Solidification microstructure and properties of \( \text{Ni}_{(60-y)}\text{Fe}_{20}\text{Co}_{10}\text{Cr}_{10}\text{Al}_{y} \) high-entropy alloys

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Abstract. A series of eutectic high-entropy alloys \( \text{Ni}_{(60-y)}\text{Fe}_{20}\text{Co}_{10}\text{Cr}_{10}\text{Al}_{y} \) (y = 0, 5, 10, 15, 20, 25) were synthesized via non-consumable vacuum melting, followed by investigation into their solidification microstructures and compression properties. The research results reveal that the solidification microstructures transition from a well-distributed FCC phase (y=0, y=5) to a coarse FCC+B2 isometric crystal structure (y=10), subsequently to a primary FCC phase with a (FCC+B2) eutectic structure (y=15), succeeded by a predominant B2 phase with a (FCC+B2) eutectic microstructure (y=20), and ultimately to a BCC+B2 biphasic structure characterized by periodic braided sheets (y=25). The FCC phase demonstrates a substantial concentration of Ni and Fe, the BCC phase shows substantial enrichment primarily in Fe and Cr, while the B2 phase exhibits significant enrichment in Ni and Al. As the Al content increases, the alloys exhibit higher strength but reduced plasticity. Specifically, alloys with y values of 20 and 25 exhibit yield strengths of 1012 MPa and 1477 MPa, respectively, coupled with remarkable plasticity of 41 and 23%, thereby demonstrating robust mechanical properties.

Keywords: Microstructure; Compressive properties; High entropy alloys.

1. Introduction

Yeh and Cantor first reported high entropy alloys (HEAs) in 2004, initially defining them as alloys containing more than five major elements with atomic fractions ranging from 5 to 35% [1, 2]. HEAs typically form structures dominated by simple solid solutions, including FCC phase [3, 4], BCC phase [5], and HCP phase [6]. The diverse composition and microstructure of HEAs endow them with a range of excellent properties, encompassing high-temperature mechanical properties [7], corrosion resistance [8], wear resistance [9], and low-temperature fracture toughness [10]. However, practical applications require materials that possess both high plasticity and strength. Unfortunately, HEAs with solid solution structures often suffer from poor castability and fluidity, significant compositional segregation, and poor formability, which hinders their industrial application [11].

Nickel-based alloys are renowned for their excellent high-temperature strength, and superior oxidation and corrosion resistance, making them essential components in the aerospace industry [12, 13]. Among these, the AlCoCrFeNi HEAs has garnered significant attention owing to its robust mechanical properties and excellent compressive strength under investigation [14, 15]. The microstructural evolution of AlCoCrFeNi HEAs can be achieved by varying the mixing ratio of transition metals (TMs) [16]. To develop alloys with superior properties and practical application potential, Lu et al. [17] pioneered the use of eutectic alloy concept to formulate HEAs. By basing the design on eutectic composition point ratios and integrating the advantages of FCC and BCC HEAs, they created a lamellar organizational structure in AlCoCrFeNi \(_{13}\) \(_{13}\) biphase eutectic HEAs. These alloys demonstrated outstanding overall mechanical properties, which provided the possibility of large-scale industrial applications of HEAs and spurring further research into systems, such as Al\(_{1.2}\)CrFeNi [18] and CoCrFeNi\(_{0.4}\) [19]. Additionally, Lee [20] and Kumar [21] studied the effect of co-interactions between pairs of elements, specifically Co-Ni and Cr-Al, on the phase composition of AlCoCrFeNi alloys. However, there is limited research on the co-interaction of Ni-Al in the eutectic alloys within the AlCoCrFeNi series.

To address the aforementioned issues, this paper focuses on the AlCoCrFeNi HEAs. Related research indicates that Al facilitates the emergence of the BCC phase, whereas Ni stabilizes the
FCC phase [22]. The Cr content is controlled at 15 at% to avoid the crystallization of hard and brittle phases due to high Cr levels [23]. Given the higher cost of Co, its content is limited to 10 at%, whereas Fe, being low-cost, strengthens the alloy and makes it suitable for medium-temperature environments, thus it is maintained at 20 at% [24]. Therefore, this study designs Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} (y= 0, 5, 10, 15, 20, 25) HEAs. Investigating how variations in the Al and Ni elements affect the solidification structure and properties of AlCoCrFeNi HEAs, we aim to create eutectic HEAs that exhibit excellent overall mechanical properties.

2. Experimental

High-purity raw materials (Ni, Fe, Co, Cr, and Al, purity > 99.9%) were employed to synthesize non-equiatomic Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} (y= 0, 5, 10, 15, 20, 25) HEAs ingots using non-consumable vacuum melting. The highest degree of chemical homogeneity was ensured in each 30 g ingot through meticulous processing, including flipping and re-melting at least five times.

Crystallographic analyses were conducted using an Ultima IV diffractometer operating at 40 kV/40 mA with CuKα radiation, scanning from 20° to 100° at a speed of 4°/min. Microstructural features and elemental composition were investigated using a Phenom Pro scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS). Specimens for SEM characterization were prepared by abrasion. Room temperature compression tests were conducted using a WDW100E universal testing machine at a strain rate of 5×10^{-4} s^{-1}.

3. Results and Discussion

3.1 Crystal Structure.

Fig. 1 illustrates the X-ray diffractograms of Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} (y= 0, 5, 10, 15, 20, 25) HEAs. As the Al element increases, the results demonstrate a pronounced shift from FCC to BCC phase. The solidification microstructure evolves from FCC structure to FCC+B2 structures, and ultimately to a configuration comprising B2+BCC structures. Alloys with Al contents of 0 and 5 display a single FCC phase. For alloys containing 10 to 20 atomic percent of Al, the microstructures reveal a combination of FCC and B2 structures, as indicated by the (100) B2 peak of the ordered BCC (B2, similar to NiAl intermetallic compounds [25]) structure first appearing at y=10, consistent with the findings of Tian Q et al. [26]. At this point, the (100) B2 peak nearly overlaps with the (111) FCC peak. A significant reduction in the intensity of the FCC phase diffraction peak is observed, accompanied by an enhancement in the intensity of the B2 structure peak, suggesting a shift towards decreased FCC phase presence and increased B2 phase presence. The B2 phase peak becomes more prominent at y=20, with the two phases distinctly separated. The existence of the FCC phase diminishes at y=25, replaced by an emerging peak indicative of the disordered BCC phase, illustrating that the HEA features a combination of B2 + BCC phases at this composition.

Fig. 1(b) displays the locally magnified diffraction patterns of the Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} HEAs, focusing on the 20 range of approximately 70° to 100°. This region was selected because higher grain surface indices correspond to smaller grain surface spacings, making peak shifts more pronounced and easier to observe [27]. The lattice constants for various Al compositions are presented in Table 1. With rising Al content, the expansion of the lattice constant in the FCC structure from 3.5388 Å to 3.5773 Å is caused by the greater atomic radius of Al than the other elements, facilitating the integration of Al atoms into the interstitial sites of the FCC phase, thereby creating a solid solution with interstitial atoms. This causes lattice distortion, leading to a leftward shift of the diffraction peaks in the FCC structure. With increasing Al content, alloys demonstrate a gradual increment in the lattice parameters of the BCC+B2 structures at y = 20 and 25.
Fig. 1 XRD patterns of the Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} \ (y = 0, 5, 10, 15, 20, 25) HEAs.
(a) in the as-cast state; (b) partially magnified

Table 1. The lattice parameters of various phases in Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y}
\ (y = 0, 5, 10, 15, 20, 25) HEAs

<table>
<thead>
<tr>
<th>HEAs</th>
<th>Lattice constant (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCC</td>
</tr>
<tr>
<td>Al-0</td>
<td>3.5388</td>
</tr>
<tr>
<td>Al-5</td>
<td>3.5559</td>
</tr>
<tr>
<td>Al-10</td>
<td>3.5664</td>
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<tr>
<td>Al-15</td>
<td>3.5773</td>
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<tr>
<td>Al-20</td>
<td>3.5187</td>
</tr>
<tr>
<td>Al-25</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Microstructure.

Fig. 2 depicts the SEM images of Ni_{60-y}Fe_{20}Co_{10}Cr_{10}Al_{y} HEAs. Table 2 presents a summary of the EDS results detailing both nominal and actual compositions across various Al contents. Fig. 2(a)-(d) indicate that the microstructures of alloys exhibit consistent or homogeneous characteristics, exhibiting a single cytosolic FCC phase. This finding aligns with the XRD analysis and can be attributed to the comparable atomic radii and electronegativity of Fe and Ni, which facilitate the formation of solid solution phases. Fig. 2(e)-(h) show that the Al-10 and Al-15 alloys present coarse equiaxed crystal structures. EDS results indicate that these equiaxed crystals are abundant in Ni-Fe (FCC phase), while the surrounding grey areas are abundant in Ni and Al, indicating the existence of the B2 phase. Notably, Fig. 2(g)-(h) illustrate that the Al-15 HEA consists of both the FCC structure and a (FCC + B2) structure, characteristic of sub-eutectic structures. During the process of solidification, the initial precipitate is the FCC phase, with Al being rejected to the grain boundaries due to oversaturation. Upon reaching the eutectic temperature and composition, a lamellar eutectic structure consisting of FCC and B2 phases is formed at the grain boundaries during solidification. With further addition of Al, Fig. 2(i) and (j) show that in the Al-20 alloy, the primary phase is B2, and tiny layered structure represents a peritectic eutectic composed of FCC + B2 phases. Fig. 2(k) displays the Al-25 alloy consists of a periodically woven lamellar structure of alternating primary and dark phases. Similar morphologies are observed in the AlCoCrFeNi HEAs [28] and the Fe_{30}Ni_{20}Mn_{25}Al_{25} HEAs [29].
For clear observation of the elemental distribution, EDS surface scanning was performed, as depicted in Fig. 3. The HEAs demonstrate relatively uniform compositions at y=0 and y=5. In the Al-10 alloy, the coarse equiaxial crystalline region displays enrichment in Ni and Fe, while the surrounding grey region exhibits enrichment in Ni-Al. For Al-15, according to the EDS results, Ni, Fe are concentrated in the lamellar region, whereas Ni-Al are distributed in the eutectic region. The EDS analysis for Al-20 reveal enrichment of Ni-Al in the lamellar region, with Ni-Fe present in the eutectic region. The BCC structure of the Al-25 alloy undergoes an AM decomposition reaction, forming a disordered structure (A2) and an ordered structure (B2). Based on the surface scanning results depicted in Fig. 3, the dark phase shows a high concentration of Ni and Al, whereas the debris exhibits a significant presence of Fe and Cr.

![Fig. 2 SEM images of Ni_{(60-y)}Fe_{20}Co_{10}Cr_{10}Al_{y} HEAs: a-b Al-0; c-d Al-5; e-f Al-10; g-h Al-15; i-j Al-20; k-l Al-25](image)

![Fig. 3 EDS surface scan images of Ni_{(60-y)}Fe_{20}Co_{10}Cr_{10}Al_{y} HEAs: a Al-0; b Al-5; c Al-10; d Al-15; e Al-20; f Al-25](image)
Table 2. Nominal composition of Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs and EDS chemical analysis across various regions or phases (at%) 

<table>
<thead>
<tr>
<th>HEAs</th>
<th>Nominal component/ at%</th>
<th>Phase</th>
<th>Unit, at%</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Ni</td>
</tr>
<tr>
<td>Al-0</td>
<td>Ni\textsubscript{60}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}</td>
<td>FCC</td>
<td>60.56</td>
</tr>
<tr>
<td>Al-5</td>
<td>Ni\textsubscript{55}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{5}</td>
<td>FCC</td>
<td>56.36</td>
</tr>
<tr>
<td>Al-10</td>
<td>Ni\textsubscript{50}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{10}</td>
<td>FCC</td>
<td>50.77</td>
</tr>
<tr>
<td>Al-15</td>
<td>Ni\textsubscript{45}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{15}</td>
<td>FCC</td>
<td>45.34</td>
</tr>
<tr>
<td>Al-20</td>
<td>Ni\textsubscript{40}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{20}</td>
<td>FCC</td>
<td>39.18</td>
</tr>
<tr>
<td>Al-25</td>
<td>Ni\textsubscript{35}Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{25}</td>
<td>BCC</td>
<td>30.69</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>51.89</td>
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<tr>
<td></td>
<td></td>
<td>B2</td>
<td>51.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
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<tr>
<td></td>
<td></td>
<td>B2</td>
<td>36.96</td>
</tr>
</tbody>
</table>

3.3 Mechanical properties.

Fig. 4 presents the stress-strain lines of Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} (y = 0, 5, 10, 15, 20, 25) HEAs at room temperature. Table 3 lists the yield strength (σ\textsubscript{0.2}), compressive strength (σ\textsubscript{p}), and fracture strain (ε\textsubscript{p}) obtained from the Fig. 4. It is evident that the fracture strain of the Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs generally decreases, while both the yield strength exhibit an upward trend. The Al-0 and Al-5 HEAs demonstrate excellent plasticity, with fracture strains reaching up to 60% without rupture, though their strengths are relatively low due to the FCC phase. Under compression, the Al-10 alloy demonstrates no fracturing, credited to the presence of the B2 phase, which significantly boosts its strength and offers secondary phase reinforcement. Additionally, the greater atomic dimensions of Al induces lattice distortion, thereby further enhancing the alloy's strength. With further increases in Al content, the Al-15 alloy fractures at 65% strain. This is attributed to the increased B2 phase content, which enhances the second-phase strengthening effect, thereby increasing the alloy's strength but reducing its ductility.

A peri-eutectic structure is observed in the microstructure of the Al-20 HEA, featuring reduced FCC phase content and increased B2 phase content. Although the compressibility decreases to 41%, the synergy between solid-solution strengthening and secondary phase strengthening results in a nearly 200 MPa increase in strength compared to the Al-15 alloy, providing good overall mechanical properties. With the Al content increased to 25 at% (Al-25), the yield strength significantly rises by 465 MPa, reaching 1477 MPa. This increase is attributed not only to solid solution and secondary phases strengthening but to the presence of a braided structure within the ordered B2 phase matrix. The finely spaced BCC/B2 interfaces impede dislocation motion, forcing dislocations to cut through or bypass the second phase, thereby further strengthening the alloy [30].
Fig. 4 True stress-strain compression lines for the Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs at room temperature

Table 3. Mechanical property of the as-cast Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs at room temperature

<table>
<thead>
<tr>
<th>HEAs</th>
<th>$\sigma_{0.2}$ (MPa)</th>
<th>$\sigma_p$ (MPa)</th>
<th>$\varepsilon_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-0</td>
<td>110</td>
<td>-</td>
<td>&gt;65</td>
</tr>
<tr>
<td>Al-5</td>
<td>152</td>
<td>-</td>
<td>&gt;65</td>
</tr>
<tr>
<td>Al-10</td>
<td>445</td>
<td>-</td>
<td>&gt;65</td>
</tr>
<tr>
<td>Al-15</td>
<td>821</td>
<td>-</td>
<td>65</td>
</tr>
<tr>
<td>Al-20</td>
<td>1012</td>
<td>1679</td>
<td>41</td>
</tr>
<tr>
<td>Al-25</td>
<td>1477</td>
<td>1694</td>
<td>23</td>
</tr>
</tbody>
</table>

Fig. 5 compares the compressibility and compressive strength of Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs with some high entropy alloys [31, 32, 33, 34]. The difference in compressive strength between Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} and NiCoFeCrAl\textsubscript{x} (x = 0.74, 1.12, 1.33) is small, despite the Ni\textsubscript{(60-x)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{x}} series containing nearly 10% less Co. Additionally, when compared to Al\textsubscript{17}Co\textsubscript{4}Cr\textsubscript{14}Fe\textsubscript{14}Ni\textsubscript{z} (x = 14.3, 28.6, z = 25.8, 40.1), AlCoCrFeNi\textsubscript{z.1} and CoCrFeNiNb\textsubscript{x} (x = 0.103, 0.155, 0.206, 0.309, 0.412), it is evident that Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} HEAs exhibit favorable overall mechanical properties, indicating their potential for applications.

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3.4 Phase prediction.

Currently, there are several criteria for determining the structural stability of HEAs and predicting the phases formed in them. The common criteria include the $\Delta H_{mix} - \delta r$ criterion proposed by Zhang [35]; Guo's study demonstrated the capability of valence electron concentration (VEC) to predict phase formation [36]; Yang defined an additional parameter $\Omega$ which accounts for the effect of mixing entropy [37]. For the cast Ni\textsubscript{(60-y)Fe\textsubscript{20}Co\textsubscript{10}Cr\textsubscript{10}Al\textsubscript{y}} (y = 0, 5, 10, 15, 20, 25) alloys, the relevant parameters are determined as follows:
\[
\delta r = \sum_{i=1}^{n} c_i \left(1 - \frac{r^2_i}{\bar{r}^2} \right), \bar{r} = \sum_{i=1}^{n} c_i r_i^2 \\
\Delta H_{\text{mix}} = \sum_{i=1}^{n} \sum_{j \neq i} 4 \Delta H_{ij}^{\text{mix}} c_i c_j \\
\Omega = T_m \Delta S_{\text{mix}} \mid \Delta H_{\text{mix}} \mid T_m = \sum_{i=1}^{n} c_i (T_m) \\
\Delta \chi = \sum_{i=1}^{n} c_i \left(\chi_i - \bar{\chi} \right)^2, \bar{\chi} = \sum_{i=1}^{n} c_i \chi_i \\
VEC = \sum_{i=1}^{n} c_i (VEC),
\]

where \(i\) represents the number of elements, \(\bar{r}\) is the average atomic radius, \(c_i\), \((T_m)\), \((VEC)\) are the atomic percentage, melting point, and valence electron concentration of the \(i\) element, respectively.

Table 4 The computed phase formation values of the Ni(60-y)Fe20Co10Cr10Al\(_y\) HEAs

<table>
<thead>
<tr>
<th>HEAs</th>
<th>(\delta r)</th>
<th>(\Delta H_{\text{mix}} / \text{KJ mol}^{-1})</th>
<th>(VEC)</th>
<th>(\Delta S_{\text{mix}} / \text{J mol}^{-1} \cdot \text{K})</th>
<th>(T_m / \text{K})</th>
<th>(\Omega)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni0</td>
<td>1.09</td>
<td>-2.96</td>
<td>9.10</td>
<td>9.05</td>
<td>1787.75</td>
<td>5.46</td>
</tr>
<tr>
<td>Al-5</td>
<td>3.27</td>
<td>-6.18</td>
<td>8.75</td>
<td>10.48</td>
<td>1748.11</td>
<td>2.97</td>
</tr>
<tr>
<td>Al-10</td>
<td>4.34</td>
<td>-8.96</td>
<td>8.40</td>
<td>11.30</td>
<td>1708.48</td>
<td>2.15</td>
</tr>
<tr>
<td>Al-15</td>
<td>5.04</td>
<td>-11.30</td>
<td>8.05</td>
<td>11.86</td>
<td>1668.84</td>
<td>1.75</td>
</tr>
<tr>
<td>Al-20</td>
<td>5.56</td>
<td>-13.20</td>
<td>7.70</td>
<td>12.23</td>
<td>1629.20</td>
<td>1.51</td>
</tr>
<tr>
<td>Al-25</td>
<td>5.92</td>
<td>-14.66</td>
<td>7.35</td>
<td>12.44</td>
<td>1589.56</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 4 summarizes the numerical results of the expression based on the provided equation. Due to the numerous parameters involved in phase prediction and their limited applicability, we focus on widely used prediction parameter methods for specific discussion. According to existing literature [37], stable solid solutions are formed when \(\Omega \geq 1.1\), \(\delta r \leq 6.6\%\), \(-15 \text{kJ mol}^{-1} < \Delta H_{\text{mix}} < 5 \text{kJ mol}^{-1}\), all of which are satisfied by experimental calculations. Guo's VEC model quantitatively predicts the formation of phases in HEAs [36]. Specifically, the BCC phase exists stably under the \(VEC \leq 6.87\), while the FCC phase exists stably under the \(VEC \geq 8\). When the VEC falls within these two values, a tendency for the simultaneous presence of FCC and BCC phases is discerned. Additionally, Yue Ma et al. concluded that BCC+B2 phase exists when the \(VEC \leq 7.4\) [30], while Songge discovered that the FCC phase exists when the \(VEC \geq 8.4\) [38]. However, scholars such as A. Oñate et al. found that the FCC+BCC phase exists stably when \(8 \leq VEC \leq 8.5\) [39]. Therefore, solid solution formation is initially judged based on \(\Omega \geq 1.1\), \(\delta r \leq 6.6\%\), \(-15 \text{kJ mol}^{-1} < \Delta H_{\text{mix}} < 5 \text{kJ mol}^{-1}\), with FCC phase at \(VEC \geq 8.5\), the BCC phase is present at \(VEC \leq 6.87\), both FCC and BCC phases are present at \(7.4 \leq VEC \leq 8.5\), and both BCC and B2 phases are present at \(6.87 \leq VEC \leq 7.4\).

4. Summary

In this paper, non-equivalent ratio Ni(60-y)Fe20Co10Cr10Al\(_y\) (\(y = 0, 5, 10, 15, 20, 25\)) eutectic HEAs were prepared to explore how the AI-Ni elements influences the microstructural evolution of the alloys and the impact of various microstructures on the mechanical properties of the system. Further conclusions can be summarized as follows:

(2) As Al content rises, the yield strength of $\mathrm{Ni}_{(60-y)}\mathrm{Fe}_{20}\mathrm{Co}_{10}\mathrm{Cr}_{10}\mathrm{Al}_{y}$ ($y=0, 5, 10, 15, 20, 25$) alloys shows an upward trend, while the compressive strain decreases. Al-20 and Al-25 exhibit a favorable balance of strength and plasticity. The yield strengths of HEAs are 1012 MPa and 1477 MPa when $y=20, 25$, with compressive strengths of 1679 MPa and 1694 MPa, and elongations at break of 41% and 23%.

(3) When the criteria $\Omega\geq1.1$, $\delta r \leq 6.6\%$, $-15kJ/mol < \Delta H_{\text{mix}} < 5kJ/mol$ are met for forming a stable solid solution, and the B2 phase represents an ordered BCC phase, phase prediction can be made based on the VEC parameter. Specifically, FCC phase emerges under $VEC \geq 8.5$, BCC phase emerges under $VEC \leq 6.87$, an FCC+BCC dual phase emerges under $7.4 \leq VEC \leq 8.5$, and BCC+B2 dual phase emerges under $6.87 \leq VEC \leq 7.4$.

References


