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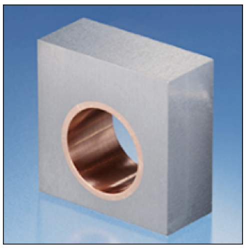

Tungsten Plate with Excellent Thermal Shock Resistance -Application for Fusion Reactors-

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The ITER project is being promoted as an international megaproject to scientifically and technically demonstrate the feasibility of fusion energy, which is one of the most promising candidates for achieving a decarbonized society. Among the components of ITER, tungsten (W) is used for a divertor, which is exposed to ultra-high temperatures above 2000°C. For stable operation of ITER, W is required to exhibit excellent thermal shock resistance under a high-temperature heating/cooling cycle. In this study, we have newly developed a W with an improved thermal shock resistance by suppressing the grain growth due to high temperature. Using the developed W, monoblocks were fabricated for small-scale mock-ups and plasma facing unit (PFU) prototypes, and their performance was evaluated by high heat flux test (HHFT) simulating a fusion reactor. HHFT results showed that no cracks occurred even under severe conditions. In particular, the evaluation results of the prototype greatly exceeded the requirements of ITER, and the developed W was certified as “unbreakable tungsten” for the first time in the world.

Keywords: tungsten, high-melting-point, decarbonization, fusion, ITER

1. Introduction

Recently, activities toward decarbonization have been gaining momentum to phase out the use of fossil fuels, such as petroleum and coal, and switch to renewable energy sources, such as solar power, hydropower, and wind power. These energy sources are widely and thinly distributed around the globe. Thus, even though the total amount of energy is large, it is difficult to collect such energy sources efficiently. Energy that uses nuclear fusion reaction does not emit carbon dioxide, which causes global warming, and such fuel exists abundantly in seawater. For these reasons, nuclear fusion has attracted much public attention as a permanent energy source that fundamentally solves energy problems and environmental problems.

Research on power generation using nuclear fusion energy, known as “A Small Sun on Earth,” started in the 1940s. With an experimental reactor under construction, we are in a phase of demonstrating feasibility from the viewpoint of science and technology. The ITER[*1] is being built in Saint-Paul-lès-Durance in southern France through international cooperation among seven parties (Japan, European Union (EU), the U.S., Russia, China, Korea, and India). According to the schedule, the ITER, which means “the path” in Latin, will create a plasma for the first time in around 2025. A full-scale burning experiment using deuterium and tritium will be conducted in around 2035. The demonstration data will lead to the construction of a nuclear fusion demonstration reactor (Demonstration Power Station, hereinafter “DEMO reactor”) to demonstrate power generation.(1)

Figure 1 shows the ITER tokamak unit. The core of the unit is a toroidal ultra-high-temperature plasma. A nuclear fusion reaction occurs in the plasma. The scale of the plasma is large: about 7 m in height, about 16 m in outer diameter, and about 800 m^3 in volume.

There is a wall about 0.5 m in thickness (called the “blanket”) which surrounds the plasma to turn the nuclear fusion output into heat and take it outside. Below the plasma, there is a component named a “divertor” to receive the high heat flow and particle flow from the plasma. The structural drawing of the divertor is shown in Fig. 2. A divertor is a component for exhausting and removing

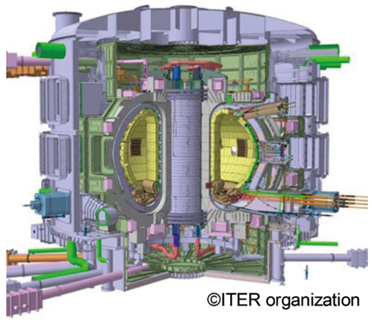

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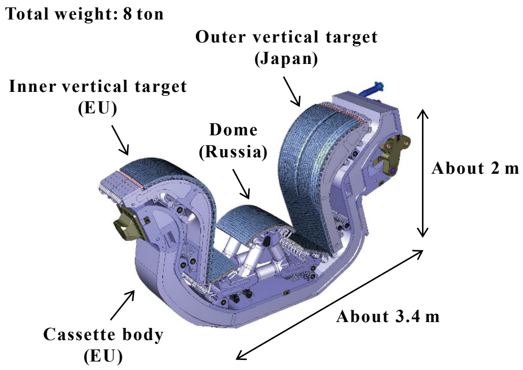
Fig. 1. ITER tokamak unit



Courtesy: National Institutes for Quantum and Radiological Science and Technology

Fig. 2. Divertor cassette

unnecessary impurities in maintaining a plasma. Japan, Europe and Russia are responsible for procuring the outer vertical target, the inner vertical target, and the dome, respectively. The surface of the divertor is expected to reach 2,300°C at the maximum. Tungsten (hereinafter, “W”) is used for all the parts.

W is one of the high-melting-point metals. In general, W powder is pressed and sintered, and final products of various shapes are manufactured by hot or warm plastic working and machining. By using the characteristics of a high melting point (3,380°C) and low vapor pressure, W is used under high heat load environments, including parts for high-temperature heating reactors.(2)

For stable demonstration experiments to be conducted at the ITER, the W must meet the requirements of thermal shock resistance, namely, it must not fracture under high temperature.

The authors have developed a tungsten material with thermal shock resistance by applying powder metallurgy technology, in which A.L.M.T. Corp. excels. This paper reports the details of the initiative to contribute to the global promotion of research on nuclear fusion not only in Japan but also in Europe and the U.S., in addition to the ITER, and early achievement of commercial power generation.

2. Method of Manufacturing a W Material and Properties of the Newly Developed W Material

Figure 3 shows the manufacturing process of a W material. The W powder was turned into a pressed body by cold isostatic pressing (CIP)*2, and hydrogen sintering was performed. The obtained sintered body was subjected to hot plastic deformation to produce a W material.

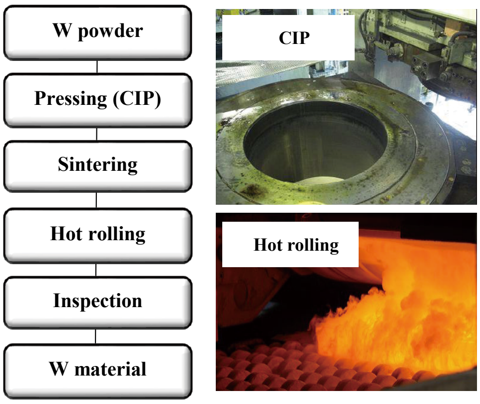


Fig. 3. W material manufacturing method

In general, a W material immediately after rolling exhibits a fibrous texture. Recrystallization*3 starts at temperatures above 1,200°C. To improve the thermal shock resistance against the heat load, it is considered effective to minimize the recrystallization grain growth when exposed to a temperature above 2,000°C. The microstructure of the newly developed W material after heat treatment at 2,300°C is shown in Fig. 4. A W material prepared based on the conventional manufacturing method was used as a comparison material. The newly developed W material maintained fine recrystallization grains compared to the conventional W material even after ultra-high-temperature heat treatment. A high heat flux test was conducted using the newly developed W material under conditions that simulated the nuclear fusion reactor environment.

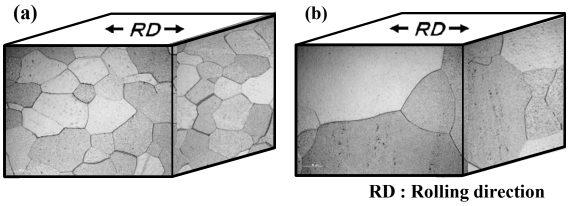


Fig. 4. Microstructure after heat treatment at 2,300°C
(a) Newly developed W material
(b) Conventical W material

3. Evaluation Simulating the Nuclear Fusion Reactor

3-1 Fabrication of small heat load specimens and results of the heat load test

In a high heat flux test, specimens of shapes similar to that of a W monoblock (Photo 1), which will be used for the ITER divertor, are used. The newly developed W material was cut into block shapes and drilled by machining. Subsequently, W and oxygen-free copper (hereinafter, “OFCu”) were bonded using a special bonding method. W and OFCu were then machined to fabricate W monoblocks for a high heat flux test. Regarding the bonding integrity of W and OFCu, a nondestructive test was conducted based on ultrasonic testing. It was confirmed that the specifications required by the ITER were met. For comparison, we prepared monoblocks made from the conventional W material. A cooling pipe made from a Cu-Cr-Zr alloy was brazed to these W monoblocks to fabricate a heat load specimen as shown in Photo 2.(3)

The high heat flux test was conducted using the high heat flux test equipment (hereinafter, “JEBIS”) owned by the National Institutes for Quantum and Radiological Science and Technology. Photo 3 shows the appearance of JEBIS and inside the equipment. The W monoblocks were exposed to an electron beam of 20 MW/m^2 (equivalent to

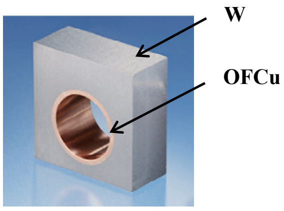


Photo 1. W monoblock

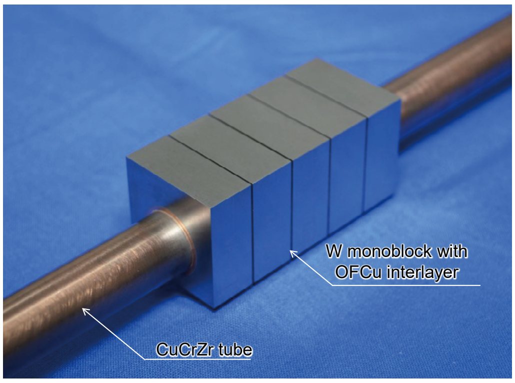


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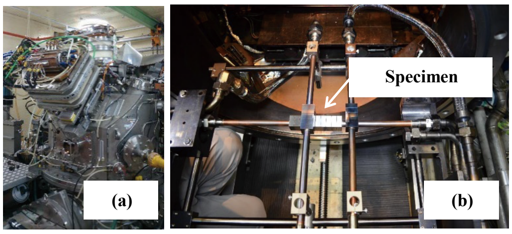
Photo 2. Small-scale mock-ups for high heat flux test



Courtesy: National Institutes for Quantum and Radiological Science and Technology

Photo 3. High heat flux test equipment (JEBIS)
(a) Appearance (b) Inside

about 2,300°C) for 10 s. After cooling for 30 s, the W monoblocks were re-exposed to an electron beam. This cycle was repeated 1,000 times (over three times the number of cycles of the ITER design requirements). The condition of the W monoblock heat load surface after the high heat flux test was confirmed. As shown in Photo 4, the W monoblock fabricated from the conventional W material exhibited swells on the heat load surface due to the increase in the size of the recrystallization grains. Meanwhile, no cracks were observed in the newly developed W material, which demonstrated not only superb thermal shock resistance but also maintained fine recrystallization grains. There were no swells on the heat load surface. The material exhibited performance suitable for a divertor.

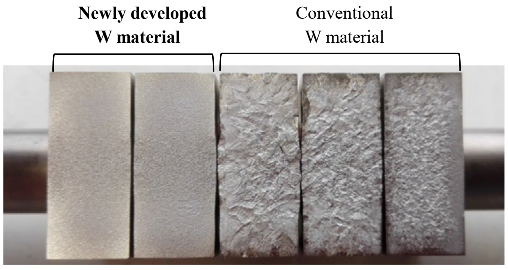


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Photo 4. W monoblocks after a high heat flux test

3-2 Evaluation of the prototype

We used the newly developed W material, which demonstrated superb thermal shock resistance in a high heat flux test, to fabricate a Plasma Facing Unit (hereinafter, “PFU”) with a divertor equivalent to the actual equipment, and evaluated the prototype. To conduct prototype evaluation, it was necessary to prepare W monoblocks, as shown in Photo 1, and W monoblocks provided with a support saddle by bonding XM-19, a special stainless steel material, to W monoblocks to maintain high positional accuracy between the PFU and the steel support structure material, which supports the PFU. Thus, we developed a technology to bond W monoblocks with XM-19 by brazing. A nondestructive test based on ultrasonic testing confirmed that the integrity of the bonding condition met the ITER requirement specifications. The strength and fatigue properties of the bonded part were also evaluated. We succeeded in developing W monoblock provided with support-leg whose properties far exceed the ITER requirements (Photo 5).

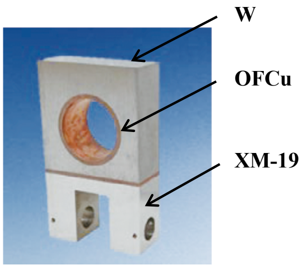
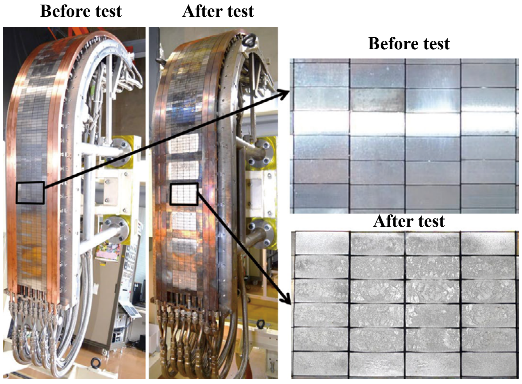


Photo 5. W monoblock with support-leg

The Full-scale PFU prototype, which was fabricated by using the W monoblocks, was subjected to a high heat flux test at the IDTF (ITER Divertor Test Facility) of Federal State Unitary Interprise Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA Efremov) in Russia, in the presence of staff of the ITER Organization and the National Institutes for Quantum and Radiological Science and Technology.[4] The test was



Courtesy: National Institutes for Quantum and Radiological Science and Technology

Photo 6. Evaluation results of Full-scale PFU prototype conducted based on numbers of cycles far exceeding the ITER requirements: 5,000 cycles for 10 MW/m^2 (ITER design requirements: 1,000 cycles) and 1,000 cycles for 20 MW/m^2 (ITER design requirements: 300 cycles). As shown in Photo 6, no cracks were observed in any of the monoblocks that used W material newly developed by A.L.M.T.Corp. These monoblocks demonstrated superb thermal shock resistance. The results showed that the monoblocks made from the newly developed W material far exceeded the ITER requirements. This became the first “Tungsten material that does not crack” in the world, and was highly evaluated. It was certified as the W material for the ITER divertor by the ITER Organization and the National Institutes for Quantum and Radiological Science and Technology.

5. Conclusion

We have developed a thermal-shock-resistant tungsten material for the ITER divertor. The divertor is currently under construction as an experiment reactor for nuclear fusion energy, which is considered a dream energy source and can achieve decarbonization. This became the first material in the world to be highly evaluated as the only tungsten material that did not crack in a heat load test using small specimens and a prototype.

A.L.M.T. Corp. supplies monoblocks made of the newly developed tungsten material for the outer vertical target undertaken by Japan. At present, the company deploys monoblocks for the inner vertical target undertaken by EU, including the convex-type (with the oxygen-free copper protruding) and the chamfer-type (whose heat load surface is not flat), as shown in Photo 7. A.L.M.T. Corp. will deploy the monoblocks for research institutes in Japan, EU and the U.S., which conduct research for the DEMO reactor and contribute to the practical application of nuclear fusion reactors.

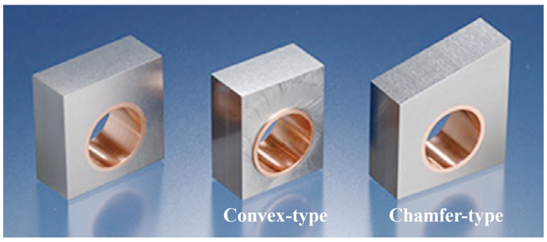


Photo 7. Lineup of W monolocks

6. Acknowledgements

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Technical Terms

＊1 ITER: ITER, the current official name, is an abbreviation for International Thermonuclear Experimental Reactor.

＊2 Cold isostatic pressing (CIP): This is a process to pressurize powder into a solid condition (powder compacting). In this method, liquid, such as water, is used as a pressure medium to apply isotropic pressure to a container containing powder.

＊3 Recrystallization: When a metal material with plastic deformation is maintained at high temperature, new crystal grains (with remarkably low dislocation density) are generated and grow using energy that is accumulated in a material as the driving force.

References

(1) Technology Nuclear Fusion Science and Technology Committee Report issued by Ministry of Education, Culture, Sports, Science, “Prototype Reactor R & D Roadmap (Primary Summary, in Japanese)” (2018)
(2) Japan Tungsten & Molybdenum Industries Association, Technical data of tungsten and molybdenum (in Japanese) (2009)
(3) M. Fukuda, Y Seki, K. Ezato, K. Yokoyama, H. Nishi, S. Suzuki, J. Nucl. Mater., 542 (2020), 152509
(4) K. Ezato, S.Suzuki, Y. Seki, K.Mohri, K. Yokoyama, F. Escourbiac, T. Hirai, V. Kuznetcov, Fusion Eng. Des., 98-99 (2015), 1281

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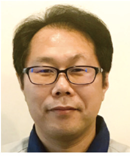

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