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**High Temperature Deformation Behavior and Strengthening Mechanisms of
Heat
Resistant High Entropy Alloys**

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14. ABSTRACT In this research, two types of heat-resistant high entropy alloys were designed, fabricated and their mechanical behaviors and strengthening mechanisms were characterized. The high entropy superalloys (HESAs) were designed and fabricated by powder metallurgy process to have a novel microstructure of homogeneously distributed stable precipitates and dispersoids in FCC structured high entropy alloy matrices. The NiCoAlCrFeTi HESA with L12 L_{12} precipitates and Y_2O_3 dispersoids showed higher yield strengths up to temperatures of 800°C with good ductility at room temperature, compared to conventional Inconel 706 or Incoloy 901. The NiCoAlCrFeTi based HESAs could be good candidate materials for heat-resistant application up to elevated temperature of 800°C. The AlxCrNbVMo based refractory high entropy alloys (RHEAs) were designed and fabricated to exhibit a novel microstructure of stable nano-sized NbO _{1-x} or Al ₂ O ₃ dispersoids in BCC structured high entropy alloy matrices fabricated by powder metallurgy process. The nano-sized dispersoids were uniformly distributed by in-situ reaction process during mechanical alloying and sintering. The AlxCrNbVMo based RHEAs exhibited superior specific yield strength showing 87 % enhancement at 1,000°C compared to that of AlMoNbTaTiZr HEA, which exhibited the best specific yield strength among the cast RHEAs. Our designed RHEAs show much higher specific yield strengths compared to those of Ni-based superalloys up to temperatures of 1000°C. The AlxCrNbVMo based RHEAs could be promising candidate materials for heat-resistant application up to elevated temperature of 1,000°C or higher.			
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Research Objectives

Due to outstanding mechanical properties at elevated temperatures of heat-resistant HEAs, they are expected to be promising future materials for the high temperature applications, such as gas turbine engine components for aerospace vehicles and power plant systems. However, there has been limited research to understand the fundamentals and scientific knowledge on the deformation behavior and strengthening mechanisms of the heat-resistant HEAs at elevated temperatures.

In this research, we are motivated to investigate the high temperature deformation behaviors, microstructure-properties relationships and strengthening mechanisms of heat-resistant HEAs. The in-depth understanding of the strengthening mechanisms at the elevated temperature will provide a fundamental basis for innovative alloy development strategies to design compositions, microstructures and mechanical properties for next-generation structural materials applications.

There have been extensive efforts to develop new compositions of HEAs having enhanced mechanical properties at room and cryogenic temperatures. On the other hand, there have been limited studies on the fundamental understanding of the deformation behaviors and strengthening mechanisms at high temperatures. In this research, we will conduct comprehensive characterizations of lattice atomic structure, precipitation, grain growth and dislocation interaction to understand deformation behaviors and to analyze the strengthening mechanisms of the HEAs at high temperatures. The fundamentals and scientific understanding on the strengthening mechanisms are essential to control the microstructure and consequently optimize mechanical properties of HEAs for heat-resistant structural applications. This research will be expected to provide innovative basis for the design and process of HEAs as next-generation heat-resistant materials.

The objective of research is to investigate the fundamental science and technology on high temperature deformation of heat-resistant HEAs. Understanding of the high temperature mechanical properties and strengthening mechanisms are important to control microstructure and enhance high temperature mechanical properties of heat-resistant HEAs, which have enormous potential to apply for next-generation heat-resistant materials. This research was focus on the investigation of the atomic structure, phase transformation, microstructure-property relationships to understand the high temperature mechanical behavior of heat-resistant HEAs.

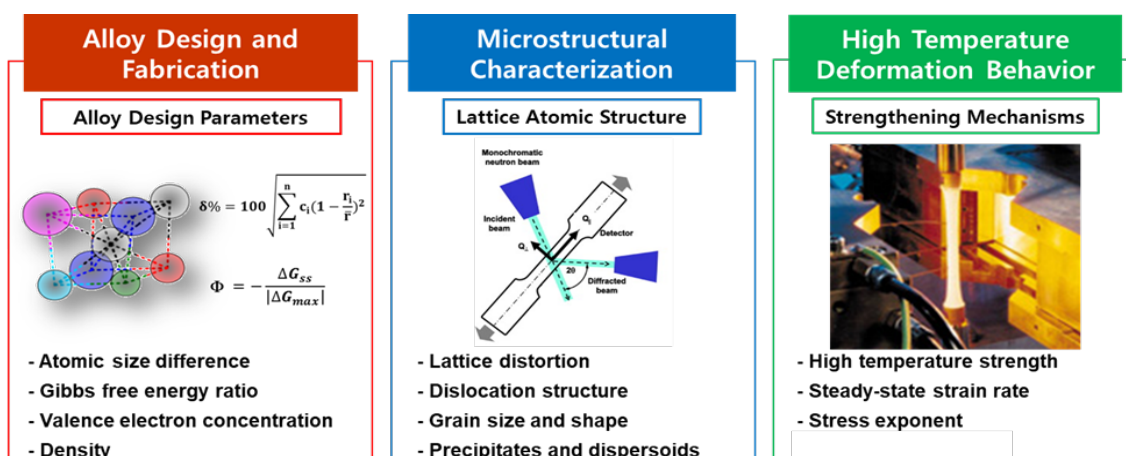


Figure 1. Key concepts of the proposed research on the deformation behavior and strengthening mechanisms of heat-resistant high entropy alloys.

Research Background

High entropy alloys (HEAs) are defined as multicomponent alloys, having high configurational entropy, consisting of more than 5 elements with 5-35 at. % of each atomic fraction [1]. Due to the high configurational entropy effect, the HEAs consist mainly of solid solution phases and show improved mechanical properties. Specific compositions of HEAs have exhibited not only stable microstructures but also enhanced mechanical properties at elevated temperatures compared to that of conventional Ni-base superalloys. However, the origins of the excellent high temperature strength of the heat-resistant HEAs have not been clearly understood yet. The fundamentals of the deformation behaviors and strengthening mechanisms of the heat-resistant HEAs are still in the incipient stage.

Based on the outstanding mechanical properties at elevated temperatures of heat-resistant HEAs, they are expected to be promising future materials for the high temperature applications, such as gas turbine engine components for aerospace vehicles and power plant systems. However, there has been limited research to understand the fundamentals and scientific knowledge on the deformation behavior and strengthening mechanisms of the heat-resistant HEAs at elevated temperatures.

In this research, we are motivated to investigate the high temperature deformation behaviors, microstructure-properties relationships and strengthening mechanisms of heat-resistant HEAs. The in-depth understanding of the strengthening mechanisms at the elevated temperature will provide a fundamental basis for development strategies of high entropy alloys to design compositions, microstructures and mechanical properties for next-generation structural materials applications.

In order to improve the energy efficiency of automobiles, aerospace vehicles, and power plants, demands for heat-resistant materials have been steadily growing to increase the operating temperature and applied stress of the gas turbine engines and power generators, etc. Recently, an innovative concept of alloy design has led to a new class of high entropy alloys, which contains multiple principal elements in equal or near equi-atomic compositions and often stabilized as a single solid solution phase owing to the major contribution of large configurational entropy. Being different from the conventional alloys, some high entropy alloys show promising results in terms of enhanced mechanical properties. However, there have been rather limited investigations to understand the mechanical behavior and strengthening mechanisms of heat-resistant high entropy alloys at elevated temperatures.

Research Accomplishments

1. Design of high entropy alloys

In this research, the heat-resistant high entropy alloys are designed based on our novel design concepts of two different types of high entropy alloys. One type is High Entropy Superalloys (HESAs) consisted of high temperature stable precipitates and dispersoids in FCC high entropy alloy matrix. The other type is Refractory High Entropy Alloys (RHEAs) consisted of high temperature stable dispersoids in BCC high entropy alloy matrix. The solid solution structures of HEA matrices can be designed based on valence electron concentrations of alloying elements.

1-1. Design concept of high entropy of superalloys (HESAs)

Design strategy of HESAs is to form precipitates and dispersoids in FCC alloy matrix with low density and high oxidation resistance. The main concept of alloy design is to form ductile FCC

matrix and distribute precipitates and dispersoids which are stable at high temperature. Design concept of HESA is based on lower density than that of the Ni-base superalloys, targeted less than 8.5 g/cm³. Form more than 40 vol% of gamma prime precipitate in FCC matrix. The microstructure of designed alloys shows very fine grained of about 500 nm FCC matrix with γ' ppt and ultra-fine oxide and carbide inclusions of about 30-60 nm as shown in schematic design concept of Figure 2.

1-2. Design concept of refractory high entropy alloys (RHEAs)

The design of RHEAs is based on the compositions are designed to have high temperature stable nano-sized dispersoids in BCC high entropy alloy matrix as shown in schematic design concept of Figure 2. The melting points of HEA matrix alloys are designed higher than 2300 Kelvin for heat-resistance at high temperature. The density is designed lower than that of the Ni-base superalloys, which is targeted 8.5 g/cm³. Al and Cr are added for oxidation resistance as protective oxide scale formers.

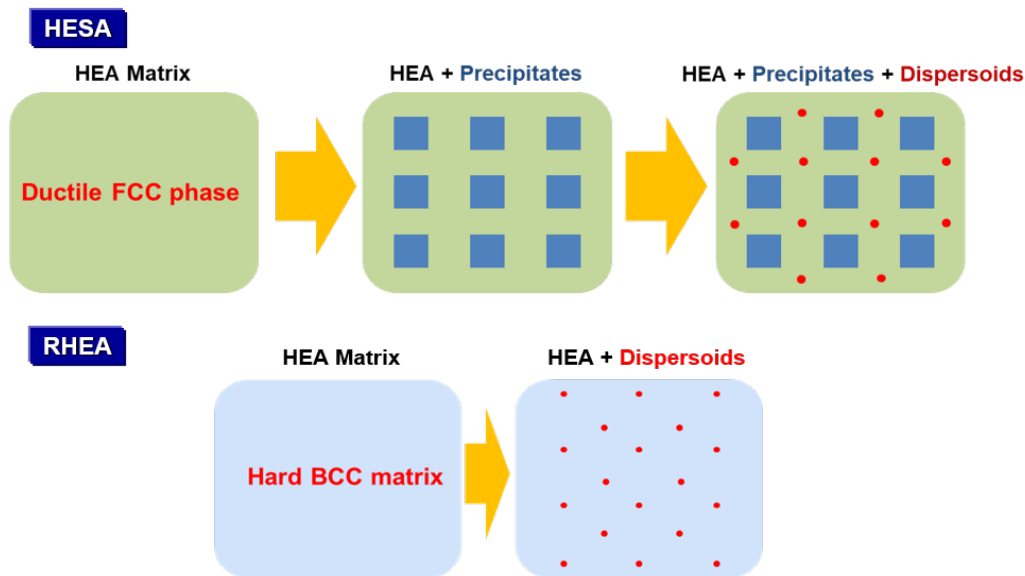


Figure 2. Design concepts of HESA and RHEA.

Based on those design concepts, we designed two HESA and four RHEA candidate alloys based on phase prediction by Thermo-Calc 2017b software (TCHEA 3.0). The physical parameters of designed alloys are summarized in Table 1.

Table 1. Designed HESA and RHEA compositions, parameters and structure.

Designed System	VEC	Density (g/cm ³)	T _m (K)	Structure
Ni ₄₆ Co ₂₂ Al ₁₂ Cr ₈ Fe ₈ Ti ₃ Mo ₁	8.2	7.82	1702	FCC + γ' (HESA)
Ni ₄₅ Co ₁₇ Al ₁₃ Cr ₁₁ Ti ₅ W ₅ Mo ₂ Nb ₁ Ta ₁	8.0	8.14	1839	
CrNbVMo (Al ₀)	5.5	8.01	2739	Single BCC (RHEA)
Al _{0.1} CrNbVMo (Al _{0.1})	5.4	7.98	2694	
Al _{0.5} CrNbVMo (Al _{0.5})	5.2	7.46	2538	
Al _{1.0} CrNbVMo (Al _{1.0})	5.0	6.95	2377	

2. Fabrication processes of designed high entropy alloys

The designed high entropy alloys were fabricated by powder metallurgy processes, include mechanical alloying, sintering and post-sintering heat treatment.

2-1. Mechanical alloying processes of high entropy alloys

The elemental powders were ball-milled in a high-energy planetary ball mill (Pulverisette 5; Fritsch). The ball-milling process was carried out at a speed of 200 RPM. To prevent oxidation during the milling process, all powder-handling procedures were conducted inside a glove box and the bowl was filled with high-purity argon before milling.

Optimized milling time was selected by considering saturation of average powder size and lamellar spacing of milled powder. To minimize oxygen contamination during mechanical alloying, milling should be stopped right after the average powder size and lamellar spacing are saturated. Average powder size and lamellar spacing with milling time at 200 RPM milling is shown in Figure 3, and optimized milling time was decided as 12 hours.

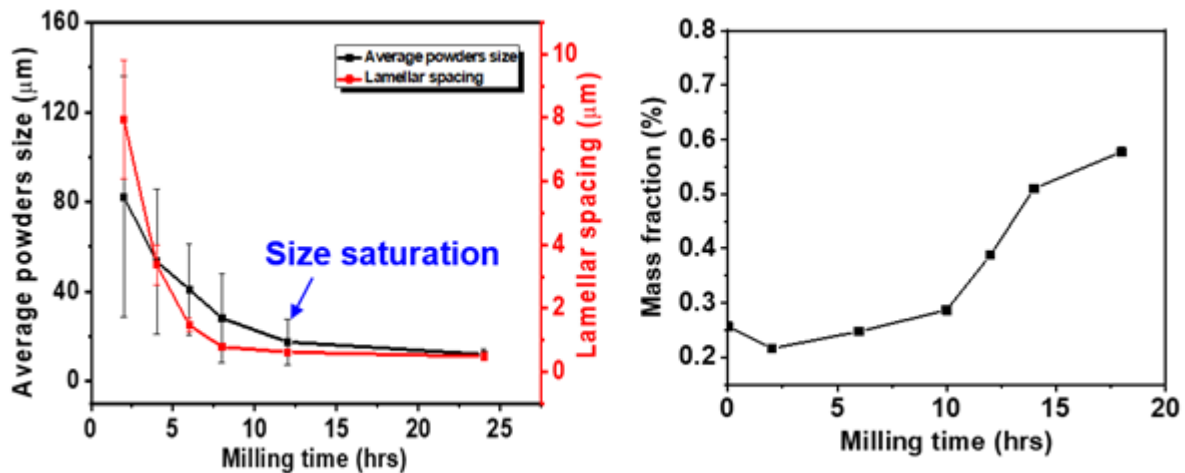


Figure 3. Average powder size, lamellar spacing, and oxygen mass fraction of milled powder with milling time at 200 RPM milling speed.

2-2. Sintering and heat treatment processes of HESAs

The mechanically alloyed powders were then consolidated to bulk specimens by spark plasma sintering (SPS; SPS-515S; Fuji Electronic Industrial). Sintering was done under the following conditions: constant compaction pressure of 50 MPa, vacuum atmosphere of 20 Pa, heating rate of $100^{\circ}\text{C min}^{-1}$, and holding time of 5 min at a sintering temperature. The sintering temperatures of each alloys were determined by completion of specimen shrinkage and relative density over 99.9%.

The mechanically alloyed powders of HESA were sintered for 5 minutes at $1,000^{\circ}\text{C}$ by spark plasma sintering (SPS). In case of HESA, we heat treated the specimen after sintering to obtain γ' precipitates. The serial heat treatment conditions are summarized in Figure 3. Firstly, we did solution heat treatment at 1200°C to dissolve all second phases formed during sintering, and made single FCC solid solution phase. Then, 2 step precipitation aging was conducted to nucleate and grow L_{12} γ' precipitates as shown in Figure 4.

2-3. Sintering process of RHEAs

The mechanically alloyed powders of RHEA were sintered for 5 minutes at $1,200^{\circ}\text{C}$ by spark plasma sintering as shown in Figure 5. In case of RHEA, there was no additional heat treatment, because desired single BCC solid solution phase was successfully formed right after SPS.

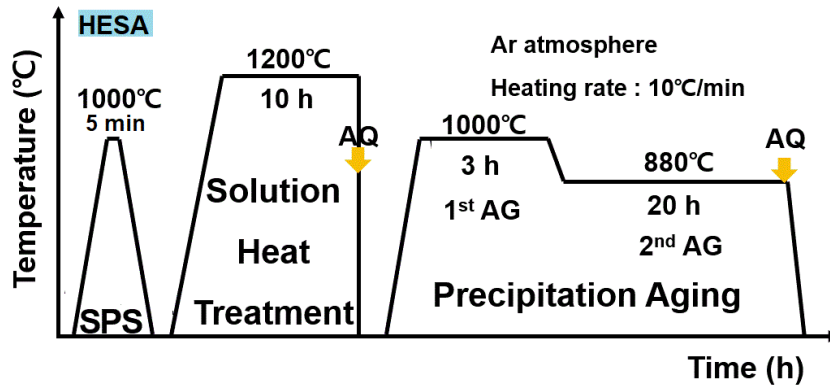


Figure 4. Sintering and heat treatment processes conditions of HESAs

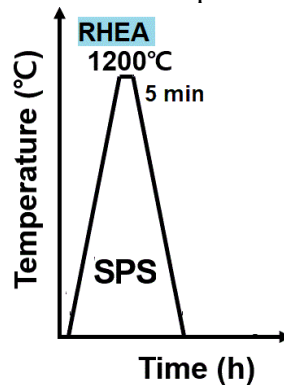


Figure 5. Sintering process condition of RHEAs

3. Analyses of microstructures and phases of high entropy alloys

The crystalline structures of the prepared alloys were investigated by X-ray diffraction (XRD; SmartLab; RIGAKU) by Cu K-a-1 X-ray with a scanning speed of 5 deg./min. The microstructures of the bulk specimens were observed by scanning electron microscopy (SEM; S4800; Hitachi), scanning electron microscope (SEM; SU5000; Hitachi), equipped with an energy-dispersive spectrometer (EDS) and an electron back-scattered diffraction (EBSD) detector and scanning transmission electron microscopy (STEM; JEM-ARM200F; JEOL) equipped with an energy dispersive spectrometer (EDS).

3-1. Analysis of microstructures and phases of sintered and heat-treated HESAs

Based on the TEM images and elemental mapping results, the phases in NiCoAlCrFeTi HESAs were classified into four different types. The chemical composition of the bright matrix phase was rich in Co, Cr, and Fe, and poor in Al and Ti, compared with the nominal composition, which was denoted as FCC solid solution matrix with average grain size of 560 nm. Grey precipitates rich in nickel (Ni), Al, and Ti were observed, which were γ' precipitates of 41 vol.% with average size of 267 nm. Also, in-situ formation of minor Al₂O₃ (1 vol.%) and TiC (4 vol.%) dispersoids while mechanical alloying was observed. Further, we also added 1 vol.% of nano-sized yttria while milling of NiCoAlCrFeTi HESAs, in order to apply oxide dispersion strengthening to NiCoAlCrFeTi HESAs. Microstructure images of HESA are shown in Figure 6.

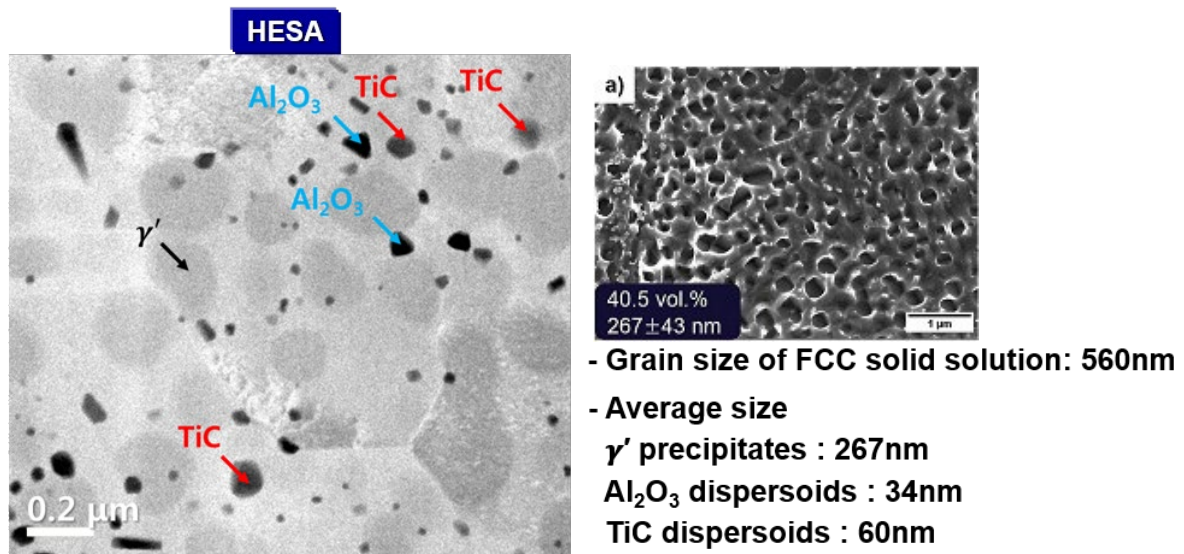


Figure 6. Microstructure of fabricated NiCoAlCrFeTi HESA.

3-2. Analysis of microstructures and phases of sintered RHEAs

In case of RHEAs, single BCC solid solution phase with larger grain size of micro meter scale was formed. The average grain sizes are varying with different aluminum composition, and the smallest in $Al_{0.1}CrNbVMo$ RHEA. It is apparent that the three alloys were grey in color with uniformly dispersed darker inclusions. The volume fraction of the dark-grey inclusions was 1.71 % for $Al_0CrNbVMo$ RHEA. The volume fractions of inclusions were analyzed 3.71 % and 3.79% for $Al_{0.5}CrNbVMo$ and $Al_{1.0}CrNbVMo$ RHEAs, respectively. The grey matrices exhibited compositions close to nominal; the dark-grey inclusions were enriched with Nb and O, and the black inclusions were enriched with Al and O in $Al_xCrNbVMo$. Given the XRD patterns of the alloys, the Nb–O rich inclusion is $NbO_{0.7} (Al_0)$, and the Al–O rich inclusions ($Al_{0.5}$ and $Al_{1.0}$) are Al_2O_3 . The microstructural images of RHEAs are shown in Figure 7.

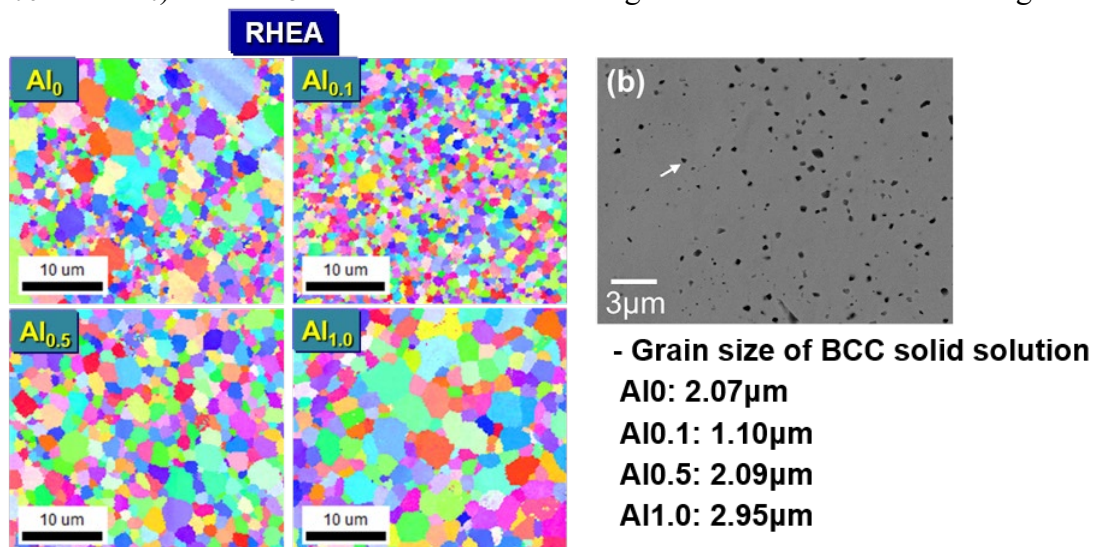


Figure 7. Microstructure of fabricated RHEA.

4. Analyses of mechanical properties of high entropy alloys

Mechanical properties of fabricated HESAs were analyzed by micro tensile test equipped with environmental chamber and strains were measured precisely by digital-image-correlation

(DIC) using ARAMIS software (ARAMIS 5 M) at room temperature, and those of RHEA were analyzed by compressive test with environmental chamber for testing temperature control. The tensile yield strengths of HESAs and compressive yield strengths of RHEA at room and elevated temperatures up to 1000°C are characterized.

4-1. Analyses of mechanical properties of HESAs

The tensile yield strength and elastic modulus increased with increasing Y_2O_3 content in HESAs. The powder metallurgy processed NiCoAlCrFeTi (PM 0Y) HESA showed a tensile yield strength of 1360 MPa, ultimate tensile strength (UTS) of 1443 MPa, and fracture strain of 8.7%. The effect of the powder metallurgy process on the mechanical properties of HESA was determined by comparing the mechanical properties of powder processed NiCoAlCrFeTi (PM 0Y) HESA and arc melted NiCoAlCrFeTi (AM 0Y) HESA. The strengthening effect of NiCoAlCrFeTi (PM 0Y) HESA originated from grain boundary strengthening and dispersion strengthening. The increase of yield strength with increasing Y_2O_3 content originated primarily from two sources: (i) the smaller grain size attributable to grain boundary pinning effect of Y_2O_3 dispersoids and (ii) dispersion strengthening by Y_2O_3 itself, due to hindering effect of dislocation movement. The powder processed NiCoAlCrFeTi HESA shows outstanding yield strengths (about 40% higher than Inconel 706) from room temperature up to 600°C, however, start to decrease above 600°C as shown in Figure 8. The grain growth treatment further enhances the yield strength higher or comparable to Inconel or Incoloy alloy up to 800°C. The addition of Y_2O_3 dispersoids further enhances the yield strength up to 1,000°C.

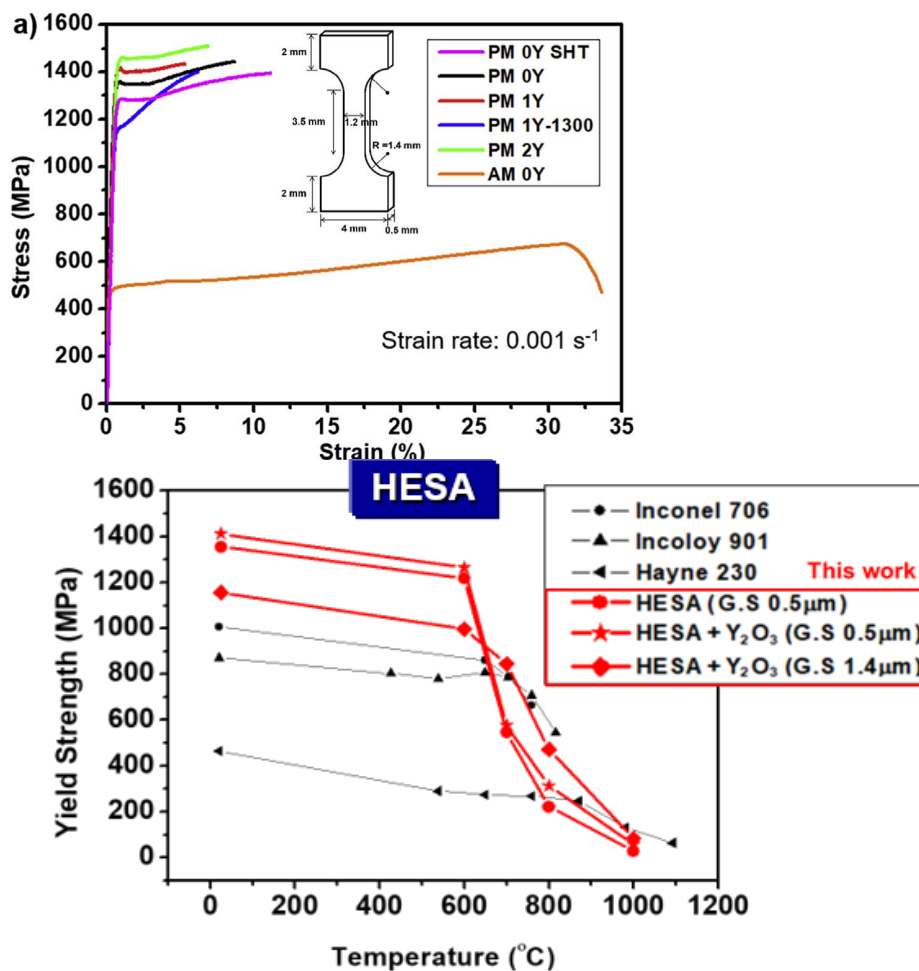


Figure 8. Stress-strain curves of HESAs from tensile tests at room and elevated temperatures.

4-2. Analyses of mechanical properties of RHEAs

The designed $\text{Al}_x\text{CrNbVMo}$ RHEAs showed excellent specific yield strength up to $1,000^\circ\text{C}$, located highest position within a circle in the plot, comparing with other reported BCC HEAs. These data were obtained in compressive test, since most of the BCC HEAs are very brittle at tensile mode. Despite of the single-phase nature of the alloys, which lacked hard intermetallic phases, they exhibited out-standing yield strength at room and elevated temperatures (> 2300 and 1000MPa , respectively). The absence of brittle intermetallic phases explained the moderate fracture strains ($> 9.9\%$), resulting in a good combination of strength and ductility.

The yield strength and specific yield strength also decreased, although there was a compensatory increase in fracture strain as the concentration of Al increased. As the most important property for high-temperature structural materials, the specific yield strength of the Al_0 , $\text{Al}_{0.5}$ and $\text{Al}_{1.0}$ RHEAs are compared with those of typical BCC RHEAs processed by casting. The specific yield strength of the $\text{Al}_x\text{CrNbVMo}$ RHEAs was much higher than those of other BCC RHEAs at both 25 and 1000°C . Surprisingly, the Al_0 alloy showed an ultra-high yield strength of 1513MPa at 1000°C . Compared to the $\text{AlMo}_{0.5}\text{NbTa}_{0.5}\text{TiZr}$, which exhibited the best specific yield strength among the cast RHEAs the $\text{Al}_0\text{CrNbVMo}$ RHEAs exhibited 27% and 87% increases at 25 and 1000°C , respectively, as shown in Figure 9.

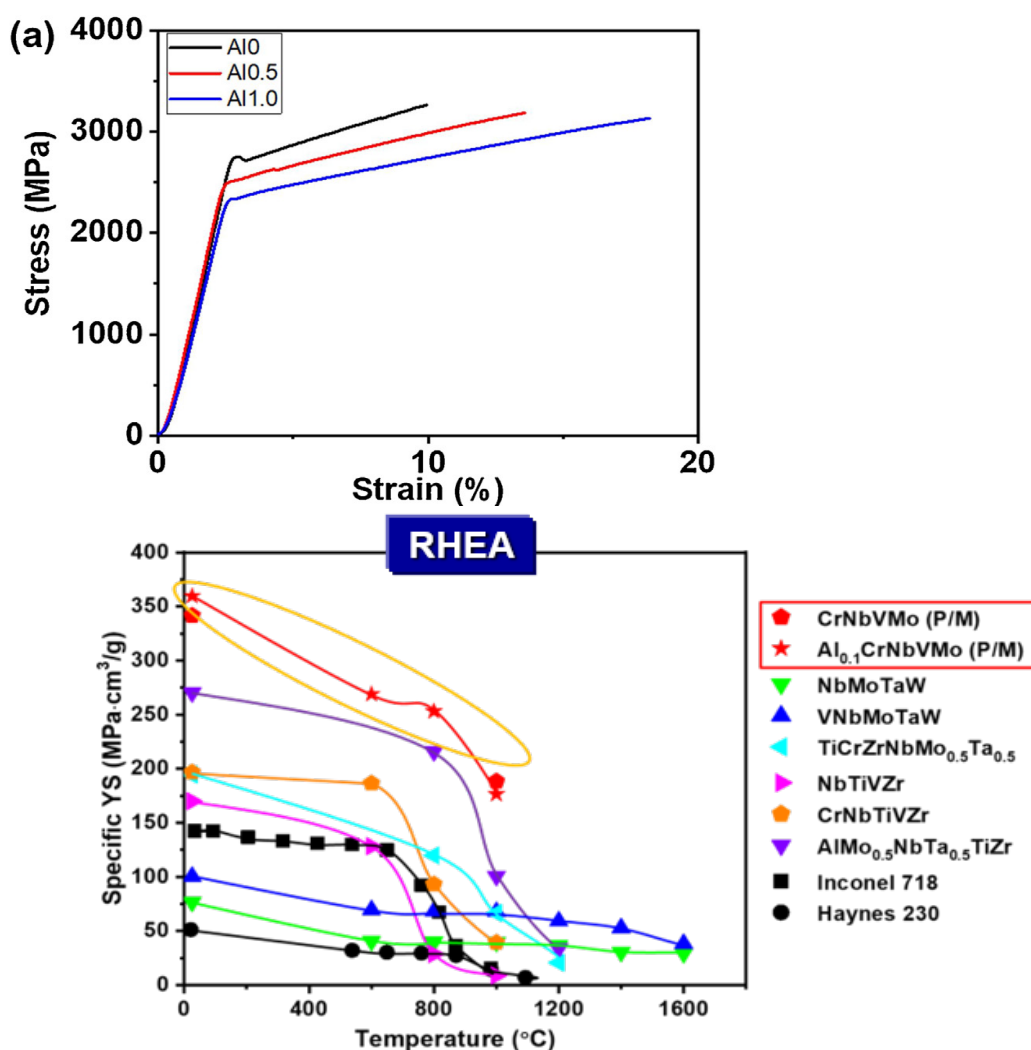


Figure 9. Stress-strain curve of RHEAs from compressive tests at room and elevated temperatures.

5. Analysis of strengthening mechanisms of high entropy alloys

Strengthening mechanisms of high entropy alloys are analyzed by existing calculation models using microstructure parameters obtained from microstructure analysis and mechanical property data obtained from tensile and compressive test. Figure 10 shows Hall-Petch relationship of fabricated HESA. Each strengthening mechanisms, utilized calculation models, required parameters, and each contribution of HESA and RHEA are summarized in Figure 11 and Figure 12.

5-1. Analysis of strengthening mechanisms of HESA

The grain size dependence of yield strength of NiCoAlCrFeTi HESAs shows a linear fitting following Hall-Petch equation in Figure 6. The Hall-Petch coefficient, K , is estimated 539 MPa $\mu\text{m}^{1/2}$ and the intrinsic stress for dislocation movement, σ_0 , can be estimated 230MPa.

The major strengthening mechanisms of NiCoAlCrFeTi HESA at RT are identified as grain boundary strengthening, solid solution strengthening, precipitation strengthening, and dispersion strengthening. Solid solution strengthening effect can be derived from Labusch model considering alloying elements. Dispersion strengthening is calculated by Orowan-Ashby equation, derived from the dislocation pinning by TiC or Al_2O_3 inclusions and Y_2O_3 dispersoids. Grain boundary strengthening is calculated by Hall-Petch equation. Precipitation strengthening can be estimated from the difference of yield strength between precipitation heat treated and solution heat treated specimens.

If we compare calculated yield strength based on acting strengthening mechanism with the measures yield strength from tensile test of NiCoAlCrFeTi HESAs, the two value are very close each other. The major strengthening mechanism of HESAs is grain boundary strengthening due to very fine grain size of FCC matrix phase.

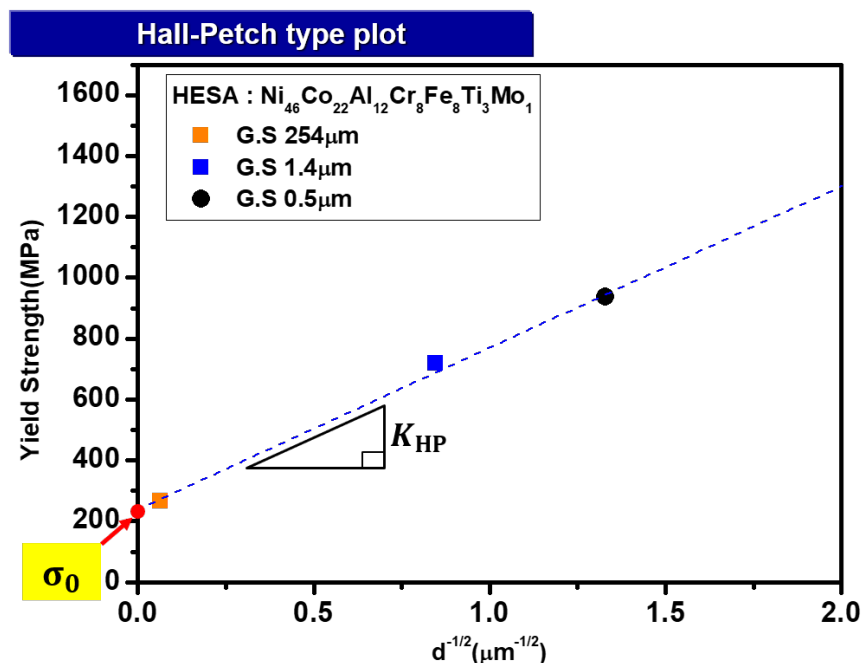


Figure 10. Hall-Petch plot of HESA with different grain size at room temperature.

Solid Solution Strengthening ($\Delta\sigma_{ss}$)

$$\Delta\sigma_{ss} = f_{\gamma} \cdot \left(\sum_i \beta_i^{3/2} c_i \right)^{2/3}$$

f_{γ} : Matrix volume fraction c_i : Concentration of i
 β_i : Strengthening factor of i

Dispersion Strengthening ($\Delta\sigma_{disp}$)

$$\Delta\sigma_{disp} = 0.538 \cdot \frac{Gb f^{1/2}}{d_p} \ln \frac{d_p}{2b}$$

G : Shear modulus b : Burgers vector
 f : Particle volume fraction d_p : Average particle size

Grain Boundary Strengthening ($\Delta\sigma_{gb}$)

$$\Delta\sigma_{gb} = K_{HP} d^{-1/2}$$

K_{HP} : Hall-Petch coefficient d : Grain size

Precipitation Strengthening ($\Delta\sigma_{ppt}$)

$$\Delta\sigma_{y,HESA P.M} - \Delta\sigma_{y,HESA SHT}$$



Specimen	σ_0 (MPa)	$\Delta\sigma_{ss}$ (MPa)	$\Delta\sigma_{ppt}$ (MPa)	$\Delta\sigma_{disp}$ (MPa)	$\Delta\sigma_{gb}$ (MPa)	Predicted σ_y (MPa)	Experimental σ_y (MPa)
HESA	230	135	0	213	717	1295	1286
HESA + PPT		78	131	213	717	1369	1360
HESA + PPT + Y_2O_3				227	465	1131	1155

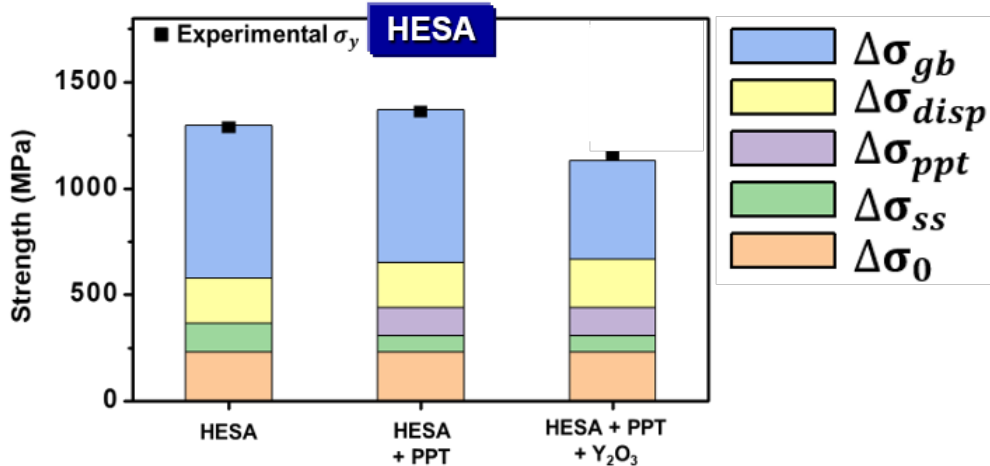


Figure 11. Calculations of yield strengths based on strengthening mechanisms of NiCoAlCrFeTi HESAs.

5-2. Analysis of strengthening mechanisms of RHEA

We have analyzed the origin of high yield strength of AlxCrNbVMo RHEA by calculating the related strengthening effects of solid solution strengthening, dislocation strengthening, grain boundary strengthening, and dispersion strengthening. It appeared the solid solution strengthening effect is very high and is the major strengthening mechanism of RHEA. The grain boundary strengthening, dislocation strengthening and dispersion strengthening are additional strengthening mechanisms for enhancing mechanical properties of RHEA. Dislocation strengthening is attributed by high dislocation density generated during the powder metallurgy process. Fine grain size of the alloys contributed to a large grain boundary strengthening effect. Dispersion strengthening also contributed from the dislocation pinning by Al_2O_3 inclusions.

The calculated yield strength values of AlxCrNbVMo RHEA are in good agreement with the experimental values, with a small deviation (< 7%). The outstanding yield strength of the alloys were mainly (about 70%) comes from the solid solution strengthening, which is based on high modulus and misfit effect from difference of atomic sizes of constituent atoms forming solid solution. Powder metallurgy processed RHEAs have advantages of additional strengthening by

grain refinement and high dislocation density which are induced during the PM process.

Dislocation Strengthening ($\Delta\sigma_{disl}$)

$$\Delta\sigma_{dis} = M\alpha Gb\rho^{1/2}$$

M: Mean orientation factor G: Shear modulus
 α : Empirical constant ρ : Dislocation density

Grain Boundary Strengthening ($\Delta\sigma_{gb}$)

$$\Delta\sigma_{gb} = K_{HP}d^{-0.5}$$

K_{HP} : Hall-Petch constant (811MPa $\mu\text{m}^{0.5}$)
d: Grain size

Dispersion Strengthening ($\Delta\sigma_{disp}$)

$$\Delta\sigma_{disp} = M \frac{0.4Gb \ln(2\bar{r}/b)}{\pi\lambda \sqrt{1-\nu}}$$

$\lambda = 2\bar{r} \left(\sqrt{\frac{\pi}{4f}} - 1 \right)$
 $\bar{r} = r\sqrt{2/3}$

ν : Poisson ratio b: Burgers vector
r: Average radius of oxide inclusion
f: Volume fraction of oxide inclusion

Solid Solution Strengthening ($\Delta\sigma_{ss}$)

$$\Delta\sigma_{ss} = \frac{G}{45} \left(\sum_i \varepsilon_i^2 c_i \right)^{2/3}$$

$\varepsilon_i = (\eta_i'^2 + \alpha^2 \delta_i^2)^{1/2}$
 $\delta_i = \frac{9}{8} \sum_j c_j \delta_{ij}$

c_i : concentration of i ε_i : Hardening factor of i
 δ_i : Size misfit by i η_i' : Modulus misfit by i

RHEA-1

Alloys	$\Delta\sigma_{gb}$ (MPa)	$\Delta\sigma_{disl}$ (MPa)	$\Delta\sigma_{disp}$ (MPa)	$\Delta\sigma_{ss}$ (MPa)	Predicted σ_y (MPa)	Experimental σ_y (MPa)
Al ₀	564	720	42	1642	2558	2743
Al _{0.1}	773	704	107	1719	2770	2544
Al _{0.5}	561	579	97	1661	2473	2497
Al _{1.0}	472	360	111	1625	2229	2326

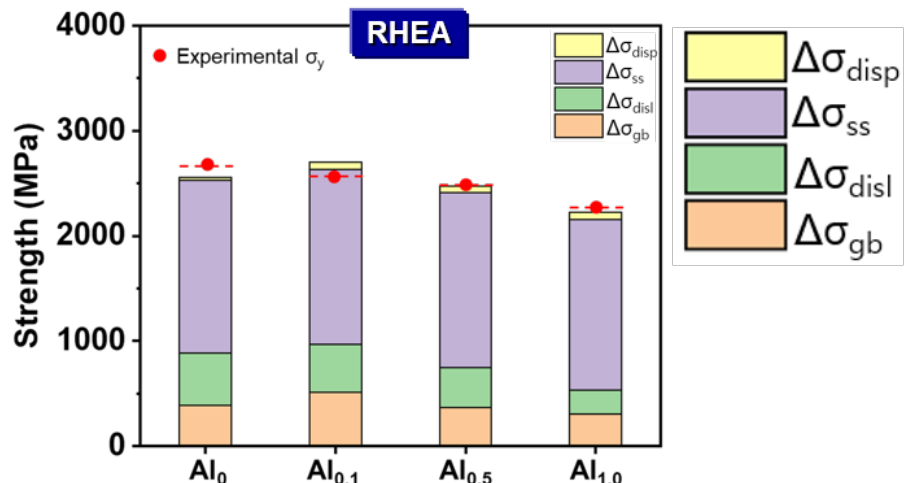


Figure 12. Calculation of yield strength based on strengthening mechanisms and of Al_xCrNbVMo RHEAs.

6. Summary

In this research, two types of heat-resistant high entropy alloys were designed, fabricated and their mechanical behaviors and strengthening mechanisms were characterized.

The high entropy superalloys (HESAs) were designed and fabricated by powder metallurgy process to have a novel microstructure of homogeneously distributed stable precipitates and dispersoids in FCC structured high entropy alloy matrices. The NiCoAlCrFeTi HESA with L1₂ γ' precipitates and Y₂O₃ dispersoids showed higher yield strengths up to temperatures of 800°C with good ductility at room temperature, compared to conventional Inconel 706 or Incoloy 901. The NiCoAlCrFeTi based HESAs could be good candidate materials for heat-resistant application up to elevated temperature of 800°C.

The Al_xCrNbVMo based refractory high entropy alloys (RHEAs) were designed and fabricated to exhibit a novel microstructure of stable nano-sized NbO_{1-x} or Al₂O₃ dispersoids

in BCC structured high entropy alloy matrices fabricated by powder metallurgy process. The nano-sized dispersoids were uniformly distributed by in-situ reaction process during mechanical alloying and sintering. The Al_xCrNbVMo based RHEAs exhibited superior specific yield strength showing 87 % enhancement at 1,000°C compared to that of AlMoNbTaTiZr HEA, which exhibited the best specific yield strength among the cast RHEAs. Our designed RHEAs show much higher specific yield strengths compared to those of Ni-based superalloys up to temperatures of 1000°C. The Al_xCrNbVMo based RHEAs could be promising candidate materials for heat-resistant application up to elevated temperature of 1,000°C or higher.

Produced Products

1. List of SCIE Journal Papers

- 1) Byungchul Kang, Taeyeong Kong, Ho Jin Ryu, Soon Hyung Hong, “The outstanding tensile strength of Ni-rich high entropy superalloys fabricated by powder metallurgical process.” *Materials Chemistry and Physics*, Vol. 235, pp. 121749, (2019)
- 2) Taeyeong Kong, Byungchul Kang, Ho Jin Ryu, Soon Hyung Hong, “Microstructures and enhanced mechanical properties of an oxide dispersion-strengthened Ni-rich high entropy superalloy fabricated by a powder metallurgical process” *Journal of Alloys and Compounds*, Vol. 839, pp. 155724, (2020)
- 3) Byungchul Kang, Taeyeong Kong, Ho Jin Ryu, Soon Hyung Hong, “Superior mechanical properties and strengthening mechanism of lightweight Al_xCrNbVMo refractory high-entropy alloys ($x = 0, 0.5, 1.0$) fabricated via powder metallurgy process”, *Journal of Materials Science and Technology*, Vol. 69, pp.32-41, (2021)
- 4) Byungchul Kang, Taeyeong Kong, Nguyen Huy Dan, Doan Dinh Phuong, Ho Jin Ryu, Soon Hyung Hong, “Effect of boron addition on the microstructure and mechanical properties of refractory Al_{0.1}CrNbVMo high-entropy alloy”, *International Journal of Refractory Metals and Hard Materials*, Vol. 100, pp. 105636, (2021)
- 5) Taeyeong Kong, Byungchul Kang, Ho Jin Ryu, Soon Hyung Hong, “Effects of Secondary Recrystallization on Mechanical Properties and Creep Behavior of Ni₄₅Co₁₇Al₁₃Cr₁₁Ti₅W₅Mo₂Nb₁Ta₁ High Entropy Superalloy” (to be submitted)
- 6) Taeyeong Kong, Ho Jin Ryu, Soon Hyung Hong, “Analysis of Deformation Mechanisms of Ni-rich Medium Entropy Superalloy at Low and Elevated Temperatures” (to be submitted)

2. List of Invited Talks at Conferences

- 1) Soon Hyung Hong “Design and Development of High Entropy Alloys for High Temperature Applications”, Aug. 2019, IMRC 2019, Cancun, Mexico (Invited)
- 2) Ho Jin Ryu and Soon Hyung Hong “Research status of powder metallurgy heat resistant high entropy alloy” April. 2021, 2021 The Korean Society for Composite Materials Spring Workshop, Gangwon, Korea (invited)
- 3) Ho Jin Ryu and Soon Hyung Hong “Design and development of high entropy alloys for heat-resistant applications” Nov. 2021, 10th IWAMSN 2021 Hanoi, Vietnam (invited)

Collaboration Highlights

We have collaborated with a research group of Prof. Rajarshi Banerjee at Dept. of Materials Science and Engineering of University of North Texas (UNT), and they analyzed our boron

added $\text{Al}_{0.1}\text{CrNbVMo}$ specimens by Atom Probe tomography (APT) to investigate the boron segregation at grain boundaries. Prof. Banerjee's support and comments were very helpful to add scientific depth of our research results and will continue collaboration between KAIST and UNT.

We also have collaborated with a research group lead by Prof. Phuong and Dr. Dan at Institute of Materials Science (IMS), Vietnam Academy of Science and Technology (VAST), through additional research grant from National Research Foundation of Korea. The KAIST has designed and fabricated advanced high entropy alloys, the IMS contributed the analyses on phases and microstructures of the high entropy alloys and expanded future applications for high temperature material.

Follow-on Research Grant

We have funded by a follow-on research grant by the National Research Foundation (NRF) grant funded by the Ministry of Science and ICT of Korea, through an International MOU Support Project titled "Development of High Entropy Alloys for Next Generation High Temperature Materials" for three years starting from 2019.01.01.

Participated Students

1. Byungchul Kang: received M.S. on 2017 and Ph.D. on 2021 at KAIST.
 - M.S. Thesis: Fabrication and characterization of WNbTaVMo and WNbTiVMo high entropy alloys with powder metallurgical process.
 - Ph.D. Thesis: Design, fabrication and characterization of light-weight, high strength refractory AlxCrNbVMo high entropy alloys.
2. Taeyeong Kong: received M.S. on 2018, and working as Ph.D. candidate at KAIST.
 - M.S. thesis: Fabrication and mechanical properties of oxide dispersion strengthened high entropy superalloys