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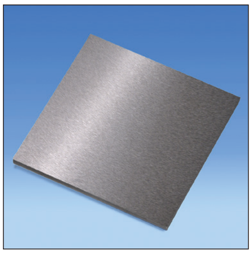

Potassium-Doped Tungsten Thick Plate for Fusion Reactor

Naoya MATSUTA* and Kei MIURA

Research on fusion energy, a key contender for achieving decarbonization, is becoming increasingly active. Tungsten (W) is used in the divertor of fusion reactors, which is exposed to extreme temperatures exceeding 2000°C. The DEMO-Reactor, designed to demonstrate power generation, is expected to operate for extended periods, requiring increased mechanical durability from W materials used in fusion reactors. In collaboration with universities and other institutions, A.L.M.T Corp. has evaluated various materials and has found the effectiveness of potassium (K)-doped W. Aiming to apply the findings to plasma-facing components, we have developed K-doped W thick plates tailored for this specific application. This paper reports the evaluation results of the main characteristics of these materials.

Keywords: fusion reactor, tungsten, potassium-doping, recrystallization, low-temperature brittleness

1. Introduction

In recent years, activities toward decarbonization through reducing dependence on oil, coal, and other fossil fuels have been accelerating. In particular, research on power generation using fusion energy called "the sun on earth" has entered the stage of constructing an experimental reactor to clarify whether or not it is scientifically and technologically feasible, and an international thermonuclear experimental reactor (ITER) is under construction in France. For the divertor of ITER, pure tungsten (W) is used as the plasma-facing material that must be durable to high thermal loads. A.L.M.T Corp. developed a pure W plate having durability against thermal loads of higher than 2000°C. This material demonstrated excellent durability in the thermal load tests conducted by the ITER Organization to determine whether or not this material can be used in actual equipment.[1] This material is currently being supplied for the ITER. The design of the DEMO-reactor*1 has already begun based on the results of research on ITER in order to demonstrate power generation using fusion energy. Since the fusion reactors to be constructed after the DEMO-reactor are expected to operate longer ITER, the plasma-facing material will accumulate thermal load and also will be subject to neutron irradiation damage over a long period of time. Therefore, the mechanical properties of W materials are required to be remarkably tough and suppress degradation in a long-term operating environment.

To address these problems, we worked on a new material in collaboration with universities and other research institutions. Aiming to find effective material modification methods, we tested prototype materials made by adding various elements. Table 1 summarizes briefly the evaluation results of small-sized prototype materials. The properties of potassium (K)-doped W, W-rhenium (Re) alloys, and other materials were evaluated, and the results were compared to those of pure W. K-doped W was found to be most promising.[2],[3]

Table 1. Property comparison between small-sized prototype material and pure W[2],[3]

	K-doped W	W-3% Re alloy
Strength	Better or comparable	Better or comparable
Low-temperature brittleness	Better	Better
Recrystallization resistance	Better	Better
Thermal conductivity	Comparable	Lower
Neutron embrittlement resistance	Better	Some concern

In the case of K-doped W, the small amount of added K controls the recrystallized structure by forming rows of fine K bubbles (Photo 1) in the material. As a result, it is known that coarsening of recrystallized grains is suppressed and deformation resistance is improved by suppressing grain boundary slip. Because of these properties, K-doped W wires and rods are used for the filaments of incandescent lamps and electrodes of electric-discharge lamps. Plasma-facing materials are required to be high in

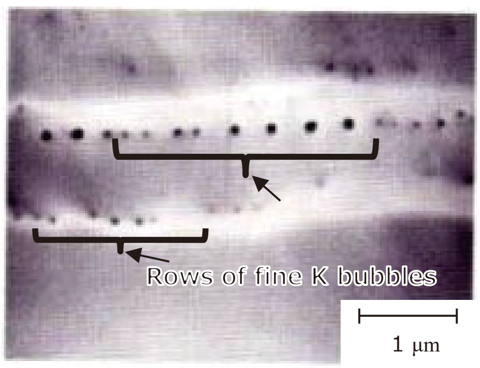

Photo 1. K bubbles in K-doped W

thermal conductivity since they must efficiently transfer the heat received from plasma to the cooling member. Compared to pure W, K-doped W has the advantage that it does not lose thermal conductivity. Despite K-doped W having a feature desirable for plasma-facing material as described above, there were few examples of its use in the form of a plate. In a series of our studies, we prototyped and evaluated small-sized K-doped W plates and confirmed that K-doped W has excellent material modification effects even in the form of a plate.

On the other hand, to embody the practical use of K-doped W for the DEMO-reactor, it was necessary to develop a thick K-doped W plate suitable for the fabrication of plasma-facing components. At A.L.M.T. Corp., we established a track record of manufacturing W monoblocks for ITER divertors, using our unique large-sized thick W plate manufacturing technology. To manufacture thick K-doped W plates by applying this technology to K-doped W, it was necessary to sufficiently verify in advance a method for incorporating the excellent properties of small-sized plates, which had been confirmed to be effective as an ITER divertor material in the past, into thick plates. In practice, we have developed a thick K-doped W plate by making full use of our unique K-doped W powder manufacturing technology, large ingot sintering technology, and rolling structure control technology. This report describes the details of our efforts.

2. Manufacture of K-doped W Plate and Its Properties

Figure 1 shows the W material manufacturing process. In the manufacture of a thick K-doped W plate, an ingot was made by press-forming and sintering K-doped W powder, and then the ingot was hot-rolled. When increasing the size of the material, attention must also be paid to the homogeneity of the property inside the material. In particular, as plate thickness increases, differences in property may arise in the plate thickness direction. Thick K-doped W plates are required to exhibit a high degree of homogeneity.

To evaluate the properties of the developed material in the thickness direction, Vickers hardness of TD cross section was measured in the thickness direction. Figure 2 shows the deviation of hardness with respect to the thickness center.

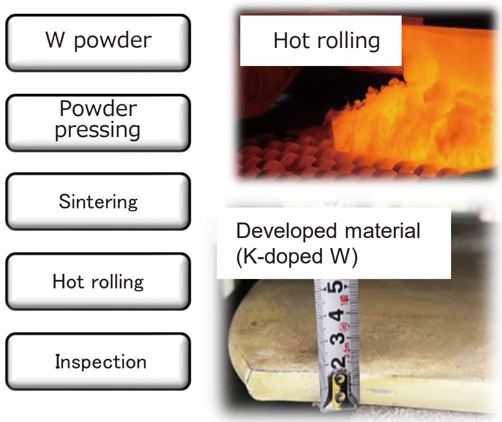

Fig. 1. W material manufacturing method

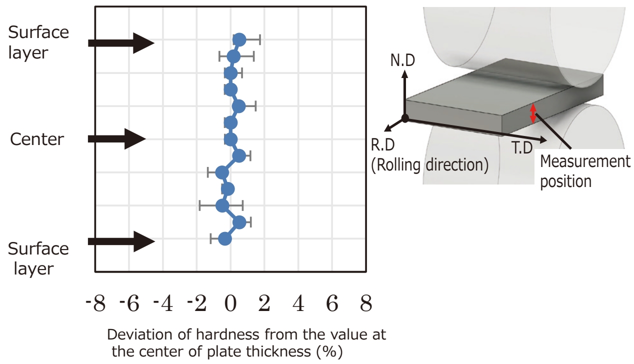

Fig. 2. Deviation of hardness of developed material in the thickness direction of TD cross section

Measurements were taken at equal intervals from the center of the plate thickness to the surface layer, and hardness was measured three times at each measurement position. The homogeneity of the plate was assessed by plotting the deviation of the hardness at each measurement position from the average of the three hardness measurements at the center of the plate thickness. With regard to the homogeneity of property, which was a problem with thick plates, the hardness deviation of the developed material was suppressed to within ± 2% as a result of strict control of rolling conditions, verifying that the property of the plate was homogeneous throughout the entire plate thickness. The microstructure of the developed material as manufactured is shown in Fig. 3. A pure W material prepared by the conventional manufacturing method is also shown as a reference material. The figure shows that the developed

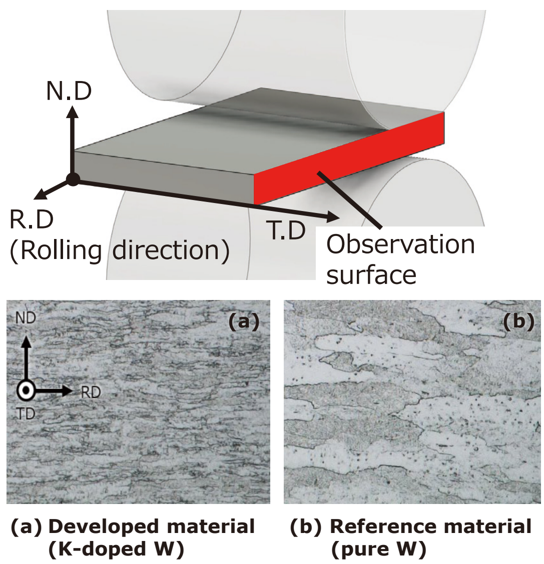

Fig. 3. Microstructure of materials as manufactured

material has very fine crystal grains. In general, the so-called Hall-Petch relation(4),(5) holds between the yield stress of a polycrystalline metallic material and its average crystal grain size. The developed material has very fine crystal grains and is expected to improve yield stress and other properties. Although a pure W material as manufactured generally exhibits a fiber structure, it starts recrystallization*2 at high temperatures and becomes coarse due to the growth of grains. Therefore, to reduce degradation of the mechanical properties of the material in the use environment of the actual equipment, it is effective to suppress the growth of recrystallized grains at the expected temperature as much as possible. Figure 4 shows the microstructure of the developed material after heat treatment at a temperature higher than that expected in the actual equipment. The recrystallized grains of the developed material were finer than those of the reference material even after heat treatment.

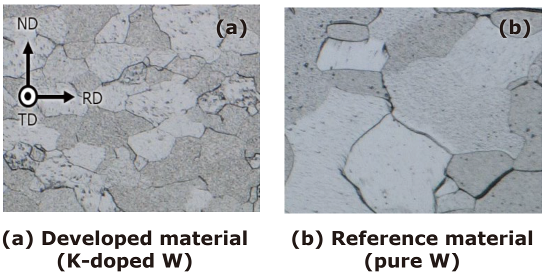

Fig. 4. Microstructure of materials after heat treatment

Photo 2 shows the scanning electron micrograph of the developed material after heat treatment at a temperature higher than that expected in the actual equipment. It was confirmed that bubbles, which were assumed to be K-bubbles, dispersed in the material, and the grain boundaries around the bubbles curled. This suggested that K-bubbles behaved as dispersion particles and exerted a pinning effect, thereby suppressing grain growth after recrystallization.

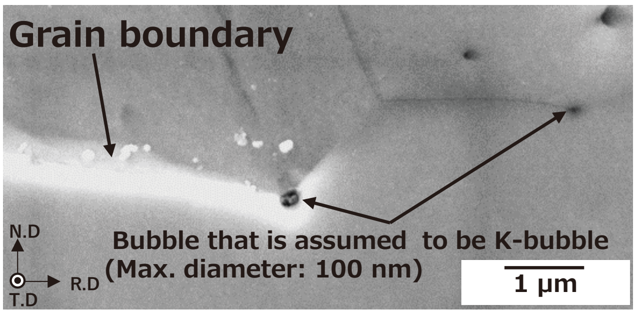

Photo 2. Scanning electron micrograph of material after heat-treatment

3. Evaluation of Mechanical Properties of Developed Material

To evaluate the mechanical properties of the developed material, the test specimen was heat-treated at a temperature higher than the thermal load expected in the actual equipment and then subjected to a tensile test. In the test, the specimen was pulled in the plate width direction (T.D) and heated to 200 to 500°C. The test results are shown in Fig 5. A value equivalent to the inner area of the stress-strain curve was defined as toughness (MJ/m^3) and used for the evaluation. The higher this value, the tougher the material, and the lower the temperature at which toughness appears, the lower the ductile-brittle transition temperature (DBTT).*3 High toughness and low DBTT are desirable for the materials used for plasma-facing components that are exposed to cooling/heating cycles. We compared the toughness of the developed material at each test temperature to that of the pure W reference material. The results showed that the developed material was tougher than the reference material at all test temperatures. The toughness of the pure W reference material was low even at a low temperature of 200°C, indicating that this material will break even when it absorbs a small amount of energy. On the other hand, the developed material exhibited a high toughness at 200°C. This suggests that the developed material will retain its toughness even after being subjected to the expected thermal load, thereby enhancing the reliability of the plasma-facing components.

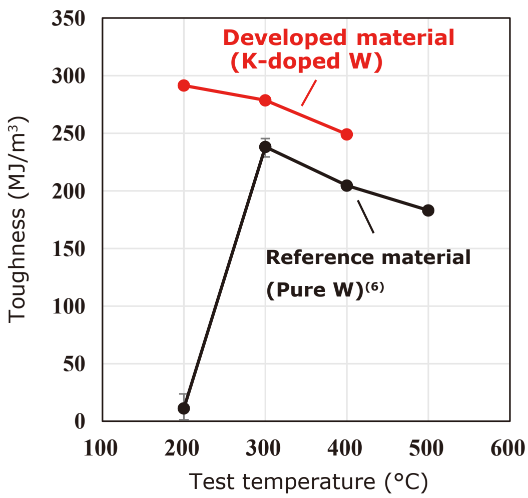

Fig. 5. Relationship between test temperature and the toughness of material after heat treatment

4. Conclusion

This report has discussed the properties of a thick K-doped W plate. The toughness of this material has been successfully improved by refining the recrystallized grain size. In the future, we will conduct thermal load tests that simulate the environment in which actual plasma-facing components are located in order to demonstrate the thermal shock resistance of the new plate. In addition, we will promote the use of this plate at research institutions in

Japan and overseas in preparation for contributing to the practical use of the DEMO reactor.

Technical Terms

∗1 DEMO-reactor: A fusion reactor for demonstrating power generation based on the findings obtained from ITER. The DEMO-reactor is currently under conceptual design.

∗2 Recrystallization: A phenomenon in which new crystal grains (with significantly low dislocation density) are created and grow with the energy stored inside the material as a driving force when a metallic material is plastically formed and held at a high temperature.

∗3 Ductile-brittle transition temperature (DBTT): The temperature at which the property of a material changes from ductile to brittle. In a temperature range below the ductile-brittle transition temperature of a material where it is embrittled, it will be broken with relatively weak force. Therefore, the ductile-brittle transition temperature of materials is preferred to be low.

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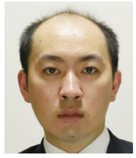
Contributors

The lead author is indicated by an asterisk (∗).

N. MATSUTA*

• Assistant manager, A.L.M.T Corp.



K. MIURA

• A.L.M.T Corp.