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Strain rate dependence of tensile properties of tungsten alloys for plasma-facing components in fusion reactors

Makoto Fukuda[a,*], Tsunenori Tabata[a], Akira Hasegawa[a], Shuhei Nogami[a], Takeo Muroga[b]

[a] *Tohoku University, 6-6-01-2 Aramaki-Aza-Aoba, Aobaku, Sendai, Japan*
[b] *National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu, Japan*

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ABSTRACT

The strain rate dependence of tensile properties such as yield stress and fracture strain of W-3%Re and K-doped W-3%Re plates in the temperature range from room temperature (RT) to 300 °C was investigated in this work. The examined W alloy plates were fabricated by the same process and with the same reduction ratios. The yield stress of W-3%Re changed significantly with increasing strain rate as compared to K-doped W-3%Re. The strain rate sensitivity of W-3%Re was decreased by K-bubble dispersion. The low-temperature strength and ductility of W-3%Re was improved by K-bubble dispersion, although the fracture strain of K-doped W-3%Re was lower than that of W-3%Re at 200 and 300 °C.

1. Introduction

Tungsten (W) is the most attractive material as a plasma-facing material (PFM) for plasma-facing components (PFCs) such as divertor and blanket in a fusion reactor. Although W has favorable material properties (e.g. low tritium retention and high melting point) as a PFM, its brittleness and the degradation of its mechanical and thermal properties during fusion reactor operation limit its use. In a fusion reactor, W is exposed to high heat flux and neutron irradiation. Because of the high heat load, the surface temperature of W will increase above the recrystallization temperature (∼1100–1300 °C) and recrystallization will occur. Recrystallization degrades the strength and ductility of W, especially at lower temperatures, causing crack formation and propagation, which in turn causes a reduction of the heat removal function of PFCs. Neutron irradiation causes irradiation embrittlement, and thus both recrystallization and irradiation embrittlement are limiting factors in the use of W as a PFM. In addition, improvement of the low-temperature brittleness is also important for suppressing crack initiation and its propagation near the cooling channels of PFCs.

Many methods to improve the resistance of W to recrystallization and irradiation embrittlement have been investigated by many researchers. In our previous works, we focused on dispersion strengthening and alloying, and we fabricated potassium (K)-bubble-dispersed and/or rhenium (Re)-added tungsten-based alloys. It is expected that the improvement of mechanical properties and recrystallization resistance by dispersed K-bubbles. In order to prevent the melting and dissolution of the dispersed second phase, K-bubbles were selected as the second phase rather than carbides and oxides. Re is the transmutation element of W during neutron irradiation in a fusion reactor; it is also known as one of the most effective solid-solution elements for improving the mechanical properties and recrystallization resistance of W. In addition, suppression of irradiation hardening by the addition of 3–10% Re has been reported [1–3]. On the other hand, the addition of Re decreases the thermal conductivity of W, and thus the trade-off between thermal conductivity, mechanical properties, and resistivity to recrystallization and irradiation embrittlement should be considered when adding Re as an alloying element. Based on the results of our previous researches, the amount of Re was selected as 3%.

Investigation of the tensile strength, recrystallization behavior, and thermal conductivity of K-bubble-dispersed and Re-added W alloys was performed in our previous works [4–6]. K-doped W-3%Re exhibited a higher recrystallization temperature than pure W and K-doped W. The tensile strength was also improved by K-bubble dispersion and 3% Re addition. Although the K-bubble dispersion and 3% Re addition into W showed positive effects on

* Corresponding author.
E-mail address: makoto.fukuda@qse.tohoku.ac.jp (M. Fukuda).

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Table 1
Chemical compositions of examined materials.

	Reduction ratio, %	Re, mass%	C, mass ppm	O, mass ppm	N, mass ppm	K, mass ppm	Al, mass ppm	Si, mass ppm
W-3%Re	60	3.0	<10	<10	<10	<5	5	<5
W-3%Re	80	3.0	<10	<10	<10	<5	2	<5
K-doped W-3%Re	60	3.0	<10	<10	<10	28	19	20

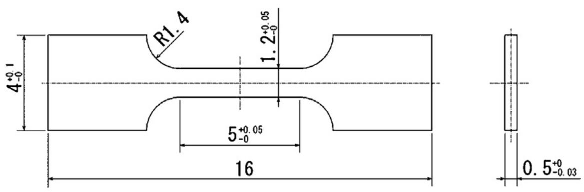

Fig. 1. Dimensions of tensile specimen (unit: mm).

the mechanical properties and the resistance to recrystallization, we did not thoroughly investigate the influence of several factors on the mechanical properties because of the limited scope of the study. One of these factors is the strain rate effect on tensile properties. Divertor components in fusion reactors are exposed to not only steady-state heat loads but also to thermal shock due to transient events such as plasma disruptions, vertical displacement events, and edge-localized modes. In addition, the temperature change between the beginning and end of reactor operation also causes thermal strain and stress. Therefore, the PFM of divertor components will be subjected to thermal strain and stress of different magnitudes and strain rates. It has already been reported that K-bubble dispersion does not significantly affect the strain rate and temperature dependence of the tensile properties of pure W [7]. The objectives of the current work are to investigate the tensile properties and strain rate dependence of W-3%Re and K-doped W-3%Re and the effect of K-bubble dispersion on the strain rate dependence of the tensile properties of W-3%Re.

2. Experimental

K-doped W-3%Re and W-3%Re plates were examined in this work. These materials were supplied by A.L.M.T. Corp., Japan, and were fabricated by cold isostatic pressing, sintering, hot rolling, and finally heat treating at 900 °C for 20 min to relieve the stress. The impurity content of these materials is listed in Table 1. Fig. 1 shows the geometry of the SS-J-type tensile specimen widely used in fusion and fission materials research [8,9]. The dimensions of the gauge section of the specimens were 5 mm long, 1.2 mm wide, and 0.5 mm thick. Specimens were cut out in the rolling direction of the plate by electro discharge machining, as shown in Fig. 2, and its surface was mechanically polished to #1500. Tensile tests were performed in vacuum and in a temperature range from RT to 300 °C using an electromotive testing machine (CATY-T3HSt/HV13, Yonekura MFG Co., Ltd., Japan).

The strain rate was in the range from 10^{-3} to 10^{-1} s^{-1}. The strain at the gauge section was measured from the displacement

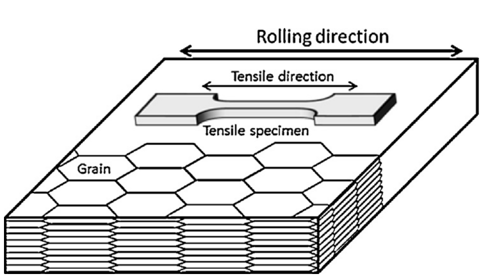

Fig. 2. Relation between tensile and rolling directions.

of the cross head. The yield stress was estimated by the 0.2% offset method. One sample was tested per each test condition.

3. Results and discussion

Fig. 3 shows the typical engineering stress–strain curves obtained by tensile tests using K-doped W-3%Re and W-3%Re at RT, 100, 200, and 300 °C. Because the strain was calculated by using the gauge length of the specimen and the displacement of the cross head, strain values obtained in this work may have been affected by machine compliance and so on, as the values are relatively large. The elongation of W-3%Re and K-doped W-3%Re decreased with increasing strain rate. W-3%Re showed elongation at 100 °C with a strain rate of 10^{-3} s^{-1}, although it fractured in the elastic region when the strain rate was 10^{-1} s^{-1}. K-doped W-3%Re showed yielding and a little elongation at a strain rate of 10^{-3} s^{-1} at RT and at strain rates of 10^{-3} and 10^{-1} s^{-1} at 100 °C. The increase of ultimate tensile strength with increasing strain rate was more clearly observed in W-3%Re than in K-doped W-3%Re. The strain rate dependence of the yield stress in K-doped W-3%Re and W-3%Re are shown in Fig. 4. The yield stress in both K-doped W-3%Re and K-doped W tended to increase with increasing strain rate, and this trend was more clearly observed in W-3%Re than in K-doped W-3%Re. The strain rate dependence of yield stress in W-3%Re and K-doped W-3%Re decreased with increasing test temperature. K-doped W-3%Re showed lower strain rate dependence as compared to W-3%Re at 200 and 300 °C.

Based on the results shown in Fig. 4, the strain rate sensitivity [10] of the samples was calculated by using the following equation:

$$m = \frac{\partial \ln \sigma_y}{\partial \ln \dot{\varepsilon}} \quad (1)$$

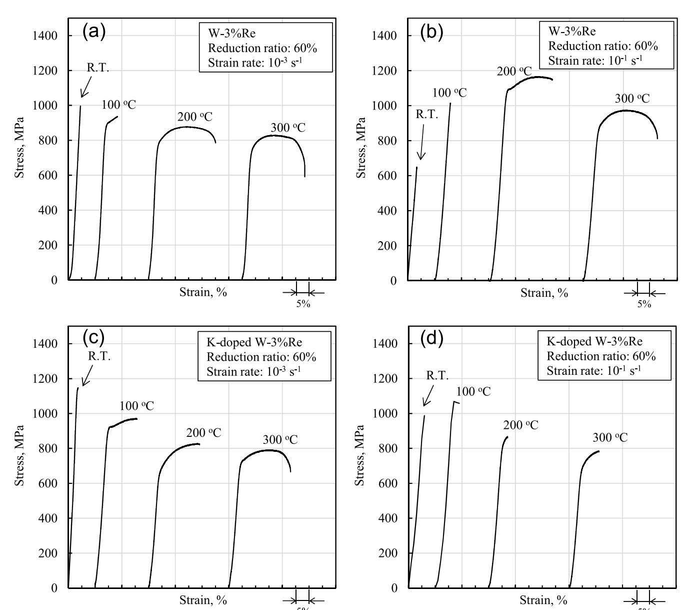

Fig. 3. Engineering stress–strain curves obtained by tensile test of W-3%Re and K-doped W-3%Re.

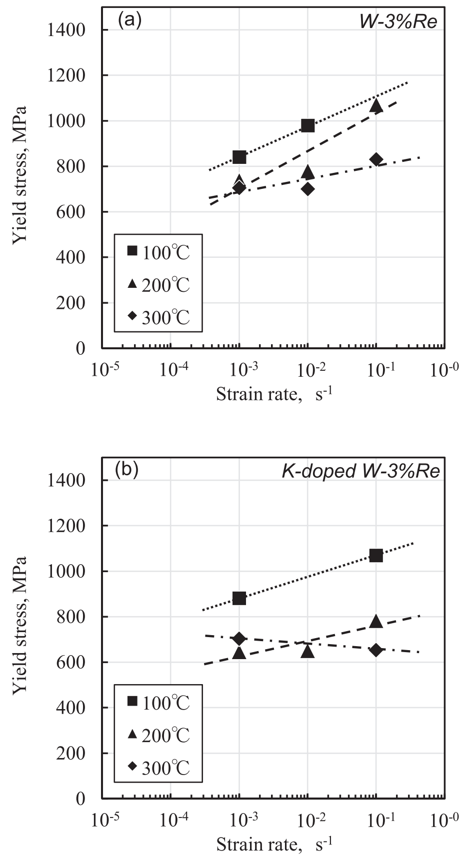

Fig. 4. Strain rate dependence of yield stress in W-3%Re and K-doped W-3%Re.

where m is the strain rate sensitivity, σ_y is the yield strength (MPa), and $\dot{\varepsilon}$ is the imposed strain rate (s^{-1}). The strain rate sensitivity of W-3%Re and K-doped W-3%Re is shown in Fig. 5. The strain rate sensitivity of W-3%Re was approximately two times higher than that of K-doped W-3%Re at 100 and 200 °C. Therefore, the yield stress of W-3%Re was significantly affected by the strain rate as compared to K-doped W-3%Re at these temperatures.

Fig. 6 shows the fracture strain of W-3%Re and K-doped W-3%Re at strain rates from 10^{-3} to 10^{-1} s^{-1} and from RT to 300 °C. Elongation was not observed in W-3%Re at RT, and a ductile to brittle transition was observed at 100 °C in W-3%Re. K-doped W-3%Re showed a little elongation at RT at a strain rate of 10^{-3} s^{-1}, and a ductile to brittle transition was observed RT. Above 100 °C, K-doped W-3%Re

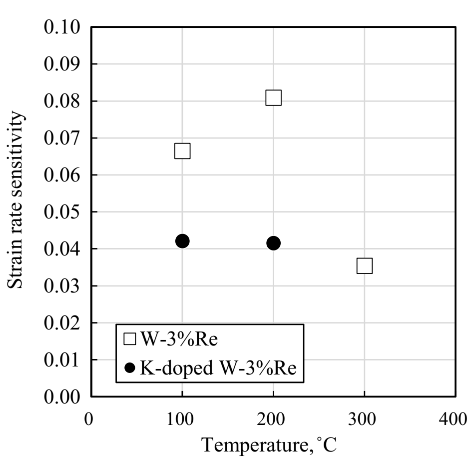

Fig. 5. Strain rate sensitivity of W-3%Re and K-doped W-3%Re.

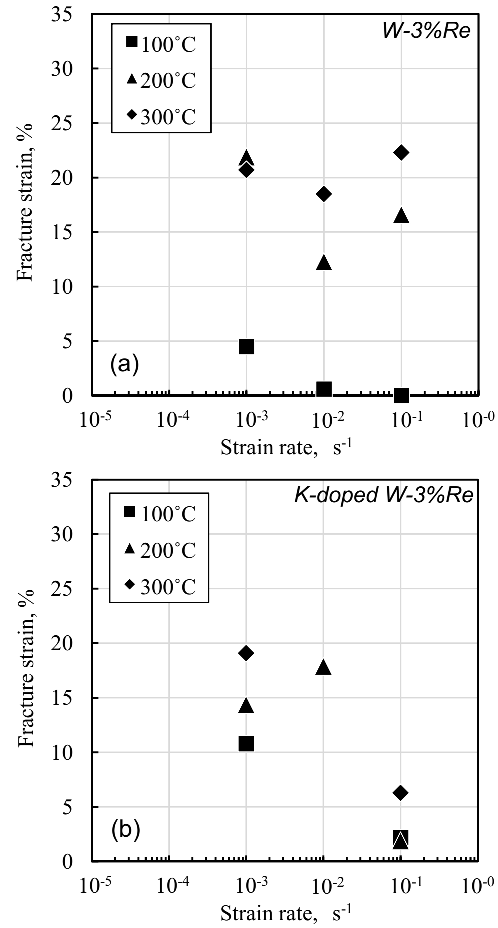

Fig. 6. Strain rate dependence of fracture strain in W-3%Re and K-doped W-3%Re.

showed elongation at strain rates of 10^{-3}–10^{-1} s^{-1}. With increasing strain rate, the fracture strain of K-doped W-3%Re decreased. W-3%Re showed larger fracture strain at a strain rate of 10^{-1} s^{-1} as compared to K-doped W-3%Re, and the strain rate dependence of its fracture strain was smaller than that of K-doped W-3%Re.

The experimental results show that the K-bubble dispersion into W-3%Re increased the tensile strength and ductility at RT–100 °C. The strain rate sensitivity of W-3%Re decreased by K-bubble dispersion. Thus, the increase of yield stress with increasing strain rate was suppressed in K-doped W-3%Re as compared to W-3%Re. The fracture strain of K-doped W-3%Re decreased more with increasing strain rate than that of W-3%Re because the strain rate dependence of the fracture strain was increased by K-bubble dispersion.

It is a well-known fact that the strain rate sensitivity is affected by microstructural characteristics such as grain size, texture, and dislocation density and structure. The average grain sizes of W-3%Re and K-doped W-3%Re were almost the same (~28 μm). The grain shapes were almost equiaxed, and typical anisotropic grain structure was not observed in either W-3%Re or K-doped W-3%Re. The possible causes are the dislocation structure and density and the crystal orientation. For instance, microstructural observation by transmission electron microscopy (TEM) and electron backscatter diffraction (EBSD) analysis may help in evaluating the effect of K-bubble dispersion on the tensile properties of W-3%Re, which is planned for our future works. The effects of K-bubble dispersion on the microstructure of pure W were reported by Snow [11]. These effects include the multiplication of dislocations during the fabrication process and pinning grain boundary motion at elevated temperatures. The multiplication of dislocations during

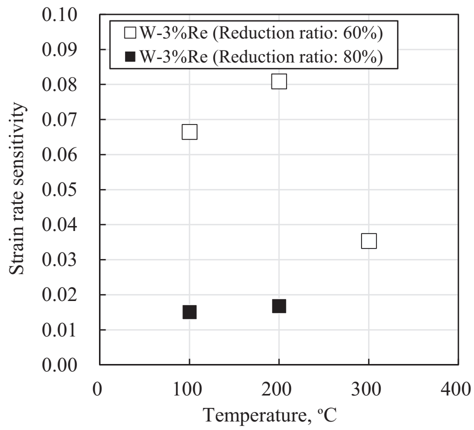

Fig. 7. Strain rate sensitivity of W-3%Re with reduction ratios of 60 and 80%.

fabrication results in a typical deformed texture. To induce such a deformed texture and assess its effect, a W-3%Re plate with a reduction ratio of 80% was fabricated and its tensile properties were investigated. The difference in yield stress between W-3%Re with reduction ratios of 60 and 80% was not clearly observed, although the strain rate sensitivity changed with increasing reduction ratio, as shown in Fig. 7. With increasing reduction ratio, the strain rate sensitivity decreased. In addition, W-3%Re with a reduction ratio of 80% showed a little elongation (~0.3%) at RT at a strain rate of 10^{-3} s^{-1}, and ductility at low temperatures improved by increasing the reduction ratio. These results indicate that there is a difference in microstructure between W-3%Re and K-doped W-3%Re for the same reduction ratios and that the strain rate sensitivity and low-temperature ductility changes according to these microstructural changes.

4. Summary

The strain rate dependence of the tensile properties of W-3%Re and K-doped W-3%Re and the effect of K-bubble dispersion on the tensile properties of W-3%Re were investigated. The results of this work are summarized as follows:

(1) The strain rate dependence of the yield stress was more clearly observed in W-3%Re than in K-doped W-3%Re, and the strain rate sensitivity of W-3%Re was higher than that of K-doped W-3%Re.
(2) K-doped W-3%Re showed larger elongation than W-3%Re at RT and 100 °C, and improvement of the low-temperature ductility by K-bubble dispersion was observed. At 200 and 300 °C, elongation decreased by K-bubble dispersion, and the strain rate dependence of the fracture strain was more clearly observed in K-doped W-3%Re than in W-3%Re.
(3) The difference in the strain rate dependence of the tensile properties between W-3%Re and K-doped W-3%Re may be caused by their differing microstructures, such as their dislocation structures and density.
(4) K-doped W-3%Re showed better ductility at low temperature across a wider strain range as compared to other W materials (i.e., pure W, K-doped W, and W-3%Re). Brittleness is one of the major drawbacks of W for fusion reactor application, therefore, K-bubble dispersion and 3% Re addition might increase the use of W materials in fusion reactors.

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