Fusion Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Investigation of tungsten/steel brazing using Ta and Cu interlayer

Wensheng Liu, Zixuan Wang, Yunzhu Ma*, Qingshan Cai

State Key Laboratory for Powder Metallurgy, Central South University, Changsha 410083, PR China

ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 11 October 2016
Accepted 4 November 2016
Available online xxx

Keywords:
Tungsten
Steel
Brazing
Interlayer
Residual stress

ABSTRACT

The brazing processes, using Ta and Cu interlayer respectively, were carried out to study the joining of W and steel with Ni–based amorphous foil filler. The W/Ta/steel and W/Cu/steel joints were conducted in vacuum at 1050 °C for 1 h. The interfacial microstructure and mechanical properties of joints were investigated by scanning electron microscopy (SEM), energy dispersive spectrometer (EDS) and tensile strength measurement. The results show that a reliable bonding between W and steel could be obtained by using both Ta and Cu interlayer. The fracture sources of W/steel brazing joints were predominantly in the tungsten substrate near the brazing seam, which agrees reasonable well with the calculation result of finite element method (FEM). The average tensile strength of W/Ta/steel and W/Cu/steel joints were 257.8 MPa and 276.7 MPa respectively. Comparing with hard interlayer Ta, soft interlayer Cu could reduce residual tress in W substrate and improve the mechanical property more effectively.

1. Introduction

The divertor components of fusion reactors facing plasma directly suffer high surface corrosion and thermal load from high–energy particles, which requires the usage of high temperature resistant and low–activation materials [1,2]. Favorable materials are tungsten and ferritic/martensitic steel. According to the design, the joining of W to reduced activation ferritic/martensitic steel is required for using as a component [3]. However, the physical and chemical properties have significant differences between W and steel, especially in elasticity modulus and coefficient of thermal expansion ($\alpha_W = 4.5 \times 10^{-6} K^{-1}$, $\alpha_{steel} = 12 \sim 14 \times 10^{-6}\ K^{-1}$). For this reason, the direct bonding of W and steel will cause a high thermal stress generated in the bonding interface during cooling, and lead to the poor joint strength even failure in manufacturing and service [4]. W. W. Basuki et al. [5] investigated the direct bonding of tungsten and EUROFER97. The result showed that the bonding seam was not able to endure the thermal loading and failed during PBHT (post bonding heat treatment).

Numerous studies proposed that adding insert materials could accommodate the physical and chemical incompatibility between dissimilar materials, and reduce the residual stress generated during the cooling process [6–8]. Therefore, Ta and Cu were chosen in this study to investigate the joining of W and steel. As hard interlayer material Ta, its thermal expansion coefficient ($\alpha_{Ta} = 6.5 \times 10^{-6}\ K^{-1}$) can accommodate the mismatch between W and steel. The soft metal Cu has lower elastic modulus and yield strength, which could relieve the residual thermal stress [9].

The objective of present work is to fabricate brazing joint of W and steel using Ni–based filler. Ni–based amorphous foil filler is widely used in the brazing of W and steel since its excellent wettability and mobility, strength, resistance to oxidation and low melting temperature [10,11]. Ta and Cu slices were chosen as residual stress compensation immediate layers respectively. W/steel brazed joints using Ta and Cu interlayer were studied both experimentally and theoretically, and compare the influence of different interlayer material on residual stress of the W/steel joint.

2. Experimental procedure

A commercial available pure W (99.95% purity) and a high–Cr ferritic stainless steel (Fe–17Cr–0.1C, wt.%) were used as base materials in this study. And samples were cut into the size of φ20 mm × 13 mm. The filler metal used for brazing was a 20–μm–thick sheet of the Ni–based amorphous alloy (Ni–7Cr–5Si–3B, wt.%). A 0.5 mm thick Ta (99.9% purity) and Cu (99.9% purity) were chosen as intermediate material for relieving residual thermal stresses. The prepared materials, assembled in the structure of W/Ta/steel and W/Cu/steel as shown in Fig. 1, were mounted in a graphite mold. The brazing of the assemblies was performed at 1050 °C for 1 h in vacuum (<10^{-3} Pa) in a hot pressing furnace (HI–MULTI–10000), and cooled down to 650 °C at a rate of 5 °C/min. The joining process curve is shown in Fig. 2.

* Corresponding author.
E-mail addresses: zhuzipm@csu.edu.cn, yunzhum@163.com (Y. Ma).

http://dx.doi.org/10.1016/j.fusengdes.2016.11.004
0920-3796/

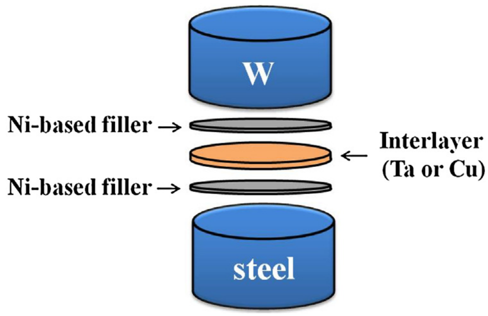

Fig. 1. Schematic diagram of assembly structure of the W/steel brazed joint.

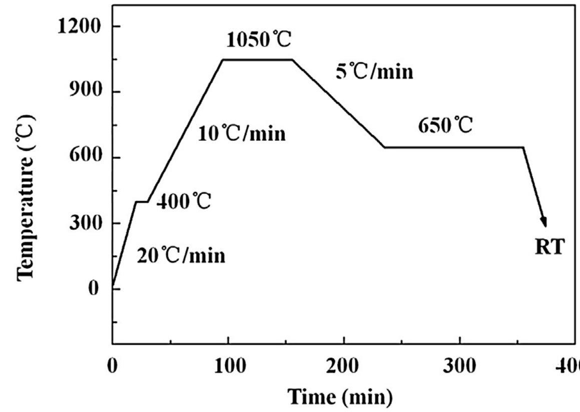

Fig. 2. The process curve of W/steel brazing.

The cross–sections of the welding joint were prepared for metallographic examination by standard polishing techniques. The microstructures were observed with scanning electron microscope (SEM) and electron probe microanalysis (EPMA) to investigate the diffusion zone structure. The tensile strength of the diffusion joint was evaluated with sub–size specimens at room temperature in a tensile testing machine (Instron–3369) at a crosshead speed of 1 mm/min. The original diffusion seam is at the center of the gauge section of the tensile samples. Tensile fracture surfaces were observed in secondary electron mode of SEM using EDS to reveal the nature.

3. Results and discussion

3.1. Microstructure characterization

Figs. 3 and 4 show scanning electron micrographs of W/Ta/steel and W/Cu/steel joints respectively. Both joints were successfully bonded using Ta and Cu interlayer. The W/Ta/steel joint and the high magnification detail of the W/Ta, Ta/steel interfaces are shown in Fig. 3 (a), Fig. 3 (b) and Fig. 3 (c) separately. It can be observed

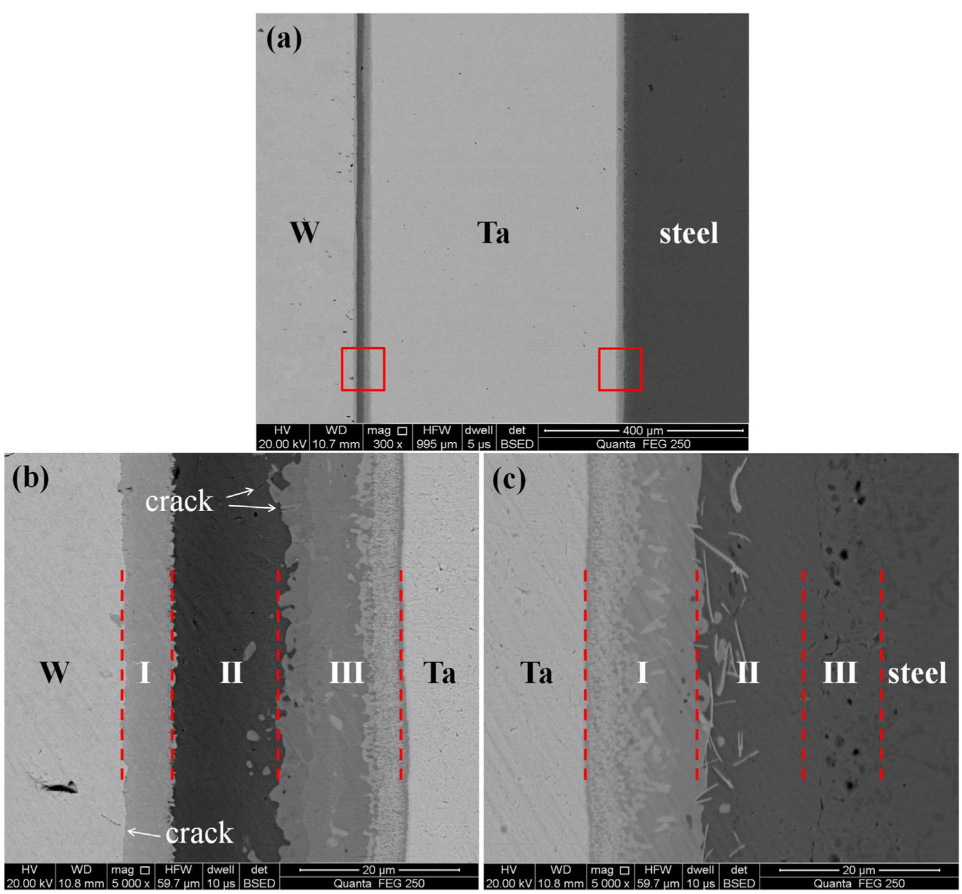

Fig. 3. SEM images of the W/Ta/steel joint.
(a) General view
(b) High magnification detail of the W/Ta interface
(I: W/filler diffusion layer II: filler layer III: filler/Ta diffusion layer)
(c) High magnification detail of the Ta/steel interface
(I: Ta/filler diffusion layer II: filler layer III: filler/steel diffusion layer)

Please cite this article in press as: W. Liu, et al., Investigation of tungsten/steel brazing using Ta and Cu interlayer, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2016.11.004

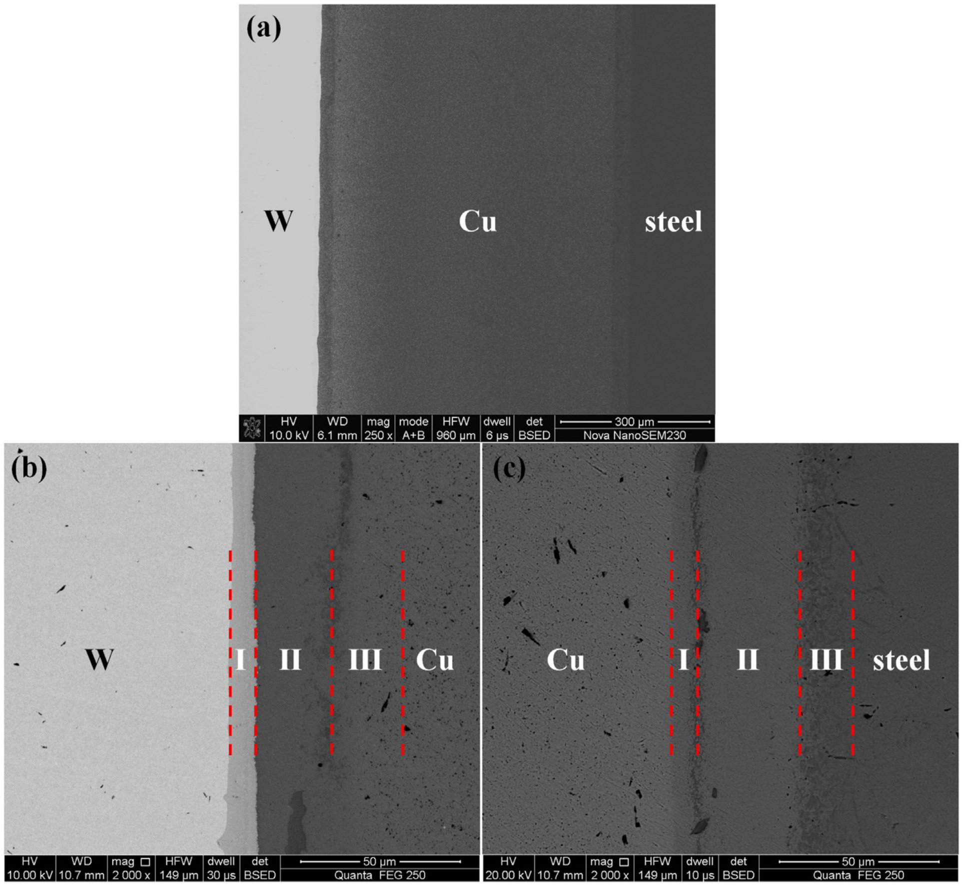

Fig. 4. SEM images of the W/Cu/steel joint.
(a) General view
(b) High magnification detail of the W/Cu interface
(I: W/filler diffusion layer II: filler layer III: filler/Cu diffusion layer)
(c) High magnification detail of the Cu/steel interface
(I: Cu/filler diffusion layer II: filler layer III: filler/steel diffusion layer)

that a certain amount of interdiffusion has occurred between the Ta interlayer and two substrates. The W/Ta interface includes W/filler diffusion layer, filler layer and filler/Ta diffusion layer. The Ta/steel interface consists of Ta/filler layer, filler layer and filler/steel layer. All interfaces were smooth and compact, and only a few cracks exist near to W/filler and filler/Ta interfaces (Fig. 3 (b)). This may due to the different atomic size of W, Ni and Ta, and the enhanced interaction at interfaces [12]. As for the W/Cu/steel joint and the high magnification detail of the W/Cu, Cu/steel interfaces shown in Fig. 4 (a), Fig. 4 (b) and Fig. 4 (c), the W/Cu interface includes W/filler diffusion layer, filler layer and filler/Cu diffusion layer. And the Cu/steel interface consists of Cu/filler layer, filler layer and filler/steel diffusion layer. The joint appeared to be sound, without cracks, pores or breaks existing in all interface areas. The corrugated deformation pattern occurred in these diffusion interfaces, which would benefit the joint strength [13]. Chen et al. [14] reported that the roughness of contact surfaces contribute to a sound bonded joint.

3.2. Mechanical properties

The reality and strength of the W/steel brazed joint are essential to its practical application. Tensile tests with miniaturized specimen of the bonded sample were carried out at room temperature. The experimental result is shown in Fig. 5. It indicates that a higher mechanical strength of the W/steel joint was obtained by using soft interlayer Cu (276.7 MPa), while the average strength of the W/Ta/steel joint was 257.8 MPa.

From the macroscopic view, both W/Ta/steel and W/Cu/steel tensile samples were broken at welding seam. The microstructure of the typical fracture surface and the EDS analysis on the W side of the W/Cu/steel joint are shown in Fig. 6. The rupture surface is characterized by the appearance of faceted grains, which indicated that the brazing joint failed in a typical brittle mode. It can be seen from the EDS analysis that the percentage content of W atomic on fracture surface is close to 100%. It means that the typical fracture of

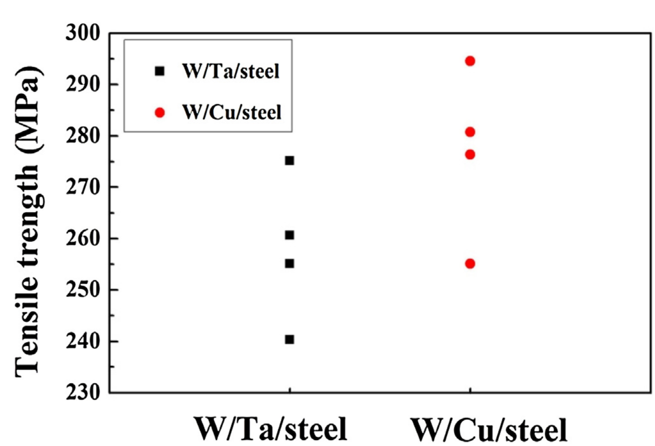

Fig. 5. Tensile strength of W/Ta/steel and W/Cu/steel joints.

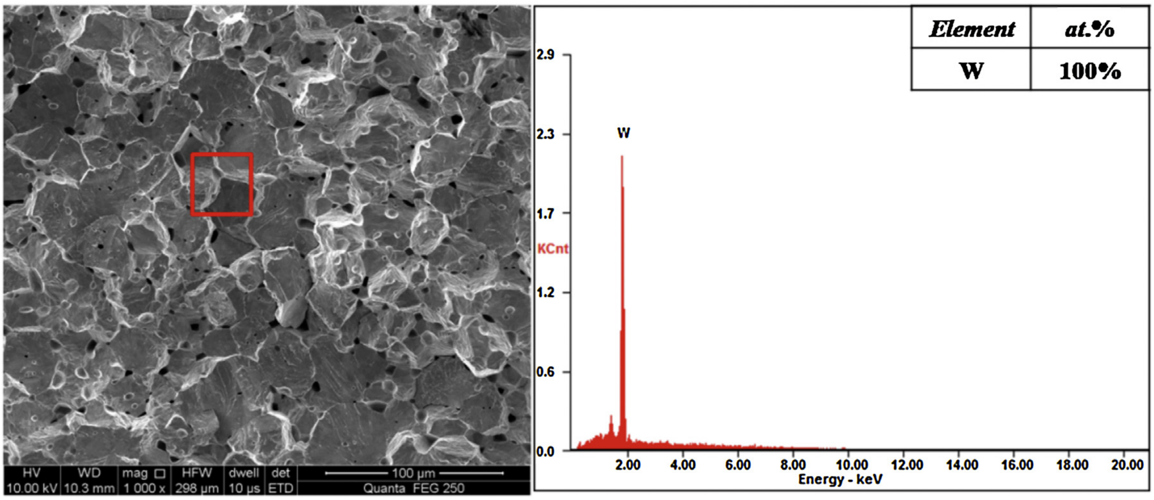

Fig. 6. The fracture appearance and EDS analysis of the W/Cu/steel joint.

the W/Cu/steel joint took place predominantly in W substrate adjacent to W/filler interface where the residual stress concentrated. It is consistent with the report studied by Conzone et al. [15] that the pre–induced residual stresses located adjacent to the joining interface in low CTE material.

Most of the W/Ta/steel tensile samples show the similar fracture characteristic as the W/Cu/steel joint (Fig. 6). The rest few of fracture appearance for the W/Ta/steel joint is shown in Fig. 7. Some phases on the fracture surface were identified as containing W, Ni and Cr by EDS. The fracture surface consists of three regions. Region A owes a lighter color and smooth cover. The percentage of

Table 1
Physical and mechanical properties employed in FEM.

Material	T (°C)	E (MPa)	ν	CTE (10^{-6}/°C−1)	σ_s (MPa)	E_{tan} (MPa)
W[a]	20	397938	0.275	4.65	1360.5	39000
	200	397270	0.28	4.71	1154.17	39737
	400	394480	0.283	4.86	947.86	39448
	600	389508	0.286	5.0	764.79	38951
	700	386210	0.289	5.07	681.67	38621
	900	377970	0.292	5.22	531.74	37797
	1050	370370	0.3	5.31	433.09	37037
Steel[a]	20	217260	0.31	10.4	500	21726
	200	207327	0.31	11.2	453	20733
	400	197123	0.31	11.9	402	19712
	600	177589	0.31	12.5	194	17759
	700	161024	0.31	12.6	100	16102
	900	155800	0.31	12.8	21	15580
	1050	130000	0.31	12.9	15	13000
Ni[b]	20	208000	0.31	15.45	148	20800
	227	197000	0.31		140	19700
	327	190000	0.31	16.1	138	19000
	527	174000	0.31	16.65	100	17400
	627	166000	0.31		69	16600
	727	158000	0.31	17.75	59	15800
	827	150000	0.31		45	15000
	1100	142000	0.31	19.85	20	14200
Cu[c]	20	130000	0.35	17.2	350	13000
	200	106000	0.35	18.5	150	10600
	400	70735	0.35	20.0	80	7073
	600	20151	0.35	20.1	10	2015
	800	7000	0.35	20.2	5	700
	1050		0.35	20.3		
Ta[c]	20	182000	0.31	6.5	400	18200
	200	181600	0.31	6.6	360	18160
	400	181300	0.31	6.7	330	18130
	600	180000	0.31	7.0	260	18000
	800	177000	0.31	7.4	180	17700
	1000	175000	0.31	7.8	120	17500
	1200	173000	0.31	8.0	90	17300

[a] Date from [4,15] and the TMA experiment.
[b] Date from [16].
[c] Date from [17] and the TMA experiment.

Please cite this article in press as: W. Liu, et al., Investigation of tungsten/steel brazing using Ta and Cu interlayer, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2016.11.004

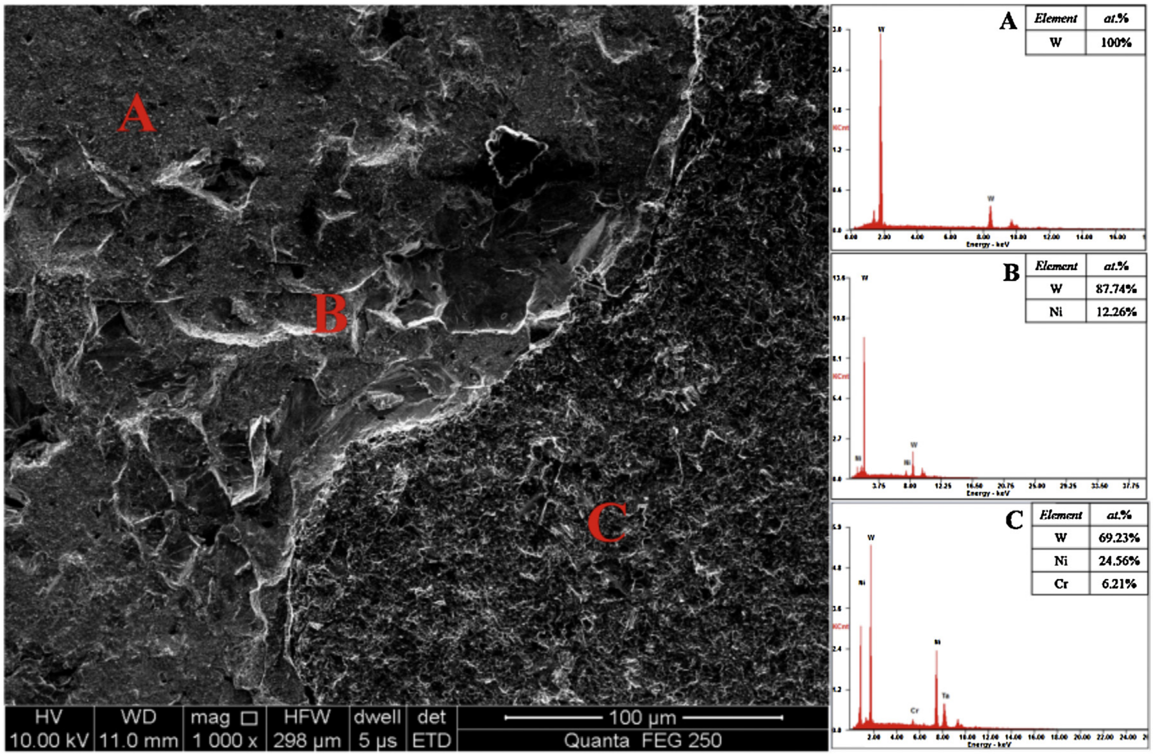

Fig. 7. The fracture appearance and EDS analysis of the W/Ta/steel joint.

W atomic here is almost 100%, which suggested that region A is in substrate W adjacent to the welding seam. The average composition of region B, covered with grooves that possessed river structure and tearing trace, identified by EDS is W (∼87.74 at%), Ni (∼12.26 at%). The cover of region C is flat and in dark color. It contains a little tearing trace. Region C is comprised of W (69.23 at%), Ni (24.56 at%) and Cr (6.21 at%). So, the mixed phase between W and Ni was likely to exist in region B and C. From analysis above, the fracture of the W/Ta/steel joint occurred in a mixed type, and belonged to the brittle mode. Most of fracture surface lie in W substrate near to the bonding interface, while others locate in W/Ni–based filler diffusion zone. It can be speculated that the crack was generated in W substrate near to the interface firstly, and then extended to W/filler diffusion zone.

Owing to the large difference in thermal shrinkage between W and steel, the thermal stress was induced during quickly cooling from brazing temperature to RT. The thermal stress concentrated in the bonding joint can significantly affect the mechanical property and failure feature of the joint. Therefore, it is essential to do the further research on residual stress distribution of the W/steel joint.

3.3. Residual stress distribution

The residual stress of W/Ta/steel and W/Cu/steel joints was investigated by FEM calculations. The model consists of Cu (0.5 mm thick) and Ta slice (0.5 mm thick) respectively as interlayer to join W and steel. Because of the axial symmetry with respect to the Y–direction of the divertor modules (Fig. 8 (a)), a symmetrical stress distribution was considered, which allowed reduction to a 2D model for reducing the computational time. The division of the finite element mesh is shown in Fig. 8 (b). Based on thermomechanical analysis (TMA) experiments and some references [4,16–18], the material properties employed are shown in Table 1.

Fig. 9 (a), (b) shows the maximum value of axial (σ_r) and radial (σ_Y) residual stress for W/Ta/steel and W/Cu/steel joints. It can be seen from Fig. 9 (a), whether axial or radial tensile stress, the maximum of Ta interlayer is higher than Cu interlayer. Similarly in Fig. 9 (b), axial and radial compressive stress of Ta and Cu indicate the same rule. It means that comparing with hard interlayer Ta, soft interlayer Cu has an advantage in relaxing thermal stress by plastic deformation [19]. This is consistent well with the previous experimental result that the W/Cu/steel brazed joint obtained the higher

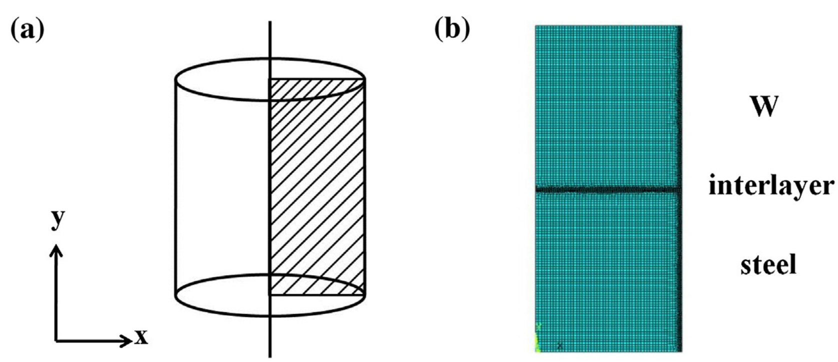

Fig. 8. (a) The simplified schematic diagram of the model geometry. (b) The mesh configuration used in the FEM calculation.

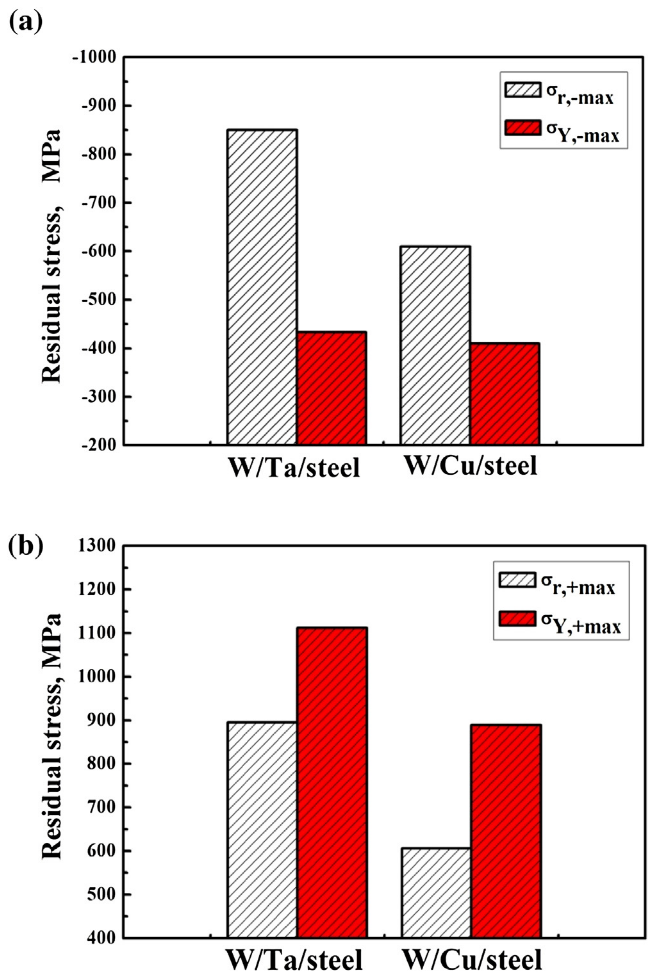

Fig. 9. The maximum value of residual stress for W/Ta/steel and W/Cu/steel joints. (a) $\sigma_{r,-max}$ and $\sigma_{Y,-max}$ (b) $\sigma_{r,+max}$ and $\sigma_{Y,+max}$.

strength than the W/Ta/steel joint. Ai Pingxian et al. [20] chose Cu and Mo to study the effect of soft or hard interlayer on the joining strength of ceramic/steel joint. They found that the relaxation of the residual stress by the creep or yield mechanism will be up to about 90% or more. So, relieving interfacial stress by using soft interlayer is much more effective than by accommodating the thermal expansion mismatch using hard interlayer. And a better strength of the joint was obtained by using soft interlayer Cu.

Fig. 10 shows the contour plots of the von Mises stress (σ_r) distribution and magnified view near the interface of W/Ta/steel and W/Cu/steel joints. It can be seen that for both W/Ta/steel and W/Cu/steel joints, residual stress mainly concentrated in W substrate adjacent to the W/filler interface. Only tiny area in Ni–based filler near to the edge of W/filler interface showed the peak value of σ_r. Therefore, it can be concluded that the residual stress has greater impact on W than steel. The FEM analysis proved that residual stress in the W substrate was intensive and maximum in the vicinity of the W/filler interface. The residual stress here might induce the fracture in W adjacent to the interface, which was in accord with the tensile experimental result and fracture analysis above. As shown in the FEM analysis, the maximum residual compressive stress of the W/Cu/steel joint was 610.49 MPa, while the W/Ta/steel joint was 895.33 MPa. It indicates that, comparing with hard interlayer Ta, the residual stress appeared in W substrate was more effectively reduces by using the Cu interlayer when cooling from the brazing temperature to RT, and achieved more superior joint properties. This may ascribe to the ability of plastic deformation for Cu interlayer.

In conclusion, the inserting of interlayer metal has relative little influence on the integral residual stress distribution of the W/steel joint, but has more obvious effect on the value of residual stress. Soft interlayer Cu could reduce residual radial stress in W substrate observably, thus enhancing the joint properties. While hard interlayer Ta contributed relative less to relieving residual thermal stress of the W/steel joint.

4. Conclusions

The brazing process of W and steel, using Ni–based amorphous foil as filler metal, has been investigated with respect to the divertor application. The soft metal Cu and the hard metal Ta were used as interlayer respectively to relax the residual thermal stress and improve the mechanical property of the W/steel joint. Microstructure, tensile strength and fracture appearance of W/Ta/steel and W/Cu/steel joints were studied. A set of FEM calculations were performed in order to characterize the residual thermal stress distribution of the brazed joint.

Conclusions are as follows:

1) Whether soft interlayer Cu or hard interlayer Ta was successful for brazing of W and steel substrate. The reliable brazed W/steel joint was obtained and all of interfaces were smooth and compact.
2) The strength of W/Cu/steel joint was 276.7 MPa, which is higher than the joint using hard interlayer Ta (257.8 MPa). The rupture surface analysis reveals that W/Cu/steel and W/Ta/steel joints

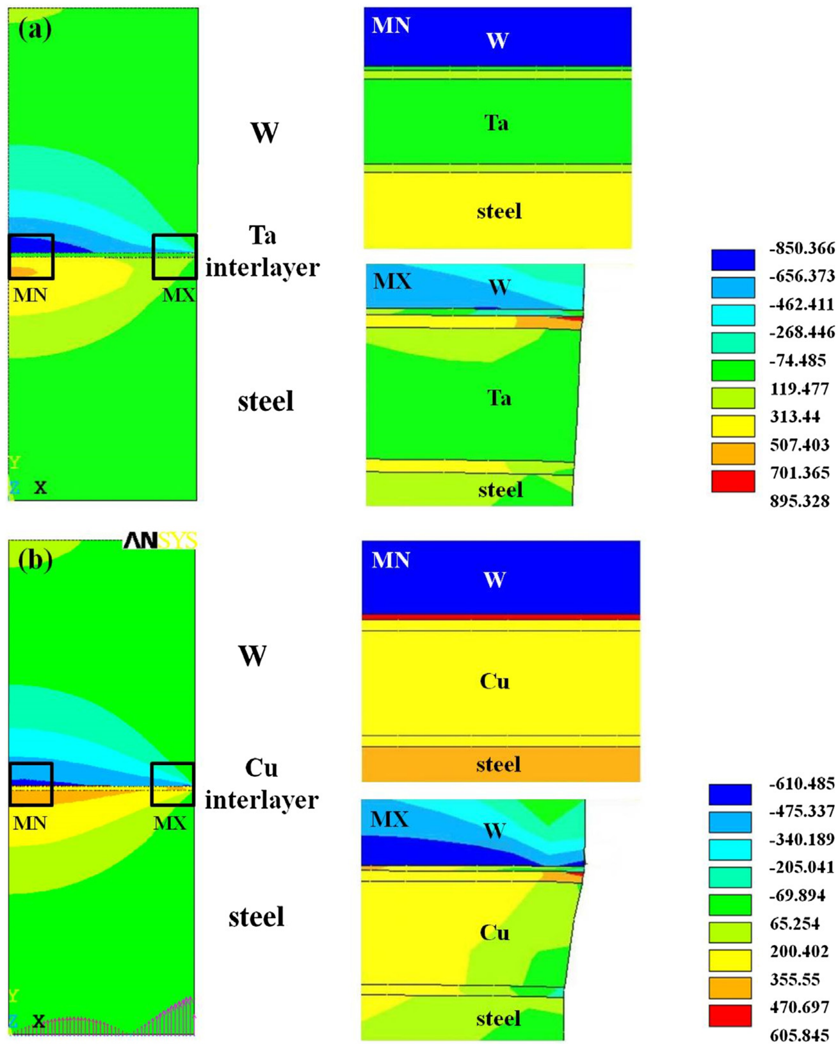

Fig. 10. Von Mises stress (σ_r) distribution (left) and magnified view near the interface (right) of (a) W/Ta/steel joint and (b) W/Cu/steel joint.

both fractured in W substrate near the welding seam, and failed in a typical brittle mode.

3) The calculation through FEM described the residual stress distribution of the W/steel joint. The calculation results show that the residual radial stress mostly concentrated in the W substrate adjacent to the welding seam, which is in agreement with previous fracture behavior analysis of the W/steel joint. The FEM simulation also suggests that, comparing with hard interlayer Ta, soft interlayer Cu could reduce residual radial stress in W substrate more effectively, thus improving the mechanical property.

Acknowledgment

The authors gratefully acknowledge the financial support from the National 863 Plan Project of China (Grant no. 2009AA034300), the National 973 Plan Project of China (Grant no. 61****02), the "Chang Jiang Scholars Program" of the Ministry of Education of China (Grant no. T2011119), and the Fundamental Research Funds for the Central Universities of Central South University (Grant no. 2014zzts025).

References

[1] P. Norajitra, L.V. Boccaccini, A. Gervash, R. Giniyatulin, N. Holstein, T. Ihli, G. Janeschitz, W. Krauss, R. Kruessmann, V. Kuznetsov, A. Makhankov, I. Mazul, A. Moeslang, I. Ovchinnikov, J. Nucl. Mater. 367–370 (2007) 1416–1421.
[2] V. Philipps, J. Nucl. Mater. 415 (2011) S2–S9.
[3] P. Norajitra, A. Gervash, R. Giniyatulin, T. Ihli, W. Krauss, R. Kruessmann, V. Kuznetsov, A. Makhankov, I. Mazul, I. Ovchinnikov, Fusion Eng. Des. 81 (2006) 341–346.
[4] T. Chehtov, J. Aktaa, O. Kraft, J. Nucl. Mater. 367–370 (2007) 1228–1232.
[5] W.W. Basuki, J. Aktaa, J. Nucl. Mater. 417 (2011) 524–527.
[6] L.M. Zhao, Z.D. Zhang, Scripta Mater. 58 (2008) 283–286.
[7] Z.H. Zhong, T. Hinoki, T. Nozawa, Y.H. Park, A. Kohyama, J. Alloys Compd. 489 (2010) 545–551.
[8] W.W. Basuki, J. Aktaa, Fusion Eng. Des. 86 (2011) 2585–2588.
[9] M. Onozuka, S. Hirai, K. Kikuchi, Y. Oda, K. Shimizu, J. Nucl. Mater. 329–333 (2004) 1553–1557.
[10] B.A. Kalin, V.T. Fedotov, O.N. Sevrjukov, A.N. Kalashnikov, A.N. Suchkov, A. Moeslang, M. Rohde, J. Nucl. Mater. 367–370 (2007) 1218–1222.
[11] Yu Weiyuan, Lu Wenjiang, Xia Tiandong, Rare Metal Mater. Eng. 42 (2013) 688–691.
[12] Z.H. Zhong, H. Jung, T. Hinoki, A. Kohyama, J. Mater. Process. Technol. 210 (2010) 1805–1810.
[13] H. Sabetghadam, A. Zarei Hanzaki, A. Araee, Mater. Charact. 61 (2010) 626–634.
[14] Shangda Chen, Fujiu Ke, Min Zhou, Yilong Bai, Acta Mater. 55 (2007) 3169–3175.
[15] S.D. Conzone, D.P. Butt, A.H. Bartlett, J. Mater. Sci. 32 (1997) 3369–3374.
[16] T. Weber, J. Aktaa, Fusion Eng. Des. 86 (2011) 220–226.
[17] R.L. Williamson, B.H. Rabin, G.E. Byerly, Compos. Eng. 5 (1995) 851–863.
[18] L. Wang, H. Bei, Y.F. Gao, Z.P. Lu, T.G. Nieh, Acta Mater. 59 (2011) 2858–2864.
[19] S.D. Peteves, G. Ceccone, M. Paulasto, V. Stamos, P.J. Yvon, JOM 48 (1996) 48–52.
[20] A.P. Xian, Z.Y. Si, J. Mater. Sci. 27 (1991) 1560–1566.

Please cite this article in press as: W. Liu, et al., Investigation of tungsten/steel brazing using Ta and Cu interlayer, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2016.11.004