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Effect of kinematic stability of initial orientation on deformation heterogeneity and ductile failure in duplex stainless steel during uniaxial tension

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Abstract

The crystal plasticity finite element method (CPFEM) was used to investigate the effect of the kinematic stability of the initial orientations on the deformation heterogeneity and ductile failure of ferrite and austenite phases in duplex stainless steel (DSS) during uniaxial tension. The individual stress–strain relationships of ferrite and austenite phases in DSS were evaluated via in situ neutron diffraction in combination with the CPFEM. A CPFEM based on the volume elements (VEs) of a unit cell of DSS with a regular banded microstructure demonstrated that the kinematic stability of the initial orientations significantly affected the deformation heterogeneity and ductile failure in the constituent phases in VEs during uniaxial tension. The regions susceptible to ductile failure were identified as being in the austenite phase near the phase boundaries of ferrite and austenite.

Keywords: Neutron diffraction; Duplex stainless steel; Lattice strain; Crystal plasticity; Kinematic stability

1. Introduction

Duplex stainless steels (DSS) consisting of ferrite and austenite phases offer greater strength and higher resistance to stress-corrosion cracking than most other types of stainless steels, and are used mainly in desalination plants, heat exchangers and marine applications [1]. Conventional DSS mostly contain chemical compositions in the ranges of 18–26% Cr, 3–8% Ni, 2–5% Mo and 1–2% Mn (in wt.%) [1]. Recently, cost-effective lean alloy systems have been developed by replacing expensive Ni and Mo with Mn and N, with no degradation of their corrosion and mechanical properties [2–5]. The mechanical properties of DSS can be influenced by not only the deformation modes of constituent phases, i.e. ferrite and austenite, but also the volume fraction of constituent phases. While the plastic deformation of ferrite (α, body-centered cubic) is mainly dominated by dislocation slip due to the high stacking fault energy (SFE), the deformation mode of austenite (γ, face-centered cubic) changes from transformation-induced plasticity (TRIP) to twinning-induced plasticity and to a planar glide of dislocations as the SFE increases [6–8]. TRIP is known as a dominant mechanism of austenite in Mn–N-bearing DSS, which has a low Ni content (austenite-stabilizing element) [2–5,7]. Recently, detailed microstructural characterization of Mn–N-bearing DSS revealed that ε-martensite is distributed heterogeneously along shear zones in austenite grains. The volume fraction of ε-martensite increases with increasing strain, although after its formation it is quickly transformed further into α'-martensite. The α'-martensite zones are located at the

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intersections, particularly of those deformation bands that are indexed as ε-martensite [4].

Contrary to the austenite in Mn–N-bearing DSS, the deformation behavior of austenite in conventional DSS, in which phase transformation does not occur, is relatively easy to explain. However, in order to capture the micromechanical behaviors of the constituent phases in DSS during plastic deformation, the stress–strain relationships between constituent phases in DSS should be accurately evaluated. The stress–strain relationships between constituent phases in DSS have been evaluated using in situ neutron diffraction techniques in combination with self-consistent (SC) polycrystal models [9–12] or in situ, high-energy X-ray diffraction in combination with a crystal plasticity finite element method (CPFEM) [13].

In the previous studies on the in situ diffraction techniques for producing DSS [9], diffraction peaks for the ferrite and austenite phases were successfully fitted by using independent Gaussian functions with different widths and positions. The lattice strains in both ferrite and austenite phases were measured along the loading direction as a function of macroscopic stress. The hardening parameters used to describe the micromechanical behavior of the constituent phases were determined from the fitting of lattice strains. Moreover, SC polycrystal models based on the hardening parameters [10,11] were applied to simulate the rolling texture and grain-orientation-dependent stresses that are developed in the constituent phases in DSS during uniaxial tension. CPFEM [13] was used to investigate the lattice strain evolution of single grains embedded in the bulk of DSS during uniaxial tension. However, since the applied true strain in most in situ diffraction experiments has been limited to less than 0.06, the hardening parameters determined in the previous studies could not properly achieve a reliable prediction of the micromechanical behaviors of the constituent phases in DSS.

In the present study, the in situ neutron diffraction technique was used in combination with CPFEM to evaluate the stress–strain relationships of the constituent phases in DSS. Individual crystallographic orientations for ferrite and austenite phases in DSS were directly obtained from the three orthogonal sections of samples using an electron backscatter diffraction (EBSD) technique. The lattice strains for each phase were calculated by fitting the diffraction peaks of ferrite and austenite phases with independent Gaussian functions with different widths and positions during in situ tensile loading. A CPFEM based on representative volume elements (RVEs) was used to simulate the micromechanical behavior of DSS during uniaxial tension. The microscopic hardening parameters of each phase were determined by fitting the measured macroscopic stress and the response of lattice strains for each phase in the loading direction. Moreover, the determined microscopic hardening parameters for each phase were used to explain the influence of the kinematic stability of the initial orientation on the deformation heterogeneity and ductile failure of constituent phases in the volume elements (VEs) of unit cells with a regular banded microstructure of DSS during uniaxial tension.

2. Experimental procedure

2.1. Material and microtexture characterization

The commercial DSS used in the present study was 1 mm in thickness with a nominal chemical composition of 0.02C–0.4Si–1.5Mn–22Cr–5Ni–2.6Mo–0.17N (wt.%). In order to conduct the 3-D simulation on the micromechanical deformation behavior of DSS in the following section, we were obliged to measure the crystallographic texture of the constituent phases. An EBSD technique [14] was used to identify the crystallographic texture of the constituent phases in DSS. Instead of measuring the full 3-D microstructure with serial sectioning via a focused ion beam, microtexture measurements were conducted in the three orthogonal (RD (rolling direction), TD (transverse direction), and ND (normal direction)) sections in the center regions through the thickness direction. The measurement step size and the scanned area were 0.5 μm and 300 μm × 300 μm, respectively.

Fig. 1(a) and (b) show the ND inverse pole figure and phase maps of DSS, respectively, for the three orthogonal sections. The microstructure of the as-received sample consisted of ferrite and austenite phases in a discrete banded microstructure along the RD. The average volume fraction of the ferrite and austenite phases was about 54.8 and 45.2%, respectively. The average grain size of the ferrite and austenite phases was 8.99 and 4.44 μm, respectively. Fig. 2(a) shows $\varphi_2 = 45°$ sections of the orientation distribution function (ODF) for the constituent phases, as measured on the ND section. Assuming cubic–orthorhombic crystal-sample symmetries, the microtexture of the ferrite phase can be characterized as a near Rotated Cube (RC) texture component ($\{0\,0\,1\}\langle 1\,\bar{1}\,0\rangle$). The major texture components in the austenite phase can be identified as three orientations of Copper ($\{1\,1\,2\}\langle 1\,\bar{1}\,1\rangle$), Brass ($\{1\,0\,0\}\langle 1\,\bar{1}\,2\rangle$) and Goss ($\{1\,0\,0\}\langle 1\,\bar{1}\,1\rangle$) texture components. Fig. 2(b) and (c) show the $\varphi_2 = 45°$ sections of ODF for the constituent phases as measured on the TD and RD sections, respectively. The microtexture analysis indicated that the three orthogonal sections possessed a similar microtexture, with the exception of the intensity near the γ-fiber texture component ($\{1\,1\,1\}\langle \bar{1}\,\bar{1}\,2\rangle$) in the ferrite phase.

2.2. In situ neutron diffraction measurements and analysis

In situ neutron diffraction experimentation was conducted to determine the lattice strains in the constituent phases of DSS under uniaxial tension. Micromechanical deformation behavior in the constituent phases in DSS can be explained by the deep penetration capability of neutrons into most metallic materials and by the unique volume-averaged bulk measurement that is characteristic of a scattering beam [15]. A Residual Stress Instrument