International Journal of Materials Science and Applications
2023; 12(3): 41-45
http://www.sciencepublishinggroup.com/j/ijmsa
doi: 10.11648/j.ijmsa.20231203.12
ISSN: 2327-2635 (Print); ISSN: 2327-2643 (Online)

Research on Ceramic/Steel Connection Using a Single Interlayer Method

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To cite this article:

Deshui Yu, Yan Zhang, Jianping Zhou, Daqian Sun, Hongmei Li. Research on Ceramic/Steel Connection Using a Single Interlayer Method. *International Journal of Materials Science and Applications*. Vol. 12, No. 3, 2023, pp. 41-45. doi: 10.11648/j.ijmsa.20231203.12

Received: July 17, 2023; **Accepted**: August 19, 2023; **Published**: August 31, 2023

Abstract: The connection of ceramics and metals together can combine the high wear resistance and corrosion resistance of ceramics and the ductility and toughness of metals to form structural parts with metallic and non-metallic properties, and the practical application value of ceramic/metal composite structural parts is much greater than that of ceramics or metals as individual materials. Due to the large difference between the coefficient of thermal expansion of ceramics and metals, the residual thermal stresses generated during the connection will damage the integrity of the joint, and the single-layer brazing method can not only realize the connection between ceramics and metals, but also alleviate the damage to the ceramics caused by residual thermal stresses. However, most of the technologies involving such additions are still in the laboratory stage and are not yet mature. The addition of a single layer of metal can be used as a thermal stress relief layer. Types of thermal stress relief layers include monolayers, composite interlayers, porous material interlayers, gradient-structured interlayers, and composite filler metals. This study mainly summarizes the research on adding monolayer metal as thermal stress relief layer in recent years and the influence of process parameters on the thickness of reaction layer of joints, which in turn affects the mechanical properties of joints, and it is an important factor to ensure the good performance of joints.

Keywords: Single Layer, Ceramic/Metal, The Residual Thermal Stresses, Mechanical Properties

1. Introduction

As modern materials sciences and the industry have developed, more and more demands have been made on the properties of the materials required. As well as some traditional mechanical properties, in some cases High-temperature strength, low-temperature impact toughness and high wearing and corrosion resistances are required. Under some situations, the properties of a single material are no longer sufficient to meet the growing demands of a rapidly evolving industry. Composite construction of different materials combines the advantages of multiple materials. It not only greatly reduces the cost, but also has good overall properties and great potential for application.

Ceramic/steel composite structural materials have the potential for high fracture toughness, catastrophe resistance, high strength, light weight, low thermal expansion, high temperature resistance, and high oxidation resistance. These types of materials exhibit greater resistance to high temperatures and aggressive environments than single metallic steel or ceramic materials [1]. On the one hand, ceramics have ceramic wear resistance, corrosion resistance and electrical insulation properties that reduce the risk of electrostatic fires and protect the user. On the other hand, some materials are composed of steel. They have certain toughness and strength. They can compensate for the brittle and fragile nature of ceramics [2]. The preparation of ceramic-steel composite structural parts can make full use of the complementary advantages of these two materials in terms of performance and economy.

During the joining process, large residual stresses can exist at the interface between the ceramic material and the steel

[3-4]. This is because there are large differences between ceramic materials and steel in physical properties such as coefficient of thermal expansion and modulus of elasticity, so that the heating of the connection and subsequent cooling process will cause uneven heat distribution and generate large residual stresses, thus reducing the performance of the joint. In this study, a single intermediate layer is used to improve the wetting of the brazing material on the surface of the ceramic material and to relieve the residual stresses in the joint, thus improving the condition and performance of the ceramic-steel joint.

2. Single Intermediate Layer Method

Ceramics possess high hardness, high wearing resistance, outstanding corrosion resistance, thermal and chemical stability as shown in Table 1. These excellent properties have led to a wide range of applications for ceramics in aerospace, energy, mechanical and optical fields [5]. But because of their inherit brittle nature, poor ductility, low machinability, tendency to fracture during service, and difficulty in generating large-scale composites, the engineering applications of ceramics [6, 7] are limited.

Table 1. *Performance parameters of several common ceramic materials [8-10].*

Ceramic	Density (g/cm^3)	Hardness (HRA)	Young's Modulus (GPa)	Coefficient of thermal expansion (10^{-6}/K)	Thermal conductivity J/(cm·s·K)
Si_3N_4	3.25-3.35	92-94	304-330	3.2-3.5	0.155-0.293
Al_2O_3	3.6	91	-	-	0.25
SiO_2	2.2-2.6	-	700	0.54-0.65	2.1
ZrO_2	5.6	88	200	8	1.8
SiC	3.16-3.2	-	410	4.4	1.2-1.8
AlN	3.34	-	310-320	4.6	1.7

During heating and subsequent cooling, large residual stresses are generated in steel/ceramic joints due to the large differences in thermophysical parameters, and the presence of these stresses can lead to degradation of the mechanical properties of the joint or even fracture [11, 12]. Some domestic and foreign scholars have carried out a lot of experimental work on the mitigation of residual stresses in joints, and a series of research results have been obtained. Adding an intermediate layer between steel and ceramic is a commonly used effective method to relieve the residual stresses inside the joint. Single intermediate layers are generally selected from Cu, Ni, Al and other metals [13], which have excellent plasticity and low yield strength and can control the joint stresses through plastic deformation and high temperature creep during the joining process. X. P. Xu et al. [14] used TiZrBCu brazing material and Cu intermediate layer brazing to join Si_3N_4 ceramics and 304 stainless steel. It was found that FeTi, Cu-Zr, Cu-Ti, Cu (s, s), Ti-Si, Zr-Si and TiN compounds were formed at the brazing interface and the bending strength of the joint reached 76 MPa. Y. Zhu et al. [15] achieved brazed connections of alumina ceramics and stainless steel by AgCuTi/Ni composite interlayer. As shown in Figure 1a, it can be found that the interface was divided into three regions: ceramic/brazing material diffusion layer, central zone and brazing material/stainless steel diffusion layer. It was found that nickel foam absorbed the stresses generated during the ceramic-stainless steel connection and the maximum shear strength of the joint was 119.86 MPa. H. Chang et al. [16] brazed the 316 stainless steel and Si_3N_4 ceramics through the Cu interlayer with AgCuTi active brazing material. As shown in Figure 1b, the Cu interlayer was completely dissolved in the adjacent braze, forming a white silver-rich zone and a black copper-rich zone. It was found that the plastic deformation caused by the dissolution of the Cu intermediate layer effectively relieved the residual stresses.

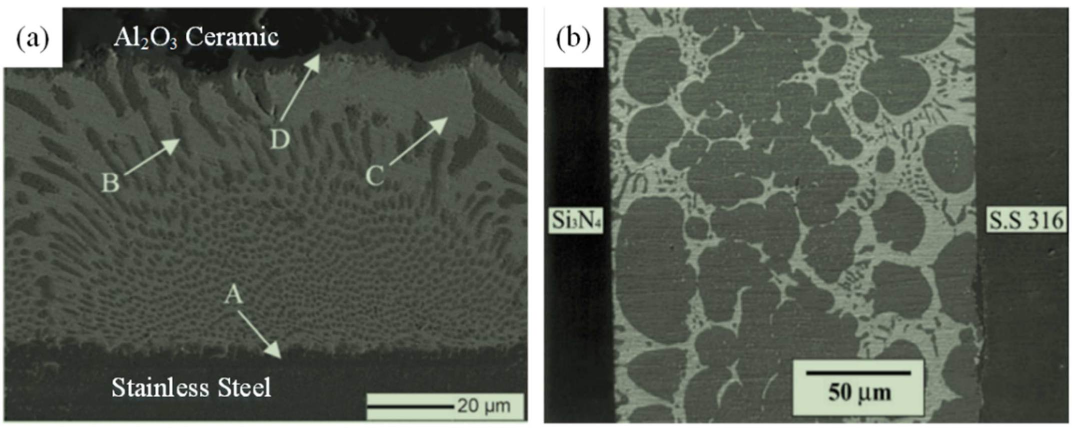

Figure 1. *Single Intermediate Layer: (a) Al_2O_3/AgCuTi/Ni/AgCuTi/SS. (b) Al_2O_3/AgCuTi/Cu/AgCuTi/SS.*

Although a single intermediate layer can relieve the residual stresses during the joining process, the strength obtained is often limited and defects such as cracks or voids tend to form at the interface.

A single interlayer can effectively reduce the residual stresses of ceramic/metal joints, which can be divided into soft and hard interlayers. Cu, Al, Ni, Nb, etc. as soft interlayers, usually have low modulus of elasticity, excellent plasticity, and poor yield strength. Good plastics transformation and worm of the material reduces and takes up the residual stresses of the joints. In the meantime, the harder interlayer has a higher modulus of elasticity and coefficient of linear expansion, for example, W, Mo and other metals, and the difference in the coefficient of linear expansion with ceramics is small, which can effectively eliminate residual thermal stresses in the joint and maintain the integrity of the joint. The hard intermediate layer prevents direct connection of the ceramic to the metal and transfers residual thermal stresses from the joint to the intermediate layer, thus enhancing the bonds of the ceramic to the metal. Xia et al [17] used Ni sandwich to connect Ti_3SiC_2 and TC4. As shown in Figure 2a, the interface structured as TC4/Ti_2Cu + α-Ti + β-Ti/Ti_2Cu + $AlCu_2Ti$ + Ti_5Si_3/Ti_5Si_3 + Ti_5Si_4/$T_{i3}SiC_2$, which gave the joint a maximum shear strength of 126 MPa. Wang et al [18] achieved a reliable joint between Ti_3Si_2 ceramics and TC4 alloy through a Cu intercalation, as shown in Figure 2b. The interstitial structure of this joint is TC4/Ti_2Cu+α-Ti+ β-Ti/Ti_2Cu+$AlCu_2Ti$+Ti_5Si_3/Ti_5Si_3+Ti_5Si_4/Ti_3SiC_2, which has a shear strength of 132±8 MPa.

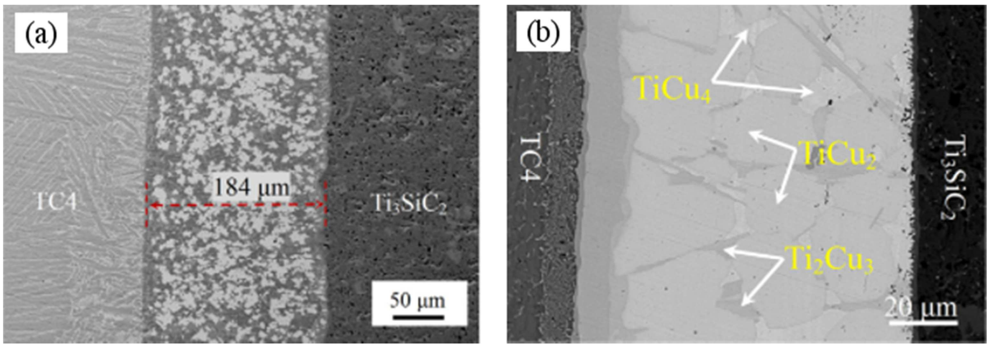

Figure 2. *Brazing of Ti_3SiC_2 ceramic to TC4: (a) Ti_3SiC_2/Ni/TC4; (b) Ti_3SiC_2/Cu/TC4.*

3. Influence of Process Parameters on Single Layer Brazing

In order to further improve the joint strength of ceramic/metal joints and enhance the interfacial structure of the weld, many scholars have investigated the effects of brazing composition, brazing temperature and heat preservation time on the organization and mechanical properties of the weld.

(1) Effect of filler metal composition on the properties of joints

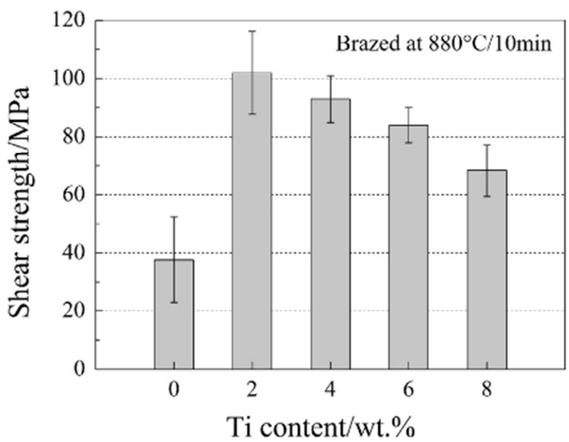

Figure 3. *Effect of Ti content on the shear strength of Al_2O_3/TiAl joint brazed at 880°C for 10 min.*

Niu et al [19] successfully joined alumina and titanium alloys by brazing using Ag-Cu-Ti as filler. The interfacial structure of this joint is Al_2O_3/Ti_3(Cu, Al)$_3$O/Ag (ss) + $AlCu_2Ti$ + Ti (Cu, Al) + Cu (ss)/$AlCu_2Ti$ + AlCuTi/TiAl, as shown in Figure 3. When using Ag-Cu eutectic, the dissolved Ti from the TiAl matrix is sufficient to react with alumina to form a thin Ti_3(Cu, Al)$_3$O layer, but the increase in Ti content inhibits the dissolution of the TiAl alloy. The maximum shear strength of the joint was 94 MPa when Ag-Cu-Ti filler metal was used. The maximum shear strength of the joint was 102 MPa when Ag-Cu+2wt% TiH2 was used. Hong et al [20, 21] used nano-AgCuNi filler to braze SiO_2 ceramics into TC4 alloy. The interfacial structuring of the joints was TC4/α-Ti+Ti2 (Cu, Ni)+Ti_2 (Ni, Cu) superstructure/Ti2 (Cu, Ni) versus α-Ti+Ti_2 (Cu, Ni)+Ti_2 (Ni, Cu) superstructure/Ti_4O_7+$TiSi_2$/SiO_2. with the increase of Ni content, the brazing joints of α-Ti+Ti_2 (Cu, Ni) + Ti_2(Ni, Cu) super eutectic structure increases, and the shear strength of brazed seams first increases and then decreases. When the Ni content is 10 wt.%, the maximum shear strength is 40 MPa.

(2) Effect of brazing temperature on the properties of joints

Dai et al [22] utilized AgCu filled metal to connected zirconium dioxide ceramics with TC4 alloy. As shown in Figure 4, the Ti-CuIMC layer near TC4 and the Cu_3Ti_3O+TiO layer near zirconium dioxide gradually thickened as the brazing temperature increased. The shear strength of the joints increased with the brazing temperature until the maximum shear strength was reached; the shear strength decreased sharply with the increase of brazing temperature. R. et al [23] has studied the influence of the time of brazing on the interstitial structure and mechanical properties of Cusil-ABA interlayer brazed cBN/steel (CK45) joints. As the brazing time increases, the reaction layer becomes thicker and more continuous, and the joint strength is higher, with a maximum shear strength of 129 MPa. Anyi 'bal et al [24] used 59Ag27. 25 Cu12.5 In1.25 Ti filler metal brazing to bond Shapal-M ceramics to 304 SS and investigated the effect of brazing temperature on the interfacial structure and strength. Ag, Cu and Cu2InTi were brazed at 750°C and Ag, Cu and Cu7InTi at 800°C and 850°C. The joint shear strengths were 148±40 MPa at room temperature and 220±32 MPa C after brazing at 800°C.

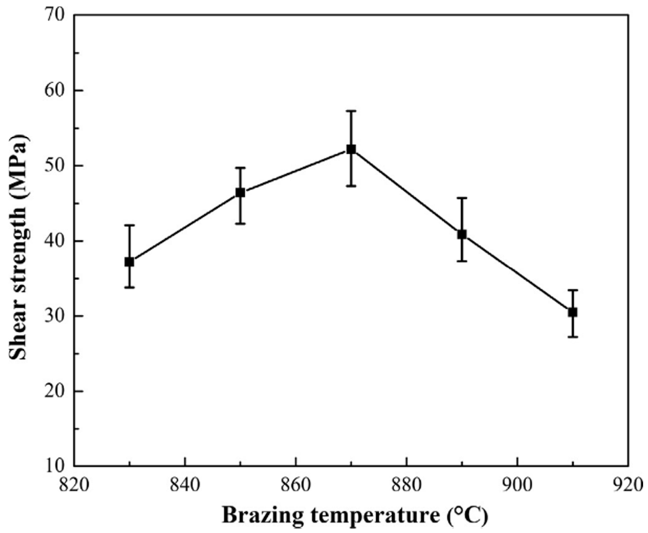

Figure 4. *Effect of brazing temperature on shear strength of ZrO_2/TC4 joints.*

A few scholars have conducted in-depth studies on the joint properties of ceramic and metal composites [25-30], such as oxidizability, airtightness, thermal shock and corrosion. Some of these studies have established a concrete base for the application of ceramic-metal composites in engineering.

4. Conclusion

Ceramic-metal connections have been extensively studied by scholars at home and abroad. The active filler metal is the key factor affecting the ceramic-metal connection. At present, there are several kinds of reactive filler metals on the available market. While joints formed with such metal fillers had no significant defects, the thickness and phase composition of the joint reaction layer could not support a joint with excellent mechanical properties. Tight joints between ceramics and metals allow for the cost-effective fabrication of complex shapes and multiple components. It also promotes the industrial application of metal-ceramics to fully utilize their excellent properties.

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