Materials Characterization 116 (2016) 18–23

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Physical mechanisms of nanocrystallization of a novel Ni-based alloy under uniaxial compression at cryogenic temperature

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ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form 30 March 2016
Accepted 31 March 2016
Available online 9 April 2016

Keywords:
Ni-based alloy
Nanocrystallization
Plastic deformation
Deformation twinning
Microstructure

ABSTRACT

A novel Ni-based alloy, which possesses a nominal chemical composition of $Ni_{52}Cu_{20}Cr_{15}Mo_5Ti_2Al_1Nb_5$ (wt.%), is designed and fabricated in order to be used for cryogenic environments. The Ni-based alloy exhibits high plasticity and high strength in the case of uniaxial compression at −150 °C. Nanocrystalline phases, in particular, are observed in the matrix of Ni-based alloy subjected to plastic deformation at −150 °C. Statistically stored dislocation (SSD) density and geometrically necessary dislocation (GND) density are found to play a significant role in nanocrystallization of Ni-based alloy. SSD density and GND density increase with the increase in the plastic strain. There appears a critical dislocation density above which the critical resolved shear stress (CRSS) for dislocation slip was greater than the CRSS for deformation twinning. Consequently, deformation twinning occurs instead of dislocation slip with increasing plastic strain. Under the simultaneous action of dislocation slip and deformation twinning, dislocation wall, dislocation cell, deformation twin, low angle grain boundary and high angle grain boundary occurs in such an alternative way that nanocrystalline grains are formed in the end.

1. Introduction

Ni-based superalloys are widely used for the structure components in the aerospace industry, such as gas turbine, jet engines, nuclear reactor and so on since they possess high-temperature mechanical properties, such as high strength, creep resistance, fatigue resistance and resistance to high temperature oxidation [1,2]. However, some Ni-based superalloys, including Inconel 718 [3], Inconel X-750 [4] and Hastelloy C276 [5], have also been used for manufacturing metal structure component under cryogenic environments due to their good structure stability and high corrosion resistance. In general, Ni-based superalloys that are used under cryogenic environments should possess high cryogenic toughness and high cryogenic plasticity. In particular, they can be subjected to large plastic deformation under cryogenic environments. It is well-known that severe plastic deformation (SPD), such as high pressure torsion (HPT) and equal channel angular extrusion (ECAE), plays a significant role in refining the microstructures of metal materials and improving the mechanical properties of metal materials [6–9]. In particular, HPT [10,11], cold rolling [12], cold drawing [13], surface mechanical attrition treatment (SMAT) [14,15] and surface mechanical grinding treatment (SMGT) [16–18] are able to lead to SPD of metal materials at or below room temperature so that they are capable of inducing substructures such as a high density of dislocations and deformation twins, nanocrystalline phase and amorphous phase. However, the Ni-based superalloy that is only used for cryogenic environments has not been reported in the literatures. Study on cryogenic Ni-based superalloy and its cryogenic plastic deformation mechanism shall become a promising perspective in the future.

In the present study, a novel Ni-based alloy was designed and fabricated in order to be used for cryogenic environments alone. Nanocrystalline phases, in particular, were observed in the matrix of the Ni-based alloy subjected to plastic deformation under cryogenic environments, which has never been reported in the literatures.

2. Materials and methods

A novel Ni-based alloy, which possesses a nominal chemical composition of $Ni_{52}Cu_{20}Cr_{15}Mo_5Ti_2Al_1Nb_5$ (wt.%), was designed and fabricated so as to be used for cryogenic environments. The Ni-based alloy was melted by means of vacuum arc melting method and subsequently was cast into a cylinder with the length of 80 mm and the diameter of 10 mm. The as-cast Ni-based alloy sample with the height of 6 mm and the diameter of 4 mm was compressed on the INSTRON-5500R universal testing machine at the strain rate of 0.001 s^{-1} and the temperature of −150 °C. The as-cast Ni-based alloy samples were subjected to uniaxial compression by 20%, 40% and 60%, respectively, in order to investigate plastic deformation mechanisms of the as-cast Ni-based alloy in the case of cryogenic atmosphere.

Microstructures of as-cast Ni-based alloy were characterized by means of optical microscope (OM) and transmission electron microscope (TEM). Furthermore, the microstructures of the compressed

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http://dx.doi.org/10.1016/j.matchar.2016.03.024
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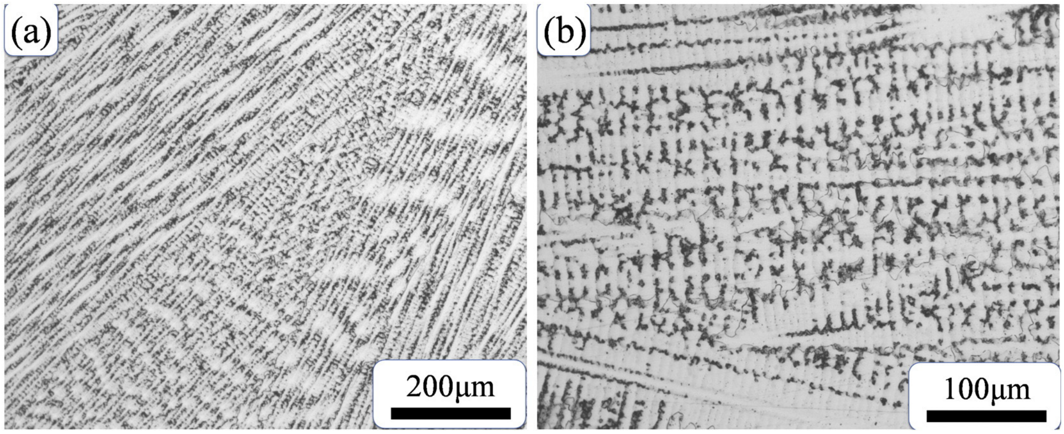

Fig. 1. Metallographic photographs of as-cast Ni-based alloy: (a) Low magnification; (b) High magnification.

samples were characterized using transmission electron microscope (TEM) alone. The specimens for OM observation were etched in a solution with the composition of HF: HNO_3: H_2O = 1: 2: 10. Subsequently, OM observation was carried out through OLYMPUS311 optical microscope. In addition, the phase composition was obtained by means of X-ray diffraction (XRD) using an X-ray diffractometer (X-pert PRO). Microstructures of the as-cast and compressed Ni-based alloy samples were characterized by TEM using FEI TECNAI G2 F30 microscope with a side-entry and double-tilt specimen stage with angular ranges of ±40° at an accelerating voltage of 300 kV. Foils for TEM observation were mechanically ground to 70 μm and were then thinned by twin-jet polishing in an electrolyte consisting of 6% $HClO_4$, 34% $C_4H_{10}O$ and 60% CH_3OH by volume fraction.

3. Results and discussion

Fig. 1 illustrates metallographic photographs of as-cast Ni-based alloy. It can be found from Fig.1 that the microstructure of the as-cast Ni-based alloy exhibits an obvious characteristic of dendrite. Fig. 2 shows TEM photograph and the corresponding diffraction pattern of as-cast Ni-based alloy. It can be observed from Fig. 2 that the as-cast Ni-based alloy belongs to γ-Ni matrix phase with face-centered cubic (FCC) structure. In addition, it can be noted from XRD map of the as-cast Ni-based alloy in Fig. 3 that there is a small amount of $Ni_3(Al,Ti)$ phase in the γ-Ni matrix.

Fig. 4 illustrates the compression stress-strain curve of as-cast Ni-based alloy subjected to compression deformation by 60% at −150 °C. The compression stress-strain curve is obtained on the basis

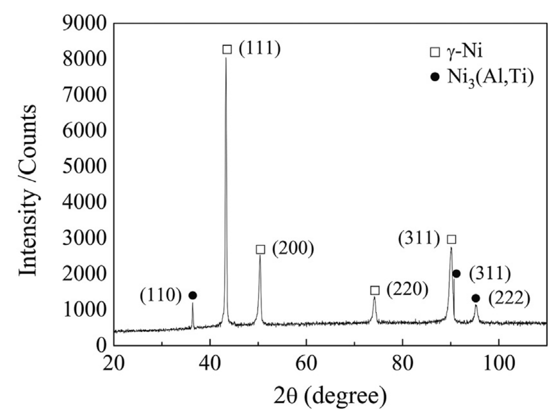

Fig. 3. XRD map of as-cast Ni-based alloy.

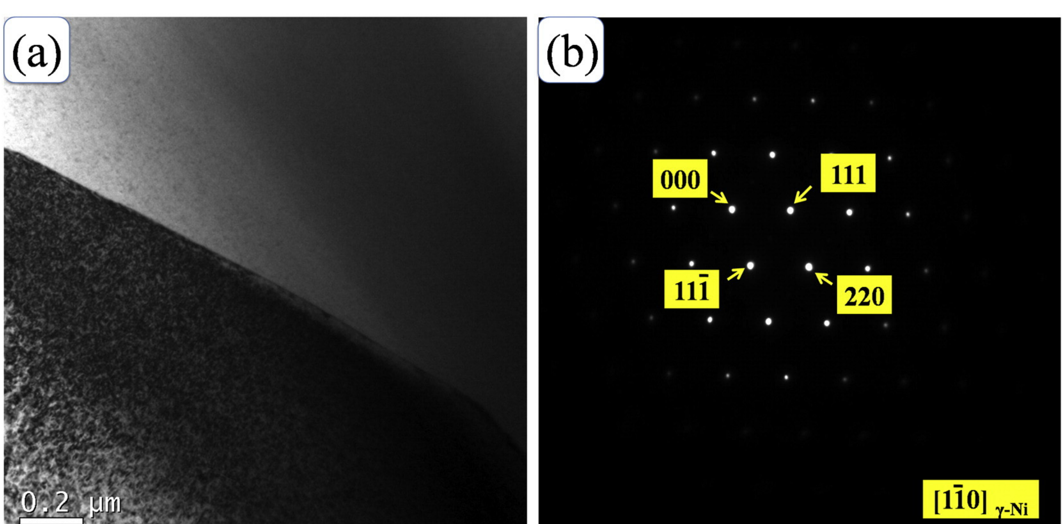

Fig. 2. TEM photographs of as-cast Ni-based alloy: (a) Bright field image; (b) Diffraction pattern of (a).