Study on the Effect of Transition Layers on the Interfacial Microstructure Between BJ Ceramic Shells and Iron-Based Metals

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Abstract: Ceramic coatings are commonly employed to enhance the wear and corrosion resistance of metal components. Among them, metal ceramic components with Al_2O_3 coatings have been widely utilized in industrial applications. However, existing ceramic coating processes typically result in thin coatings with limited wear and corrosion resistance. Moreover, achieving efficient and high-quality coating on the surfaces of complex metal components remains challenging. In this study, complex Al_2O_3-based ceramic shells were prepared using Binder Jetting technology based on additive manufacturing principles. Subsequently, transition layers including Cr, Ni, and 316 stainless steel were coated on the surface of the shells, followed by liquid pouring of iron-based metal, and controlled temperature treatment to achieve metallurgical bonding at the Al_2O_3/Fe interface. The influence of transition layers on the microstructure of the Al_2O_3/Fe interface was explored. Experimental results indicate that coatings using silica sol as a solvent facilitate better bonding between the transition layer aggregate and the Al_2O_3 ceramic matrix. The transition layer effectively suppresses the formation of cracks at the Al_2O_3/Fe pouring interface, with the Cr transition layer demonstrating significant effectiveness.

Keywords: coating,Al_2O_3/Fe Interface; binder jetting; microstructure

1 Introduction

The ceramic/metal (coating/matrix) interface, as a functional coating system, has been widely applied in various fields such as aerospace, energy, electronic devices, and mold steel industries [1–2]. Currently, ceramic coatings on metal surfaces are primarily prepared using surface coating methods. These methods are costly, and it is challenging to achieve efficient, high-quality coatings on complex metal parts. Additionally, the ceramic layer is relatively thin (100–600 μm thick), resulting in limited improvements in wear and corrosion resistance [3]. In recent years, the rapidly developing additive manufacturing (AM) technology has provided new approaches for the rapid fabrication of complex ceramic shells [4]. Binder Jetting (BJ), as one of the main ceramic additive manufacturing technologies, offers low cost, high forming efficiency, and does not require support structures during forming. It has significant potential for development and industrial application [5].

In this study, high-strength Al_2O_3-based ceramic shells fabricated using BJ [6] were used as shell blanks. Through dipping, Cr, Ni, and 316 stainless steel coatings were applied as intermediate layers. High-temperature sintering was performed to tightly bonds the coatings with the ceramic substrate, followed by casting to achieve transitional bonding at the Al_2O_3/Fe interface. The effects of various intermediate layers on the interfacial structure and properties between the BJ ceramic shell and the iron-based metal were explored. The ceramic/metal interface was observed, and its microstructure and interfacial bonding mechanisms were analyzed. This study provides a new method for further enhancing the wear and corrosion resistance of iron-based metals.

2 Experimental procedure

The raw materials used included Al_2O_3 powder (d_{50}=15.1 μm), MnO_2 powder (d_{50}=12.9 μm), chromium, nickel, and 316 stainless steel powders (d_{50}=13.7 μm), phenolic resin binder, titanium dioxide sol, silica sol, sodium carboxymethyl cellulose (CMC-Na), silicone, and 65Mn spring steel. The overall preparation process for the Al_2O_3/Fe ceramic/metal samples is illustrated in Fig. 1, and mainly includes the following steps: BJ fabrication of the ceramic shell, preparation and dipping of coatings, sintering of the coatings, and casting of the metal liquid.

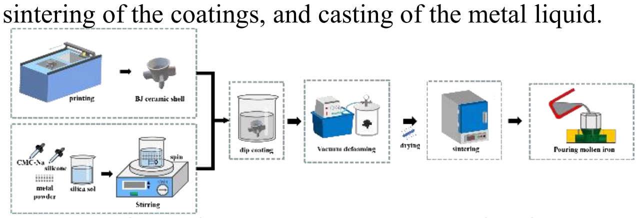

Fig. 1 Overall fabrication process diagram of Al2O3/Fe ceramic/metal specimens and components.

$$\rho_b = \frac{m_1}{m_3 - m_2} \times \rho_1 \quad (1)$$

$$D = \frac{\rho_b}{\rho_t} \times 100\% \quad (2)$$

where ρ_b is the bulk density (g/cm³), ρ_1 is the density of water (g/cm³), m_3 is the weight of the water-saturated sample in air (g), m_1 is the dry weight of the sample (g), m_2 is the weight of the water-saturated sample in water (g), ρ_t is the true density (g/cm³), and D is the relative density (%).

3 Result and discussion

To ensure good coating performance on the ceramic substrate, the coating should exhibit shear-thinning characteristics. Additionally, after application, the coating must maintain high viscosity to prevent cracking and delamination. The coating performance of each metal powder on the Al_2O_3 substrate should remain stable within a certain viscosity range. Using Cr coating as an example, the rheological properties of the coating at various Cr solid contents and their impact on the substrate performance after coating are shown in Fig. 2.

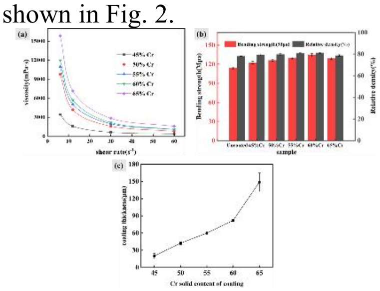

Fig. 2 Effects of different Cr contents on the properties of coatings and ceramic samples: (a) rheological properties of the coatings; (b) properties of the sintered ceramic substrate; (c) coating thickness.

As shown in Fig. 2, the coating exhibits shear-thinning characteristics, with viscosity increasing as the Cr solid content increases. The flexural strength and relative density of the coated samples are both improved compared to the uncoated samples. However, the flexural strength and relative density of the coated samples initially increase and then decrease with the increase in Cr solid content. The adhesion of the Cr coating on the Al_2O_3-based ceramic surface primarily relies on the reaction between SiO_2, produced by the decomposition of silica sol at high temperatures, and the Al_2O_3 substrate, forming mullite ($3Al_2O_3 \cdot 2SiO_2$). A small amount of mullite can enhance the physical properties of Al_2O_3-based ceramic, while an excess amount, due to its brittleness, can lead to a decline in the physical properties of the Al_2O_3 ceramics.

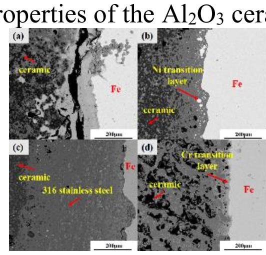

Fig. 3 Al_2O_3/Fe interface: (a) without transition layer; (b) with Ni transition layer; (c) with 316 stainless steel transition layer; (d) with Cr transition layer

As shown in Fig. 3, the bright region on the right is iron, while the black and gray region on the left is Al_2O_3-based ceramic. The Al_2O_3/Fe interface without a transition layer exhibits significant cracks. This is due to the large difference in the coefficient of thermal expansion (CTE) between Fe ($(9.2\text{-}11.8)\times10^{-6}$ K^{-1}) and Al_2O_3 ($(7.85\pm0.02)\times10^{-6}$ K^{-1}), along with the presence of a substantial amount of iron oxides at the interface, leading to interface cracking.

After adding metal transition layers, the Al_2O_3/Fe interface showed significant improvement, with no large cracks observed. When the 316 stainless steel transition layer was added, a few pores were still present at the transition layer and Fe interface boundary, which could lead to cracks under external force. With the addition of the Ni transition layer, no obvious cracks or pores were found at the transition layer and Fe interface boundary. However, there were regions of Ni element segregation and enrichment, as shown in Fig. 3(b). This segregation and enrichment of Ni could cause stress concentration at the interface, reducing interface performance. The Cr transition layer showed the best improvement for the interface, with no significant cracks or elemental segregation observed.

4 Conclusion

The metal transition layer coatings prepared according to the viscosity range of 60% wt. Cr solid content can form transition layers on the Al_2O_3-based ceramic surface and improve the flexural strength and relative density of the ceramic substrate. The transition layers significantly enhance the microstructure of the Al_2O_3/Fe interface, with the Cr transition layer showing the best improvement in the interfacial properties.

Acknowledgments

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