Effect of Electron Beam Irradiation on Fracture and Fatigue Characteristics of TZM

Takeshi Denda, Toshinori Nishimura
Nippon Mining Company, Ltd., Tokyo, Japan
Tokuo Teramoto, Masakatsu Saito
University of Tsukuba, Tsukuba, Japan

INTRODUCTION

Fusion reactor development presents one of most difficult problems to current material development works. Fusion reactor materials are desired to be used under severe conditions such as extremely high temperature and high thermal cycle. Another condition is radiation environment inherent in fusion reactor. First wall will be subjected to large fluxes consisting of high energy neutrons and energetic charged particles, when plasma disruption takes place. This seems to be far beyond present industrial level to produce fusion reactor materials. The successful development of first wall materials is strongly required in the technological feasibility for fusion reactor.

In recent studies on structural materials for first wall materials(Miya 1987), several heat sources have been used to simulate the heat flux of plasma disruption such as laser beam, ion beam and electron beam. Mechanical and thermal characteristics of several materials were investigated after or during heat irradiation by these heat sources.

In this report, we studied mechanical characteristics of TZM on which electron beam was locally irradiated in order to simulate high heat flux due to plasma disruption. As a result, the effect of electron beam irradiation on fracture and fatigue behavior of TZM was clarified to a great extent. Microscopic examination was also made to correlate these behavior with the variation of TZM microstructure due to irradiation.

GENERAL FEATURES OF TZM

TZM is considered to be one of suitable materials for the first wall because of its high temperature strength, high melting point and high thermal conductivity(Saito 1987). Figure 1 shows the calculated curves of the relation between admissible heat flux and material thickness. The admissible heat flux was obtained so as to satisfy ASME code section III when the cooling side temperature is fixed at 90°C. It is assumed that the plasma side is subjected to steady heat flux and neutron irradiation effect is not taken into consideration. This figure shows excellent property of TZM at least when only high heat flux is applied to the wall surface.

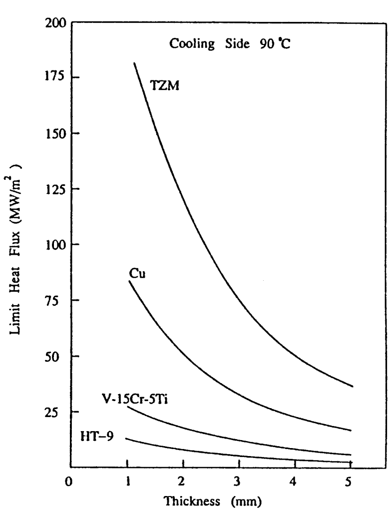


Fig.1 Admissible heat Flux vs. Thickness

TZM has a ductile brittle transition temperature(DBTT) near room temperature. Recrystallization of TZM can also cause brittleness once TZM is used over recrystallization temperature. In general, TZM can be worked between these two temperature thresholds. Recrystallization temperature ranges from 1200°C to 1400°C and DBTT ranges from room temperature to 100°C. However, these thresholds are considered to depend on the history of deformation and dimension of specimen.

TZM contains 0.5% titanium, 0.07% zirconium in molybdenum matrix. TZM used in our experiments is powder metallurgical product. Comparing with pure molybdenum, TZM has a rather high recrystallization temperature and rather large high temperature strength because dispersed particles finally prevent grain growth at higher temperature. In addition, it is estimated that the thermal properties in TZM are not very different from those in pure molybdenum.

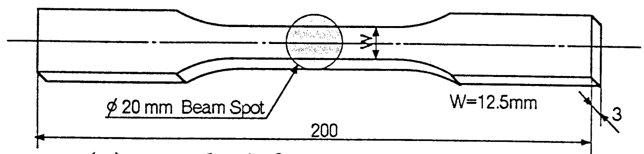
EXPERIMENT

Electron beam can provide enough heat flux to simulate plasma disruption. While electron beam is irradiated, contamination of atmospheric gases and heat conduction to the atmosphere are eliminated by vacuum maintained at pressure range of 10^{-4}mbar. Electron beam irradiation technique is well established in the fields of welding, evaporating and melting of metals, and is easy and reliable for repetition of experiments.

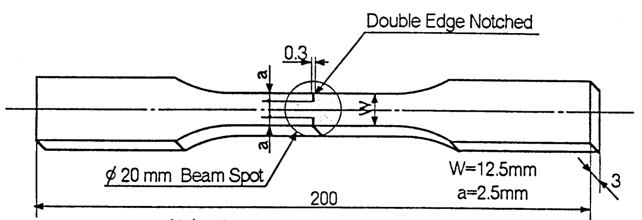
Electron beam is focused on the object so as to have a diameter of 20mm, and irradiated on the center of TZM specimen at power of 3 to 13.5kW for 5seconds. This means that the power density of electron beam was estimated to be 9.6 to $43MW/m^2$. Actual heat fluxes given to specimens were considered to be 60% of the rated power densities, because back scattering and reflected electrons still had enough energy. Efficiency of electron beam input is strongly affected by irradiation conditions and kinds of objects. When the beam is irradiated at right angles on the object, the efficiency is given as a function of $\sqrt{Z}$, where Z is atomic number of metal(Schiller 1982).

Before irradiation on the specimen, electron beam was dumped to a dummy target until emission current became stable and the specified power density was obtained. Then stabilized beam on the dummy was deflected to the specimen, by means of magnetic deflection coils. After 5seconds of irradiation, the beam was deflected back to the dummy and turned off.

TZM specimens were taken in rolling direction from commercial rolled sheet in hot rolled and annealing condition. Figure 2 shows the specimen dimensions and beam spot on the specimen. The specimen was simply supported at both ends by steel blocks, and is not compulsorily cooled during and after irradiation. After cooled down to room temperature in the vacuum chamber of electron beam irradiation system, specimens were set to servo-hydraulic machine equipped with high frequency induction heater, and all experiments were conducted under atmospheric condition. Details of mechanical tests are described in the following section.



(a) tensile & fatigue test specimen



(b) fracture test specimen

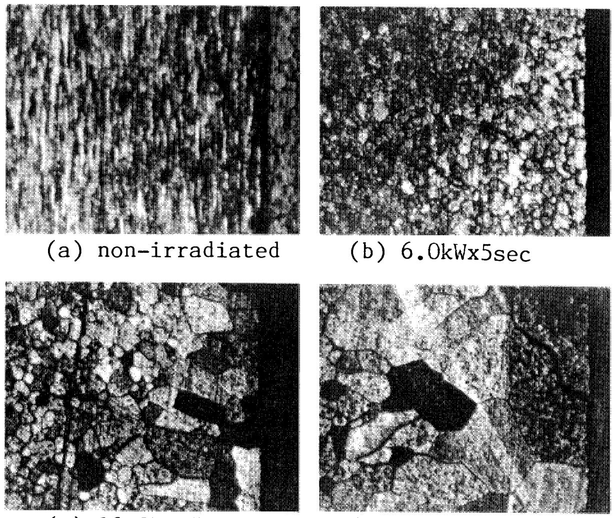
Fig.2 Test Specimen

RESULTS AND DISCUSSION

1.ELECTRON BEAM IRRADIATION EFFECTS ON TZM MICROSTRUCTURE

The microstructure of cross section located at the center of beam spots were observed by optical microscope. Figure 3 shows four representative structures. In all cases, electron beam was irradiated at right angles on specimen surface. Irradiated surface is shown in the right side of each picture.

It is clearly found that the recrystallization was already initiated at 6kW irradiation. At 10kW irradiation, melted layer was not observed by naked eye, however the grain growth appeared near by the surface and small blowholes were detected mainly on the grain boundaries. At 13.5kW irradiation, melted and resolidified layer which has about 1mm depth was formed. Large grains and blowholes were observed and some grain boundaries seemed to be separated.



(a) non-irradiated (b) 6.0kWx5sec

(c) 10.2kWx5sec (d) 13.5kWx5sec

Fig.3 Microstructure of TZM

2.TENSILE PROPERTIES

Tensile test was conducted at room temperature, 250°C and 500°C with cross head speed of 0.2mm/min. The specimen's dimension is shown in Fig.2(a). Figure 4 shows stress-strain curves at room temperature, and Fig.5 shows stress-strain curves at higher temperatures.

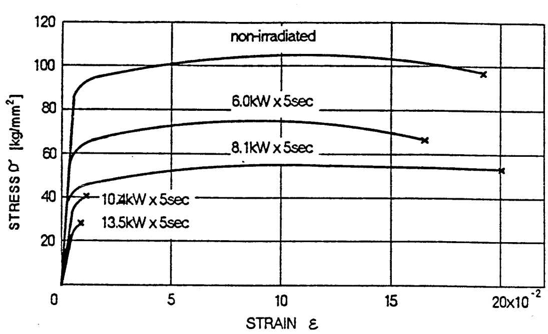


Fig.4 Stress-Strain Curve at room temperature

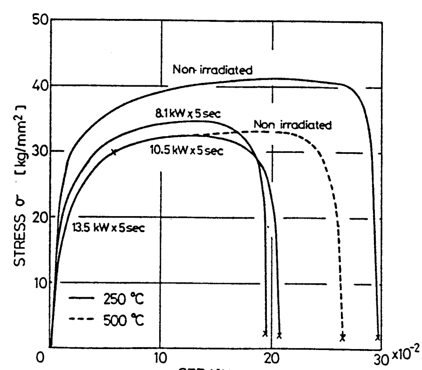


Fig.5 Stress-Strain Curve at high temperature

As shown in Fig.4, it was observed that the tensile strength decreased at room temperature with the increase of beam power. Same phenomenon was observed at higher temperature as shown in Fig.5. At room temperature, elongation is abruptly decreased at beam power of 10.2kW. It seemed that there was a threshold beam power between 8.1 and 10.2kW. Above this threshold TZM turns to quite brittle. This threshold beam power is considered to correspond with the initiation of undesirable grain growth near by the surface containing defects such as blowholes. Besides the specimens to which electron beam was irradiated at the power under 8.1kW had relatively uniform grain size even if recrystallization was initiated. At higher temperature, such brittleness was remarkably improved. The cleavage planes were observed in fracture surfaces of specimens tested at room temperature, and were not observed in fracture surface tested at higher temperature.

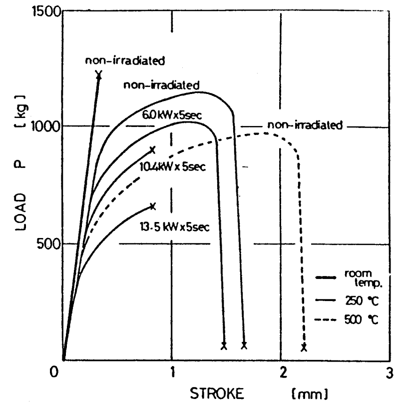


Fig.6 Load-Stroke Curve

3.FRACTURE TOUGHNESS

We used double edge notched specimen shown in Fig.2(b) for evaluating fracture toughness on TZM at room temperature and 250°C, and cross head speed was 0.2mm/min. Figure 6 shows the load-stroke curves for representative experiments. As shown in this figure, TZM specimen with cracks is quite brittle at room temperature and large scale plastic deformation was not observed. Stress intensity factor was considered to be suitable parameter to describe TZM's fracture toughness at room temperature. In this study, K_{IC} was given as following equation using dimension correction factor(Tada 1973).

$$K_{IC} = \sigma_c\sqrt{\pi a}\cdot F(2a/W) \ : \ \xi = 2a/W$$

$$F(\xi) = \frac{1.122-0.561\xi-0.15\xi^2+0.091\xi^3}{\sqrt{1-\xi}}$$

while σ_c : gross stress when the specimen was fractured

On the other hand, it might not be appropriate to apply stress intensity K to fracture toughness at higher temperature, because ductility increased. J integral value is generally used to describe the fracture behavior which is accompanied with elastic plastic deformation. J integral value can be converted into equivalent K value using following equations(Hutchnson 1977).

$$K = \sqrt{J\cdot E}$$

$$J = G + \frac{1}{bt}\left(2\int Pdu - Pu\right)$$

while E : Young's modulus
G : elastic energy release rate
b : ligament
t : specimen thickness
P : load
u : load point displacement
$\int Pdu$: area given in Fig.7

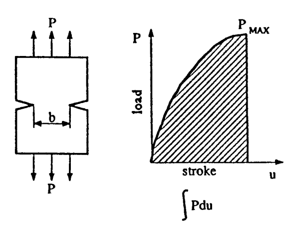


Fig.7 Schematic Illustration of J Integral

Figure 8 shows the K_{IC} vs beam power curves, while K_{IC} at 250°C is converted from J_{IC} using equations mentioned above. At higher temperature, fracture toughness was remarkably improved. However, at a beam power over 10.2kW, fracture toughness was abruptly decreased.

4.FATIGUE CHARACTERISTICS

Fatigue test was conducted at room temperature, after electron beam was irradiated at the power of 13.5kW, 10.2kW and 8.1kW The specimen's dimension is shown in Fig.2(a). Cyclic tensile stress with sin curve of 10Hz was applied to the specimens and the load ratio was 0.1. The relations between applied stress and cycles to failure are shown in Fig.9.

Fatigue limits were gradually decreased along with increase of beam power up to 8.1kW, and then abruptly reduced at the power over 8.1kW. As it is clearly observed in Fig.10, fracture surface in 13.5kW irradiated specimen contain blowholes in its melted and resolidified layer. As shown in Fig.3, some grain boundaries seemed to be separated. These defects were considered to cause fatigue crack initiation and reduction in fatigue limits. It seems that stress concentration due to these defects promotes the fatigue crack growth up to certain length. Finally brittle fracture took place at fatigue crack tip, and the crack was propagated continuously along with cleavage of grains.

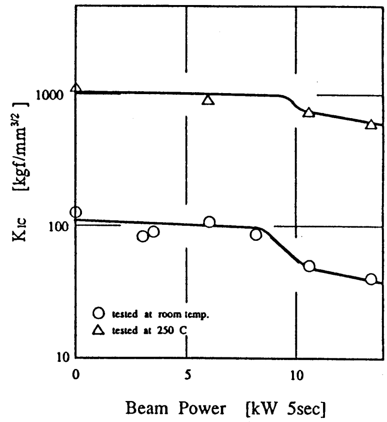


Fig.8 K_{IC} vs. Beam Power

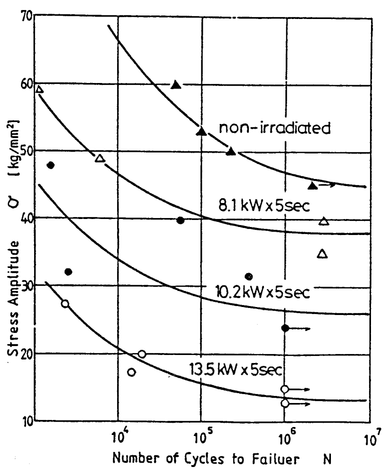


Fig.9 Stress Amplitude vs. Number of Cycles to Failure

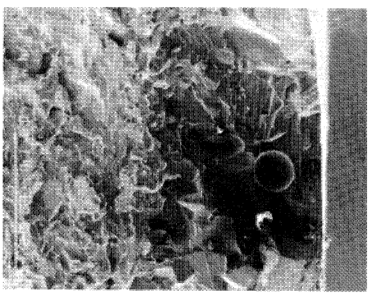


Fig.10 Fracture surface(13.5kWx5sec)

5.ELECTRON BEAM IRRADIATION EFFECTS ON CHEMICAL COMPOSITION

Figure 11 shows the titanium contents along with cross sections measured by means of EPMA while the abscissa means the direction of thickness from irradiated surface. In the melted layer of 13.5kW irradiated specimen, titanium contents were decreased from 0.5% to 0.2-0.3%. There were almost no changes of zirconium contents even in the melted layer. This slight loss in titanium near irradiated surface may contribute to the degradation of mechanical characteristics although detail investigation is necessary in relation with this point.

At the melted point of molybdenum which is 2620°C, titanium has vapor pressure of about 10-10^2mbar(Kubashewski 1979), which is 10^3 times larger than molybdenum.

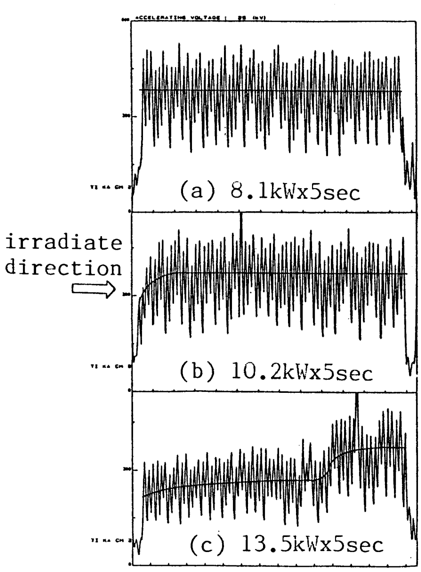


Fig.11 Titanium contents of TZM

CONCLUSIONS

1. Tensile strength and elongation of TZM are gradually decreased along with the increase of beam power up to 8.1kW, but remarkable degradation was not recognized as long as TZM has uniform grains. Although recrystallization was already initiated at beam power of 6kW, grain size was formed uniformly up to 8.1kW.
2. Once melted and recrystallized layer was formed on TZM's surface, mechanical properties at room temperature became degraded abruptly. This phenomenon was commonly observed on tensile, fatigue and fracture toughness tests. From microscopic observation, it was clear that the melted and recrystallized layer contained blowholes, and some grain boundaries seemed to be separated. Fatigue crack might be initiated from these defects and propagated continuously along with cleavage surface of grains.
3. Fracture toughness at 250^o was extremely improved comparing with fracture toughness at room temperature. Actual environmental temperature in fusion reactor must be higher than DBTT, and this means that TZM's brittleness at lower temperature does not give rise to a problem.
4. Electron beam irradiation in this study was conducted at rather severe conditions, comparing with plasma disruption which is estimated to yield 200MW/m^2 irradiation for 20msec(JAERI 1983). 200MW/m^{2}x20msec irradiation corresponds with 0.8MW/m^{2}x5sec irradiation in energy amount, which is equivalent to 2.5kWx5sec irradiation with 20mm diameter beam spot. This irradiation cannot form melted layer on the surface.
5. Since TZM shows excellent characteristics at high temperature, it can be regarded as useful material for the first wall from the view point of structural design.

REFERENCES

Hutchnson,J.W., Paris,P.C.,(1977) Stability Analysis of J-Controlled Crack Growth Elastic-Plastic Fracture, ASTM STP 668

JAERI, (1983), First Wall Erosion during a Plasma Disruption in Tokamak JAERI-M 83-058

Kubashewski,O., Alcock,C.B.,(1979) Metallurgical Thermochemistry(5th Edition)

Miya,K., Seki,M., Araki,M.,(1987) Present Status of High Heat Flux Experiments in Relation to Fusion Reactors Journal of the Atomic Energy Society of Japan, No.10(1987)

Saito,M., Teramoto,T.,(1987) Design Comparison among Plasma Wall Candidate Materials with use of ASME code 1987 Fall Meeting of the Atomic Energy Society of Japan

Schiller,S., Heisig,U., Panzer,S.,(1982) ELECTRON BEAM TECHNOLOGY

Tada,H., Paris,P.C., Irwin,G.R.,(1973) The Stress Analysis of Cracks Handbook, Del Research Corporation