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Preparation of the high heat flux materials for CFETR divertor

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China Fusion Engineering Test Reactor (CFETR) as a post-ITER thermonuclear fusion facility is to fill up the gap of ITER and fusion reactors, and will play most of the roles of a fusion demonstration reactor (DEMO). According to the new design of CFETR divertor, the maximal heat flux at the divertor targets will be up to 20 MW/m2. Therefore, water cooling divertor could be one of the best options. However, based on the ITER water cooling divertor design and its high heat load experiment data, divertor targets of monoblock structure made by high purity tungsten (W) and CuCrZr alloy can only sustain 10 MW/m2 steady-state heat flux and hundreds of cycles at 20 MW/m2 transient heat flux (10s). In order to meet the design requirements of CFETR divertor, the advanced tungsten and copper based materials with much better high temperature performances than pure W and CuCrZr alloy will be required in addition to the modifications of W/CuCrZr monoblock geometry.
Dispersion strengthening with nano-size oxide or carbide particles as the second phase doping is one of the most effective ways for improving the properties of pure W, especially for the recrystallization temperature and the strength, and combining with the appropriate thermoplastic processing technology, it is forseen to develop the advanced tungsten alloys both with high-temperature performances (high recrystallization temperature, RCT) and low-temperature ductility (low ductile-brittle transition temperature, DBTT). Up to now, two kinds of high performances tungsten alloys have been developed in China **1**, one is W-TiC alloy made by mechanical alloying and hot rolling process, the other one is W-Y2O3 alloy made by wet chemistry powder making and following by high energy rate forging (HERF) or swaging. Both of them have very high strength at room temperature and the elevated temperature, high recrystallization temperature (the final recrystallization temperature is up to 1600℃, much higher than that of pure W -1300℃) and very low DBTT (close to 100℃, much lower than that of pure W-400℃), meanwhile sustain relatively high thermal conductivity (close to pure W) as shown in figure 1. One kind of W-Y2O3 alloy even has room temperature ductility (DBTT is close to RT). In addition, wet chemistry powder making has the advantage of large-scale manufacturing compared with mechanical alloying, It may be an important development direction of advanced tungsten-based materials.

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Similarly, copper alloy as the heat sink of CFETR W/Cu divertor targets will work at higher temperature than ITER divertor. As we known, the upper temperature limit of long-term safety operation for CuCrZr alloy is 400-450℃ owing to its relative low high temperature strength and poor high temperature creep performances. In order to meet the operation requirements of CFETR divertor at 20 MW/m2 steady-state heat flux, the safety operation temperature of copper heat sink will have to be increased to 550-600℃. Nowadays, there are two main methods to improve the high temperature properties of copper heat sink, they are ODS-Cu normally by means of mechanical alloying and tungsten or SiC fiber reinforced copper, however, The former will face complex technological problems and difficult to scale production, and the latter would have to sacrifice the thermal conductivity of copper heat sink. Thereby, CuCrZrFeTiY alloy and casting ODS-Cu are studied in China. CuCrZrFeTiY alloy adopts the same fabrication technology with ITER grade IG-CuCrZr, but the Cr and Zr content are slightly increased, and Fe and Ti content are controlled to less than 0.3%, Y is about 0.06%. The purpose is to increase high melting point precipitates and the high friction of low-ΣCSL grain boundaries (mainly Σ3) with low energy detected in the matrix **2**. Casting ODS-Cu adopts Cu-Y-O amorphous parent alloy as the additives of Cu casting to ensure uniform distribution of nano-size Y_2O_3 precipitates. Preliminary results indicate that the UTS of the novel copper alloys is larger than 300 MPa at 600℃, and their operation temperature may increase by 100-150℃ compared with IG-CuCrZr alloy. Meanwhile, their thermal conductivity is still kept at a high level (~300 W/m.K). As an example, the tensile and hardness tests of the CuCrZrFeTiY alloy in the temperature range of 450-600℃ are shown in Fig.2.

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In a word, the present study on advanced tungsten and copper alloys could supply a solution of the CFETR divertor materials. The technology optimization for mass production and material's further characterization are under way.

1 Xiang Liu, et al, "Progress of advanced tungsten base materials developed for fusion applications in China", invited talk, ICFRM2019, LAS, USA,Oct.27-Nov.1, 2019.
2 Mingyang Li et al, "Microstructures and mechanical properties of the novel CuCrZrFeTiY alloy for fusion reactor", J. Nucl. Mater., 532 (2020)152063.
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