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A novel dual phase high entropy casting alloy with high damping capacity

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Abstract

The microstructure, phase structure, mechanical properties and damping capacity of Al$_x$Fe$_2$CrNiCu (x = 0.0, 0.5, 0.75, 1.0, 1.5) (x in molar ratio) HEAs were investigated. The results show that with the increase of x value, the volume fractions of BCC phase increase from 0 for x = 0.0 to 100% x = 1.5 for the as-cast Al$_x$Fe$_2$CrNiCu HEAs. Among them, a novel dual phase microstructure consisting of 51 vol. % FCC and 49 vol.% BCC with large interface area was obtained in Al$_{0.5}$FeCrNiCu HEA. Especially the compressive yield strength of the alloy with FCC structure is more than 5 times larger than that of the alloy with BCC structure, indicating that a typical damping alloy with a soft second phase distributed on the hard matrix was successfully fabricated. Compared with other HEAs, the damping capacity (Q$^{-1}$) of Al$_{0.5}$ HEA is 0.1, which is the largest one obtained up to now. The foundational contribution of this paper is to show that the damping capacity of the HEAs can be adjusted by tuning the volume fraction of BCC and FCC phases.

1. Introduction

In 2004, a new type of multi-component alloys, so called high entropy alloys (HEAs), was proposed by Yeh and Cantor et al [1, 2]. HEAs have received considerable attention from many scholars in recent years. Different from traditional alloys, HEAs with five or more than five elements, each ranging from 5 to 35 at%, have promising properties, such as excellent corrosion resistance [3, 4], high strength [5, 6] and good wear resistance [7, 8]. The high entropy of HEAs makes them tend to form simple solid solutions rather than an array of intermetallic compounds. Therefore, many studies on HEAs focus on their crystal structure of solid solution [9–11] by adjusting such elements as Fe, Co, Cr, Ni, Cu, Mn and Al, etc Usually, HEAs with different kinds and content of these elements have different crystal structures, e.g., face centered cubic (FCC) and body centered cubic (BCC) structures or combination between them [6, 12–23].

Noise and vibration arisen in machine operation not only have a bad effect on human health, but also have a negative effect on the performances of machines, such as reducing the service life of mechanical parts and the processing precision, etc Therefore, how to improve the damping performance of materials used in the machine parts is a crucial direction of material research. Damping material has the absorption of vibration mechanical energy, through the internal mechanism irreversibly converted into heat energy or other forms of energy consumption, resulting in internal friction. Such as submarine propeller, brake disc, shield machine, gear, and crusher, etc, the application prospect is very broad. There are several types of traditional damping alloys: the multiphase damping alloys (e.g. gray cast-iron [24]), the dislocation damping alloys (e.g. Mg-Zr alloys [25]), the twin-boundary damping alloys (e.g. Mg-Cu alloys [20]), the superplastic damping alloys (e.g. Zn-Al alloys [26]), and the domain damping alloys (e.g. Fe-Cr alloys [27]). Although the traditional damping alloys have good damping performances, their applications are still limited. For example, the Mg-based damping alloys are limited to use for machine parts due to their low strength, the Cu-based damping alloys are usually used in a low working temperature area, whereas anticorrosion treatment is often required for the Fe-based damping alloys.
Therefore, it becomes essential to develop the alloys to overcome these shortcomings. The emergence of HEAs provides a new way to address this topic.

In this work, the aim is to explore a kind of HEA system with both high damping capacity and high mechanical properties, the initially strong emphasis made on HEAs is to obtain a single solid solution phase structure [1]. However, it has been found that the HEAs with dual phases or even poly phases usually exhibit a better combination of mechanical properties [28]. HEAs with single FCC structure usually show superior ductility but lower strength [12], whereas HEAs with single BCC structure show much higher strength [29] but lower ductility. Therefore, in order to overcome the shortcomings and fully utilize the advantages of FCC and BCC phases, HEAs with both FCC and BCC phases were developed [30]. Previous studies have shown that variation in Al content affects the microstructure and mechanical properties of HEAs [22]. With the increase of Al content, HEAs tends to form the crystal structure of BCC, and the strength and hardness increase correspondingly [31, 32]. Guo et al [33] reported that AlCrCuFeNi2 HEA with the BCC as the matrix and the FCC crystal structure as the secondary phase exhibited excellent mechanical properties, which stimulates this study to develop the dual phase HEAs by combining the BCC matrix and FCC second phase embedded on the matrix. In order to obtain higher strength and reduce material cost, the content of Fe was increased in this study. Therefore, in present work, the AlFe2CrNiCu HEAs were designed and fabricated. The phase constituent, microstructure, mechanical properties and damping capacity of the HEAs were investigated systematically.

2. Method

Iron, chromium, nickel, copper and aluminum with 99.9 wt% purity or better were used as raw materials for fabrication of the HEAs. Alloy ingots with nominal composition of Al_{x}Fe_{2}CrNiCu (x = 0.0, 0.5, 0.75, 1.0, 1.5, and the alloys were denoted as Al_{0.0}, Al_{0.5}, Al_{0.75}, Al_{1.0} and Al_{1.5}, respectively) were prepared by arc melting in Zr-gettered high-purity argon atmosphere and a water-cooled copper crucible. All the ingots were remelted five times in order to ensure the compositional homogeneity. Then the HEAs were cast in the vacuum induction furnace into a steel mold. The crystal structure of all the samples was identified by X-ray diffraction (XRD, Shimadzu 7000, Kyoto, Japan) with Cu-Kα (λ = 0.154 nm) radiation at a step of 0.02°, scan rate of 4 (°)/min and 2 theta range from 10° to 90°. For observing the microstructure, the ingot samples were ground, polished, and etched with aqua regia (HCl: HNO3 = 3:1). The microstructure and morphology of the specimens were characterized by scanning electron microscopy (SEM) using the Zeiss Gemini operated at 20 kV and the chemical composition distribution was investigated by energy dispersive spectrometry (EDS). The volume fraction of phases in the samples was measured using Oxford electron backscatter diffraction (EBSD) detector at a step size of 1 μm. Thin sheets with a thickness of 1 mm were cut from the samples for the high-resolution microstructure observation using JEM-2100 (Kyoto, Japan) transmission electron microscopy (TEM) operated at 200 kV. TEM samples were mechanically ground and thinned by Gatan-691 precision ion polishing system to 50 μm in thickness. The compressive samples with the dimension of 4 mm in diameter and 6 mm in height were taken by electro-spark wire-electrode cutting. These samples were ground and then tested on the MTS-E45 electronic universal material testing machine with a strain rate of 10^{-3} s^{-1} at room temperature. For each alloy, at least three samples were tested to ensure the reliability of the result. The hardness measurement was conducted using a Vickers hardness tester (THV-1MDT) under a load of 100 g for 10 s. Five measurements were made on each sample to obtain the averaged experimental data. The prepared damping samples [34] with dimension of 2 × 12 × 35 mm³ were tested by Q800 dynamic mechanical analyzer (DMA) at room temperature, and the damping property was represented by the internal friction, Q^{-1} (Q^{-1} = tan δ, where δ is the phase lagged between the applied cyclic stress and the resulting strain). The single cantilever was selected as the test mode, and the testing frequency of 1 Hz and strain amplitude varying from 1 × 10^{-5} to 1 × 10^{-3} were used.

3. Results and discussion

3.1. Crystal structure

The XRD patterns of as-cast AlFe2CrNiCu alloys are shown in figure 1. With the increase of x value, the crystal structure of the alloy system transforms from FCC structure to BCC structure. For the Al-free alloy, it displays as FCC structure. When the Al content is increased to the molar ratio of 0.5, the diffraction peaks of (111)_{FCC} and (200)_{FCC} begins to weaken, and the diffraction peaks of (110)_{BCC}, (200)_{BCC} and (211)_{BCC} begin to appear. When the ratio of Al is 0.75, the diffraction peak of the (111)_{FCC} continues to decline and the diffraction peak of (110)_{BCC} continues to rise. When the content of Al is 1.0. The intensity of (111)_{FCC} peak becomes to the minimum and (200)_{FCC} peak disappears. However, the intensity of (100)_{BCC} begins to appear. Therefore, the
alloys are composed of FCC and BCC dual phase structure when the $x$ value is increased from 0.5 to 1.0. Further increased $x$ to 1.5, however, the x-ray diffraction shows only BCC phase. The results indicate that the crystal structure transforms from FCC to BCC structures in the Al$_x$Fe$_2$CrNiCu alloys. So, the magnitude of Al value is the determining factor of BCC phase formation in the investigated HEAs.

3.2. Microstructures

Figure 2 shows the changes of the microstructure of as-cast Al$_x$Fe$_2$CrNiCu HEAs with the increase of $x$. Figure 2(a) shows the microstructure of Al$_{0.0}$ HEA with typical dendritic structure. It seems that both the dendritic and interdendritic phases have the sole FCC structure since only one set of FCC peaks was detected by XRD as shown in figure 1 and determined by EBSD in figure 5(a). The FCC dendritic structured phase is remained in Al$_{0.5}$ alloy (figure 2(b)), although the matrix has changed to BCC structure, which is determined by EBSD in figure 5(b) and TEM, in which a specific observation of bright-field TEM image (figure 3) presents a short rod (B2 phase, an ordered BCC phase indicated by selected area electron diffraction (SAD) as figure 3(c)) precipitated and distributed uniformly in the matrix. The B2 phase also observed in Al$_{x}$CrCuFeNi$_2$ HEAs [33]. The SAD pattern shown in figure 3(b) also indicates that the bulk phase with FCC structure is distributed in the matrix with BCC structure. Therefore, the microstructure of the as-cast Al$_{0.5}$ HEA consists of FCC and B2 phases distributed in the BCC matrix. It is known that the phase structure is generally related with the composition segregation. According to the elemental distribution alone the line across the dendritic and interdendritic phases, as shown in figure 4, the content of Cu in interdendritic phase is higher than that in BCC phase, the content of Al is also slightly higher than that in dendritic phase. However, both the Fe and Cr contents are dropped significantly in the same position. Therefore, the positive segregation of Cu in the FCC phase and Fe, Cr in BCC phase indicate that they are favored to the formation of FCC and BCC structures, respectively. However, the same segregation tendency of Al in the FCC structure conflicts with many other results [22, 35, 36], which will be discussed in the following section. The microstructure and EBSD phase map of the as-cast Al$_{0.75}$ alloy is shown in figures 2(c) and 5(c), in which the matrix presents BCC structure with a large volume fraction. Compared to Al$_{0.5}$ alloy, the FCC phase in Al$_{0.75}$ alloy becomes slender and distributes between the BCC dendritic structures. Therefore, it seems that dendritic in figure 2(b) has changed to interdendritic in figure 2(c) without structure change. Furthermore, with increasing the atomic ratio of Al to 1.0 or 1.5, as shown in figures 2(d) and (e), respectively, both the interdendritic and dendritic phases on the microstructure are BCC structure (figures 5(d) and (e)). The difference between them is the inter dendritic phase in the matrix of Al$_{1.5}$ alloy becomes more reticulated and thicker than in Al$_{1.0}$ alloy.

It is well-known that the mechanical properties are dependent of the microstructure for HEAs [22, 35, 37]. Usually, the higher the volume fraction of BCC phase in microstructure, the higher the yield strength of HEAs, contrarily, the higher the volume fraction of FCC phase, the higher the ductility of HEAs. Therefore, EBSD was employed to further analyze the phase evolution for Al$_x$ HEAs, which is shown in figure 5. From figure 5(a) it can be observed that for the Al-free HEA, there is none of BCC phase and only totally FCC phase in the microstructure.

As indicated in the figures 5(b)–(d), respectively, it is seen that the FCC and BCC phases are coexisted for all the Al$_{0.5}$, Al$_{0.75}$ and Al$_{1.0}$ HEAs. Furthermore, the corresponding volume fractions of FCC and BCC phases are
49% and 51%, 11% and 89%, 1% and 99%, respectively. For the Al\textsubscript{1.5} HEA all the dendritic and interdendritic phases are transformed into BCC structure. Table 1 shows the volume fraction of FCC and BCC phases of Al\textsubscript{x}Fe\textsubscript{2}CrNiCu (x = 0.0, 0.5, 0.75, 1.0, 1.5) HEAs.

Combining the EBSD results shown in figure 5 and the line scanning results shown in figure 4, it can be inferred that the process of phase transformation in Al\textsubscript{x}Fe\textsubscript{2}CrNiCu HEAs is changed from FCC to BCC structure, and Al is a crucial element in determining the phase formation. Firstly, the Fe-Cr-Ni-rich dendritic FCC structure for the Al-free HEA are partially transformed into BCC structure when the Al mole ratio is 0.5 in the alloy system. At same time, the Cu-rich and Al-rich interdendritics regions remain the FCC structure. This is why a little higher Al content can be observed in the FCC phase shown in figure 4(d). Secondly, with further increasing Al addition to the ratio of 1.0, the FCC phase existed in figure 2(d) (or figure 5(d)) is almost entirely changed into BCC structure, only tiny FCC phase is formed in-between the interdendritic BCC phase. This means that when the Al content is up to a critical value, all the FCC phase in Al\textsubscript{x}Fe\textsubscript{2}CrNiCu HEAs is changed into BCC structure. Al is a strong BCC-stabilizing elements in HEAs system. Many experiments \cite{1, 22, 31, 38} have confirmed this phenomenon. The atomic size of Al element is larger than other elements. The solid solution of Al element into the FCC crystal structure will cause large lattice distortion, this leads to lattice instability. Therefore, the solid solubility of Al atoms in the crystal is small, and it is easy to be repelled and enriched in the crystal grains during solidification. Moreover, the mixing enthalpy of Al-Ni is low, and the bonding ability of the two atoms is strong, so Ni atoms are easily attracted by Al, causing Ni atoms to also segregate between dendrites, resulting in a

Figure 2. SEM images of as-cast Al\textsubscript{x}Fe\textsubscript{2}CrNiCu HEAs, where x = 0.0, 0.5, 0.75, 1.0, 1.5, corresponding to the subfigures (a)–(e), respectively.
second phase BCC phase, which changes the material microstructure. And also the theory of valence electron concentration of HEAs \([39]\) also verifies this view. The lower value of the valence electron concentration of Al element \((\text{AlVEC} = 1)\) is also conducive to the formation of BCC phase.

And the resultant volume fractions of FCC or BCC phases caused by the phase structure evolution is a crucial factor influencing the strength and plasticity of the HEAs. In general, the HEAs with more FCC phase have higher plasticity and lower strength, while the HEAs with more BCC phase show the opposite effect.

EBSD inverse pole figures (IPF) shown in figure 6 indicate the size and orientation of grains in the HEAs. It is apparently observed that the grain size and orientation of each HEA are different. Among them, the grain of Al0.5 alloy is the finest and well dispersed, and that of Al0.75 alloy is the second. In which some fine FCC phases are dispersed at both the grain boundaries and in the grains by comparison with the images shown in figures 2(b) and (c). Except for Al0.5 (figure 6(b)) and Al0.75 (figure 6(c)), the grain sizes from small to large are in the order of Al1.0 (figure 6(d)), Al0.0 (figure 6(a)) and Al1.5 (figure 6(e)).

3.3. Mechanical properties

Figure 7 presents the room-temperature compressive stress-strain curves of the Al\(x\)Fe2CrNiCu HEAs. The yield strengths increase basically with the \(x\) value, while the fracture strengths decrease from 1934 MPa to 1440 MPa with the \(x\) value increasing from 0.75 to 1.5. No fracture behavior is observed for the Al-free \((x = 0)\) and Al0.5 HEAs since the compressive plasticity is so large that the compressive experiments have to be interrupted. It is obvious that the other three HEAs, i.e., Al0.75, Al1.0, Al1.5, exhibit limited compressive strain, and the maximum of plastic strain is about 30% for Al0.75 HEA. In order to show the change tendency of mechanical properties with the phase evolution given by figures 6–8 shows the relationship between the yield strength \((\sigma_y)\) or hardness \((Hv)\) and the BCC phase volume fractions.

The yield strength and hardness increase from 248 MPa and 153 Hv to 1396 MPa and 641 Hv, respectively, with the BCC phase volume fractions increasing from zero to 100%. It is obvious that the yield strength of the HEAs with more FCC phase is quite lower than that of HEAs with more BCC structure. When the volume fraction of BCC phase is increased from 0 to 100%, the yield strength of the Al1.5 HEA is increased more than four times. At the same time, the hardness is also increased to more than four times. The soft second FCC phase embedded in the hard matrix of BCC phase indicates a good damping capacity of the alloys, which will be discussed in the following section. It is also noticed from figure 8 that the higher the volume fractions of FCC phase, the larger the compressive strain, which is opposite to the change trend of strength (Since there is no fracture in the compression experiment of the two alloys, the compression deformation can be roughly and reasonably inferred according to the trend and can be visually represented by the dotted line in the figure). Now it can be concluded that the mechanical properties of HEAs can be adjusted by tuning the volume fractions of FCC or BCC phases.
Figure 4. Elements distribution between the two phases in Al HEAs alloy by EDS analysis: (a), (c), (e), (g), (i) EDS scanning line across the interdendritic and dendritic phases. (b), (d), (f), (h), (j) distribution of elements between two phases.
Figure 5. EBSD images of Al$_x$Fe$_2$CrNiCu HEAs, where $x = 0.0, 0.5, 0.75, 1.0, 1.5$, corresponding to subfigures (a)–(e), respectively (Blue and red colors indicate FCC and BCC phases, respectively).

Table 1. The volume fractions of FCC and BCC phases of Al$_x$Fe$_2$CrNiCu$_x$ (x = 0.0, 0.5, 0.75, 1.0, 1.5) HEAs.

| HEAs   | BCC% | FCC% |
|--------|------|------|
| Al$_{0.0}$ | 0    | 100  |
| Al$_{0.5}$ | 51   | 49   |
| Al$_{0.75}$ | 89   | 11   |
| Al$_{1.0}$  | 99   | 1    |
| Al$_{1.5}$  | 100  | 0    |
3.4. Damping capacity

Figure 9 shows the variation of the internal friction (IF) $Q^{-1}$ with the strain amplitude for the alloy system. The values of internal friction increase rapidly and reach a maximum within a small strain range and then all these values begin to decline at a slower rate. Not surprisingly, the $Al_{0.5}$ alloy with dual phase structure has the highest damping performance with the peak value of $Q^{-1} = 0.10$, which exceeds many traditional damping alloys, such as Fe-Al [27] (up to 0.04) and Mn-Cu [40] (up to about 0.055 at room temperature) alloys and exceeds previously reported Fe$_{50}$Mn$_{20}$Co$_{5}$Cr$_{15}$ high-entropy alloys (up to 0.076) [41]. The soft FCC phase uniformly distributed in the hard BCC matrix and the ratio of about 1:1 between the two phases result in the large damping capacity for the $Al_{0.5}$ HEA due to a large number of interfacial surfaces between the soft and hard phases. When loaded or deformed by external force, the softer FCC dendritic phase will undergo plastic deformation while the harder BCC phase will undergo elastic deformation. In this way, the inconsistent deformation at the interface of the two phases will consume a lot of energy. This is the damping mechanism of the multiphases. In addition, the

![EBSD IPF images of $Al_{x}Fe_{2}CrNiCu$ HEAs](image)

Figure 6. EBSD IPF images of $Al_{x}Fe_{2}CrNiCu$ HEAs, where $x = 0, 0.5, 0.75, 1.0, 1.5$ are corresponding to subfigures by (a)–(e), respectively.
Figure 7. Compressive stress-strain curves of as-cast Al$_x$Fe$_2$CrNiCu ($x = 0.0, 0.5, 0.75, 1.0, 1.5$) HEAs.

Figure 8. Change of Hardness, yield strength, and compressive strain with BCC phase volume fractions in Al$_x$Fe$_2$CrNiCu ($x = 0.0, 0.5, 0.75, 1.0, 1.5$) HEAs.

Figure 9. Damping capacity of Al$_x$Fe$_2$CrNiCu ($x = 0.0, 0.5, 0.75, 1.0, 1.5$) HEAs.
magnetic domain damping mechanism for the phase with the crystal structure of BCC is another factor to influence the damping capacity \[42\]. Furthermore, the finest grain size (see figure 6(b)) of the Al\(_{0.5}\) HEA also contributes to the increase of its damping capacity. By comparison, the damping capacity, approximately 0.07, of the Al\(_{0.75}\) alloy ranks the second in Al\(_x\)Fe\(_2\)CrNiCu (\(x = 0.0, 0.5, 0.75, 1.0, 1.5\)) HEAs. This is due to the fact that the soft FCC phase is distributed in-between the BCC dendritic matrix and the interface between two phases is less because the volume of fraction FCC phase is relatively small. Therefore, compared to the Al\(_{0.5}\) HEA, the damping capacity of the Al\(_{0.75}\) alloy is small. However, the damping capacity of the Al\(_{1.0}\) and Al\(_{1.5}\) HEAs is further decreased to 0.067 and 0.066, respectively, due to both the interdendritic and dendritic of the two alloys are of the same BCC structure with little hardness difference resulted in the same level of the damping peaks. Compared to the phase with BCC structure, the Al-free Al\(_{0.0}\) alloy with FCC structure shows the lowest damping performance with \(Q^{-1}\) of 0.06, which, perhaps, is reduced by the effect of domain damping mechanism in the alloy.

### 3.5. Phase stability

HEAs have a series of outstanding properties mainly because they are easy to form solid solutions rather than intermetallic compounds, and there are lots of influence factors that affect the formation and stability of solid solution phases [43–45], such as the mixing entropy (\(\Delta S_{\text{mix}}\), equation (1)), the mixing enthalpy (\(\Delta H_{\text{mix}}\), equation (2)), the atomic size difference (\(\delta\), equation (3)), and the valence electron concentration (VEC, equation (4)). Table 1 shows the parameters mentioned above with different \(x\) value in Al\(_x\)Fe\(_2\)CrNiCu (\(x = 0.0, 0.5, 0.75, 1.0, 1.5\)) HEAs. The base data required in table 2, i.e., the chemical mixing enthalpies for atomic pairs and atomic size of the experimental elements are presented in tables 3 and 4, respectively. Zhang et al. [44] proposed that the formation and stability of solid solution can be predicted by \(\Delta H_{\text{mix}}\).

\[
\Delta S_{\text{mix}} = -R \sum_{i=1}^{n} (c_i \ln c_i)
\]

(1)

\[
\Delta H_{\text{mix}} = \sum_{i=1}^{n} \Omega_{ij} c_i c_j = 4\Delta H_{ij}^\text{max}
\]

(2)

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**Table 2.** VEC, \(\Delta H_{\text{mix}}\), \(\Delta S_{\text{mix}}\) and \(\%\) of Al\(_x\)Fe\(_2\)CrNiCu (\(x = 0.0, 0.5, 0.75, 1.0, 1.5\)) HEAs.

| HEAs  | VEC  | \(\Delta H_{\text{mix}}\)/KJ·mole\(^{-1}\) | \(\Delta S_{\text{mix}}\) | \(\%\) |
|-------|------|--------------------------------------|-----------------|-----|
| Al\(_{0.0}\) | 8.60 | 2.88 | 1.33R | 1.10 |
| Al\(_{0.5}\) | 7.86 | 0.066 56 | 1.51R | 4.22 |
| Al\(_{0.75}\) | 7.60 | -2.812 96 | 1.54R | 4.87 |
| Al\(_{1.0}\) | 7.33 | -4.111 08 | 1.56R | 5.34 |
| Al\(_{1.5}\) | 6.84 | -6.1065 | 1.56R | 5.96 |

**Table 3.** The chemical mixing enthalpies (KJ/mol) for atomic pairs among alloying elements [46].

|     | Fe   | Cr   | Ni   | Cu   | Al   |
|-----|------|------|------|------|------|
| Fe  | 0    | -1   | -2   | 13   | -11  |
| Cr  | 0    | -7   | 12   | -10  |
| Ni  | 0    | 4    | -22  |
| Cu  | 0    | -1   |

**Table 4.** The valence electron concentration (VEC) and radius of the experimental elements [37].

|     | Fe   | Cr   | Ni   | Cu   | Al   |
|-----|------|------|------|------|------|
| Radius/pm | 126 | 128  | 124  | 127  | 143  |
| VEC  | 8    | 6    | 10   | 11   | 1    |
\[ \delta^\% = 100\% \left( \sum_{i=1}^{n} c_i \left( 1 - \frac{\sigma_i}{\sum_{j=1}^{n} c_j \sigma_j} \right) \right)^2 \] 

Where \( c_i \) and \( r_i \) denote the atomic fraction and atomic radius of the \( i \)th element and \( \Delta H_{ij}^{\text{mix}} \) is the enthalpy of mixing of the binary liquid between the \( i \)th and \( j \)th elements at an equiatomic composition.

When \( 0\% < \delta \leq 6\% \) and \(-15 \text{kJ mol}^{-1} \leq \Delta H_{\text{mix}} \leq 5 \text{kJ mol}^{-1} \), the alloy is more favored to form solid solution. As displayed in table 1, with increasing the \( x \) value, the atomic size difference, \( \delta \), increases and the enthalpy of mixing, \( \Delta H_{\text{mix}} \), decreases, however, their values are basically in the defined range for solid solution formation. Even though \( \Delta H_{\text{mix}} \) and \( \delta \) can effectively predict the formation of solid solution, they cannot distinguish the crystal structure of the alloys. So, another parameter, VEC, was reported [43] to predict the crystal structure of HEAs.

The VEC is calculated using equation (4):

\[ \text{VEC} = \sum_{i=1}^{n} c_i (\text{VEC})_i \] 

Where \((\text{VEC})_i\) is the VEC for the \( i \)th element. When \( 6.87 < \text{VEC} < 8 \), the HEAs consist of FCC phase and BCC phase. And when \( \text{VEC} > 8 \), only the single FCC phase is formed. Whereas \( \text{VEC} < 6.87 \), only BCC phase is formed. The phase structures of \( \text{Al}_x\text{Fe}_2\text{CrNiCu} \) \((x = 0.0, 0.5, 0.75, 1.0, 1.5) \) HEAs are consistent with the prediction based on the calculated VEC values.

### 4. Conclusions

In this study, the microstructure, phase structure, mechanical properties and damping capacity of \( \text{Al}_x\text{Fe}_2\text{CrNiCu} \) \((x = 0.0, 0.5, 0.75, 1.0, 1.5) \) HEAs were investigated. In summary, conclusions can be drawn as follows.

1. With the increase of \( x \) value, the volume fractions of BCC phase increase from 0 for \( x = 0.0 \) to 100% for \( x = 1.5 \) in the as-cast \( \text{Al}_x\text{Fe}_2\text{CrNiCu} \) \((x = 0.0, 0.5, 0.75, 1.0, 1.5) \) HEAs. A novel dual phase microstructure consisting of both FCC and BCC phase was obtained for the \( \text{Al}_x\text{Fe}_2\text{CrNiCu} \) \((x = 0.0, 0.5, 0.75, 1.0, 1.5) \) HEAs.

2. The yield strength of the alloys increases from 248 MPa to 1396 MPa with the \( x \) value increasing from zero to 1.5, while the fracture strain decreases from 30% to 4% with the \( x \) value increasing from 0.75 to 1.5. No fracture behavior was observed for the alloys when \( x = 0.0 \) and 0.5.

3. The damping capacity of HEAs is affected greatly by the volume fractions of soft FCC phase distributed on the BCC matrix. The high damping capacity with \( Q^{-1} = 0.1 \) was obtained for the \( \text{Al}_{0.5} \) HEA.

4. The phase selection of \( \text{Al}_x\text{Fe}_2\text{CrNiCu} \) \((x = 0.0, 0.5, 0.75, 1.0, 1.5) \) HEAs is coincided with the prediction based on VEC value and phase volume fractions can be adjusted by tuning such value.

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### Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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