

W-B-C Radiation Shielding Materials for Fusion Reactors

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A shielding material to protect superconducting coils of fusion reactors from radiation faces the challenge of limited space, thus necessitating the development of materials with superior shielding performance. Tungsten-boron (W-B) compounds exhibit excellent shielding performance, but suffer from low fracture toughness. In this study, A.L.M.T. Corp. aimed to enhance the mechanical properties, particularly fracture toughness, by adding carbon (C) to W-B compounds. The shielding performance was evaluated using the Monte Carlo particle transport simulation code PHITS. The fabricated materials were characterized by measuring density, Vickers hardness, and fracture toughness. This report details the shielding performance and various properties of the developed material.

Keywords: fusion, tungsten, shielding material, powder metallurgy, fracture toughness

1. Introduction

In recent years, fusion energy has attracted attention as a next-generation energy source for realizing a decarbonized society, and research and development of fusion reactors*¹ have been actively advancing worldwide. Among these, the D-T fusion reaction using deuterium (D) and tritium (T) is expected to be a promising energy source because the fuel can be obtained from seawater-derived resources, which presents fewer resource constraints. On the other hand, the D-T reaction produces fast neutrons of approximately 14 MeV, significantly affecting in-vessel materials. In particular, superconducting coils that generate strong magnetic fields to confine plasma are susceptible to performance degradation caused by neutron*² irradiation and to quenching due to heating, making the installation of appropriate shielding materials indispensable. Moreover, since the space available for shielding materials inside the fusion reactor is limited, the development of materials that provide high radiation shielding performance with minimal thickness is required. Against this background, tungsten boride (W-B) compounds have attracted attention as materials with high shielding efficiency.⁽¹⁾ However, W-B compounds exhibit low mechanical properties, such as fracture toughness, which must be improved to apply them as structural materials.

Therefore, A.L.M.T. Corp. has developed a new shielding material composed of tungsten-boron-carbon (W-B-C) compounds, aiming to improve mechanical properties while maintaining the excellent shielding performance of W-B compounds. The primary purpose of carbon addition is to form a tungsten carbide (W-C) phase with relatively high fracture toughness in the W-B matrix, thereby enhancing the overall fracture toughness.

2. Sample Fabrication and Experimental Methods

2-1 Sample fabrication and characterization

Figure 1 shows the fabrication process of the developed materials. The developed materials were fabricated by powder metallurgy; W, B, and C raw materials were mixed and pressure-sintered using a hot-pressing apparatus. After sintering, both sides of the sintered body were ground, and one side was mirror-polished.

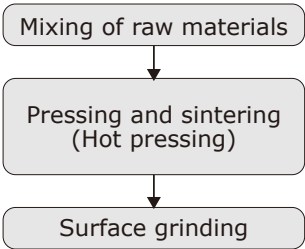


Fig. 1. Fabrication process

Table 1 lists the fabricated samples. The developed W-B-C materials mentioned above are hereafter referred to as WBC_A1 in Table 1, Table 2, two following figures, and in the main text. In addition, W-B compounds W₂B₅ and WB were fabricated as reference materials.

For each sample, phase identification was performed using X-ray diffraction (XRD), followed by measurements of density (Archimedes' principle), Young's modulus

Table 1. List of fabricated samples

Specimen	W ₂ B ₅	WB	WBC_A1
Purpose	Reference material		Developed material (Carbon-added)

(ultrasonic pulse method), Vickers hardness, and fracture toughness (indentation fracture [IF] method).

2-2 Evaluation of shielding performance by simulation

The shielding performance was evaluated using the Monte Carlo particle transport simulation code PHITS⁽²⁾ ver.3.31. Neutron flux was calculated by inputting parameters such as design composition and density. The transmittance (T) was defined by the following Eq. (1), and the shielding performance was assessed accordingly. The transmittance calculation model is shown in Fig. 2.

$$T = F_1 / F_0 \quad \dots\dots\dots (1)$$

where:

F_1 = neutron flux after passing through the shielding material (1/cm²/source)

F_0 = neutron flux before passing through the shielding material (1/cm²/source)

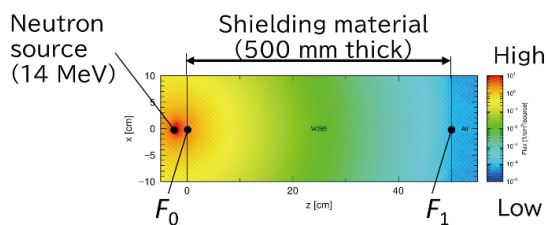


Fig. 2. Transmittance calculation model in PHITS

The neutron source energy was set to 14 MeV, which corresponds to the energy of neutrons generated by the D-T reaction.

A smaller transmittance (T) indicates higher shielding performance of the material. In this development, the relative transmittance $T_{\text{sample}}/T_{\text{WB}}$, calculated with respect to T_{WB} , was used to compare the shielding performance among the samples.

3. Experimental Results

3-1 Confirmation of density and composition of fabricated samples

Table 2 presents the characterization results of the fabricated samples. All fabricated samples exhibited relative densities exceeding 97%, showing values close to their theoretical densities.

Table 2. Measurement results

Properties		W ₂ B ₅	WB	WBC_A1	Method
Density	(g/cm ³)	10.87	15.41	15.50	Archimedes' principle
Relative density	(%)	97.23	97.88	98.55	
Young's modulus	(GPa)	578.8	523.4	535.9	Ultrasonic pulse method
Hardness	HV30	2246	1897	1719	Vickers hardness
Fracture toughness	(MPa m ^{1/2})	(4.5)	4.5	5.2	IF method

The presence of the W-C phase in the developed material was confirmed, as designed.

Figure 3 shows the fracture toughness values measured by the IF method. Following the JIS R1607 standards, fracture toughness values were calculated using Vickers hardness, crack length, and Young's modulus. Figure 4 shows the images of the indentations. For W₂B₅, many indentations exhibited partial edge chipping as shown on the right side of Fig. 4; thus, the fracture toughness values for W₂B₅ are considered reference values as they did not meet the standard conditions.

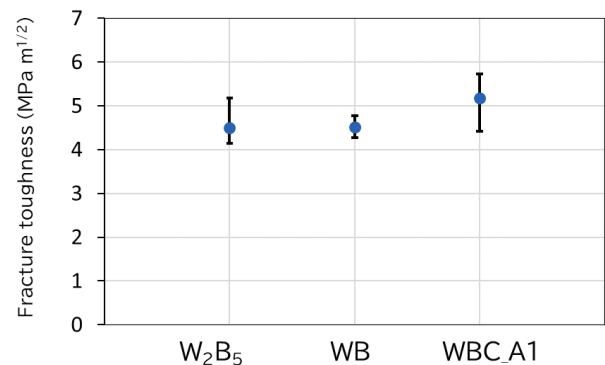


Fig. 3. Fracture toughness of the developed material

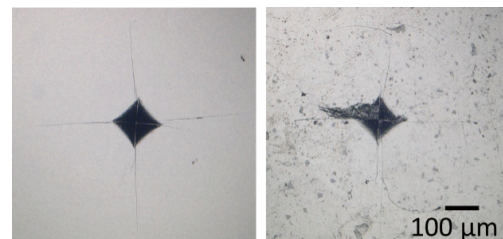


Fig. 4. Example of Vickers indentations

As shown in Fig. 5, the percentage of damaged Vickers indentations in W₂B₅ was higher than that of other samples. The intrinsic brittleness of W₂B₅ and its manufacturing process may have caused the indentation damage.

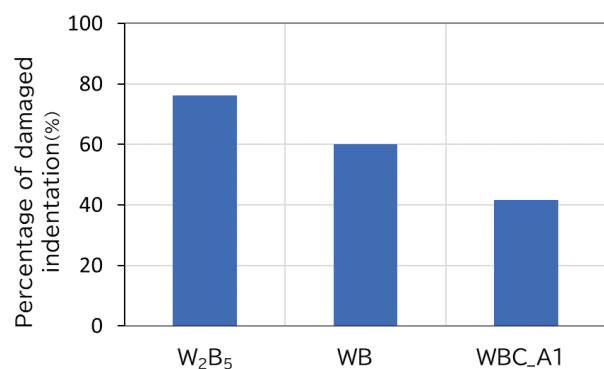


Fig. 5. Percentage of damaged Vickers indentations

3-2 Evaluation of shielding performance by PHITS

The shielding performance was calculated using PHITS for all samples except for W₂Bs, whose fracture toughness values were considered reference values due to non-compliance with standards. To simulate shielding performance under practical operating conditions, the measured density values of the shielding materials were used in the calculations. As shown in Fig. 6, the shielding performance of WBC_A1 was approximately equivalent to that of WB.

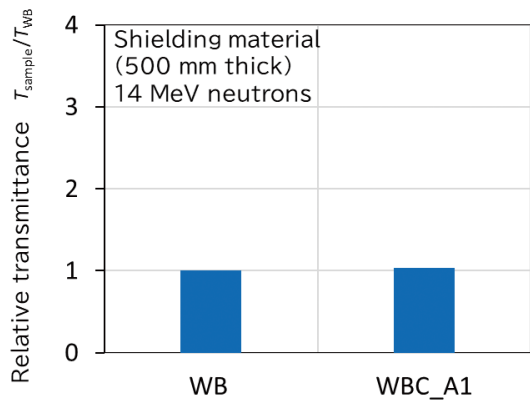


Fig. 6. Relative comparison of shielding performance of the developed material

4. Conclusion

A.L.M.T. Corp. has successfully developed a proto-type shielding material composed of W-B-C. This developed material exhibits the shielding performance equivalent to that of the existing W-B compounds, as well as enhanced mechanical properties.

Commercialization of fusion reactors requires downsizing the reactor vessel. To meet this requirement, shielding materials that provide high performance within limited space are essential. Moreover, to enhance structural reliability, properties such as fracture toughness are likely to be required. A.L.M.T. Corp. has long been engaged in the development and promotion of the shielding material, attracting significant attention both in Japan and abroad. A.L.M.T. Corp. will continue to optimize the manufacturing process and composition of the shielding material to further enhance its mechanical properties for adoption in future fusion reactors.

Technical Terms

- *1 Fusion reactor: A fusion reactor that uses fusion reactions, unlike existing nuclear reactors based on fission reactions. In the fusion reaction between deuterium and tritium, helium and neutrons are produced.
- *2 Neutron: A neutral particle that, together with protons, constitutes the atomic nucleus. Compared to other types of radiation, neutrons easily penetrate materials, making them difficult to shield against, and they cause irradiation damage and activation in materials.

References

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