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Examination of material performance of W exposed to high heat load: Postmortem analysis of W exposed to TEXTOR plasma and E-beam test stand

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Abstract

We have examined the behavior of high Z limiters exposed to TEXTOR edge plasma and found that under certain conditions high Z materials are compatible with plasmas. In high density Ohmic plasmas the accumulation of a high Z impurity in the plasma center with significant radiation is observed, whereas an auxiliary heating like NBI and ICRH enhances the impurity exhaust with saw tooth activity. For a practical use of high Z plasma facing materials, extremely high heat load from the plasma becomes a serious concern. In the present work we have conducted the high heat load tests of tungsten (W) using two different heat sources, one is the W limiter exposed to TEXTOR plasma and the other is various W samples heat loaded with an intense E-beam using the JEBIS facility in Japan Atomic Energy Research Institute (JAERI). From the test results we have to conclude that W, if applied in the form of the bulk material, should be used above the ductile brittle transition temperature (DBTT) but below about 1500°C to avoid the recrystallization. Maximum heat load tolerable without surface melting is about 20 MW/m^2 for several seconds. The monocrystalline used at high temperatures shows very good performance, though the production of the monocrystalline with a desired shape is not easy. Considering its brittle nature, hard machining and heavy mass, bulk W cannot be a structure material but be used as a thin tile or deposited film on some structure materials. Unfortunately, however, the thermal expansion coefficient of W is so small that brazing of W to a heat sink material like Cu which has a much larger thermal expansion coefficient would easily result in cracking due to the large thermal stress. Thus the development of tungsten plasma facing component (PFC) needs much effort in future.

Keywords: TEXTOR; Limiter; Plasma-wall interaction simulator; Energy deposition; High Z wall-material

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1. Introduction

Tungsten (W) is now planned to be used as divertor tiles in ITER. Although accumulation and high radiation losses of W in plasma center are main concerns for its application as a plasma facing material (PFM), the materials stability and tolerance to high heat load are also serious concerns from engineering aspects [1,2]. W is usually produced by a powder metallurgy and its material properties quite depend on the production process, materials history, crystalline structure and impurities. Moreover W is very brittle below a ductile brittle transition temperature (DBTT) which is usually near or under room temperature (RT) and hence machining is hardly possible at RT.

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Due to the lack of ductility, the utilization of W as a structure material does not seem easy nor reliable. In addition recrystallization and grain growth are serious concerns for the high temperature usage of W. Surface melting and accompanied effects have not been examined well because of the lack of an experimental facility which can heat up the bulk W over its melting point in a very short time duration.

Thus the high heat load test of W is very urgent to find the operation conditions or window, e.g. temperature region, suitable heat treatment, maximum tolerable heat load and so on, of W as a PFM. In the present work we have conducted high heat load tests of W using two different high heat sources, one is the exposure of the W limiter to the TEXTOR plasma and postmortem analysis and the other is an E-beam high heat load test performed with the JEBIS facility in Japan Atomic Energy Research Institute (JAERI).

2. Experimental

A W test limiter produced by powder metallurgy (PM-W supplied by Plansee) was inserted into the TEXTOR plasma through the limiter lock from the bottom of the torus up to 2 cm closer to the plasma than to the main ALT-II graphite limiter. The shape of the limiter is the part of a sphere of 15 cm in diameter with dimensions of 12 cm long, 8 cm wide and 5 cm high (see Fig. 2). The limiter was normally preheated at around 500°C to avoid the thermal stress induced brittlement. TEXTOR was operated at $I_p = 340$ kA and $B_t = 2.2$ T. Co NBI heating with a power of about 1.3 MW was used for auxiliary plasma heating. Recent W limiter experiments were done under prolonged plasma duration of 6 s, whereas graphite (EK98) and Mo limiters in the previous experiments were exposed to 3 s plasmas [3–5].

The thermal response of the limiter was analyzed with a temperature calibrated IR camera together with image processing as well as two thermocouples which were embedded 7 mm beneath the limiter surface on both the ion and electron drift sides. The limiter was thermally isolated from the support and the temperature increment measured with the thermocouple was also used for calorimetry to determine the deposited energy on the limiter. Details of an experimental setup and data-analysis have been given elsewhere [3–5].

E-beam high heat loaded tests for two different kind of W specimens, an E-beam melted mono crystalline (EBSC-W) and high purity polycrystalline W (PM-W) produced by powder metallurgy (both supplied by Daido Steel), were carried out by the JEBIS facility at JAERI [6,7] with 70 keV × 3.9 A E-beam for 2.0 ms equivalent to the peak heat load of about 1100 MW/m^2. In order to see DBTT effect, the E-beam loading was done at two different temperatures (near DBTT and far above DBTT) i.e. 150°C and 800°C for EBSC-W and 150°C and 1150°C for PM-W.

3. Results and discussion

3.1. Performance of W limiter exposed to TEXTOR plasma

Similar to the previous experiments with the Mo limiter in TEXTOR [3,5,8–10], W impurity accumulation in plasma center was observed in high density Ohmic plasmas. The accumulation of W was pronounced when saw tooth activity became small [8–10]. Either ICRH and NBI heating enhanced the saw tooth activity and hence the W accumulation was weakened. The details of the influence on the main plasma and the release behavior of the W impurity by plasma sputtering are discussed elsewhere [8,10,11]. Here we concentrate on material performance.

Fig. 1 compares time sequences of the surface temperatures monitored by IR camera between graphite (EK98) and W under similar heat loading conditions. The latest W limiter experiments were done under prolonged plasma duration of 6 s, whereas the graphite limiters were exposed to 3 s plasma. Hence the total deposited energy on the W limiter was higher than that on the graphite by a factor of about 1.5. One can clearly see that the surface temperature rising rate is lower for W because of its higher thermal conductivity in spite of the larger deposited energy. Maximum power fluxes of about 20 MW/cm^2 for 4 s could be loaded on the W limiter without severe damage. The 20 MW/cm^2 would be over the maximum even for actively cooled W to avoid melting, because the time duration of the present heat load is very short and nearly equivalent to the inertial cooling condition.

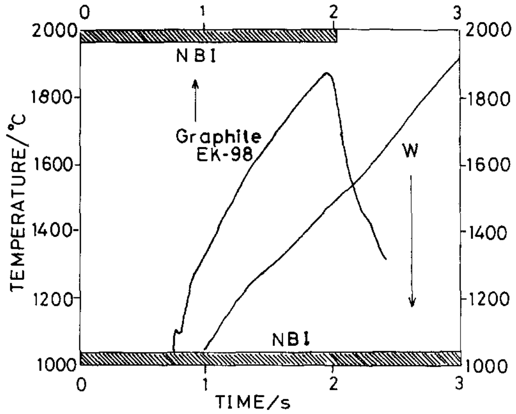


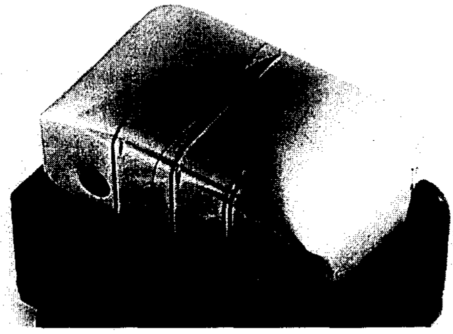
Fig. 1. Comparison of time sequences of surface temperatures monitored by IR camera between graphite (EK98) and W exposed to similar power plasmas. Time zero is referred as the starting time of NBI. The W limiter was exposed to 6 s plasma, whereas the graphite limiter was exposed to 3 s plasma (see text).

During the several highest heat load shots, the maximum surface temperature exceeded 3500°C which was confirmed by local surface melting. In Fig. 2(b) one can clearly see the trace of molten liquid spilled over the limiter surface, which was likely caused by a hydrodynamic force or plasma pressure. The surface melting, however, could not be perceived by an increase in the radiated power which is most sensitive for W accumulation in the plasma core. This is probably because the evaporated impurities are promptly redeposited after their ionization and gyromotion [5]. Beneath the trace of the molten layer one can see grain boundaries which indicate slight grain growth. Even under such short pulse operation of several seconds as in TEXTOR compared to ITER, the cyclic operations thus resulted in the grain growth.

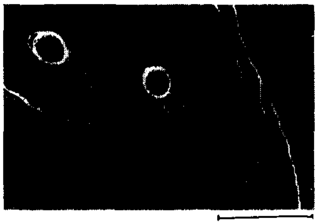
The limiter surface showed no serious damage under normal operations in which the limiter was preheated at about 500°C. However, one day the limiter experiments were conducted with the preheating of about 150°C unintentionally. As a result, the limiter was seriously damaged with large cracks running over the whole limiter (see Fig. 2(a)). The cracks were not initiated at the surface but from holes drilled for introducing thermocouple from the bottom and extended all over the surface. The cross-section of the cracked region (Fig. 2(c), (d)) shows a typical pattern of the intergranular crack propagation in brittle materials. This indicates that the cracks were initiated by the residual stress introduced by the manufacturing process of the limiter.

We have tried to find the particular shot in which the cracking occurred by detailed examination of the IR camera pictures but failed. The cracking very likely happened after the shot, since the thermal stress in the cooling phase is usually much larger than that during the heating phase. These results show again that the PM-W cannot be operated below DBTT.

As noted in Ref. [2], reflection coefficients both of a particle and energy are higher for higher Z materials. This means the deposited energy to PFM under the same plasma condition should be less for the higher Z materials. Until now such comparison has not been made in any tokamak, because the PFM of most of the present tokamak is carbon (TEXTOR as well). Therefore a comparison of the deposited energies to the Mo limiter and the W one in TEXTOR experiments is worth being mentioned. The hydrogen reflection coefficient of W is about 2 times larger than that of Mo. In Fig. 3 the deposited energy on the W limiter is compared with that of the Mo limiter under similar plasma conditions. One can note that the former is a little smaller than the latter, though the difference is not as large as that expected from the hydrogen reflection coefficients.

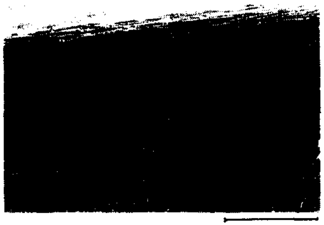


(a) Overview



(b)Surface with molten layer

(c) Cracked sufrace



(d) Cross-section of crack

Fig. 2. Appearance of W limiter after usage in TEXTOR. (a) Overview, (b) SEM image of surface with trace of molten layer, (c) SEM image of cracked part and (d) SEM image of cross-section of crack.

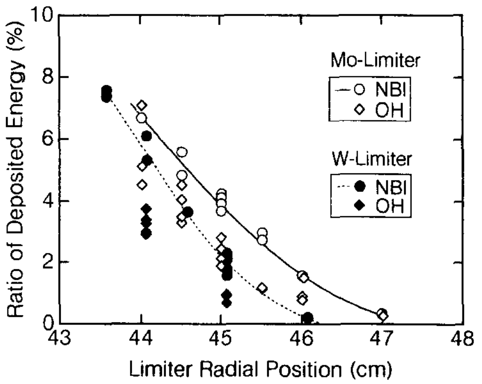
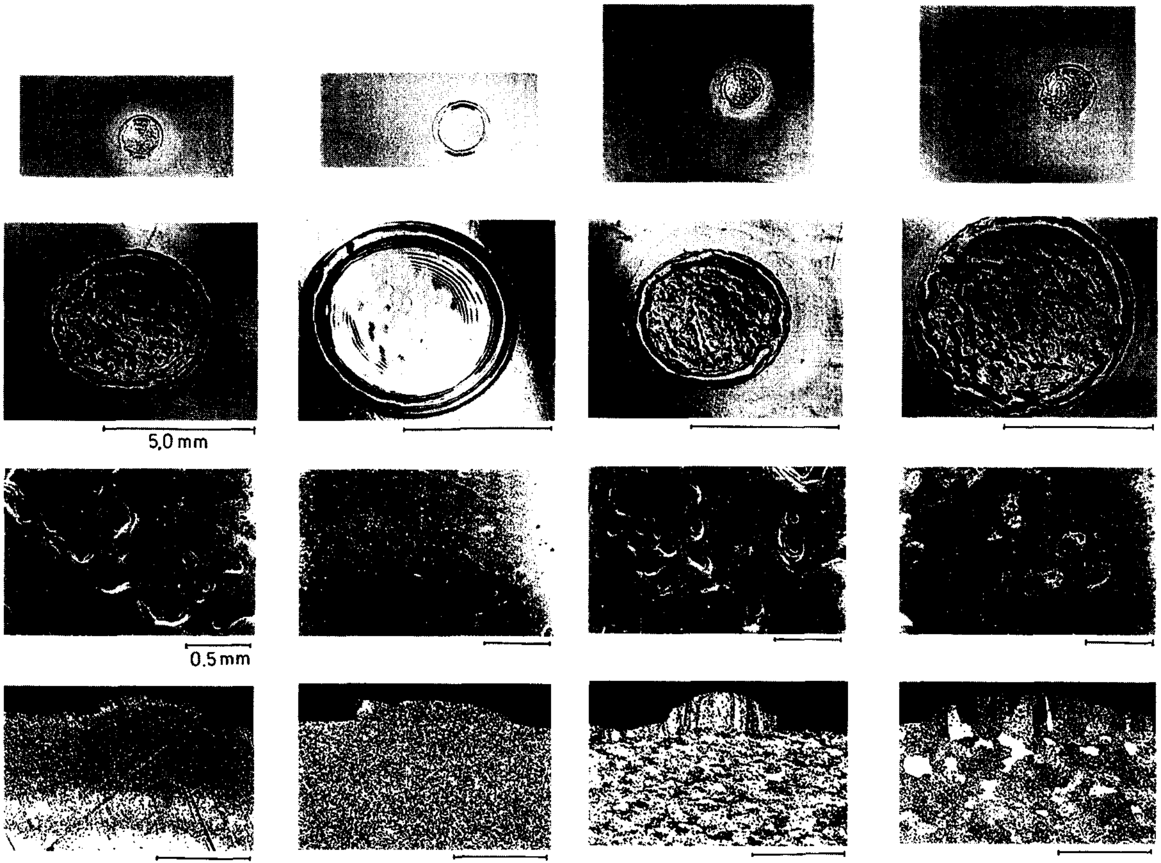


Fig. 3. Comparison of the ratios of the deposited energy on the W limiter and the Mo limiter to the total convective energy in the plasma in terms of the limiter position. The main ALT-II graphite limiter is located at 46 cm.

In the limiter experiments in TEXTOR only several % of the total convected energy to the plasma was deposited on the test limiter and most of the plasma materials interactions (PMI) occurred at the main ALT-II graphite limiter. This might result in a sub-monolayer coverage of the limiter surface with carbon which could influence particle and energy reflections. In addition there is an argument that if the limiter material was changed, the plasma near the limiter should be modified according to the accompanied changes of not only the reflection coefficient but also secondary electron yield, sputtering yield and so on. Thus the observed difference in Fig. 3 is not so pronounced as compared with experimental errors. Nevertheless the higher reflection coefficient of high *Z* materials is very attractive if it truly results in the less energy deposition. The influence of different reflection coefficients of PFM on the plasma performance must be studied in more detail.

3.2. E-beam heat load test

E-beam heat load tests of two different types of W, EBSC-W and PM-W, were carried out with the JEBIS facility at JAERI. Appearances of the E-beam loaded



(a) EBSC-W at 150°C **(b) EBSC-W at 800°C** **(c) PM-W at 150°C** **(d) PM-W at 1150°C**

Fig. 4. Results of E-beam high heat load tests for (a) EBSC-W irradiated at 150°C, (b) EBSC-W irradiated at 800°C, (c) PM-W irradiated at 150°C and (d) PM-W irradiated at 1150°C. Surface appearances, Surface craters, SEM surface images and cross-sections are respectively shown from the top to the bottom.

Table 1
Results of E-beam high heat load test

Sample:	EBSC-W	EBSC-W	PM-W	PM-W
Irradiation temp. °C):	150	800	150	1150
Dimension (mm^3):	5 × 14 × 30	5 × 14 × 30	5 × 25 × 30	5 × 25 × 30
Sample purity (%):	99.98	99.98	99.996	99.996
Density (g/cm^3):	19.3	19.3	19.3	19.3
Weight loss (mg):	0.68	1.58	0.70	1.70
Surface appearance:	rough	smooth	rough	rough
Crack:	yes in grain	no	yes along grain boundary	no
Recrystallization:	no	no	yes grain growth	yes significant grain growth

Irradiation 70 keV × 3.09 A × 20 ms.

surface and cross-section of the sample are given in Fig. 4 and the results are summarized in Table 1. Due to such a intensive peak heat load as 1100 MW/m^2 all samples were melted. However, the surface appearance was quite different with each other. As clearly seen Fig. 4 the EBSC-W irradiated at 800°C shows the smoothest surface (Fig. 4(b)). In the previous high heat load test of Mo [12], surface roughness after the melting was clearly correlated with residual gas impurity. In the present case, however, the roughness can not be correlated with the purity because the PM-W which showed more rough surface has higher purity as seen Table 1. The motive force to make the surface rough after the melting is not clear at present. In any case the appearance of the once melted region would be significantly modified by a hydrodynamic force or plasma pressure in a plasma machine as appeared in Fig. 2(b).

No marked difference was observed in the weight loss or erosion yield between EBSC-W and PM-W samples (see Table 1). That is because the erosion is mainly caused by evaporation. It is noteworthy that the EBSC-W irradiated at 800°C showed no new grains nor cracks after the melting, indicating that the recrystallization proceeded from the bulk to the surface in the cooling phase without any nucleation of new grains. Although the EBSC-W irradiated at 150°C also returned to monocrystalline after the melting, it exhibited a sharp straight crack caused by the loss of ductility at such lower temperature as seen in the bottom of Fig. 4(a).

The PM-W irradiated at 150°C (Fig. 4(c)) shows many small cracks along the grain boundaries, which is a typical intergranular cracking pattern of the brittle materials. The cause of the cracking of the W limiter seen in Fig. 2 is the same. Significant recrystallization remaining columnar grains grown to the surface normal is appreciable in the cross-sections of both of the PM-W samples (Fig. 4(c), (d)). The cracks propagated through the boundary between the columnar grains and the matrix in the PM-W irradiated at 150°C. In the PM-W irradiated at 1150°C even matrix grains grew large, though no cracks were observed because the PM-W is ductile at 1150°C.

In conclusion, for the utilization of PM-W, we have to optimize the operation temperature to avoid both the embrittlement due to the thermal stress at lower temperatures and grain growth at higher temperatures. In this respect the monocrystalline W operated at higher temperatures is very attractive, though it is not easy to produce the monocrystalline W with a desired shape.

Considering its brittle nature, hard machining and heavy mass, W can not be a structure material but be used as thin tiles or deposited film on some structure materials. Unfortunately, however, the deposited film by either CVD or PVD is a polycrystalline and hence the recrystallization and grain growth would degrade its mechanical properties. In addition the thermal expansion coefficient of W is so small that brazing of W to heat sink materials like Cu which has a much larger expansion coefficient easily results in cracking due to the large thermal stress [2]. The development of PFC with W coating needs much effort in future.

4. Conclusion

High *Z* limiter experiments in TEXTOR indicate that high *Z* materials can be applied as PFM under plasma conditions where accumulation is prevented. However extremely high heat load to the high *Z* brittle materials has been a serious concern for their practical use. In the present work we have conducted high heat load tests of W using two different high heat sources, one is the post-mortem analysis of the W limiter exposed to the TEXTOR plasma and the other is an E-beam high heat load tests performed with the JEBIS facility in JAERI.

Since the hydrogen reflection coefficient of W is about two times larger than that of Mo, the deposited energy on the W limiter could be smaller than that of the Mo limiter under the similar plasma condition. Although the former was found a little smaller than that on the latter, the difference was not as large as that expected from the reflection coefficients. A higher reflection coefficient, corresponding to lower energy deposition, could be a benefit of the high Z PFM. However it is likely that if the limiter material was changed, the plasma near the limiter should be modified according to accompanied changes of not only the reflection coefficient but also secondary electron yield, sputtering yield and so on, and hence deposited energy be modified. To confirm the effect of the reflection further work is needed.

From the high heat load tests we can conclude that W, if applied in the form of a bulk material, should be used above DBTT but below about 1500°C to avoid the recrystallization. Maximum heat load tolerable without surface melting was about 20 MW/m^2 for several seconds. High temperature use of a single crystal or mono block of W, if it is available, is very attractive, because it retains the crystallinity even after melting. Considering its brittle nature, hard machining and heavy mass, commercially available PM-W cannot be a structure material but can be used as thin tiles or deposited film on some structure materials. Unfortunately, however, the deposited film by either CVD or PVD is usually a polycrystalline and hence the recrystallization and grain growth would degrade their mechanical properties. The large difference in thermal expansion coefficients between W and a heat sink material like Cu (the former is much smaller than the latter) would give also problems on the adhesion.

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