



# Microstructural and mechanical characterizations of W/CuCrZr and W/steel joints brazed with Cu-22TiH<sub>2</sub> filler

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## ABSTRACT

Microstructural characterizations of both W/CuCrZr and W/SS301 (stainless steel 301) joints reveal the favorable bonding of the filler to the substrates and negligible occurrence of inter-diffusions (or interfacial reactions) at the W/filler layer interface. The filler layer of W/CuCrZr joint is mainly made up of Cu-based solid solution (Cu (ss)) and intermetallic Ti-Cu phases. In the case of the W/SS301 joint, the filler layer comprises Cu (ss) and intermetallics including Ti-Cu and Ti-Fe. A reaction layer of Fe<sub>2</sub>Ti with a thickness of about 10 μm is formed adjacent to the filler layer through the reaction of Ti with Fe from the SS301 substrate. A diffusion layer containing σ-phase is developed at the interface between the Fe<sub>2</sub>Ti reaction layer and the SS301 substrate. The mechanical characterizations including microhardness and shear strength of both W/CuCrZr and W/SS301 joints have been performed. The results of microhardness in the interfacial zone are highly related to the joint microstructure.

## 1. Introduction

Tungsten (W) and its alloys are of great interest for electrical and nuclear applications thanks to their desirable properties such as excellent high-temperature resistances, relatively low coefficients of thermal expansion, high thermal conductivities and superior radiation resistances. However, there are still some stumbling blocks (e.g., brittleness and poor workability) which restrict their applications. In some cases, applications of W and its alloys depend extensively to the successful joining and integration techniques. For instance, Chen et al. (2015) demonstrated that fabrication of W-type divertors in the fusion reactors may greatly rely on the joining of W to Cu or to steels.

Several joining techniques have been developed to join W to Cu and to steels, such as diffusion bonding, hot isostatic pressing (HIP) bonding, pulse plasma sintering, explosive joining and brazing, etc. Krauss et al. (2017) investigated the diffusion bonding of W to Cu parts using an interlayer of 10 μm-thick Pd by electroplating. Zhong et al. (2010) studied the diffusion bonding of W to ferritic steel with a nickel interlayer and the influence of bonding temperature on the microstructure and strength of joints. Saito et al. (2002) conducted the HIP bonding of W to Cu using oxygen-free copper and Au foil as intermediate layers. Rosiński et al. (2011) fabricated a W/Eurofer 97 steel joint with four different interlayers by pulse plasma sintering method.

Li et al. (2007) developed the explosive joining of W to Cu.

Janczak-Rusch (2011) illustrated that brazing was highly effective due to its simplicity, reliability and good repeatability. With respect to the brazing of W to Cu or to steels, extensive studies have been performed and various fillers have been developed. Easton et al. (2016) introduced the eutectic Au-Cu filler for brazing W to Cu and to 316L austenitic steel. Liu et al. (2014) investigated the W/CuCrZr brazing with low activation Cu-Mn filler for the divertor components fabrication. Premjit Singh et al. (2017) studied the vacuum brazing of W-Cu bimetallic material (Cu casting on W) to CuCrZr with NiCuMn-37 filler at 1243 K for 10 min. Qu et al. (2014) developed the Ti-Zr based amorphous filler jointly with (or without) interlayers for brazing W/CuCrZr and discovered that the average strength of the joint with Cu/Mo interlayers reached 140.8 MPa, remarkably higher than that obtained without interlayer (16.6 MPa).

Munoz et al. (2011) studied the laser brazing of W to Eurofer steel using a 55Ni-45Ti alloy as filler. Zhang et al. (2014) prepared the brazed joints including W/Cu, W/Eurofer97 and W/SS316L with a thin Au-Cu-Fe braze foil (Au80Cu19Fe1, in wt.%). de Prado et al. (2017a,b) evaluated the mechanically alloyed 80Cu-20Ti powders as filler for brazing W to Eurofer and obtained the joints with shear strength of 94 ± 23 MPa. Zhu et al. (2017) designed three-layered Ti-Fe-Sn thin film assemblies for brazing W to steel (CLF-1 RAFM) at 1363 K. Cai

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et al. (2015) developed the diffusion brazing of W to steel using Ti-Ni liquid forming interlayer at 1323 K. Liu et al. (2016) investigated the brazing of W to steel with Ni-Cr-Si-Bi based amorphous fillers and introduced Ta and Cu interlayers for the relaxation of residual stresses of joints.

In this study, vacuum brazing of W to a copper alloy (CuCrZr) and to an austenitic stainless steel (SS301) have been carried out at 1173 K using Cu-22TiH<sub>2</sub> filler. The microstructure and mechanical properties of joints have been characterized. It is expected that this study can provide useful information on joining of W to Cu-based and Fe-based alloys for fusion applications.

## 2. Experimental

The W substrates with a density of 19.13 g/cm<sup>3</sup> and dimension of 10 × 10 × 5 mm<sup>3</sup> were supplied by Zhuzhou Cemented Carbide Cutting Tools Co., Ltd. (China). The CuCrZr alloys (0.4 ~ 1 wt% Cr, 0.03 ~ 0.15 wt% Zr, other Cu) and SS301 alloys (16.0 ~ 18.0 wt% Cr, 6.0 ~ 8.0 wt% Ni, max. 2.0 wt% Mn, max. 1.0 wt% Si, max. 0.15 wt% C, max. 0.045 wt% P, max. 0.03 wt% S, other Fe) were joined to the W substrates. The CuCrZr with a density of 8.90 g/cm<sup>3</sup> and SS301 with a density of 7.8 g/cm<sup>3</sup> were supplied by Shenzhen Heshuo Metal Products Co., Ltd. (China) and Wuxi Taiyao Metal Products Co., Ltd. (China), respectively. The CuCrZr and SS301 samples were machined to the cubic pieces with dimension of 10 × 10 × 10 mm<sup>3</sup>. The joining surfaces of all the samples were processed by polishing with 1.0 μm diamond paste and subsequently by ultrasonic cleaning in alcohol for 30 min.

The Cu-22TiH<sub>2</sub> filler (denoting the composition of 78 wt% Cu and 22 wt% TiH<sub>2</sub>) used for joining W to CuCrZr and to SS301 was prepared by ball milling the mixtures of copper and TiH<sub>2</sub> powders. The detailed description of Cu and TiH<sub>2</sub> powders can be found elsewhere (Mao et al., 2015).

The Cu-22TiH<sub>2</sub> paste was obtained by mixing the filler powders with a little glycerin. Then, the paste was applied to the polished surfaces of joining samples. Fig. 1 shows the assembly schematic for brazing W to CuCrZr or to SS301 using Cu-22TiH<sub>2</sub> filler. A pressure of 9.6 kPa was applied on the assembly to ensure an intimate contact of the filler to the substrates.

The high temperature brazing of W to CuCrZr and to SS301 were performed under a vacuum of  $4.0 \times 10^{-2}$  Pa. The assembly was heated to 773 K at a rate of 10 K/min and held for 1 h to volatilize the binder in the filler. After the temperature increased to 973 K at a rate of 10 K/min and was stabilized for 30 min to decompose TiH<sub>2</sub> powders, the assembly was heated to the brazing temperature of 1173 K at a rate of 5 K/min, held for 10 min and cooled down to room temperature by furnace cooling.

The polished cross-sections of the W/CuCrZr and W/SS301 joints were examined with a JEOL JXA-8230 electron probe micro-analyzer

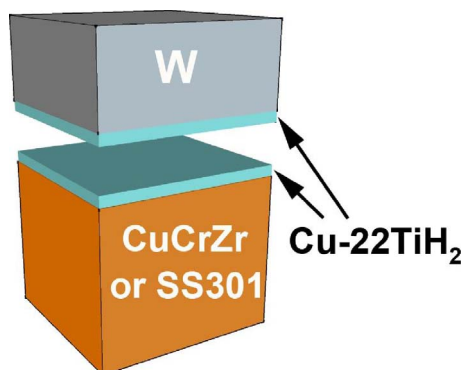


Fig. 1. Schematic of the assembly for brazing W to CuCrZr and to SS301 using Cu-22TiH<sub>2</sub> filler.

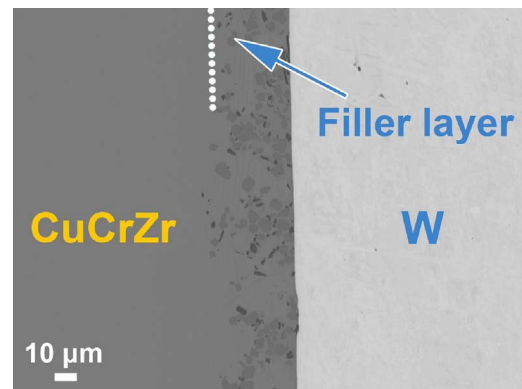


Fig. 2. Microstructure image of the interfacial zone in the W/CuCrZr joint brazed with Cu-22TiH<sub>2</sub> filler.

(EPMA) and an Oxford Inca X-Act energy-dispersive X-ray spectrometer (EDS). The phases of the interfacial zone of joints were detected with a Bruker D8 Advance X-ray diffraction spectrometer (XRD) with Cu-Kα radiation at 40 kV.

The microhardness and shear strength of both the W/CuCrZr and W/SS301 joints were measured. The microhardness measurements were performed on the brazed joints and as-received substrates using a HXS-1000AKY Vickers indenter with an applied force of 0.98 N and a dwell time of 10 s. The average hardness was calculated by more than three indentations measured on the similar areas of joints. The shear strength of W/CuCrZr and W/SS301 joints was determined using a GP-TS2000 s electronic universal materials testing machine as described schematically by Mao et al. (2015).

## 3. Results and discussion

### 3.1. W/CuCrZr joint

Fig. 2 shows the microstructure image of the interfacial zone in the W/CuCrZr joint brazed with Cu-22TiH<sub>2</sub> filler at 1173 K for 10 min. A filler layer with a thickness of about 30 ~ 50 μm can be observed between W and CuCrZr. The interfacial zone is free of structural imperfections such as cracks or voids, revealing an intimate interfacial bonding of the filler to the substrates.

Fig. 3 displays the magnified micrograph and the corresponding EDS maps of the interfacial zone in the W/filler layer side of the joint. The EDS maps shown in Fig. 3b–d indicate that the filler layer primarily contains elements Cu and Ti. More specifically, the element Cu is enriched in the grey matrix, whereas the element Ti mainly exists in the dark-grey and dark zones dispersed in the matrix. It is noted that no element W is observed in the filler layer and neither element Cu nor Ti is detected in the W substrate. A similar observation was obtained by de Prado et al. (2016), who claimed that the brazing temperature of 1233 K was not high enough to cause inter-diffusions or interfacial reaction between W substrate and Cu-Ti filler layer. Therefore, it is conceivable that neither inter-diffusions nor interfacial reactions occur at the W/filler layer interface at 1173 K (brazing temperature).

The compositions of microzones in the filler layer have been determined by EDS measurements and the corresponding data are shown in Table 1. The grey microzone A in the filler layer consists of elements Cu (88.15 at.%) and Ti (11.85 at.%), determined as Cu-based solid solution (Cu (ss)) with minor intermetallic Ti-Cu. The EDS result of grey microzone B also reveals the formation of Cu (ss) and Ti-Cu phases, but relatively much Ti exists in the acicular structure area. The grey microzone C close to the W/filler layer interface shows a composition of Cu (80.06 at.%) and Ti (19.94 at.%), corresponding to TiCu<sub>4</sub> phase. Both the dark-grey microzone D and the dark microzone E are inferred to Ti-Cu phases on account of the corresponding compositions listed in

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