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Advances in Residual Stress Relief Strategies at Ceramic/Metal Joint Interfaces

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Abstract: As service conditions become more challenging and fabrication complexity increases, there is an increasing demand for enhanced comprehensive performance of ceramic/metal heterostructures. At present, brazing technology has been widely utilized for ceramic-metal heterogeneous joints. However, the residual stress relief in these welding joints is complicated and necessary. Because metals and ceramics have different properties, especially in their coefficients of thermal expansion (CTE). Welding joints exhibit large residual stresses during the cooling process. The relatively high residual stresses may significantly degrade the joint properties. For this issue, this paper systematically reviews four alleviation routes: optimization of process parameters, setting an intermediate layer, surface structure modulation, and particle-reinforced composite solder. Eventually, upcoming prospects and challenges of residual stress research on ceramic/metal heterostructures are pointed out.

Key words: Ceramics; Metals; Brazing; Interfacial residual stress; Stress relief

1 Introductory

Ceramic/metal heterojunctions exhibit various advantages, including good hardness, wear resistance, thermal conductivity, corrosion resistance, and high chemical stability. These joints also display excellent photoelectric qualities, achieving wide application in the aerospace, electronic information and communications, instrumentation production, and other fields [1-3]. Ceramic/metal joints also play an important role in manufacturing functional components, lightweight structures, and thermal protection systems. In the engines and protection systems of space vehicles [4,5], SiC and GaN are typical broadband materials that represent the third generation of semiconductors [6-8]. The combination of bioceramic composites and Ti alloys also exhibits extensive applications in orthopedics and dentistry, such as the connection of Ti and Al_2O_3 ceramics [9]. In the field of power electronics, IGBT modules featuring Si_3N_4 ceramics and copper connections, bonded with the reactive metal solder, have been widely applied in automotive power control systems [10]. In the automotive industry, diesel engine valves have to interact with cams at relatively high frequencies, making ceramic-metal connections crucial to this process [11]. However, the connection between ceramics and metals still presents certain challenges [12,13]. The significant differences in microstructure and physicochemical properties between these materials make it difficult to achieve simultaneous wetting with conventional solder [14]. Furthermore, there are noticeable disparities in bonding properties, as ceramics exhibit covalent bonding while metals display metallic bonding. These differences in the modulus of elasticity and the coefficient of thermal expansion can easily result in significant residual stresses during cooling processes. This can weaken

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the bond between ceramics and metals, thereby affecting properties of the components [15]. This phenomenon often leads to the formation of cracks and microcracks [16]. As the dimensions of structural components increase and application conditions evolve, the demand for joint strength and reliability is also increasing. However, large-scale joints that contain microcracks tend to be unstable. Because relatively high residual stresses often directly contribute to ceramic fracture. Consequently, the excellent bonding of high-strength ceramic/metal joints relies on the effective regulation of residual stresses at the interfaces.

Residual stress relief is a critical focus in the global research of metal/ceramic brazing interfaces. Currently, four primary techniques are employed to mitigate these residual stresses. (1) Optimization of process parameters: this technique involves adjusting holding times and brazing temperatures to achieve optimal bonding conditions. (2) Utilization of an intermediate layer: employing intermediate layers, such as metal foils, foam metal layers, or carbon materials, can effectively withstand loads and prevent deformation of the base material, thereby reducing the gradient in the coefficient of linear expansion [17]. (3) Enhancement of composite solders: incorporating particles such as high-temperature alloys, carbon materials, ceramic particles, and materials with negative thermal expansion into composite solders can absorb stresses and modify solder properties, thereby mitigating residual stress. Particle-reinforced solders demonstrate excellent caulking ability, resulting in high-temperature strength and impact resistance at the joints. (4) Regulation of surface structure: techniques such as drilling, corrosion, and pre-oxidation can be applied to ceramics or composites to enhance surface structure, improving joint integrity and facilitating the gradient transmission of joint performance while reducing stress concentrations [18]. These techniques effectively alleviate residual stresses, ensuring robust connections between ceramic and metal joints. These methods significantly enhance the quality of brazed joints and contribute to the progression of industrial manufacturing processes in the energy, communications, and aerospace sectors.

This article provides a concise discussion on the optimization of process parameters, utilization of an intermediate layer, enhancement of composite solders, and regulation of surface structure. Additionally, it points out the limitations of current research on residual stress relief. Furthermore, the article also proposes future directions for development, offering valuable references for engineering research and technological advancements in related fields.

2 Progress in Residual Stress Relief at Ceramic/Metal Joint Interfaces

Numerous investigations have been conducted worldwide to explore the alleviation of residual stresses in joints. The primary mitigation methods encompass the optimization of process parameters, utilization of intermediate layers, enhancement of composite solders, and regulation of surface structures. The physical and mechanical properties of ceramics (such as Poisson's ratio, yield strength, elastic modulus, and coefficient of thermal expansion) differ significantly from those of metals. Consequently, residual stresses are prone to occur at the interfaces between them [19]. Recent techniques have concentrated on minimizing residual stresses specifically at ceramic/metal joints, demonstrating successful applications in various joint configurations.

2.1 Process parameter optimization

The optimal process parameters can be determined by experiments and calculation simulations. This can enhance the brazing quality and improve the mechanical properties of the joints. For instance, adjusting the brazing temperature, holding time, and cooling rate can enhance the bonding strength and weld quality at the joints [20].

The optimization of process parameters can effectively reduce shear stresses in joints. Barrena et al. [21] conducted experiments to assess residual stresses in 90MnCrV8 and WC-10Co joints. The increase in brazing time does not correspond proportionally to the enhancement of joint shear strength. Specifically, joint strength decreases as brazing temperature increases. Maximum shear strength and minimized residual stress at the optimized joints can achieved within the holding time of 8 to 12 minutes.

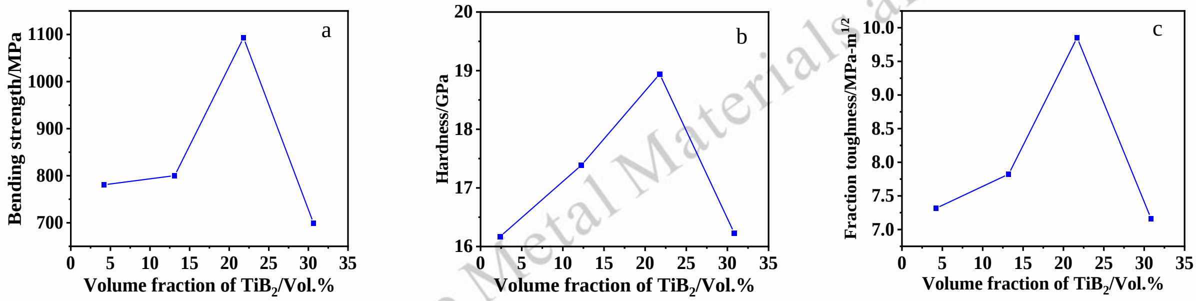

Fig. 1 Changes in mechanical properties and their retention period

However, the study did not explain the influence of the reaction layer formed during diffusion in the brazing process on residual stress relief. Wang [22] et al. prepared Ti(C7, N3)/TiB_2/WC metal-ceramic joints. As illustrated in Fig. 1, the mechanical properties of these joints initially increased and subsequently decreased as holding time extended. The flexural strength, hardness, and fracture toughness of the tool material reached their peak values (1096.45 MPa, 18.9 GPa, and 9.85 MPa-m1/2) with holding 30 minutes. This method effectively demonstrates the impact of brazing temperature and holding time on the residual stresses within the joints through adjustment of process parameters.

Modifying the experimental parameters during the brazing process is essential for enhancing material properties. By effectively regulating the process parameters, it is possible to achieve joints with superior performance and stronger bonding characteristics.

2.2 Setting of an intermediate layer

If the material shrinkage exceeds the permissible limits of the joints, stresses will develop in the brazed joints during the cooling process. Low-plasticity and high-strength joints may experience significant strains, leading to fracture potentially. To ensure complete bonding during brazing and enhance joint strength, a transition layer is incorporated between the metals or ceramics to create a “sandwich” structure. This approach to regulating residual stresses can effectively mitigate stress concentrations and improve plastic deformation characteristics of joints

2.2.1 Metal layers

Copper, nickel, and molybdenum foils serve as intermediate layers in the brazing process. Specific requirements of brazing processes are important for selecting intermediate layers [23-25]. These metallic intermediate layers exhibit a high CTE, a low modulus of elasticity, a low yield point, and a high degree of plasticity, which collectively facilitate yielding. There are also processes of plastic deformation and creep that can mitigate residual joint stresses in these metals.

The interlayer thickness is carefully chosen, and the brazing process is adjusted accordingly. Wang et al. [26] investigated the effect of copper interlayer thickness on the strength and residual stress of Si_3N_4-Invar joints. The results indicate that as the copper interlayer thickness increases, the residual stress gradually decreases. Additionally, the joint shear strength increases progressively with an interlayer thickness of 200 μm, reaching a maximum value of 256 MPa. However, the intrinsic mechanism underlying the inhibition of Fe_2Ti and Ni_3Ti compound formation requires further analysis.

The intermediate layer can achieve substantial enhancements despite a small specific surface area. Wu et al. [27] selected Cu, Nb, and Mo foils as the intermediate layers. The results indicated that the Cu interlayer effectively alleviates residual stress and prevents cracking in the joints. In contrast, the Nb interlayer tends to dissolve and aggregate into bands at the interface, leading to the formation of noticeable cracks. Furthermore, the Mo interlayer exhibits limited capacity for relieving residual stresses. Yang et al. [28] employed finite element analysis to simulate the effects of various interlayers (Cu, Ti, Ni, and composite interlayers of these elements) on the distribution of residual stresses. The findings revealed that the Cu interlayer has a more pronounced impact on residual stress relief, as illustrated in Figure 2. Notably, the composite interlayer demonstrates superior residual stress relief compared to single-layer interlayers. The combination of a 0.4 mm Ti layer and a 0.6 mm Cu layer yields the most significant reduction in residual stresses.

Therefore, the thickness of the intermediate layer and brazing process should be adjusted rationally. Furthermore, the intermediate layer has the capacity to provide significant enhancements with a small specific surface area.

2.2.2 Porous layer

To enhance the distribution of interlayer delamination and improve the performance of brazing interlayers, the use of porous structures is siginificantly effective. Foam metal, characterized by its three-dimensional network-like porous architecture, serves as a representative example of such materials. Porous metal foam materials are extensively employed for residual stress relief within brazing interfaces. Notable representatives include Cu [29], Ni [30], stainless steel [31],and polyurethane [32]. Additionally, porous ceramics [33] can

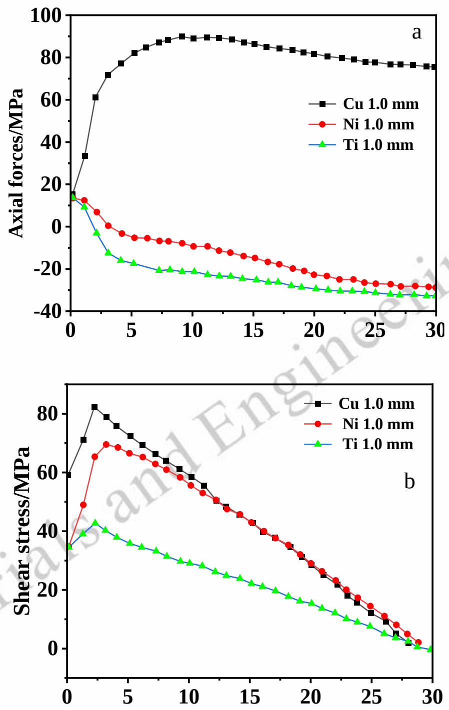

Fig. 2 (a) Extension from the edge to the interior at the interface between the ceramic and the interlayer/mm
(b) Extension from the edge to the interior at the interface between the ceramic and the interlayer/mm

also be utilized as interlayers to reduce the differences in CTE, thereby facilitating residual stress relief.

The porous metal foam is uniformly distributed throughout the brazed joint in a three-dimensional configuration. Guo [34] found that the incorporation of a Ni foam interlayer significantly enhanced the thermal cycle life of brazed joints. This could achieve an average shear strength (180 MPa) with a 0.2 mm layer of nickel foam (as illustrated in Fig. 3a). The Ni foam functions as a buffer layer, effectively mitigating residual thermal stresses and reducing thermal stress concentrations.

Metal foams with substantial energy absorption properties have been widely employed as interlayer materials. Wang [35] utilized copper foam as an interlayer to braze ZrB_2-SiC ceramics with Inconel 600 alloy. The molten AgCu solder partially filled the pores of the copper foam following wetting of the substrate surface. The addition of copper foam resulted in a reduction of residual stress in the joints, decreasing from -0.635 to -0.35 GPa. This indicates a substantial reduction in residual stress and a corresponding increase in joint strength, rising from 36 to 77 MPa with the Cu foam metal.

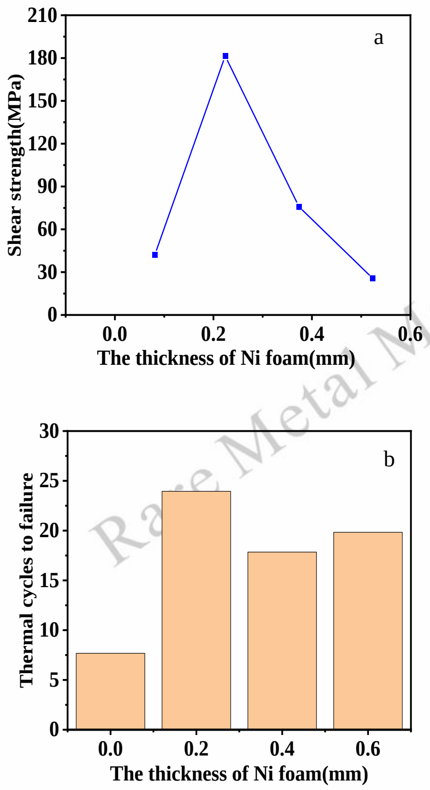

Fig. 3 Effect of nickel foam thickness on shear strength (a) and thermal cycle failure (b) of Si_3N_4/Invar brazed joints

Porous Si_3N_4 [36] and porous lithium chalcopyrite interlayers [37] can effectively relieve residual stresses in brazed joints. These interlayers not only mitigate stress concentrations and inhomogeneities but also ensure that the porous homogeneous structure functions as a stabilizing factor. Furthermore, the porous material can serve as a carrier for incorporating reinforcing phases, which are uniformly distributed throughout the brazed joint. For instance, a porous interlayer composed of stabilized carbon fiber can be utilized, with a synthetic tungsten nanophase as the reinforcing component [38]. To establish a robust connection, the solder forms a TiC reaction layer within the carbon fiber matrix. Additionally, the tungsten nanophases are evenly dispersed across the carbon fiber surface to further reduce residual stress. This principle is analogous to the in-situ production of CuO nanosheets on porous copper surfaces [39].

2.3 Particle-reinforced composite solder

The CTE of a joint is reduced by the uniform distribution of reinforcing particles within the solder [40,41]. This distribution enables the particles and the solder to share thermal stresses, thereby reducing residual stress concentrations and enhancing the bearing capacity of the brazed joints [42]. To mitigate residual stresses in the joints, various reinforcing phases, such as high-temperature alloys, carbon materials, and ceramic particles, are incorporated into conventional solder. These modified solders exhibit improved caulking ability, as well as enhanced joint strength and mechanical properties. Currently, the primary areas of focus in this research include high-temperature alloys, carbon materials, ceramic particles, and materials with negative CTE.

2.3.1 Ceramic particles

To ensure metallurgical reactivity, it is essential to incorporate a reinforcing phase composed of micron-sized or stabilized ceramic particles that contain active elements.

A portion of the stress will be absorbed at the interface between the substrate and the ceramic particles, thereby reducing the partial stress within the joint. Qin [43] specifically selected AgCuTi solder reinforced with 4.6 μm-sized SiC particles for brazing TC4 alloys and C/C composites. When the SiC content reached 15 vol.%, the SiC particles were uniformly distributed throughout the brazed joints. They also interacted with the Ti element in the solder to form an interfacial layer, as illustrated in Fig. 4a. This interaction successfully combined the solder and the reinforcing particles. Additionally, the presence of ceramic particles led to a reduction in residual stress, resulting in an increase in joint strength from 22 to 29 MPa. Wang [44] conducted brazing of GH3044 alloy with C/C composites, incorporating TiC particles into the AgTi solder. When the TiC content was increased to 24 vol.%, the joint strength improved from 40 to 67.2 MPa due to effective bonding between TiC and Ti, as shown in Fig. 4b. Finite element simulations indicated an approximate 20.1% reduction in residual stresses. It is noteworthy that there exists a gap between the reinforcing action and the nanoscale phase, with the uniformity of distribution of micrometer-sized reinforcing particles being limited. Zhou [45] utilized nanoscale Al_2O_3 particles to

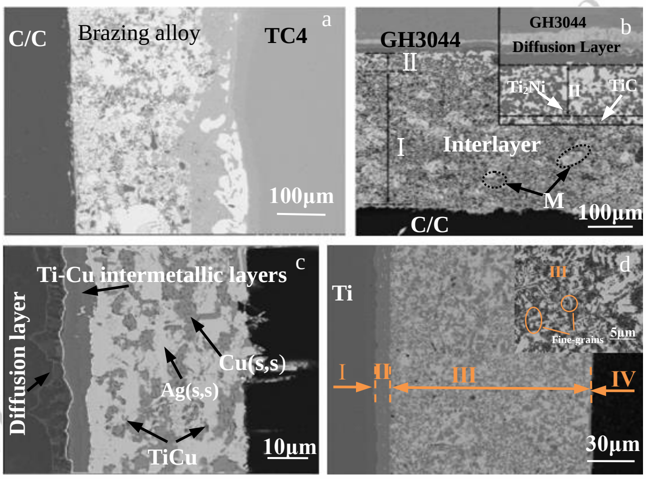

Fig. 4 Microstructure of brazed joints with particle-reinforced solder:(a) SiC particles reinforced AgCuTi; (b) TiC particles reinforced AgCuTi; (c) Al_2O_3 particles reinforced AgCuTi; (d) BN particles reinforced AgCuTi

reinforce AgCuTi solder for joining C/C and TC4. The Al_2O_3 particles were uniformly distributed and stabilized within the joint, as depicted in Fig. 4c. The joint strength achieved with the addition of 0.3 wt.% Al_2O_3 reached 27.8 MPa. Furthermore, the inclusion of TiN particles [46] and B4C the addition of 0.3 wt.% Al_2O_3 reached 27.8 MPa. Furthermore, the inclusion of TiN particles [46] and B4C particles [47] in the solder effectively facilitated stress relief. Yang [48] incorporated 3 wt.% BN particles into AgCuTi solder. As illustrated in Fig. 4d, the BN particles reacted fully with the titanium alloy, resulting in the formation of TiN and TiB phases. These compounds subsequently diffused, alleviating residual stresses in the joints and attaining a high strength of 31.4 MPa.

To further enhance the dispersion of the particles, an alternative approach involves the in-situ synthesis of the reinforcing phase. In this method, the ceramic phase is generated through a reaction between the ceramic constituents, reactive elements, and solders. The in-situ synthesis technique facilitates a uniform distribution of the reinforcing phase while allowing for the controlled dissolution of reactive elements from the metallic material into the solder. This approach helps to prevent excessive reactions with the ceramic material. When reacting with active elements, particles such as Si_3N_4 [49], B [50], TiO_2 [51], and WC [52] can be transformed into uniformly distributed reinforcing phases. This transformation ensures the stability and uniformity of the joint properties. Although the in-situ synthesis method yields good dispersion and an appropriate size of reinforcing phases, the CTE of resultant product is significantly higher than that of conventional ceramics.

Generally, there exists a gradient in the CTE between metals and ceramics, which effectively reduces residual stress at the brazing joints. This phenomenon is attributed to the low CTE and excellent stability of most ceramic particles. Consequently, this approach has been widely adopted as a method for particle reinforcement.

2.3.2 Carbon materials

Various carbon materials exist, and research focused on reducing residual stress has accelerated the widespread application of these materials due to their low CTE, making them particularly effective for managing residual stress.

Carbon nanotubes (CNTs) have been shown to enhance

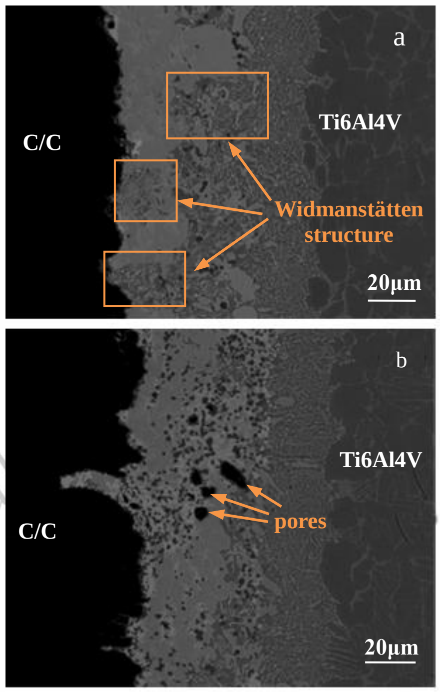

Fig. 5 BSE images of brazed joints with added carbon nanotubes (a) 0.5 wt.%; (b) 3 wt.%

wettability, thereby facilitating the solder's ability to fill gaps. Song [53] utilized carbon nanotube-reinforced TiCuZrNi amorphous solder to braze C/C composites and TC4 alloys. When the CNT content was increased to 3%, a significant consumption of Ti in the solder was observed due to the interaction with the carbon nanotubes. However, the reaction between the carbon/carbon composite and the solder was relatively minimal, as illustrated in Figure 5. The optimal CNT content for achieving the highest shear strength (38 ± 2 MPa) was determined to be 1 wt.%, resulting in a 73% increase in joint strength compared to the joints without CNTs. This enhancement in joint strength can be attributed to the alleviation of thermal stresses within the joints and the reinforcing effect associated with the formation of TiC particles.

Qi [54] synthesized CNTs on their surfaces. Figure 6 presents a schematic diagram of the solder enhanced with carbon nanotubes. The incorporation of CNTs accelerates the dissolution and diffusion of Nb. Additionally, the uniform distribution of CNTs and Nb significantly alleviates residual stress while enhancing the mechanical and high-temperature properties of the brazed joints. Notably, when the content of CNTs was increased to 1.5 vol.%, the joint strength improved from 49 to 85 MPa. Thus, CNTs play a crucial role in enhancing the mechanical properties of brazed joints and in reducing residual stresses. However, the formation of a mesh structure between CNTs and TiH_2-Ni powders remains inadequately explained.

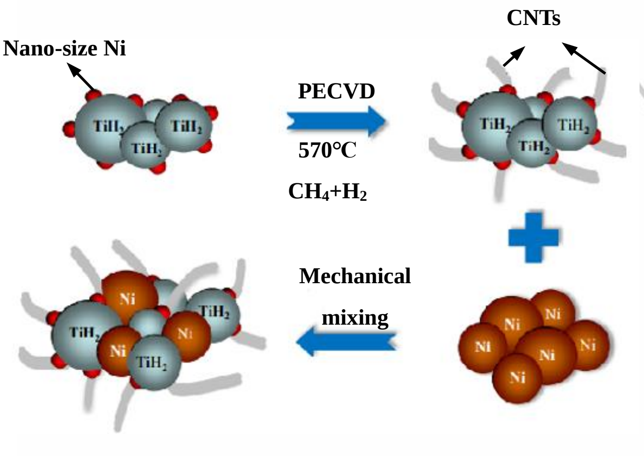

Fig. 6 Schematic diagram of in situ synthesized carbon nanotube reinforced solder

Based on these studies, it is essential to achieve a strong integration and uniform distribution of the reinforcing phase within the solder. This approach can effectively alleviate residual stress and enhance joint strength. Carbon materials can react with active solders to form ceramic particles, a process that may consume active elements and contribute to the mitigation of residual stress. Therefore, ensuring the uniform distribution of carbon materials is critical for relieving residual stress and preventing agglomeration.

2.3.3 Negative expansion materials

When the concentration of particulate reinforcing phases exceeds a certain threshold, defects such as precipitation, cracks, and voids may occur within the joint. In comparison to carbon materials, reinforcing phase materials with low coefficients of thermal expansion demonstrate a more effective capacity for relieving residual stresses.

Negative expansion materials serve as effective expansion inhibitors, capable of regulating positive thermal expansion. Wang [55] incorporated $Y_2Mo_3O_{12}$ particles, which exhibit negative CTE, into AgCuTi solder. This addition significantly enhanced the negative thermal expansion behavior, resulting in a marked decrease in the CTE of the solders. Consequently, residual stresses were substantially reduced, leading to improved interfacial structure and bonding strength, with a maximum shear strength of 42 MPa—1.6 times greater than that of joints without the additive. Ba [56] reinforced silver-copper solder with nanoscale ZrP_2WO_{12} particles, also characterized by negative CTE. Finite element analysis indicated that the addition of 3 wt.% of these nanoparticles could reduce residual stress by 52.9 MPa (Fig. 7). Furthermore, the average shear strength of the joints increased to 146.2 MPa, representing a 70.8% improvement compared to joints without nanoparticles. In addition to ZrP_2WO_{12} and $Y_2Mo_3O_{12}$ particles, $Y_2Mo_3O_{12}$ [57] and $Sc_2(WO_4)_3$ [58] also demonstrate significant stress-relief effects while maintaining their negative expansion properties during brazing. Therefore, negative expansion particles are suitable for effectively controlling the CTE of both base materials and solders [59,60].

In general, negative expansion materials serve to compensate for mismatches in thermal expansion behavior at the joint. However, the amount of negative expansion material must be carefully controlled. When its content exceeds a critical threshold, defects such as cracks and voids may develop in the brazed joints. Therefore, the research focus for particle-reinforced negative expansion materials should encompass the following key objectives: (1) preserving the negative expansion properties of the materials, and (2) preventing undesirable complex reactions within the joints. By meeting these criteria, the residual stresses in brazed joints can be effectively reduced.

2.3.4 High-temperature alloys

The incorporation of particle-reinforced composite solder consumes numerous reactive elements through interfacial reactions during the brazing process, which can lead to the formation of cracks and voids at the interface. Achieving complete interfacial bonding can be accomplished by immersing the base material, allowing the composite solder to dissolve and diffuse. This process relies on the use of a high-temperature alloy characterized by a low CTE.

He [61] successfully brazed Si_3N_4 ceramics to 42CrMo steel using (Ag-Cu-Ti) + Mo composite solders. The incorporation

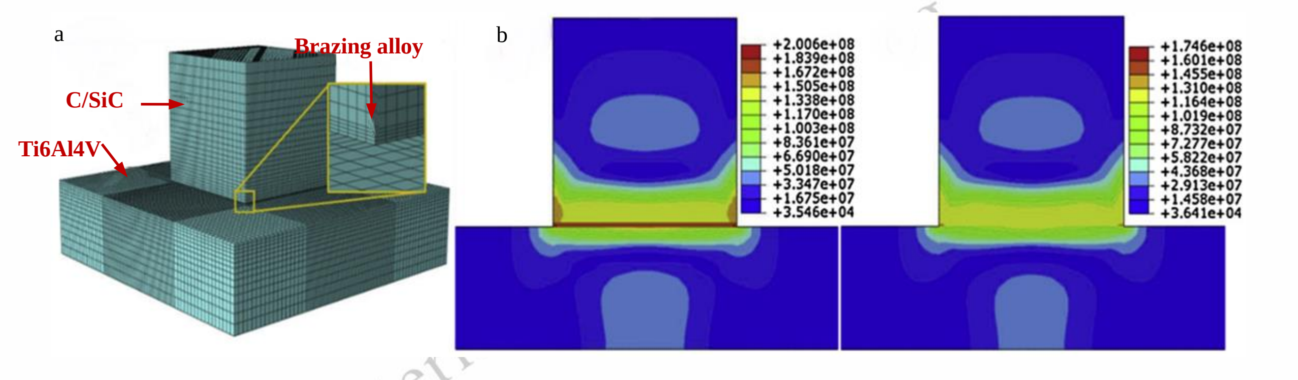

Fig. 7 (a) Finite element model mesh of C/SiC-Ti6Al4V joints Residual stress distribution in brazed joint; (b) AgCu; (c) AgCu+3wt.% ZrP_2WO_{12}

of Mo facilitated the formation of fine grains and eutectic structures within the joint. Notably, the maximum flexural strength of the joints containing 10 vol.% Mo reached 587.3 MPa.This value was 414.3% higher than that of joints without Mo particles, with a shear strength of 587.3 MPa. High-temperature metal particles can diminish the presence of excess active ingredients during brazing, as well as lower the CTE of both metals and ceramics, thereby mitigating the effects of residual stresses.

Gui [62] conducted brazing of Cf/SiC composites and TC4 alloys using (Ti-Zr-Cu-Ni) and W composite solders. The elemental diffusion facilitated the formation of a diffusion-reactive layer at the interface between the solder and the alloy, as illustrated in Figure 8. The incorporation of an appropriate amount of W powder into the brazed joints effectively reduced residual stresses, with the maximum shear strength reaching 166 MPa.

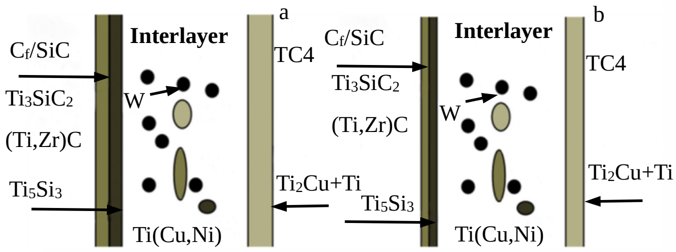

Fig.8 Interfacial evolution model (a) Interfacial reaction layer and interlayer formation (b) Joint molding

W, Mo [63], and other high-temperature metals characterized by minimal expansion properties play a crucial role in managing residual stresses. The primary bonding mechanisms between high-temperature metal particles and solders involve solid solution dissolution and diffusion. The interface between the particles and the solder is subjected to stress. These particle phases can effectively distribute the stress and alleviate strain within the joint. Furthermore, the capacity of the particle phase to extend the crack propagation path significantly enhances joint strength. However, this also influences the overall processing parameters.

2.4 Surface Structure Regulation

At brazed joints, the distinct characteristics of metal and ceramic materials lead to significant stress concentrations. Within the ceramic, the reaction layer becomes the weakest segment of the entire joint, making it particularly susceptible to fracture due to its composition of predominantly brittle materials. During the cooling process, the ceramic-metal interface experiences residual strains following brazing. By designing ceramics with surfaces that are machined into curved or other complex geometries, the connection area can be increased. This facilitates improved wetting between the base material and the ceramic. This approach promotes a smoother transition between ceramic and metal properties. Common techniques for modulating the surface structure of ceramics include drilling [64,65], corrosion [66], and pre-oxidation [67].

While the drilling method enhances the contact area, it may also induce irreversible damage to the brazed joints. Wang [68] et al. utilized AgCuTi solder to braze C/C composites with TiAl alloys. As illustrated in Fig. 9, the infiltration region exhibits a three-dimensional gradient transition zone in contrast to a planar interface. This design effectively mitigates residual stresses resulting from the mismatch between different substrate materials, allowing for stress relief as energy is dispersed through the interface. Consequently, the joint maintains high strength over time, with the shear strength

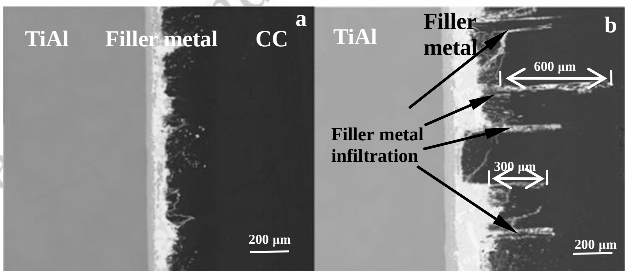

Fig. 9 Comparison of interface morphology (a) planar interface; (b) permeable interface

after penetration increasing to 26.4 MPa, which exceeds 80%

of that of the C/C substrate.

With advancements in industrial technology, femtosecond laser processing has found extensive applications in micromachining. Li [69] improved the brazing technique for YSZ and Ti6Al4V by employing surface processing with a femtosecond laser. This approach resulted in a nonlinear distribution of residual stresses within the brazed joints, effectively impeding the propagation of cracks. The shear strength of the joints increased to 150 MPa, representing a 95.2% enhancement compared to joints that did not undergo this process. Additionally, the lifespan of the joints was prolonged when the ceramic surface was machined to achieve a reduction in the maximum shear stress.

A combination of methods can effectively modify the substrate material. Yang [70] enhanced the interfacial structure of Nb-C/C copper welded joints by employing pre-oxidation treatment and the in-situ growth of carbon nanotubes. This process resulted in the formation of adjustable annular gaps around the carbon fibers, facilitating the penetration of the brazing alloy into the composite ceramic. Consequently, the shear strength of the joint increased from 29 to 57 MPa.

In summary, controlling the surface structure can reduce the concentration of internal residual stresses throughout the joints. A gradient transition can mitigate interfacial residual stresses, thereby strengthening the brazed joints. Selecting an appropriate processing treatment is essential based on the characteristics of the base material. Certain oxide ceramics exhibit excellent wear and corrosion resistance, rendering chemical corrosion unnecessary for surface treatment. Additionally, it is crucial to choose suitable methods that ensure a robust connection between ceramics and metals, considering actual production conditions.

3 Conclusions and perspectives

In precision instrumentation, electronic information technology, and aerospace applications, the demand for ceramic/metal joints is increasing due to their unique requirements. Consequently, we focus on the critical issue of excessive residual stress in ceramic/metal brazed joints, which arises from the significant differences in the CTE between metal and ceramic materials. This disparity can result in high residual stress at the interface, making joint failure more likely. To effectively mitigate residual stress, we summarize four methods: optimization of process parameters, utilization of an intermediate layer, enhancement of composite solders, and regulation of surface structure. These approaches can substantially enhance the practical performance of ceramic and metal composite components. Nonetheless, recent studies still exhibit several shortcomings:

(1) Residual stress relief at the ceramic/metal interface primarily focuses on experimental and exploratory research. However, the mechanisms underlying residual stress generation have not yet been fully analyzed and clarified. The existing methods for stress adjustment tend to be relatively simplistic and exhibit significant limitations. A combination of different approaches may combine their respective advantages, with the composite method anticipated to be more effective in alleviating residual stresses. Nonetheless, this strategy may also entail higher costs and reduced efficiency. Further research is necessary to investigate the potential for integrating these various methods to effectively regulate residual stresses.

(2) Practical applications necessitate the regulation of stress in large-scale structural components. Currently, these adjustments at experimental joints are often limited to small-scale applications. However, large structural components in industrial manufacturing predominantly consist of ceramic and metal composite materials. Residual stresses can significantly impact the operational integrity of the entire system, highlighting the need for more stringent requirements for joint stress regulation. Most existing research indicates that residual stresses in metal-ceramic joints and their interfaces are often negligible and relatively easy to mitigate. However, in the context of large-scale equipment manufacturing, where components are large, the challenges of residual stress relief become more pronounced. Consequently, achieving greater uniformity in stress distribution is essential, as lower overall residual stress levels are critical for larger joints. Even minor flaws in a specific location may pose a significant risk to the integrity of the entire joint. Therefore, an effective solution for bonding ceramic to metal heterogeneous joints is essential and indispensable, particularly for suitability in industrial production.

(3) Functional applications of ceramic/metal heterogeneous joints following stress relief warrant particular emphasis. While the mechanical properties of traditional ceramic-metal brazed joints have been extensively studied, aspects such as wear resistance, corrosion resistance, and thermal shock resistance have not received adequate attention. Future research should prioritize these properties, as they will be crucial for effective residual stress regulation. A robust integration of theoretical frameworks and practical applications is essential in this regard. As the utilization of semiconductors continues to expand, ceramic/metal composite components are expected to gain increased prominence in future applications. Therefore, a comprehensive focus on the properties and functionalities of ceramic/metal heterostructures will significantly broaden their applicability.

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陶瓷/金属连接界面残余应力缓解策略研究进展

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摘　要：随着苛刻环境恶劣化和加工制造复杂难度增加，对陶瓷/金属异质结构综合性能提出更高要求。目前钎焊技术被广泛应用于陶瓷与金属异质连接，而二者焊接接头残余应力缓解难题非常棘手。由于陶瓷与金属的性能差异，特别是热膨胀系数的差异，钎焊接头在冷却过程中会产生过多的残余应力。残余应力较高会严重破坏接头性能。为缓解残余应力，本文从工艺参数优化、施加中间层、颗粒增强复合钎料和表面结构调控 4 种缓解途径进行系统评述。概述陶瓷与金属钎焊接头残余应力状态与分布规律，介绍残余应力的产生与检测，最后展望未来陶瓷/金属异质结构残余应力研究面临的机遇和挑战。

关键词：陶瓷；金属；钎焊；界面残余应力；应力缓解

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