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Interlayer design for joining pressureless sintered sialon ceramic and 40Cr steel brazing with $Ag_{57}Cu_{38}Ti_5$ filler metal

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An interlayer design and test was made to enhance the joining strength of the pressureless sintered sialon ceramic and 40Cr steel. Joining was preformed by vacuum brazing using $Ag_{57}Cu_{38}Ti_5$ filler metal. The joint strength was evaluated by four-point bending. A strong interfacial bond of the $Ag_{57}Cu_{38}Ti_5$ filler metal on the sialon ceramic with formation of Ti_2AlN, Ti_5Si_4 and TiAg was obtained at brazing temperatures over 1123 K, which could be weakened by a brazed metal such as Kovar or Ni–15Cr–15Co alloy. The joint strength of sialon ceramic with 40Cr steel can be improved by using a layer of soft interlayer such as Cu with a suitable thickness, particularly by the composite interlayer such as Cu/Nb alloy, Cu/Ta, Cu/Mo etc. The maximum strength of the ceramic/steel joint, 280 MPa, was obtained by using Cu/Nb alloy as interlayer and brazing at 1153 K for 5 min. Finally, we discuss how to design an interlayer in ceramic/metal joining.

1. Introduction

A strong ceramic/metal joint is dependent on both chemical and physical factors. It includes a strong interfacial bond between ceramic and metal, which is controlled by the interfacial reaction between ceramic and metal; and a favourable stress gradient in the ceramic/metal interfacial zone which is controlled by an interfacial structure. A strong interfacial bond between ceramic and metal is dependent on a design of an active brazing filler metal and the control of brazing parameters in direct brazing. Major research on ceramic/metal joining has been focused on this field [1–10]. A promising active brazing filler metal, $Ag_{57}Cu_{38}Ti_5$ ternary alloy, has been developed in recent years [7–10], as it has excellent wettability, flowability and adhesion on most ceramic surfaces. On the other hand, a favourable stress gradient in the interfacial zone is dependent on interfacial design, in which the selection of an inserted interlayer between ceramic and brazed metal will be critical. It has not been possible to achieve a strong ceramic/metal joint, or to achieve acceptable joining [11], without an interlayer.

Some elastic stress analyses [12–15], finite element calculations [16] and X-ray residual stress determination [17] have been performed for a ceramic/metal joint, confirming that there is a high residual stress gradient around the ceramic/metal interface. A low joint strength would be unavoidable if the steep stress gradient were not effectively relaxed. Some research has suggested the insertion of an interlayer to improve the strength of a ceramic/metal joint [18, 19]; however the general understanding of how to design an interlayer is still insufficient. This investigation aims to improve the joint strength of pressureless sintered sialon ceramic to 40Cr steel by interlayer design. The choice of the ceramic and steel as the specimen materials in this study is based on the fact that they are promising structural ceramic/metal components in heat engines. The possible candidate interlayer materials are Cu, Ta, Mo, Kovar and Ni alloy, each having a different coefficient of thermal expansion, yield strength, ductility, modulus of elasticity, creep strength and a different interaction with $Ag_{57}Cu_{38}Ti_5$ brazing filler metal. Hence this effort should help us to understand the behaviour of interlayers in joining ceramics to metals. Finally, a method of making an interfacial engineering design to solve the residual stress problem in joining dissimilar materials is also suggested.

2. Basic considerations

A joining system for a ceramic/metal joint is shown in Fig. 1. As the joining of each part in the system consisted of a series, joint strength depended on the weakest link in the series system. Since the strength of the metal/metal interfacial bond, the brazing filler metal and the brazed metal itself is higher than that of the ceramic/metal interfacial bond and the ceramic itself, the fracture of the metal/ceramic joint can be divided as follows.

(1) Fracture occurs rigorously at the ceramic/metal interface, named as fracture type A. Without interfacial residual stress, the strength can be regarded as the true joining strength of ceramic and metal. This fracture type corresponds to the very low strength of a

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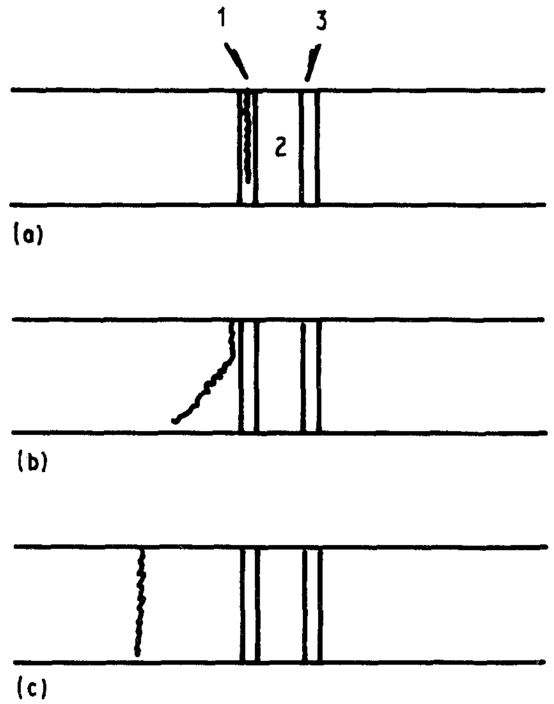

Figure 1 Schematic diagram illustrating three kinds of fracture of a ceramic/metal joint. 1, 3; reaction layer between ceramic and brazing filler metal or brazing filler metal and brazed metal, respectively. 2, Braze seam. (a) Fracture occurs rigorously at the ceramic/metal interface because of a low interfacial adhesion strength; (b) fracture occurs at ceramic very near the interface because of better adhesion strength between ceramic and metal, but a high residual stress there; (c) fracture is independent on the interface because of both better adhesion strength between ceramic and metal and a favourable stress gradient in the interfacial zone.

ceramic/metal joint, and can be improved by the design of active brazing filler metal and the control of brazing parameters such as temperature, time, atmosphere, etc. As $Ag_{57}Cu_{38}Ti_5$ brazing filler metal is an excellent active filler metal for silicon nitride ceramics [10], a poor interfacial bond strength of the ceramic to the active filler metal is mainly due to the influence of brazing temperature or brazed metal, which can control the interfacial reaction between ceramic and brazing filler metal.

(2) Cracks occur in ceramics very near the interface and their propagation often deviates away from the interface due to a phase angle $\psi = 90°$ [21, 22], named as fracture type B. The strength is regarded as the apparent joining strength of a ceramic and a metal, which reflects a strength loss of the ceramic near the interface because of a steep stress gradient there. This fracture type corresponds to a medium joint strength of ceramic to metal. The steep stress gradient in the interfacial zone between ceramic and metal can be relaxed by design of a suitable interlayer. There are two kinds of interlayers in physics: (a) a hard interlayer, characterized by W or Mo, which has a lower coefficient of thermal expansion but a relatively high strength both at room and high temperature, and a decrease of residual stress due to direct reduction of the mismatch of thermal expansion between ceramic and brazed metal; and (b) a soft interlayer, characterized by Ag or Cu, which has a lower strength and better ductility, but a relatively high coefficient of thermal expansion. An improvement in the steep stress gradient in the interfacial zone is due to a relaxation of the stress by creep or yield mechanism. The combination of the two kinds of interlayer materials is also considered in order to further reduce the stress in the joint and enhance the strength of a ceramic/metal joint.

(3) Fracture occurs in ceramics independently of the interface: fracture C. The joint strength is the strength of the ceramic itself. In this case, there is both an excellent interfacial bond strength of ceramic to metal and a favourable stress gradient in-the interfacial zone. Hence the maximum joining strength of a ceramic/metal joint should be expected, and this joint is ideal, which implies that corresponding interfacial design is very successful. The experimental design in the present work was made according to the above basic considerations.

3. Experimental procedure

The β'-α'-sialon ceramic with a density of 3.44 g cm^{-3} and a coefficient of thermal expansion $\alpha = 3.2 \times 10^{-6}$ K^{-1}, obtained from Shanghai Institute of Ceramics, Academia Sinica, was made by sintering active Si_3N_4 powder with Y_2O_3 and AlN additives at 2073–2123 K for 2 h in N_2. The two-phase ceramic has a good high-temperature strength. This is because the second phase α'-sialon in a β'-sialon substrate can trap the big trace anions Y^{3+}, Ca^{2+}, and Li^{+} etc from the raw materials [22]; otherwise the anions will segregate on the grain boundary to form a glass phase, which would cause the high-temperature strength of the ceramic to deteriorate. The chemical compositions of the candidate interlayer metals and brazed 40Cr steel are listed in Table I, and the physical and mechanical properties of the candidate interlayer in Table II. The $Ag_{57}Cu_{38}Ti_5$ brazing filler metal was prepared by melting twice in a vacuum-arc furnace, and then rolling into a 100 µm strip. The surface to be brazed of the ceramic bar or 40Cr steel bar was polished with diamond paste or emery paper no. 500, respectively. The surface of the interlayer metal and the brazing filler foil were polished with emery paper No. 500, then carefully cleaned in acetone before brazing. The assemblage of the sandwich joint, consisting of two ceramic bars or a ceramic bar and a 40Cr steel bar both with 2.5 × 5 × 20 mm, and an inserted interlayer and brazing filler metal between them, was fixed in an iron jig (as shown in Fig. 2) in order to ensure the alignment of the ceramic/steel joint. The jig was rapidly heated in a cold-wall type vacuum brazing furnace to brazing temperature, and was held there for 5 min. A dynamic pressure of the furnace chamber was kept between 1×10^{-4} and 1×10^{-5} torr during brazing. The flexural strength of the ceramic/ceramic or ceramic/steel joints was measured in air at room temperature by four-point bending with cross-head speed of 0.2 mm min^{-1}. The details of the brazing procedure and the strength measurement have been published previously [10].

TABLE I Chemical composition of interlayer materials and 40Cr steel (wt %)

Material	C	Si	Mn	Cr	Fe	Zr	W	Nb	Mo	Ti	Ni	Co	Cu	Ta
40Cr	0.42	0.25	0.65	1.0	Bal.									
Nb alloy						3.5	10	Bal.						
Mo									Bal.	0.5				
Kovar	0.05	0.30	0.50		Bal.						32	15		
Ni alloy				15							Bal.	15		
Cu													99.9	
Ta														99.9

TABLE II Physical and mechanical properties of interlayer metals for the sialon ceramic/40Cr steel joint

Material	α (10^6)	E (GPa)	$\sigma_{0.2}$ (MPa)	σ^{700K} (MPa)	δ_5 (%)	Melting point (K)
Cu	17	124	60	–	48	1356
Mo	6.4	294	900	606*	–	2898
Ta	6.5	186	250	–	–	3252
Nb alloy	8.75	106	400	300	–	–
Kovar	6.9	139	343	–	32	1773
Ni alloy	–	225	–	20†	–	1726
40Cr	14.4	200	402	304	21.5	1673

* Yield strength at 1144 K.

† Creep strength at 1073 K (10^{-7} s^{-1}).

α is the coefficient of thermal expansion, E is Young's modulus, $\sigma_{0.2}$ is yield strength, σ^{700K} is high-temperature strength at 700 K, δ_5 is the percentage of elongation.

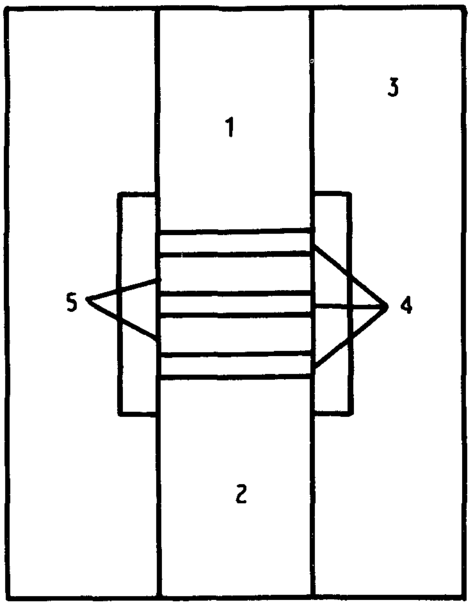

Figure 2 Assemblage of a sandwich specimen of the ceramic/steel joint 1, β′-α′-sialon; 2, 40Cr steel; 3 iron jag; 4, $Ag_{57}Cu_{38}Ti_5$ brazing filler metal; 5, interlayer material.

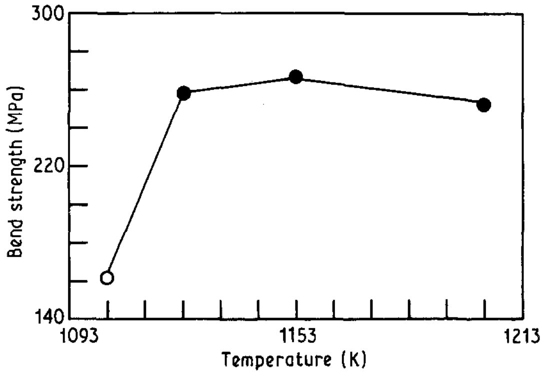

Figure 3 Brazing temperature dependence of the strength of the sialon/sialon ceramic joint using $Ag_{57}Cu_{38}Ti_5$ filler metal. ○, Fracture occurred at interface; ●, fracture occurred at ceramic independently of interface.

4. Results and discussion

4.1. Joining of ceramic to ceramic

Fig. 3 shows the brazing temperature dependence of the bond strength of the ceramic/ceramic joint with $Ag_{57}Cu_{38}Ti_5$ brazing filler metal. The joint strength brazing at 1103 K was low and fracture occurred at interface, which was due to an insufficient interfacial reaction between the ceramic and the brazing filler at lower temperature [10]. The interfacial bond strength of the joint when brazing was performed over 1123 K was high, and fracture occurred in the ceramic independently of the interface, which indicated that the interfacial bond strength was higher than that of the ceramic itself.

In order to make clear the relationship between the bond strength and interfacial reaction, a piece of $Ag_{57}Cu_{38}Ti_5$ brazing filler metal with 8 × 8 mm in area and 0.10 mm thickness was placed on the surface of a sialon ceramic with the same area, then heated in vacuum to 1153 K and held there for 5 min. A small contact angle (5°) of the brazing filler metal on the surface of the sialon ceramic was observed. After mechanically removing the brazing filler metal from the surface of the sialon ceramic, a hard metal reaction layer with a bright gold–yellow colour appeared, but X-ray diffraction (XRD) (Fig. 4a) showed that a thin layer of Ag and Cu still existed on the reaction layer.

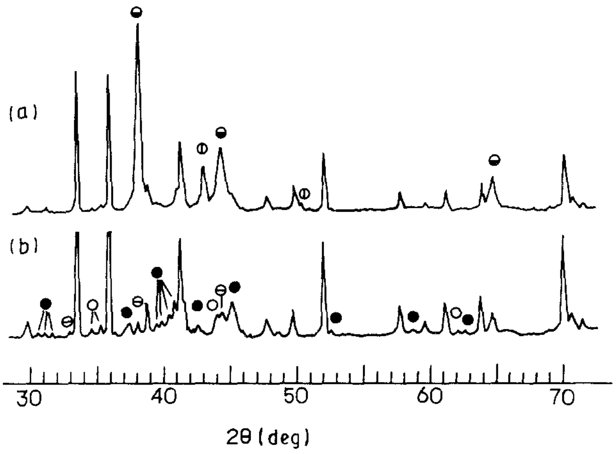

Figure 4 XRD patterns of interface reaction layer between sialon ceramic and $Ag_{57}Cu_{38}Ti_5$ filler metal (wetting at 1153 K for 5 min). Unmarked peaks belong to sialon ceramic. (a) Apparent reaction layer after mechanically removing Ag–Cu brazing filler; (b) true reaction layer after chemically removing thin Ag–Cu layer in 50% HNO_3 for 10 sec. ◒, Ag; ⦶, Cu; ●, Ti_5Si_4; ○, Ti_2AlN; ⊖, TiAg.

After chemically removing the thin Ag–Cu layer in 50% HNO_3 for about 10 sec, a true reaction layer with a dark gold–yellow colour appeared. XRD (Fig. 4b) showed that the interfacial reaction layer consisted of Ti_2AlN, Ti_5Si_4 and TiAg, based on a layer transition model on the ceramic/metal interfacial zone [1, 10], a series system with a sialon/Ti_2AlN/Ti_5Si_4/TiAg/Ag-Cu layer structure formed which resulted in a strong bond between the sialon ceramic and the brazing filler metal. From Fig. 3, it is expected that the bond strength of the ceramic/ceramic joint using the active brazing filler is not sensitive to brazing temperature and time within a broad range. Therefore $Ag_{57}Cu_{38}Ti_5$ brazing filler metal is an excellent active brazing filler metal for β′-α′-sialon ceramic, which agrees with the results for the joining of hot-pressed Si_3N_4 [10].

4.2. Selection of interlayer

4.2.1. Chemical compatibility

Although the chemical compatibility of an interlayer material with an active brazing filler metal is very important, relatively little effort has been directed towards its identification. A thermodynamic prediction for the chemical compatibility is difficult, since an interfacial reaction in a multicomponent system is often controlled by kinetics because of more thermodynamic degrees of freedom [23, 24]. The chemical compatibility of an interlayer material with $Ag_{57}Cu_{38}Ti_5$ was only evaluated by the strength data: a detailed analysis is not given in the present work.

Table III shows the strength data for the sandwich joint ceramic/interlayer/ceramic brazing at 1123 K for 5 min. The application of a very thin foil was to reduce the influence of the residual stress on the joint strength. Joint strength was high when using Cu or Ta as interlayer metals; fracture was independent on the interface (shown in Fig. 5a), which implies a good chemical compatibility of Cu or Ta with $Ag_{57}Cu_{38}Ti_5$. Cu has no reaction with Si_3N_4 ceramic, and Ta is an active metal for Si_3N_4 ceramic based on a thermodynamic prediction [25], the reduced reaction of Si_3N_4 ceramic by Ta

$$Si_3N_4 + 4Ta \;=\; 4TaN + 3Si \qquad (1)$$

$\Delta G^\circ = -62.73\ \text{kJ mol}^{-1}$ at 1098 K, hence Ta can take part in the interfacial reaction between ceramic and metal, and form adhesion with the ceramic, if Ta exists in the melt filler metal during brazing.

On the other hand, joint strength was relatively low when using Kovar or Ni alloy as the interlayer metal: fracture occurred at the interface (Fig. 5b) which implies a poor chemical compatibility of Kovar or Ni alloy with $Ag_{57}Cu_{38}Ti_5$. In fact, Ni and Co in the alloy had no reaction with Si_3N_4 ceramic, and thermodynamic calculations for the reactions [25]

$$Si_3N_4 + 4Cr \;=\; 4CrN + 3Si \qquad (2)$$

$$Si_3N_4 + 8Fe \;=\; 4Fe_2N + 3Si \qquad (3)$$

showed $\Delta G^\circ = +61.64\ \text{kJ mol}^{-1}$ at 698 K for Reaction 2 and $\Delta G^\circ = +144.70\ \text{kJ mol}^{-1}$ at 898 K for Reaction 3. Hence both Cr and Fe cannot react with the ceramic to form a strong adhesion. However, a strong interaction between Ti in the brazing filler metal and Fe, Cr or Ni can decrease the activity of Ti in the brazing filler metal, which would result in an insufficient interfacial reaction between the ceramic and the brazing filler metal. Moreover, it was found that Fe exists on the interface with a very low joint strength of Si_3N_4 ceramic to 40Cr steel, using Ti as interlayer, however the mechanism to affect an interfacial bond is not yet clear. These results, however, strongly suggest that the chemical compatibility of interlayer material is an important factor in interlayer design.

4.2.2. Soft or hard interlayer

Two kinds of different interlayer materials, Cu and Mo, were chosen to study the effect of soft or hard interlayers on the joining strength of the ceramic/steel joint. A better strength of ceramic/steel joint was obtained by using a soft metal Cu as interlayer (see below). However, the strength of the ceramic/steel joint using a hard interlayer (Mo) was so low that the maximum strength was only 23 MPa by inserting a layer of 0.5 mm Mo as interlayer between the ceramic and the steel brazing at 1123 K for 5 min. A spontaneous crack occurred in the ceramic underlying the interface in some joints, which resulted in an unacceptable joint strength. A similar observation by Naka *et al.* [14] was consistent with this result: they found that there was no acceptable joining strength of Si_3N_4 ceramic to Al_2O_3, MgO or ZrO_2 ceramic brazing with $Cu_{50}Ti_{50}$, although the mismatch of thermal expansion between them is very small. According to the previous analysis for residual stress in a soft interlayer inserting into a ceramic/metal joint [15], the relaxation of the residual stress in the joint by a creep or yield mechanism during slow cooling from joining temperature will be up to about 90% or more. However, for a hard interlayer material, a high residual

TABLE III Joint strength of β′-α′-sialon to sialon ceramic using $Ag_{57}Cu_{38}Ti_5$ brazing filler at 1123 K for 5 min with various interlayer metals (four-point bend test)

Interlayer	Thickness of interlayer (mm)	Bond strength (MPa)	Fracture type
Ni alloy	0.1	177	A
Kovar	0.1	177	A
Cu	0.08	315	C
Ta	0.08	305	C

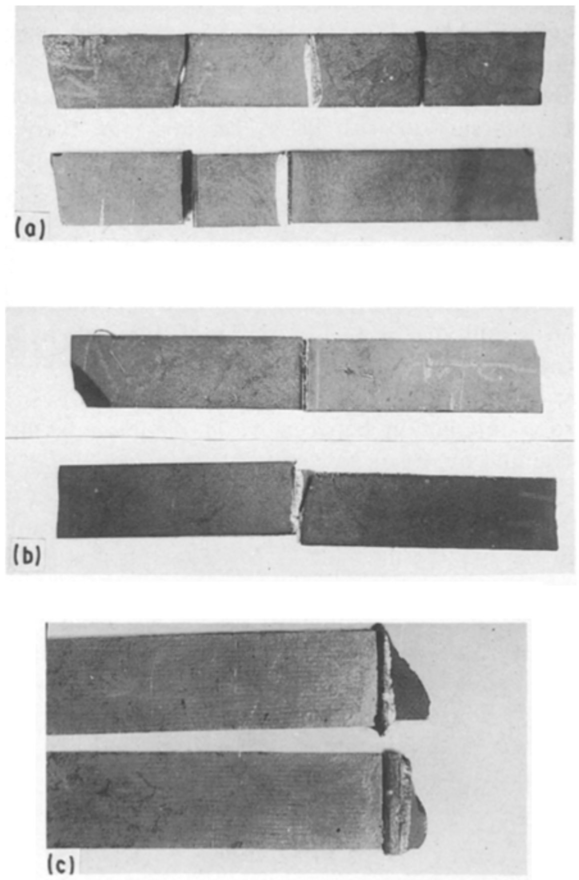

Figure 5 Fracture position of ceramic/ceramic or ceramic/metal joint after four-point bending. (a) Sialon/Ta/sialon; (b) sialon/Kovar/sialon and sialon/Ni alloy/Ni alloy/sialon; (c) sialon/Cu/sialon. Magnification × 2.

stress gradient would be unavoidable due to the lack of a stress relaxation. The very poor joint strength reflected this conclusion. Therefore in an interlayer design to improve the joint strength of ceramic to metal, it is more important to relax the interfacial stress by a soft interlayer with low strength than to avoid the stress by a hard interlayer with a low coefficient of thermal expansion.

4.2.3. *Interlayer thickness*

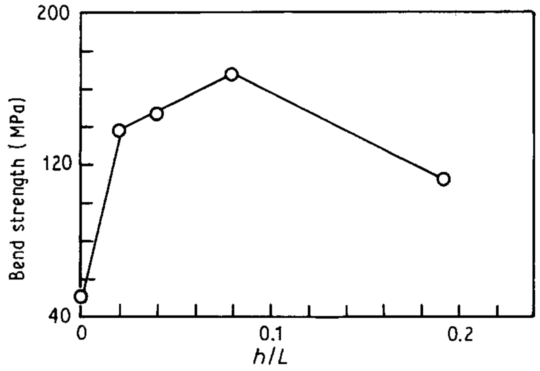

Figure 6 Relationship between strength of sialon/steel joint and thickness of interlayer Cu brazing at 1123 K for 5 min using $Ag_{57}Cu_{38}Ti_5$ filler metal. h = Thickness of interlayer Cu; L = length of sialon ceramic/40Cr steel joint, 5 mm.

Fig. 6 shows the variation in strength of the ceramic/steel joints as a function of thickness of the interlayer metal Cu. A crack occurred in the ceramic near the interface and propagated away from the interface for all the joints (Fig. 5c). A very low strength of the ceramic/steel joint, only 49 MPa, was obtained without using an interlayer to mitigate the residual stress due to a large mismatch ($\Delta\alpha = 11.2 \times 10^{-6}\ K^{-1}$) of thermal expansion between the ceramic and the steel. In the case of using a soft interlayer with a suitable thickness ($h/L = 0.02$–0.08), a better joint strength was obtained. An elastic analysis [15] revealed a very high residual shear stress in the soft interlayer. The maximum residual shear stress is approximately proportional to L/h (a ratio of length to thickness of the interlayer). The maximum residual shear stress will decrease with increasing thickness of the soft interlayer, which will result in an increase in joint strength. However, a quantitative analysis in this area is still lacking. On the other hand, if the interlayer is too thick, the distribution of the residual stress will be the same as that of Cu/ceramic without an interlayer, resulting in a decrease in strength of the ceramic/steel joint because of the high coefficient of thermal expansion of Cu.

4.3. *Composite interlayer*

In order to improve further the strength of the ceramic/steel joint, a composite interlayer of Cu/Ta, Cu/Mo, Cu/Nb alloy, or Cu/Kovar alloy was designed, in which one was soft metal (Cu) with a low strength and low modulus of elasticity, and the other was Ta, Mo, Nb alloy or Kovar alloy, each with a low coefficient of thermal expansion. The results are shown in Table IV. A better strength of the ceramic/steel joint was achieved for all joints with the double interlayer. The strength of the ceramic/steel joints is about the same level as that of the

TABLE IV Joint strength of β'-α'-sialon to 40Cr steel – inserted double interlayer using $Ag_{57}Cu_{38}Ti_5$ filler metal brazing at 1123 K for 5 min (four-point bend test)

Ceramic	First interlayer	Second interlayer	Steel	Flexural strength (MPa)	Fracture type
Sialon	0.2Cu	0.2Cu	40Cr	173	B
"	0.2Cu	0.2Mo	40Cr	255	B
"	0.2Cu	0.1Ta	40Cr	238	B
"	0.2Cu	0.3Kovar	40Cr	268	B
"	0.2Cu	0.35Nb	40Cr	281	C

ceramic/ceramic joint shown in Fig. 3, hence the interlayer design was very successful in reducing the stress gradient in the interfacial zone and improving the strength of the ceramic/metal joint.

A stress distribution in a brazed seam zone will be changed by inserting a hard interlayer with a coefficient of thermal expansion lower than that of the steel. A preliminary analysis for the composite interlayer problem is shown in Fig. 7. The second interlayer, due to its lower coefficient of thermal expansion, will become a barrier layer and influence the steel bar with a high coefficient of thermal expansion. With the thicker second interlayer, a real difference of thermal expansion will become the difference between the ceramic and the second interlayer material, which is independent of the coefficient of thermal expansion of the steel. Tensile stress applied to the first interlayer as a reaction force by the second interlayer will mitigate the stress applied to the ceramic by the first interlayer, based on an elastic analysis for a soft interlayer inserted in a ceramic/metal joint [15]. There is a transfer of the interfacial stress from ceramic/first interlayer with a relatively low bond strength to second interlayer/brazed metal interface with a higher bond stress. And the total difference of thermal expansion between the ceramic and the brazed steel is distributed on three different interfaces with a composite interlayer rather than two interfaces with single interlayer or one interface without an interlayer. Hence the stress gradient is effectively decreased here. A multi-interlayer such as Cu/Ta/Cu, Cu/Ta/Cu/Ta etc., can also be designed to further improve the joint strength; however in this chain system the possibility of brazing defects will also be increased, resulting in an unstable joining. Therefore it would be of little value to increase the number of interlayers above two.

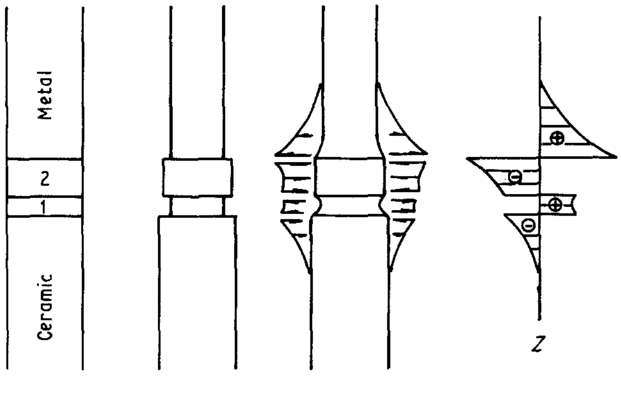

Figure 7 Schematic diagram illustrating stress distribution in an interfacial zone due to inserting a composite interlayer into a ceramic/metal joint. 1, First layer of interlayer – soft metal with low strength and relatively high coefficient of thermal expansion; 2, second layer of interlayer – hard metal with relatively low coefficient of thermal expansion. (a) Initial state at brazing temperature; (b) free shrink of each material after cooling down from brazing temperature without an interfacial bond; (c) stress state of each material in joining system for displacement continuity at interface; (d) stress distribution in radial along *z*-axis.

From the above results, it is suggested that, in a interlayer design for joining a ceramic/metal joint, three important factors should be considered: a strong interfacial bond of the interlayer material with the ceramic to ensure basic joining, a layer of soft metal with a low strength and a suitable thickness to relax interfacial stress; and a suitable second layer with a low coefficient of thermal expansion to reduce the mismatch of the dissimilar materials.

5. Conclusions

Pressureless sintered sialon ceramics with AlN and Y_2O_3 as aids were joined to 40Cr steel using $Ag_{57}Cu_{38}Ti_5$ filler metal and various interlayer metals. An interlayer design and test were devised from the basic considerations of a strong interfacial bond and a favourable stress gradient in the ceramic/metal interfacial zone.

The strong interfacial bond of the brazing filler metal on the sialon ceramic was obtained when brazing temperature was over 1123 K, which corresponded to the formation of Ti_2AlN, Ti_5Si_4 and TiAg at the ceramic/metal interface. It is important to maintain the strong interfacial bond of the filler metal on the ceramic in selection of an interlayer material to improve the strength of the ceramic/steel joint. A preliminary test showed that Cu or Ta as an interlayer contacting the ceramic is better for the ceramic and the brazing filler metal, but Kovar or Ni–15Cr–15Co is poor.

The joint strength of the sialon ceramic to 40Cr steel without an interlayer was very low, but could be improved by inserting a layer of soft interlayer Cu with a suitable thickness. In particular, a composite interlayer such as Cu/Nb alloy, Cu/Kovar or Cu/Mo, etc. was designed to decrease the stress in the joint and improve the strength of the ceramic/steel joint. The design was very successful. Better strength of the ceramic/steel joint was achieved for all joints with a composite interlayer. The maximum strength of the ceramic/steel joint, 280 MPa, was obtained by using Cu/Nb alloy as interlayer and brazing at 1153 K for 5 min. Finally, an interfacial engineering design to enhance the strength of the ceramic/metal joint was also suggested.

Acknowledgement

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References

1. M. NAKA, I. OKAMOTO, T. NISHINO and S. URAI, *Trans. JWRI* **18** (1989) 189.
2. M. NAKA, M. KUBO and I. OKAMOTO, *ibid.* **18** (1989) 194.
3. A. J. MOORHEAD, *Weld. J.* **62** (1983) 17.
4. A. J. MOORHEAD and H. KEATING, *ibid.* **65** (1986) 17.
5. M. G. NICHOLAS, T. M. VALENTINE and M. J. WAITE, *J. Mater. Sci.* **15** (1980) 2197.
6. R. R. KAPOOR and T. W. EAGAR, *Metall. Trans.* **20B** (1989) 919.
7. *Idem.*, *J. Amer. Ceram. Soc.* **72** (1989) 448.
8. H. MIZUHARA and K. MALLY, *Weld. J.* **64** (1985) 27.
9. H. MIZUHARA, US Patent No. 4 591 535 (1986).
10. A. P. XIAN and Z. Y. SI, *J. Mater. Sci.* **25** (1990) 4483.
11. J. P. KRUGERS and G. DEN OUDEN, in Proceedings of the Third International Conference on Joining Ceramic, Glass and Metal, April 1989, edited by W. Kraft (DGM Informationsgesellschaft Oberursel, 1989) p. 89.
12. D. B. BOGY, *J. Appl. Mech.* **43** (1975) 93.
13. A. G. EVANS, M. RÜHLE and M. TURWITT, *J. Physique* **46** (1985) c4–613.
14. M. NAKA, T. TANAKA and I. OKAMOTO, *Trans. JWRI* **14** (1985) 285.
15. A. P. XIAN and Z. Y. SI, *J. Amer. Ceram. Soc.* **73** (1990) 3462.
16. H. P. KIRCHNER, J. C. CONWAY and A. E. SEGALL, *ibid.* **70** (1987) 104.
17. O. T. IANCU, D. MUNZ, B. EIGENMANN, B. SCHOLTES and E. MACHERAUCH, *ibid.* **73** (1990) 1144.
18. K. H. THIEMANN, H. J. WEINERT and W. RAUCHLE, UK Patent No. 2 151 173A (1985).
19. K. SUGANUMA, T. OKAMOTO, M. KOIZUMI and M. SHIMADA, *J. Mater. Sci. Lett.* **4** (1985) 648.
20. H. C. CAO, M. D. THOULESS and A. G. EVENS, *Acta Metall.* **36** (1988) 2037.
21. A. G. EVANS, M. RÜHLE, B. J. DALGLEISH and P. G. CHARALAMBIDES, *Mater. Sci. Engng* **A126** (1990) 53.
22. L. P. HUANG, Z. K. HUANG, Y. R. QU and X. R. FU, *J. Inorg. Mater.* **1** (1986) 123.
23. M. RÜHLE and A. G. EVANS, *Mater. Res. Soc. Symp. Proc.* **120** (1988) 293.
24. M. RÜHLE and A. G. EVANS, *Mater. Sci. Engng* **A107** (1989) 187.
25. A. P. XIAN and Z. Y. SI, *Chin. J. Met. Sci. Tech.* **7** (1991) 292.

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