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Heavy carbon alloyed FCC-structured high entropy alloy with excellent combination of strength and ductility

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ABSTRACT

The effects of carbon content on the microstructure and room-temperature mechanical properties of $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ high-entropy alloy (HEA) were systematically investigated. The results showed that heavy carbon alloyed HEA could possess supreme combination of high tensile strength (935 MPa) and high ductility (~ 74%). The excellent mechanical properties were ascribed to as follows: the high content interstitial carbon atoms strengthens the matrix greatly through suppressing dislocation motion and promoting the deformation-induced twinning at room temperature, which enhance the strength and ductility. Simultaneously, the ductility is further secured for single FCC structure maintained due to appropriate carbon alloying. Our findings provide a novel strategy for developing HEAs with excellent mechanical properties.

1. Introduction

High-entropy alloys (HEAs) have attracted tremendous attention due to their potential application as high performance structural materials [1–4]. The face-centered cubic (FCC) structured HEAs is one of the most developed alloys, which have good plasticity and excellent cryogenic temperature fracture toughness [1,5–7]. However, their room temperature strength is relatively low (only about 200 MPa in the cast state) [8,9] and far lower than the required strength of metallic structural materials. The shortcoming of low strength hinders their application as a practical structural material. The strengthening mechanisms of traditional metal such as fine grain strengthening [10,11] and precipitation strengthening [12], have been applied to improve the strength of FCC-structured HEAs. However, above strengthened alloys were also suffered the deterioration of plasticity [10,12], followed the strength–ductility trade-off dilemma. Recently, interstitial strengthening offers another route to achieve improvements in mechanical properties [8,9,13,14]. For examples, 0.5 at% C was added by Wu et al. [8] into FeCrNiCoMn HEA and thus increased its strength but, unfortunately also greatly decreased its plasticity. Wang et al. [9] investigated the effect of interstitial carbon on the mechanical properties of $Fe_{40.4}Ni_{11.3}Mn_{34.8}Al_{7.5}Cr_6$ HEA and found that both strength and plasticity of the HEA were increased when up to 1.1 at% C was added in the alloys. Regardless of the high potential for interstitial strengthening in HEAs, the added interstitial element contents in FCC-structured HEAs were usually low (< 1.3 at%) [8,9,13,15] and there was no other reports whether or not more C content (> 1.1 at%) could further improve the strength and plasticity of the $Fe_{40.4}Ni_{11.3}Mn_{34.8}Al_{7.5}Cr_6$ HEA [9]. Moreover, transformation-induced plasticity (TRIP), twinning-induced plasticity (TWIP) and mix of them [7,13,16], had also been involved in HEAs. Not surprisingly, the above mentioned HEAs still display unsatisfactory room temperature strength despite of good ductility [7,10].

Here, a FCC-structured twinning induced plasticity (TWIP)HEA with a composition of $Fe_{40}Mn_{40}Co_{10}Cr_{10}$(at%) was selected as the starting material. Different amount of carbon contents (up to 8.9 at% i.e. 2.11 wt%) were added into this HEA and their mechanical properties were systematically investigated. The results showed that the large amount of interstitial carbon atoms could suppress dislocation motion by enhancing the lattice friction stress, and further promote twinning induced plasticity. Moreover, appropriate carbon addition prior to carbide precipitation maintained the single FCC structure at room temperature to ensure excellent ductility. Thereafter, a carbon alloyed TWIP HEA with combination of high-strength and excellent tensile ductility was developed.

2. Experimental procedure

Alloy ingots with a nominal composition of $(Fe_{40}Mn_{40}Co_{10}Cr_{10})_{100-x}C_x$ (x = 0, 2.2, 3.3,4.4, 6.6 and 8.9 at%), labeled as C0, C2.2, C3.3, C4.4, C6.6 and C8.9 respectively, were prepared by arc melting pieces of 99.9% Fe, 99.8% Mn, 99.9% Co, 99.8%

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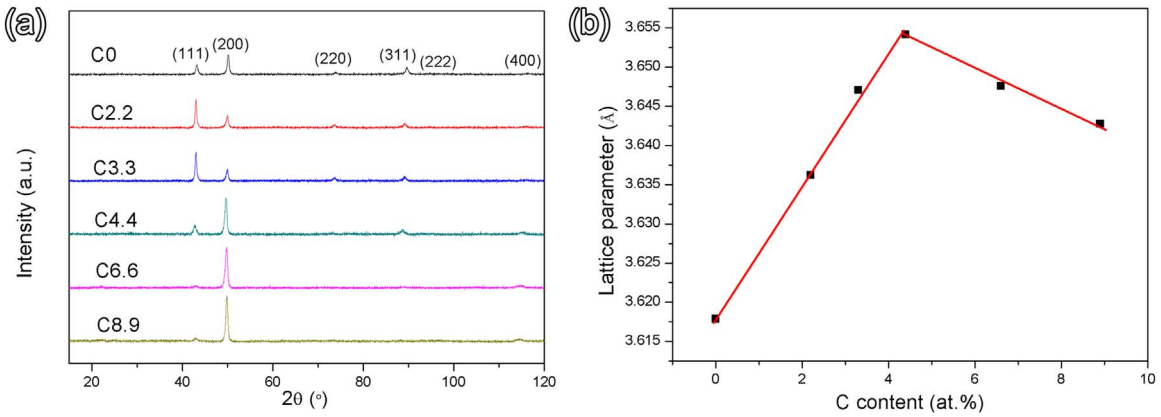

Fig. 1. (a) XRD patterns of $Fe_{40}Mn_{40}Cr_{10}Co_{10}$ HEAs with different carbon contents. The carbon content is shown on each curve, all are single FCC phases. (b) The Lattice parameter versus carbon content of the HEAs.

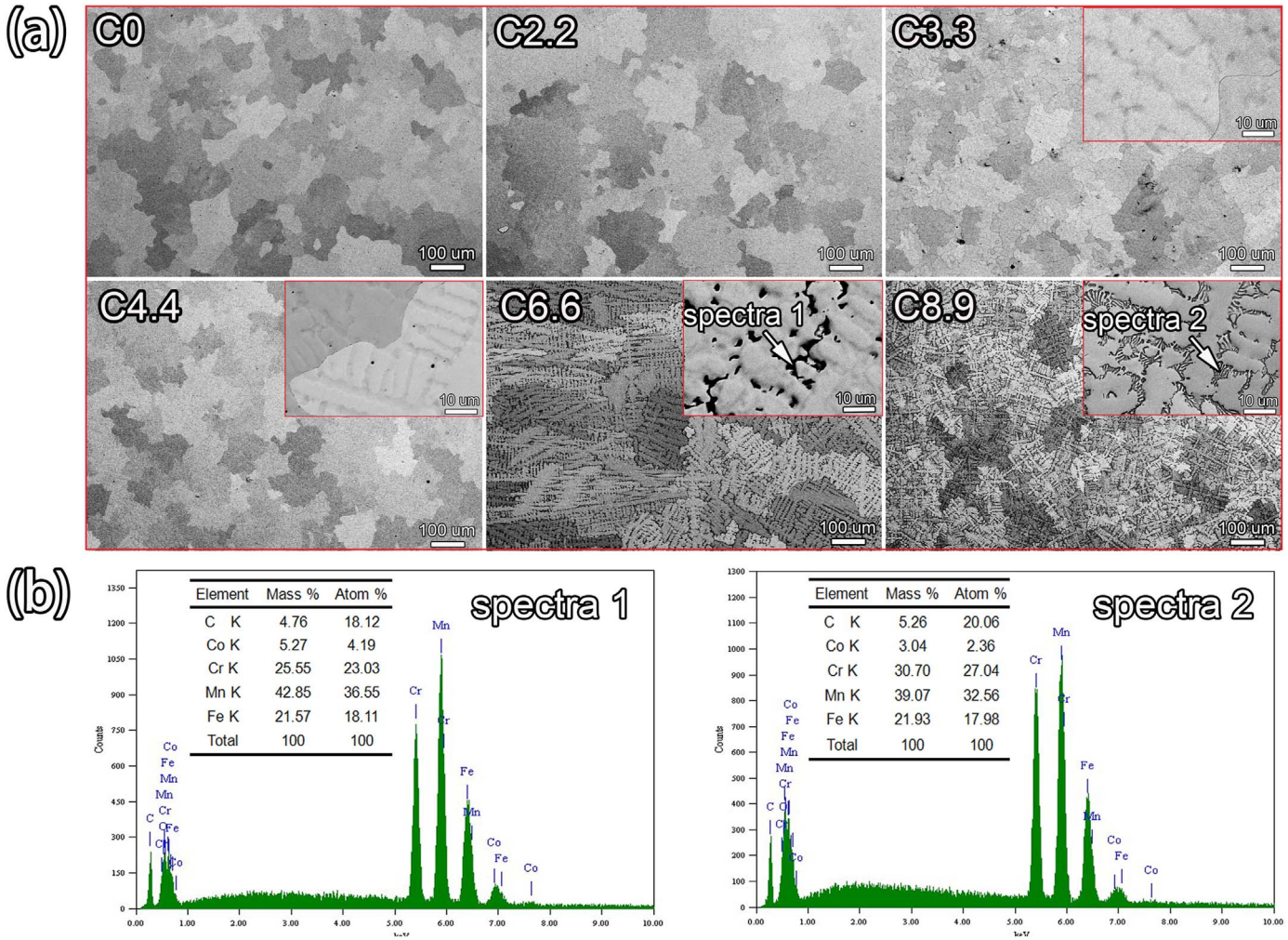

Fig. 2. (a) BSE images of the $Fe_{40}Mn_{40}Cr_{10}Co_{10}$ HEAs with different carbon content, the insets are the magnified images. (b) EDS spectra of carbides in C6.6 and C8.9 HEA respectively.

Cr and 99% graphite under a Ti-gettered high-purity argon atmosphere in a water-cooled copper hearth. The corresponding mass fraction (wt %) of C in C0, C2.2, C3.3, C4.4, C6.6 and C8.9 is 0, 0.5, 0.75, 1.0, 1.5 and 2.11 respectively. Additional 5 wt% Mn was added to compensate for the loss of Mn by evaporation during melting. To ensure chemical homogeneity, each ingot was flipped and re-melted 5 times with electromagnetic stirring and then drop casted into a plat with dimension of 60 mm × 40 mm × 10 mm.

The microstructure was examined by X-ray diffraction (XRD) using Cu-K_α radiation and transmission electron microscope (TEM) in JEM-2100F. For examination in the scanning electron microscope (SEM), specimens were firstly mechanical polished and then electro-polished for approximate 30 s using an electrolyte consisting of 25% nitric acid in methanol at a temperature of 250 K, an applied voltage of 20 V and a current of 50 mA. Polished and etched as-cast specimens were examined using back scattering electron (BSE) imaging and fracture surfaces were examined using secondary electron (SE) imaging on a HITACHI SU6600 SEM equipped with energy dispersive spectrometry