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Development of W-monoblock divertor components with included thermal barrier interfaces

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In the case of DEMO fusion reactor, the divertor should be able to extract a steady heat flux of about 10 MW/m2. A promising concept is the W-monoblock. which should be connected to a CuCrZr or an advanced Cu ODS alloy pipe passing through the W component. Taking into account the optimum operating temperature windows for W and existing Cu-based alloys and the thermal expansion coefficients mismatch of these two materials, a "thermal barrier" interface material is inserted in between in order to mitigate the thermal stresses and to optimize the heat flow through divertor components. In this work we investigate the feasibility to realize such divertor components using materials produced by FAST (field assisted sintering technology). This powder metallurgy technique was used firstly to produce W or W-based composites and the thermal barriers in an almost final shape and then to join the materials in realistic divertor mock-ups. The thermal barrier materials are various Cu-based composites which are included both as single material or as functionally graded components. The interface quality between different materials is investigated by scanning electron microscopy and the heat flow through components is evaluated using simulations.

Keywords: W-monoblock, thermal barrier, FAST

1. Introduction

The DEMO [1] fusion reactor currently designed [2] is supposed to be able to extract an expected heat flux of about 10-20 MW/m^2. The baseline option for the plasma-facing components (PFC) is the ITER-type tungsten monoblock (however, with a reduced size) with CuCrZr tube passing through it [3, 4] for water cooling. W temperature operating window is limited at low temperature by the ductile to brittle transition at about 300-400 °C [5] and by recrystallization at high temperatures (at about 1200 °C). In fact, the optimum operating temperature for W is considered to be around 800-1000 ºC, taking into account recovery considerations [6-9]. On the other hand, CuCrZr alloys have a temperature operating window between 180°C and about 350°C [4, 10, 11]. In order to optimize the heat flow through such divertor components and to avoid stresses generated by the large difference between the W and CuCrZr thermal expansion coefficients (CTE), a thermal break or thermal barrier (TB) interface material was proposed [12-14]. In our previous works [15, 16] we have proposed various Cu-ceramic composites produced by SPS (spark plasma sintering) or FAST (field assisted sintering technology) route as potential thermal barrier materials. The most promising of them are Cu-C, Cu-SiC and Cu-ZrO2 composites which can be produced with very large ceramic volume content ranging up to 90% for Cu-ZrO2 [16]. Depending on ceramic content, the thermal conductivity can be decreased down to about 1 W/m/K while the materials CTE's are between that of W and CuCrZr for temperatures up to 1000 °C [15, 16]. Based on these results, in this work we investigate the feasibility to realize DEMO monoblock divertor components using materials produced and joined by FAST. This powder metallurgy technique is used firstly to produce W monoblocks in an almost final shape, then the thermal barriers materials and further to join the these materials in realistic divertor mock-ups. The interface quality between different materials is investigated by scanning electron microscopy. Considering a quasi-stationary heat load of 10 MW/m^2, as expected for the normal divertor operation [4], we have evaluated by FEM the heat flow through such components including thermal barriers both as single materials or as functionally graded components.

2. Experiments and results

2.1 Materials processing

The W monoblocks are fabricated from W powders with average particle size around 800 nm. The powders have been manipulated (put in moulds) in a glovebox under Ar atmosphere and then sintered by SPS at using a 2 temperature plateaus cycle as depicted in figure 1. This type of heat treatment was initially tested on mixtures of W powders (~ 80 μm particle size) and Ta fibbers or powders [17] and led to lower densifications, below 90% of the theoretical value. Using mixtures of W powders with different sizes [18] (70 nm, 1-2 μm and 80 μm) allowed for increased densities, up to 97.5% of the theoretical value for a combination of powders with 70 nm and 1-2 μm sizes. In the present case with 800 nm W particles the density reaches 97% of the theoretical value. While SPS processing route is not the most suited method for W processing it still has some important advantages in comparison with other methods which provide better materials, like PIM (powder injection moulding) [19] followed by classic or HIP sintering: i) it provides near final shape pieces, ii) it preserves the fine

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grained structures and iii) it is well suited for composite processing like W-ZrC [20] or W-W_2C [21].

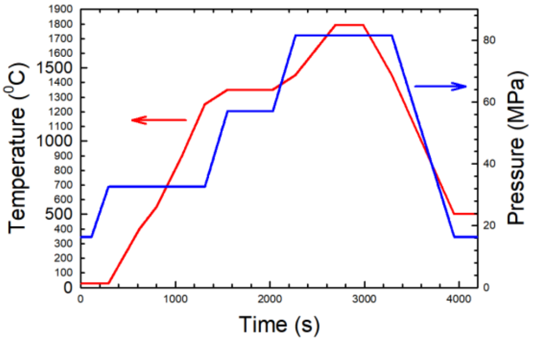

Fig. 1. Sintering cycle for W components. Note that due to the special designed graphite moulds, the real temperature value are higher than the SPS equipment set value with about 250 ºC at the highest temperature level.

The Cu based thermal barrier materials have been prepared using micrometric (average particle size, APS = 40 µm Cu powders and different dispersions like SiC (20 nm), ZrO_2 (20 nm) and C (graphite, ~400 nm). The powders have been mixed in Ar protective atmosphere in various volume proportions, ranging from 10 to 90 % for the dispersed materials, using a planetary ball mill at low speed (50 rpm). The homogenized compositions have been sintered in graphite moulds using a spark plasma sintering (SPS) equipment at about 900-1000 °C for 5 min. The thermal barrier specimens were produced as discs with a 20 mm diameter and ~ 6 mm height, or as rectangular bars with 10 mm ×30 mm section and various heights in order to create suited gradient materials. The microstructure and the thermophysical properties of these materials have been previously characterized [15, 16]. In figure 2 the thermal conductivity values for different materials are sumarized.

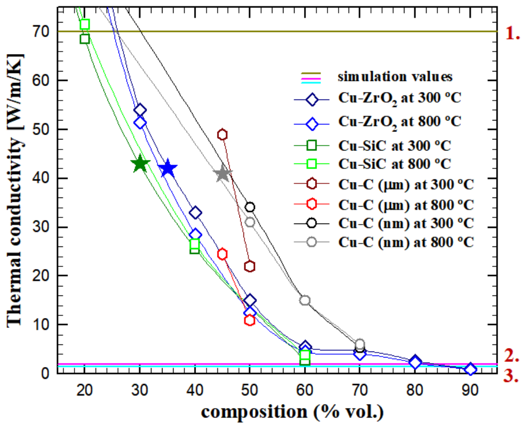

Fig. 2. Summary of thermal conductivity data for Cu-ZrO_2, Cu-SiC and Cu-C thermal barriers. The star symbols corrrespond to the values selected for single material thermal barrier ring fabrication (see text) and the dashed lines are the values determined from the FEM simulations as suited for a graded thermal barrier ring (see text and figure 6. c).

2.2 Single material thermal barriers

A therma barrier material included between the W armor and the CuCrZr should also control the heat flow through the component. In an ideal case, the W temperature should be kept in the 800-1200 ºC temperature operation window while the CuCrZr pipe should not exceed 300 ºC. That means to keep a 500 ºC temperature difference over 1 mm thick thermal barrier which gives an estimated needed thermal conductivity of 10 W/m/K for the material. As shown in figure 3 a), the simulation on the monoblock geometry (similar to DEMO for a 10W/m^2 steady heat flow and a 20 ºC water cooling at 40 l/s) demonstrates that the W exposed surface temperature will reach 1840 ºC while the lower part of the monoblock will be cooled below 300 ºC.

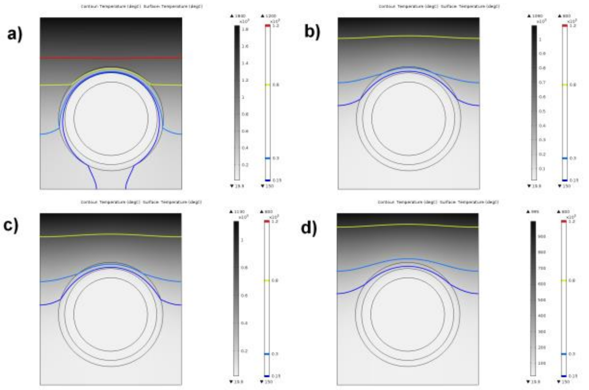

Fig. 3. FEM simulations of a 10 W/m^2 heat flowing to the W-monoblock divertor component using: a) a generic 10 W/m/K thermal barrier material; b) a 35% vol. Cu-ZrO_2 TB; c) a 30% vol. Cu-SiC TB; d) a 45% vol. Cu-C TB.

Thus, for the first tests we have a trade-off between keeping the exposed surface below 1200 ºC and keeping the lower part of the monoblock well below the W DBTT value. The materials have been chosen using the data plotted in figure 2, having thermal conductivity values close to 40W/m/K approximately in the entire temperature range. Such values correspond to volume concentrations of ~35%, ~ 30% and ~45% for ZrO_2, SiC and nanometric C dispersions, respectively. The corresponding heat flow simulations using the experimentally obtained thermal conductivity data are plotted in figure 3, b, c and d panels, respectively. The materials were produced as 20 mm diameter discs with a height of 6 mm and have been sent to KIT to be included in the first mock-ups.

2.3 Graded composition thermal barriers

In order to obtain an improved heat flow across the W monoblock we have investigated the possibility to create a graded composition material. The easiest way to produce such a material is to stack different composition layers as displayed in figure 4 a). The pre-sintered compositions can be further joined by FAST or, the layered material can be processed in one step by SPS, which can assure a more gradual variation due to inter-diffusion of the compositional layers. To cut the rings from the bulk material, a CNC milling machine was used. As shown in figure 4 b) the process is rather time consuming since the material should also firstly be brazed on a Cu plate and after cutting the ring should be carefully cut at the required height. In figure 4 c) the the ring is inserted in a W monoblock (ITER shaped type). Beside the long time needed to produce a component, the procedure has some certain disadvantages like a lot of material being wasted, or the fact that a failure at the TB level during the components joining using a brazing route or HRP (hot radial pressing) can be seen only after the complete mock-up is produced.

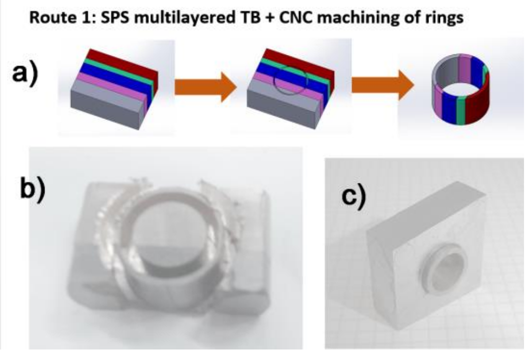

Fig. 4. Processing route for thermal barrier rings with gradual composition: a) process schematic; b) machined ring with 3 different layers; c) W-monoblock with inserted ring.

To avoid such difficulties we have designed a new processing route, using the SPS also to join the materials and reducing the mechanical machining to minimum. In this approach, the different composition thermal barrier materials are produced as discs, with suited dimensions for the W-monoblock hole. Than the discs are cut in radial slices, that is like "cake slices" which are assembled in the monoblock hole as depicted in figure 5. The entire ensemble is then processed by SPS, using the W monoblock as a mold. A major advantage is that a disc with a given composition can be used for slices in several components, reducing the material loses and considerably improving the reproducibility, at least at the mock-up level.

FEM simulations have been used to find the most suited combination of thermal barrier materials, as shown in figure 6. We have started with 20º angled slices and progressively connected the slices with close thermal conductivity values. The constraints were the same as before, adding also a 1050 ºC upper limit for the barrier.

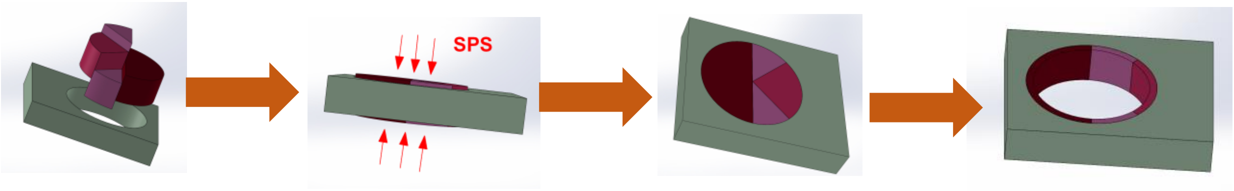

Fig. 5. "Cake slices" processing route for thermal barrier rings with gradual composition: produce thermal barrier discs, cut disc slices, insert slices, SPS the assembled monoblock, drill a hole for the CuCrZr pipe.

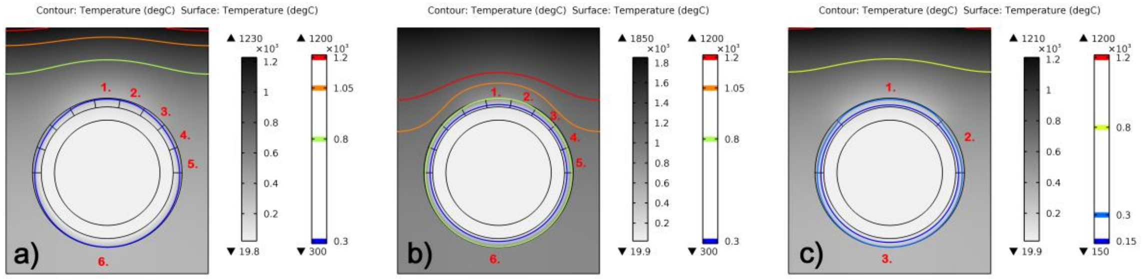

Fig. 6. FEM simulations of a 10 W/m^2 heat flowing to the W-monoblock divertor component: a) optimization of the heat flow to keep W over 300 ºC and the exposed W surface below 1200 ºC; b) optimization to keep W over 800 ºC and the CuCrZr pipe below 300 ºC; c) optimization of the number and geometric of the thermal barrier slices with the constraints from a).See text for the thermal conductivity values used in simulations.

As shown in figure 6 a), using a graded thermal barrier it is possible to better control the heat flow in the W-monoblock and to keep both the W lower part above 300 ºC and the exposed W surface below 1200 ºC. The thermal barrier materials are symmetrically disposed and have thermal conductivity values corresponding to the numbers 1 to 6 from the figure 6 a) as 80, 75, 30, 5, 1.8 and 1.5 W/m/K, respectively. These values can be found among the Cu-ceramic composite materials already produced and investigated.

In the next step we have tried to adjust the thermal conductivity values used in the heat flow simulations to increase the W overall lower temperature limit to 800 ºC, while maintaining the upper temperature limit of the CuCrZr pipe below 300 ºC. As shown in figure 6 b), this is possible at the expenses of the plasma exposed surface temperature which is increased in this case up to 1850 ºC. To obtain this result the following thermal conductivity values have been used and corresponding to the numbers 1 to 6 from the figure 6 b): 28, 26, 7, 3, 1 and 0.5 W/m/K, respectively. While the first 5 values can be found among the available Cu-ceramic composites, the last value of 0.5 W/m/K is very small and until now it was not possible to achieve in a bulk material. However, as shown in ref. [16], in the case of a joined component the thermal conductivity can be further decreased by the thermal contact resistance. This means also a weaker mechanical strength at the interface and this might lead to the component failure since the corresponding slice spans half of the connection area.

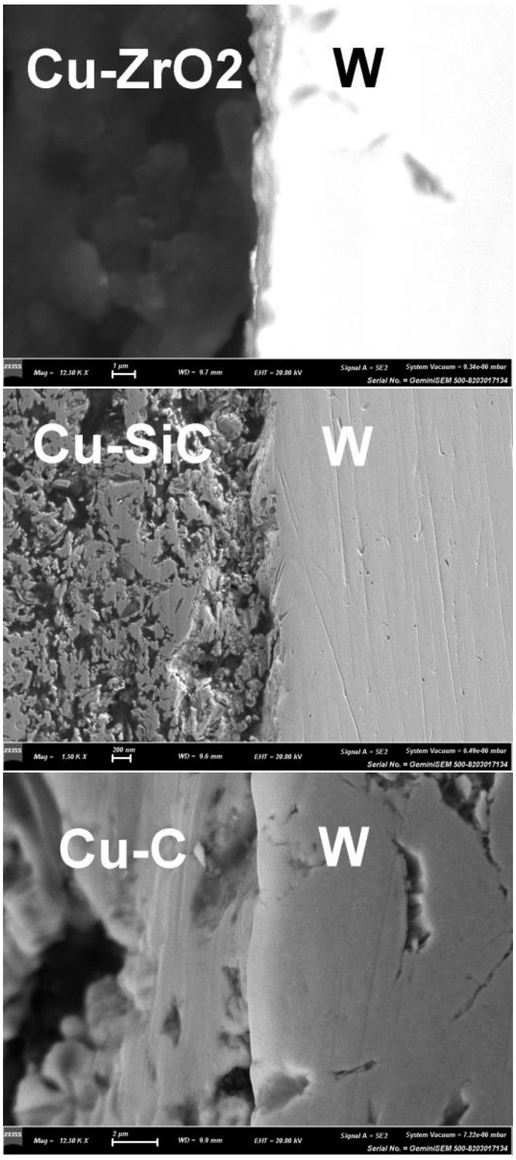

Fig. 7. Microstructure investigation of W-thermal barrier joints produced by FAST: top Cu-ZrO_2 (55% vol.); middle Cu-SiC (50% vol.); bottom Cu-C (65% vol.).

Keeping in mind that the 20º angled slices are not very easy to cut, we have tried in the next step to optimize the slices' geometry in order to decrease the number of slices and also to increase their angle. The best result up to now is shown in figure 6 c). The W-monoblock is here kept in the 300-1200 ºC temperature range while the CuCrZr pipe is also kept below 300 ºC. This could be achieved only with 3 different slices of 90º, 45º and 180º angles, corresponding to the numbers 1-3 from figure 6 C). The thermal conductivity values are in the same order 70, 2 and 1.5 W/m/K. These values are already obtained in the available composites and are displayed as horizontal lines in figure 2, with the corresponding numbered labels.

To test the W-thermal barrier joints quality we have examined the microstructure of such components using a high resolution FE-SEM. Since good W-Cu joints can be easily obtained by FAST [15,16], in order to obtain a relevant information we have firstly tested joint with thermal barrier having about 10 W/m/K thermal conductivities, corresponding to 55, 50 and 65 volume percent for ZrO_2, SiC and C, respectively. The results shown in figure 7 show that in all cases the W-Cu parts are consistently joined. For Cu-ZrO_2 and Cu-C materials, at these concentrations, during the SPS processing the Cu covers the ZrO_2 and C agglomerations of nanometric powders and therefore the contact to W is mostly from the Cu part. In the case of SiC the differences between Cu and SiC regions can be seen at sub-micron size but a roughly 50% of the contact surface is between Cu and W.

3. Conclusions

We have investigated the possibility to realize DEMO monoblock divertor components with an included thermal barrier interface using materials produced and joined by FAST. As TB, Cu-ZrO_2, Cu-SiC and Cu-C composites were produced with suited thermo-physical properties. A ring shaped thermal barrier interfaces can be designed and produced also with a graded composition. FEM simulations have shown that is possible to design a graded interface able to keep W between 300 ºC and 1200 ºC. The TB design optimization lead to a simple solution including only 4 components from 3 different thermal barrier materials. The processing route for such components was tested. Future work will be devoted to produce mock-ups with several monoblocks HHF tests.

Acknowledgments

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