IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta

Phys. Scr. **T170** (2017) 014020 (10pp) https://doi.org/10.1088/1402-4896/aa8921

Development and application of W/Cu flat-type plasma facing components at ASIPP

Q Li[1], S X Zhao[2], Z X Sun[1], Y Xu[1], B Li[1], R Wei[1], W J Wang[1], S G Qin[3], Y L Shi[3], C Y Xie[1], J C Wang[1], X L Wang[1], M Missirlian[4], D Guilhem[4], G H Liu[3], Z S Yang[1] and G-N Luo[1]

[1] Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), Hefei, People's Republic of China
[2] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, People's Republic of China
[3] Advanced Technology & Materials Co. Ltd (AT&M), Beijing, People's Republic of China
[4] French Atomic Energy Commission (CEA), Saint-Paul-lez-Durance, France

E-mail: gnluo@ipp.ac.cn

Received 23 May 2017, revised 17 August 2017
Accepted for publication 30 August 2017
Published 19 September 2017

Abstract

W/Cu flat-type plasma facing components (PFCs) were widely used in divertor of fusion device because of its advantages, such as low cost, light in weight and good machinability. However, it is very difficult to manufacture them due to the large mismatch between the thermo-mechanical properties of W and Cu. Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) has successfully developed W/Cu flat-type PFCs for EAST W/Cu divertor project by hot isostatic pressing (HIP) technology. This paper presents the development and application of W/Cu flat-type PFCs at ASIPP. The optimized manufacturing process is to cast pure copper onto the rear side of W tiles at temperature of 1200 °C firstly, and then to HIP the W/Cu tiles onto CuCrZr heat sink at temperature of 600 °C, pressure of 150 MPa and duration of 3 h. W/Cu flat-type testing mock-up for EAST survived 1000 cycles at heat load of 5 MW m^{-2} in high heat flux tests. And then ASIPP prepared two mock-ups for CEA's tungsten environment in steady-state tokamak (WEST) project. One mock-up withstood successfully 302 cycles of 20 MW m^{-2}, which are far beyond the design requirement. Since 2014, W/Cu flat-type PFCs were wildly used in EAST upper divertor as baffle and dome components which showed excellent performance in 2015 and 2016 campaigns. Given the success in EAST upper divertor, W/Cu flat-type concept is as well applied in the design of actively cooled Langmuir probes which will be mounted onto EAST divertor targets soon.

Keywords: plasma-facing components, flat-type, divertor, tungsten, EAST

(Some figures may appear in colour only in the online journal)

1. Introduction

In comparison with monoblock conception, W/Cu flat-type plasma facing components (PFCs) have some advantages, such as low cost, light in weight and good machinability. Meanwhile, they have some disadvantages, like stress singularity in the corner, risk of delamination of W tiles and higher constraints induced by electromagnetic loads due to more copper materials. In view of these, W/Cu flat-type PFCs were widely used in the baffle and dome regions because of the relatively low heat fluxes. However, it is very difficult to manufacture them due to the large mismatch between the thermo-mechanical properties of W and Cu. Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) has developed W/Cu flat-type PFCs for EAST W/Cu divertor project by hot isostatic pressing (HIP) technology since 2012 [1–4]. The optimized manufacturing process is to cast pure copper onto the rear side of W tiles at temperature of 1200 °C firstly, and then to HIP the W/Cu tiles onto CuCrZr heat sink plate at temperature of 600 °C, pressure of 150 MPa and duration of 3 h. Small-scale testing mockups for EAST survived 1000 cycles of heat loads of 5 MW m^{-2} in high heat flux (HHF) tests via an e-beam facility. Two W/Cu flat-type test mockups prepared for CEA's tungsten environment in

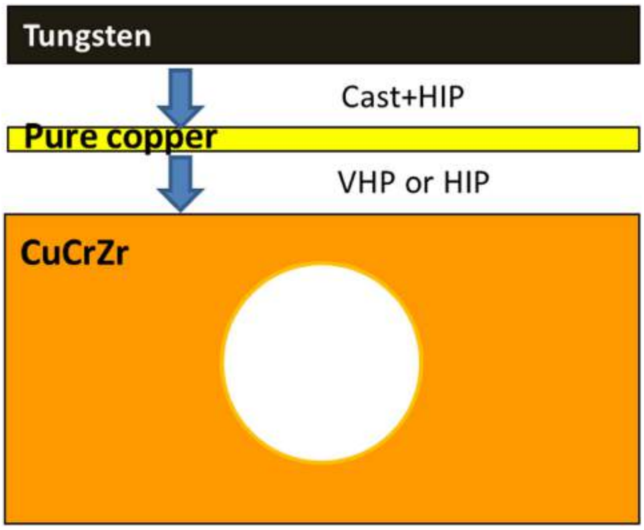

Figure 1. Sandwich structure of W/Cu flat-type PFCs consists of tungsten armor, pure copper interlayer and CuCrZr heat sink.

steady-state tokamak (WEST) project showed outstanding performance in HHF tests carried out on JUDITH-1. One mockup withstood successfully 102 cycles of 10 MW m^{-2}, 102 cycles of 15 MW m^{-2} and 302 cycles of 20 MW m^{-2} in succession, which are far beyond the design requirements. In the spring of 2014, W/Cu flat-type PFCs were produced in batch and installed onto EAST upper divertor as baffle and dome components [1, 2]. After resolving the leaking issues appeared in the commissioning of 2014 campaign, W/Cu flat-type PFCs showed excellent performance in 2015 and 2016 campaigns. Given the success in EAST upper divertor, W/Cu flat-type concept is as well applied in the design of actively cooled Langmuir probes which will be mounted onto EAST divertor targets.

In this paper, development and application of W/Cu flat-type PFCs will be described in detail in the following five sections. Firstly, development of W/Cu flat-type PFCs will be introduced in section 2. And then, HHF test will be presented in section 3. Sections 4 and 5 show their applications in EAST upper divertor and the design of actively cooled Langmuir probes, respectively. Finally, section 6 draws a conclusion.

2. Development of W/Cu flat-type PFCs

The main characteristic of W/Cu flat-type PFCs is their sandwich structure, which consists of tungsten armor, pure copper interlayer and CuCrZr heat sink, as shown in figure 1. For EAST upper divertor, tungsten armor tiles with thickness of 2 mm were cut from rolled tungsten plates (12 mm in thickness) with an overall reduction of 70%. The rolling direction of the tungsten was selected to be perpendicular to the plasma facing surface in order to avoid the formation of parallel cracks which would affect heat transfer from tungsten to CuCrZr heat sinks. Since the rolling direction is perpendicular to the plasma facing surface, the width of tungsten tiles are 12 mm in maximum, which is limited by the thickness of rolled tungsten plates. The thickness of pure copper is 1 mm, which can relieve the thermal stresses during manufacturing and HHF testing. With its high thermal conductivity and excellent mechanical performance, CuCrZr alloy was selected as heat sink material. Both tungsten and CuCrZr plates were supplied by Advanced Technology & Materials Co. Ltd (AT&M). Given their sandwich structure, the manufacturing process of W/Cu flat-type PFCs was divided into two steps, i.e. the bonding of W/Cu and Cu/CuCrZr interfaces, which will be prescribed in detail in following subsections.

2.1. Bonding of W/Cu interface

Due to the good wettability of molten copper on tungsten, a high quality bonding between tungsten and copper can be obtained by casting process. The wetting contact angle of molten copper on tungsten decreases with the increasing of the casting temperature which is above melting point of copper. Its value decreases to zero at temperature more than 1350 °C, which means that the tungsten is fully wetted by molten copper [5]. However, recrystallization starts for most of the W grades at temperature higher than 1200 °C. For this reason the maximum casting temperature is limited to ~1200 °C. To manufacture W/Cu tiles for EAST upper divertor, casting was performed at temperature of 1200 °C in a graphite crucible within a high vacuum furnace because of poor compatibility between copper and carbon that is good for demoulding. Figure 2 shows the SEM images of W/Cu interface bonded by casting at temperature of 1200 °C and 1300 °C. It can be seen that the bonding of W/Cu interface is excellent for casting at temperature of 1200 °C and tungsten is recrystallized and cracked if the casting temperature rises to 1300 °C. After casting, some pores always appear in re-solidified copper. Therefore, a HIP process at temperature of 930 °C was carried out to close the pores. Figure 3 is a picture of W/Cu tiles manufactured by this method for EAST upper divertor, which have a dimension of 45 mm (length) × 12 mm (width) × 3 mm (thickness).

2.2. Bonding of Cu/CuCrZr interface

There are many bonding techniques that can be used to join the Cu/CuCrZr interface, such as brazing, electron beam welding (EBW), vacuum hot pressing (VHP) and HIP [6–8]. Both VHP and HIP process have been studied to bond Cu/CuCrZr interface at ASIPP. W/Cu flat-type mock-ups have been successfully manufactured by VHP process at temperature of 600 °C, pressure of 20 MPa and duration of 2 h. However, it is difficult to fabricate large dimension and curved components with VHP process. Thus, HIP process was chosen to manufacture W/Cu flat-type PFCs for EAST upper divertor. High temperature and high pressure are two indispensable elements for diffusion bonding of HIP process. However, the HIP temperature is limited by the properties of CuCrZr heat sink after annealing which would be degraded seriously. It can be found from figure 4 that the tensile and yield strength start to decrease at the annealing temperature of

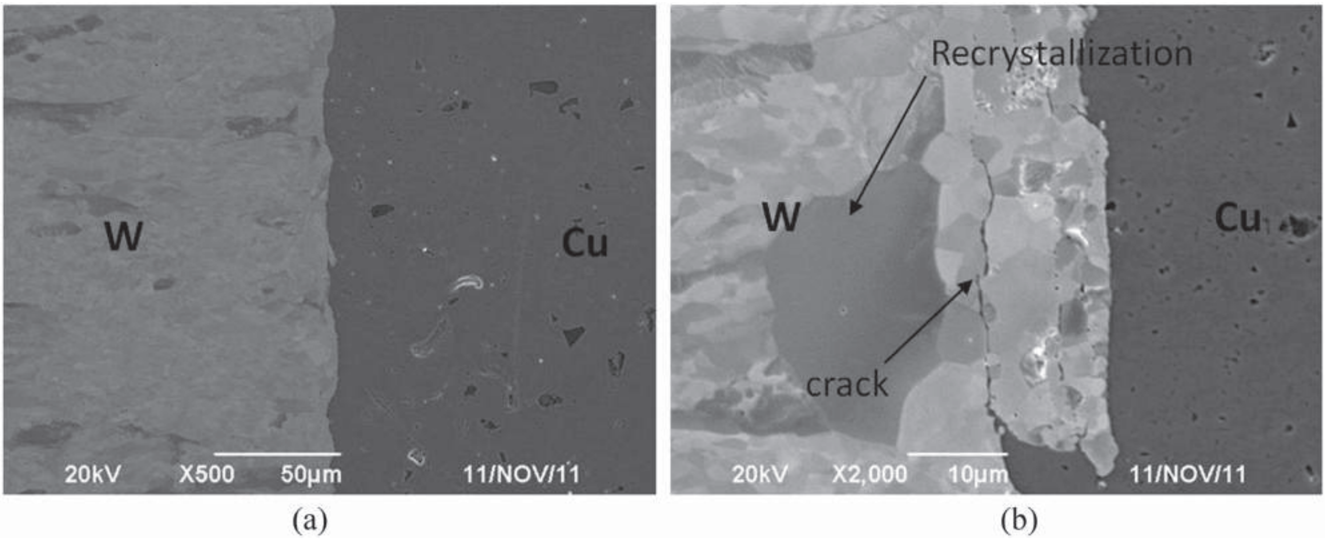

Figure 2. SEM images of W/Cu interface bonded by casting at temperature of (a) 1200 °C and (b) 1300 °C. Tungsten is recrystallized and cracked if the casting temperature rises to 1300 °C.

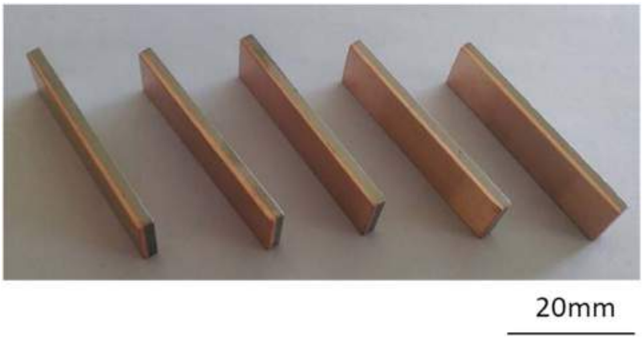

Figure 3. A picture of W/Cu tiles manufactured for EAST upper divertor.

500 °C with holding time of 2 h and their values at the temperature above 650 °C can hardly meet the required values after manufacturing which are 280 MPa and 175 MPa, respectively, corresponding to ITER's requirement. Therefore, the HIP temperature is set as 600 °C.

In order to optimize the manufacturing process, four HIP experiments were designed in the initial R&D stage to investigate bonding quality of Cu/CuCrZr interface, as shown in table 1. To improve the diffusion and prevent oxidization, a layer of Ni coating with thickness of $\sim$6 μm was electroplated on the surface of CuCrZr heat sink for experiment 3# and 4#. The conventional tungsten inert gas (TIG) welding was applied to seal the HIP capsules for experiment 1#, 2# and 3#. Figure 5 shows SEM images of W/Cu/CuCrZr interfaces for experiment 1#, 2# and 3#. Cu/CuCrZr interface for experiment 1# can be seen clearly, nevertheless, it is very blur for experiment 2# and 3#. This means that the quality of Cu/CuCrZr interface for experiment 2# and 3# is better than that for experiment 1#. However, some microcracks at the Cu/Ni interface for experiment 3# can be found in the backscattered electron (BSE) image with a higher magnification time, as shown in figure 6(a). A possible reason for the weak bonding in experiment 1#, 2# and 3# is that the copper surface of the W/Cu tiles suffered from oxidation during TIG welding. It was testified by the fact that the copper surface of all the W/Cu tiles was coated with a copper oxide layer judged from the color after unpacking a TIG welded capsule [9].

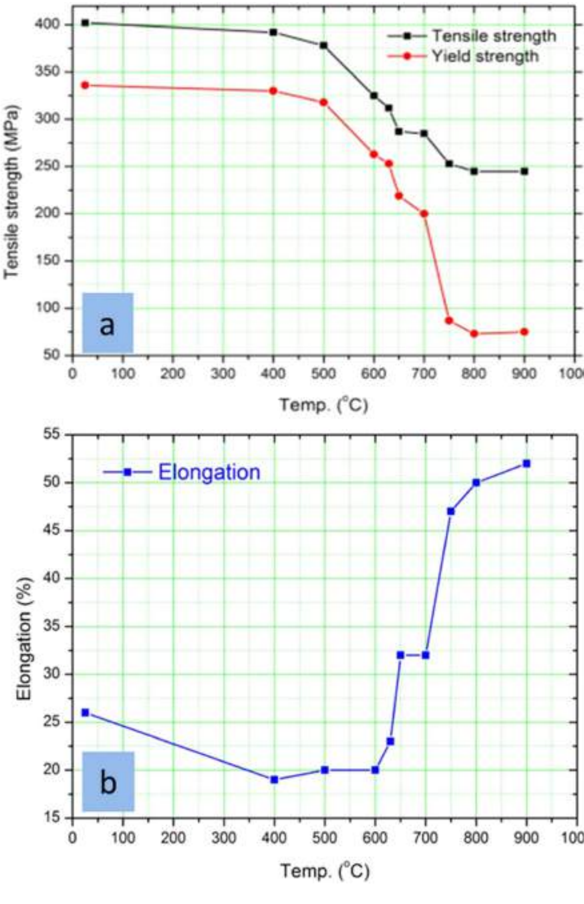

Figure 4. (a) Tensile and yield strength and (b) elongation of CuCrZr heat sink as a function of annealing temperature.

Table 1. Four HIP experiments designed to optimize the manufacturing process.

HIP experiment	Temperature (°C)	Pressure (MPa)	Duration (h)	Ni coating on CuCrZr	Encapsulation method
1#	600	100	2	No	TIG
2#	600	120	3	No	TIG
3#	600	150	3	Yes	TIG
4#	600	150	3	Yes	OFE

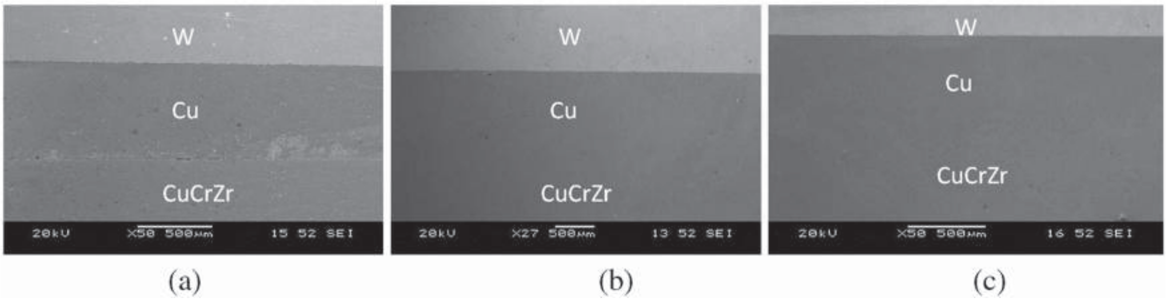

Figure 5. SEM images of W/Cu/CuCrZr interfaces for experiment (a) 1#, (b) 2# and (c) 3#.

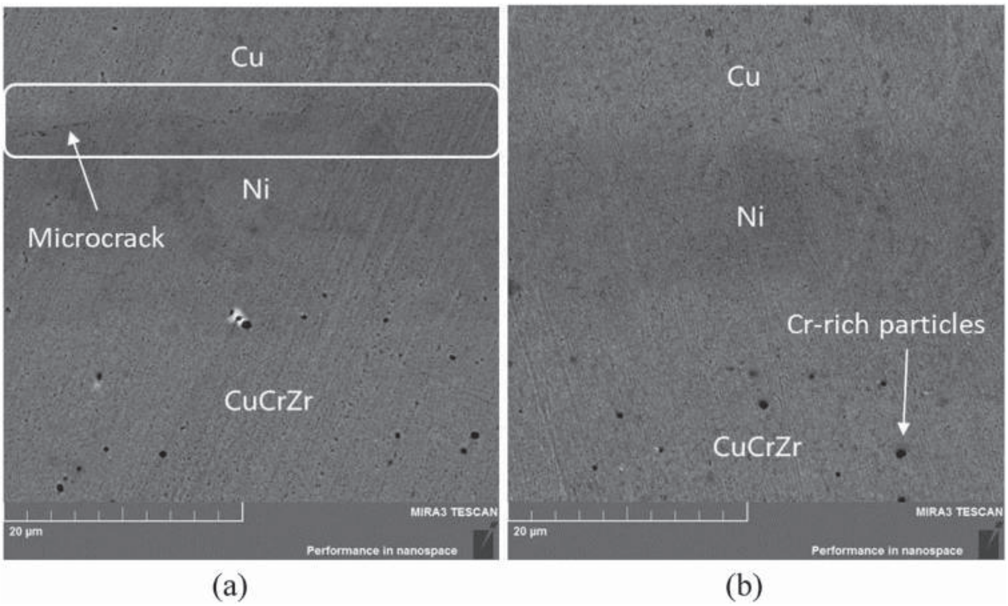

Figure 6. BSE image of OFC/Ni/CuCrZr interfaces for experiment (a) 3# and (b) 4#. No micro-crack was found at Cu/Ni interface for experiment 4# employing encapsulation method of OFE.

In order to resolve the oxidation issue, a new method of oxidation-free encapsulation (OFE) technique was developed. The key to this technique is to seal the HIP capsule in a high vacuum environment or deoxidize it after sealing. This new method of OFE was used in experiment 4#, which HIP parameters are the same as experiment 3# except for encapsulation method. Figure 6(b) shows BSE image of Cu/Ni/CuCrZr interfaces for experiment 4#. No micro-crack was found at Cu/Ni interface. So, it can be speculated that the copper oxide at Cu/Ni or Cu/Cu interface might played a role as diffusion barrier to suppress the mutual diffusion between Ni (or Cu) and Cu elements during HIP process due to its high thermal stability. Therefore, the optimal HIP parameters to bond Cu/CuCrZr interface are temperature of 600 °C, pressure of 150 MPa, duration of 3 h and employing encapsulation method of OFE.

3. HHF tests

To qualify W/Cu flat-type PFCs, the assessment of their behavior under cycling heat loads is essential. The HHF tests for a series of W/Cu flat-type test mock-ups were carried out by means of electron beam facilities in the R&D stage. Initially, VHP mock-up was tested by electron beam facility of EMS-60 at Southwest Institute of Physics, Chengdu [10]. Tungsten tiles of VHP mock-up are 5 mm thick and their rolling directions are parallel to the plasma facing surface.

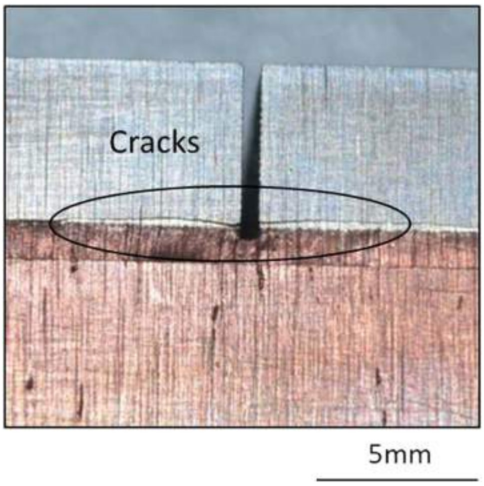

Figure 7. Parallel macro-cracks appear in the corner of tungsten tiles of VHP mock-up, which affect severely the heat transfer from tungsten to CuCrZr heat sink and cause temperature rise of the VHP mock-up.

The cooling water conditions are inlet velocity of 4 m s^{-1}, inlet temperature of 20 °C and inlet pressure of 0.4 MPa, which are identical with that for EAST upper divertor. After 300 cycles of heat load of 5.4 MW m^{-2}, the surface temperature rose drastically and some parallel macro-cracks appeared in the corner of tungsten tiles, as shown in figure 7. The results testify that it is beneficial for improving the HHF testing performance of PFCs if the rolling direction is perpendicular to the plasma facing surface. Therefore, in the following R&D and mass production of W/Cu flat-type PFCs for EAST upper divertor, the rolling direction of tungsten tiles is set to be perpendicular to the plasma facing surface.

HHF tests of HIP-TIG mock-up, which was manufactured by experiment 3#, were also performed by means of EMS-60. It should be noted that the capsule for experiment 3# was sealed by TIG welding. The dimension of HIP-TIG mock-up is 60 mm (length) × 30 mm (width) ×26 mm (height). The thickness between the top of cooling channel and the mock-up surface is 8.5 mm. The cooling channel, drilled directly in CuCrZr heat sink, has a diameter of 12 mm. The cooling water conditions were inlet velocity of 4 m s^{-1}, inlet temperature of 20 °C and inlet pressure of 0.4 MPa. After 200 cycles at heat load of 5 MW m^{-2}, overheated areas emerged at the side of the tungsten tiles, as shown in figure 8. Post mortem visual inspection revealed that the debonding took place at the Cu/Ni interface rather than the W/Cu interface, although the mismatch of expansion coefficient between tungsten and copper is greater than that between copper and nickel. It can be explained that microcracks at the Cu/Ni interface grew up during HHF test and resulted in the failure of HIP-TIG mock-up. HIP-OFE mock-up which has a similar dimension with HIP-TIG mock-up was made by experiment 4# with OFE technique. HHF tests of HIP-OFE mock-up were performed via an electron beam facility with the power of 6 kW at Beijing Zhongke Electric Co. Ltd [9, 11]. HIP-OFE mock-up survived successfully 1000 cycles at heat load of 5 MW m^{-2} with cooling water of 4 m s^{-1}, 20 °C, 0.4 MPa. Figure 9 shows IR-images of HIP-OFE mock-up before and after thermal cycling. No damage was observed except for a slight deformation of the pure copper layer. These results illustrate that preventing the oxidation of the copper during HIP process is beneficial for improving the HHF testing performance of PFCs, as well [9].

In 2015, ASIPP prepared two W/Cu flat-type test mock-ups for CEA's WEST project [1]. The HHF tests were performed in JUDITH-1 facility at Julich, Germany [12]. The two mock-ups, marked as FT1 and FT2, were manufactured by HIP process which parameters were identical with experiment 4#. Each mock-up, with a dimension of 84 mm (length) × 30 mm (width) × 17 mm (height), consists in 7 tungsten tiles (thickness of 2 mm) bonded on the CuCrZr heat sink with a cooling channel of 8 mm in diameter drilled in it. It is 6 mm thick between the top of cooling channel and the surface of mock-ups. The cooling water conditions were inlet velocity of 10 m s^{-1}, inlet temperature of 20 °C and inlet pressure of 2.25 Mpa. Mock-up FT1 withstood successfully 102 cycles of 10 MW m^{-2}, 102 cycles of 15 MW m^{-2} and 302 cycles of 20 MW m^{-2} in succession; mock-up FT2 withstood 302 cycles of 10 MW m^{-2}, 102 cycles of 15 MW m^{-2} and 102 cycles of 20 MW m^{-2}, as shown in figure 10. Figure 11 shows IR-images of mock-up FT1 before and after thermal cycling at heat load of 20 MW m^{-2}. The results of the mock-ups are far beyond the WEST design requirement of 8–10 MW m^{-2}. However, strong deformation of the pure copper interlayer occurred on both mock-ups after HHF tests, as shown in figure 12. Since only the pure copper interlayer below tungsten tiles 3#, 4# and 5# were damaged, one can exclude the heat load at 10 MW m^{-2} as a potential cause for this strong deformation. The observed strong deformation can be explained by creeping of the pure copper interlayer caused by its high temperature for heat load of 15 or 20 MW m^{-2}. Nevertheless, by comparing screening tests before and after thermal cycling at different loading steps, no obvious degradation of the thermal performance of the mock-ups took place. Thus, it can be concluded that this deformation of the pure copper interlayer hardly impacted the heat removal capability of the mock-ups.

4. Applications in EAST upper divertor

W/Cu flat-type PFCs were widely applied in EAST upper divertor, such as dome, baffle, connection plate (CP) and manifold box (MB). Dome component consists of two parts, namely upper W/Cu plate and lower CuCrZr plate. After joining supporting legs and inlet/outlet cooling tubes to the lower CuCrZr plate by EBW, the two parts of dome component were assembled by EBW as well [13]. In order to relieve stress emerged after EBW, two grooves were machined in advance on the both sides of the seams between the two parts of dome component, as shown in figure 13. Figure 14 shows pictures of outer target of EAST upper divertor. For inner or outer target, W/Cu flat-type baffle was connected to monoblocks via a CP by EBW. MB, acting as the cooling connection between monoblocks and cassette

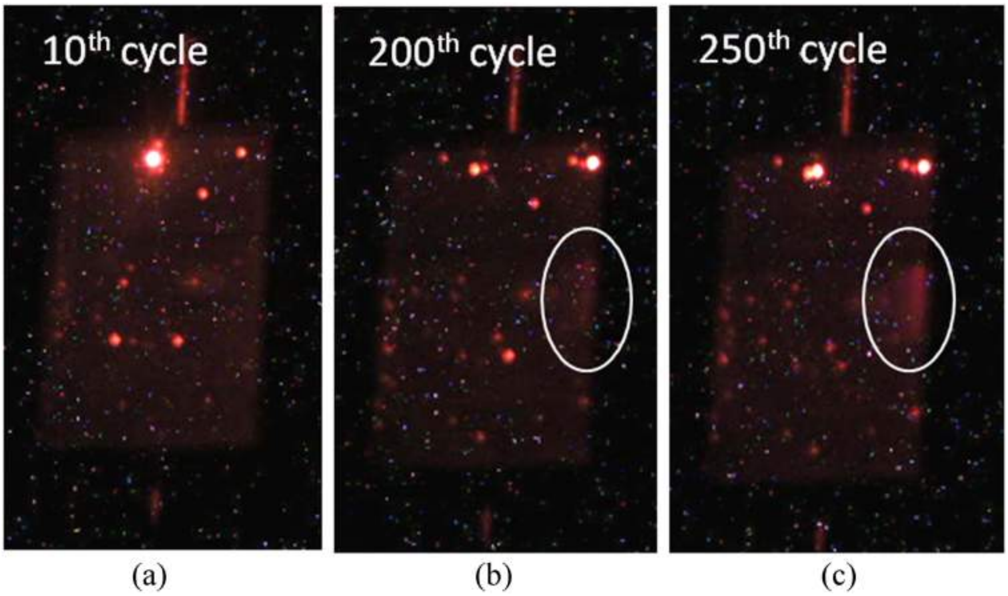

Figure 8. CCD images of HIP-TIG mock-up during HHF test at (a) 10th cycle, (b) 200th cycle and (c) 250th cycle.

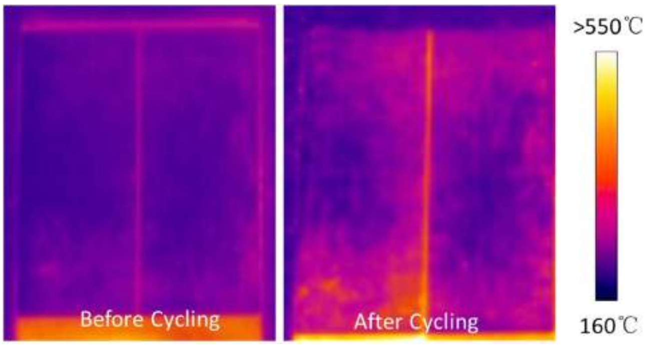

Figure 9. IR-images of HIP-OFE mock-up before and after thermal cycling at heat load of 5 MW m^{-2}.

body (CB) to meet the very limited space, was joined to monoblocks by EBW as well.

In 2014 EAST campaign, some leakages of the EBW seams between cooling tube and CuCrZr heat sink for dome and MB were found, which may be caused by thermal stress and weak welding of seams [1]. In the previous design, the cooling tubes were TIG-welded directly to the CB, leading probably to high stress at EBW seams during baking and abnormal events. In order to reduce the stress, the design of TIG welding between tubes and CB was changed into a flexible connection using soft bellows between tubes, as shown in figure 15. To ensure the depth of the EBW seams between cooling tube and CuCrZr heat sink to meet requirement, a specific ultrasonic technique to test the seams was developed and applied in the following repairing of the W/Cu PFCs. After repairing and upgrading, W/Cu flat-type PFCs showed good performance in 2015 EAST campaigns, during which tens of shots of upper single null (USN) discharge with the input heating power of ∼4 MW and one shot plasma with pulse length of 30 s and H-mode of 10 s were obtained. In 2016 campaigns, W/Cu flat-type PFCs withstood much more severe discharges and no leak occurred. A one minute long pulse H-mode USN discharge (shot 67341) was achieved [14, 15]. These campaigns demonstrated a successful application of W/Cu flat-type PFCs in EAST upper divertor.

5. Applications in the design of actively cooled Langmuir probes

Langmuir probes fixed on EAST divertor target face some issues of erosion and melting during plasma discharge, which impair their lifetimes severely. In order to avoid the damage, Langmuir probes have to possess the capability to remove heat loads up to 10 MW m^{-2}, which are flow from scrape-off layer onto the divertor target. In view of the success in HHF testing up to 20 MW m^{-2}, W/Cu flat-type concept is applied in the design of actively cooled Langmuir probes which will be mounted onto EAST divertor targets. Figure 16 shows a sketch map of Langmuir probe. The probe, with diameter of 8.5 mm, consists of tungsten armor (thickness of 2 mm) directly facing plasma, pure copper interlayer and CuCrZr heat sink with a hole of 6.5 mm in diameter drilled from the rear side. A pipe made of stainless steel (inner diameter of 4 mm and wall thickness of 0.5 mm) is inserted into the hole and cooling water jetting from the pipe cools down the W armors efficiently. In order to insulate electrically the probe from PFCs, the probe is covered by a ceramic tube laterally and cooling water is deionized. The temperature distribution of the probe under heat load of 10 MW m^{-2} is simulated by ANSYS FLUENT code. The cooling water conditions are inlet velocity of 5 m s^{-1}, inlet temperature of 20 °C and inlet pressure of 1 MPa. The maximum temperature of the probe is about 510 °C, as shown in figure 17, which means that the probe has an excellent heat removal capability. The manufacturing of these actively cooled Langmuir probes is under

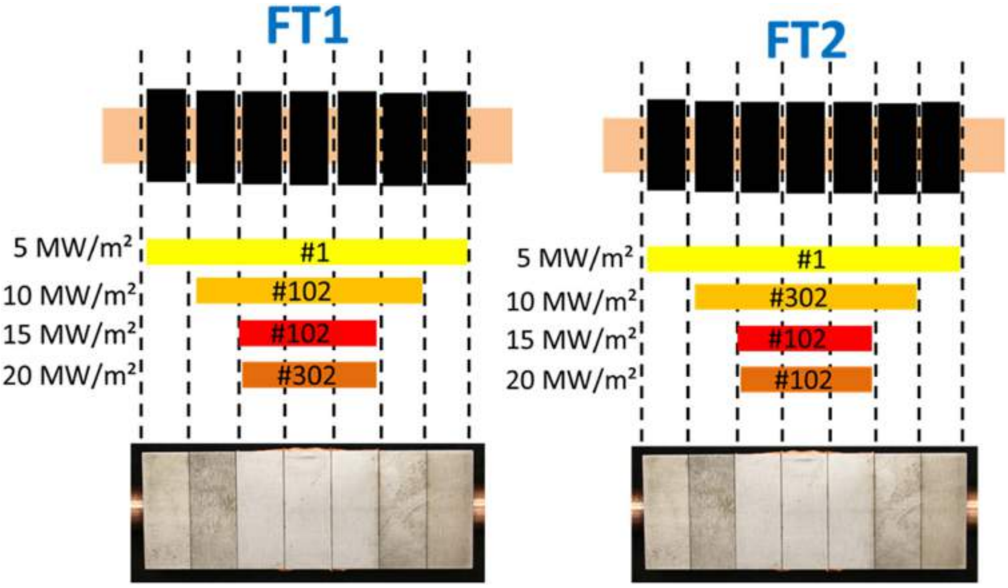

Figure 10. High heat flux test for mock-ups (a) FT1 and (b) FT2.

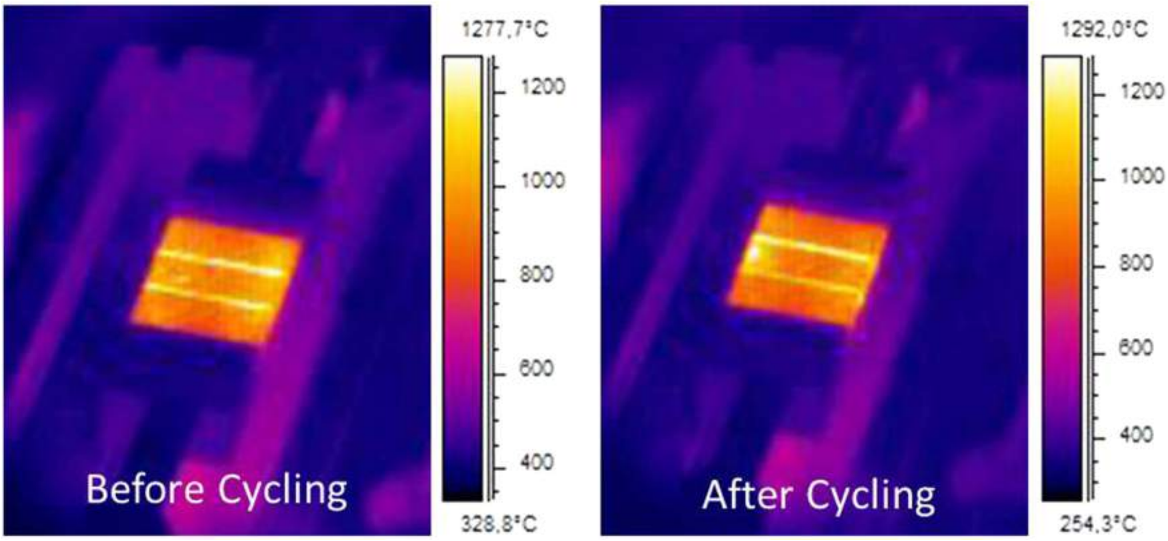

Figure 11. IR-images of mock-up FT1 before and after thermal cycling at heat load of 20 MW m^{-2}.

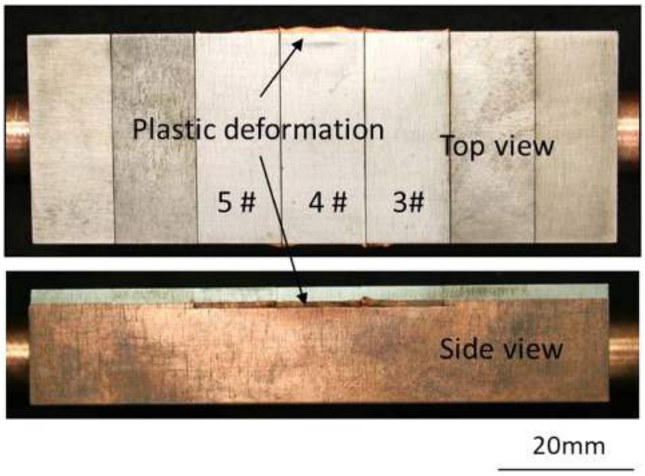

Figure 12. Deformation of Cu interlayer on mock-up FT1 after HHF tests.

way via casting and HIP process which are the same as that for W/Cu flat-type PFCs. And the probes with this new design will be mounted onto EAST divertor target in the near future.

6. Summary

After several years of R&D, manufacturing technologies for W/Cu flat-type PFCs become increasingly mature at ASIPP. And then, ASIPP realized industrial production of W/Cu flat-type PFCs for EAST. Even though some leakages occurred during the 2014 commissioning campaign, 2015 and 2016 EAST campaigns demonstrated a successful application of W/Cu flat-type PFCs in EAST upper divertor. This paper can be concluded as follows:

Figure 13. Dome component for EAST upper divertor consists of two parts, namely upper W/Cu plate and lower CuCrZr plate, which are assembled by EBW.

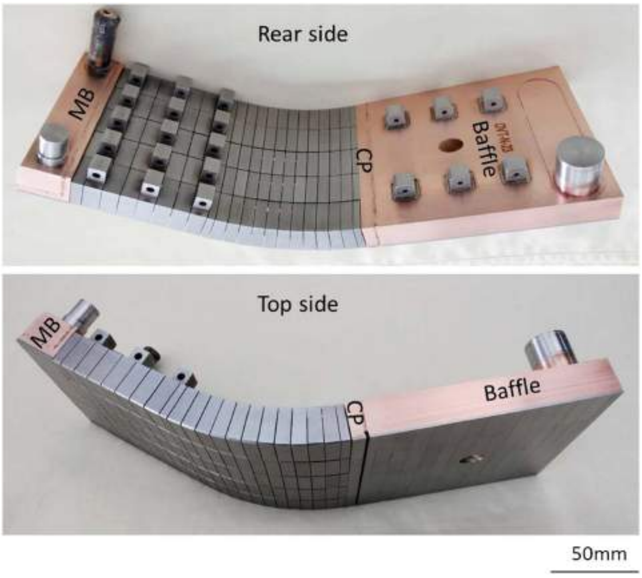

Figure 14. Outer target for EAST upper divertor consists of flat-type baffle, connection plate, manifold box and monoblocks, which are assembled by EBW as well.

- The optimized manufacturing process is to cast pure copper onto the rear side of W tiles at temperature of 1200 °C firstly, and then to HIP the W/Cu tiles onto CuCrZr heat sink plate at temperature of 600 °C, pressure of 150 MPa and duration of 3 h. OFE technique that prevents the oxidation of pure copper during HIP plays a key role in improving the bonding quality of Cu/CuCrZr interface.
- Small-scale testing mockups for EAST survived 1000 cycles at heat loads of 5 MW m^{-2} in HHF tests via an e-beam facility. One W/Cu flat-type test mock-up prepared for CEA's WEST project withstood successfully 102 cycles of 10 MW m^{-2}, 102 cycles of 15 MW m^{-2} and 302 cycles of 20 MW m^{-2} in succession, which are far beyond the design requirement.
- W/Cu flat-type PFCs were widely employed in EAST upper divertor, such as dome, baffle, CP and MB. However, some leakages of the EBW seams between cooling tube and CuCrZr heat sink for dome and MB were found in 2014 EAST campaign. After repairing and upgrading, W/Cu flat-type PFCs showed excellent performance in 2015 and 2016 campaigns. In 2016 campaigns, a one minute long pulse H-mode USN discharge (shot 67341) was achieved.
- In view of the success in HHF testing up to 20 MW m^{-2}, W/Cu flat-type concept is applied in the design of

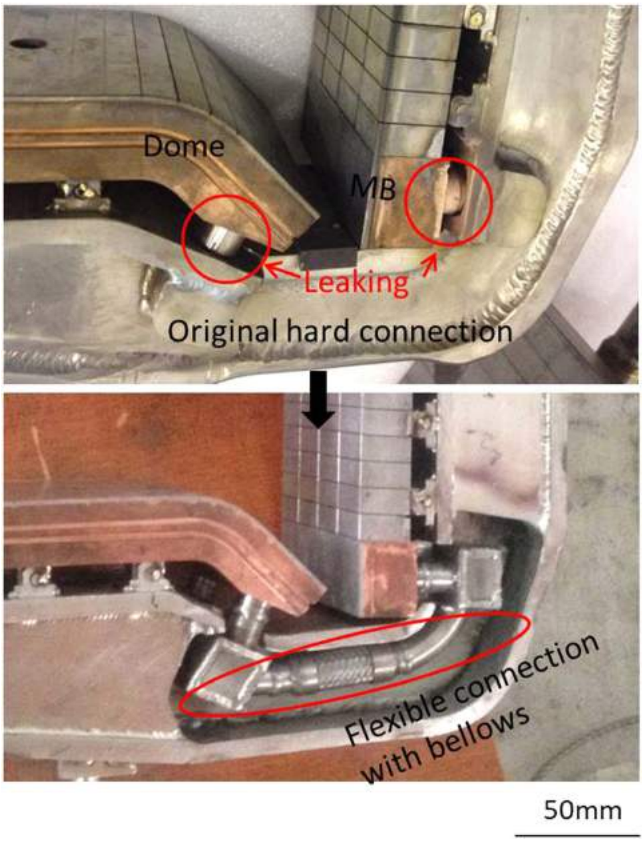

Figure 15. Leakages of the EBW seams between cooling tube and CuCrZr heat sink for dome and MB and advance in connection design for cooling tube to reduce thermal stress.

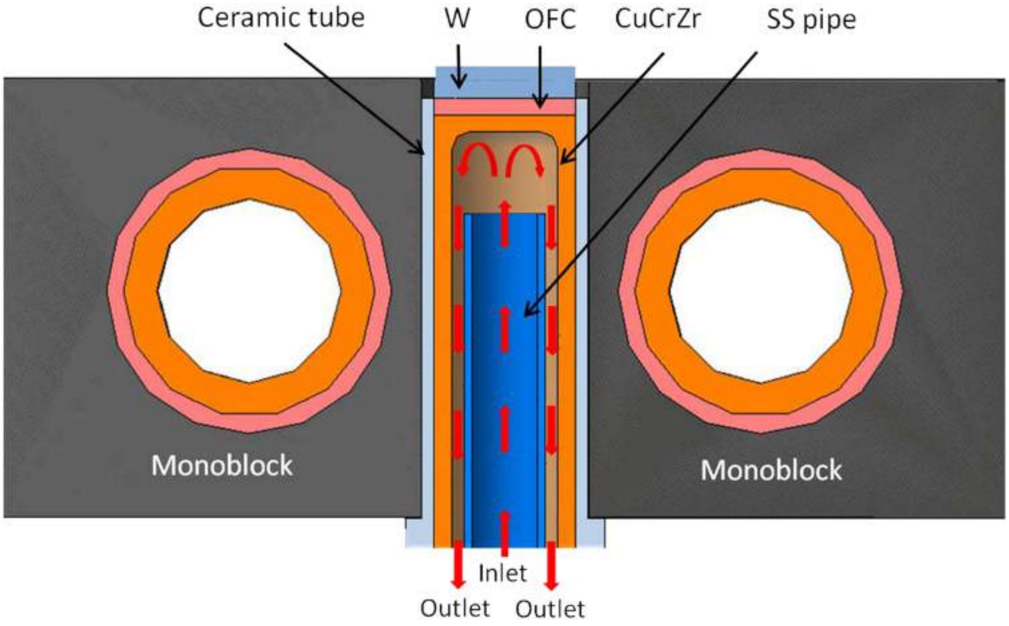

Figure 16. The actively cooled Langmuir probe consists of tungsten armor directly facing plasma, pure copper interlayer and CuCrZr heat sink with a hole drilled from the rear side. A pipe made of stainless steel is inserted into the hole and cooling water jetting from the pipe cools down the W armors efficiently.

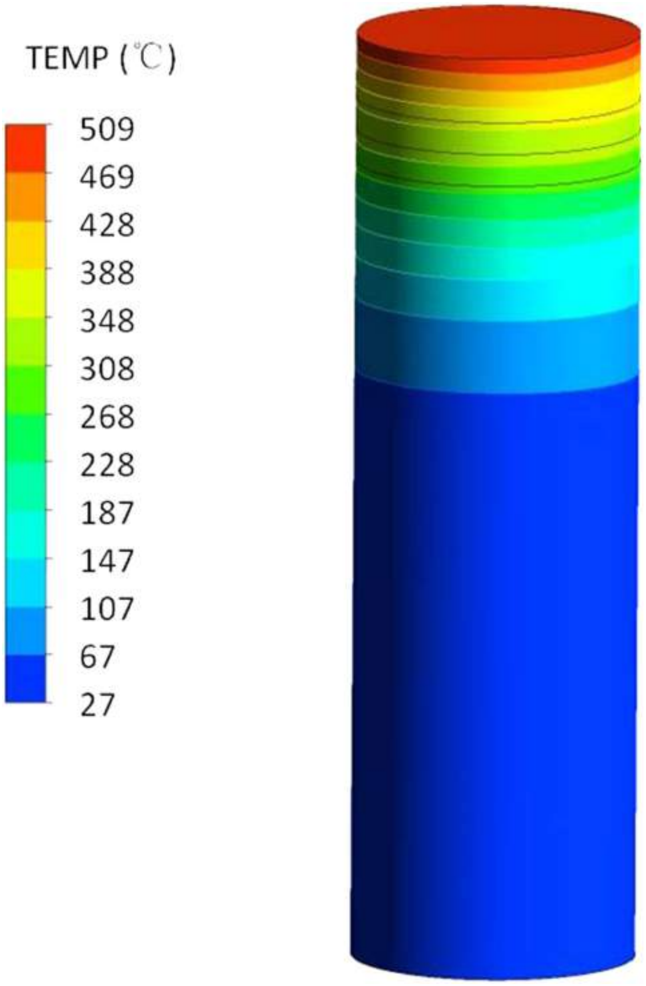

Figure 17. Temperature distribution of Langmuir probe under heat load of 10 MW m^{-2} simulated by ANSYS FLUENT code.

actively cooled Langmuir probe which will be mounted onto EAST divertor targets. The maximum temperature of the new designed Langmuir probe under heat load of 10 MW m^{-2} simulated by ANSYS FLUENT code reaches about 510 °C, which demonstrates that the probe has an excellent heat removal capability.

Acknowledgments

This work is partially funded by the National Natural Science Foundation of China under Contract Nos 11305213 and 11575242, the National Magnetic Confinement Fusion Science Program under contract Nos 2013GB105001 and 2013GB105002.

References

[1] Luo G-N *et al* 2017 Overview on decade development of plasma-facing components at ASIPP *Nucl. Fusion* **57** 065001
[2] Yao D M *et al* 2016 Design, R&D and commissioning of EAST tungsten divertor *Phys. Scr.* **T167** 014003
[3] Yao D M *et al* 2015 Overview of the EAST in-vessel components upgrade *Fusion Eng. Des.* **98–99** 1692–5
[4] Li J G *et al* 2014 Plasma facing components for the experimental advanced superconducting tokamak and CFETR *Phys. Scr.* **T159** 014001
[5] Merola M *et al* 2002 Overview on fabrication and joining of plasma facing and high heat flux materials for ITER *J. Nucl. Mater.* **307–311** 1524–32
[6] Litunovsky N *et al* 2011 Development of the armoring technique for ITER Divertor Dome *Fusion Eng. Des.* **86** 1749–52

[7] Li Q *et al* 2013 Manufacturing and testing of W/Cu mono-block small scale mock-up for EAST by HIP and HRP technologies *Fusion Eng. Des.* **88** 1808–12

[8] Lian Y Y *et al* 2016 Manufacturing and high heat flux testing of brazed flat-type W/CuZrZr plasma facing components *Plasma Sci. Techol.* **18** 184–9

[9] Zhao S X *et al* 2015 Influence of interfacial oxidation on the high-heat-flux performance of HIP-manufactured flat-type W/Cu plasma-facing components for EAST *Fusion Sci. Technol.* **67** 784–91

[10] Lian Y Y *et al* 2013 Preparation and properties of CVD-W coated W/Cu FGM mock-ups *Fusion Eng. Des.* **88** 1694–8

[11] Zhao S X *et al* 2014 Axial strain localization of CuCrZr tubes during manufacturing of ITER-like mono-block W/Cu components using HIP *Fusion Eng. Des.* **89** 3083–8

[12] Hirai T *et al* 2009 Failure modes of vacuum plasma spray tungsten coating created on carbon fibre composites under thermal loads *J. Nucl. Mater.* **392** 40–4

[13] Wang W J *et al* 2015 Application of e-beam welding in W/Cu divertor project for EAST *Fusion Eng. Des.* **98–99** 1415–8

[14] Wan B N *et al* 2017 Overview of EAST experiments on the development of high-performance steady-state scenario *Nucl. Fusion* **27** 102019

[15] Gong X Z *et al* 2017 Realization of minute-long steady-state H-mode discharges on EAST *Plasma Sci. Technol.* **19** 032001