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A new pseudo binary strategy to design eutectic high entropy alloys using mixing enthalpy and valence electron concentration

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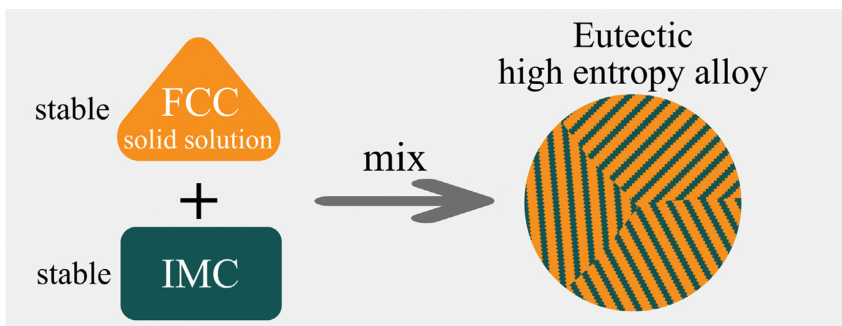
HIGHLIGHTS

- A pseudo binary strategy was proposed to design eutectic high entropy alloys;
- An eutectic high entropy alloy can be obtained by mixing a stable FCC-structured solid solution and a stable IMC;
- Three eutectic high entropy alloys were successfully prepared using this strategy;
- All the three alloys exhibited excellent tensile properties, with fracture strength > 1000 MPa and elongation > 10%.

GRAPHICAL ABSTRACT



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ABSTRACT

Eutectic high entropy alloys (EHEAs) have attracted wide attention of material scientists and engineering scientists due to the good castability, phase stability as well as excellent mechanical properties. However, it still remains a huge challenge to design EHEAs accurately on account of the inaccuracy of multicomponent phase diagram calculation and complexity of experimental exploration. Here, a simple and practicable pseudo binary method was proposed to design EHEAs using the parameters of valence electron concentration (VEC) and mixing enthalpy ($\triangle H_{mix}$). Using this strategy, a series of nanostructured EHEAs composed of ordered body centered cubic (B2) phase and face centered cubic (FCC) phase were successfully developed. All the designed alloys in the current work exhibited excellent comprehensive mechanical properties, with a tensile fracture strength higher than 1000 MPa and a total elongation > 10%. The combination of high strength and good plasticity indicates a significant potential application in engineering field. Furthermore, this new strategy is not only suitable for the current work but also available for the majority of reported EHEAs, which shows great universality in designing EHEAs.

1. Introduction

Traditional alloys designed based on one principal element have been used for thousand years, which lay a foundation for modern industry. Recently, a new kind of multicomponent alloys, namely, high entropy alloys (HEAs) were proposed by Yeh et al. [1]. HEAs were primarily designed as a kind of alloys composed of five or more elements in equimolar or near-equimolar ratio. Afterwards, a general definition stated that alloys with a mixing entropy higher than 1.5R (R is gas constant) can be called HEAs [2]. HEAs have attracted great interest for their simple phase composition and good structure stability, and numerous HEAs have been reported to consist of a single body centered cubic (BCC) or face centered cubic (FCC) structure [3,4]. However, alloys

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consisted of a single FCC phase usually show good plasticity but low strength while those consisted of a single BCC phase always exhibit high strength but poor ductility [5,6]. HEAs with a mixture of soft FCC phase and hard BCC phase are supposed to achieve excellent comprehensive properties [7,8]. Therefore, many parameters have been adopted for designing dual phase HEAs, such as mixing entropy ($\triangle S_{mix}$), mixing enthalpy ($\triangle H_{mix}$), valence electron concentration (VEC), atom radius difference (δ) [9–12].

In fact, some of dual phase HEAs do not possess outstanding properties on account of the irregular phase morphology, nonuniform phase distribution or the unmatched phase volume fracture [13]. More recently, Lu et al. has proposed a new strategy to balance the strength and ductility efficiently, i.e. to achieve eutectic high entropy alloys (EHEAs) composed of soft FCC and hard BCC phases [14]. It is believed that this kind of EHEAs contain both the advantages of eutectic alloys and HEAs. The eutectic microstructure provides excellent castability while the combination of FCC and BCC phases contributes to the comprehensive mechanical properties. Using this strategy, a $AlCoCrFeNi_{2.1}$ EHEA was successfully designed and has attracted great attention due to its combination of high strength (944 MPa) and good ductility (25.6%) [14]. The strength of cold rolled $AlCoCrFeNi_{2.1}$ alloy even reached up to 1.8 GPa, while the elongation remains ~6% [15]. Gao et al. [16] deeply analyzed the mechanism for the combination of high strength and good ductility of $AlCoCrFeNi_{2.1}$ alloy and attributed the excellent performance to the back stress caused by lamellar ordered face centered cubic ($L1_2$)/B2 structure. To be specific, vast accumulation of dislocations and stacking faults near the phase interfaces are responsible for the high strain hardening and ductility. Cr-enriched nanoprecipitates embedded in B2 phases further enhance the strength while the synchronous deformation of B2 and $L1_2$ phases improves the high ductility. In fact, the majority of EHEAs are found to achieve a microstructure of fine alternative lamellar phases, which were beneficial to hinder the moving of dislocation and the growth of crack [17]. He et al. [18] studied the stability of $CoCrFeNb_{0.65}Ni$ EHEAs and found that lamellar structure was stable up to 750 °C, which shows great utilization potentiality at high temperature. The excellent casting property and phase stability at elevated temperature of eutectic structure immensely improved the EHEAs' industry application values. Despite the brilliant application prospect, how to design EHEAs is still a huge challenge. Till now, three main methods have been reported to design EHEAs. The first one is calculation of phase diagram (CALPHAD) method [19]; the second one is experimental method, namely, assuming one EHEA and then regulating the crucial element [14]; the last one is substitution method, namely, replacing one element in an EHEA by another element based on binary mixing enthalpy [20]. However, neither of the first two methods can be adopted to develop EHEAs easily due to the guideless assumption and the complexity and inaccuracy of multicomponent phase diagram calculation and experimental determination. The last method can be used to explore new EHEAs easily and effectively based on a known EHEA, but the requirement of a known EHEA limits its wide application.

In the present work, a simple and practicable method was proposed to design pseudo binary EHEAs composed of FCC/B2 dual phases using parameters VEC and ΔH_{mix}. In our design, the two components of traditional binary alloy phase diagram are replaced by a solid solution phase with FCC structure and NiAl intermetallic compound (IMC), respectively. Undoubtedly, this replacement can only been conducted when the FCC phase and intermetallic phase are stable enough compared

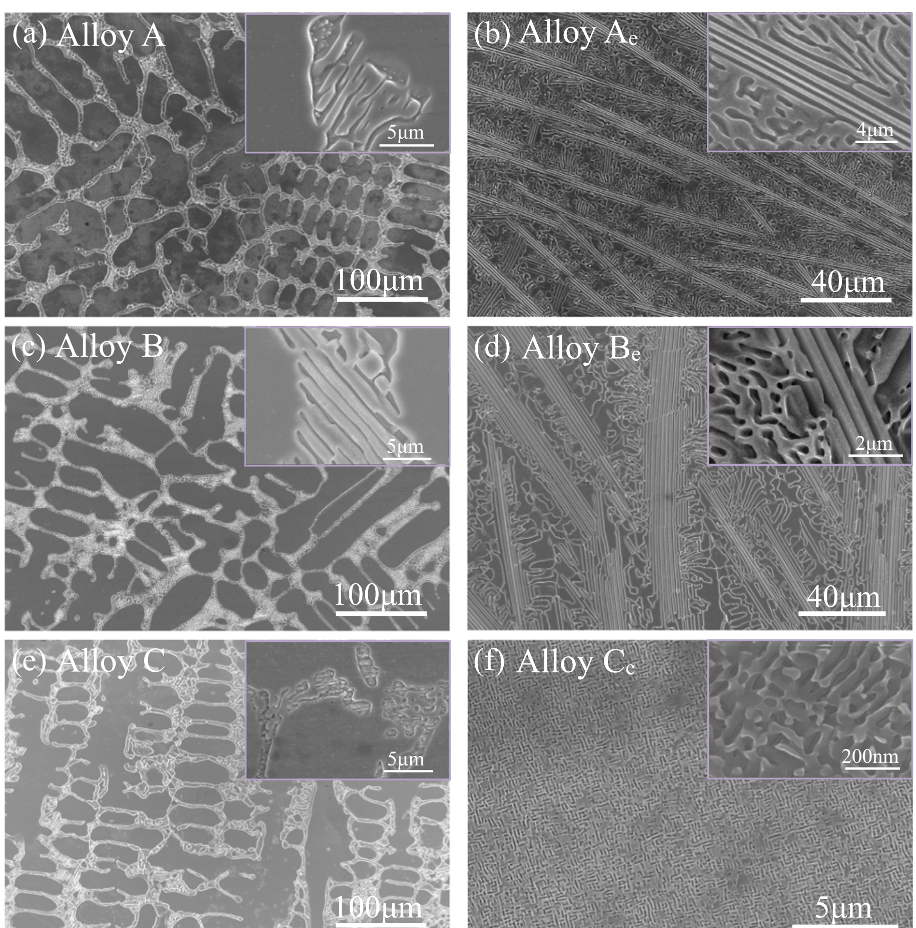

Fig. 1. SEM images of as-cast HEAs; (a) alloy A, (b) alloy A_e, (c) alloy B, (d) alloy B_e, (e) alloy C, (f) alloy C_e. Illustrations show magnified microstructure of corresponding.