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A novel modifier on the microstructure and mechanical properties of Al-7Si alloys

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ABSTRACT

In this work, the AlCoCrFeNiTi high-entropy alloy (HEA) was prepared as an inoculant to refine the α-Al and silicon phases in Al-7Si alloy. The modification mechanism and the existing form of HEA in Al-7Si alloy were studied. The results show that Fe-rich intermetallics including Al, Si, Co, Fe and Ni, precipitated when the 0.2% AlCoCrFeNiTi HEA was added into Al-7Si alloy. In addition, the elements of Ti and Cr uniformly distributed within Al-7Si alloy. The morphology of the eutectic silicon changed from long needle structure to short rod and granular structure. Moreover, the size of α-Al grains significantly decreased in Al-7Si-0.2HEA alloy. The mechanical properties of Al-7Si alloy significantly improved.

1. Introduction

Aluminium-silicon alloys have been widely used in the automotive and aerospace industries due to their high specific strength, light weight, good thermal conductivity, excellent wear resistance and corrosion resistance [1]. In recent years, the massive applications of lightweight Al-Si alloys in the automotive industry have reduced energy consumption and emissions [2]. Thus, the Al-Si alloys are considered to be a good candidate replacing the cast iron. However, the morphology of the eutectic silicon in Al-Si alloys exists in the form of coarse needle-like structure, which results in low ductility and fracture resistance [3,4]. Therefore, the microstructure must be modified and refined to improve its mechanical properties by changing the morphology and decreasing the grain size in hypoeutectic Al-Si alloys.

High-entropy alloys (HEAs) is defined as a multi-component alloy that contains at least five principal elements with each having a concentration that ranges between 5 and 35 at%. In general, these alloys tend to form a simple microstructure of solid solutions [5,6]. In this work, the morphology of eutectic silicon changed significantly from long needle shape to short rod and fine granularity and the grain size of α-Al significantly reduced when trace amounts of AlCoCrFeNiTi alloy were added into Al-7Si alloy. Moreover, the mechanism of the modification is discussed in detail.

2. Experimental details

2.1. Preparation of AlCoCrFeNiTi HEA

The AlCoCrFeNiTi HEA (nominal composition is equimolar for each element) including high-purity Al, Co, Cr, Fe, Ni and Ti elements was prepared using vacuum arc furnace. The alloys were remelted at least five times to ensure that the alloy had the uniform chemical composition and microstructure. The phases and elemental distribution of HEA were analyzed by X-ray diffraction (XRD) instrument (D/max-2400) and electron probe micro-analysis (EPMA).

2.2. Modification of the Al-7Si alloy via AlCoCrFeNiTi HEA

The Al-7Si alloy was prepared using commercially available pure aluminum (99.8%) and hypereutectic Al-20Si alloy in a clay graphite crucible with Si-C rod melting furnace heated to the temperature of 800 °C. Subsequently, a nominal amount (0.2 wt%) of AlCoCrFeNiTi HEA was added into the melt, held for 60 min and stirred every 10 min to ensure homogeneity of the composition.

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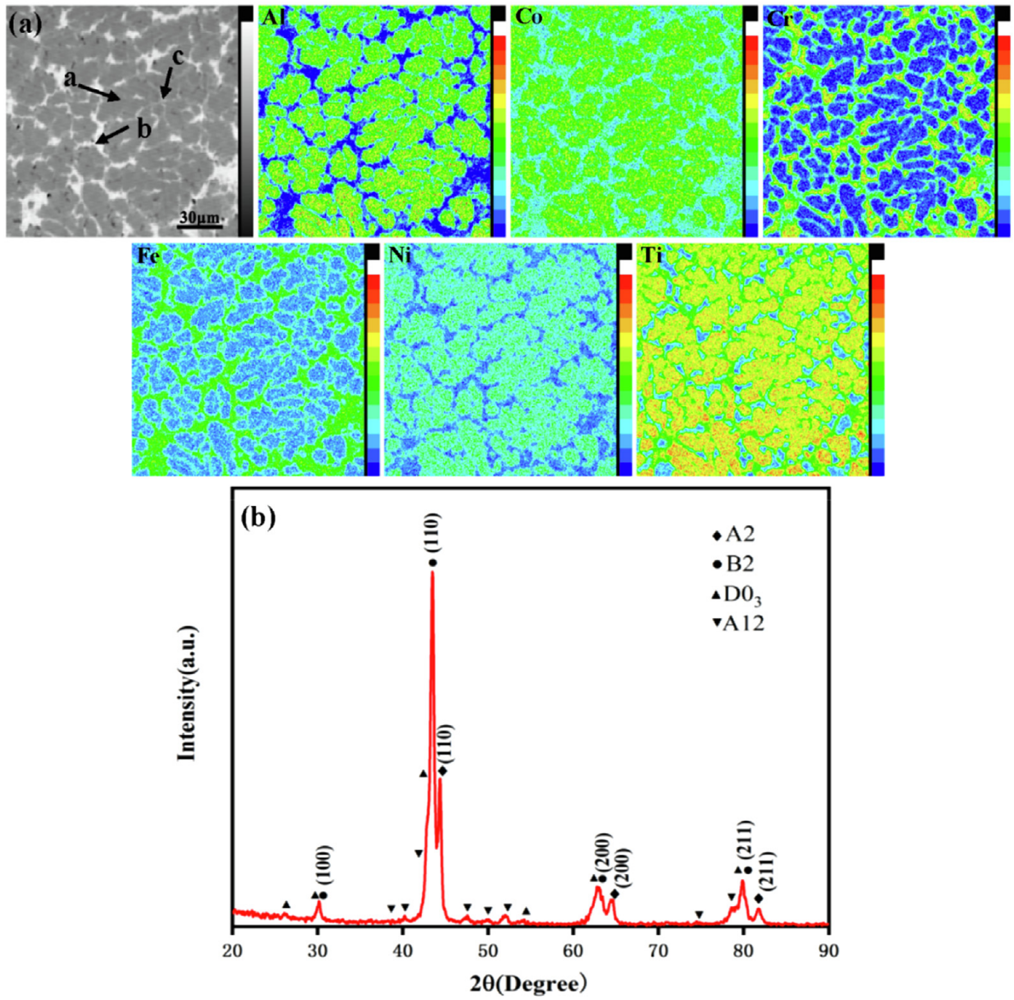

Fig. 1. EPMA analysis and XRD pattern of AlCoCrFeNiTi HEA.

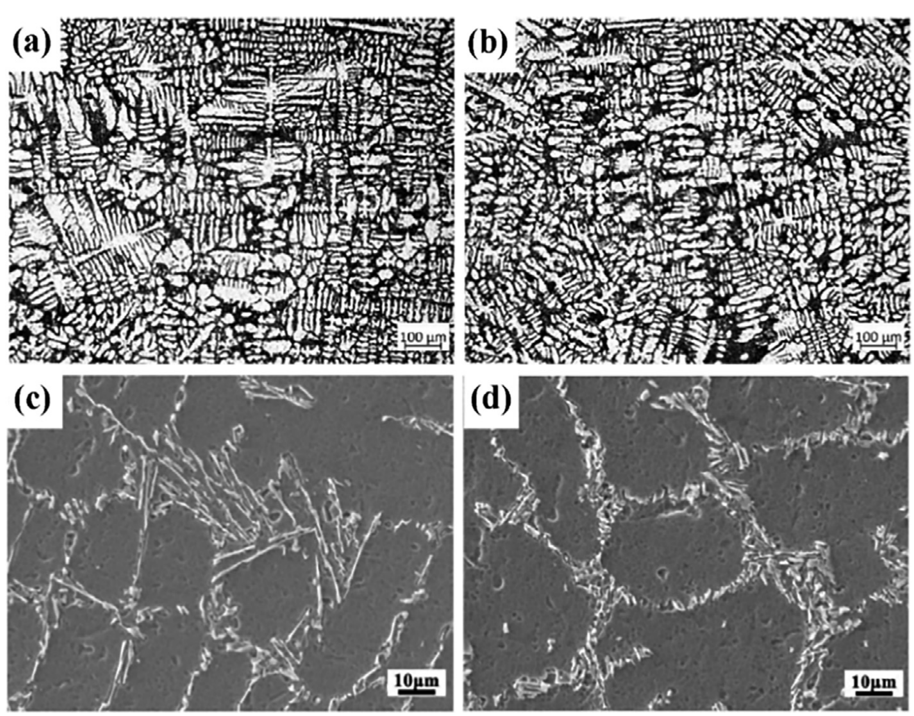

Fig. 2. Images of α-Al and eutectic Si: (a), (c) without HEA; (b), (d) 0.2%HEA.

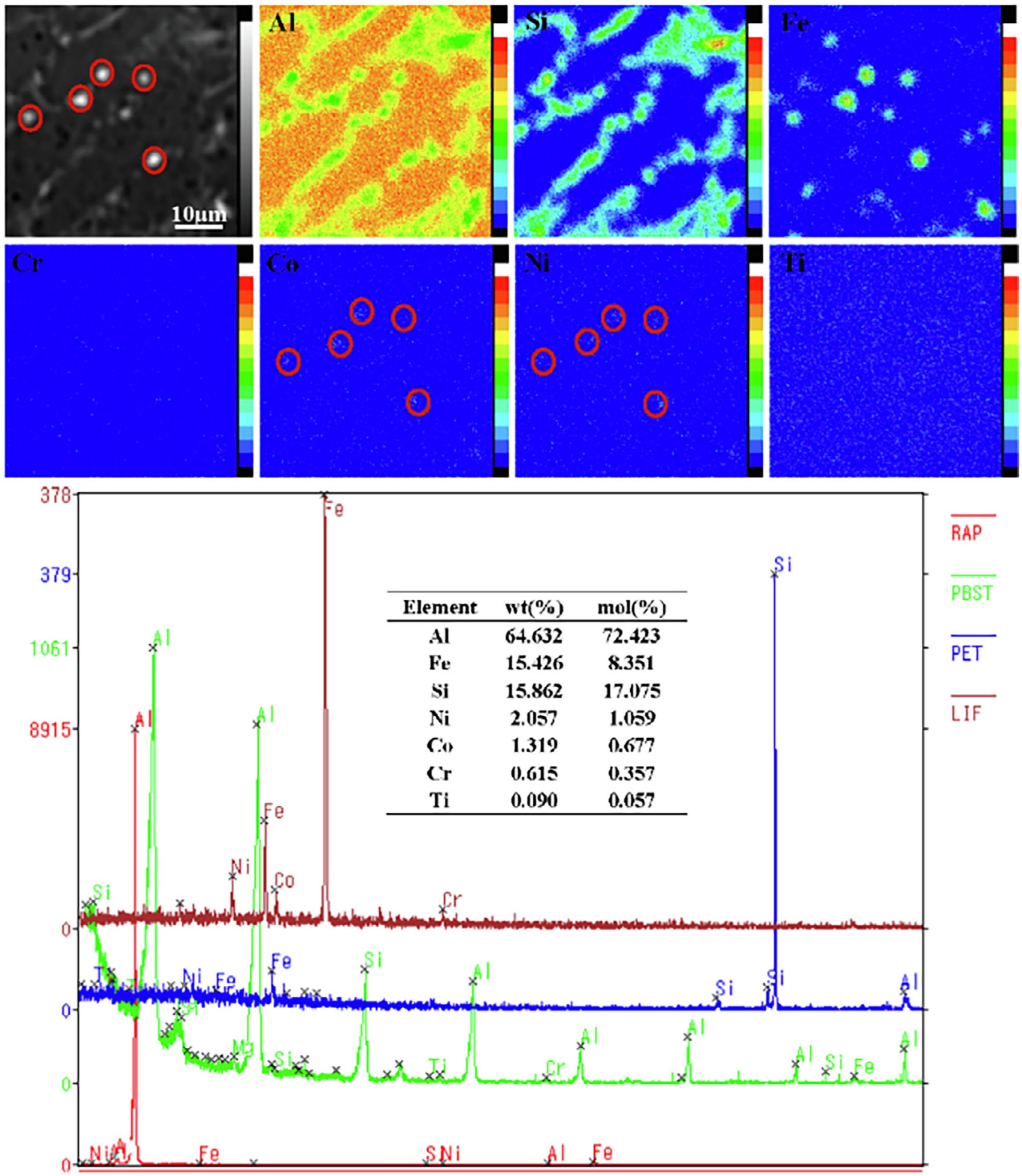

Fig. 3. EPMA analysis and WDS analysis of Al-7Si-0.2HEA.

Finally, the hexachloroethane (C_2Cl_6) was introduced into the melt. After that, the melt is poured into the steel mold that was preheated to 200 °C when the melt temperature drops to 720 °C.

The samples were taken at the same position of each ingot and metallorgraphic samples were prepared according to standard procedures. The microstructural evolution of the Al-7Si alloy was analyzed using optical microscopy, field emission scanning electron microscope (SEM), EPMA and transmission electron microscopy (TEM).

3. Results and discussion

Fig. 1(a) shows the mapping analysis of the AlCoCrFeNiTi HEA using EPMA. It is seen that the dendritic phase contains mostly Al, Co, Ni and Ti (phase a), while the Fe and Cr elements mainly distribute in the interdendrite region (phases b and c). Fig. 1(b) shows the XRD patterns of the AlCoCrFeNiTi HEA, indicating that the diffraction peaks consist of two simple body-centered cubic (BCC) phases (denoted as B2 and A2) and two complex structure phases (denoted as $D0_3$ and A12). The literature shows that the B2-BCC ordered phase is the NiAl based solid solution formed in the dendritic region, while the A2-BCC disordered phase is generated from Cr-Fe rich precipitation [5]. The $D0_3$ is the solid solution with $AlFe_3$-type structure, and the A12 is the solid solution with α-Mn type structure [6].

The micrographs of the primary α-Al and the eutectic silicon in the Al-7Si alloy are shown in Fig. 2. Fig. 2(a) and (b) show the optical micrographs of the primary α-Al. It is obvious that the grain size of α-Al significantly decreased when the 0.2% HEA was added into the melt. In addition, Fig. 2(c) and (d) show the SEM micrographs of the eutectic silicon structure. It is clearly observed that the morphology of the eutectic silicon changed from long needle shape to short rod and fine granularity. This result indicates that the HEA can effectively refine the primary α-Al dendrites and modify the eutectic silicon structure of Al-7Si alloy.

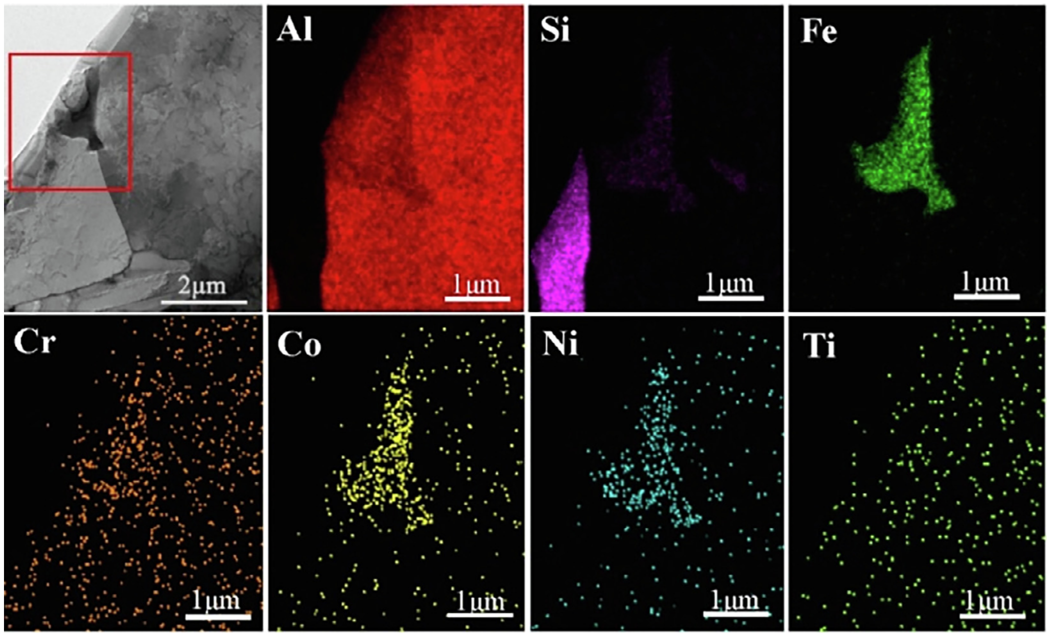

Fig. 4. Dark field TEM micrograph from casting and mapping by EDS to indicate the distribution of Al, Si, Fe, Cr, Co, Ni and Ti elements in modified Al-7Si-0.2HEA alloys.

Table 1
The results of mechanical properties.

Alloy	UTS(MPa)	El(%)
Base alloy	168	12.1
Base alloy +0.2%HEA	195	18.3

Kogtenkova et al. [7,8] investigated the transition of grain boundary wetting from incomplete to complete wetting in Cu-Co alloys, and found that the fraction of complete wetted grain boundaries increases with improving temperature. The transition is associated with the differences in grain boundary σ_{GB} and interphase boundary σ_{IB} energies. Therefore, improving the temperature should be beneficial for increasing the wettability of the particles and alloy matrix. The mapping and point analyses of the Al-7Si-0.2HEA alloy were carried out to confirm the existence and distribution of the HEA elements using EPMA, as shown in Fig. 3. It is observed from the back-scattered electron image (BSE) in Fig. 3 that the precipitated particles distribute in the alloy matrix with an average size of approximately 3.5 μm. In addition, the HEA effectively refined the primary α-Al dendrites and modified the eutectic silicon structure in Al-7Si alloy as shown in Fig. 2. Hence the precipitated particles and the alloy melt have good wettability. Moreover, it is obviously found that the particles mainly contain Al, Si, Fe, Co and Ni, but the elements of Ti and Cr uniformly distribute in the Al-7Si alloy. The refining role of Ti solutes element is significant for the α-Al dendrites in Al-7Si alloy. The growth restriction factor (Q) is usually used to quantify the effect of solutes on the grain refinement, as given by Eq. (1) [9]:

$$Q = C_0 M_L (k - 1) \tag{1}$$

where C_0 is the initial solute concentration, M_L is the liquidus slope, and k is the equilibrium partition coefficient of the alloy. Generally, the grain size significantly decreases as the Q increases [10]. The literature indicates that Ti has the largest Q value among all the solute elements of the considered aluminum alloy [11]. Therefore, the refinement of α-Al grains in Al-7Si alloy is because the Ti restricts the growth of the α-Al phase and increases the nucleation rate.

To further investigate the modifications to the eutectic silicon for Fe-rich intermetallics in the Al-7Si alloy, Fig. 4 shows TEM micrographs for the Fe-rich particles in the alloy with 0.2% HEA inoculant. The mean particle size is approximately 2 μm and mainly contains Al, Si, Fe, Co and Ni as shown in Fig. 4. Moreover, it is obviously observed that the particles exist at the Si/Al interface, which prevents the growth of eutectic Si and α-Al during the solidification process. Based on the above discussion, it is concluded that the addition of the AlCoCrFeNiTi HEA can not only effectively modify the eutectic silicon, but also can significantly refine the α-Al dendrites in Al-7Si alloy.

Table 1 shows the mechanical properties of the base Al-7Si alloy and the alloy with 0.2% HEA inoculant. The UTS increased by 16.07% from 168 MPa to 195 MPa and the El increased by 51.24% from 12.1% to 18.3% because of the refinements and modifications for the primary α-Al and eutectic Si phases. In addition, the fine Fe-rich particles uniformly distributing in the alloy matrix can improve the strength of Al-7Si alloy [12].

4. Conclusions

The effect of AlCoCrFeNiTi HEA on the microstructure in Al-7Si alloys was investigated. The results show that:

1. The addition of the AlCoCrFeNiTi HEA effectively hindered the growth of the eutectic silicon and α-Al phases in the Al-7Si alloy. The morphology of the eutectic silicon changed from long needle shape to short rod and fine granularity.
2. The addition, the 0.2% AlCoCrFeNiTi HEA precipitates Fe-rich particles of 3.5 μm that contain Al, Si, Co, Cr, Fe and Ni.
3. When adding 0.2% HEA in the Al-7Si alloy, the UTS increased by 16.07% from 168 MPa to 195 MPa and the El increased by 51.24% from 12.1% to 18.3% because of the refinement and modification of the primary α-Al and eutectic Si phases.

Declaration of Competing Interest

None.

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