severe and intensive with remarkable protrusions and intrusions (Fig. 2c).

Statistical measurement of the surface undulation by confocal laser scanning microscope (CLSM) indicates that PSB-like SBs in *nt*-γ grains are shallow with the average height of 53 nm (Fig. 2d). Such height undulation is lower than that in DS/NG regions (averagely 73 nm, Fig. 2e). Moreover, over ~60% of PSB-like SBs regions occurred in the deformed matrix (mainly in dislocation structures). Hence, *nt*-γ grains exhibit a better resistant to the generating and propagation of PSB-like SBs in comparison with DS/NG regions in this as-DPD nanotwinned 316L samples.

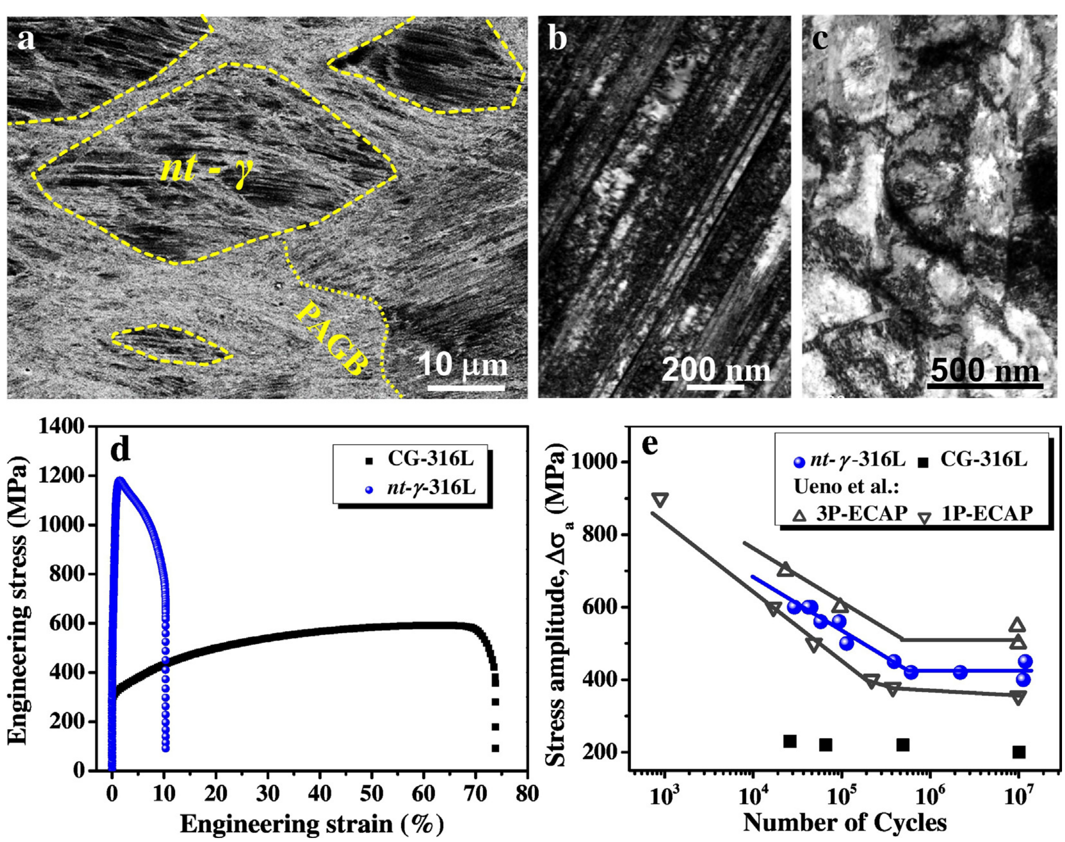

Fig. 1. (a) A typical cross-sectional SEM-ECC image showing *nt*-γ grains (outlined by dashed line) embedded in the severely deformed DS/NG regions in the as-DPD nanotwinned 316L samples. Prior austenitic grain boundaries (PAGBs, dotted line) are still clear. TEM observations of (b) nanotwins in *nt*-γ grains (c) dislocation structures in DS/NG regions. (d) Tensile engineering stress-strain curves and (e) stress amplitude-numbers of cycles (S-N) curves of as-DPD nanotwinned and CG 316L samples. S-N curves of 1passed and 3passed-ECAPed 316L samples are also included for comparison [14].