Rare Metal Materials and Engineering
Volume 48, Issue 8, August 2019
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Rare Metal Materials and Engineering, 2019, 48(8): 2413-2417.

ARTICLE

Analysis of Heat Absorption Ratio of TZM

Zi Pengfei[1,2], **Li Lei**[1], **Cao Lei**[1], **Yao Damao**[1]

[1] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China; [2] University of Science and Technology of China, Hefei 230026, China

Abstract: Titanium-Zirconium-Molybdenum (TZM) alloy as the plasma facing material (PFM) will continues to be used in large quantities in the experimental advanced superconducting Tokamak (EAST) device. In this paper, the heat absorption ratio of TZM in rolled and forged state was tested by the e-beam device of Shenzhen University. The results show that the heat absorption ratio of TZM in both rolled and forged state is about 0.7, and it is not affected by the change of cooling effect and high temperature of the material. This work will be very helpful in judging the safety of TZM, which is important for long-term development of EAST.

Key words: heat absorption ratio; TZM; PFM; EAST

Experimental advanced superconducting Tokamak (EAST) is a fully superconducting Tokamak with the experimental missions from 2006[1]. During the mid-campaign of 2016, EAST obtains H-mode plasma more than 60 s [2]. Furthermore, an achievement of 101.2 s plasma discharge with long-pulse H-mode was completed in 2017[3]. However, the heat flux rises on the surfaces of the in-vessel components along with the enhancement of the experimental parameters. Therefore, it is very important to study the heat absorption characteristics of plasma facing materials (PFM) for researching the surface temperature of materials. There are many options for EAST's PFM, such as tungsten, TZM and graphite, which are currently being used[4]. In the current research, the graphite will be replaced by TZM or other materials in the latest in-vessel component upgrade activities as graphite has problems of brittleness and pollution. TZM is more advantageous than tungsten in the low heat load area due to its easy processing and lower price. The proportion of TZM in EAST plasma facing components (PFC) is higher than 50% at present (Fig.1). A lot of work about characteristics of tungsten in EAST has been done, which provides a great deal of help for the latest or further test [5]. During the thermal analysis of the PFCs, the heat absorption ratio is an important parameter that directly affects the availability of the design structure. So it is very necessary to study the characteristics of TZM. This paper mainly introduces the heat absorption ratio of TZM in rolled and forged state, which was tested by an e-beam device of Shenzhen University. The test results can provide an important reference for PFC material selection in EAST. All selection of internal parts material and test parameters for EAST will provide an important reference for future construction of CFETR[6].

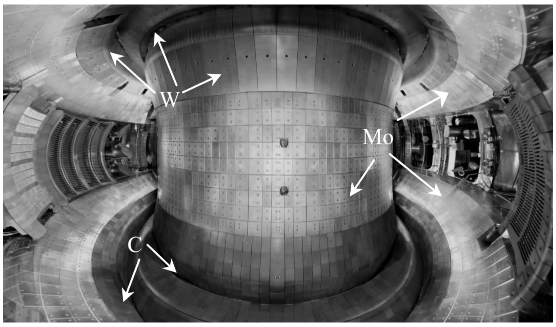

Fig.1 Material distribution of EAST PFCs

1 Experiment

1.1 Experimental principle

Received date: August 13, 2018
Foundation item: National Key Research and Development Program of China (2017YFE0300400, 2017YFA0402500); Science Foundation of Institute of Plasma Physics, Chinese Academy of Sciences (Y45ETY2302)

Corresponding author: Li Lei, Ph. D., Assistant Professor, Fusion Reactor Integration Design Division, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, P. R. China, Tel: 0086-551-65594276, E-mail: lilei@ipp.ac.cn

The heat absorption ratio refers to the ratio of the energy absorbed by the object to the total incident energy when heat ray is projected onto the object. The object that absorbs all flux is black body and its absorption ratio is 1. The actual object absorption ratio is less than 1[7].

It is well known that the fraction of the incident electron beam energy is reflected by PFM surface due to backscattered electrons. This fraction may reach values up to 50% for high *Z* materials such as tungsten[8]. Since the thermal load of the EAST PFCs is mainly derived from electron bombardment, this test simulates the actual EAST environment by high-speed electron beam scanning as the heating method[9].

In this test, the heat absorption ratio of TZM was calculated by theoretical calculation using the difference in inlet and outlet water temperature of the heat sink under TZM[10]. Fig.2 shows the experimental schematic diagram, and 1~5 are the temperature measurement point (TMP) at different positions. In order to establish the worst thermal condition for EAST heat sinks, the cooling pipe was not placed asymmetrically with regard to the heated area. It would not affect the absorption ratio of the test results because the absorbed heat would be taken away by water at steady state, no matter where the water pipes were located.

The exact size and location of the actual heating area can be determined and measured after the test (Fig.3), and the heat flux density can be calculated.

It can be obtained from the formula according to the energy conservation law:

$$Q_{\mathrm{L}} = Q_{\mathrm{A}} + Q_{\mathrm{R}} \tag{1}$$

where Q_{L} is the total loaded power, Q_{A} is the total absorbed power, and Q_{R} is the total reflected power.

$$q = Q_{\mathrm{A}} / Q_{\mathrm{L}} = UI / (Q_1 + Q_2 + Q_3 + Q_4) \tag{2}$$

where q is the heart absorption ratio, U is the voltage of e-beam, I is the electric current of e-beam, Q_1 is the heat dissipation in the coolant, Q_2 is the heat loss of heat radiation, Q_3 is the heat loss of heat conduction, and Q_4 is the heat required to achieve steady state.

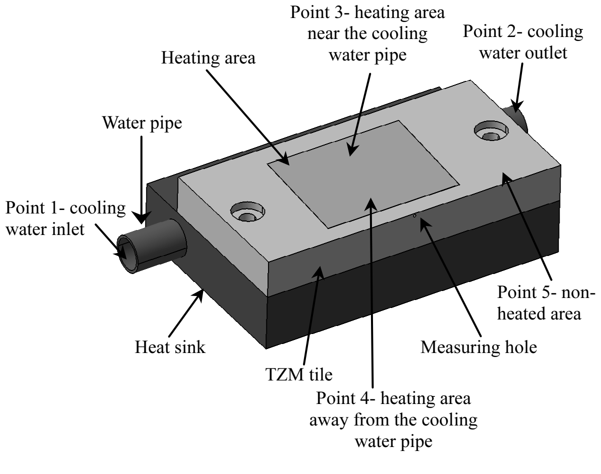

Fig.2 Experimental schematic diagram of heat sink

Fig.3 Surface of TZM after heating test

Since the purpose is to obtain the value in steady state, Q_4=0.

This test used the G10 board as a heat insulation material to reduce the heat loss of heat conduction, so Q_3 can be ignored because the thermal conductivity of G10 material is less than 0.5 W/m·K.

The test was carried out in a vacuum chamber with the vacuum level of 1×10^{-3} Pa , according to the formula:

$$Q_2 = \varepsilon AC(T_2^4 - T_1^4) < \varepsilon A_1 C(T_{21}^4 - T_1^4) + \varepsilon A_2 C(T_{22}^4 - T_1^4) \tag{3}$$

where ε is TZM (R_a=1.6) emissivity [11], and it can be determined as follows:

$$\varepsilon = \begin{cases} 0.08 \sim 0.13 \ (0\text{~}1000\ ^\circ\mathrm{C}) \\ 0.13 \sim 0.19 \ (1000\text{~}1500\ ^\circ\mathrm{C}) \\ 0.16 \sim 0.26 \ (1500\text{~}2000\ ^\circ\mathrm{C}) \end{cases}$$

Stefan-Boltzmann constant $C = 5.67\times10^{-8}\,\mathrm{W/m^2\cdot K^4}$; A_1 and A_2 is the area of the heated area and non-heated area, respectively; T_{21} is the maximum temperature of the heated area, T_{21}=1000 °C; T_{22} is the maximum temperature of the non-heated area, T_{22}=450 °C; T_1 is the ambient temperature in the vacuum chamber, T_1=50 °C.

In order to simplify the calculation of radiation energy, only two temperatures of –1000 and 450 °C were used, providing an upper bound for the actual value, and the result would be much larger than the actual value. Even so, the calculated heat loss amounted to less than 1% of the loaded power. And it can be completely ignored without affecting the result. So, Q_2 is ignored.

In fact,

$$q \approx \frac{Q_1}{Q_L} = \frac{Cm\Delta T}{UI} = \frac{C\rho vA(T_2 - T_1)}{UI} \tag{4}$$

where, C is the specific heat capacity of water, ρ is the density of water, v is the flow rate of water, A is the cross-sectional area of the cooling pipe in the heat sink, T_2 is the outlet temperature of the water, and T_1 is the inlet temperature of the water.

1.2 Experimental platform

The e-beam device from Shenzhen University was used for the test. The TZM specimen was fixed in the same way as the EAST internal connection. TZM and heat sinks were bolted together with the graphite paper in the interlayer, ensuring a good contact, which is widely used in EAST device. The heat sink was fixedly connected to the bottom plate, and a heat shield made of G10 material was placed in the middle. A number of thermocouples were fixed on the bottom plate to measure the temperature of each TMP of the TZM. A temperature collector for testing the temperature inside the vacuum chamber was also installed. Finally, the bottom plate was fixed on the test platform, which can be moved by 2 degrees of freedom to adjust the location of the heating area.

1.3 Experimental procedure

1) Get the temperature of heated and non-heated area of TZM and the inlet and outlet water temperatures through temperature collector (the K-type thermocouple is used in this test).

2) Heat TZM specimen with electron beam, and record the temperature data when the temperature of each temperature collection point reaches steady state.

3) Slightly increase or decrease the power of the electron beam in order to change the heating flux density of TZM. Record the temperature of each point again.

4) Repeat above processes until the surface temperature of TZM reaches 1000 °C, for protecting the test equipment and considering the thermocouple capacity limitation.

5) Change the speed of the water in the cooling water pipe (flow rate is set to 3, 3.5, 4 and 4.5 m/s) and repeat above procedure. Then, calculate the heat absorption ratio according to Eq.(4).

This experiment involved two kinds of processes, one of which is recording the data at six steady-state points in the process of increasing the heat flux density (process Ⅰ); the other is recording the data at the same steady-state points in the process of decreasing the heat flux density (process Ⅱ). The purpose is to decide whether the material will have some change affecting the results due to high temperature, such as hysteresis effect. Fig.4 shows the incident heat flux density for each experiment, which can describe the process more clearly.

2 Result and Discussion

2.1 Effect of manufacturing process and cooling flow rate on the heat absorption ratio

The heat absorption ratios of TZM in forged and rolled state at four different flow rates are shown in Fig.5, which are all obtained in the process of increasing the heat flux density. It can be seen that more than 90% of the heat absorption ratio is about 0.7, which varies between ±0.03, and has no big fluctuation when the cooling water flow rate and heating flux density change. There is also no significant difference between the rolled and forged states.

2.2 Effect of increasing and decreasing the heat flux density on the heat absorption ratio

Fig.6 shows the reproducibility test data obtained during decreasing heat flux density process in each case. It can be seen that about 90% of the data is also about 0.7 and it varies between ±0.03. There is no significant difference between the results obtained with the increase of heat flux density. Thus, increase and decrease of the heat flux density have few effects on the heat absorption ratio of TZM.

2.3 Data comparison of temperature collection points in repeated experiments

In this experiment, multiple sets of data at different

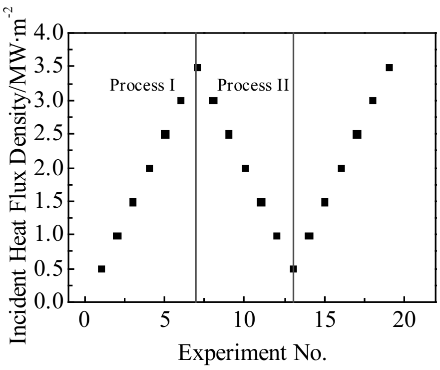

Fig.4 Incident heat flux density in the experiment

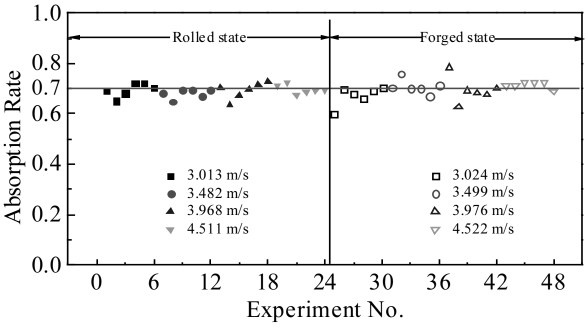

Fig.5 Heat absorption ratio of TZM at different flow rates during increasing the heat flux density

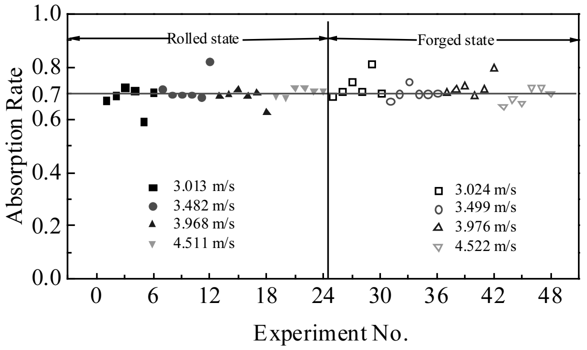

Fig.6 Heat absorption ratio of TZM at different flow rates during decreasing the heat flux density

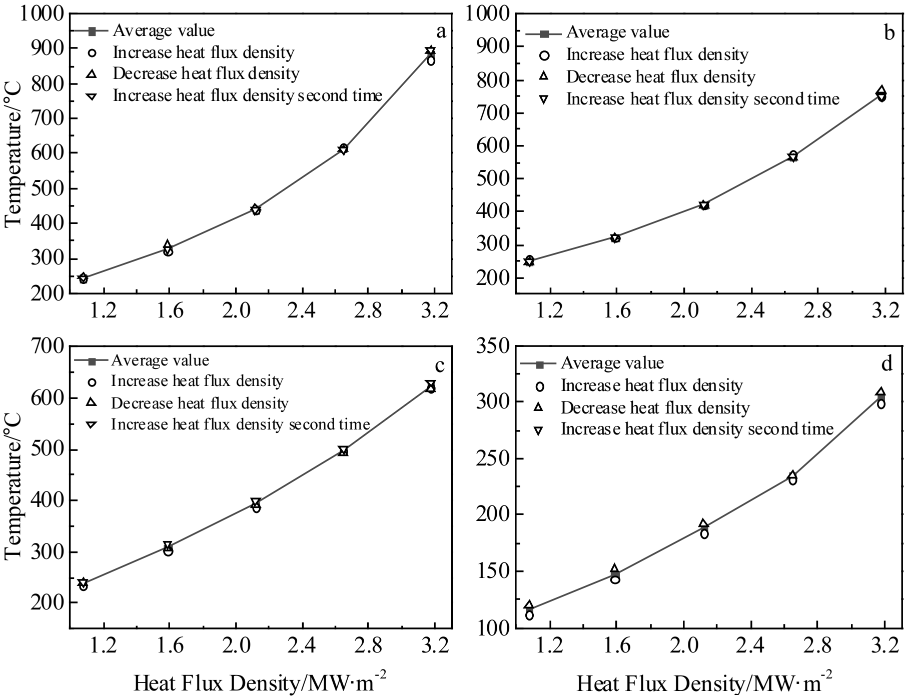

Fig.7 Data of TMPs at different flow rates: (a) point 3, 3.0 m/s; (b) point 4, 3.5 m/s; (c) point 4, 4.0 m/s; (d) point 5, 4.5 m/s

temperature collection points in the process of increasing and decreasing the heat flux density were also compared, as shown in Fig.7. The test data are very close at different heat flux densities and different flow rates, and the maximum error does not exceed 3%. So, the accuracy of this experimental result can be guaranteed.

3 Conclusions

1) The heat absorption ratio of TZM heated by e-beam is nearly about 0.7.

2) There is also no significant difference in the heat absorption ratios of the TZM specimens between the rolled and forged states.

3) The value of the heat absorption ratio does not change with the flow rate, so it can be concluded that the cooling condition has few effects on the heat absorption ratio value and can be neglected.

4) High temperatures (≤1000 °C) may do not affect the heat absorption ratio of the TZM specimens.

References

1 Tobita K, Nishio S, Sato M *et al. Nuclear Fusion*[J], 2007, 47(8): 892

2 Tillack M S, Raffraya A R, Wang X R *et al. Fusion Engineering and Design*[J], 2011, 86(1): 71

3 Eich T, Leonard A W, Pitts R A *et al. Nuclear Fusion*[J], 2013, 53(9): 93 031

4 Zhou Z B, Yao D M, Cao L *et al. IEEE 25th Symposium on Fusion Engineering*[C]. Washington: IEEE Computer Society, 2013

5 Zhou Z B, Yao D M, Cao L *et al. IEEE Transactions on Plasma Science*[J], 2014, 42(3): 580

6 Zhou Z B, Yao D M, Cao L *et al. Journal of Fusion Energy*[J], 2015, 34(1): 93

7 Shih T M. *Numerical Heat Transfer*[M]. New York: Hemisphere Publishing Corporation, 1984

8 Li Q, Qin S G, Wang W J *et al. Fusion Engineering and Design* [J], 2013, 88(9-10): 1808

9 Chen Y P. *Nuclear Fusion*[J], 2002, 42(3): 227

10 Li L, Yao D M, Liu C L *et al. Plasma Science and Technology*[J], 2015, 17(5): 435

11 Bramson M A. *Infrared Radiation*[M]. New York: Plenum Press, 1968

TZM 材料的热吸收率分析

訾鹏飞 [1,2]，李　磊 [1]，曹　磊 [1]，姚达毛 [1]

(1. 中国科学院 等离子体物理研究所，安徽 合肥 230031)

(2. 中国科学技术大学，安徽 合肥 230026)

摘　要：钛锆钼合金（TZM）作为面对等离子体材料（PFM）将会继续在实验型先进超导托卡马克（EAST）中大量使用。利用深圳大学的电子枪设备分别对轧制态及锻造态的 TZM 进行了热吸收率的测试并对相关结果进行了分析。结果显示，轧制态及锻造态的 TZM 的热吸收率均在 0.7 左右，并且这个数值不会受到冷却效果及材料温度的影响而产生变化。这一结果将对判断 TZM 在使用中的安全性有巨大帮助，同时对 EAST 的远期升级及 CFETR 的建设都具有重要的参考价值。

关键词：热吸收率；钛锆钼合金；面对等离子体材料；EAST

作者简介：訾鹏飞，男，1987 年生，博士，中国科学院等离子体物理研究所聚变堆总体研究室，安徽 合肥 230031，电话：0551-65594276，E-mail: zipengfei@ipp.ac.cn