ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 275–280

journal of nuclear materials

Effects of interface edge configuration on residual stress in the bonded structures for a divertor application

K. Kitamura [a,*], K. Nagata [a], M. Shibui [a], N. Tachikawa [a], M. Araki [b]

[a] *Heavy Apparatus Engineering Laboratory, Electromagnetic Engineering Department, Toshiba Corporation, 2-4 Suehiro-cho, Tsurumi-ku, Yokohama 230, Japan*

[b] *Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka-machi, Naka-gun, Ibaraki-ken 311-01, Japan*

Abstract

Residual stresses in the interface region, that developed at the cool down during the brazing, were evaluated for several bonded structures to assess the mechanical strength of the bonded interface, using thermoelasto-plastic stress analysis. Normal stress components of the residual stresses around the interface edge of graphite–copper (C–Cu) bonded structures were compared for three types of bonded features such as flat-type, monoblock-type and saddle-type. The saddle-type structure was found to be favorable for its relatively low residual stress, easy fabrication accuracy on bonded interface and armor replacement. Residual stresses around the interface edge in three armor materials/copper bonded structures for a divertor plate were also examined for the C–Cu, tungsten–copper (W–Cu) and molybdenum alloy-copper (TZM–Cu), varying the interface wedge angle from 45° to 135°. An optimal bonded configuration for the least value of residual stress was found to have a wedge angle of 45° for the C–Cu, and 135° for both the W–Cu and TZM–Cu bonded ones.

1. Introduction

The carbon-fiber-composite (CFC)/copper and W–Cu bonded structures have received consideration for use as a divertor plate in a conceptual and an engineering design activities (CDA, EDA) of the International Thermonuclear Experimental Reactor (ITER) [1,2]. Some bonded features such as monoblock-type and saddle-type structures are proposed to enhance the thermal and mechanical performances [1–3], because a flat-type bonded feature has been recognized to have an interfacial fracture around the interface edge that developed from the stress singularity problem for its free-edge geometry [3–7]. An optimization study has been performed on the effect of armor/heat sink material combination on residual stress for several types of bonded structures [8]. A monoblock-type bonded structure, proposed to avoid the free-edge geometry [3,4], has significant problems on the fabrication and maintenance because of its linked configuration between armor and cooling tube. Consequently, a saddle-type bonded structure has been recently proposed as an intermediate configuration [3,8,9].

Cyclic heat loads decrease the residual stress on a divertor plate with bonded armor that developed during the brazing [10]. Therefore, reduction of the residual stress, especially, of the normal stress component to the bonded interface at the edge is of great importance because it is considered to be one of possible driving forces for interfacial fracture [9,11].

Then, the normal stress components of the residual stresses around the interface edge of the C–Cu bonded structures were compared for three types of bonded features such as flat-type, monoblock-type and saddle-type, using a thermoelasto-plastic stress analysis. The residual stresses around the interface edge in the C–Cu, W–Cu and TZM–Cu bonded structures were also examined by varying the interface wedge angle from 45° to 135°, to investigate an optimal edge configuration of the bonded structure.

* Corresponding author. Tel.: +81 45 510 6696; fax: +81 45 500 1427; e-mail: kazunori.kitamura@toshiba.co.jp.

0022-3115/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(98)00284-0

2. Thermoelasto-plastic FEM analysis

The bonded structures with three armor materials examined here consist of an oxygen-free copper (OFCu) with an isotropic graphite for the C–Cu, with a high-purity tungsten for the W–Cu and with a molybdenum alloy (Mo–0.5Ti–0.1Zr) for TZM–Cu bonded structures, respectively. The material properties of graphite, tungsten, TZM and copper used in the analysis are shown in Table 1 [8,9,11–13].

In the analysis, graphite, tungsten and TZM were assumed to behave as an elastic material. For copper, elastic–plastic behavior without time-dependent effect was taken into account. Stress–strain curves of copper are shown for several elevated temperatures in Fig. 1, which was annealed at 850°C for 30 min, considering the maximum brazing temperature of 850°C. Stress free temperature was considered to be 650°C [12]. The analysis was performed with a plane stress model for the comparison of three types of C–Cu bonded features, and with an axisymmetric model for the investigation of interface wedge angle effect on residual stress in three armor materials/copper bonded structures, using the thermoelasto-plastic structural analysis code ABAQUS [14].

Table 1
Material properties of tungsten, graphite, TZM and copper used in the analysis

Material	Temp. (°C)	Young's modulus E (GPa)	Poisson's ratio v	Thermal expansion coeff. α (10^{-6}/°C)
Graphite	20	9.3	0.18	4.70
	300	9.4	0.18	5.10
	500	9.5	0.18	5.50
	800	10.3	0.18	5.60
	1200	10.8	0.18	6.00
Tungsten	20	408	0.28	5.25
	200	402	0.28	5.35
	600	382	0.29	5.55
	800	370	0.29	5.70
	1000	355	0.29	5.80
	1200	340	0.29	5.92
TZM	20	300	0.32	5.30
	500	260	0.32	5.54
	800	236	0.32	5.84
	1000	220	0.32	6.00
	1200	188	0.32	6.20
OFCu	20	82	0.33	15.40
	200	74	0.33	16.60
	400	69	0.33	18.30
	600	62	0.33	20.00
	800	59	0.33	21.60

3. Analytical results

3.1. Comparison of three types of bonded features

In general, thermal stress at the edge of the bimetallic interface shows singular behavior [5–7,11], and the stress value extremely depends on the FEM mesh size near the interface edge [6,7,12]. Then, elastic–plastic FEM analyses on the three types of the bonded features were carried out with an approximately same order mesh size of 0.07×0.13 mm^2 around the interface edge, in the case of the flat-type and saddle-type structures, having the free edge configuration on the bonded interface. The analytical results of residual stress distributions along the bonded interface are shown in Fig. 2.

In the monoblock-type structure, both the normal and parallel stress components(σ_N, σ_P) to the interface gradually vary along the interface length. On the other hand, both the flat-type and saddle-type structures have sudden stress variations around interface edges. Maximum values of the normal stress components were estimated to be 44 MPa for the flat-type, 13 MPa for the saddle-type and 7 MPa for the monoblock-type structures, respectively, which were obtained from an extrapolation of FEM analytical results.

3.2. Effect of interface wedge angle on residual stress

An axisymmetric analytical model without the cooling tubes, as shown in Fig. 3, was selected for analytical simplicity.

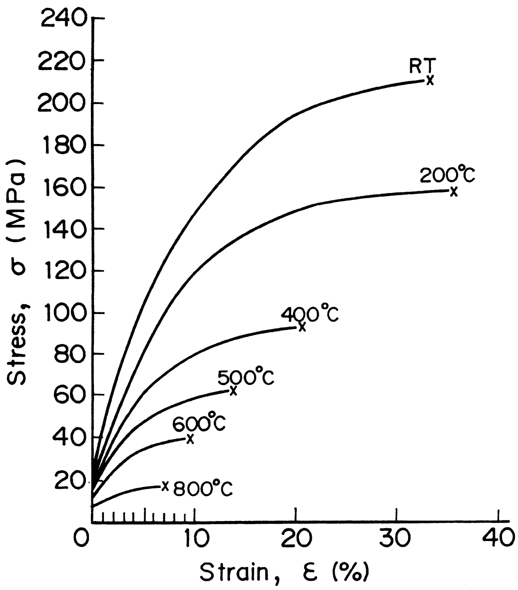

Fig. 1. Stress–strain curves of copper for several elevated temperatures.

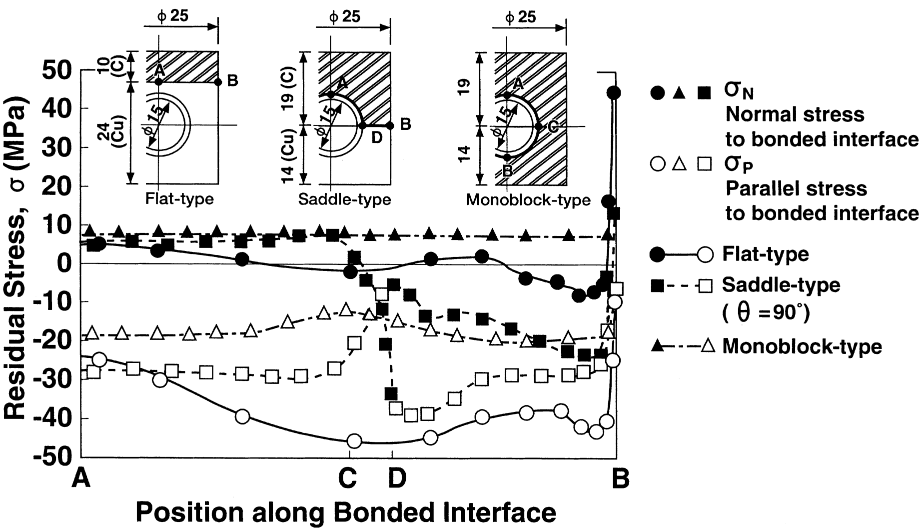

Fig. 2. Residual stress distributions along bonded interface for three-types of graphite–copper bonded structures.

(1) *C–Cu bonded structure:* A relationship between the residual stresses and wedge angle at the interface edge was obtained for the C–Cu bonded structure, as shown in Fig. 3. Residual stress at the center on the graphite top surface, σ_C, was estimated to be about 5 MPa without dependence on the wedge angle, θ. Normal stress component, σ_N around the interface edge, however, was compressive in the range of $\theta < 80°$ and tensile for $\theta > 80°$. This shows a maximum stress value of about 60 MPa around $\theta = 120°$ and a minimum value of about −65 MPa around $\theta = 45°$. Since the normal stress component seems to primarily cause the crack initiation and crack propagation at the interface edge, it needs to be reduced as much as possible in the view of mechanical design and will be favorable to be compressive for crack closing. Therefore, an optimal bonded configuration of the C–Cu bonded structure was found to have a wedge angle of 45°.

(2) *W–Cu bonded structure:* The influence of the wedge angle at the interface edge on the tungsten residual stresses is shown in Fig. 4. Residual stress at the top surface was estimated to be about 100 MPa without dependence on the wedge angle. However, normal stress component around the interface edge was tensile in the

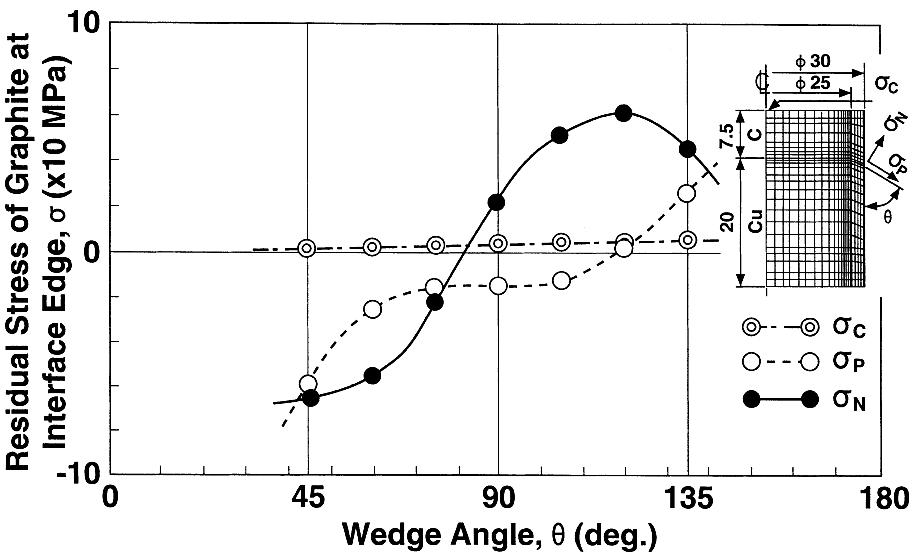

Fig. 3. Effect of wedge angle at the interface edge on residual stress for graphite–copper bonded structure.

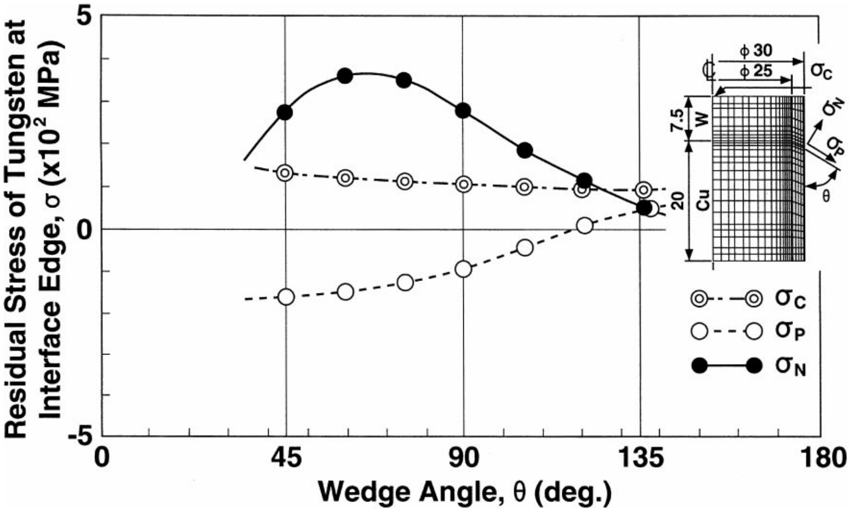

Fig. 4. Influence of wedge angle at the interface edge on residual stress for tungsten–copper bonded structure.

range of 45° $< \theta <$135°, having a maximum stress value of 370 MPa around $\theta = 60°$ and a minimum value of 60 MPa around $\theta = 135°$. Then, the optimal configuration of the W–Cu bonded structure was found to have a wedge angle of about $\theta = 135°$. The optimal configuration of the TZM–Cu bonded structure was also found to have a wedge angle of about $\theta = 135°$ in the same manner as the W–Cu one.

4. Discussions

4.1. Comparison of three types of bonded features

Table 2 gives a comparison of three interface types of bonded features in view of their fabricability, maintenability of armor replacement and mechanical strength. The monoblock-type bonded structure surely seems to be favorable for the widest margin in passive safety and the lowest residual stress value. However, it has disadvantages in armor replacement only, and in the required high fabrication accuracy between the inside of armor and copper tube. The saddle-type, in comparison, has a proper mechanical strength with a maximum edge stress sufficiently below a tensile stress limit of about 40 MPa (100 MPa for compessive), and for its unlinked configuration between armor and cooling tube advantages in avoiding some of the problems related to the monoblock geometry. Then, the most favorable selection is the saddle-type which seems to be reasonable.

4.2. Optimal wedge angle at the interface edge

An optimal configuration of the bonded structure would have a wedge angle to make the least value of the normal stress component on the residual stress around the interface edge. Then, the optimal wedge angle around the interface edge turns out to be 45° for the C–Cu bonded structure, and 135° for both the W–Cu and TZM–Cu ones. At the cool-down during brazing, a bending moment between the armor plate and copper block in the axial direction is induced in a manner to restrict their free deformations for their thermal expansion mismatch and the difference of their bending stiffness, and axial residual displacements remain on the armor top surface [12]. Fig. 5 shows the effect of wedge

Table 2
Comparison of three-types of graphite–copper bonded structures

		Flat-type	Saddle-type ($\theta = 90°$)	Monoblock-type
Fabricability		Easy	Possible	Possible
Maintainability [a]		Easy	Possible	Difficult
Residual stress	σ_C	14	9	1.5
after brazing,	σ_P	−10	−7	−20
σ (MPa) [b]	σ_N	44	13	7

[a] For only armor replacement.

[b] σ_C: Max. stress on graphite top surface; σ_P: Max. parallel stress to bonded interface; σ_N: Max. normal stress to bonded interface.

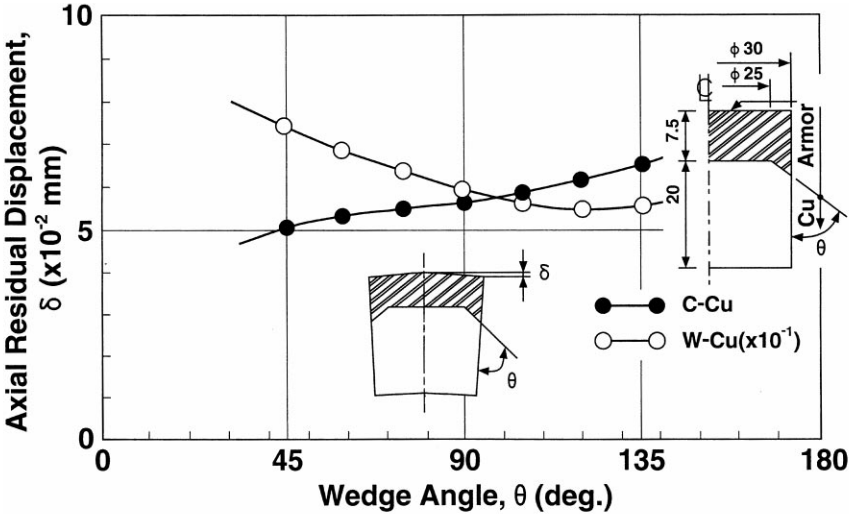

Fig. 5. Effect of wedge angle at the interface edge on axial residual displacement on the armor top surface for graphite– and tungsten–copper bonded structures.

angle on axial residual displacements on the armor top surface for C–Cu and W–Cu bonded structures. The axial displacement increases with the increase of wedge angle for the C–Cu, but it is reduced with the increase of wedge angle for the W–Cu. Relationship of wedge angle and bending moment around the interface edge is also predicted to be in the same manner as that on the axial residual displacement. Therefore, residual stress around the interface edge leads to minimum value at the wedge angle of 45° for the C–Cu, and of 135° for both the W–Cu and TZM–Cu bonded structures.

Since bonded structures used in the investigation of interface wedge angle effect on residual stress in three armor materials/copper bonded structures, have a free-edge geometry around the interface edge, edge stress problems of those bonded structures yield singularities at the interface edge in the elastic solution. Results by eigenvalue analysis on stress singularity of the bonded structures indicate that there is no singularity at $\theta < 60°$ and at $\theta \sim 120°$, but strong singularity at $\theta \sim 165°$ for C–Cu, and no singularity at $\theta \sim 60°$ and at $\theta > 120°$, but strong singularity at $\theta \sim 20°$ for W–Cu [11,15]. The wedge angle of 45° for C–Cu and 135° for W–Cu, giving the least residual stress around the interface edge, were within no singularity region mentioned above.

5. Conclusions

The residual stresses in the interface region, that developed at the cool down during the brazing, were evaluated for the several bonded structures to assess the mechanical strength of the bonding interface, using thermoelasto-plastic stress analysis.

1. The normal stress components of the residual stresses around the interface edge of the C–Cu bonded structures were compared for three types of bonded structures, namely flat-type, monoblock-type and saddle-type ones. Consequently, the saddle-type structure was found to be favorable for its relatively low residual stress, easy fabrication accuracy on the bonded interface and maintenance of armor replacement.
2. Residual stress around the interface edge in the three armor materials/copper bonded structures for a divertor plate were also examined for C–Cu, W–Cu and TZM–Cu bonded materials, varying the interface wedge angle from 45° to 135°. An optimal bonded configuration for the least value of residual stress was found to have a wedge angle of 45° for the C–Cu, and 135° for both the W–Cu and TZM–Cu bonded materials, in the range of a wedge angle from 45° to 135°.

References

[1] T. Kuroda et al., ITER plasma facing components, ITER CDA documentation series, no. 30, IAEA, Vienna, 1990.
[2] Technical basis for the iter interim design report, Cost review and safety analysis, ITER EDA documentation series, no. 7, IAEA, Vienna, 1996.
[3] M. Akiba, R.D. Watson, Thermo-Hydrodynamic Coupling with Coolants, Elsevier, Amsterdam, 1993, pp. 455–480.
[4] Sandia National Laboratory Annual Report, 1989, pp. 52–53.
[5] V.L. Hein, F. Erdogan, Int. J. Fracture and Mech. 7 (3) (1971) 317–330.
[6] J.D. Whitcomb, I.S. Raju, J.G. Goree, Comput. Struct. 1 (1982) 23–37.

[7] K. Mizuno, K. Miyazawa, T. Suga, J. Faculty of Eng. XXXIX (4) (1988) 401–412.
[8] I. Smid, M. Akiba, M. Araki, S. Suzuki, K. Satoh, JAERI-M 93-149, 1993.
[9] K. Kitamura, K. Nagata, N. Tachikawa, M. Shibui, M. Akiba et al., in: Proceedings of the 15th SOFE, 1993, pp. 863–866.
[10] K. Kitamura, K. Ohsemochi, K. Nagata, J. Ohmori, M. Shibui, M. Seki, Mechanical behavior on residual stress in a tungsten–copper duplex structure after cyclic heat loads for a divertor application (ISFNT-4), Fusion Eng. Design, in press.
[11] M. Shibui, K. Kitamura, K. Nagata, T. Fuse, N. Tachikawa, in: Proceedings of the 14th SOFE, 1991, pp. 368–371.
[12] K. Kitamura, K. Nagata, M. Shibui, T. Fuse, N. Tachikawa et al., Fusion Eng. Design 18 (1991) 173–178.
[13] Metallwerk Plansee Documentation.
[14] ABAQUS User's Manual, ver. 5.3, Karlson & Sorenssen, 1995.
[15] M. Shibui, K. Kitamura, K. Nagata, T. Fuse, N. Tachikawa et al., in: Proceedings of The 69th JSME Fall Annual Meeting, no. 910–962, vol. A, 1991, pp. 250–252.