Design of Eutectic High Entropy Alloys

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Eutectic high entropy alloys (EHEAs) are emerging as an exciting new class of structural alloys as they have shown promising mechanical properties. However, how to design these alloys has been a challenge. In this work, a thermodynamic approach based on the phase rule is developed for designing EHEAs. Furthermore, the ideas of compositional phase diagrams and mixing eutectic alloys are introduced, and it is shown how these methods could be used for designing new EHEAs. The approach is applied for alloy systems Al–Co–Cr–Fe–Ni and Co–Cr–Fe–Ni–Ti, and several EHEAs are predicted for these alloy systems. The predicted results are verified with thermodynamic simulations and experimental data. The results show that the introduced approach can be considered as a feasible and easy-to-use method for designing EHEAs. Based on the developed approach, a procedure is provided in this work for designing EHEAs which can be applied for any binary or ternary eutectic system.

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I. INTRODUCTION

HIGH entropy alloys (HEAs) are a new class of metallic alloys which are founded on the idea that an alloy could have multiple (at least three) principal elements instead of one dominant element. Based on this “fundamentally new idea”, new alloys, mostly selected from the central part of the multicomponent phase diagrams, are being designed and investigated; the aim is to identify alloys with enhanced properties in comparison with traditional alloys. Initially, the focus was on equiatomic alloys such as CoCrFeMnNi, CoCrFe, TiTaVMo, ..., but currently, non-equatomic alloys are also being investigated. The exploration has led to the discovery of some alloys with new physical phenomena and promising properties. For example, one may name eutectic high entropy alloys (EHEAs) which are firstly reported by Lu et al. Due to their fine in-situ lamellar composite microstructures, EHEAs have shown very favorable combinations of strength and ductility which have encouraged materials’ scientists to focus on EHEAs as a promising new class of structural alloys.

A challenge for further development of EHEAs is how to design these alloys. That is because the phase diagrams are not available for the majority of quaternary and quinary alloy systems. In fact, most of the EHEAs were found by trial and error methods. Several strategies are reported for designing EHEAs. Although these methods have been successful in designing EHEAs, they have their own limitations. A simple approach was recently introduced by the author for designing EHEAs in Al–Co–Cr–Fe–Ni system. It was assumed that EHEAs originate from binary and ternary eutectic systems. As a result, the compositions of binary and ternary eutectic alloys were used for finding the composition of EHEAs. Furthermore, the concept of eutectic lines was introduced, and it was proposed that new eutectic or near-eutectic compositions can be obtained by mixing the alloys which are located on the same eutectic line. In the present work, a thermodynamic approach and the concept of eutectic hyperspaces are used to further explain the method introduced in Reference 19. By using the concept of eutectic hyperspaces, the relation between the composition of binary and ternary eutectic alloys and the composition of EHEAs can be more easily understood. The approach is then applied for alloy systems Al–Co–Cr–Fe–Ni and Co–Cr–Fe–Ni–Ti, and new eutectic alloys are designed by using the introduced approach. The results show that the developed approach is a feasible and easy-to-use approach for designing EHEAs. Based on the developed approach, any binary or ternary eutectic alloy can be employed for designing multicomponent eutectic alloys.

II. METHODOLOGY

The ingots of designed AlCoCrFeNi and CoCrFeNiTi alloys were prepared via arc melting under a Ti-gettered
high-purity argon atmosphere. High-purity constituent elements [Ni(99.9 pct wt pct), Co(99.99 pct wt pct), Al(99.999 pct wt pct), Cr (99.9 pct wt pct), and Ti (99.9 pct wt pct)] were used for making the alloys. The ingots were remelted four times to achieve compositional homogeneity. The homogenized ingot were then suction casted into 4-cm-long and 8-mm-diameter rods using a water-cooled copper mold. The samples were further sectioned perpendicular to their length for microstructural investigations which were performed by optical microscope. Because the main objective of the present work is designing eutectic high entropy alloys, the goal was just observing eutectic microstructures. All of the simulations and thermodynamic calculations in the present work are performed by JMatPro® software version 7.0.0 developed by Sente Software Ltd. An alloy is considered as eutectic if simulation results predict that the solidification occurs in a narrow temperature range ($\Delta T_{\text{max}} = 10 ^\circ\text{C}$), and if during the solidification, simultaneous formation of two solid phases occurs. It should be noted that because a temperature range and not a fixed temperature is considered for the solidification of alloys, it can be interpreted that the alloys are in fact quasi-eutectic alloys.

III. MODEL DEVELOPMENT

In binary alloy systems, a binary eutectic reaction (e.g., $L \rightarrow \gamma + B_2$) can be considered as a three-phase equilibrium (liquid and two solid phases) with zero degree of freedom according to the phase rule ($F = C - P + 1$, $F = 2 - 3 + 1 = 0$). Therefore, a three-phase equilibrium appears as a point in a binary phase diagram (Figure 1(a)). In ternary alloy systems, a binary eutectic reaction becomes a three-phase equilibrium with 1 degree of freedom ($F = 3 - 3 + 1 = 1$). Therefore, the traces of the phase compositions appear as lines in ternary phase diagrams (Figure 1(b)). In quinary systems, a binary eutectic reaction has three degree of freedom ($F = 5 - 3 + 1 = 3$). Therefore, three-phase equilibria will form a hyperspace within the quinary phase diagrams. This is schematically shown in Figure 1(c) for alloys with three-phase equilibrium $L \rightarrow \gamma + B_2$ in the quinary phase diagram Al-Co–Cr–Fe–Ni. Every alloy which is selected within this hyperspace will

![Fig. 1](https://example.com/figure1.png)

**Fig. 1**—(a) The eutectic point in the phase diagram of Al–Co; (b) the eutectic line in the phase diagram of Al-Co-Ni; (c) the schematic of eutectic hyperspace for alloys with three-phase equilibrium $L \rightarrow \gamma + B_2$ within the phase diagram of Al–Co–Cr–Fe–Ni system.
go through a binary eutectic reaction during solidification. Therefore, if this hyperspace can be defined, then designing eutectic alloys will be straightforward, and for designing EHEAs, the objective should be defining this hyperspace.

As explained above, the traces of the liquid composition of three-phase equilibria form a hyperspace within quinary phase diagrams. Such hyperspaces cannot be easily represented. Furthermore, there are not enough experimental data to find these hyperspaces. One simple approach to show a hyperspace could be finding the two-dimensional projections of that hyperspace. This is schematically shown in Figure 2 where a eutectic hyperspace is projected on two projections. These two-dimensional projections in fact define the limits of a eutectic hyperspace within a phase diagram. Although these projections cannot exactly define a eutectic hyperspace, but they could be considered as good approximations for it and, therefore, they could be used for predicting the composition of EHEAs. If an alloy can be selected in a way to be located in these two-dimensional projections, then with a great probability that alloy will be located within the eutectic hyperspace and that alloy will be eutectic. This is the approach presented here for designing EHEAs. So, the question now is how to find these projections. It is shown below that the compositions of binary and ternary eutectic alloys (which can be easily found from binary and ternary phase diagrams) can be used for finding the two-dimensional projections of a eutectic hyperspace. That is because binary and ternary eutectic alloys are also a part of that eutectic hyperspace. This point is further explained below for the alloy system Al–Co–Cr–Fe–Ni.

### IV. AL–CO–CR–FE–NI SYSTEM

The alloy system Al–Co–Cr–Fe–Ni is considered here first. This system is one of the extensively studied alloy systems in the field of HEAs. One of the eutectic reactions in this alloy system is \( L \rightarrow \gamma + B_2 \). The chemical compositions of some of the verified binary and ternary eutectic alloys with this eutectic reaction are shown in Table I. According to the ternary phase diagrams,25–29 alloys with this eutectic reaction are located along a line in ternary systems;25–29 therefore, ranges of compositions are listed for these ternary eutectic alloys in Table I. Some of the experimentally verified EHEAs in this system are also listed in Table II.

Figure 3(a) shows the Al concentration vs (Ni + Co) concentration, and Figure 3(b) shows the Al concentration vs (Ni + Co + Fe) concentration of all eutectic alloys in Tables I and II. Ternary eutectics are shown by lines in Figure 3. It can be seen that there are regions limited by binary and ternary eutectics in which all EHEAs are located. So it can be hypothesized that eutectic regions in Figure 3 are in fact two-dimensional projections of the eutectic hyperspace within the phase diagram of Al–Co–Cr–Fe–Ni. Furthermore, it can be postulated that all EHEAs in Al–Co–Cr–Fe–Ni system should be located within these eutectic regions. Eutectic regions in Figure 3 provide references for evaluating the Al concentration of EHEAs in Al–Co–Cr–Fe–Ni.

Similar to the compositional diagrams in Figure 3, compositional diagrams in Figure 4 are plotted by using the concentration of eutectic alloys in Tables I and II.

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**Table 1. The Chemical Compositions of Some of the Experimentally Verified Binary and Ternary Eutectic Alloys in Al–Co–Cr–Fe–Ni System**

| Alloy       | Chemical Composition (At Pct) | Eutectic Reaction |
|-------------|-------------------------------|-------------------|
| AlCo\[^{[30]}\] | 20 80 — — — | \( L \rightarrow \gamma + B_2 \) |
| AlCoFe\[^{[38,39]}\] | 15 to 20 63 to 80 — 0 to 22 — | \( L \rightarrow \gamma + B_2 \) |
| AlFeNi\[^{[25]}\] | 17 to 22 — — 10 to 50 33 to 68 | \( L \rightarrow \gamma + B_2 \) |
| AlCoNi\[^{[28,29]}\] | 20 to 23 7 to 80 — — 0 to 70 | \( L \rightarrow \gamma + B_2 \) |
| AlCoCr\[^{[40]}\] | 19 to 20 56 to 80 0 to 25 — — | \( L \rightarrow \gamma + B_2 \) |
| AlCrNi\[^{[26, 27]}\] | 17.5 to 23 0 4 to 31 0 51.5 to 73 | \( L \rightarrow \gamma + B_2 \) |
According to the diagrams in Figure 4, again it can be seen that there are narrow regions limited by binary and ternary eutectic compositions in which all EHEAs are located. So, it can be anticipated that the Cr, Fe, and Ni concentrations of all \((\gamma + B2)\) EHEAs in Al–Co–Cr–Fe–Ni system should be within the eutectic regions which are shown in Figure 4.

The eutectic regions in Figures 3 and 4 can be considered as two-dimensional projections of the eutectic hyperspace within the phase diagram of Al–Co–Cr–Fe–Ni. If an alloy can be designed in a manner to be located within all of the eutectic regions in Figures 3 and 4, the chance of that alloy to be located within the eutectic hyperspace is very high and that alloys could be eutectic. Therefore, to design new EHEAs in Al–Co–Cr–Fe–Ni system, it is necessary to determine the chemical composition of the alloy that should be located within all eutectic hyperspace.

### Table II. The Chemical Compositions of Some of the Experimentally Verified EHEAs in Al–Co–Cr–Fe–Ni System

| Alloy          | Chemical Composition (At. Pct) | Eutectic Reaction |
|----------------|-------------------------------|-------------------|
| AlCoFeNi       | 19 20                         | L \(\rightarrow \gamma + B2\) |
| AlCoCrNi       | 19 15 15                      | L \(\rightarrow \gamma + B2\) |
| AlCoCrNi       | 17.4 21.7 21.7 0              | L \(\rightarrow \gamma + B2\) |
| AlCrFeNi       | 16 38.6 22.7 0                | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16 30 10 10 32               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 16.4 16.4 16.4 34.4      | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 17 28.6 14.3 14.3 25.8        | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 17 14.3 14.3 14.3 40.1        | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 17 30 10 10 32               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 30 10 10 32               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 27.34 27.34 27.34 27.34    | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 30 10 10 32               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 24 10 10 36               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 20 10 10 40               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16 41 15 10 18               | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 13 16.4 16.4 37.8        | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 19.7 16.4 16.4 31.1      | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 16.4 19.7 13 34.5        | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 16.4 13 19.7 34.5        | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 9.8 16.3 23.3 34.3       | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 19.7 16.4 13.2 34.3      | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 19.7 16.4 13.2 34.3      | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 16.4 19.7 16.4 13.2 34.3      | L \(\rightarrow \gamma + B2\) |
| AlCoCrFeNi     | 18 30 10 10 32               | L \(\rightarrow \gamma + B2\) |

*These alloys contained 2 at. pct of W for improving the mechanical properties.

Fig. 3—The Al concentration vs \((\text{Ni} + \text{Co})\) and \((\text{Ni} + \text{Co} + \text{Fe})\) concentration of binary and ternary (●) and quaternary and quinary (▲) eutectic alloys in Tables I and II, and designed alloys (▲). Adapted from Ref. [19].
An alloy should be designed in a manner to be located in all of the eutectic regions shown in Figures 3 and 4. For example, three alloys Al_{19}Co_{47}Cr_{8}Ni_{26}, Al_{18}Co_{24}Cr_{7}Fe_{17}Ni_{34}, and Al_{18}Co_{34}Cr_{11}Fe_{8}Ni_{29} were designed. These alloys were designed in a way to be located within all of the eutectic regions in Figures 3 and 4. The thermodynamic simulation results for these alloys are shown in Figure 5. The simulation results clearly show that these alloys are eutectic indicating that the approach and the eutectic regions introduced in this work could be used for designing EHEAs. It should be emphasized that eutectic regions in Figures 3 and 4 are just approximately showing the eutectic hyperspace within the phase diagram of Al–Co–Cr–Fe–Ni, and each alloy which is located inside of these eutectic regions is not necessarily eutectic. The alloys which are located in eutectic regions just have a good chance to be eutectic. If more compositional diagrams similar to Figures 3 and 4 could be designed and used for projecting the eutectic hyperspace, then more accurate results will be obtained. In other words, if more compositional diagrams can be designed, then the eutectic hyperspace can be projected more accurately and, as a result, more accurate eutectic compositions can be obtained.

V. MIXING EUTECTIC ALLOYS FOR OBTAINING NEW EUTECTIC ALLOYS

A good estimation of a eutectic composition can be obtained by mixing eutectic alloys. That is because if two eutectic alloys are mixed together, the obtained alloy will also be probably inside the eutectic hyperspace. This is schematically shown in Figure 6. Specifically, binary and ternary eutectic systems can be mixed for obtaining other eutectic compositions. That is because binary and ternary eutectic alloys form the boundaries of eutectic regions in Figures 3 and 4. For
example, alloy Al$_{19}$Co$_{47}$Cr$_8$Ni$_{26}$ was obtained by mixing eutectic alloys Al$_{20}$Co$_{80}$ and Al$_{15}$Co$_{15}$Cr$_{15}$Ni$_{51}$ in a 1:1 molar ratio. As it was shown, this alloy is located inside all of the eutectic regions in Figures 3 and 4. The idea of mixing eutectic alloys for obtaining other eutectic alloys was first reported in Reference 19 and is based on the idea that EHEAs are originated from binary and ternary eutectic alloys and the point that eutectic alloys can be connected via eutectic lines. The existence of eutectic lines between eutectic alloys is also schematically shown in Figure 6.

Alloys Al$_{18}$Co$_{24}$Cr$_7$Fe$_{17}$Ni$_{34}$, Al$_{19}$Co$_{47}$Cr$_8$Ni$_{26}$, and Al$_{18}$Co$_{34}$Cr$_{11}$Fe$_8$Ni$_{29}$ which were designed in this work were made by casting. Optical images from the microstructures of these alloys are shown in Figure 7. It can be seen that the microstructures of these alloys consist from a fine intimate mixture of two phases indicating that designed alloys are eutectic. So the approach was successful in predicting new eutectic alloy compositions.

SEM images from the microstructures of designed alloys are shown in Figure 8. It can be seen that the
Eutectic alloys show similar microstructures consisting from two phases. The EDX analysis results are shown in Table III. According to the EDX results, it can be seen that the chemical composition of alloys is close to the designed alloys. Moreover, it can be seen that the Al concentration in darker regions in Figure 8 is higher in comparison with lighter regions. Ni, Co, Cr, and Fe are distributed almost equally between light and dark regions.

The XRD results for the eutectic alloys are shown in Figure 9. According to the XRD results, it can be seen that the diffractions are the same for all of the alloys, and the alloys have a dual FCC + B2 structure which is in accordance to the eutectic reaction $L \rightarrow \gamma (\text{FCC}) + \text{B2}$. Because Al stabilizes BCC phases,\(^{[18]}\) therefore, it can be concluded that the BCC peaks in XRD results are related to the darker regions in Figure 8. The FCC peaks in XRD results can be attributed to the lighter regions in Figure 8 which are poorer in Al.

The approach presented above for finding the composition of EHEAs in Al–Co–Cr–Fe–Ni system can be applied for any eutectic reaction in any alloy system. Therefore, the following steps can be proposed for designing EHEAs from a binary eutectic alloy:

1. Selecting a eutectic reaction and the associated binary eutectic alloy from a binary phase diagram (e.g., Al$_{20}$Co$_{80}$)
2. Selecting the elements which want to be added to the binary eutectic alloy (for example adding Ni, Fe, and Cr to Al$_{20}$Co$_{80}$ for developing AlCoCr-FeNi EHEAs with eutectic reaction $L \rightarrow \gamma + \text{B2}$)
3. Finding the ternary eutectic alloys of that eutectic reaction from ternary phase diagrams
4. Plotting eutectic regions similar to the procedure used in Figures 3 and 4, and finally
5. Designing EHEAs by using the plotted eutectic regions (the first approximation can be obtained by mixing binary and ternary eutectic alloys)

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**Fig. 7**—Optical images of the microstructure of alloys (a, b) Al$_{19}$Co$_{47}$Cr$_{8}$Ni$_{26}$, (c, d) Al$_{18}$Co$_{24}$Cr$_{7}$Fe$_{17}$Ni$_{34}$, and (e, f) Al$_{18}$Co$_{34}$Cr$_{11}$Fe$_{8}$Ni$_{29}$. 

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It should be noted that if a more number of compositional diagrams can be used, then the eutectic hyperspace will be projected more accurately and, as a result, more accurate eutectic compositions will be obtained. In the following section, the approach is applied for the alloy system Co–Cr–Fe–Ni–Ti.

Table III. EDX Analysis Results of the Chemical Compositions of the Alloys and the Dark and Light Regions in Eutectic Microstructures in Fig. 8

|                | Al  | Co  | Cr  | Fe  | Ni  |
|----------------|-----|-----|-----|-----|-----|
| \( \text{Al}_{19}\text{Co}_{47}\text{Cr}_{8}\text{Ni}_{26} \) | 19  | 47  | 8   | —   | 26  |
| Alloy Composition by EDX | 17.54 | 49.24 | 8.36 | —   | 24.86 |
| Dark Regions | 19.87 | 48.66 | 7.94 | —   | 23.53 |
| light Regions | 14.85 | 52.17 | 8.57 | —   | 24.41 |
| \( \text{Al}_{18}\text{Co}_{24}\text{Cr}_{7}\text{Fe}_{17}\text{Ni}_{34} \) | 18  | 24  | 7   | 17  | 34  |
| Alloy Composition by EDX | 17.19 | 22.53 | 8.17 | 17.7 | 34.42 |
| Dark Regions | 18.02 | 22.73 | 7.54 | 17.5 | 34.21 |
| light Regions | 13.16 | 24.25 | 6.54 | 18.69 | 37.36 |
| \( \text{Al}_{18}\text{Co}_{34}\text{Cr}_{11}\text{Fe}_{8}\text{Ni}_{29} \) | 18  | 34  | 11  | 8   | 29  |
| Alloy Composition by EDX | 17.64 | 35.26 | 10.75 | 8.56 | 27.79 |
| Dark Regions | 19.76 | 34.68 | 10.32 | 7.98 | 27.26 |
| light Regions | 14.65 | 37.45 | 10.35 | 8.05 | 29.5 |
VI. CO–CR–FE–NI–TI SYSTEM

To the best of the authors’ knowledge, no EHEA is reported for this alloy system. Different binary eutectic reactions could be considered for this alloy system. One of the binary eutectic reactions is $L \rightarrow \gamma + Ni_3Ti$ which occurs in a binary alloy with the composition $Ni_{84}Ti_{16}$. This eutectic reaction can also be found in ternary alloy systems Cr–Ni–Ti, Co–Ni–Ti, and Fe–Ni–Ti as they are shown in Figure 10. It can be assumed that there are alloys with eutectic reaction $L \rightarrow \gamma + Ni_3Ti$ in quinary alloy system Co–Cr–Fe–Ni–Ti. Alloys with this eutectic reaction will occupy a hyperspace within the phase diagram of Co–Cr–Fe–Ni–Ti as it is schematically shown in Figure 11. Eutectic hyperspaces for two other eutectic reactions are also schematically shown in Figure 11. The eutectic reaction $L \rightarrow \gamma + Ni_3Ti$ is considered here.

By using the composition of binary and ternary eutectic alloys in Figure 10, the compositional diagrams in Figure 12 are plotted. Ternary eutectics are shown by lines in Figure 12. Dashed regions which are shown in...
Fig. 11—The schematic of eutectic hyperspaces within the phase diagram of Co–Cr–Fe–Ni–Ti system for three different eutectic reaction.

Fig. 12—(a to d) Compositional diagrams for eutectic reaction L → Ni + Ni3Ti in quinary alloy system Co–Cr–Fe–Ni–Ti, and the designed eutectic alloy (●).

Fig. 13—Thermodynamic simulation results for alloy Co11Cr7Fe11Ni54Ti17.
Figure 12 could be considered as two-dimensional projections of the eutectic hyperspace related to the reaction $L \rightarrow \gamma + Ni_3Ti$. Therefore, EHEAs with eutectic reaction $L \rightarrow \gamma + Ni_3Ti$ are expected to be located within the dashed regions in Figure 12. To design eutectic alloys, an alloy should be designed in a manner to be located inside all of the dashed regions in Figure 12. Alloy Co$_{11}$Cr$_7$Fe$_{11}$Ni$_{54}$Ti$_{17}$ was designed by mixing three eutectic alloys Ni$_{50}$Fe$_{33}$Ti$_{17}$, Cr$_{21}$Ni$_{62}$Ti$_{17}$, and Co$_{31}$Ni$_{49}$Ti$_{18}$ in an equimolar ratio. The designed alloy is shown by a red circle in Figure 12. As it can be seen, this alloy is located inside all of the dashed regions meaning that this alloy could be eutectic.

The thermodynamic simulation results for alloy Co$_{11}$Cr$_7$Fe$_{11}$Ni$_{54}$Ti$_{17}$ are shown in Figure 13. The simulation results clearly show that this alloy is eutectic and the solidification of this alloy occurs in a narrow range of temperature.

Alloy Co$_{11}$Cr$_7$Fe$_{11}$Ni$_{54}$Ti$_{17}$ was prepared via casting, and the microstructure of this alloy is shown in Figure 14. It can be seen that the microstructure of the alloy consists of an intimate mixture of two phases indicating that the designed alloy is eutectic. So the approach presented here for designing eutectic alloys was successful.

A SEM image from the microstructure of alloy Co$_{11}$Cr$_7$Fe$_{11}$Ni$_{54}$Ti$_{17}$ is shown in Table IV. The XRD results are shown in Figure 16. According to the XRD results, it can be seen that the alloy has a dual FCC + Ni$_3$Ti microstructure in accordance to the eutectic reaction $L \rightarrow \gamma + Ni_3Ti$. Because the darker regions in Figure 15 are richer in Ti, they can be attributed to the phase Ni$_3$Ti. The lighter regions in Figure 15 show the $\gamma$ phase with FCC crystal structure.

**VII. DISCUSSIONS**

The thermodynamic phase rule indicates that liquid compositions of a three-phase equilibrium such as $L \rightarrow \gamma + B2$ will form a hyperspace within a quinary phase diagram. Therefore, if these hyperspaces can be defined, then designing eutectic alloys will be straightforward. Compositional diagrams are introduced which can be used for projecting these hyperspaces and designing EHEAs. It is shown how these diagrams can be obtained by using the composition of binary and ternary eutectic alloys. These compositional diagrams reveal the composition range within which EHEAs can exist. Although these compositional diagrams cannot exactly define a eutectic hyperspace within a phase diagram, they can be considered as good estimates of that eutectic hyperspace. It should be emphasized that eutectic regions which are shown in compositional diagrams are just approximately showing the eutectic hyperspace within a phase diagrams. Each alloy which is located inside of these eutectic regions is not necessarily eutectic. The alloys which are located in eutectic regions just have a good chance to be eutectic. If a more number of compositional diagrams are used for projecting a eutectic hyperspace, then a more accurate projection of that eutectic hyperspace will be obtained and, as a result, more accurate eutectic compositions can be obtained.
By investigating the compositional diagrams in Figures 3 and 4, it can be seen that eutectic regions, in which EHEAs are located, are limited by the composition of binary and ternary eutectic alloys. This observation suggests that a relation should exist between the composition of binary and ternary eutectic alloys and the composition of EHEAs. Furthermore, it can be postulated that EHEAs originate from binary and ternary eutectic alloys. In other words, it can be hypothesized that EHEAs are made by adding new elements to binary and ternary eutectic alloys. For example, it can be assumed that \((\gamma + B2)\) EHEAs in Al–Co–Cr–Fe–Ni system are made by adding elements Ni, Cr, and Fe to the binary eutectic alloy Al20Co80.

The idea of mixing eutectic alloys and the compositional diagrams introduced in this work can be used together for designing EHEAs in any alloy system. In general, they provide simple approaches for designing EHEAs. Two alloy systems are considered here, but the approach can be extended to other alloy systems. The author applied this approach for alloy systems Co–Cr–Fe–Ni and Co–Cr–Fe–Ni–Ta, and the results can be found in Reference 35. An interesting case could be eutectic refractory high entropy alloys which are reported very recently.\[36,37\] Another application of the developed approach could be designing EHEAs with low melting temperatures which could have possible applications in brazing and soldering. An alloy system which could be suggested in this regard is Al–Ag–Bi–Sn–Zn. Further research and experiments are needed in this regard.

VIII. CONCLUSIONS

The thermodynamic phase rule indicates that a eutectic hyperspace should exist for a three-phase equilibrium reaction such as \(L \rightarrow \gamma + B2\) in quinary phase diagrams. Compositional diagrams can be used for defining these eutectic hyperspaces within quinary phase diagrams. These compositional diagrams clearly show that a connection exists between the composition of binary and ternary eutectic alloys and the composition of EHEAs implying the point that EHEAs originate from binary and ternary eutectic alloys. It is shown how these compositional diagrams can be used for designing new eutectic alloys. The idea of mixing eutectic alloys is introduced in this work, and it is shown how by mixing binary and ternary eutectic alloys new eutectic alloys can be designed. By using the ideas of compositional diagrams and mixing eutectic alloys, several eutectic high entropy alloys are designed for alloy systems Al–Co–Cr–Fe–Ni. Furthermore, for the first time, a eutectic high entropy alloy \((Co_{11}Cr_{11}Fe_{11}Ni_{15}Ti_{18})\) is designed for Co–Cr–Fe–Ni–Ti system. The designed eutectic alloys are verified with thermodynamic simulations and experimental data. The results show that the idea of mixing eutectic alloys and the compositional diagrams can be successfully used together for designing EHEAs. Based on the developed approach, any binary eutectic alloy can be used for designing multicomponent eutectic alloys.

CONFLICT OF INTEREST

The corresponding author states that there is no financial or personal relationship with a third party whose interests could be positively or negatively influenced by the article’s content. The corresponding author states there is no conflict of interest for this paper.

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