Microstructure and mechanical properties variation with Ni content in Al<sub>0.8</sub>CoCr<sub>0.6</sub>Fe<sub>0.7</sub>Ni<sub>x</sub> (x = 1.1, 1.5, 1.8, 2.0) eutectic high-entropy alloy system

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Abstract
Eutectic high-entropy alloys have drawn extensive attention because of their remarkable performance on the combination of strength and plasticity. In this study, a new Al<sub>0.8</sub>CoCr<sub>0.6</sub>Fe<sub>0.7</sub>Ni<sub>x</sub> (x = 1.1, 1.5, 1.8, 2.0) eutectic high-entropy alloy system was designed; the microstructure and mechanical properties variation of alloys with the change in Ni content were investigated detailly. All of four alloys exhibited FCC+B2 dual-phase structure, while the volume fraction of FCC phase increased from 44% to 90% with an increase in Ni content. Meanwhile, the microstructure of alloys varied from an irregular dendrite morphology to a lamellar eutectic microstructure, and finally to a hypoeutectic microstructure composed by primary FCC phase and the rest eutectic mixture. Accordingly, the yield strength of alloys decreased from 625 MPa to 415 MPa, and the total elongation increased from 7.4% to 21.8%. The Al<sub>0.8</sub>CoCr<sub>0.6</sub>Fe<sub>0.7</sub>Ni<sub>1.5</sub> alloy displayed a nano-scale lamellar eutectic microstructure and exhibited a relatively good combination of strength and plasticity in these four alloys, with a yield strength of 490 MPa, an ultimate strength of 980 MPa and a total elongation of 14.8%. The findings could contribute to explore HEAs with good combination of strength and plasticity and promote the applications of high-entropy alloys in industrial fields.

1. Introduction

High-entropy alloys (HEAs) were initially proposed by Yeh et al as a new alloy design philosophy, which contain at least five elements with equimolar or near-equimolar proportions [1]. Since being proposed, HEAs have caused extensive attention due to their unique composition characteristic and diverse properties [2–5]. Although exhibiting multifarious engineering applications, great efforts still be made on HEAs to pursue more excellent mechanical properties. The typical strengthening mechanisms such as precipitation-hardening [6–8], TWIP (twinning-induced plasticity) [9, 10], TRIP (transformation-induced plasticity) [11, 12], and dual-phase structure [13–26] was introduced in HEAs to achieve the good combination of high strength and large plasticity. Among these strengthening mechanisms, dual-phase structure was widely used and found being able to effectively achieve a balance of strength and plasticity by reasonably collocating the constituent phase.

Eutectic HEAs (EHEAs), as a type of typical dual-phase HEAs, were firstly designed by Lu et al with the purpose of obtaining good castability and mechanical properties [16]. Up to now, multiple as-cast EHEAs with different constituent phases were reported to exhibited excellent mechanical properties [16–26]. Among these newly reported EHEAs, the FCC-based/BCC-based structure EHEAs were found displaying a favorable processability, as well as a desirable combination of strength and plasticity after thermo-mechanical treatment, which greatly promoted the engineering applications of HEAs in industrial fields [16, 17, 20, 23–26]. The excellent performance of this kind of EHEAs could be ascribed to not only the fine lamellar microstructure constituting by the alternative ductile and hard phases, but also the plenty of phase interface which induced significant interface hardening effect. However, the actual microstructure of EHEAs was generally prone to
deviate from the fine lamellar microstructure with a slight variation in constituent elements content, especially for the large-scale industrial production [20, 26, 27]. Thus, the investigation about the influence of constituent elements on the microstructure and mechanical properties of EHEAs is important and necessary. In the AlCoCrFeNi$_2$ eutectic high-entropy alloy system reported previously, the microstructure of this alloy system changed from the hypo-eutectic to the eutectic, and finally to the hypereutectic morphology when the molar ratio of Ni element mildly altered from 2.0 to 2.2, along with a variation of tensile property [20]. However, how would the Ni element affect the microstructure and mechanical properties of alloys in a larger content scope was still unclear, which promoted the current work.

In this work, we proposed a new Al$_{0.8}$Co$_{0.6}$Cr$_{0.7}$Fe$_{0.7}$Ni$_x$ (x = 1.1, 1.5, 1.8, 2.0) HEAs. The phase structure, microstructure and mechanical properties transition of alloys with a great change in Ni content were discussed detailly. The Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_{1.5}$ alloy was found exhibiting a eutectic microstructure and a relatively good combination of strength and plasticity.

2. Materials and methods

2.1. Preparation of alloys

Ingot (each about 80 g) with nominal composition of Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_x$ (denoted as Nix alloy hereafter) were prepared by arc melting a mixture of the constituent metals in a Ti-gettered high-purity argon atmosphere. The purity of constituent metals was higher than 99.9 mass %. Each ingot was re-melted at least five times to ensure chemical composition homogeneity. All ingots were 12 mm in height and 35 mm in diameter.

2.2. Characterization of alloys

The phase structure of Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys was examined using x-ray diffraction (XRD, Bruker D8 Advance) with Cu K$_\alpha$ radiation ($\lambda = 1.5418$ Å). The scanning angle was from 20° to 100°, and the scanning rate was 2° min$^{-1}$. The working current and voltage were 40 mA and 40 kV, respectively. The microstructure of alloys was investigated by scanning electron microscope (SEM, ZEISS SUPRA55). The specific chemical composition in different region of alloys was analyzed using energy dispersive spectrometer (EDS) connected to the SEM mentioned above. The hardness of alloys was tested using Wilson Vickers hardness machine (VH 1102–01–0040) under a load of 2000 g force and a holding time of 13 s. The tensile mechanical property of alloys was measured using testing machine (CMT 4305) under a strain rate of 10$^{-3}$ s$^{-1}$. The specimens for testing were bone-shaped with a gauge length of 10 mm, width of 3 mm and thickness of 1 mm. Three tests were performed on each set of specimens to ensure the reproducibility and accuracy of data.

3. Results

3.1. Phase constitution and microstructure

Figure 1(a) shows the XRD patterns of Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys. As can be seen, all of these alloys displayed an FCC + BCC dual-phase structure. Apparently, the intensity of main diffraction peak of BCC phase in Ni1.1 alloy was higher than that of FCC phase, indicating a larger volume fraction of BCC phase. However, as for the other three alloys, the FCC phase had a larger volume fraction relatively. These results suggested that the volume fraction of constituent phases varied with an increase in Ni content. Due to the closed interplanar spacing, the diffraction peak of (111) crystal plane of FCC phase was overlapped with the diffraction peak of (110) crystal plane of BCC phase in Ni1.8 and Ni2.0 alloys. To accurately acquire the lattice constants of constituent phases, the overlapping diffraction peaks were fitted and separated using Lorentz function, as shown in figure 1(b). Table 1 lists the specific lattice constants of two phases in Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys. Obviously, the lattice constant of FCC phase exhibited a monotonic decrease with an increase in Ni content, and the lattice constant of BCC phase linearly increased accordingly, suggesting that not only the volume fraction, but also the element distribution of constituent phases changed with a change in Ni content.

Figure 2 presents the SEM images of Al$_{0.8}$Co$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys. Figures 2(a), (b) show that the Ni1.1 alloy exhibit an irregular dendrite (the dark phase) and inter-dendrite (the light phase) microstructure, and the size of dendritic phase were several tens of microns. The Ni1.5 alloy exhibited a typical lamellar eutectic microstructure; the width of light and dark lamellas was 1.2 μm and 0.5 μm approximately, as shown in figures 2(c), (d). It was noteworthy that the lamellar eutectic microstructure of Ni1.5 alloy exhibited two types of morphologies: the long, straight lamella (marked by A) and the short, irregular lamellas (marked by A and B in figure 2(d), respectively). Figures 2 (e)-(h) reveal that both the Ni1.8 and Ni2.0 alloys were composed of the primary dendritic phase and rest eutectic microstructure formed in the inter-dendrite region, which means that these two alloys exhibited typical hypo-eutectic microstructure The dendrite arm width of primary phase was several tens of microns, and the width of lamellas was also less than 1 μm. Similar to the Ni1.5 alloy, the eutectic
microstructure in Ni1.8 and Ni2.0 alloys also presented two types of morphologies: the straight and curve lamellas (marked by A and B, respectively). In addition, it was observed that the area proportion of primary dendritic phase in Ni2.0 alloy was obviously larger than that in Ni1.8 alloy, once again verifying the volume fraction variation of constituent phases with the change in Ni content.

TEM technique was used to analysis whether the ordered structure exist in Ni1.5 alloy. The bright-field TEM image of alloy was shown in figure 3(a), and the SAED patterns of dark (region A) and light (region B) lamellas were shown in and figures 3(b) and (c), respectively. The (110) diffraction spot did not be observed in figure 3(b), while the weak (100) diffraction spot did not be observed in figure 3(c). Therefore, the dark and light lamellas were identified as disordered FCC and ordered BCC (B2) phases, respectively.

Figure 4 shows the EDS maps of constituent elements in Ni1.5 and Ni1.8 alloys. As shown in figure 4(1), the light and dark lamellas in Ni1.5 alloy were enriched in Cr–Fe–Co and Al–Ni elements, respectively. Apparently, the enrichment degree of Ni, Fe and Co elements was relatively lower than that of Al and Cr elements. Figure 4(2) shows that the elements distribution of eutectic microstructure in Ni1.8 alloy was similar to that in Ni1.5 alloy. In addition, the primary dendritic phase in Ni1.8 alloy was enriched in Cr–Fe–Co and depleted from Al–Ni elements, which was similar to the light eutectic lamella. Table 2 lists the regional chemical composition in Al0.8CoCr0.6Fe0.7Ni alloys. The results shown in table 2 were completely consistent with figure 4. As can be seen from table 2, the dendrite and inter-dendrite regions in Ni1.1 alloy were enriched in Cr–Fe–Co and Al–Ni elements respectively, and the elements distribution in Ni2.0 alloy exhibited a similar trend as well as the Ni1.8 alloy. Generally, in Al–Co–Cr–Fe–Ni HEAs, the Al content in B2 phase is much more than that in FCC phase, which could be effectively used to distinguished the phase structure of different region [28]. Therefore, based on the EDS results displayed in figure 4 and table 2, it could be concluded that the dark dendritic phase in Ni1.1 alloy, the light eutectic lamella in Ni1.5, Ni1.8 and Ni2.0 alloys, and the primary dendritic phase in Ni1.8 and Ni2.0 alloys exhibited an FCC structure, and the rest regions were B2 structure accordingly.

Combined the XRD, SEM and EDS results, the volume fractions of constituent phases in Al0.8CoCr0.6Fe0.7Ni alloys were calculated and depicted in figure 5. Obviously, the volume fraction of FCC phase increased from 44% (Ni1.1 alloy) to 90% (Ni2.0 alloy), indicating that the Ni element promoted the formation of FCC phase. In addition, the volume fraction of eutectic microstructure decreased from 100% (Ni1.5 alloy) to 31% (Ni2.0 alloy). Furthermore, it was found that in alloys exhibiting entirely and partly eutectic microstructure, the volume fraction ratio of FCC/B2 phases in eutectic microstructure was closed to 7:3, which basically complied with the level-law of phase diagram of eutectic alloys.

![Figure 1](image_url)

**Figure 1.** (a) XRD patterns of the Al0.8CoCr0.6Fe0.7Ni alloys; (b) The overlapping diffraction peaks were separated using Lorenz function.

| Lattice constant (Å) | Ni1.1 | Ni1.5 | Ni1.8 | Ni2.0 |
|----------------------|-------|-------|-------|-------|
| FCC phase            | 3.595 | 3.593 | 3.589 | 3.586 |
| BCC phase            | 2.878 | 2.882 | 2.884 | 2.886 |
3.2. Mechanical properties

Figure 6 shows the Vickers hardness of Al$_{0.8}$CoCr$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys. The hardness of these alloys, from high to low, were 323 HV, 301 HV, 284 HV and 264 HV in turn. Apparently, as the Ni content increased, the hardness of four alloys linearly decreased. It could be inferred that the hardness reduction of alloys was mainly ascribed to the volume fraction increase of FCC phase.

Figure 7 displays the tensile engineering stress-strain curves of Al$_{0.8}$CoCr$_{0.6}$Fe$_{0.7}$Ni$_x$ alloys under a strain rate of $10^{-3}$ s$^{-1}$. Table 3 lists the specific yield strength, ultimate strength and total elongation of alloys. Obviously, both the strength and plasticity displayed monotone variation with an increase in Ni content. When $x$ increased from 1.1 to 2.0, the yield strength of alloys decreased from 625 MPa to 415 MPa, the ultimate strength decreased from 1065 MPa to 870 MPa, and the total elongation increased from 7.4% to 21.8%. That is, a longstanding
Figure 3. (a) TEM image and (b)–(c) corresponding SAED patterns of different regions in Ni1.5 alloy.

Figure 4. (a) SEM image and EDS maps of (b) Al, (c) Ni, (d) Co, (e) Cr and (f) Fe elements in (1) Ni1.5 and (2) Ni1.8 alloys.
Table 2. Specific chemical composition of different regions in Al_{0.8}Co_{0.6}Cr_{0.6}Fe_{0.7}Ni_{x} alloys.

| Alloy  | Region          | Phase          | Element (at%) |
|--------|-----------------|----------------|---------------|
|        |                 |                | Al  | Co  | Cr  | Fe  | Ni  |
| Ni1.1  | Nominal composition | FCC + B2      | 19.0 | 23.8 | 14.3 | 16.7 | 26.2 |
|        | Dendrite        | FCC            | 13.4 | 25.6 | 17.3 | 19.3 | 24.4 |
|        | Inter-dendrite  | B2             | 24.4 | 22.4 | 11.2 | 14.1 | 27.9 |
| Ni1.5  | Nominal composition | FCC + B2      | 17.4 | 21.7 | 13.1 | 15.2 | 32.6 |
|        | Light eutectic lamella | FCC    | 13.5 | 23.0 | 16.4 | 17.0 | 30.1 |
|        | Dark eutectic lamella | B2  | 27.3 | 19.8 | 6.5  | 11.4 | 36.1 |
| Ni1.8  | Nominal composition | FCC + B2      | 16.3 | 20.4 | 12.3 | 14.3 | 36.7 |
|        | Primary dendrite | FCC            | 13.4 | 22.2 | 13.6 | 15.7 | 33.1 |
|        | Eutectic microstructure | FCC + B2  | 18.1 | 19.6 | 11.4 | 12.4 | 38.3 |
|        | Light eutectic lamella | FCC | 12.6 | 20.7 | 15.8 | 14.3 | 36.6 |
|        | Dark eutectic lamella | B2  | 28.2 | 15.8 | 6.1  | 9.3  | 40.6 |
| Ni2.0  | Nominal composition | FCC + B2      | 15.7 | 19.6 | 11.8 | 13.7 | 39.2 |
|        | Primary dendrite | FCC            | 13.3 | 22.1 | 12.2 | 15.0 | 37.4 |
|        | Eutectic microstructure | FCC + B2  | 18.9 | 18.4 | 10.2 | 11.2 | 41.3 |
|        | Light eutectic lamella | FCC | 12.0 | 20.9 | 13.6 | 15.0 | 38.5 |
|        | Dark eutectic lamella | B2  | 28.7 | 13.6 | 5.7  | 8.8  | 43.2 |

Figure 5. Volume fractions of constituent phases in Al_{0.8}Co_{0.6}Cr_{0.6}Fe_{0.7}Ni_{x} alloys.

Figure 6. Vickers hardness of the Al_{0.8}Co_{0.6}Cr_{0.6}Fe_{0.7}Ni_{x} alloys.
strength–plasticity tradeoff phenomenon was also observed in the present alloys. In summary, the Ni1.1 alloy exhibited a relatively great strength and low plasticity, while the Ni2.0 alloy was just the reverse. The Ni1.5 eutectic alloy displayed a favorable combination of strength and plasticity, with a yield strength of 490 MPa, a ultimate strength of 980 MPa and a total elongation of 14.8%.

4. Discussion

4.1. Microstructure evolution

Previous reports showed that in Al–Co–Cr–Fe–Ni HEAs system, the necessary composition condition to form EHEAs was that the molar ratio of Ni/Al elements was in the range from 1.0 to 3.00 [16, 23, 26, 27]. Therefore, to located the eutectic composition, the content range of Ni element in the current alloys was set in between 0.8 and 2.4. In addition, it was reported by Guo et al. [29] that when the VEC values were in the range from 6.87 to 8.00, the alloys were liable to form FCC + B2 dual-phase structure. Consequently, on the basis of VEC values scope proposed by Guo et al., the Ni content range of alloys was further adjusted in between 0.8 and 2.0, whose VEC values was in between 7.33 and 7.96. Furthermore, the mixing enthalpy (ΔH_mix), as the most widely reported and effective parameter to design EHEAs, was used to finally determine the compositions of present alloys. According to previous reports, the ΔH_mix values of AlCoCrFeNi2.1 [16], Al19Co20Fe20Ni41 [23], and Al0.8CrFeNi2.2 [27] EHEAs were calculated to be −11.94 kJ mol⁻¹, −12.23 kJ mol⁻¹, and −12.21 kJ mol⁻¹ respectively. All of these values were found being closed to −12.00 kJ mol⁻¹. Thus, the Ni content range was further adjusted in between 1.0 and 2.0, whose ΔH_mix values was in between −12.58 kJ mol⁻¹ and −11.90 kJ mol⁻¹. Based on these reasons mentioned above, as well as the aim of investigating the effect of Ni element on the microstructure and mechanical properties of alloys in a larger content scope, the Ni content was finally set as 1.1, 1.5, 1.8, and 2.0. It was inferred that these alloys could well exhibited the dual-phase structure and was near the eutectic composition. In reality, the inference was subsequently verified; the Ni1.5 alloy was found to exhibit a fine lamellar microstructure composed by the FCC and B2 phases, as shown in figures 1–2.
In the present AlxCoCrxFe0.7Ni1-x alloys, as seen from figure 5, the volume fraction of FCC phase increased with the increase in Ni content, indicating that the Ni element promoted the formation of FCC phase. Previous literature presented that the elements with a higher VEC value, such as Ni and Cu, were conductive to form the FCC phase, while the elements with a lower VEC value resulted in a larger volume fraction of BCC phase, such as Al and Cr [28]. However, recent report proposed that if the element distributed more in FCC phase, it can be considered as an FCC stabilizing or forming element, thereby increase the FCC volume fraction. Apparently, our result was consistent with the first viewpoint rather than the second one, although the Ni element was found to distribute more in BCC phase, as shown in table 2.

Table 1 shows that the lattice constant of FCC phase linearly decreased with the increase in Ni content, and the lattice constant of B2 phase was just the reverse, which could be explained by the change of distribution in Al element. As exhibited in table 2, the content of Al element in B2 phase gradually improved from 24.4 at% to 28.7 at% with an increase in Ni content. On account of the fact that the atomic radius of Al element (1.43 Å) is larger than that of the other constituent elements (<1.28 Å), therefore the improvement of Al content was supposed to promote the expansion of Co–Cr–Fe–Ni matrix crystal cell and increase of constant lattices of alloys [30]. In addition, it is noted that although the Ni1.5, Ni1.8 and Ni2.0 alloys exhibited entirely and partly eutectic microstructure, the composition of eutectic microstructure in these alloys revealed obviously difference, as shown in table 2. Similar result was found in CrFeNi1–xAlx EHEAs [26]. This may be ascribed to the fast solidification and cooling process of as-cast alloys, which were reported significantly influencing on the microstructure of HEAs [31].

### 4.2. Relationship between the microstructure and mechanical properties

To achieve a favorable combination of strength and plasticity, great efforts were applied to design the HEAs combining the ‘ductile’ FCC and ‘hard’ BCC phases. For the dual-phase alloys, the mechanical properties strongly depend on the strength-plasticity configuration, compatible deformation capability, as well as the content, size, morphology and distribution of constituent phases. Therefore, EHEAs with the FCC+B2 dual-phase structure and nano-scale lamellar microstructure attracted extensive attention due to their favorable mechanical properties. As shown in figure 6, the Al0.6CoCr0.6Fe0.7Ni0.2 alloys exhibited a typical yield strength-plasticity trade-off with the change of Ni content under the tensile loading. The monotone decrease of yield strength and increase of plasticity was firstly ascribed to the increase of volume fraction in ‘ductile’ FCC phase, and then related to the variation of morphology and distribution in constituent phases. As can be seen from figures 2(a), (b) and 5, the volume fraction of FCC phase of Ni1.1 alloy was minimum in four alloys, and the ‘ductile’ FCC phase in Ni1.1 alloy with a separately dendrite morphology was surrounded by the connected ‘hard’ BCC phase, which resulted in that the plastic deformation capacity of FCC phase was restricted partly. Therefore, the Ni1.1 alloy exhibited the highest strength and the lowest plasticity in four alloys. Figures 2(c), (d) and 5 shows that the Ni1.5 alloy had a larger volume fraction in FCC phase, and displayed a typical lamellar eutectic microstructure. The large content of FCC phase played a considerable effect on the improvement of plasticity, and the substantial coherent interfaces caused by the fine lamellar eutectic microstructure could effectively hinder the dislocation motion, which greatly enhanced the strength and improved the plasticity [16]. Thus, the Ni1.5 alloy exhibited a relatively favorable combination of strength and plasticity in four alloys. Compared with the Ni1.1 and Ni1.5 alloys, the Ni1.8 and Ni2.0 alloys exhibited a more considerable outperformance in plasticity, which was attributed to not only the large volume fraction of FCC phase (shown in figure 5), but also the disappearing of long, straight lamellar eutectic microstructure existed in Ni1.5 alloy (shown in figures 2(e)–(h)). As shown in figures 2(c), (d), the length of long and straight lamella in Ni1.5 alloy was reached to several hundred microns, which may result in the long and straight phase interface. Therefore, when the alloy sustained the tensile stress, the cracks expanded easily and rapidly along the phase interface. However, for the Ni1.8 and Ni2.0 alloys which exhibited a hypoeutectic microstructure composed by the primary FCC phase and eutectic microstructure with an FCC+B2 dual-phase structure, the primary phase could effectively decrease the straight lamella content and block the crack propagation, thereby improve the plasticity of alloys to some extent.

The mechanical properties of reported EHEAs (CrFeNi0.8Al0.8, AlCoCrFeNi0.5, and Al19Co20Cr20Ni41) were listed in table 3. All of these EHEAs have a lamellar eutectic microstructure and a similar composition as the present alloys. Compared with the other three EHEAs, both the strength and plasticity of Ni1.5 alloy are in intermediate level. The mechanical properties of these alloys were considered to be related to the types and sizes of constituent phases, which were also listed in table 3. Due to the composition and preparation method differences, the constituent phases of these alloys exhibited different types and sizes. Both the AlCoCrFeNi0.5 and Al19Co20Cr20Ni41 EHEAs were composed by the L12 and B2 phases, and the other two alloys were composed by the FCC and B2 phases. Generally, the ordered phase was deemed to be the intermetallic compounds which exhibit higher strength than the disordered phase with the same lattice type. In addition, the lamellar thickness
of eutectic microstructure in AlCoCrFeNi2.1 and Al19Co20Cr20Ni41 EHEAs was obviously less than that in the other two alloy. For the dual-phase alloys, the smaller size of constituent phases usually means the better mechanical properties \[32, 33\]. Therefore, both the AlCoCrFeNi2.1 and Al19Co20Cr20Ni41 EHEAs exhibited higher strength and better plasticity than the CrFeNi2.2Al0.8 and Al0.8CoCr0.6Fe0.7Ni EHEAs.

5. Conclusions

In this study, a new Al0.8CoCr0.6Fe0.7Ni \(x\) \((x = 1.1, 1.5, 1.8, 2.0\), denoted as Nix alloy) eutectic high-entropy alloy system was proposed. The phase structure, microstructure and mechanical properties variation of alloys with the change in Ni content were investigated in detail. The main conclusions are summarized as follows:

(1) All of these four alloys exhibited an FCC + B2 dual-phase structure. The FCC and B2 phases were enriched with the Al–Ni and Cr–Fe–Co elements. With an increase in Ni content, the volume fraction of FCC phase increased from 44% to 90%. The microstructure of alloys varied from an irregular dendrite morphology (Ni1.1 alloy) to a fine lamellar eutectic microstructure (Ni1.5 alloy), and finally to a hypoeutectic microstructure composed by the primary FCC phase and rest eutectic mixture (Ni1.8 and Ni2.0 alloys), and the volume fraction of eutectic microstructure firstly increase from 0% (Ni1.1 alloy) to 100% (Ni1.5 alloy), and then decrease to 31% (Ni2.0 alloy).

(2) With the Ni content increased from 1.1 to 2.0, the hardness of alloys linearly decreased from 323 HV to 264 HV, the yield strength of alloys decreased from 620 MPa to 410 MPa, and the total elongation increased from 7.4% to 21.8%. The Ni1.5 eutectic alloy displayed a relatively good balance of strength and plasticity in four alloys, with a yield strength of 490 MPa, an ultimate strength of 980 MPa and a total elongation of 14.8%.

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Author contributions

Lili Ma designed the research project and wrote the manuscript; Jianing Wang, performed the experiments and characterization; Lili Ma performed the analysis of the data; Peipeng Jin supported in the analysis and characterization.

Conflicts of interest

The authors declare no competing financial interests.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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