Status of Oxide Dispersion Strengthened High Entropy Alloys Development

SeungHyeok Chung, Ho Jin Ryu*
Department of Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehakro, Yuseong, 34141, Republic of Korea
**Corresponding author: hojinryu@kaist.ac.kr*

1. Introduction

As demand for electricity rises, the increase in utilization of nuclear energy is inevitable. To maximize the safety and efficiency of nuclear power plants and consider the economic and nonproliferation issues, the GEN-IV nuclear power plants which have harsh operating conditions such as higher temperatures and irradiation doses than current nuclear power plants have been developing [1]. Advanced materials are needed to withstand the extreme environment. Therefore, a lot of advanced materials research, with regard to being used in the GEN-IV nuclear power plants, have been investigated. Although ferritic-martensitic steels (FMS) are the promising candidate for the GEN-IV nuclear power plants and fusion plant structural materials, using FMS is limited up to around 600°C due to inferior tensile and creep strength at a higher temperature [2]. The term of High Entropy Alloys is coined for the first time by Cantor and Yeh. They defined the High Entropy Alloys containing at least 5 elements with a roughly equal concentration between 5 and 35 atomic percent. Their complicated microstructure was anticipated to cause of brittleness and difficult to processing at the very first time of manufacturing. Nevertheless, the solid solution of High Entropy Alloys tends to be stable because of their large mixing entropies [3].

The research of Oxide Dispersion Strengthened ferritic steels was started in 1985. ODS ferritic steels are identified by the presence of fine oxide particles dispersed coherently throughout the matrix of the alloys [4]. The small grain sizes and fine dispersions of nanoclusters in ODS ferritic steels give rise to increased defect density [5].

The addition of the nano-sized oxide particles into the matrix of HEA microstructure can overcome the yield strength and the ultimate tensile strength drop at high temperatures and enhance the creep resistance of HEAs [6]. In the present study, the status of Oxide Dispersion Strengthened High Entropy Alloys (ODS-HEAs) were analyzed to evaluate the feasibility of ODS-HEAs for the GEN-IV nuclear power plant applications.

2. Manufacturing method and Analysis

In this part, the manufacturing methods of ODS ferritic steels and ODS-HEAs are surveyed and then the characteristics of ODS ferritic steels and ODS-HEAs are also compared.

2.1 Manufacturing methods of ODS ferritic steels and ODS-HEAs.

Pre-alloyed powder and Y_2O_3 oxide powder were mechanically alloyed using a high energy attrition ball mill with steel balls. After the mechanical alloying process, the metal powders were degassed and consolidated into a bar by hot extrusion at the high temperature above 1,000°C. The fine Y_2O_3 particles are trapped easily due to the lamellar microstructure of the MA powders [7,8].

Pure elemental powders of HEAs and Y_2O_3 were employed for synthesizing ODS-HEAs. HEAs and oxide dispersoids were synthesized independently and milled together to produce oxide dispersed HEAs. To synthesize oxide dispersoids, Y_2O_3 and Ti were milled together. On the other hands, HEAs elements are taken in equal atomic percentage and milled. After the milling, MA powder was consolidated by Spark Plasma Sintering (SPS) [9].

2.2 Characteristics of ODS ferritic steels and ODS-HEAs

The dispersed oxide in the ferritic steel matrix increases the yield strength and the tensile strength by interfering with the movement of dislocations. ODS ferritic steels have significant irradiation resistance compared with ferritic steels which have no oxide dispersoids in the matrix [10].

The tensile strength varies heavily with the microstructure. The recrystallized state is characterized by the lower value of yield stress. Nonetheless, recrystallization treatments enhanced the ductility, in particular, the values of reduction in area to rupture, which is one of the main concerns in the ODS alloy development [11].

The research which studied about HEAs ion irradiation done by Xia et al. indicates that there is no momentous ordering, amorphization, or phase separation, pointing to great phase stability under heavy ion irradiation at room temperature to high dpa [12]. This effect may be explained by reduced defects mobility in the disordered phase. In addition, thermal conductivity is excessively reduced and immense atomic stress in disordered high-entropy solid solution may give a self-healing effect [12]. Kumar et al. represented mechanical properties of HEAs near room temperature is similar to conventional austenitic alloys. On the contrary way to this, HEAs have an excellent performance at the high temperature [13].

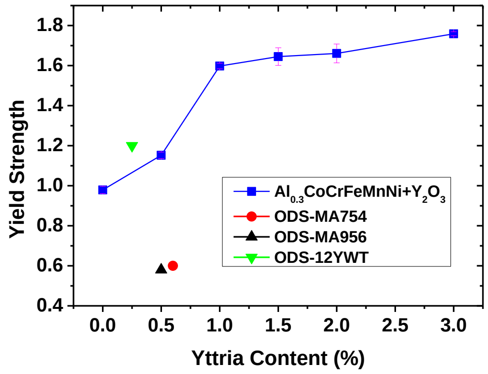

Fig.1. Effects of the yttria content on the yield strength of $Al_{0.3}$CoCrFeMnNi based HEA compared to ODS ferritic steels [14, 15].

The experiment for Y_2O_3 content effects on $Al_{0.3}$CoCrFeMnNi based HEA is conducted by Pohan et al [14]. As shown in Fig. 1, the yield strength of $Al_{0.3}$CoCrFeMnNi based HEA was increased up to 1.7 GPa, as the Y_2O_3 content increased. Compared with ODS-HEA($Al_{0.3}$CoCrFeMnNi+Y_2O_3) and ODS ferritic steels, yield strength with similar content of yttria is analogous or ODS ferritic steels have lower yield strength. Fig. 2 represents ODS-HEAs have the highest yield strength compared to similar HEAs systems [14, 15].

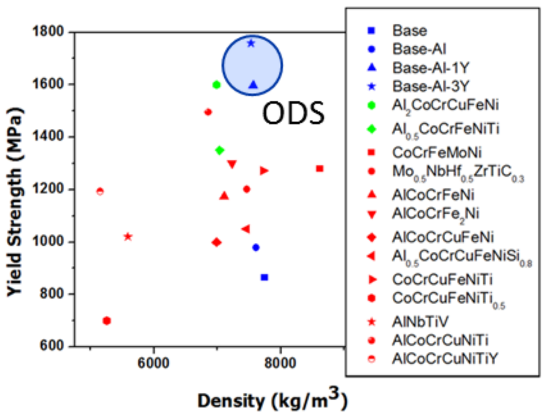

Fig.2. The yield strength comparison with similar alloy systems [14].

Hadraba et al. conducted an experiment of the Y_2O_3 nano-oxide dispersion strengthened one phase FCC HEA by the mechanical alloying. The introduction of nano-oxide into the HEA microstructure resulted in the presence of effective grain boundary and dislocation pinning effects. ODS-HEA exhibited 50% grain boundary reduction. The ultimate tensile strength and the yield strength of ODS-HEA increased about 70% at 800℃ which is the operating temperature for the GEN-IV nuclear reactor. ODS-HEA exhibited higher stresses, however, this was compensated by decreasing plasticity. The creep strain rates for ODS-HEA were significantly lower compared with non-ODS-HEA [6].

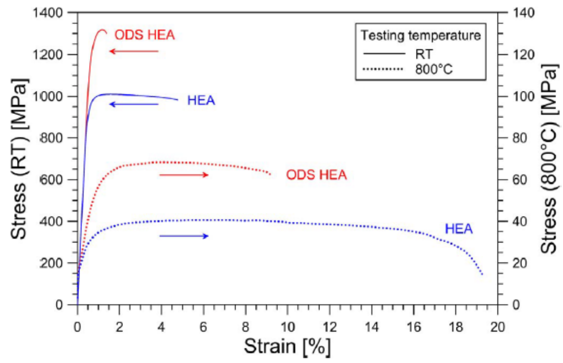

Fig.3. Tensile stress-strain curves of HEA and ODS-HEA tested at room temperature (RT) and at 800℃ [6].

3. Conclusions

In the present study, the characteristics of ODS-HEAs were investigated in comparison with ODS ferritic steels. ODS ferritic steels generally have excellent irradiation resistance and mechanical properties. However recrystallization occurred notably at the temperature below 600℃. HEAs show excellent characteristics at a high dose and high temperature even above 600℃. Especially at a high temperature, ODS-HEAs have better properties than non-ODS-HEAs. Consequently, ODS-HEAs can be promising alloys to apply to the GEN-IV nuclear power plants which are operated at a high dose and a high temperature.

Acknowledgment

This research was supported by National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2015R1A5A1037627) and by the KUSTAR-KAIST Institute, KAIST.

REFERENCES

[1] Klueh, R. L., & Nelson, A. T. (2007). Ferritic/martensitic steels for next-generation reactors. *Journal of Nuclear Materials*, *371*(1), 37-52.

[2] Odette, G. R., Alinger, M. J., & Wirth, B. D. (2008). Recent developments in irradiation-resistant steels. *Annu. Rev. Mater. Res.*, *38*, 471-503.

[3] Yeh, J. W., Chen, S. K., Lin, S. J., Gan, J. Y., Chin, T. S., Shun, T. T., ... & Chang, S. Y. (2004). Nanostructured high‐entropy alloys with multiple principal elements: novel alloy design concepts and outcomes. *Advanced Engineering Materials*, *6*(5), 299-303.

[4] Gregory, J. K., Gibeling, J. C., & Nix, W. D. (1985). High temperature deformation of ultra-fine-grained oxide dispersion strengthened alloys. *Metallurgical Transaction*

[5] Kevin, G., & Howard, R. H. (2016). Status of FeCrAl ODS Irradiations in the High Flux Isotope Reactor.

[6] Hadraba, H., Chlup, Z., Dlouhy, A., Dobes, F., Roupcova, P., Vilemova, M., & Matejicek, J. (2017). Oxide dispersion strengthened CoCrFeNiMn high-entropy alloy. *Materials Science and Engineering: A*, *689*, 252-256.

[7] Ukai, S., Harada, M., Okada, H., Inoue, M., Nomura, S., Shikakura, S., ... & Fujiwara, M. (1993). Alloying design of oxide dispersion strengthened ferritic steel for long life FBRs core materials. *Journal of Nuclear Materials*, *204*, 65-73.

[8] Odette, G. R., Alinger, M. J., & Wirth, B. D. (2008). Recent developments in irradiation-resistant steels. *Annu. Rev. Mater. Res.*, *38*, 471-503.

[9] Praveen, S., Anupam, A., Sirasani, T., Murty, B. S., & Kottada, R. S. (2013). Characterization of oxide dispersed AlCoCrFe high entropy alloy synthesized by mechanical alloying and spark plasma sintering. *Transactions of the Indian Institute of Metals*, *66*(4), 369-373.

[10] Jae Hoon Lee, Jeoung Han Kim. (2013). Trend in Research of Irradiation Tolerant Oxide Dispersion Strengthened Ferritic Steel Produced by Powder Metallurgy Processing. *Journal of Korean Powder Metallurgy Institute*, *20*(3), 228-235.

[11] Alamo, A., Lambard, V., Averty, X., & Mathon, M. H. (2004). Assessment of ODS-14% Cr ferritic alloy for high temperature applications. *Journal of Nuclear Materials*, *329*, 333-337.

[12] Xia, S., Gao, M. C., Yang, T., Liaw, P. K., & Zhang, Y. (2016). Phase stability and microstructures of high entropy alloys ion irradiated to high doses. *Journal of Nuclear Materials*, *480*, 100-108.

[13] Kumar, N. K., Li, C., Leonard, K. J., Bei, H., & Zinkle, S. J. (2016). Microstructural stability and mechanical behavior of FeNiMnCr high entropy alloy under ion irradiation. *Acta Materialia*, *113*, 230-244.

[14] R.M.Pohan, Junho Lee, JunYeon Hwang, H.J.Ryu, S.H.Hong (2016). "Fabrication Process of ODS High Entropy Alloys", 30th Conference on Advanced Structural Materials, 2016, Pohang, Republic of Korea.

[15] El-Genk, M. S., & Tournier, J. M. (2005). A review of refractory metal alloys and mechanically alloyed-oxide dispersion strengthened steels for space nuclear power systems. *Journal of Nuclear materials*, *340*(1), 93-112.