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Short communication

Intermediate strain rate deformation behavior of a CoCrFeMnNi high-entropy alloy

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ABSTRACT

The intermediate strain rate tensile behaviors of a CoCrFeMnNi high-entropy alloy were investigated. Dislocation slips combined with deformation twinning dominated the initial stage of deformation. A phonon drag mechanism became evident after necking; this extended post-elongation gave rise to a ductility superior to that displayed at a static strain rate.

1. Introduction

High-entropy alloys (HEAs) have recently come into the spotlight due to their excellent properties, such as high strength [1,2], good wear resistance [3], corrosion resistance [4], and thermal stability [5]. Additionally, HEAs have the potential for further undiscovered properties due to cocktail effects [6]. The CoCrFeMnNi HEA, in particular, has been actively researched because of its good cryogenic properties, attributed to deformation twinning, and is expected to have cryogenic applications [7–10]. For HEAs to be practically applied, it is necessary to understand their deformation behaviors in the intermediate strain rate range of $1\ s^{-1}$ to $500\ s^{-1}$, i.e. the strain rates required for high-speed forming processes such as stamping [11]. However, few studies have been carried out on the deformation behavior of HEAs at an intermediate strain rate. In this work, an intermediate strain rate tensile test was performed on the CoCrFeMnNi HEA. The deformation behavior was investigated in the pre-necking region and post-necking region through transmission electron microscopy (TEM) and digital image correlation (DIC) analysis, respectively.

2. Experiment

A CoCrFeMnNi HEA was prepared by vacuum induction melting (VIM) using high-purity elements. The ingot was homogenized at 1200 °C for 24 h, and rolled at 700 °C with a reduction ratio of 93% (< 10% /pass). The slight edge cracks in the hot-rolled HEA sheet were eliminated by machining. The HEA was rolled at room temperature until it acquired a thickness of 1.35 mm. It was then annealed at 900 °C for 30 min, and cooled in air.

The CoCrFeMnNi HEA was mechanically polished and electro-etched in a solution of 8% $HClO_4$ and 92% CH_3COOH. Electron back-scattered diffraction (EBSD, acceleration voltage 15 kV, step size: 0.1 µm) analysis was conducted using an FE-SEM (model: SU-6600, HITACHI) equipped with an EDAX-TSL OIMTM data collection system. Disk specimens of 3 mm were electro-polished by a twin-jet polisher (model: Tenupol-5, Struers, Denmark) in the same solution (8% $HClO_4$ and 92% CH_3COOH) for TEM analysis. Microstructures were observed by TEM (model: JEM 2100, JEOL).

Plate-type tensile specimens (gage length: 25 mm, gage width: 6 mm, thickness: 1.35 mm) for low strain rate (LSR) tensile tests were prepared along the rolling direction. These were tested at a strain rate of $0.001\ s^{-1}$ by a universal testing machine (model: Instron 5982). For the intermediate strain rate (ISR) tensile tests, plate-type tensile specimens (gage length: 32 mm, gage width: 6 mm, thickness: 1.35 mm) were prepared along the rolling direction, and tested at a strain rate of $100\ s^{-1}$ by a high-speed material testing machine (model: Instron VHS-65/80-25). Photographs of the tensile specimen surface during the ISR tensile test were taken using a high-speed camera (model: Photron SA-X2) to analyze the local deformation strain during the tensile test. The high-speed camera snapped 100,000 images per second. The testing procedures have been described in detail in previous papers [12,13].

3. Results and discussion

3.1. Mechanical properties and hardening behavior

Fig. 1(a) shows the initial microstructure of the wrought CoCrFeMnNi HEA alloy, in which a completely recrystallized microstructure and many annealing twins can be seen. The average grain size is 9.8 µm and it consists of a single fcc phase (Fig. 1(b)). Fig. 2 and Table 1 show

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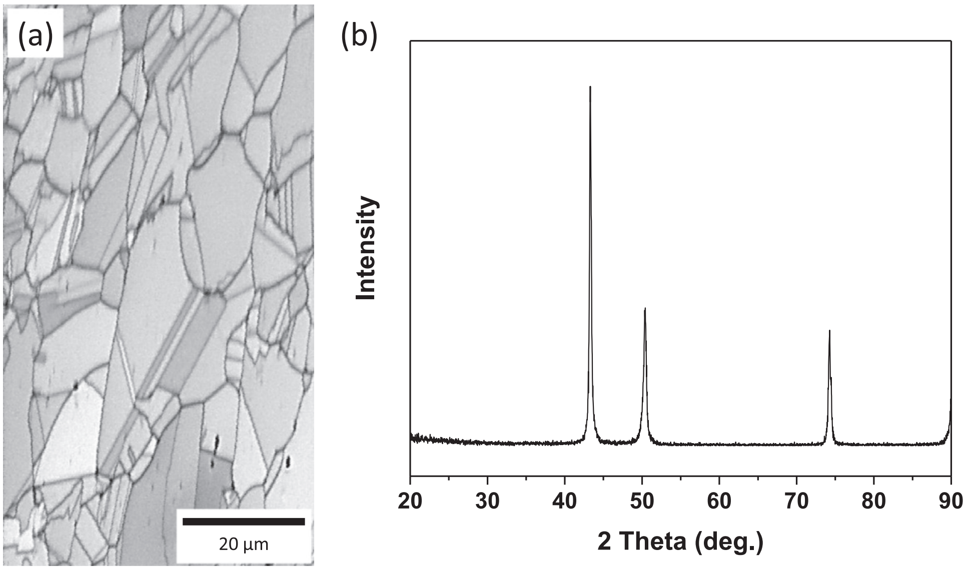

Fig. 1. (a) EBSD image quality (IQ) map and (b) XRD of initial microstructure.

the tensile properties under a LSR (0.001 s^{-1}) and ISR (100 s^{-1}). As the strain rate increases, the yield strength also increases from 484 MPa to 650 MPa, while the tensile strength increases from 853 MPa to 968 MPa. An improved total elongation can be observed, despite the decrease in uniform elongation, due to the large post-elongation of the ISR specimen (20%).

In general, the strengths of fcc metals are relatively less sensitive to the strain rate [14,15]. However, this HEA displays a larger increase in strength at the early stage of the deformation. To understand the reason behind this, we examined the microstructural differences between the samples tested under LSR and ISR. It was difficult to stop the ISR tensile test in the middle of the deformation process due to limitations of the high-speed material testing machine; hence, a fractured specimen was prepared to observe the microstructure under ISR. It was assumed that the non-necking region of fractured ISR specimen was around 30% which is correspond to the uniform elongation. A strain of 30% for the LSR test was achieved by interrupted tensile testing.

Fig. 3(a) and (b) show the EBSD image quality (IQ) maps of the HEAs after 30% deformation. The LSR specimen shows thick annealing twins, which were present in the initial microstructure, without deformation twins. In contrast, the IQ map of the ISR specimen shows many narrow deformation twins. To verify the existence of the deformation twins, TEM analysis was conducted. Fig. 4(a) through (d) show the TEM micrographs for the LSR and ISR specimens at a strain of 30%. From the LSR tensile test, it can be clearly observed that deformation takes place primarily by a dislocation slip mechanism (Fig. 4(a)). Planar as well as wavy slips have occurred, and the planar dislocations are aligned along the $(1-11)$ slip planes, as indicated by the dotted lines in Fig. 4(a). The ISR specimen shows streaked diffraction spots resulting from stacking faults that are formed by partial dislocations in fcc materials [16,17], which are regarded as a precursor to twinning. In other grains, deformation twins can be seen (Fig. 4(c) and (d)). The deformation mechanisms of fcc materials are related to their stacking fault energies [18], and those of the HEAs have been widely reported [19,20]. However, there are a few studies on the deformation behavior of HEAs at high strain rates [21,22]. As opposed to the results of A. Gali et al., who found that CoCrFeMnNi HEAs exhibit a weak strain-rate dependence [21], we observed a significant increase in the strength for an ISR. This is because higher strain rates affect the critical stresses for slip and twinning. In fcc metals, it is well-established

Table 1
Tensile properties at low strain rate (10^{-3} /s) and intermediate strain rate (10^{2} /s).

Strain rate	Yield Strength (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Post Elongation (%)
LSR (0.001 s^{-1})	484	853	33	11
ISR (100 s^{-1})	650	968	28	20

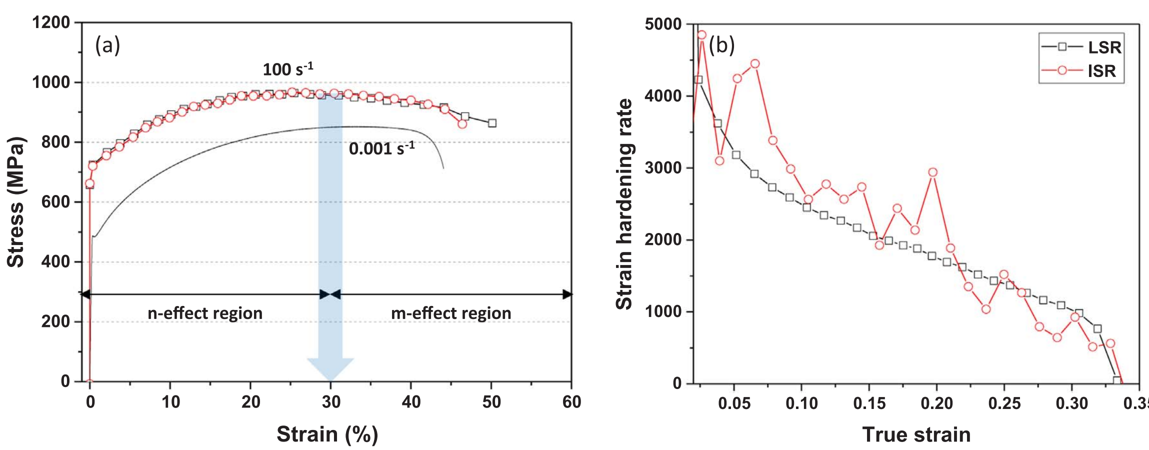

Fig. 2. (a) Tensile stress-strain curve at low and intermediate strain rate, and (b) strain hardening rate curve. CoCrFeMnNi HEA shows higher strength and extended post-elongation at intermediate strain rate without increase in hardening rate.