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Characterization of the Crack and Recrystallization of W/Cu Monoblocks of the Upper Divertor in EAST

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Abstract: The microstructure of and damage to the upper divertor components in EAST were characterized by using metallography, EBSD, and SEM. Under the synergistic effect of heat load and plasma irradiation, cracking, recrystallization, and interface debonding were found in the components of the upper divertor target. The crack propagates downward from the heat loading surface along the heat flux direction, and the crack propagation mode is an intergranular fracture. The thermal loads deposited on the edge of monoblocks raise the temperature higher than the recrystallization temperature of pure tungsten, and the microstructure changes from being in a rolled state to being recrystallized. Additionally, cracks exist in both recrystallized and rolled areas. EBSD boundary maps show that the range of the recrystallization area is determined via the heat flux distribution. The Cu/CuCrZr interface of the cooling components near the thermal loading area is debonded, and the structural integrity is destroyed.

Keywords: crack; recrystallization; divertor; EAST



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1. Introduction

The selection and preparation of divertor materials to be implemented as plasma-facing materials has become one of the bottlenecks limiting the development of nuclear fusion. Plasma-facing components in nuclear fusion reactors can withstand harsh environments, such as steady thermal loads, transient thermal shock, plasma irradiation, and neutron irradiation [1]. The divertor is used to withstand the particles and heat flux coming from the core plasma, and at the same time, exhausts the helium ash generated in the nuclear fusion reaction process [2]. The advantages of tungsten and its alloys include having a high melting point, good thermal conductivity, good thermomechanical properties, a high sputtering threshold, low atomic activity, low deuterium and tritium retention, and resistance to plasma erosion [3]. In existing tokamak devices, such as EAST [4], WEST [5], JET [6], ASDEX-U [7], and KSTAR [8], tungsten and its alloys are widely used as plasma-facing materials, especially for divertor components. A tungsten divertor with a W/Cu block structure will also be used in ITER [9]. In addition, tungsten and its alloys are preferred as plasma-facing materials in other future fusion experimental reactors, such as DEMO [10] and CFETR [11]. However, during the process of plasma discharge, recovery and recrystallization will occur under a high heat flux and melting will happen under a higher heat load, which become the main constraints [12] that cause recrystallization brittleness [13], resulting in a decline in mechanical properties, a lower fracture toughness, and a higher ductile-to-brittle transition temperature [14,15]. It seems that the recrystallization phenomenon and fatigue degradation mechanism caused by high temperatures and cyclic thermal loads increases the possibility of crack initiation and propagation [16]. Changes in the near-surface microstructure induced by transient heat

loads, as well as the impact of combined plasma/heat loads, are likely to reduce the heat dissipation properties of tungsten, resulting in a reduction in the power-handling capability of the divertor target [17].

ITER has clear requirements for the microstructure and state of tungsten, which requires that the rolling direction of the rolled tungsten plate, that is, the grain elongation direction, should be parallel to the heat conduction direction. By limiting the grain direction and directing the crack propagation to occur along the grain elongation direction, the generation of cracks parallel to the surface can be reduced and the risk of plasma contamination caused by grain delamination and ejection can be minimized [18].

To clarify the service characteristics of tungsten under the relevant severe conditions, a series of experiments have been carried out on tungsten under the relevant heat loads or plasma irradiation. Through heat load or plasma irradiation experiments, T. Hirai [19] and Jeong-ha You [20] found vertical macrocracks in the middle of the thermal load surface. Long periods of servicing under high temperatures in the recovery and recrystallization process cannot be avoided. The recrystallization process will degrade the mechanical properties of materials and change the thermal shock resistance of tungsten [21], and thus, cracking is more likely to occur when suffering under repeated thermal cycling [22]. Although the macrocrack will not affect the heat dissipation capacity of the component, it still needs to be avoided as much as possible, considering its effects on the core plasma, such as the potential melting risk caused by the leading-edge effect [23]. Shah [16] conducted a more detailed analysis of microstructures and damage evolution in monoblocks. Thermal stress introduced via a cyclic heat load on a monoblock resulted in surface deformation and surface roughness. The depth of the recrystallization area was examined by using EBSD and a hardness test, and the grain orientation and the initial texture were compared and analyzed. The behavior of tungsten and monoblocks has been investigated in many facilities, but fewer have studied the monoblocks that are located on the fusion experimental reactor and have experienced discharge campaigns.

In the fusion experimental device, due to the synergistic effect of heat load and plasma irradiation [24], the actual conditions are more complex. The simultaneous exposure to transient heat and stationary plasma loads has been shown to worsen the cracking behavior in tungsten samples [25]. EAST is a fully superconducting tokamak with both single- and double-null divertor configurations possible, which aims to achieve high-power and long-pulse, steady-state plasma operation scenarios relevant to ITER and CFETR [26]. The upper divertor component of EAST was replaced in 2014 [27] by using actively cooled ITER-like tungsten plasma-facing components (PFCs) with W/Cu monoblocks as the target to develop the exhaust ability at a higher power [28]. Additionally, each W/Cu monoblock employed W, oxygen-free high-conductive copper (OFHC-Cu), and copper–chrome–zirconium (CuCrZr) as the plasma-facing material, intermediate layer, and heat sink, respectively. It is the first large-scale application of such actively cooled, ITER-like W/Cu plasma-facing components in a long-pulse tokamak [23]. During the plasma discharge process, the actual steady heat load of EAST is generally lower than 3 MW/m^2 [29], which is far lower than the maximum heat removal capacity of 10 MW/m^2 found in the high heat load experiment [4,27]. However, in the actual service process, due to the assembly error of adjacent components that form the misalignment, parts of the leading edge will receive an extremely high heat flux, inducing high thermal stress and strain concentrations at the center of the leading edges, at which thermal fatigue cracking or even a melting phenomenon [30] could be initially generated [23]. The macromorphology, temperature distribution, and plasma parameters were also analyzed [22,23,30], but a detailed analysis of the evolution of the monoblocks' microstructure has not been carried out. The damage to these monoblocks is due to the loss of coolant. In addition, at the same time, the misalignment between neighboring monoblocks leads to changes in the plasma strike point and an increase in the heat flux, which also causes damage to the monoblock [29]. At the same time, with the further improvements of the discharge power of the experimental fusion reactor, divertor

components must withstand even hard load conditions, and therefore, the studies on and the optimization of monoblocks need to be further strengthened.

EAST is an experimental device that can provide a certain degree of reference value for ITER-related W plasma-facing component research and a scientific basis for the ITER [31]. In this paper, we characterized the damaged W/Cu monoblock components from the upper divertor and analyzed the damage morphology, the microstructure evolution, and the recrystallization behavior, which are of great significance for the production process, installation requirements, and lifetime prediction of the monoblock components.

2. Materials and Methods

The sample is from the EAST upper divertor's G3 outer target (Figure 1), which employs five strings of W/Cu monoblocks with the aim to withstand high projected heat loads up to 10 MW/m^2 on the top surface [23]. The tungsten part was prepared via the powder metallurgy process. It was sintered at 2000°C , and then warm-rolled at 1100°C with a thickness reduction of 50%. After rolling, tungsten plates were partitioned by using electrical discharge machining (EDM) wire cutting. The CuCrZr/Cu tube was welded with hot isostatic pressure (HIP) technology and then installed and commissioned in EAST [23].

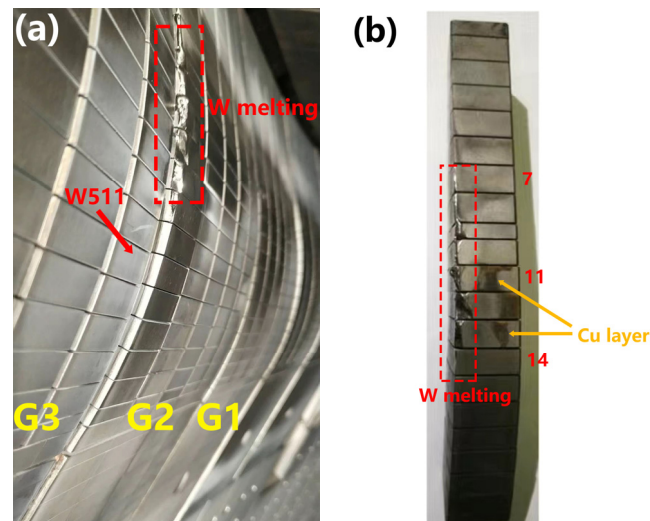


Figure 1. (a) View of the damaged G2 CM in the vacuum chamber of EAST (number represents the monoblock number, and the arrow points to the monoblock #W511); (b) the leftmost string of W/Cu monoblocks with severe leading-edge-induced melting of the W and Cu layer on the surface after disassembly (number represents the monoblock number, and the arrows point to the cooper layer).

After a melting failure during the plasma campaign in 2019, parts of the damaged outer targets were replaced. As shown in Figure 1a, melting and resolidification occurred at the G2 outer target. Figure 1b shows the most severe melting string in the G2 outer target from Figure 1a. Besides the severe leading-edge-induced melting of W armor, a Cu layer is visible on the surface of the failed W/Cu monoblocks, and such a Cu layer is also found on the edge sides of the toroidal gap between the W/Cu monoblocks [30]. The plasma strike point in EAST is concentrated around monoblocks #7 to #14. Therefore, in this paper, the monoblocks were located at the same place, where the monoblocks numbered #W511-7, #W511-11, and #W511-14 in string No. W511 were located in the G3 outer target, which is the adjacent string to G2 in Figure 1a.

The string was cut into a single monoblock via EDM. The surface of the monoblock was observed by using an optical microscope. The surfaces of the samples were prepared for optical microscope observation via mechanical grinding with a silicon carbide paper and polishing with a $1 \mu\text{m}$ diamond. The corrosion solution was a boiled H_2O_2 solution with a 3% volume fraction, and the corrosion time was about 40–60 s depending on the sample condition. Samples for EBSD measurements were first prepared via mechanical

polishing and then via electropolishing; the polishing solution was a 2% NaOH solution, and the current density was 0.02 A/mm^2 . The electropolishing time was about 200 s. EBSD measurements were performed with an Oxford C-Swift detector in a Zeiss Gemini 500 SEM using a voltage of 20 kV. A step size of $1 \mu\text{m}$ was chosen to study the details of the deformed microstructure and the recrystallization grains. The open-source software MTEX [32] was used to analyze the EBSD data. Monoblocks were cut from the rolled plate, and the height (H), width (W), and thickness (T) direction of the monoblocks corresponded to the RD (rolling direction), TD (transverse direction), and ND (normal direction) of the rolled plate (Figure 2b). Both the length and width of each W/Cu monoblock were designed to be 26 mm, whereas the thickness of the monoblocks varied from 7–12 mm according to the requirements. The distance from the top surface (W-T plane) to the tube wall was 6 mm. The inner diameter of the CuCrZr coolant tube was 12 mm, and the thickness was 1.5 mm. The thickness of the OFHC-Cu interlayer between the CuCrZr coolant tube and the W armor was 1 mm [23]. Generally, to mitigate the leading-edge-induced high thermal effects, both of the leading edges of each W/Cu monoblock were chamfered with dual chamfering shaping ($1 \text{ mm} \times 1 \text{ mm}$) [33] since EAST operates in both the normal and reverse magnetic field directions. However, the H-T plane on the outer side (blue arrow) in string No. W511 is a curved surface that is also designed to alleviate the high heat effect in the leading edge [30], and the exitance of the curved surface is not convenient for testing; thus, the H-W plane was selected for EBSD analysis. The W/Cu/CuCrZr interfaces were analyzed by using SEM after mechanical polishing.

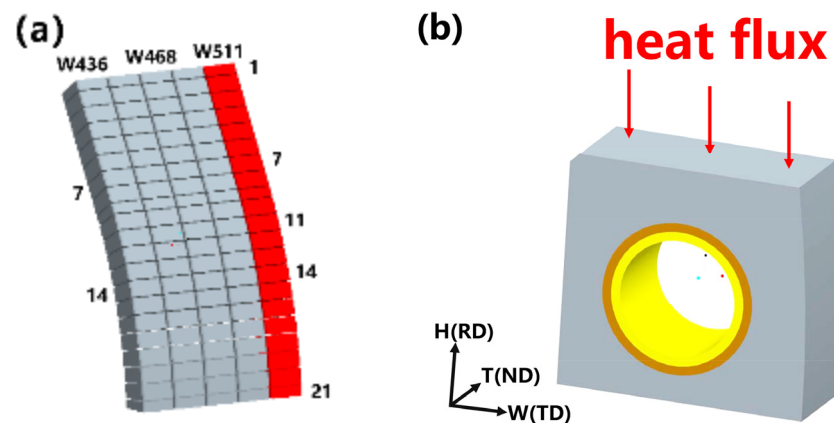


Figure 2. Schematic diagram of the outer target: (a) composition diagram of the outer target (number represents the monoblock number); (b) schematic diagram of monoblock (the arrow represents the direction of heat flux).

3. Results and Discussion

Considering the melting phenomenon in Figure 1b, the melting site of G2 was exposed to a very high heat flux, and string No. W511 in the adjacent region withstood high temperatures due to thermal radiation. From the direction of the view shown in Figure 3a, it can be seen that the heat load of the monoblock caused cracking and recrystallization on the leading edge. As shown in Figure 3b, the recrystallization area is concentrated on the upper part of the monoblock, corresponding to the heat load on the top surface. The recrystallization depth on the left side is greater than that on the right side. On the left side of monoblock #W511-7 is monoblock #W511-8; thus, it can be seen that #W511-8 will have a great depth of recrystallization, corresponding to the higher heat flux. On the contrary, #W511-6 on the other side may have a shallow recrystallization depth, or no recrystallization may have occurred. The red circle in Figure 3e–g has a higher magnification than in Figure 3b–d. The recrystallized grains near the heat load surface can be seen in these pictures. Cracks start from the leading edge and extend from the recrystallized area to the deformed area. #W511-7 has the least number of cracks, but also has a deep crack propagation, in which the maximum crack length is $2376 \mu\text{m}$ and the maximum crack width

is 57.5 μm . In Figure 3c, recrystallization also appears in the leading edge of #W511-11. The maximum crack length is 2394 μm , which is the deepest crack in these monoblocks, but the number of cracks increases significantly and the maximum crack width is 44.5 μm . In Figure 3d, only a few recrystallized grains are found in the upper right corner near the heat load surface. The maximum crack length of #W511-14 is 1410 μm , with a maximum crack width of 38.6 μm , and the number of cracks is similar to that in #W511-11. However, since the monoblock #W511-14 only has a few recrystallization grains in the upper right corner, all of the cracks occurred in the deformed state. The propagation mode of all of the cracks is an intergranular fracture in these monoblocks. In most cases, when recrystallization occurs, cracks develop as a microcrack network [18], but in Figure 3b–d, only macrocracks appeared and no crack networks were found. Commonly, recrystallization will reduce the mechanical strength of materials [34], leading to a decrease in the cracking threshold [35], which is then more likely to generate cracks with high thermal stress. However, #W511-14 had cracks without recrystallization, where the cracks may have been formed before recrystallization. Even though #W511-7 withstands the highest heat flux and has the largest recrystallization area, a fewer number of cracks are found in it, whereas the widest crack releases most of the energy. For mono-blocks with smaller crack widths, more cracks were generated during the process of releasing thermal stress. From the current results, it was found that the primary cracks were not propagated deep enough to reach the cooling tube due to such self-castellation effects [23].

The metallographic microstructure of the monoblocks' H-W plane is shown in Figure 4. There is a large recrystallization area in the upper right corner of #W511-7, and the difference in the microstructure is obvious, as shown in Figure 4b. A similar recrystallization process happened in #W511-11, whereas the area where the microstructure changed is smaller, and there is no recrystallized grain found at the same area in #W511-14, as shown in Figure 4c,d, respectively. From the results mentioned before, #W511-7 has the largest high-temperature distribution area and the highest temperature, which is higher than the recrystallization temperature of pure tungsten. During the operation of EAST, the monoblocks bear an uneven thermal load, and the maximum heat is often concentrated at the leading edge [30]. Recrystallized grains were observed in the upper right corner of Figure 3d, whereas no recrystallized grains were observed in Figure 4d; this happened on the same monoblock, indicating that #W511-14 suffered more heat flux at the corner near #W511-13 (upper right corner in Figure 3d), where there exists a temperature gradient along the T/thickness direction. Although the above monoblocks showed recrystallization and cracking, the dimensions of the leading edge which received the most critical heat flux had no obvious change. The microstructure had changed partly, but the structural integrity was still intact. Contrary to the previous studies by G. Pintsuk [36], no macrocracks were found in the center of the monoblock, which may be due to the difference in the heat flux and heat flux angle.

The grain orientation maps are shown in Figure 5. Recrystallization grains are seen in #W511-7 and #W511-11, and the recrystallization area is concentrated on the leading edge of the monoblocks, which corresponds to the temperature concentration area in Figure 3 and the metallography pictures in Figure 4. Besides the recrystallization area, the original deformed structure that has not been affected by heat flux can also be seen in the grain orientation maps. The color in the maps indicates different orientations of grains. The difference in the original microstructure can be seen from the different orientations of three blocks in the area of the deformed state. Considering the position of string No. W511 in EAST, we believe that the strings on both sides of the outer target will suffer high temperatures and be recrystallized. One side receives a high heat flux due to the large misalignment, and the other side suffers from heat radiation from the adjacent string.

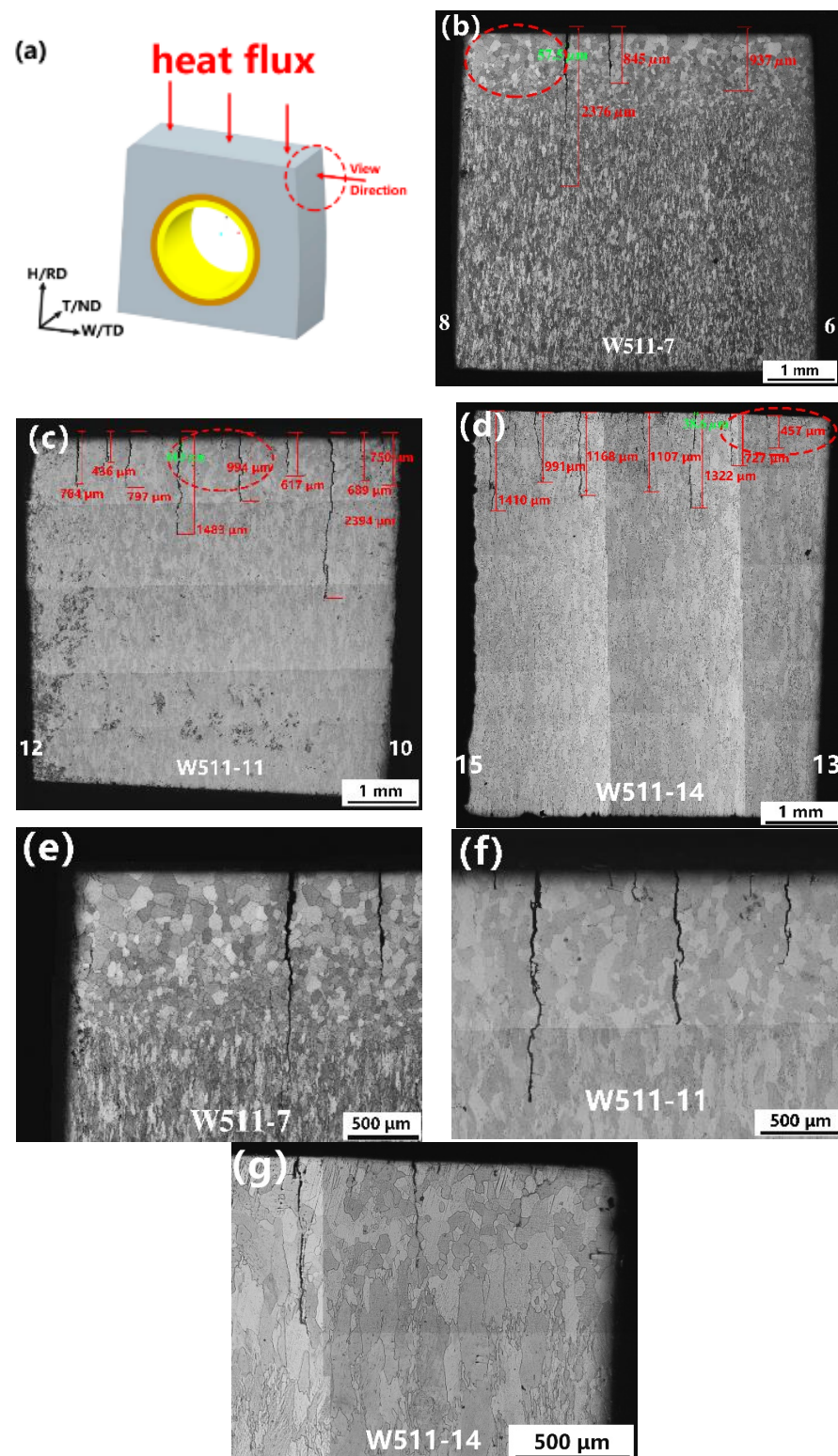


Figure 3. (a) Monoblock view direction (the viewing direction is shown by the arrow, and the viewing area is shown by the circle); (b) H-W plane of the metallographic picture of #W511-7 (the red circle part is shown in (e)); (c) H-W plane of the metallographic picture of #W511-11 (the red circle part is shown in (f)); (d) H-W plane of the metallographic picture of #W511-14 (the red circle part is shown in (e), the numbers on the lower side of the picture represent the number of adjacent monoblocks); (e) the higher magnification of the metallographic picture in the red circle in (b); (f) the higher magnification of the metallographic picture in the red circle in (c); (g) the higher magnification of the metallographic picture in the red circle in (d).

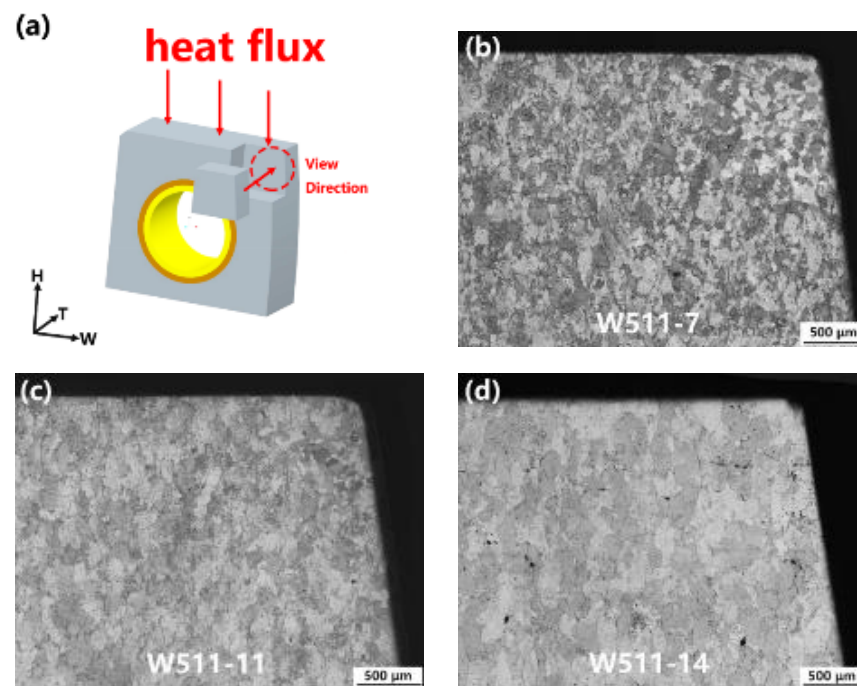


Figure 4. (a) Monoblock view direction (the viewing direction is shown by the arrow, and the viewing area is shown by the circle); (b) H-W plane of the metallographic picture of #W511-7; (c) H-W plane of the metallographic picture of #W511-11; (d) H-W plane of the metallographic picture of #W511-14.

The grain boundary maps shown in Figure 6 can accurately characterize the recrystallization range and recrystallization grains. The recrystallization range of monoblocks #W511-7 and #W511-11 is 1000–1100 μm along the H direction, but #W511-7 has a larger recrystallization range along the W direction, indicating that #W511-7 sustained a larger high-temperature distribution area. The recrystallization area is consistent with the contour distribution of the temperature analyzed in reference [30], in which the isothermal region extends for longer in the W direction, whereas there is little extension in the H direction. The top-surface grain size near the heat load is larger in the area close to the deformed state but is still recrystallized; in Figure 6a,b, there are some white grains, which contain some low-angle boundaries (green lines in the figure), and therefore, these grains are not identified as recrystallized grains. The difference in image size is meant to unify the scale bar.

The damage and recrystallization statistics of three typical tungsten monoblocks are shown in Figure 7. Even though #W511-7 has the largest recrystallization area, its crack density (crack numbers per unit length along the T direction) is the lowest, whereas the crack density of #W511-11 and #W511-14 increased significantly. Although the temperature of #W511-7 is higher during the plasma discharge campaign, it does not lead to more cracks in the thermal load area, but rather only results in the widest crack. The generation of the widest crack releases most of the thermal stress, and thus, the crack density of #W511-7 is the lowest. Notably, #W511-11 has a recrystallization area and the deepest crack at the same time. The maximum crack length of #W511-14 is the shortest, and no recrystallization is observed in Figure 6c. The recrystallization of each monoblock is different due to the poloidal distribution of the heat load during plasma discharges, but #W511-11 and #W511-14 have similar short crack patterns, whereas the maximum crack lengths of #W511-7 and #W511-11 are the same. The maximum depth of such a crack is generally below 5 mm in all of the inspected W/Cu monoblocks. With this primary crack formation and propagation, the stress and strain concentration at the middle of the leading edge was thus alleviated. After that, new stress and strain concentrations will occur in the middle of the two isolated sections separated by the primary crack, giving rise to secondary cracks [23].

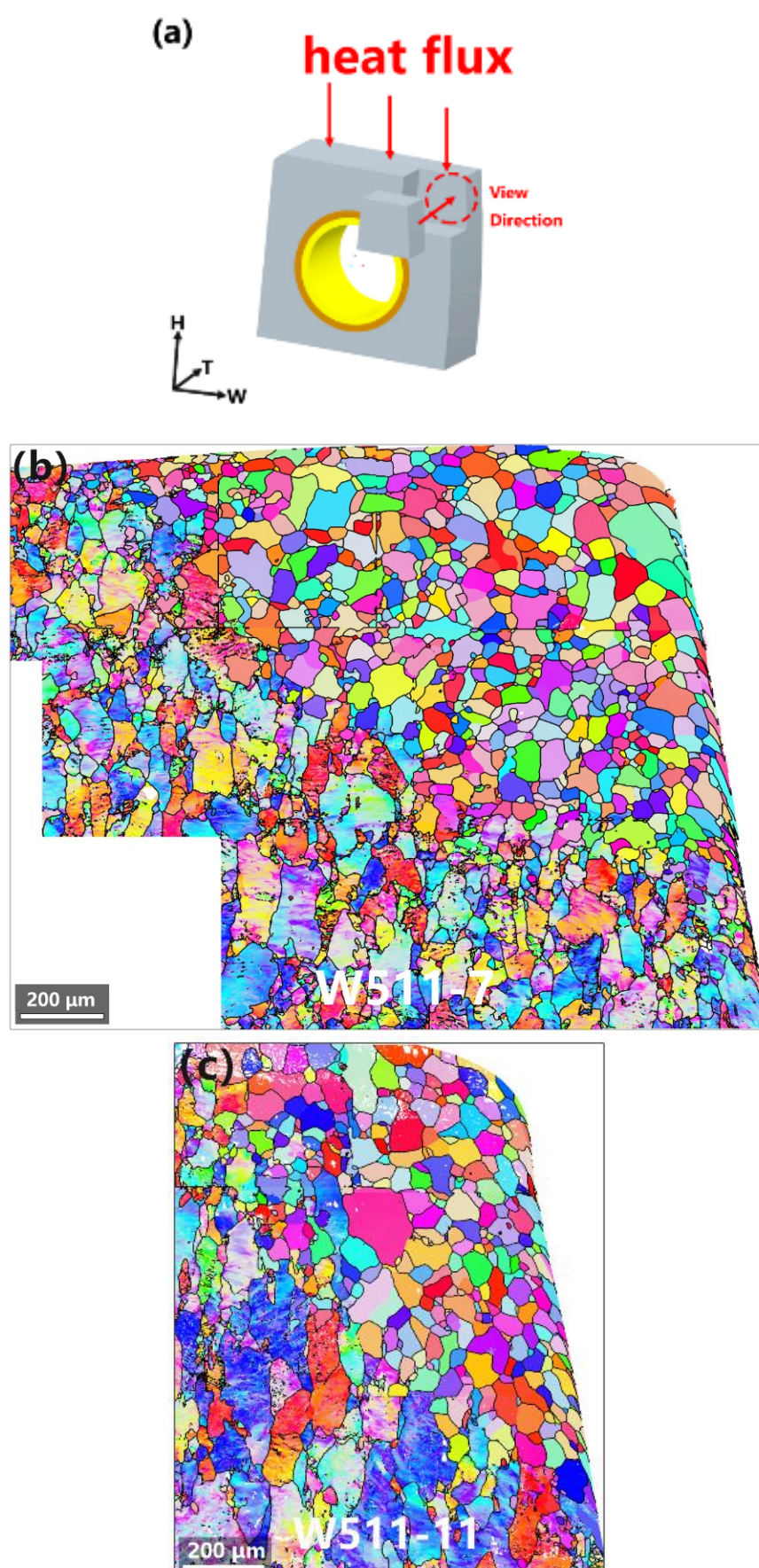


Figure 5. Cont.

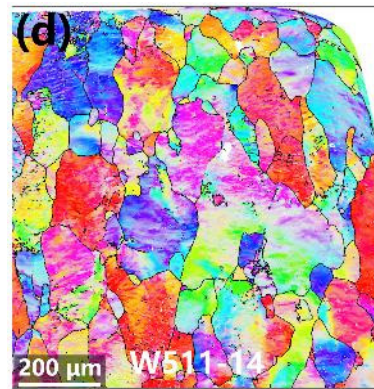


Figure 5. (a) Monoblock view direction (the viewing direction is shown by the arrow, and the viewing area is shown by the circle); (b) grain orientation of #W511-7; (c) grain orientation of #W511-11; (d) grain orientation of #W511-14.

The grain size was statistically analyzed, as shown in Figure 8. Most of the grains are below 50 μm , whereas there are some large grains larger than 100 μm . In #W511-7, there are some grains with a larger aspect ratio than in #W511-11 and #W511-14, which indicates the inhomogeneity of the deformed state. #W511-11 has a slightly larger aspect ratio, and more small grains of about 50 μm are more significantly found than those of #W511-14. In #W511-14, due to the selection of the region, the statistical number of the grain is smaller, as most grain sizes are less than 50 μm and the aspect ratio is generally smaller. The difference in grain size and aspect ratio reflects the inhomogeneity of the initial structure, which may be another reason for the difference in crack behavior.

However, it can be observed in Figure 3d that on #W511-14, some equiaxed grains are visible on the leading edge near #13, but they cannot be seen near #15. The view of the grain boundary map of #W511-14 from another direction (Figure 9a) is shown in Figure 9b. Several recrystallized grains appear in the view of the H-W plane of #W511-14 from this direction near #W511-13. In Figure 6c, no obvious recrystallized grains are found, which indicates that the inhomogeneous heat flux is distributed along the T direction. Maybe this is related to the distribution of plasma strike points in EAST.

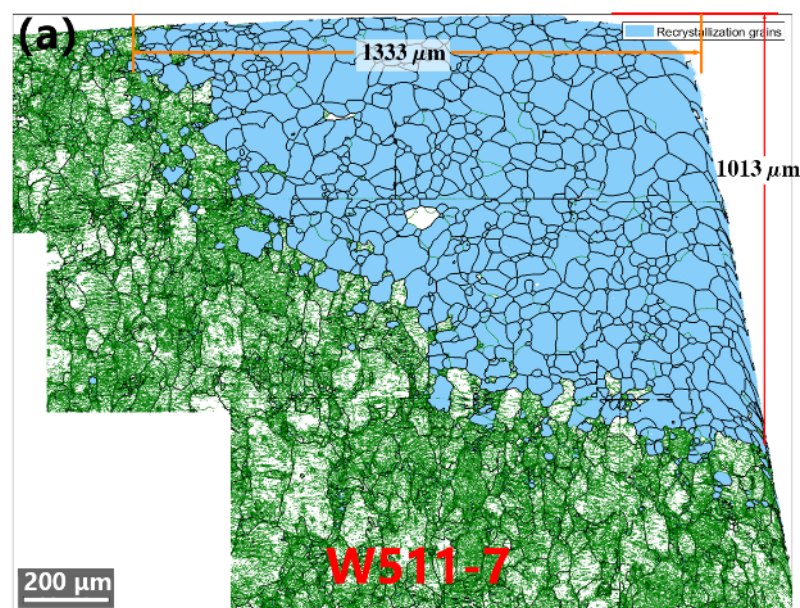


Figure 6. Cont.

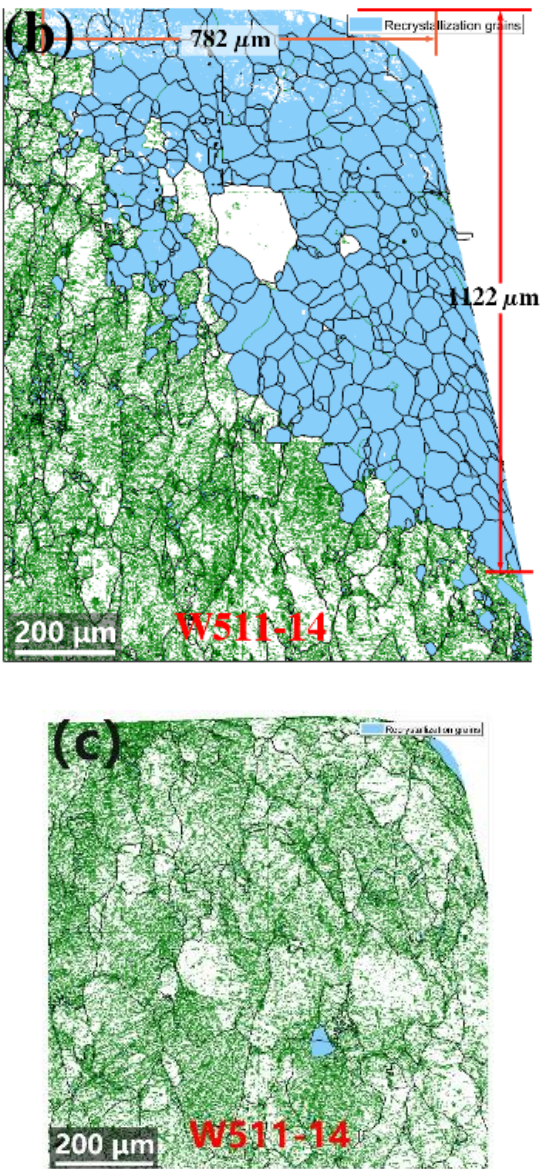


Figure 6. Grain boundary maps: (a) #W511-7; (b) #W511-11; (c) #W511-14.

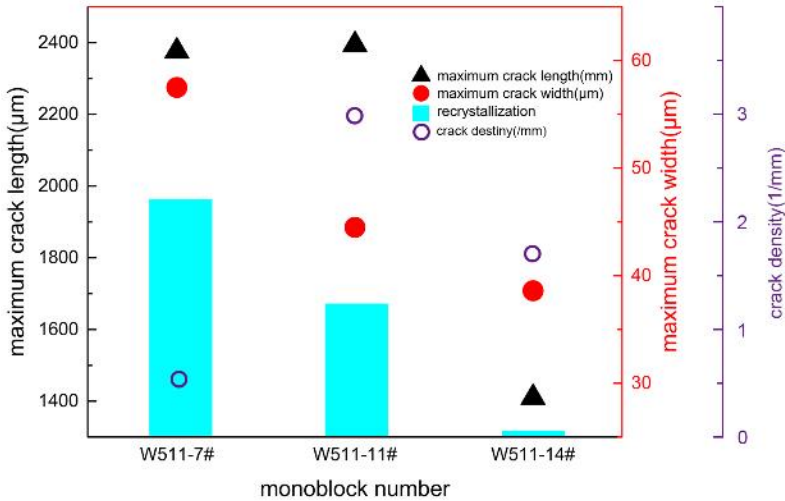


Figure 7. Comparison of recrystallization and crack damage in different monoblocks.

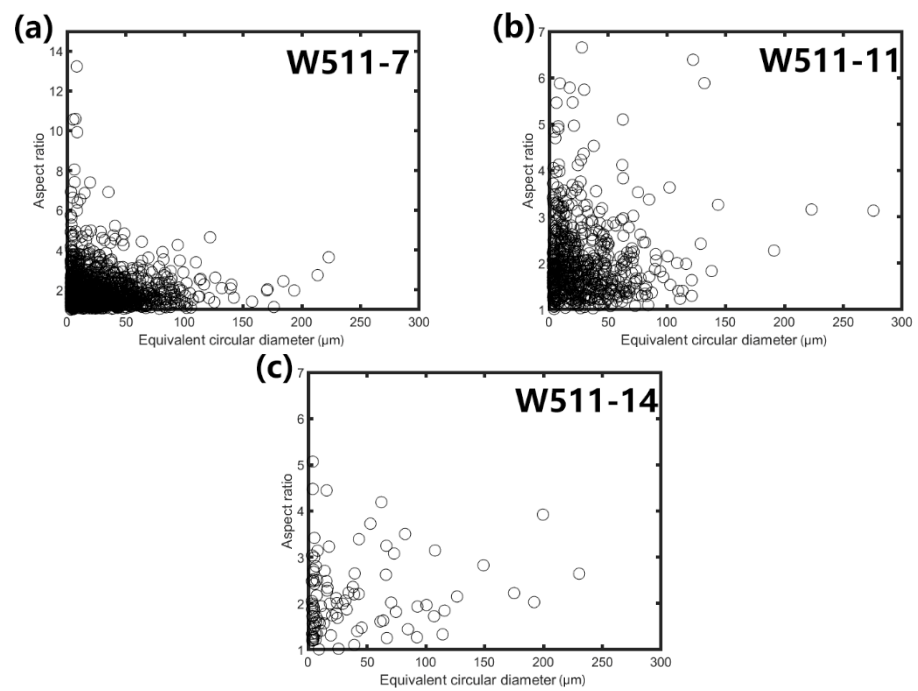


Figure 8. Equivalent circle diameter and grain aspect ratio: (a) #W511-7; (b) #W511-11; (c) #W511-14.

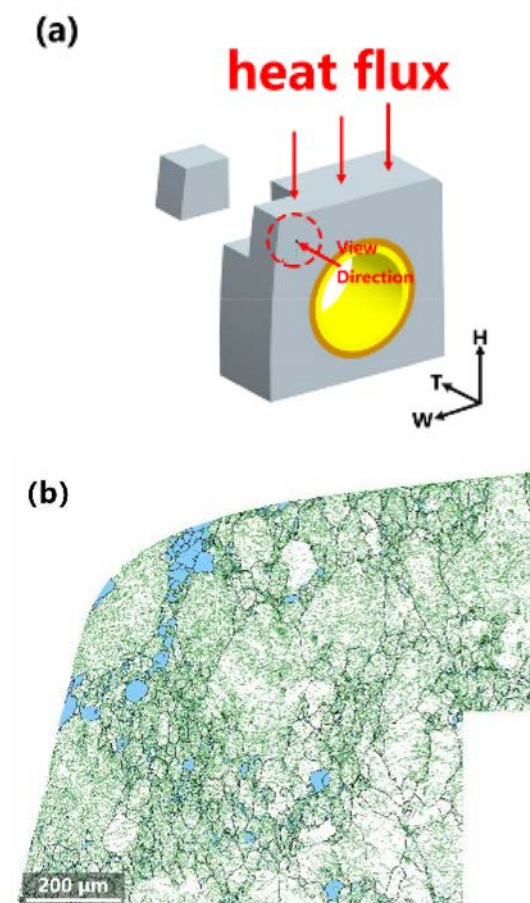


Figure 9. (a) Monoblock view direction (the viewing direction is shown by the arrow, and the viewing area is shown by the circle); (b) grain orientation of #W511-14.

The temperature of #W511-14 is close to the recrystallization temperature, resulting in a gradient distribution of recrystallized grains along the T direction. This shows that the total length of the monoblocks above the recrystallization temperature is at least 70 mm along the T direction from #W511-7 to #W511-13; when considering the recrystallization in #W511-14, the actual length of recrystallization may be longer. During the subsequent use and maintenance of EAST, special attention should be paid to the damage to the above-numbered monoblocks. In the process of judging the damage and service life of the divertor, the damage to these numbered monoblocks should also be taken as an important judgment basis.

Considering the high heat flux, high thermal stress, and strain caused by the high-temperature gradient, interface debonding easily occurs between different materials, which causes fatal damage to the structural integrity. For #W511-7 with the highest heat load, the debonding between the W and Cu materials is shown in Figure 10. The debonding of the W/Cu and Cu/CuCrZr interfaces is seen in the part of the cooling tube near the heat load surface. In addition to the debonding of Cu/CuCrZr near the recrystallization area, debonding is also found in the area where no recrystallization occurs. The damaged area of the interfaces is larger than the recrystallization area. Predictably, debonding caused by a heat load will lead to a decrease in the heat dissipation capacity, resulting in a temperature increase in the debonding area, and even leading to the melting of the leading edge of the monoblock. The rising temperature of tungsten will eventually lead to the melting of the cooling pipe. For #W511-14, the debonding of the Cu/CuCrZr interface can still be seen in the region close to the heat load surface, as shown in Figure 11b,c, but the degree of debonding is smaller than that of #W511-7. In Figure 11a, no debonding was observed at the interface of W/Cu and Cu/CuCrZr. The debonding in different areas corresponds to the heat flux distribution. In #W511-14, there was a maximum heat flux at position c, and thus, the interface debonding in Figure 11c is the most obvious, whereas at position a, which is far from the heat flux, no debonding was observed on all of the interfaces. With the decrease in heat flux, the debonding situation is reduced. Debonding may occur at the interface of W/Cu and Cu/CuCrZr, but more occurs at the Cu/CuCrZr interface, which was also found by Sun [37]. Further optimization is needed in the selection of materials for the cooling pipe and intermediate layer. The process of welding or the defect detection methods still needs to be improved. Additionally, the plastic deformation-induced changes in the Cu interlayer still need to be studied considering the initial state.

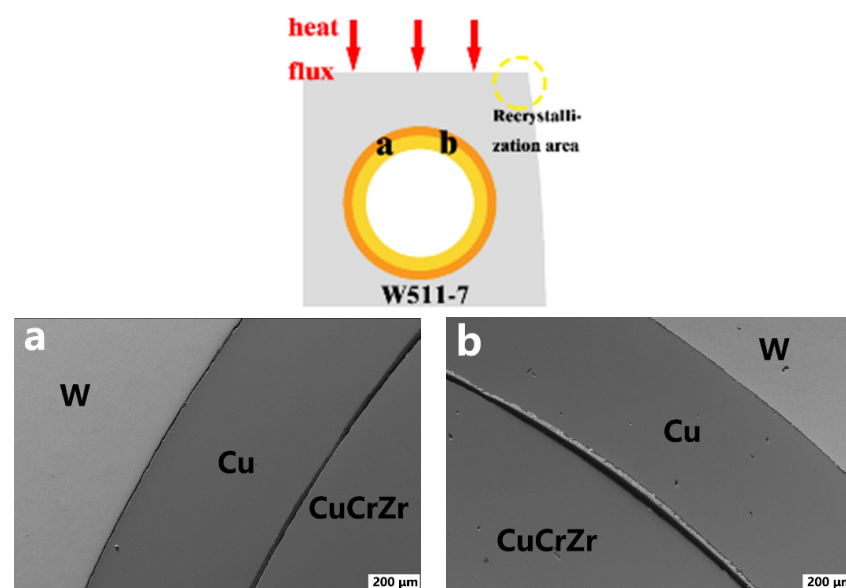


Figure 10. The interface of #W511-7 (the arrow represents the direction of heat flux): (a) interface at position a; (b) interface at position b.

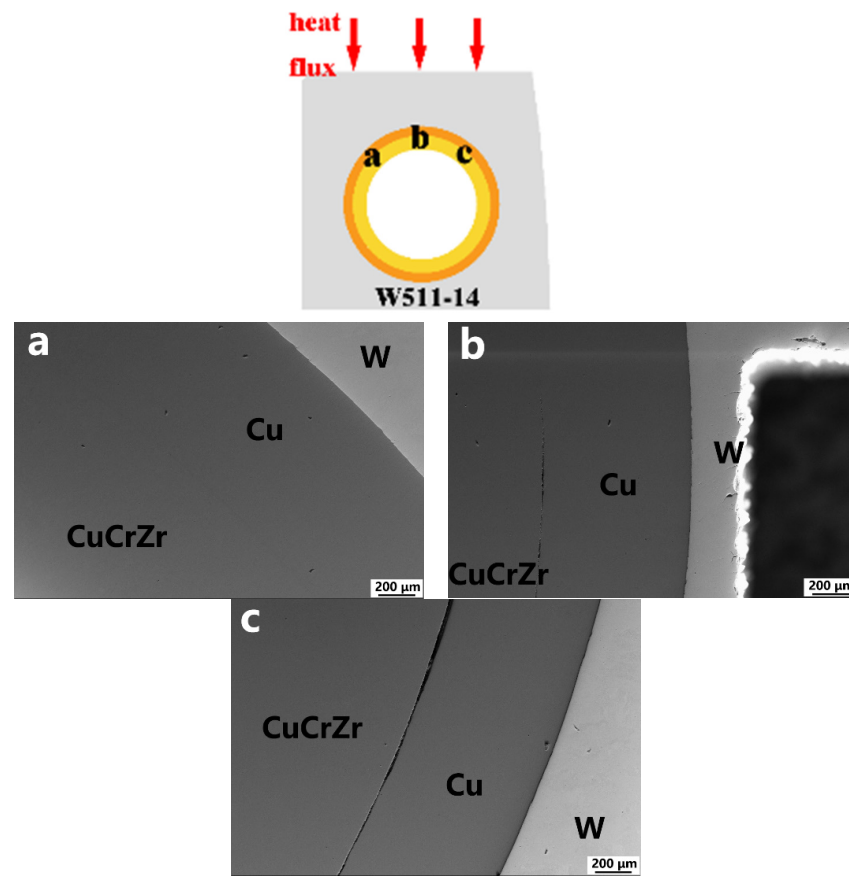


Figure 11. The interface of #W511-14 (the arrow represents the direction of heat flux): (a) interface at position a; (b) interface at position b; (c) interface at position c.

Predictably, debonding caused by a heat load will lead to a decrease in the heat dissipation capacity, resulting in a temperature increase in the thermal load area. The effect of debonding on thermal conductivity during service needs to be further studied through experiments and simulation. In future studies, the optimization of the monoblocks' structure and materials, the control of the plasma striking point, and the monitoring of coolant will be used to avoid such problems.

4. Conclusions

The damage morphology and microstructure evolution of the monoblocks on the outer target of the EAST upper divertor were studied in this paper. The main conclusions are as follows:

- (1) The region affected by the heat load is concentrated on the leading edge of the monoblocks, and several macrocracks appear in this area, with a maximum crack depth of 2394 μm . The crack propagation mode is intergranular and extends from the recrystallized region to the deformed area. With the increased heat flux, the crack width is wider.
- (2) Recrystallization occurs at the leading-edge area, with a maximum depth of 1122 μm along the H direction and a maximum width of 1333 μm along the W direction. In the No. W511 string, the heat load decreases gradually from #W511-7 to #W511-14, and the temperature from #W511-7 to #W511-13 is higher than the recrystallization temperature. The total length of the leading edge where recrystallization occurs will be at least 70 mm in length.
- (3) The Cu/CuCrZr interface of the cooling components is debonded. With the decrease in the heat load, the degree of debonding is reduced. Debonding may occur at the interfaces of W/Cu and Cu/CuCrZr, especially at the Cu/CuCrZr interface.

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References

- Pitts, R.A.; Carpentier, S.; Escourbiac, F.; Hirai, T.; Komarov, V.; Lisgo, S.; Kukushkin, A.S.; Loarte, A.; Merola, M.; Naik, S.A.; et al. A full tungsten divertor for ITER: Physics issues and design status. *J. Nucl. Mater.* **2013**, *438*, S48–S56. [\[CrossRef\]](#)
- Panayotis, S.; Hirai, T.; Barabash, V.; Amzallag, C.; Escourbiac, F.; Durocher, A.; Komarov, V.; Martinez, J.M.; Merola, M. Fracture modes of ITER tungsten divertor monoblock under stationary thermal loads. *Fusion Eng. Des.* **2017**, *125*, 256–262. [\[CrossRef\]](#)
- Philipps, V. Tungsten as material for plasma-facing components in fusion devices. *J. Nucl. Mater.* **2011**, *415*, S2–S9. [\[CrossRef\]](#)
- Yao, D.M.; Luo, G.N.; Zhou, Z.B.; Cao, L.; Li, Q.; Wang, W.J.; Li, L.; Qin, S.G.; Shi, Y.L.; Liu, G.H.; et al. Design, R&D and commissioning of EAST tungsten divertor. *Phys. Scr.* **2016**, *T167*, 014003.
- Missirlian, M.; Firdaouss, M.; Richou, M.; Languille, P.; Lecocq, S.; Lipa, M. The WEST project: PFC shaping solutions investigated for the ITER-like W divertor. *Fusion Eng. Des.* **2013**, *88*, 1793–1797. [\[CrossRef\]](#)
- Horton, L. Operation of JET with an ITER-like Wall. *Fusion Eng. Des.* **2015**, *96–97*, 28–33. [\[CrossRef\]](#)
- Herrmann, A.; Greuner, H.; Jaksic, N.; Balden, M.; Kallenbach, A.; Krieger, K.; de Marne, P.; Rohde, V.; Scarabosio, A.; Schall, G.; et al. Solid tungsten Divertor-III for ASDEX Upgrade and contributions to ITER. *Nucl. Fusion* **2015**, *55*, 063015. [\[CrossRef\]](#)
- Hong, S.-H.; Kim, K.; Kim, H.; Bang, E.; Choi, H.; Kim, H.-C.; Pitts, R.A. Damage and melting of ITER-like flat-type tungsten castellated blocks exposed to long pulse H-mode plasmas. *Fusion Eng. Des.* **2018**, *136*, 1518–1522. [\[CrossRef\]](#)
- Hirai, T.; Carpentier-Chouchana, S.; Escourbiac, F.; Panayotis, S.; Durocher, A.; Ferrand, L.; Martinez-Garcia, M.; Gunn, J.P.; Komarov, V.; Merola, M.; et al. Design optimization of the ITER tungsten divertor vertical targets. *Fusion Eng. Des.* **2018**, *127*, 66–72. [\[CrossRef\]](#)
- Federici, G.; Bachmann, C.; Biel, W.; Boccaccini, L.; Cismondi, F.; Ciattaglia, S.; Coleman, M.; Day, C.; Diegele, E.; Franke, T.; et al. Overview of the design approach and prioritization of R&D activities towards an EU DEMO. *Fusion Eng. Des.* **2016**, *109–111*, 1464–1474.
- Wan, Y.; Li, J.; Liu, Y.; Wang, X.; Chan, V.; Chen, C.; Duan, X.; Fu, P.; Gao, X.; Feng, K.; et al. Overview of the present progress and activities on the CFETR. *Nucl. Fusion* **2017**, *57*, 102009. [\[CrossRef\]](#)
- Linsmeier, C.; Rieth, M.; Aktaa, J.; Chikada, T.; Hoffmann, A.; Hoffmann, J.; Houben, A.; Kurishita, H.; Jin, X.; Li, M.; et al. Development of advanced high heat flux and plasma-facing materials. *Nucl. Fusion* **2017**, *57*, 092007. [\[CrossRef\]](#)
- Xie, Z.M.; Miao, S.; Liu, R.; Zeng, L.F.; Zhang, T.; Fang, Q.F.; Liu, C.S.; Wang, X.P.; Lian, Y.Y.; Liu, X.; et al. Recrystallization and thermal shock fatigue resistance of nanoscale ZrC dispersion strengthened W alloys as plasma-facing components in fusion devices. *J. Nucl. Mater.* **2017**, *496*, 41–53. [\[CrossRef\]](#)
- Yuan, Y.; Greuner, H.; Böswirth, B.; Krieger, K.; Luo, G.N.; Xu, H.Y.; Fu, B.Q.; Li, M.; Liu, W. Recrystallization and grain growth behavior of rolled tungsten under VDE-like short pulse high heat flux loads. *J. Nucl. Mater.* **2013**, *433*, 523–530. [\[CrossRef\]](#)
- Terentyev, D.; Riesch, J.; Lebediev, S.; Bakaeva, A.; Coenen, J.W. Mechanical properties of as-fabricated and 2300 °C annealed tungsten wire tested up to 600 °C. *Int. J. Refract. Met. Hard Mater.* **2017**, *66*, 127–134. [\[CrossRef\]](#)
- Shah, V.; van Maris, M.P.F.H.L.; van Dommelen, J.A.W.; Geers, M.G.D. Experimental investigation of the microstructural changes of tungsten monoblocks exposed to pulsed high heat loads. *Nucl. Mater. Energy* **2020**, *22*, 100716. [\[CrossRef\]](#)
- van Eden, G.G.; Morgan, T.W.; van der Meiden, H.J.; Matejcek, J.; Chraska, T.; Wirtz, M.; De Temmerman, G. The effect of high-flux H plasma exposure with simultaneous transient heat loads on tungsten surface damage and power handling. *Nucl. Fusion* **2014**, *54*, 123010. [\[CrossRef\]](#)
- Hirai, T.; Pintsuk, G.; Linke, J.; Batilliot, M. Cracking failure study of ITER-reference tungsten grade under single pulse thermal shock loads at elevated temperatures. *J. Nucl. Mater.* **2009**, *390–391*, 751–754. [\[CrossRef\]](#)
- Hirai, T.; Panayotis, S.; Barabash, V.; Amzallag, C.; Escourbiac, F.; Durocher, A.; Merola, M.; Linke, J.; Loewenhoff, T.; Pintsuk, G.; et al. Use of tungsten material for the ITER divertor. *Nucl. Mater. Energy* **2016**, *9*, 616–622. [\[CrossRef\]](#)
- Li, M.; You, J.-H. Interpretation of the deep cracking phenomenon of tungsten monoblock targets observed in high-heat-flux fatigue tests at 20 MW/m². *Fusion Eng. Des.* **2015**, *101*, 1–8. [\[CrossRef\]](#)
- Zan, X.; Yan, J.; Sun, H.; Wang, K.; Lian, Y.; Tan, X.; Luo, L.; Liu, X.; Wu, Y. Surface damage during transient thermal load of 50% thickness reduced W-2% (Vol.) Y₂O₃ sheet with different recrystallization volume fraction. *Int. J. Refract. Met. Hard Mater.* **2020**, *88*, 105197. [\[CrossRef\]](#)

22. Zhu, D.; Li, C.; Ding, R.; Wang, B.; Chen, J.; Gao, B.; Gu, Y.; Gong, X.; EAST Team. Characterization of the in situ leading-edge-induced melting on the ITER-like tungsten divertor in EAST. *Nucl. Fusion* **2020**, *60*, 016036. [\[CrossRef\]](#)
23. Zhu, D.; Li, C.; Gao, B.; Ding, R.; Wang, B.; Guo, Z.; Xuan, C.; Yu, B.; Lei, Y.; Chen, J. In situ leading-edge-induced damages of melting and cracking W/Cu monoblocks as divertor target during long-term operations in EAST. *Nucl. Fusion* **2022**, *62*, 056004. [\[CrossRef\]](#)
24. Linke, J.; Du, J.; Loewenhoff, T.; Pintsuk, G.; Spilker, B.; Steudel, I.; Wirtz, M. Challenges for plasma-facing components in nuclear fusion. *Matter Radiat. Extrem.* **2019**, *4*, 056201. [\[CrossRef\]](#)
25. Wirtz, M.; Kreter, A.; Linke, J.; Loewenhoff, T.; Pintsuk, G.; Sergienko, G.; Steudel, I.; Unterberg, B.; Wessel, E. High pulse number thermal shock tests on tungsten with steady state particle background. *Phys. Scr.* **2017**, *T170*, 014066. [\[CrossRef\]](#)
26. Wan, B. Recent experiments in the EAST and HT-7 superconducting tokamaks. *Nucl. Fusion* **2009**, *49*, 104011. [\[CrossRef\]](#)
27. Luo, G.N.; Liu, G.H.; Li, Q.; Qin, S.G.; Wang, W.J.; Shi, Y.L.; Xie, C.Y.; Chen, Z.M.; Missirlian, M.; Guilhem, D. Overview of decade-long development of plasma-facing components at ASIPP. *Nucl. Fusion* **2017**, *57*, 065001. [\[CrossRef\]](#)
28. Yao, D.; Luo, G.; Du, S.; Cao, L.; Zhou, Z.; Xu, T.; Ji, C.; Liu, C.; Liang, C.; Li, Q.; et al. Overview of the EAST in-vessel components upgrade. *Fusion Eng. Des.* **2015**, *98–99*, 1692–1695. [\[CrossRef\]](#)
29. Liu, B.; Dai, S.Y.; Kawamura, G.; Zhang, L.; Feng, Y.; Wang, D.Z. 3D effects of neon injection positions on the toroidally symmetric/asymmetric heat flux distribution on EAST. *Plasma Phys. Control. Fusion* **2020**, *62*, 035003. [\[CrossRef\]](#)
30. Li, C.; Zhu, D.; Ding, R.; Wang, B.; Chen, J.; Gao, B.; Lei, Y. Characterization on the melting failure of CuCrZr cooling tube of W/Cu monoblocks during plasma operations in EAST. *Nucl. Mater. Energy* **2020**, *25*, 100847. [\[CrossRef\]](#)
31. Lei, Y.; Zhu, D.; Li, C.; GeSangZhuoMa; Gao, B.; Wang, B.; Ding, R.; Chen, J.; Yu, B.; Xuan, C. Result and discussion on the evolution of in-situ leading edge-induced melting on W divertor targets in EAST. *Nucl. Mater. Energy* **2021**, *27*, 100997. [\[CrossRef\]](#)
32. Bachmann, F.; Hielscher, R.; Schaebe, H. Grain detection from 2d and 3d EBSD data—specification of the MTEX algorithm. *Ultramicroscopy* **2011**, *111*, 1720–1733. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Wang, B.; Zhu, D.; Ding, R.; Chen, J. Thermal analysis on the EAST tungsten plasma facing components with shaping structure counteracting the misalignment issues. *Plasma Sci. Technol.* **2017**, *19*, 025603. [\[CrossRef\]](#)
34. Guan, W.; Nogami, S.; Fukuda, M.; Sakata, A.; Hasegawa, A. Effect of Grain Structure Anisotropy and Recrystallization on Tensile Properties of Swaged Tungsten Rod. *Plasma Fusion Res.* **2015**, *10*, 1405073. [\[CrossRef\]](#)
35. Ren, D.; Xi, Y.; Yan, J.; Zan, X.; Luo, L.; Wu, Y. Surface Damage and Microstructure Evolution of Yttria Particle-Reinforced Tungsten Plate during Transient Laser Thermal Shock. *Metals* **2022**, *12*, 686. [\[CrossRef\]](#)
36. Pintsuk, G.; Antusch, S.; Weingaertner, T.; Wirtz, M. Recrystallization and composition dependent thermal fatigue response of different tungsten grades. *Int. J. Refract. Met. Hard Mater.* **2018**, *72*, 97–103. [\[CrossRef\]](#)
37. Sun, Z.; Li, Q.; Wang, W.; Wang, J.-C.; Wang, X.; Wei, R.; Xie, C.; Luo, G.; Hiral, T.; Escourbiac, F.; et al. Post examination of tungsten monoblocks subjected to high heat flux tests of ITER full-tungsten divertor qualification program. *Fusion Eng. Des.* **2017**, *121*, 60–69. [\[CrossRef\]](#)

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