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Tensile properties of an AlCrCuNiFeCo high-entropy alloy in as-cast and wrought conditions

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ABSTRACT

Extensive multistep forging at 950 °C was applied to the cast AlCuCrFeNiCo high-entropy alloy to transform the cast coarse dendritic structure into a fine equiaxed duplex structure consisting of the mixture of BCC and FCC phases, with the average grain/particle size of $\sim 1.5 \pm 0.9\,\mu m$. Tensile properties of the alloy in the as-cast and forged conditions were determined in the temperature range of 20–1000 °C. The hot forged alloy was stronger and more ductile during testing at room temperature, than the as-cast alloy. The yield stress (YS), ultimate tensile strength (UTS), and tensile ductility (δ) of the forged condition were 1040 MPa, 1170 MPa, and 1%, respectively, against 790 MPa, 790 MPa and 0.2% for the as-cast condition. In both conditions, the alloy showed brittle to ductile transition (BDT), with a noticeable increase in the tensile ductility within a narrow temperature range. In the as-cast condition, this transition occurred between 700 and 800 °C, while in the forged condition, it was observed between 600 and 700 °C. With an increase in the testing temperature above the BDT, a continuous decrease in tensile flow stress and an increase in tensile ductility were observed. In the temperature range of 800–1000 °C, the forged alloy showed superplastic behavior. The tensile elongation was above 400% and reached 860% at 1000 °C.

1. Introduction

Modern technological developments and progress in engineering, particularly in the aerospace industry, require the development and utilization of new structural materials that would provide higher performance compared to the currently used structural materials. In the last decade, a new class of materials, so called high-entropy alloys (HEAs) was proposed and developed [1–3]. These alloys contain five to thirteen principal elements at equimolar or near-equimolar compositions, thus the atomic fractions of each element cannot be less than 5% and more than 35% [1]. The high entropy of mixing has been found to prevent formation of intermetallic phases and these alloys predominantly consist of a mixture of simple solid solutions and favorable combination of compression strength and ductility [1,4–13].

Many HEAs have high hardness, strength, wear resistance, and their microstructure is very stable against heat treatment [1,14,15]. This combination of properties is attractive for a wide range of applications; however, the main obstacle for using such materials is low ductility and brittleness of many HEAs, especially at room temperature. Annealing has been found to improve ductility of cast HEAs [9,16]. Due to their low ductility, almost all reported mechanical properties of high entropy alloys were obtained by compression testing or measuring hardness. Only several publications are yet available where tensile properties of HEAs are reported [10,17]. It is necessary to point out that almost all reported properties of HEAs were obtained in cast conditions and the properties of cast alloys are known to be almost always inferior to the properties of wrought alloys. Such structural constituents as shrinkage porosity, coarse dendritic structure, chemical heterogeneity, metastable eutectic at grain boundaries weaken mechanical properties of cast alloys. The microstructure and properties of castings can be improved by thermo-mechanical treatment, including extensive hot working [18–22]. Unfortunately, no publications have yet been available in the open literature on the effect of hot working processes on the properties of HEAs.

In this paper, microstructure and tensile properties of a severe plastically deformed AlCrCuNiFeCo high entropy alloy are presented and compared with those of the cast alloy. This alloy was selected for study because it has been most widely studied among all other HEAs [1,9,23–25] and the approximate phase diagram has been reported [24], which allowed selection of the temperature range for the thermomechanical treatment.

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Table 1
Chemical composition of the studied alloy.

	Al	Cr	Cu	Ni	Fe	Co
Atomic %	16.16 ± 0.63	15.86 ± 0.05	17.42 ± 0.01	16.65 ± 0.23	15.96 ± 0.15	17.07 ± 0.19
Weight %	8.20 ± 0.40	15.65 ± 0.05	20.95 ± 0.05	18.55 ± 0.25	17.80 ± 0.10	18.10 ± 0.20

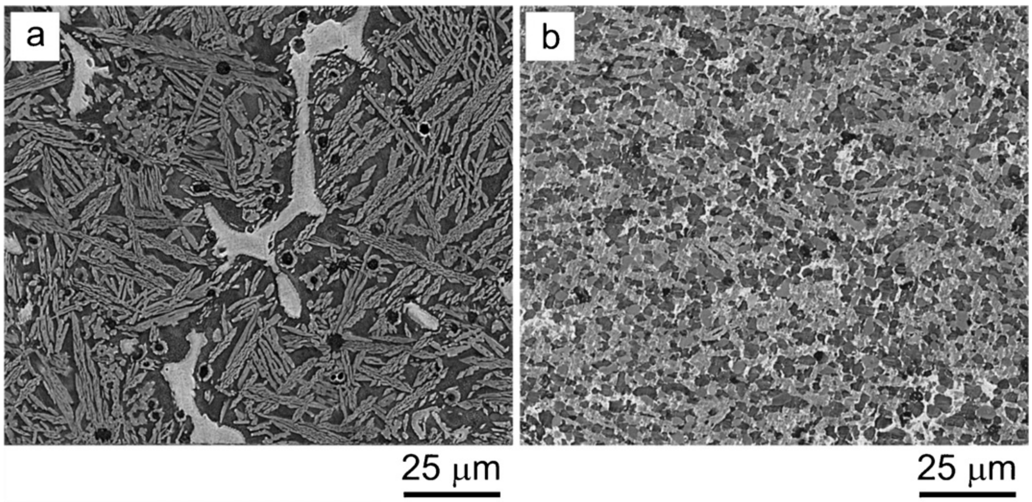

Fig. 1. Microstructure of the AlCrCuNiFeCo HEA in (a) as-cast and (b) hot forged conditions.

2. Experimental procedures

A 40 mm in diameter and 90 mm in height cylindrical ingot of the AlCrCuNiFeCo high-entropy alloy was produced by induction melting of the constituent elements followed by electro-slag re-melting and casting into a water-cooled copper mold. The chemical composition of the ingot is given in Table 1. Two slices, about 10 mm thick, were cut-out from the top and bottom of the cast ingot, and a blank of 40 mm in diameter and 35 mm long was extracted from the remaining part. This blank was homogenized by holding for 50 h at 960 °C. After homogenization, the blank was extensively hot worked at 950 °C using multistep *a*–*b*–*c* forging in three orthogonal directions [20–22]. A hydraulic press DEVR 4000 with the maximum force of 0.4 MN, equipped with a radial furnace, was used for the isothermal forging. The ram speed was 1 mm/s and the total true strain achieved during forging was ∼1000%.

Microstructure of cast and deformed samples was studied on polished cross-sections using scanning electron microscopes Quanta 200-3D and Quanta 600 equipped with backscatter electron detector, as well as with energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) detectors. Vickers microhardness, HV, was measured on polished cross-section surfaces using a 136° Vickers diamond pyramid under a 250 g load applied for 15 s. Uniaxial tensile tests were conducted in air using an Instron 5882 testing machine equipped with a furnace for heating up to 1200 °C. The testing was conducted at temperatures in the range of 20–1000 °C, and a ram speed of 0.016 mm/s (initial strain rate of 10^{-3} s^{-1}) was used. The tensile samples had the gauge length of 16 mm and a rectangular gauge cross-section of 3 mm × 1.5 mm.

3. Results and discussion

3.1. Effect of multi-step forging on microstructure

The dendritic microstructure of the as-cast alloy is shown in Fig. 1a. The dendrite size is about 50 μm. According to the EBSD analysis, the microstructure consists of a BCC matrix (dark regions, the volume fraction is ∼53%) and FCC particles (lighter regions, the volume fraction is ∼47%). The FCC particles located at grain boundaries (i.e. inter-dendritic regions) are larger and brighter than the gray particles located inside the BCC grains (dendrites). Chemical analysis by EDS shows that the inter-dendritic FCC particles have much larger amount of Cu than the intra-dendritic FCC particles. X-ray diffraction analysis of the as-cast sample reveals the presence of a BCC and two FCC phases, Fig. 2a, with the lattice parameters *a* = 2.88 Å (BCC), 3.60 Å (FCC1) and 3.63 Å (FCC2).

Considerable refinement of the cast microstructure occurs after extensive multi-step forging at 950 °C (Fig. 1b). The non-homogeneous dendritic structure typical to the as-cast condition transforms to a recrystallized, duplex-type structure. The BCC grains become fine and equiaxed, whereas the FCC particles are refined, have near-equiaxed shape and are homogeneously distributed in the forged samples. According to the EBSD analysis, the volume fraction of the BCC phase after forging increases to ∼60% and the FCC phase decreases to ∼40%. The X-ray diffraction pattern from the forged sample, shown in Fig. 2b, reveals that in addition to the BCC and two FCC phases, which lattice parameters are

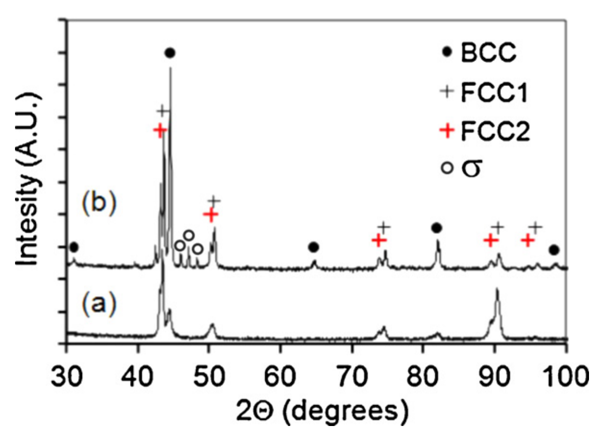

Fig. 2. X-ray diffraction pattern of the AlCuCrFeNiCo alloy in (a) as-cast and (b) forged conditions.