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Phase reverted transformation-induced nanograined microalloyed steel: Low temperature superplasticity and fracture

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ABSTRACT

The novel concept of phase reverted transformation involving severe cold deformation of martensite at room temperature followed by controlled annealing was adopted to obtain nanograined (NG) microalloyed steel. The NG microstructure was characterized NG (< 100 nm) and few ultra-fine (100–300 nm) ferrite grains, together with ~50–80 nm cementite and ~10–20 nm V(C,N) precipitates. The microalloyed steel exhibited superplastic behavior at a low temperature of 500 °C ($<0.5T_m$) with total elongation exceeding 100%. The fracture surface of the superplastic alloy was characterized by elongated cavities that nucleated and grew parallel to the applied tensile stress. The growth of cavities in the plastically deformed region involved interlinkage of cavities and significant plastic deformation occurred around the cavity, which is envisaged to be the cavitation growth mechanism. Electron microscopy of the deformed region close to the tip of the fracture surface indicated grain boundary migration during plastic deformation, an attribute of grain boundary sliding associated with superplasticity, a significant finding in microalloyed steels.

1. Introduction

We have recently obtained high strength-ductility combination in nanograined (NG) austenitic alloy using the innovative concept of phase reversion-induced NG materials [1–4]. The controlled deformation-annealing approach to obtain NG stainless steels with high strength-high ductility combination involved cold deformation (~60–80%) of metastable (FCC) austenite (γ) to strain-induced body-centered cubic (BCC) martensite (α′). Upon annealing at ~700–800 °C for short duration of ~100 s (depending on the dimensions of the sample), martensite transformed back to austenite via a diffusional-reversion mechanism, without affecting the texture [1–4]. The success of this approach in obtaining NG structure was dependent on the predominance of dislocation-cell type structure in the severely deformed martensite. The concept enabled us to explore deformation mechanisms in a single material from CG (coarse-grained) to NG regime, using identical processing parameters. Motivated by the success of the approach, we extended the innovative concept to microalloyed steels to obtain NG structure that was characterized by low temperature superplasticity at a temperature significantly below the melting point ($<T_m$). The experimental reports on superplasticity at low temperatures ($<0.5\ T_m$) are rare, and this is particularly true with low carbon microalloyed steels.

Superplastic materials sustain high degree of plastic deformation (≥ 100%) [5–7]. One of the important requirements of superplasticity is fine-grained structure. The interest in superplasticity arises from the fact that superplastic behavior can be exploited to form complex shapes using relatively inexpensive forming methods [6,7], particularly if the deformation temperature can be reduced. However, in majority of the nanograined/ultrafine-grained (NG/UFG) alloy systems, the ductility is limited because of lack of strain hardening ability [8,9]. Considering that grain boundary sliding is widely recognized as an important deformation mechanism to explain superplastic behavior, it is envisaged that superplasticity may occur in NG/UFG alloy systems with high fraction of grain boundaries and high strain rate hardening ability. Grain boundary sliding is an important mechanism of superplasticity, because the number of grain boundaries involved in sliding are expected to be high [10]. In sequel to our preliminary observations [11], we explore here the mechanism of low temperature superplasticity in a low carbon microalloyed at temperatures below $0.5T_m$ through the study of deformation and fracture and discuss the findings in the context of extensive knowledge on superplasticity available in the literature.

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2. Experimental procedure

The microalloyed steel of nominal composition (in weight%) Fe-0.1C-1.55Mn-0.16Si-0.1V-0.02Al-(0.5–1Ni)-0.018N was melted in a vacuum induction furnace and cast as 50 kg ingot of ~45 mm thickness. The as-cast steel was heated to ~1200 °C for 3 h and air-cooled to 920 °C, followed by rolling to ~5.5 mm thickness involving 7 passes on a rolling mill with roll diameter of 450 mm. The finish temperature was 805 °C and accelerated cooled to room temperature. To obtain NG/UFG structure, the as-hot rolled microalloyed steel was subjected to combination of cold-rolling and annealing in a manner similar to the concept of phase reversion induced NG/UFG structure, applied to stainless steel, which has been widely studied in recent years by Misra's group [1–4]. First, the as-hot rolled steel of 5.5 mm thickness and 50 mm width was reheated at 900 °C for 5 min in an electric furnace, followed by water quenching to room temperature at a cooling rate of 90 °C/s to obtain martensite. Second, after removal of the surface scale, the steel of 5 mm thickness was cold rolled to 1.6 mm and 0.9 mm thickness, respectively, with total reduction of 68% and 82%. Approximately, 0.3–0.5 mm reduction was given in each pass. Third, the cold rolled steel was annealed at 550 °C and 650 °C in a tubular furnace for 5 min at a heating rate of 10 °C/s, water-quenched to room temperature to prevent coarsening of the microstructure. Samples were mechanically polished using standard metallographic procedure and chemically etched with 4 vol% nital solution and the microstructure examined in SEM at 15 kV and precipitates analyzed by energy-dispersive X-ray spectroscopy (EDX). Tensile tests were carried out using dog-bone shaped samples (10 mm gage length and 5 mm gage width) at room temperature and 500 °C at strain rates of 1×10^{-4} and 2.5×10^{-4}/s. To conduct tensile test at 500 °C, the tensile specimens were heated to 500 °C for 5 min prior to the application of load. The tensile data is an average of five tests for each condition.

Fracture surface of tensile samples was studied via scanning electron microscope (SEM, Hitachi 6400). Furthermore, to study

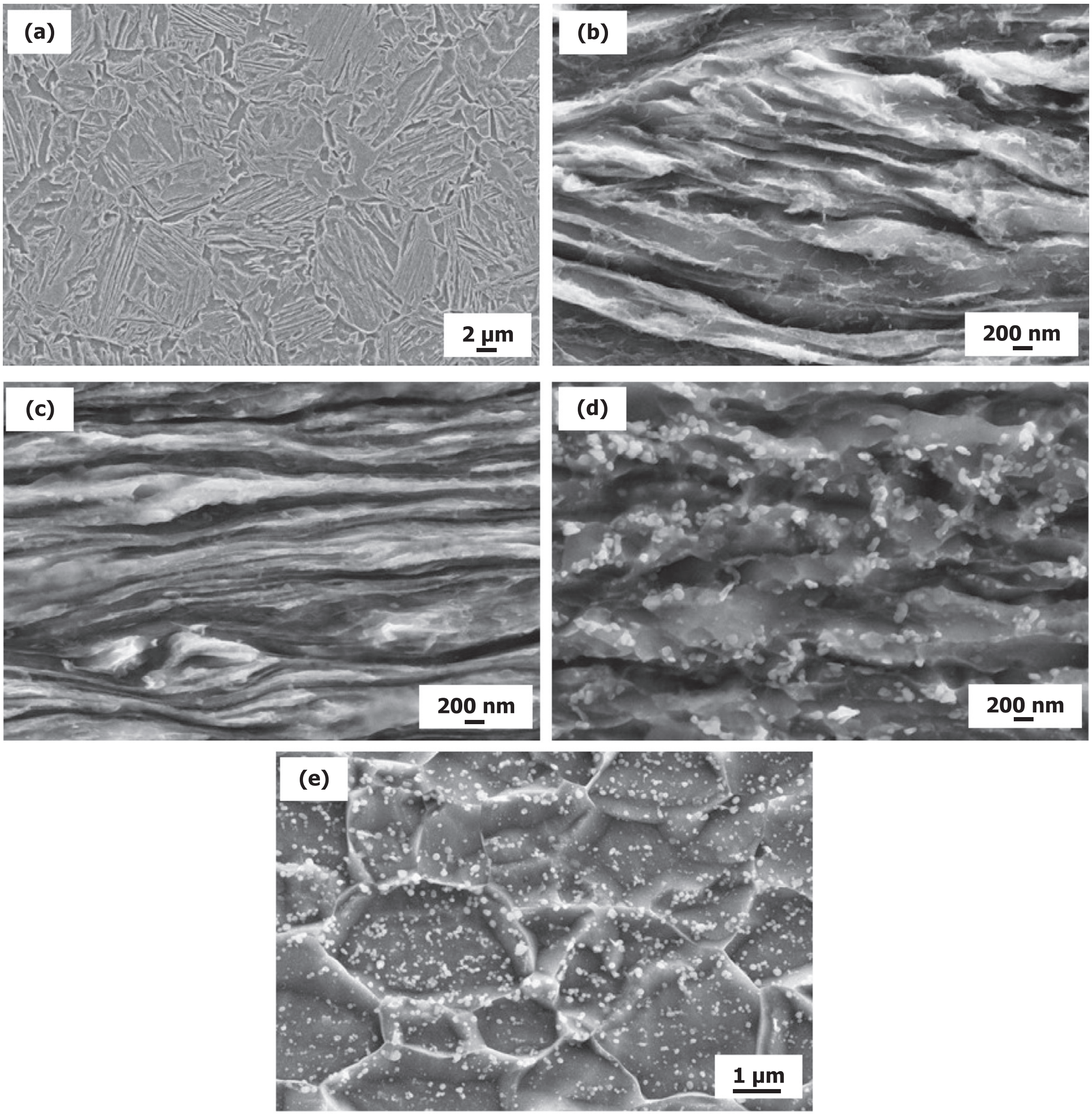

Fig. 1. Scanning electron micrographs of (a) steel reheated to 900 °C for 5 min and water-quenched, (b) cold rolled structure of as-quenched steel reduced to 1.6 mm thickness and (c) cold rolled structure of as-quenched steel reduced to 0.9 mm thickness. Cold rolling to 0.9 mm thick led to refinement of martensite (width ~100–150 nm), (d) cold rolled (0.9 mm thickness) and annealed steel, 550 °C for 5 min: NG/UFG steel, and (e) cold rolled (0.9 mm thickness) and annealed steel, 650 °C for 5 min: FG steel [adapted from Ref. [11]].