

# Research on Ceramic/Steel Connection Using the Composite Brazing Method

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**Abstract:** Ceramic/metal connectors are widely used in aerospace, microelectronics, precision instruments, fuel cells and other fields. Ceramics' poor machinability, low ductility and impact toughness, high brittleness, and other defects severely limit their application in the wear-resistant materials industry. Due to the large difference between the coefficient of thermal expansion of ceramics and metal, the residual thermal stresses generated during the connection process will destroy the integrity of the joint, thus increasing the difficulty of connecting ceramics and metal. The composite brazing method can effectively eliminate the residual thermal stress, which is one of the ideal methods to solve the problem of ceramic-metal connection. Composite brazing will be able to regulate the thermophysical properties of the material, thus greatly reducing the damage of residual thermal stresses on the joint, and then improve the strength of the ceramic/metal joint, the method not only increases the wettability of the brazing material on the ceramic side, which is irreplaceable in improving the bonding of the joint, but also eliminates the residual thermal stresses and ensures the integrity of the joint. This paper summarizes the current research status of ceramic/steel composite brazed joints in recent years, and investigates the mechanical properties and microinterfacial structure composition of the joints.

**Keywords:** Ceramic/Metal, Brazing, Mechanical Properties, Microinterfacial Structure

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## 1. Introduction

With the rapid development of modern science, a variety of harsh working environment has put forward higher requirements for materials. Common metallic steels have good room temperature strength, excellent plasticity and toughness, and good machinability and weldability, but their mechanical properties at high temperatures are poor [1, 2]. Ceramic materials have excellent properties such as high strength, wear and corrosion resistance, and maintain good performance at high temperatures and in chemically aggressive environments. However, ceramics themselves are brittle and difficult to be machined into structurally complex components [3, 4]. Therefore, the combination of rigid and ceramic together to prepare composite components can form a good complementary performance.

Metals are materials that have properties such as shiny,

extensible, easily conducting, heat transfer, etc. Table 1. Metals are plentiful in all of nature and are widely used in everyday life. They are vital to modern technology and are frequently used in industry. Titanium alloys, for example, have superior low density, high-temperature strength, superior resistance to creep and corrosion, and other properties. Because of such properties, these alloy components will be used in aerospace, shipping, petrochemicals, nuclear energy and other industrial applications. However, high-priced and weak processing and joining properties of such alloys have limited their wide application. Stainless steel is one of the most commonly used structural materials because of its good mechanical properties, weldability, ease of processing and low price.

**Table 1.** Performance parameters of several common metals [6, 7].

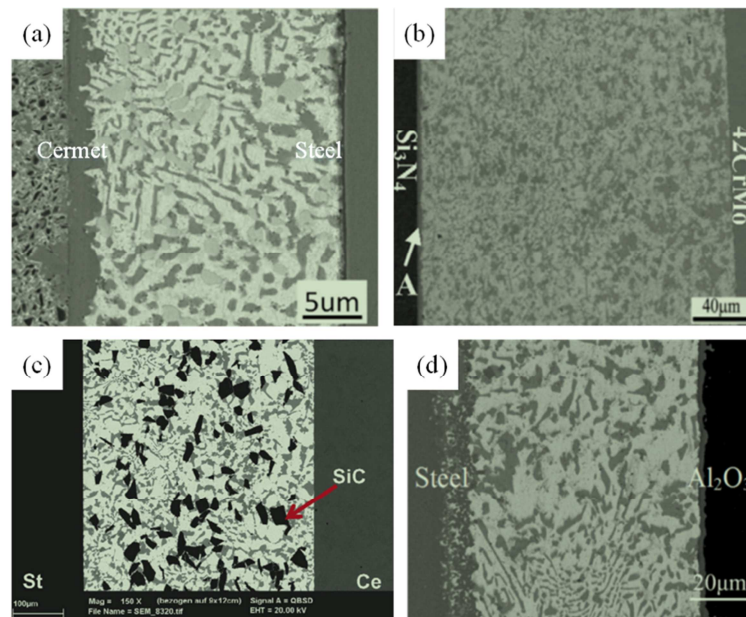
Metals	Density (g/cm <sup>3</sup> )	Melting point (°C)	Hardness (HV)	Young's modulus (GPa)	Coefficient of linear expansion (10 <sup>-6</sup> /K)	Thermal conductivity (W·m <sup>-1</sup> ·K <sup>-1</sup> )
304 SS	7.93	1398-1454	210	193	17.2	16.3
TC4	4.51	1538-1649	288	110	7.89	7.955
Copper	8.9	1083	70	107.9	16.92	390
Inconel600	8.47	1354-1413	120-170	205	12.35	12.85
Kovar 4J29	8.17	1420-1455	160	138	5-5.3	19.26

However, due to the large differences between ceramics and steel in terms of chemical properties, composition and physicochemical properties, and the difficulty of wetting the ceramic surface with common brazing materials [5]. Secondly, the coefficient of thermal expansion and modulus of elasticity of ceramics and steel do not match each other, so that a large residual stress is generated at the joint interface during the joining process, which reduces the performance of the joint. In recent years, scholars at home and abroad have conducted a lot of researches to relieve the residual stresses at the interface, and have made some progress. The composite brazing method can not only improve the wetting of brazing material on the ceramic surface, but also effectively relieve the residual stresses in the joint.

## 2. Composite Brazing Method

Composite brazing materials, where a certain amount of reinforcing phase is added to the brazing material, thus adjusting the thermophysical coefficient inside the brazing material for the purpose of absorbing interfacial welding stresses. During the interfacial reaction, the braze melts while the added phase does not participate in the reaction and is distributed in the braze joint to form a metal matrix composite [8]. H. He *et al.* [9] used molybdenum particles reinforced with AgCuTi braze to achieve the brazed joint of Ti(C, N) ceramics and steel. As shown in Figure 1a, the joint

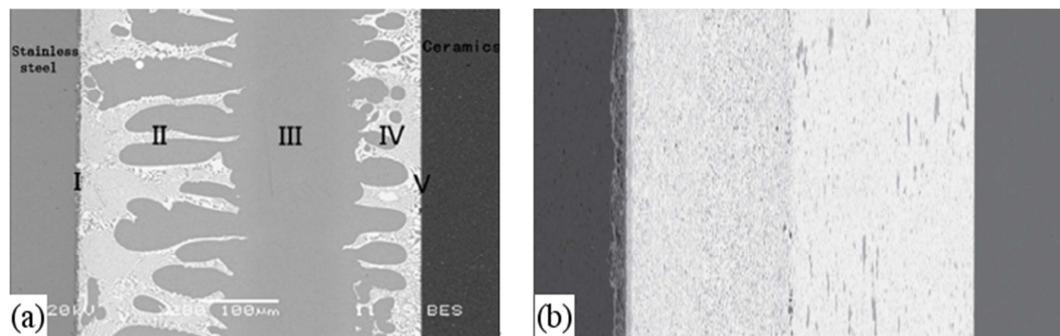
interface was ceramic/Ni<sub>3</sub>Ti+Cu<sub>3</sub>Ti<sub>2</sub>/Ag(s, s)+Cu(s, s)+TiCu+Mo/Ti(s, s)+FeTi+Fe<sub>2</sub>Ti/steel. The joint shear strength of up to 263 MPa was achieved with the addition of 8 wt.% Mo particles to the brazing base. Y. M. He *et al.* [10] used Ag-Cu-Ti/Mo composite fillers to achieve brazed connections between silicon nitride ceramics and high-strength steels. As shown in Figure 1b, a Ti<sub>5</sub>Si<sub>3</sub> reaction layer and a reaction layer consisting of Fe<sub>2</sub>Ti and FeTi were generated on the ceramic side and the steel side, respectively, and Mo particles, Ag(s, s), Cu(s, s), and Cu-Ti compounds were generated in the central part. The joint strength was 587.3 MPa when the percentage of Mo particles was 10 vol.%. G. Blugan *et al.* [11] used silicon carbide powder reinforced with AgCuInTi braze to braze joint Si<sub>3</sub>N<sub>4</sub> ceramics and steel. As shown in Figure 1c, the interface connection was tight and the SiC particles were distributed in the brazing material and did not contact the base material on both sides, but were more concentrated in the central region of the brazed joint. The average bending strength of the joint was 395 MPa. Z. W. Yang *et al.* [12] achieved a brazed joint of stainless steel and alumina ceramic using a hybrid brazing material of Ag-Cu-Ti+graphene. As shown in Figure 1d, Fe-Cr layers, TiFe<sub>2</sub>, Cu(s, s), TiC, Ag(s, s), and Ti<sub>3</sub>(Cu, Al)<sub>2</sub>O were formed in the brazed weld region. when the percentage of graphene in the mixed filler reached 0.1 wt.%, the strength of the joint reached a maximum of 212 MPa.



**Figure 1.** Composite brazing material: (a) Ti(C, N) ceramic/AgCuTi+Mo/45 steel. (b) Si<sub>3</sub>N<sub>4</sub>/AgCuTi+Mo/42CrMo Steel. (c) Steel/AgCuInTi+SiC/Si<sub>3</sub>N<sub>4</sub>-TiN. (d) SS/AgCuTi+Graphene/Al<sub>2</sub>O<sub>3</sub>.

Composite interlayers consist of different single layers in several types of combinations, such as soft interlayers with hard interlayers or hard interlayers with hard interlayers. X. et al [13] successfully connected  $\text{Si}_3\text{N}_4$  ceramics and 304 SS by using Cu/Ag-Cu/Ti composite sandwich as shown in Figure 2a. The interfacial structure of the joints exhibits different four regions,  $\text{TiFe}_2$  in region I, Ag-Cu eutectic + Cu(s) in region II, Cu(s, s) in region III, Cu(s)+Ag-Cu eutectic in region IV, and  $\text{Cu}_3\text{Ti} + \text{TiN}/\text{Si}_3\text{N}_4$  in region V, which are located in between the 304SS and  $\text{Si}_3\text{N}_4$  ceramics, the maximum strength of the joint was 57 MPa. Alpigg et al [14] used  $\text{Ag}_{57}\text{Cu}_{38}\text{Ti}_5$  and Cu/Nb composite interlayer to realize the connection between

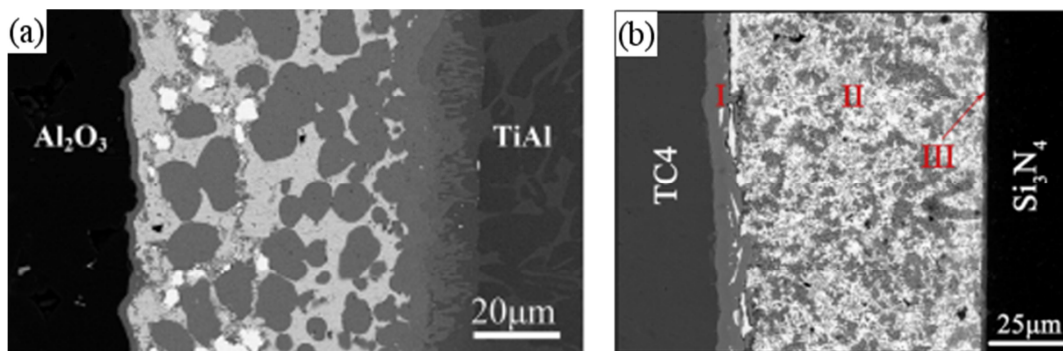
SiAlON ceramics and 40Cr steel. Reaction of SiAlON ceramics with  $\text{Ag}_{57}\text{Cu}_{38}\text{Ti}_5$  resulted in the formation of  $\text{Ti}_2\text{AlN}$ ,  $\text{Ti}_5\text{Si}_4$  and TiAg interfaces, which gave a joint strength of 280 MPa for SiAlON/40Cr. Zhong et al [15] used W-Pd-Ni interlayer to connect the SiC ceramic with SS with the joint morphology shown in Figure 2b. Elemental diffusion and a chemical reaction took place in the reaction zone, where the elements Pd, Ni, and W reaction with SiC produced  $\text{Pd}_2\text{Si}$ ,  $\text{Ni}_2\text{Si}$ , C,  $\text{W}_5\text{Si}_3$ , and WC. It is important to protect the joints by reducing the residual thermal stresses in the joints with W-Pd-Ni interlayer, and the average shear strength of SiC/SS joints is 33 MPa.



**Figure 2.** Ceramic/metal composite layer brazing: (a) for 304SS/Cu/Ag-Cu/Ti/Si<sub>3</sub>N<sub>4</sub> interfacial structure; (b) for SiC/W-Pd-Ni/stainless steel interfacial structure.

The diverse methods of the addition reinforcement phase can be categorized into additive and primary generation methods, which are characterized by the fact that they can effectively control the type and content of the reinforcement phase, but not its distribution. Yang et al [16] using AgCuTi+W composite metal filler to braze  $\text{Al}_2\text{O}_3$  ceramics into TiAl alloys. As shown in Figure 3a, the joint has an inter-facial structure of  $\text{AlCu}_2\text{O}_3 / \text{Ti}_3(\text{Cu, Al})_3\text{O} / \text{W} + \text{Ag}(\text{s, s}) + \text{TiCu} + \text{AlCu}_2\text{Ti} / \text{AlCu}_2\text{Ti} + \text{Ag}(\text{ss}) / \text{AlCu}_2\text{Ti} \text{ layer} + \text{AlCuTi} \text{ layer} / \text{TiAl}$ . The incorporation of W particles relieved the residual stresses between the  $\text{Al}_2\text{O}_3$  ceramics and the metal,

which improved the joint strength with a maximum shear strength of 148 MPa. However, it was observed that excess W particles resulted in microcracks and micropores in the joints, which decreased the shear strength. Zhao et al [17] used AgCu with  $\text{Si}_3\text{N}_4$  nanoparticles and microtitanium particles to connect silicon nitride ceramics and TC4 alloys. As shown in Figure 3b, the inter-facial structure of the TC4/Si<sub>3</sub>N<sub>4</sub> joint is TC4/Ti-Cu/particle-reinforced silver matrix composite/TiN+Ti<sub>5</sub>Si<sub>3</sub> layer/Si<sub>3</sub>N<sub>4</sub>, and the shear strength of this joint is 73.9 MPa.



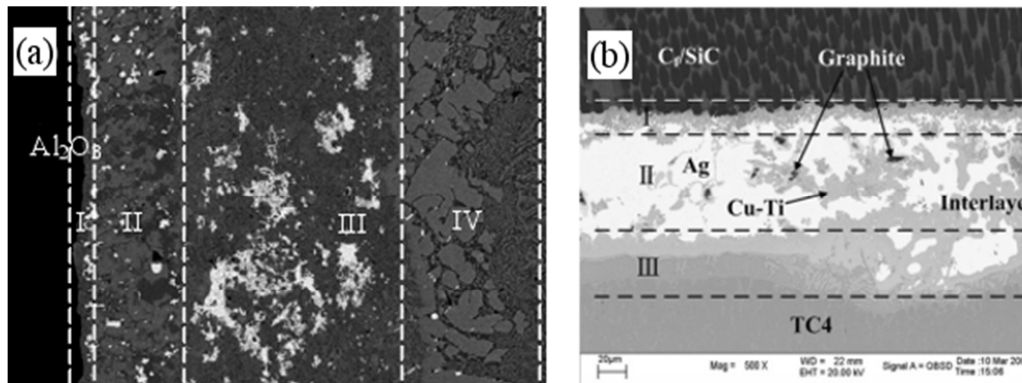
**Figure 3.** Joining of ceramic to metal with composite filler metal by addition method: (a)  $\text{Al}_2\text{O}_3/\text{AgCuTi+W/TiAl}$ ; (b)  $\text{TC4/AgCu+Ti+Si}_3\text{N}_4/\text{Si}_3\text{N}_4$ .

Yang [18, 19] developed a method to strengthen ceramic/metal joints by in-situ TiB whiskers using in-situ molding technique as shown in Figure 4a. The inter-facial structure of this joint has  $\text{Al}_2\text{O}_3 / \text{Ti}_3\text{Cu}_2\text{AlO} / \text{Ti}_2\text{Cu} + \text{Ti}_2(\text{Cu, Al}) + \text{Ti}_3\text{Al} / \text{Ag}(\text{ss}) + \text{Ti}(\text{Cu, Al}) + \text{TiB} / \text{Ti}_2\text{Cu} + (\text{Ti}(\text{s, s}) + \text{Ti}_2\text{Cu}) + \text{Ti}_3\text{Al} / \text{TC4}$ . During brazing, the B particles and Ti atoms in the filler metal react to form TiB whiskers, affecting the diffusion of atoms and refining the structural grains, making the delamination more and more pronounced. The joint has a maximum shear strength of 77.9 MPa. Cui et al

s)+ $\text{Ti}_2\text{Cu}$ ) +  $\text{Ti}_3\text{Al} / \text{TC4}$ . During brazing, the B particles and Ti atoms in the filler metal react to form TiB whiskers, affecting the diffusion of atoms and refining the structural grains, making the delamination more and more pronounced. The joint has a maximum shear strength of 77.9 MPa. Cui et al

[20] used Ag-Cu-Ti-(Ti+C) hybrid powder to incorporate Cf/SiC composite into TC4 alloy as showed in Figure 4b. The interfacial structure is Cf / SiC /  $\text{Ti}_3\text{SiC}_2$ +TiC /Ti-Cu + $\text{Ti}_5\text{Si}_3$ /Ag+Ti-Cu+TiC+C/(Ti<sub>2</sub>Cu+Ti)/Ti<sub>2</sub>Cu/TiCu/Ti<sub>3</sub>Cu<sub>4</sub>/

TC4. In-situ synthesis of TiC reduces the difference in thermal expansion between Cf/SiC composites and TC4 alloy, which gives the joint a maximum shear strength was 145 MPa.



**Figure 4.** Original composite filler metal interlayer joining ceramic to metal by formation method: (a)  $\text{Al}_2\text{O}_3$ /Ag-Cu-Ti-B/TC4; (b) Cf/SiC/Ag-Cu-Ti-(Ti+C)/TC4.

### 3. Conclusion

Through the method of composite brazing material, the strengthening stage makes the internal thermophysical coefficient of the brazing material close to the internal thermophysical coefficient of the base material, so as to achieve the purpose of absorbing the interfacial weld stress, thus effectively improving the performance of the joints (up to 587.3MPa), and the interfacial structure or reaction product consists of TiN,  $\text{Ti}_5\text{Si}_3$ ,  $\text{Fe}_2\text{Ti}$ , FeTi. This indicates that the ceramic/steel joint can be realized efficiently by using composite brazing.

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