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Recent improvement and evaluation of radiation resistance and magnetic properties of high entropy alloys and their applications

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ABSTRACT

High-entropy alloys tend to have high strength and ductility due to their inherent properties. They are one of the new materials that have attracted attention from various fields, as they have recently been considered as a promising alloy system not only for future industrial applications but also for enhancing the durability of radiation-affected equipment in nuclear and radiological environments. The high entropy alloys have higher hardness compared to conventional industry iron-based alloys. In this study, we have fabricated two types of high-entropy alloys (Fe-Mn-V-Cr-Al-C and Fe-Si-W-Cr-V) which composes of low radio-activation elements (free of Ni and Co) and have evaluated its basic properties, aiming to apply it to new functional materials for high-energy accelerator target system components, nuclear reactors and fusion reactors. The two materials being developed in this research are thought to have unique properties, and the former is expected to develop as a fundamental study of motor-based materials as new structural materials and magnetic properties that share the characteristics of high strength and low activation. The latter is expected to be applied as a new functional material in the field of engineering targeting such properties by mixing tungsten, which has a high melting point, and vanadium, which has a considerably high melting point, to increase the melting point of the alloy and to design an alloy with high strength.

Video and Presentation to this article can be found online at https://doi.org/10.1016/j.sctalk.2023.100278.

Figures and tables

Table 1
Two types of iron-based high entropy alloys, melting methods, and analysis methods applied in this study.

Materials	• Fe-20Mn-15Cr-10 V-10Al-2.5C • Fe-23Si-23 W-12 V-10Cr (in at.%) • The alloys compose with low radio-activation elements.
Melting method	• High frequency melting/Casting and Heat treatment (for FeMnCrMnAlC) • Arc Melting (for FeSiWCrV)
Analysis method	• Structural analysis by X-Ray diffraction (XRD) • Density Measurement (Mass, Volume) • Vickers Hardness and Nano-Indentation Tests • STEM + EDS (200 kV - 300 kV), SEM + EDS, Diffraction analysis • Magnetic domain observation (DPC-STEM: differential phase contrast imaging) and Vibrating sample magnetometer • Elastic modulus evaluation (ultrasonic measurement) • Electric resistivity, etc.

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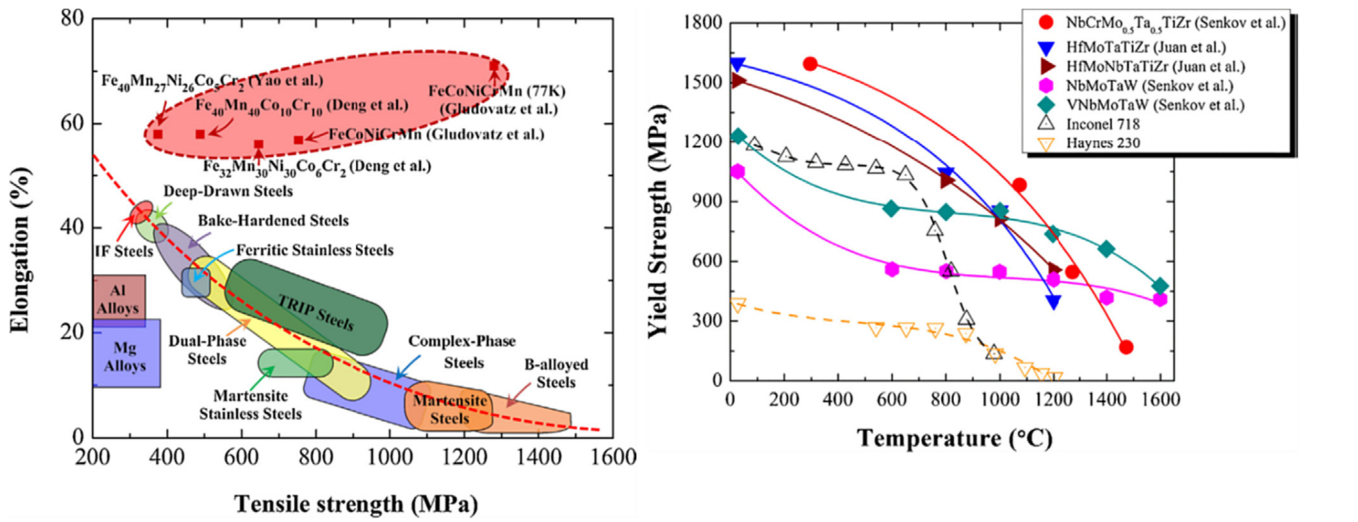

Fig. 1. High-entropy alloys (HEA) are characterized not only by high strength but also by good ductility [1].

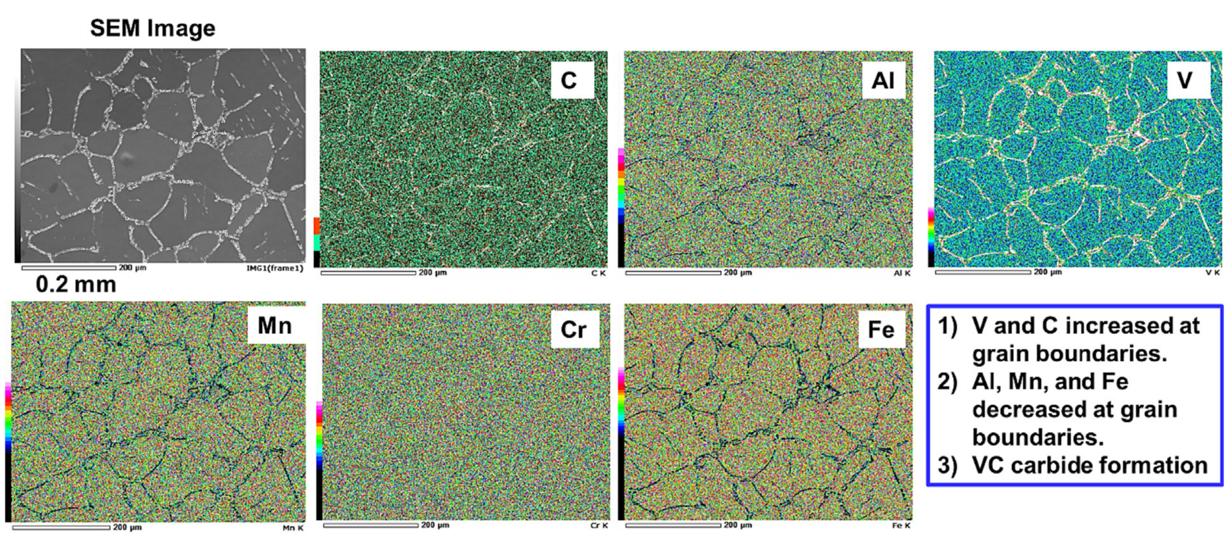

Fig. 2. Microstructures (SEM image) and Elemental Mapping (C, Al, V, Mn, Cr, Fe) in Fe-Mn-Cr-V-Al-C high entropy alloy. Grain boundaries with a spider web-like shape were observed.

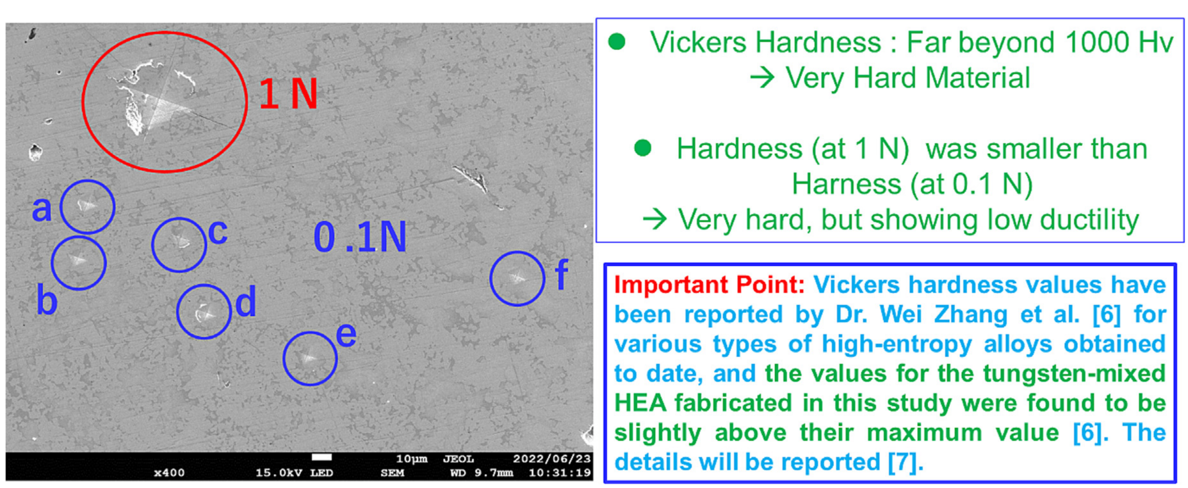

Fig. 3. Vickers Hardness Test at 0.1 N and 1 N in Fe-Si-W-Cr-V high entropy alloy.

CRediT author statement

Eiichi Wakai: .Writing – original draft, Conceptualization, Investigation, **Hiroyuki Noto**: Strucutral analysis and Hardness evalution, **Tamaki Shibayama**: TEM/STEM analysis support, Reviewing, **Kazuyuki Furuya**: SEM/EDS analysis and Vickers Hardness support, **Takashi Wakui**: Ultrasonic analysis, **Masami Ando**: Nano-indentation and Micro-Vickers, **Shunsuke Makimura**: Conceptualization, **Taku Ishida**: Conceptualization.

Data availability

The data that has been used is confidential.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Further reading

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Eiichi Wakai is a Senior Principal Researcher at the J-PARC Center, Japan Atomic Energy Agency. He has developed new materials for nuclear, high-energy accelerator, and industrial applications such as high entropy alloys, tungsten alloys, and titanium alloys, and is an expert in material irradiation damage. He is also developing new non-destructive measurement systems for use in radiation environments. He has participated in several international collaborations and is a leader in this field. He has contributed to the field by chairing the Roadmap Committee of the Materials Division of the Atomic Energy Society of Japan and completing the roadmap in 2021.

Hiroyuki Noto is a researcher specializing in fusion reactor materials at the National Institute for Fusion Science. His research and development of tungsten materials doped with titanium carbides not only have high heat resistance and high toughness, but also very good irradiation resistance. He is also involved in new research efforts in: (i) ultra-high performance of ultra-high temperature materials such as divertors, (ii) development of copper alloys for high performance heat sinks, (iii) joining technology between ultra-high temperature materials and dissimilar materials, etc., and (iv) new materials that are considered by many fields to be the technological backbone for the next industrial revolution and collaboration in the creation of new materials.

Tamaki Shibayama is an expert in the field of materials science using state-of-the-art scanning and transmission electron microscopy with various capabilities and peripheral equipment at the Faculty of Engineering, Hokkaido University, and a leader in the field concerned. He is currently conducting research mainly on the following themes: (1) basic research on energy conversion mechanisms and material creation by plasma application, (2) basic research on materials using quantum beams, (3) development of advanced materials for harsh environments, (4) highly efficient quantum energy conversion materials, and materials related to atomic energy.

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Takashi Wakui is a Associate Principal Researcher at the J-PARC center, Japan Atomic Energy Agency, Japan. He is an expert on spallation neutron source target fabrication techniques (including welding techniques and inspection methods) at the J-PARC center and is engaged in research and development of target vessel (316 L stainless steel) on improvement of operational power intensity and remote handling techniques. He is also an expert in the analysis of plastic behavior by the finite element method, including the irradiation material analysis and the spallation target vessel's design.

Masami Ando is a Principal Researcher at Fusion Energy Directorate, National Institute of Quantum Science and Technology, Japan. He is working on research and development of structural materials for fusion reactors (reduced-activation ferritic/martensitic steels), specializing in nano-indenter analysis and microstructural characterization by (scanning) transmission electron microscopy to investigate irradiation hardening behavior using multiple-ion beam irradiation and the synergistic effects of helium and displacement damage on it. He is also an expert in the relationship studies between mechanical properties, such as tensile and creep behaviors, and microstructures for fusion reactor design.

Shunsuke Makimura is a researcher and engineer at the Hadron Research Facility of the J-PARC center. His expertise includes mechanical design, materials development, FEM simulation, and remote operation of high activation equipment in accelerator facilities. As a new target development in this facility, he is leading the research and development of grain boundary reinforced high toughness tungsten materials with excellent heat resistance, high strength and irradiation resistance. He is a leader in one topic of US-Japan cooperation in the field of high-energy physics.

Taku Ishida is evaluating the J-PARC neutrino facility beam dump, beam window, and production target. He has contributed to the development of neutrino oscillation research by increasing the accelerator intensity through international collaboration with Rutherford Appleton Laboratory (UK), University of Colorado at Boulder (US), TRIUMF (Canada), and others. The accelerator has contributed to the development of neutrino oscillation research through its high power operation. Recently, we have been promoting research on advanced accelerator target environment materials, focusing on advanced titanium alloys, in order to realize further high-power operation.