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Tungsten joining with copper alloy and its high heat load performance

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ABSTRACT

W–CuCrZr joining technology by using low activation Cu–Mn filler metal was developed at Southwestern Institute of Physics (SWIP) for the manufacturing of divertor components of fusion experiment devices. In addition, a fast W coating technology by chemical vapor deposition (CVD) was also developed and CVD-W/CuCrZr and CVD-W/C mockups with a W coating thickness of 2 mm were prepared. In order to assess their high heat flux (HHF) performances, a 60 kW Electron-beam Material testing Scenario (EMS-60) equipped with a 150 keV electron beam welding gun was constructed at SWIP. Experimental results indicated that brazed W/CuCrZr mockups can withstand 8 MW/m^2 heat flux for 1000 cycles without visible damages and CVD-W/CuCrZr mockups with W–Cu gradient interface can survive 1000 cycles under 11 MW/m^2 heat flux. An ultrasonic inspection method for non-destructive tests (NDT) of brazed W/CuCrZr mockups was established and 2 mm defect can be detected. Infinite element analysis and heat load tests indicated that 5 mm defect had less noticeable influence on the heat transfer.

1. Introduction

Recently a full-tungsten divertor configuration was determined from the beginning operation phase of ITER [1]. Two kinds of W/CuCrZr mockup structure are considered as ITER divertor components, one is the monoblock structure used for the target plates and another one is the flat structure used for the dome regions. The former one will be manufactured by pure copper casting followed by hot isostatic pressing (HIP) or hot radial pressing (HRP) and the latter one will be fabricated by brazing technology. The present research indicated that flat type W/CrCrZr mockups made by brazing have the capability of enduring at least 7 MW/m^2 steady state heat flux [2] and small scale mockups can withstand even up to about 20 MW/m^2 heat flux [3]. A fast brazing technology of W–Cu and Be–Cu joining has been developed by Russia, and the semi-prototype qualification of W/CuCrZr and Be/CuCrZr mockups is ongoing [4,5]. According to the fusion development strategy of China, a Chinese fusion experiment testing reactor (CFETR) is being designed and an ITER-like divertor wall might be installed during the first operation phase. Meanwhile, a new tokamak machine HL-2M is being constructed and experiments using tungsten as plasma facing material are planed. Therefore, flat structure W/CuCrZr joining technology and a fast W coating technology by chemical vapor deposition (CVD) on graphite or CuCrZr substrates [6] were developed for the purposes above since the carbon base materials were designed as the original structure of the HL-2M first wall, and W as first wall material could easily be realized by coating technology without replacement of the plasma facing components.

Up to now, W/CuCrZr brazing technology has been optimized and series mockups from 25 × 25 mm to 50 × 200 mm have been manufactured [7], component unit with a size of 50 × 400 mm and hypervapotron cooling channel are being fabricated. CVD-W coated graphite was prepared by PVD (physical vapor deposition) using Mo or Si as an interlayer with a thickness of 10–20 μm, and CVD-W coated CuCrZr was made by means of graded W–Cu layers as the interface. In order to evaluate the joining quality, the microstructure and chemical composition of the joining region were analyzed, and the bonding strength was measured both by shear strength and tensile strength tests. An ultrasonic inspection technology was developed for non-destructive test (NDT) of brazed W/CuCrZr mockups and a 60 kW Electron-beam Material testing Scenario (EMS-60) was constructed for the high heat load assessments [8]. In addition, numerical simulations based on finite element (FE) analysis using the ANSYS code was also applied for the structural design and comparison with experiments. In this paper, the HHF mockup fabrication both by W–CuCrZr braze joining and CVD-W coating technology, and their characterization are reviewed.

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2. Experimental

2.1. W–CuCrZr braze joining and CVD-W coated mockups

Tungsten blocks used for W/CuCrZr braze joining are supplied by Xiamen Honglu Tungsten Molybdenum Industry Co., Ltd. (XTC). This material has a purity of 99.95% and made from hot rolling state. Its average grain size is about 150 μm, and its main thermo-mechanical properties meet the requirements of ITER grade W plates besides high temperature strength, which slight lower than the requirement of ITER. CuCrZr alloy was supplied by Chinalco Luoyang Copper Co., Ltd. in agreement with the ITER specification of CuCrZr alloy, and the as-received CuCrZr blocks were made by solid solution, cold rolling and aging treatments [9]. Two kinds of Cu–Mn filler metals were prepared by vacuum melting followed by forging machining and cold rolling into foils with a thickness of about 0.1 mm, in which one has 1 wt.% nickel addition with the purpose of improving the wettability of filler metal with W armor and CuCrZr base. In order to reduce the impurity contents, especially the oxygen content, multiple melting processes are adopted. The composition and processes of the filler metals are summarized in Table 1 and it can be seen that re-melting processes can reduce the oxygen content significantly. Two filler metals have been used for W–CuCrZr brazing and no obvious difference was found [10]. Nowadays only filler metal No. 1# without Ni is used for brazing joining for low activation reasons.

The melting temperature of the developed Cu–Mn filler metals is about 900 °C, which allows the brazed W/Cu mockups to withstand high heat load without failure due to melting of the filler metal. However, how to maintain the properties of CuCrZr alloy will be a key issue for high temperature brazing since the high braze temperature will induce grain growth and strength loss of CuCrZr alloy, therefore a fast cooling followed by aging treatment was used for the brazing process. The brazing process has been optimized, optimized technique shown schematically in Fig. 1. The braze process was as follows: after W tiles, filler metal foils and CuCrZr substrates were installed in the vacuum furnace, the temperature was increased to 400 °C and kept for 1 h for sufficiently degassing, then rapidly heated to the braze temperature of about 950 °C for 10–15 min incubation time, after that fast cooling by introducing Ar gas into the vacuum chamber to cool down the brazed mockup with a cooling rate of more than 60 °C/min. and sustain at 480 °C for 1–2 h. Finally the mockup was naturally cooled to room temperature. This brazing process was similar to solid solution and aging treatment of the CuCrZr alloy, in this way the strength loss of the CuCrZr alloy can be controlled within 20%. Using this technology W/CuCrZr brazed mockups from small size (25 × 25 mm) to intermediate size (50 × 200 mm) have been manufactured successfully.

On the other hand, CVD-W coating with a fast deposition rate up to 0.5 mm/h has been developed in cooperation with XTC, which has relatively big columnar grains of about 50 × 1000 μm and very high purity up to 99.9999% with a fluorine content lower than 0.1 ppm. The density, thermal diffusivity, thermal conductivity, coefficient of thermal expansion and hardness of the CVD tungsten are similar to commercial pure tungsten [6]. Small size mockups of CVD-W coated graphite with 20 μm PVD-Si interlayer and CVD-W coated CuCrZr alloy with graded W–Cu interfaces have been prepared for high heat flux tests, more details can be found in the references [8,11].

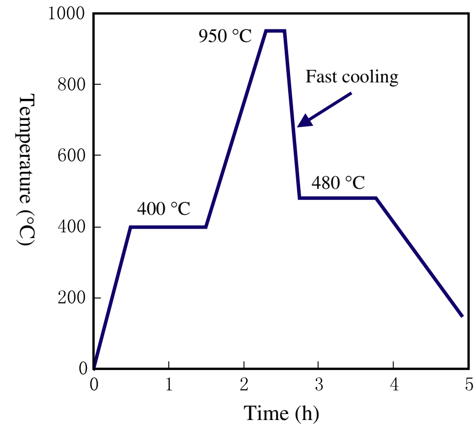

Fig. 1. The technical process of W/CuCrZr braze joining.

2.2. Characterization of the brazed and CVD-W coated mockups

In order to characterize the brazed W/CuCrZr mockups, the interface microstructure and element distribution were analyzed and a good joining structure was observed [10]. The shear strength and tensile strength of W/CuCrZr joints were measured and a shear strength higher than 65 MPa and a tensile strength larger than 130 MPa were achieved. The tensile testing results of three samples with length of 50 mm and thickness of 3 mm are shown in Fig. 2, it shows the characteristics of brittle fracturing and the fracture occurs at the joining surface of the filler and tungsten. This result indicates that a pure copper compliant layer is required to improve the bonding performance, and this work is ongoing. As for CVD coated mockups on graphite or CuCrZr bases, a bonding strength of more than 50 MPa was measured by means of a glue stick test.

NDT was another important assessment method for brazed mockups. A standard defect mockup was prepared by drilling dif-

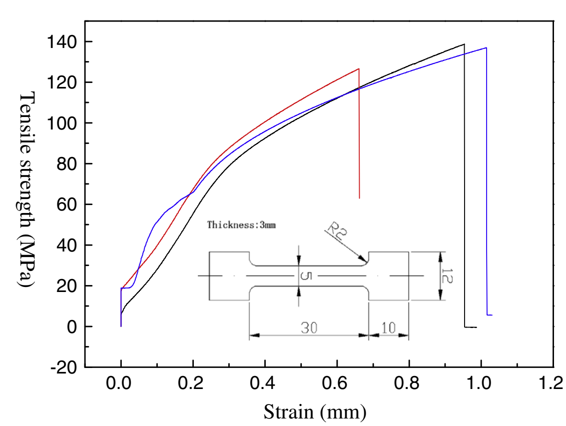

Fig. 2. Tensile tests of W/CuCrZr braze joints.

Table 1
Main chemical compositions of the Cu–Mn filler metals.

Types	Cu (wt.%)	Mn (wt.%)	Ni (wt.%)	O (ppm)	Processes
1#	75	25	/	126/42	Re-melting for once/twice
2#	74	25	1	122/40	Re-melting for once/twice