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On the characteristics of substructure development through dynamic recrystallization

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Abstract

Substructure development in an austenitic Ni–30%Fe model alloy was investigated within a dynamic recrystallization (DRX) regime. The substructure characteristics of the deformed matrix and DRX grains were markedly different regardless of the grain size and orientation. The former largely displayed 'organized', banded subgrain arrangements with alternating misorientations, resulting from a limited number of active slip systems. In contrast, the substructure of DRX grains was generally more 'random' and exhibited complex subgrain/cell arrangements characterized by local accumulation of misorientations, suggesting multiple slip. The proposed mechanism of the unique substructure development within DRX grains suggests that the DRX nuclei, forming along pre-existing grain boundaries and triple points, essentially represent grain boundary regions, which experience multiple slip to preserve the compatibility with neighbouring deformed grains. This results in the formation of a complex cell/subgrain structure, which progressively extends as the grain boundary regions expand outwards during DRX growth.

Keywords: Dynamic recrystallization; Substructure; Austenite; Hot torsion; Crystallographic texture

1. Introduction

Polycrystalline metals undergoing plastic deformation can be considered to be composite structures consisting of grain interiors and grain boundary regions. In the grain interior the majority of slip is generally concentrated on a limited number of active slip systems for most grain orientations. This leads to the formation of specific families of planar extended dislocation walls, frequently aligned with the most active slip planes, constituting banded structures [1–4]. However, the requirement of maintaining strain compatibility between adjacent grains leads to the simultaneous activation of multiple slip systems in the vicinity of grain boundaries, which generally results in the formation of more complex, enclosed dislocation cells/subgrains [5–7]. The relative volume of the grain boundary region is a function of grain size, as well as the deformation conditions (i.e. temperature [5–7] and mode [8]). This results in a critical grain size, below which the grain boundary region extends over the entire grain and the enclosed cell/subgrain structure becomes the dominant feature of substructure development [5–8]. As the grain size increases, the dislocation cells/subgrains become progressively restricted to the vicinity of grain boundaries and the banded structure formed in the grain interior gradually becomes a widespread feature.

The experimental conditions have so far been limited to cases where the grain boundaries had limited mobility, although Kashyap and Tangri [6] employed 316L stainless steel containing boron to enhance grain boundary mobility at elevated temperatures. Nevertheless, the results obtained did not reveal any specific difference in substructure development compared with 316L steel without boron over a range of deformation temperatures from ambient to 700 °C [6]. However, a recent study on the hot deformation of an austenitic Ni–30%Fe model alloy within a dynamic recrystallization (DRX) regime [9] by the current authors has shown that there were distinctly different substructure

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characteristics in the deformed matrix and the DRX grains. While the former largely revealed a banded structure, the latter systematically displayed a complex substructure having a variety of subgrain/cell morphologies, even for grain orientations for which slip is expected to be highly concentrated on a single slip plane. The formation of DRX grains involves simultaneous grain boundary movement as straining proceeds. However, it is not clear whether boundary movement during the formation of DRX grains contributed to cell/subgrain formation or whether the finer DRX grain size obtained in Beladi et al. [9] was indeed in a range where multiple slip systems are activated throughout the entire grain.

The aim of the current study was to investigate the effect of grain boundary movement on the characteristics of substructure development within the DRX regime. Hence, different thermo-mechanical processing routes were employed to produce a range of DRX grain sizes at a given deformation temperature. The development of dislocation substructure was investigated using electron back-scattered diffraction (EBSD) in conjunction with transmission electron microscopy (TEM).

2. Experimental procedures

The composition of the alloy used in the present work was Ni–29.5 Fe–0.01 C–0.02 Mn (in wt.%). The alloy has a comparable stacking fault energy to austenite in pure iron and low carbon steels [10] and does not undergo any transformation on cooling, allowing characterization of the high temperature deformation structure in austenite [9,11,12]. Torsion samples with a gauge length of 20 mm and a diameter of 6.7 mm were machined from the 20 mm hot rolled plate, with the longitudinal axis parallel to the rolling direction. A hot torsion deformation simulator, described in detail elsewhere [13], was employed for thermo-mechanical processing. Von Mises equivalent stress–strain values were calculated from the torque–twist data using a method based on the analysis by Fields and Backofen [14].

Two sets of roughing deformation schedules were employed to obtain two initial grain sizes. The specimens were reheated to either 1200 °C or 1000 °C, held for 80 s and then subjected to two roughing deformation steps using equal strains of 0.4 performed at a strain rate of 1 s^{-1}. Each deformation step was followed by holding for either 40 s at 1200 °C or 60 s at 1000 °C. This led to a homogeneous and fully recrystallized grain structure with average grain sizes of ~110 and 80 μm at roughing deformation temperatures of 1200 °C and 1000 °C, respectively. The specimens deformed at 1200 °C were subsequently cooled (2 °C s^{-1}) to 1000 °C, held for 120 s and deformed to strains of either 0.5 or 6 at strain rates of 1, 0.1 and 0.01 s^{-1}. The samples produced using roughing at 1000 °C were further held isothermally for 120 s and deformed at a strain rate of 0.01 s^{-1}. The samples were water quenched immediately (i.e. <0.5 s) after deformation.

Microstructural characterization was performed on specimen tangential sections at a depth of ~100 μm below the surface of the gauge length. The crystallographic texture and deformation substructure were investigated using EBSD and TEM. Samples for EBSD were prepared by standard mechanical polishing, finished with a colloidal silica slurry polish. EBSD was performed on a FEG LEO 1530 scanning electron microscope operated at 20 kV. The instrument was equipped with a fully automatic HKL Technology EBSD attachment. HKL Channel 5 software was used to perform data acquisition and post-processing, including the Kuwahara filter routine for orientation averaging.

EBSD maps were acquired using either a step size of 0.1 μm for characterization of the grain substructure or 3 μm to study the overall microstructure and crystallographic texture characteristics. An area of $\sim 5 \times 1$ mm^2 was scanned at each strain level to investigate the crystallographic texture of both the dynamically recrystallized and deformed matrix grains during hot deformation. The orientation distribution function (ODF) was calculated from the EBSD data, adopting monoclinic symmetry of the torsion specimens [15]. The mean grain size was determined as an average of the mean linear intercepts measured in the horizontal and vertical directions, disregarding $\sum 3$ annealing twin boundaries.

In order to produce TEM foils, discs of 3 mm in diameter were taken from the tangential sections at a depth of

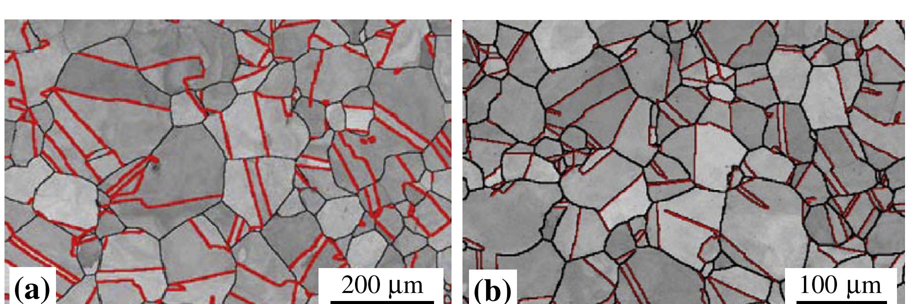

Fig. 1. Microstructure of the Ni–30%Fe alloy for different roughing temperatures: (a) 1200 °C, (b) 1000 °C. The red and black lines represent annealing twin and high angle grain boundaries, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)