Improved mechanical properties of AlCrFeNi high-entropy alloy with gradient structure

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Abstract:
Two kinds of gradient structures, normal gradient structure synthesized by surface mechanical grinding treatment and inverse gradient structure by ultra-high frequency electromagnetic induction heating treatment, were fabricated on an AlCrFeNi high-entropy alloy and its effects on mechanical properties were investigated. Uniaxial tensile results show that the normal gradient structure slightly improved the yield strength but deteriorated the tensile ductility. In contrast, inverse gradient structure exhibits an obviously enhanced tensile ductility without sacrifice the strength. Structure analysis indicates that the improved tensile ductility of the inverse gradient structure is attributed to a phase transformation from B2→FCC and recrystallized grain, which providing additional work hardening ability to the global sample. Relaxed residual stress and declined dislocation density are also beneficial to the tensile ductility.

Keywords: high entropy alloy; gradient structure; defects; microstructure; deformation and fracture; phase transformation;

1. Introduction
High-entropy alloy (HEA) has attracted intensified attention in recent years due to its high strength and ductility, outstanding fracture toughness, good corrosion, oxidation and thermal-softening resistances [1, 2]. However, high strength and good ductility are generally exclusive to each other in most HEAs. Single-phased body-centered cubic (FCC)-structured HEAs have high strength but limited ductility, and face-centered cubic (FCC)-structured HEAs are the opposite [3]. To improve the mechanical properties of HEAs is still challenging in materials research community.

Recently, gradient nanograined structure (GNS) has been approved to be effective in improving mechanical properties in many pure metals and alloys [4, 5]. Nevertheless, limited literatures reported gradient structures in HEAs [6]. In addition, inverse gradient structures also exhibits superior strength-ductility synergy in AISI 316L stainless steel, as reported by Long et al. [7]. In this work, we explore the possibility of strengthening and toughening HEAs with gradient structures. Two kinds of gradient structures, i.e., normal gradient structure induced by surface mechanical grinding treatment (SMGT) [8] and inverse gradient structure (IGNS) [7] induced by electromagnetic induction heating (EMIH) were synthesized in an AlCrFeNi HEA and its mechanical properties were investigated. Specially, effects of different gradient structures on the mechanical properties were elucidated.

2. Experimental
AlCrFe2Ni2 HEA bars with 8 cm in diameter were cut from a cast ingot. The initial average grain size is about 300 mm. To fabricate the GNS, the AlCrFeNi HEA bar was grinded by a hemi-sphere WC-Co tip for 20 passes. The initial feed depth is 60 mm. In each pass, an extra 60 mm is accumulated to the feed depth. The rotate speed is 200 r/min and the feed speed is 10 mm/min. To fabricate the IGNS, an electromagnetic induction heater with ultra-high frequency is adopted. The AlCrFeNi HEA bar was placed in the coil and heated by the eddy current. Due to the skin effect, heat is concentrated in the surface and decays exponentially with depth.

Gradient structures were then characterized by X-ray diffraction, scan electro microscopy (SEM) and electro back scatter diffraction (EBSD). Microhardness test was applied and uniaxial tensile test were performed on an Instron S898 with non-contact optical extensometer. Tensile strain rate is set to be 1×10⁻⁴.
3. Results and discussion

The as-cast AlCrFe2Ni2 HEA composed of AlNi-riched regions with B2 phase (in gray contrast in Fig. 1) and FeNi-riched regions with FCC structure (in bright). Fig. 1a presents the GNS produced by SMGT after 20 passes. In the surface, initial grain boundaries and phase boundaries are totally eliminated by severe plastic deformation. Grains are substantially refined. EDS analysis show that element distribution becomes uniform. It is noted that microcracks are presented in this layer, as marked by arrows in Fig. 1a. As the depth increased, a distinct boundary appears and sharply separates the deformed layer and the matrix layer beneath. Across the boundary, the structure is similar to the as-cast state. Generally, sharp boundaries are likely to cause stress concentration, which is bad for the tensile ductility.

![Fig. 1. Back scatter diffraction images show the morphology of (a) GNS and (b) IGNS. Arrows in (a) indicate the microcracks.](image1)

Fig. 1b shows the morphology of the AlCrFeNi HEA after EMIH treatment. In the surface, the bright area which representing the FCC structure is evidently enlarged. EBSD and X-ray diffraction results confirmed that most of the B2 phase has transformed into FCC phase. EDS analysis shows no obvious change in the composition. The thickness of this layer is ~15 mm. No micro-crack has been observed. As the depth increased, a transient layer appears. In this layer, the B2 structure is reserved. And the lamella thicknesses of both phases are evidently coarsened. With the further increased depth, the heat decays rapidly. Beyond the depth of 30 mm, phase structure and lamella thickness are similar to that of the as-cast state.

Cross-sectional hardness profile confirms the formation of GNS and IGNS. As shown in Fig. 2a, the surface hardness of the GNS reached 3.7 GPa due to the severe grain refinement. With increasing depth, the hardness dropped steeply. At depth of 300 mm, the hardness profile levels off and stabilizes at 3.01±0.06 GPa. This hardness value is similar to that of the as-cast state (3.0±0.07 GPa). Compared with microstructure observation, the estimated thickness of the GNS layer based on hardness profile is evidently larger. It indicates that grains under the sharp boundary are also affected by the deformation. In contrast, the surface hardness of the IGNS is substantially lowered to 2.47 GPa after the EMIH treatment. And the hardness increased exponentially with increasing depths. At depth of 200 mm, the hardness is stabilized and fluctuated around 3.06±0.02 GPa.

![Fig. 2. (a) Hardness profiles of GNS and IGNS compared with the as-cast. (b) Uniaxial tensile curves of GNS and IGNS compared with the as-cast.](image2)
Uniaxial tensile results of the GNS and IGNS sample were illustrated in Fig. 2b. The as-cast sample was adopted for comparison. The as-cast sample yields at 634 MPa and maintains a uniform elongation about 8.5%. The GNS sample exhibits enhanced yield strength about 655 MPa. Grain refinement induced by SMGT is beneficial to the strength. The limited improvement on the yield strength is due to the small fraction of the GNS layer. Based on the SEM and hardness profile, the volume fraction of the GNS is estimated to be 14% where the most severely deformed layer is less than 1.5%. Meanwhile, the GNS sample exhibits a reduced uniform elongation about 8.1% in relative to the as-cast sample. Apparently, microcracks are detrimental to the tensile ductility since pre-mature fracture of the surface layer usually initiates from the microcracks. In contrast, the IGNS sample exhibits yield strength about 616 MPa, slightly lower than that of the GNS. The reduced yield strength was attributed to the softened surface layer. But the declination is also small because of the small volume fraction of the IGNS layer. The overall thickness of the IGNS layer is less than 100 mm, implying a volume fraction less than 5%. Nevertheless, the uniform elongation has prolonged to 11%. A superior strength-ductility synergy is obtained in the IGNS AlCrFeNi HEA.

Fig. 3. IPF image of the IGNS surface layer after tensile strained 11%.

Apparently, the modified mechanical properties of the GNS and IGNS sample originate from the unique surface layer. Severely deformed surface layer in GNS enhances the yield strength but also deteriorates the tensile ductility. While in IGNS, the softened surface layer significantly improved the tensile ductility without sacrifice the yield strength. Three reasons contribute to the improved ductility. Firstly, the brittle B2 structure in the surface has transformed into FCC structures. As illustrated by EBSD images in Fig. 3, both the volume fraction and lamella thickness of the FCC are obviously increased. FCC structures generally have better plastic deformability than B2 structures. The phase transformation provides a more ductile surface layer, providing better work hardening ability to the global sample. Post-mortem hardness results confirm the surface hardness of the IGNS increased from 2.3 GPa to 3.7 GPa. Secondly, the induction heat eliminates pre-existed dislocations. During casting and solidification, abundant dislocations are generated to accommodate the strain mismatch across different phases. Dislocations with high density aggregate around phase boundaries which is harmful to the ductility. The elimination of those dislocations will provide plenty room for the generation and motion of new dislocations. Therefore, the declination of pre-existed dislocations is beneficial to the ductility. Hardness results prove that after tensile deformation, hardness in the core center slightly increased to 3.64±0.09 GPa. Meanwhile, surface materials are quickly work-hardened, leading to a uniform hardness distribution across the whole sample. In addition, inter-lamellar spacing in the transient layer is evidently coarsened. It provides large rooms for the dislocation activities, which is also advantageous to the ductility. Thirdly, high residual stress commonly exists in the cast HEAs. As illustrated in Table 1, the residual stress in the as-cast alloy ranges from -797 to 5836 MPa. It indicated that high stress concentration was induced during the casting. After 20 passes of SMGT, the residual stress in the GNS declined to -380±97 MPa. In contrast, the IGNS sample exhibits an averaged compressive residual stress about -24 MPa. During EMIH treatment, the stress concentration in the phase boundaries is effectively released.

Table 1. XRD measured residual stress of different structures

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<th>GNS</th>
<th>IGNS</th>
<th>As-cast</th>
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<tr>
<td>Residual stress</td>
<td>-380±97 MPa</td>
<td>-24 MPa</td>
<td>-797~5836 MPa</td>
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4. Conclusion

In summary, gradient structures (including GNS and IGNS) were synthesized on an AlCrFeNi high-entropy alloy. Tensile results show that the ductility of GNS sample was deteriorated, which was mainly attributed to the microcracks in the GNS layer. In contrast, the tensile ductility of the IGNS sample was evidently enhanced without sacrificing the yield strength. Microstructure analyses show that the improved tensile ductility is attributed to the $\text{B2} \rightarrow \text{FCC}$ phase transformation and recrystallization. Multiple slip systems and ample rooms are beneficial to the ductility. In addition, declined dislocation density and residual stress also contribute to the improvement in the mechanical properties.

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References


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