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Research on Self-Propagating High-Temperature Synthesis of Ceramic Matrix Composites

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Abstract: Ceramics have excellent properties such as high hardness, corrosion resistance, and wear resistance, and have great potential for applications in harsh environmental conditions. However, the hard and brittle nature of ceramics makes processing and modification very difficult, which requires its composites to form ceramic matrix composites with other materials with complementary performance advantages. Currently, ceramic composites are synthesized using brazing, diffusion welding and self-propagating high-temperature synthesis techniques. The residual thermal stresses in ceramic composites prepared by brazing and diffusion welding have a large impact on the mechanical properties of the joints, and self-propagating high-temperature synthesis can alleviate this drawback. Self-propagating high-temperature synthesis (SHS) technology is a technology that utilizes the high chemical reaction heat energy generated between the reactants to join the desired materials in a very short period of time, which can effectively alleviate the large residual stresses due to the differences in mechanical properties, such as coefficients of thermal expansion, between the parent materials. It has the advantages of simple synthesis process, simple equipment, low energy consumption, no external energy supply when the reaction occurs, and environmental pollution. This paper reviews the research progress of SHS technology in recent years in ceramic/metal dissimilar materials joining, and analyzes the micro-morphology and mechanical properties of ceramic/metal interfaces, and puts forward the advantages and disadvantages of SHS technology.

Keywords: Ceramic Matrix Composites, Mechanical Properties, SHS, Residual Thermal Stress

1. Introduction

Ceramic materials are characterized by good wear resistance, excellent corrosion resistance, as well as good thermal and chemical stability, and have important applications in aerospace, marine, and mechanical fields [1, 2]. However, ceramics are characterized by high brittleness, low ductility, and poor machinability, which makes it difficult to manufacture large and complex ceramic components, limiting their use in industry [3]. Metallic materials are commonly found in life and are widely used in modern industries. Steel is the most commonly used industrial metal material, possessing excellent toughness and strength, as well as weldability and processability [4]. However, stainless steel has a high specific gravity and is less resistant to corrosion and wear.

There are currently some challenges in achieving an effective connection between ceramics and steel [5]. The chemical properties of ceramics and steel are significantly different. Some conventional brazing materials, although they can wet the metal surface, have poor wettability for ceramic materials. The ceramic-steel connection interface is prone to the formation of a variety of complex brittle compounds such as oxides and carbides. These compounds are usually characterized by high hardness and brittleness, and the distribution at the interface is more complex, which can easily cause brittle fracture of the joint. The elastic modulus and thermal expansion coefficient of ceramic materials and steel are very different, and during the heating and cooling process, a large amount of residual stress is easily generated, which causes stress concentration at the interface between ceramic and metal joints and reduces the bonding strength of the joints.

2. Self-Propagating High-Temperature Synthesis

The self-propagation high-temperature synthesis method is a technique that uses the higher heat generated between reactants and by conduction to connect the base materials for reception welding. The filling material is changed during the joining process to form reaction products that can relieve large residual stresses due to differences in physical properties between the base materials [6]. S. F. Yu et al. [7] used Fe_2O_3 powders and Al powders as reaction materials, and then heated the reaction materials using a strong current to finally generate Al_2O_3 ceramics in situ on the upper surface of stainless steel. As shown in Figure 1a, the stainless steel melted and formed a metallurgical bond with the ceramic, and the combined interface was tightly connected without defects such as pores and cracks. Al_2O_3, α-ferrite and FeO-Al_2O_3 phases were found in the joint weld area. X. H. Hou et al. [8] achieved the high-temperature synthesis of Al_2O_3 ceramic-lined steel tubes by adding $Na_2B_4O_7$ to the Al-Fe_2O_3-Cr_2O_3 mixed feedstock. As shown in Figure 1b, the ceramic coating consisted of Al_2O_3-FeCr alloy-$(Al0.9Cr0.1)_2O_3$ composite phase, and it was found that with the increase of $Na_2B_4O_7$ content, the residual Fe-Cr alloy particles in the ceramic coating increased and were uniformly distributed, forming a dense ceramic coating.

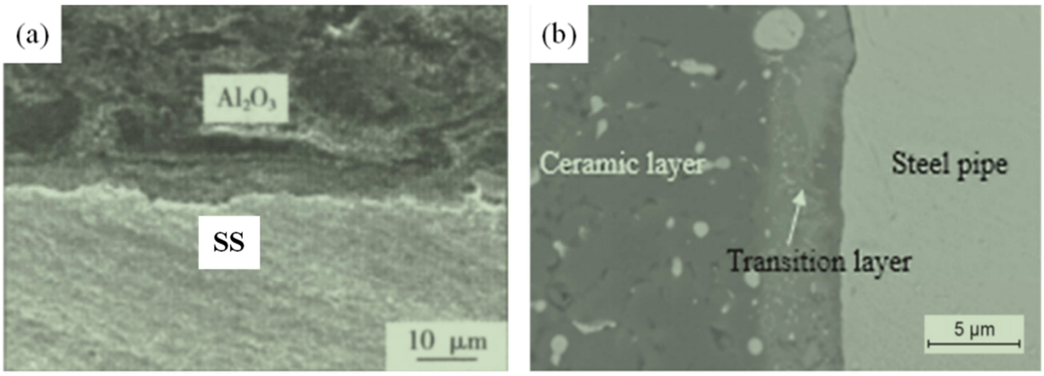

Figure 1. *Self-propagating high-temperature synthesis: (a) Al_2O_3/Fe_2O_3+Al powders/Steel. (b) Al_2O_3/Al-Fe_2O_3-Cr_2O_3+$Na_2B_4O_7$/Steel.*

Y [9] et al. prepared TiB_2-TiC ceramic coatings using the self-spreading high temperature synthesis (SHS) technique to improve the hardness and wear resistance of Ti. The microhardness of TiB_2-TiC ceramics was 2140 $HV_{0.5}$, and the wear rate was 5.5×10^{-3} mm^{-3} min^{-1}-N^{-1} due to the ultra-low porosity and high strength TiB_2/TiC interface improves the mechanical properties. Liang [10] et al. investigated the SHS reaction behavior of the Cu - Ti - C system at different Cu contents. Cu also plays an important role in the ignition behavior of the SHS reaction. With the increase of Cu content, the combustion temperature decreases abruptly and the ignition time decreases and then increases. When the Cu addition was 20 wt.%, the ignition time of the system is the shortest. The SHS reaction involves two consecutive phases of combustion with different brightness intensities. These two combustion phases correspond to the formation of TixCuy compounds and TiC particles, respectively. The SHS reaction products of the Cu - Ti - C system with different Cu contents consisted of TiC and Cu without an intermediate phase. Song [11] et al. prepared TiC particles in situ by a self-propagating high-temperature synthesis reaction and investigated the reaction behavior and generation pathways of TiC. It was shown that with the increase of Al content, the reaction temperature decreased and the size of TiC particles decreased significantly. The Al additive plays an important role in determining the size, morphology and formation pathway of TiC particles during SHS processing. Z [12] et al. prepared TiC/TiB_2 ceramic matrix composites by self-propagating high-temperature combustion synthesis and pseudo-thermal isostatic pressing method using Ti, B4C and carbon powder as raw materials. The introductions of additional rod-like TiB_2 grains into the TiC/TiB_2 ceramics resulted in a significant increase in the fracture toughness of the dense materials synthesized by TC05 and TC06. Macedo [13] et al. synthesized $Bi_4Ti_3O_{12}$ ferroelectric ceramics by SHS technique and investigated the microstructure and electrical properties of $Bi_4Ti_3O_{12}$ ferroelectric ceramics. This study discusses the characterization of BIT ceramics produced by SHS, compares their microstructural and electrical properties with those of samples produced by conventional solid-state reactions, and concludes that the differences in conductivity and relative permittivity are attributed to differences in grain size and defect concentration. Miloserdov [14] et al. prepared, Al_2O_3-Cr_2O_3 + TiC ceramic composites by SHS method using TiO_2, Al and C powders as raw materials with the addition of Cr_3 and Al. The research on the mechanical properties of this material showed that this material seems to be promising to be used as a tool for machining high-strength steels with hardness up to 49 HRC. Nakashima [15] et al. successfully prepared Al_4SiC_4 high temperature resistant ceramics by SHS method using Si, Al and C as raw materials. It was found that Ar pressure is more suitable for the synthesis of Al_4SiC_4 because higher Ar pressure allows gaseous substances such as SiF_4 to be retained in the particle mixture and the reaction can be carried out stoichiometrically, and the Polytetrafluoroethylene additives promote the formation of silicon carbide. Furthermore, the oxide layer on the surface of the silicon particles inhibits the reaction between silicon and carbon. Merz [16] et al. used an induction furnace-assisted SHS method for the rapid preparation of MAX-phase Mn_2AlB_2 ceramics from Al, Mn and B powders. The advantage of this method is the short synthesis time, which provides a unique solution for the large-scale preparation of MAB-phase powders.

3. Conclusion

Self-propagation high-temperature synthesis has the advantages of low energy consumption, high productivity, and low thermal effect on the base material. However, due to the fast reaction rate of self-propagation synthesis itself, the burning time of filler is difficult to control, thus leading to a complicated and difficult to control interfacial reaction.

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