Sintering Method of Pure Boron Pellet for Advanced Fusion Reactor

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The proton-boron (B) fusion reaction, which has recently garnered increasing attention, requires pure boron-11 as fuel. In previous boron injection experiments in fusion reactors, small cylindrical capsules containing boron powder were used as pellets. However, this injection method posed several critical challenges, including contamination of capsule elements and low injection volume. To address these issues, our group developed capsule-free pure boron pellets, specifically for plasma experiments using boron. This paper presents the fabrication processes and mechanical properties of the pure boron pellets, which were successfully injected into the Large Helical Device (LHD).

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Boron (B) is an essential element for the proton-boron (p-B) fusion reaction [1], plays a significant role in enhancing high-temperature plasma performance [2], and serves as an effective material for boronization of the vacuum vessel wall during the deuterium (D)-tritium (T) operation [3–4]. As the range of boron applications in fusion reactors continues to grow, its importance in fusion research is increasing. In response, plasma experiments using boron are actively being conducted at the Large Helical Device (LHD) at National Institute for Fusion Science in Japan. Current boron injection methods include pellet injection method and a free-fall method using a powder dropper. Among these, the pellet injection method is more effective at delivering boron to the plasma core. Consequently, the demand for pelletization of pure boron has been steadily increasing recently.

Pure boron, however, has the disadvantage of being susceptible to contamination by impurity elements such as carbon. Boron compounds containing such impurity elements, like boron carbide, exhibit poor processability and are difficult to sinter, making pelletization a major challenge. In previous experiments, materials with poor processability were pelletized using small cylindrical capsules filled with the injection material. However, this method presented significant drawbacks, including low injection efficiency and contamination from capsule materials. To address these issues, our group proposed a simple pure boron injection test using pure boron pellets without relying on small cylindrical capsules, and initiated research into developing an effective sintering process for pure boron pellets. In the initial stages, there were concerns that carbon impurities from the high-temperature furnace could bond to the original boron powder surface, and, therefore, the impurity carbon would inhibit the interdiffusion of the original boron particles for sintering. To prevent surface carbonization, we developed a sintering process using tantalum (Ta) foil, which acts as a carbon getter through its impurity-trapping effect [5]. In this paper, we present the fabrication process and mechanical properties of newly developed pure boron pellets.

For boron pellet preparation, the initial boron powder (purity: 99%, particle size: 40 μm) and Ta foil (purity: 99.9%, thickness: 50 μm) were procured from The Nilaco Corporation and Furuuchi Chemical Corporation, respectively. The powder was inserted into a circular Ta foil, with the edges sealed to form a capsule. This sealed Ta foil capsule was then annealed in a vacuum graphite furnace at 2,000°C for 1–10 hours in 1×10^{-3} Pa without applying external load. Following the heat treatment, the Ta foil was removed, leaving behind a sintered B ingot. The ingot was subsequently cut into pellets (approximately 1.3–1.7 mm in diameter) to fit into the barrel of the LHD impurity pellet injector, as illustrated in Fig. 1. The crystal structure, mechanical properties, and chemical composition of the B pellet were characterized using X-ray crystallography, Vickers hardness testing (average of five tests with the standard deviation), and chemical analysis techniques: inductively coupled plasma mass spectrometry for tantalum and combustion infrared absorption method for carbon.

After sintering at 2,000°C for 1 hour, the concentra-

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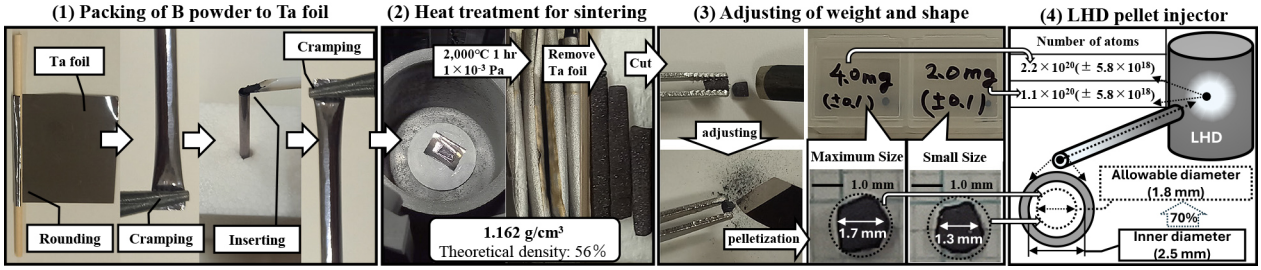

Fig. 1. Fabrication process of boron pellet and the pellet injection into LHD.

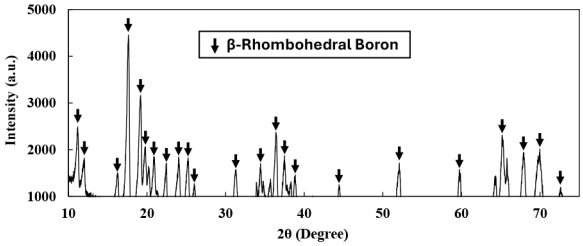

Fig. 2. X-ray diffraction spectra of the B pellet after sintering at 2,000°C for 1 hour [6].

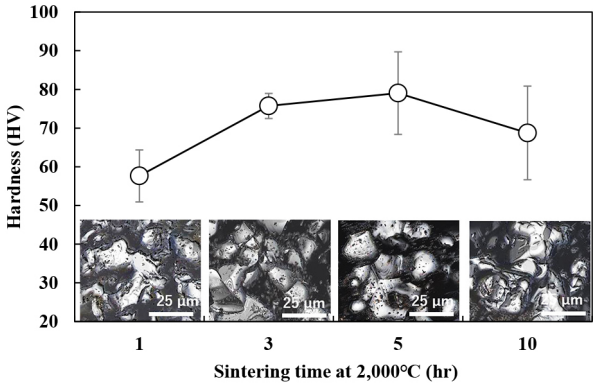

Fig. 3. Effect of sintering duration on hardness and particle necking in boron.

tions of tantalum and carbon as possible contaminants in the boron pellet were 0.02 wt% and 0.64 wt%, respectively. Ta contamination from the foil was below the detectable limit, and despite the use of a graphite furnace for sintering, carbon contamination remained minimal, implying that sintered boron was largely unaffected by carbonization.

Figure 2 presents the XRD analysis results of the boron pellet. The XRD peaks show that the B pellet formed pure boron crystal of a β-rhombohedral structure without the formation of B4C compound.

In 2024, a total of 37 injection experiments were conducted using these pellets in the LHD, and boron emission spectroscopy was successfully performed without causing ablation of the plasma edge [7–8].

Figure 3 illustrates the effect of sintering time on the hardness of boron pellet and the corresponding microstructural changes, particularly at the particle necks. The results show that the pellet sintered at 2,000°C for 5 hours exhibited the highest hardness among all samples. Microstructural observations revealed that, with increasing sintering time, the necks between boron powder particles grew progressively, with the most pronounced growth observed after 10 hours. However, despite this growth, the hardness of the pellet decreased after 10 hours of sintering. This suggests that grain coarsening associated with 5–10 hours' sintering time may lead to a decrease in hardness. Therefore, considering both hardness and microstructural evolution, the pure B pellet sintered 2,000°C for 5 hours appears optimal and may be suitable for high-density boron injection experiments in the future.

Based on the fabrication process and results described above, our group has planned an advanced injection test using "enriched ^{11}B pellets" for the next LHD experimental campaign. The upcoming results are expected to contribute to the global advancement of nuclear fusion experiments using B pellets.

The conclusions of this study are as follows:

1. The newly developed pure boron pellets, containing impurity levels below the detection limit, exhibit a β-rhombohedral crystal structure. These pellets were successfully injected into the plasma, enabling effective emission spectroscopy of boron.
2. Considering the effect of sintering time on the hardness of the B pellets, the highest hardness was observed after sintering at 2,000°C for 5 hours. This condition is expected to support future development of higher-density boron pellets suitable for injection.

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