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Insert Layer Design Using Residual Stress in Si_3N_4 /Steel Joining as Parameter[†]

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Abstract

The present paper investigates the complex relation among insert layer and cracking susceptibility in simple brazed Si_3N_4 /steel joints.

The relation among insert metal chemistry, hardness (yield stress), microstructure and thickness of the insert layer, and cracking susceptibility was evaluated using a series of binary Cu-X insert metals (Cu-5wt.%Cr, Cu-1wt.%Nb, Cu-3wt.%V, Cu-5wt.%Ti and Cu-10wt.%Zr). The use of higher yield stress insert metal increased the critical insert layer thickness at which cracking occurred in Si_3N_4 /steel joints. These results were consistent with the mechanical modelling results presented previously. Crack-free joints could be made using Cu-5wt.%Cr insert metal in a simple brazing operation, when the diameters of the silicon nitride and steel substrates were ≤ 10 mm, and the insert layer thickness was around 0.2 mm. When the diameter of the ceramic and metal substrates was ≥ 15 mm, a special low expansion-high ductility (LE-HD) joining technique produced crack-free joints. This technique involved the combination of a 5 mm thick layer of tungsten insert metal with two ductile, 0.4 mm thick layers of Cu-5wt.%Cr insert metal.

KEY WORDS: (Dissimilar joining) (Brazing) (Insert materials) (Insert layer design)
(Residual stress) (Crack susceptibility)

1. Introduction

The residual stress produced when ceramics are joined to metal substrates is created by the difference in thermal expansion mismatch between the two substrates. It has already been observed that final joint strength decreases when the difference in thermal expansion of alumina and different metal substrates is increased¹⁾. In order to decrease the difference in thermal expansion mismatch, a ceramic substrate such as Si_3N_4 should be joined to a steel substrate using an insert layer which has a thermal expansion close to that of the ceramic. This contention was supported during brazing of Si_3N_4 to a range of metal substrates (Fe, Cu, Invar, Kovar and AISI stainless steel)²⁾.

However, it has been shown recently that although thermal expansion directly controls residual stress formation, the residual stress in a dissimilar joint is also dependent on the insert metal yield stress and ductility^{3), 4), 5)}. In effect, there are two mechanical situations

which determine the residual stress in a ceramic/metal joint, namely, one where fully elastic behavior dominates, and another where plastic deformation of the insert metal and/or steel substrate is the critical factor.

The present paper investigates the complex relation among insert metal chemistry/microstructure/yield stress, insert layer thickness and cracking susceptibility in simple brazed Si_3N_4 /steel joints. Guidelines for selection of insert layer materials are provided founded on an analysis of the residual stress produced in ceramic/steel joining as the parameter. Based on these derivations, experiments are carried out using a number of specially-made binary copper-based insert metals.

2. Effect of Insert Metal Yield Stress on Residual Stress Generation

2.1 General concept

Considering the effect of the insert metal yield stress

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based on joining mechanics, there are two mechanical situations which determine the residual stress in a dissimilar materials joint.

For elastic conditions, the thermal stress in the ceramic substrate is given for a simple one-dimensional model⁴⁾:

$$\sigma = \Delta\alpha\Delta T \{E_1 E_2 / (E_1 + E_2)\} \quad \text{-----(1)}$$

where,

$\Delta\alpha$ is the difference in the coefficient of thermal expansion between the ceramic and metal substrates

ΔT is the temperature difference between the bonding temperature and room temperature

E_1 and E_2 are the Young's modulus of the metal and ceramic substrates.

When the metal substrate becomes plastic, the thermal stress in the ceramic substrate is calculated using the following equation,

$$\sigma = \sigma_Y + [\Delta\alpha\Delta T E_p] \quad \text{-----(2)}$$

where,

E_p is the strain hardening coefficient of the metal substrate

σ_Y is the yield stress of the metal substrate.

In Eq. (2), the thermal stress depends on σ_Y and on the strain hardening term, $[\Delta\alpha\Delta T E_p]$, but predominantly on the yield stress since it is much larger than the other term. Figure 1 shows the thermal stress generated for a given temperature change when two ceramic/metal combinations, Si_3N_4/Cu and Si_3N_4/Mo , are used. When the temperature change is small, the residual stress is dominated by thermal expansion mismatch, and the Si_3N_4/Cu combination produces the highest thermal stress. However, if the temperature change is large, the residual stress depends on the yield stress of the metal substrate. In this situation, the lowest thermal stress is produced using the Si_3N_4/Cu combination.

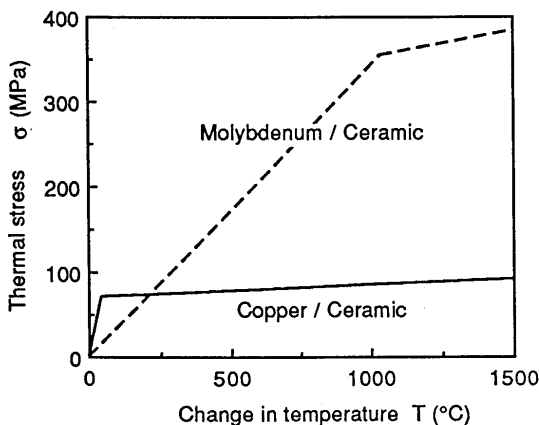


Fig.1 Relation between thermal stress and temperature change for two ceramic/metal composites.

It is important to point out that the Eq. (2) was developed using a simple, one-dimensional solution. Consequently, Eq. (2) can only indicate *qualitatively* the situation which exists in actual joints, where an axisymmetric, 3-dimensional stress system generally operates. In spite of this, Eq. (2) explains the beneficial use of ductile insert materials for dissimilar joining. For example, Zhou et al³⁾ found that the highest tensile strength in $Si_3N_4/steel$ joints occurred when a copper insert metal was employed during brazing. Equation (2) also qualitatively explains the results produced by a number of investigators when they used ductile insert metals^{6), 7)}.

2.2 Modelling by FEM

The effect of insert metal yield stress on residual stress generation during $Si_3N_4/steel$ joining has been modelled by FEM⁵⁾. Figure 2 shows the transient maximum principal stress, $|\sigma_1|_{max}$, produced perpendicular to the bondline when the joint is cooled to room temperature. When the yield stress of the $t=0.25$ mm thick steel insert is varied, the $|\sigma_1|_{max}$ produced in the ceramic substrate depends on the yield stress of the insert material.

Figure 3 confirms that decreasing the yield stress of the insert metal lowers the $|\sigma_1|_{max}$ value. Consequently, the use of a low yield stress ductile insert

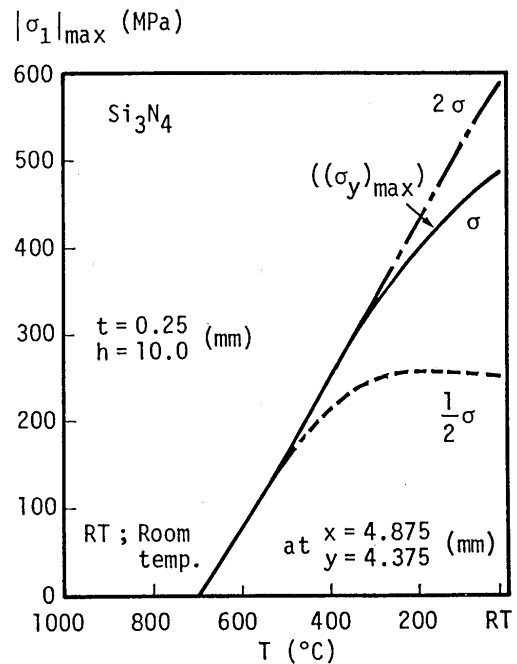


Fig.2 Effect of insert layer yield stress on the principal stress, $|\sigma_1|$, produced adjacent to the bondline, at the joint periphery. The yield stress of the insert layer varies from half to twice the initial value(base metal).

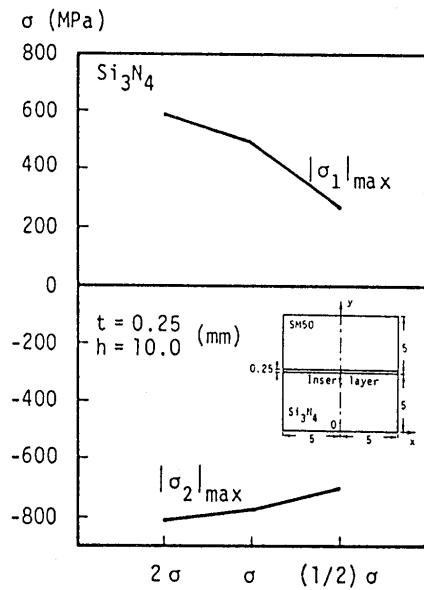


Fig.3 Effect of insert metal yield stress on the maximum principal stress, $|\sigma_1|_{max}$ and $|\sigma_2|_{max}$.

metal material will effectively reduce $|\sigma_1|_{max}$.

Figure 4 shows the residual deformation and the vectors of principal stress, σ_1 and σ_2 , with and without an insert layer. At the joint interface, the steel (SM50) is prevented from shrinking freely. However, the vectors of principal stress and the location where they attain maximum values are not changed.

Since insert metal yielding is critically important, any factor that affects the yielding process will directly influence residual stress generation in dissimilar joints. In particular, when the thickness of the insert layer is very thin, the rigid restraint produced by the higher strength/modulus steel substrate induces a triaxial stress state which inhibits yielding⁵). In contrast, when the thickness of the insert layer increases, the restraint produced by the steel substrate diminishes and the insert metal yields, so that the residual stress becomes small. Figure 5 shows the effect of insert layer thickness on residual stress generation during Si_3N_4 /steel joining (The insert metal yield stress is decreased by 50% of the steel substrate yield stress.). In a simple brazing operation, the thickness of the insert layer following the joining operation is around 0.15 mm and consequently, the ability of this material to yield depends on the insert metal chemistry employed, on the microstructure at the joint centerline, on the mechanical properties of the steel being joined, and on the joint configuration used.

The results in Figs. 2, 3, 4 and 5 were developed using a thermal elastic-plastic, 2-dimensional plane stress assumption and support the qualitative indications presented in Eq. (2).

3. Experimental Procedure

3.1 Materials

Brazing was carried out using pressureless sintered

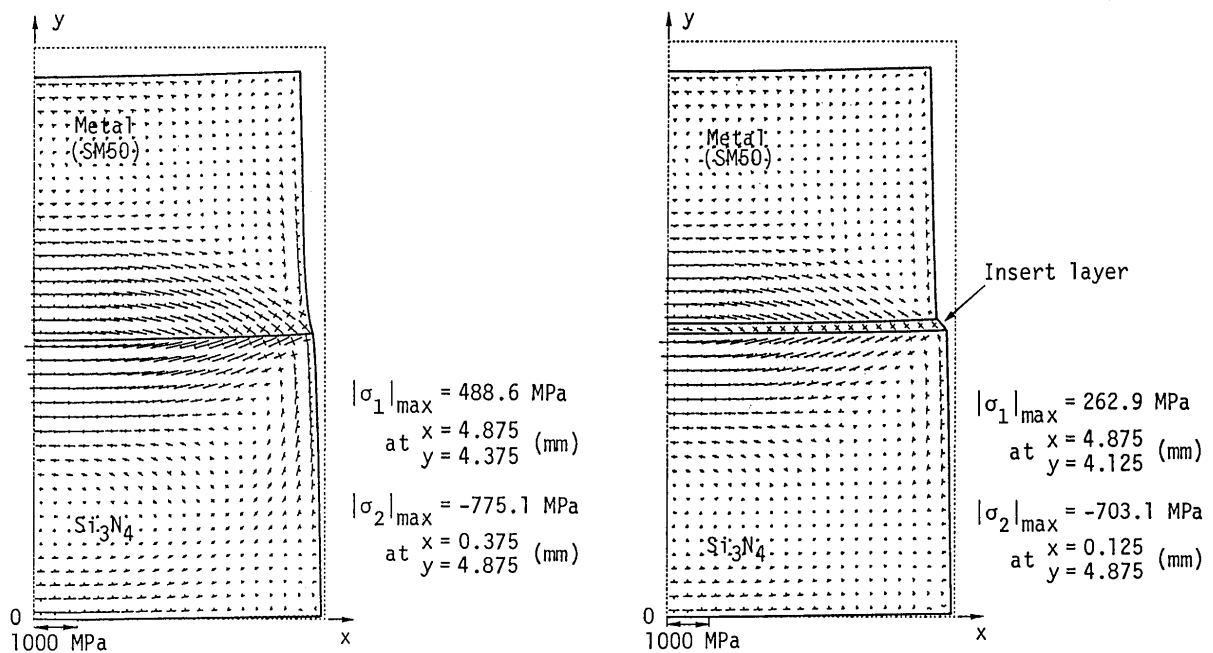


Fig.4 Deformation after dissimilar joining and vectors of principal stress, σ_1 and σ_2 .

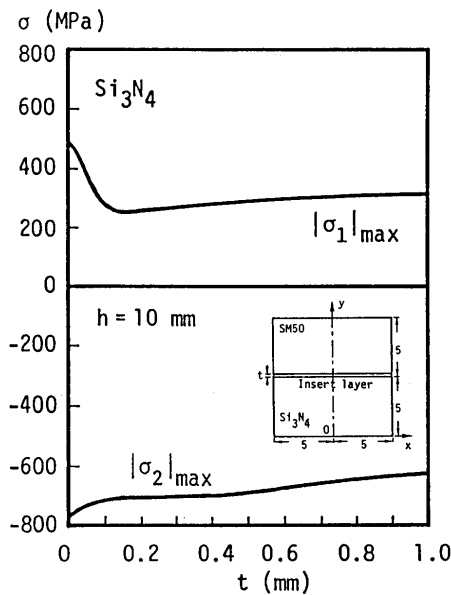


Fig.5 Effect of insert layer thickness on the maximum principal stress, $|\sigma_1|_{max}$ and $|\sigma_2|_{max}$.

Si_3N_4 (Kyocera Co. SN-220) and SCM435 steel (of composition; 0.33%C, 0.24%Si, 0.68%Mn, 0.013%P, 0.011%S, 0.95%Cr, 0.17%Mo).

The diameters of the Si_3N_4 and steel substrates were 10, 13, 15, 17 and 20 (in mm) respectively. The thickness of the Si_3N_4 and steel substrates were 10 mm. Tungsten/ Si_3N_4 joints were employed in tests which assessed the hardness (yield stress) of the insert layer produced using specially-made Cu-X binary insert metals since it is well-known that tungsten is completely insoluble in the copper-based brazing alloys. In these tungsten/ Si_3N_4 joints, the tungsten substrate was 10 mm diameter and 10 mm thick.

3.2 Brazing conditions

Vacuum brazing was carried out using the following conditions; 1250 °C for 0.63 ks (for the Cu-5wt.%Cr, Cu-1wt.%Nb and Cu-3wt.%V insert metals); 1100 °C for 1.8 ks (for the Cu-5wt.%Ti insert metal); 1150 °C for 1.8 ks (for the Cu-10wt.%Zr insert metal). The rate of heating to the brazing temperature was 0.16 °C/s and all test samples were furnace-cooled following the brazing operation.

3.3 Effect of insert metal chemistry

The following binary insert metals were made by induction melting in argon; Cu-5wt.%Cr, Cu-1wt.%Nb, Cu-3wt.%V, Cu-5wt.%Ti and Cu-10wt.%Zr. These alloys encompass the regimes where the amount of solid solubility of the element in copper is low (in the Cu-

5wt.%Cr, Cu-1wt.%Nb and Cu-3wt.%V insert metals), where the alloy solidifies as a eutectic of copper solid solution and $CuZr_5$ phases (with the Cu-10wt.%Zr insert metal), and as a eutectic of copper solid solution and $\beta TiCu_4$ phases (with the Cu-5wt.%Ti insert metal).

3.4 Evaluation of cracking susceptibility

The relation among insert metal thickness, insert metal chemistry and cracking susceptibility in Si_3N_4 /SCM435 steel joints was evaluated as follows:

The thickness of the insert layer was maintained at any desired level using tungsten wire spacers. Prior to joining, the thickness of each insert metal exceeded the diameter of the tungsten spacer by 0.2 mm. Following the joining operation, the insert layer thickness equalled that of the tungsten wire.

In joints which were produced without the use of tungsten wire spacers, the insert metal thickness was 0.4 mm prior to joining and approximate 0.2 mm after the brazing operation. Two tests were carried out at each joining condition, and the integrity of the Si_3N_4 /steel joints was evaluated using a combination of dye-penetrant, non-destructive testing and optical microscopy.

4. Result and Discussion

It is generally known that the hardness of different binary alloys is proportional to their yield stress and, therefore, the Knoop hardness of the insert layer was taken as the measure of yield stress of each material. The effect of insert metal chemistry on insert layer hardness (yield stress) was evaluated in Si_3N_4 /tungsten joints.

The effect of insert layer chemistry on hardness (yield stress) values is shown in Table 1. The hardness of the insert layer increased in the order: Cu-5wt.%Cr, Cu-1wt.%Nb, Cu-3wt.%V, Cu-5wt.%Ti and Cu-10wt.%Zr.

Table 1 Hardness of insert layer using different Cu-X insert metal chemistries.

Insert metal	Average Knoop hardness of copper enriched layer*	Critical thickness of copper enriched layer for crack prevention (mm)
Cu-5%Cr	116	0.20
Cu-1%Nb	118	0.20
Cu-3%V	142	0.25
Cu-5%Ti	154	0.65
Cu-10%Zr	192	0.75

* the copper enriched layer is the thickness of the insert layer between the tungsten substrate and the reaction zone at the ceramic/insert layer interface.

This hardness variation was a direct result of the different microstructures produced at the insert layer centerline. The microstructures produced using Cu-5wt.%Cr, Cu-1wt.%Nb and Cu-3wt.%V insert metals comprised copper-rich material at the insert layer centerline, with

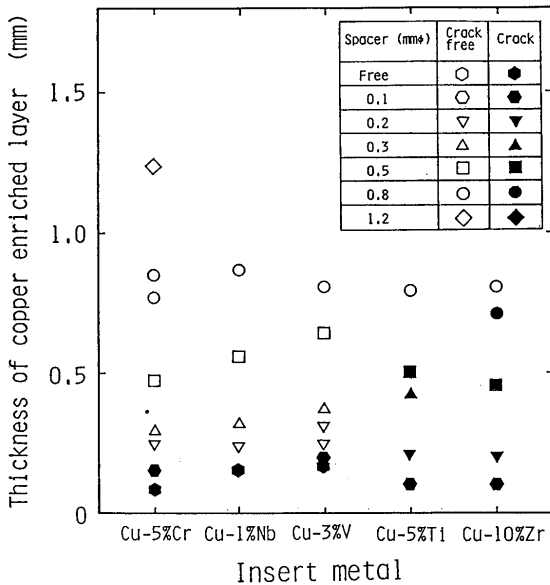


Fig.6 Relation between the thickness of copper-enriched layer and the incidence of cracking in Si₃N₄/SCM435 steel joints produced using a range of insert metal chemistries. [The substrate diameters are 10 mm and the copper-enriched layer is the region between the reaction zone at the ceramic/insert metal interface and the tungsten substrate].

negligible amounts of intermetallic formation at grain boundary regions. The Cu-5wt.%Ti insert metal produced which comprised copper solid solution and βTiCu₄ and Ti₅Si₃ intermetallic phases. The Cu-10wt.%Zr insert metal produced a microstructure at the insert layer centerline which comprised copper solid solution and ZrCu₄ and ZrCu₅ intermetallic phases⁸).

Figure 6 shows that the critical thickness at which cracking occurred when higher hardness (yield stress) insert metals were employed. All cracks initiated in the ceramic substrate, in the region adjacent to the ceramic/insert metal interface, at the joint periphery and crack-free joints were produced using Cu-5wt.%Cr and Cu-1wt.%Nb insert metals when the insert layer thickness was 0.2 mm. Also, crack-free joints were produced when the insert layer thickness was 0.25 mm for the Cu-3wt.%V insert metal. In contrast, the insert layer thicknesses that produced crack-free joints with the Cu-5wt.%Ti and Cu-10wt.%Zr insert metals, were 0.65 mm and 0.75 mm respectively. These experimental results correspond with the results of computer modelling discussed previously. The principal stress decreased when the insert metal yield stress decreased, and thicker insert layers were required when the insert layer strength increased.

The results in Fig.6 consider a situation where the substrate diameters are both 10 mm. However, for a given insert layer thickness, increasing the diameter of the Si₃N₄ and steel substrates will increase the

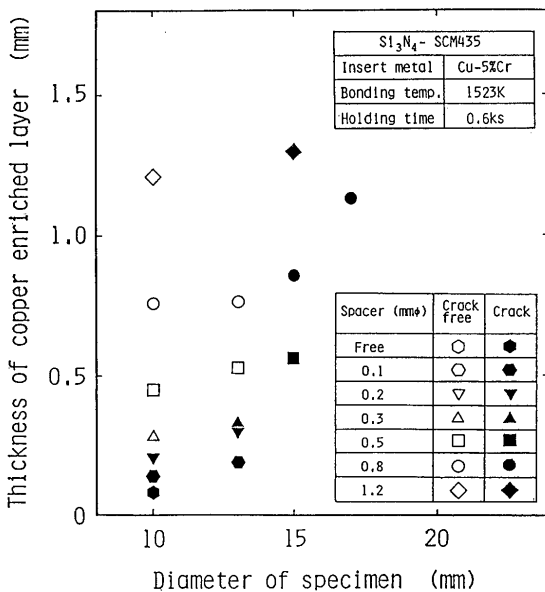


Fig.7 Effect of substrate diameter on the cracking susceptibility in Si₃N₄/steel joints brazed using Cu-5wt.%Cr insert metal.

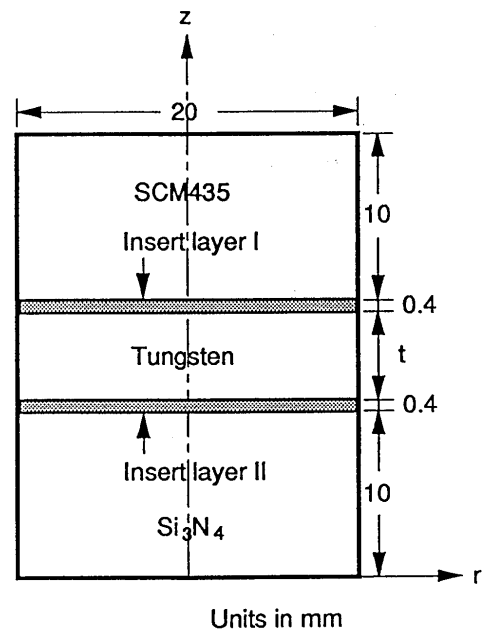


Fig.8 Schematic showing the low expansion-high ductility (LE-HD) joining technique. [The tungsten insert metal is brazed to the Si₃N₄ and the joint is completed by SMC435].

likelihood of cracking during dissimilar joining. **Figure 7** shows the effect of increased substrate diameter (from 10 mm to 17 mm) on the cracking susceptibility during Si₃N₄/steel joining. All dissimilar joints were cracked when the substrate diameter exceeded 15 mm (even when the insert layer thickness was as large as 1.2 mm). An alternative insert layer joining technique is required when larger diameter (>13 mm) Si₃N₄/steel combinations are considered. A low expansion-high ductility (LE-HD) insert layer joining method has been developed which produces crack-free joints when 20 mm diameter Si₃N₄ and steel substrates are employed. In the LE-HD method, a 5 mm thick tungsten insert metal is combined with two ductile Cu-5wt.%Cr insert layers (see **Fig.8**). Crack-free joints are produced since the location of the maximum principal stress is shifted to the center of tungsten insert metal^{5), 9)}. A variant of this joining technique involves the use of bi-metallic copper/tungsten or copper/Kovar strips, of sufficient thickness to reduce residual stress³⁾. In this case, the copper side of the strip contacts the Si₃N₄ substrate and the tungsten (or Kovar) strip contacts the steel substrate.

5. Conclusions

The relation among insert metal chemistry, hardness (yield stress), microstructure and thickness of the insert layer, and cracking susceptibility was evaluated using a series of binary Cu-X insert metals (Cu-5wt.%Cr, Cu-1wt.%Nb, Cu-3wt.%V, Cu-5wt.%Ti and Cu-10wt.%Zr).

The principal results are as follows.

- (1) The use of higher yield stress insert metal increased the critical insert layer thickness at which cracking occurred in Si₃N₄/steel joints. These results were

consistent with the mechanical modelling study presented previously⁵⁾.

- (2) Crack-free joints could be made using Cu-5wt.%Cr insert metal in a simple brazing operation, when the diameters of the silicon nitride and steel substrates were ≤ 10 mm, and the insert layer thickness was approximately 0.2 mm.
- (3) When the diameter of the ceramic and metal substrates was ≥ 15 mm, a special low expansion-high ductility (LE-HD) joining technique produced crack-free joints. This technique involved the combination of a 5 mm thick tungsten insert layer with two ductile, 0.4 mm thick layers of Cu-5wt.%Cr insert metal.

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