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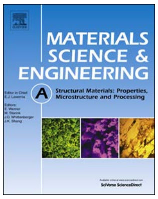

Mechanical properties and deformation twinning behavior of as-cast CoCrFeMnNi high-entropy alloy at low and high temperatures

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ABSTRACT

Tensile properties of an as-cast CoCrFeMnNi high-entropy alloy were investigated at various temperatures ranging from −160 to 1000 °C. The tensile strength and ductility did not vary significantly with loading direction, despite the alloy's strongly preferred crystallographic orientation. The impact toughness values of the as-cast high-entropy alloy were much higher than those of many traditional alloys, particularly at low temperatures. The mechanical properties of the as-cast high-entropy alloy were compared with those of wrought high-entropy alloy and noticeable differences between the two alloys were found. The maximum tensile ductility and three different strain hardening stages were observed at 500 °C in the as-cast structure. Transmission electron microscopy observations demonstrated that the initiation of deformation twinning was very active even at 500 °C. A simple calculation suggests that very large grains of the as-cast structure induced a reduction in twinning stress, retarding the onset of strain localization.

1. Introduction

High-entropy alloys (HEAs) are materials that contain five or more elements in roughly equal proportions [1]. This new family of alloys has attracted considerable attention because of their unique properties and consequently their scientific importance [2]. For example, the face-centered cubic (fcc) CoCrFeMnNi HEA, which was first reported by Cantor et al. [3], exhibits improvements in both strength and ductility [4] due to deformation twinning at low temperatures. Hence, HEAs are expected to replace conventional austenite steel for cryogenic applications such as cryogenic pipes (wrought steel) or cryogenic valves (cast steel).

The HEAs are often produced by vacuum arc melting followed by drop-casting into a copper mold [5–7]. They are then homogenized at high temperatures (above 1000 °C) for several hours to prevent dendritic segregation. After homogenization, the alloys are hot-rolled to break down their cast structures and obtain a recrystallized microstructure. HEA materials have been produced both by hot rolling at temperatures around 800–1000 °C [8,9] and by cold rolling without any intermediate annealing [6,10,11]. Such an excellent room-temperature workability is ascribed to deformation twinning, which is one of the few mechanisms that can simultaneously increase strength and ductility [12–14]. The formation of deformation twins is known to be significantly affected by strain, strain rate, temperature, stacking fault energy (SFE), loading direction, and grain size [7]. In particular, deformation twinning seems to be very sensitive to the change of temperature, grain size, and loading direction. As a result, twinning behavior has been extensively studied by many researchers [14,15].

Most of the previous reports mentioned above have dealt with wrought CoCrFeMnNi HEA alloys, which either have a fine grain size (generally less than several tens of microns) or are dendrite-free after the cast structure solidifies. However, the first step in preparing wrought CoCrFeMnNi is to break down the dendritic cast structure of the alloy ingot. In addition, it is necessary to pay attention to mechanical properties of CoCrFeMnNi alloy in as-cast dendritic state to examine the applicability of as-cast CoCrFeMnNi alloy. Therefore, in the present work, we investigated the mechanical properties and deformation behavior of CoCrFeMnNi HEAs in as-cast dendritic state at various temperatures. Tensile and Charpy impact tests were conducted along different loading directions to characterize the anisotropy of the alloy.

2. Materials and experimental methods

Ingots (8 kg) with nominal compositions were fabricated by vacuum induction melting. The melt was poured into a Y-block graphite mold to

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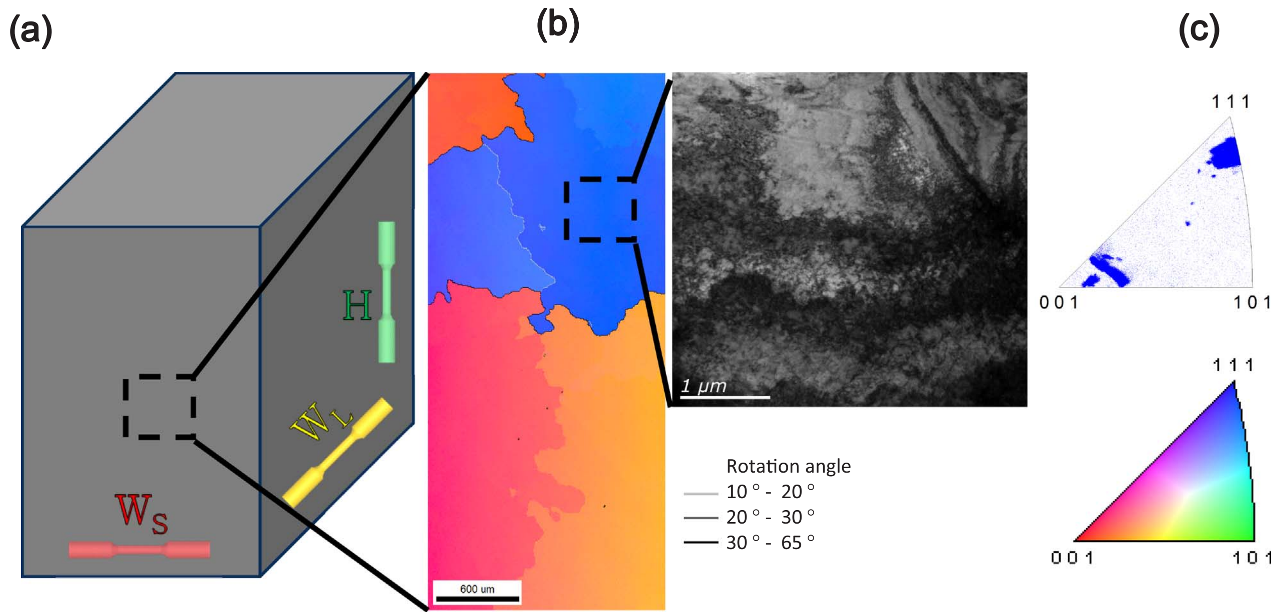

Fig. 1. Schematics showing (a) the cutting directions of the tensile test samples, (b) an electron backscatter diffraction (EBSD) map and TEM image, and (c) the related inverse pole figures of the as-cast CoCrFeMnNi high-entropy alloy (HEA) ingot.

minimize the size of the shrinkage cavity in the bottom part of the ingot (the dimensions of this part were 110 × 60 × 80 mm). Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to measure the chemical compositions of the top and bottom regions of the ingot. These were 21.5Co-18.4Cr-20.1Fe-18.4Mn-21.2Ni-0.2Si-0.05C and 21.5Co-18.5Cr-20.1Fe-18.4Mn-21.2Ni-0.2Si-0.05C (in wt%), respectively, which demonstrates the excellent chemical uniformity of the ingot. To investigate the mechanical properties and deformation behavior of the as-cast ingots, uniaxial tensile tests (ASTM E8) were conducted at temperatures ranging from -160 to 1000 °C with a strain rate of $1 \times 10^{-3}\,s^{-1}$. Charpy impact tests (ASTM E23) were also carried out at temperatures ranging from -150 to 150 °C using V-notched samples. To examine the anisotropy, the tensile and impact tests were performed along three directions of the as-cast ingot, W_S, W_L, and H (Fig. 1a).

The microstructures were examined on the gage sections of the as-cast tensile test specimens before straining. Electron backscatter diffraction (EBSD) patterns were collected before deformation using a JEOL-7100F scanning electron microscope (SEM) equipped with an EDAX-TSL HIKARI detector, operated at an accelerating voltage of 20 kV. The samples were carefully mechanically polished, then electropolished in a mixture of 90% acetic acid and 10% perchloric acid at room temperature at an applied voltage of 27 V for 15 s. High-resolution transmission electron microscopy (HRTEM) was conducted using a JEOL-2100F field emission instrument operated at U = 200 kV.

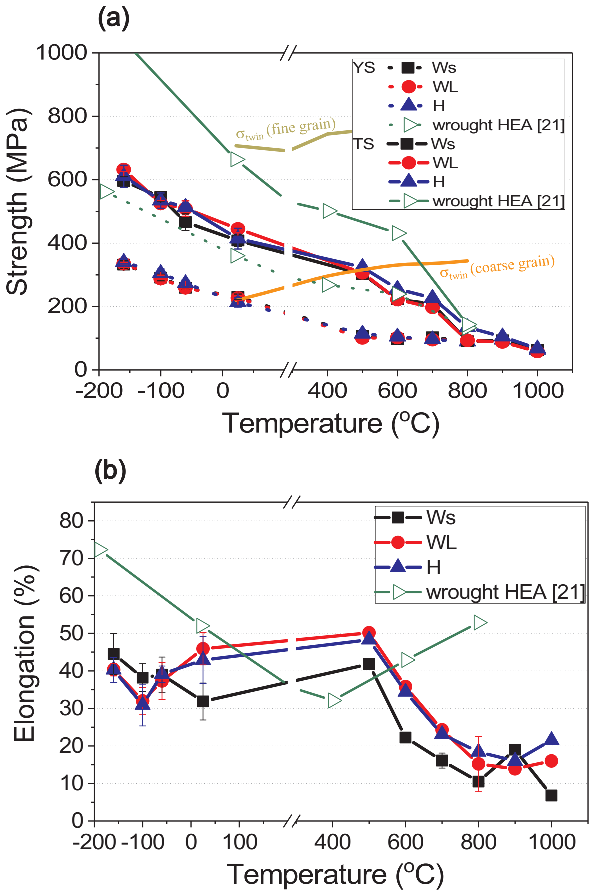

Fig. 2. Variations of (a) engineering strength and (b) elongation to fracture with temperature (-160 °C to 1000 °C) and loading direction. Initial strain rate was $10^{-3}\,s^{-1}$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

3. Results

3.1. Anisotropy behavior from tensile and Charpy notch impact tests

Fig. 1a and b show the machining directions used to obtain the tensile test samples and microstructures of the as-cast HEA, respectively. Prior to tensile testing, the average measured grain size was very large at over 1000 μm, with a strongly preferred crystal orientation distribution. Fig. 1c represents the inverse pole figures (IPFs) along the W_L direction. The grains were oriented close to the ⟨111⟩ or ⟨001⟩ planes with reference to the W_L analysis direction, demonstrating that the as-cast HEA had a strong crystallographic texture.

Fig. 2 summarizes the dependencies of the tensile yield strength (YS), ultimate tensile strength (TS), and elongation to fracture (E_f) on temperature and loading direction, based on the engineering stress–engineering strain curves. YS, TS, and E_f all strongly depended on temperature. The maximum YS and TS were obtained at the lowest