Ceramic Mold with Integral Core and Shell for Hollow Turbine Blades Fabricated by Integrated Additive Manufacturing Technology

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Abstract: Ceramic molds are extensively applied in investment casting processes of hollow turbine blade due to their outstanding high-temperature chemical stability and creep resistance. Herein, laser powder bed fusion (LPBF) method was utilized to fabricate an ceramic mold with integral core and shell (CMCS). The vacuum infiltration process was adopted to improve mechanical properties of ceramic after the sintering, where the solid loading of ceramic slurry was investigated. After the first infiltration and pre-sintering, the separated two parts were bonded by a ceramic binder and then underwent second infiltration and final-sintering to obtain a complete CMCS. The ceramic mold fabricated through LPBF and post-treatment possessed low sintering shrinkage (1.51–2.03%), adequate apparent porosity (30.82 ± 0.01%), and room-temperature strength (13.03 ± 2.90 MPa for unbonded specimen, 9.72 ± 1.34 MPa for bonded specimen). Strikingly, the subsequent casting experiment has proved that the method proposed in this paper is promising to fabricate superior ceramic based CMCSs.

Keywords: ceramic mold, laser powder bed fusion, infiltration, turbine blade

1 Introduction

Superalloy turbine blades with intricate interior cooling passages are the key components of gas turbine engines[1]. The traditional method of fabricating ceramic mold involves a series of procedures including die-casting, shaping wax patterns, stuccoing etc., and all of these steps require long production cycles and high cost but the yield is not satisfactory. Additive manufacturing (AM) technology shows capability of producing parts with complex structures in a layer-by-layer mode, which makes it possible to eliminate these complicated and time-consuming processes in the fabrication of ceramic casting molds[2]. In recent years, researchers have made remarkable progress on the application of AM to fabricate ceramic core and shell molds. With the development of ceramic AM technology and related post-treatment technology, the preparation of core and shell respectively are becoming more mature. But the separated ceramic core and shell must be assembled to form a complete mold before the casting process, and the assembly accuracy is hard to control. Therefore, producing a ceramic mold with integral core and shell (CMCS) is a preferred choice in this aspect[3]. The structures of ceramic molds for large-scale gas turbine blades are sophisticated. The total height of the mold could reach about 700−800 mm, while the narrowest gap in the mold cavity is only about 1−2 mm in width, and there are only two narrow openings on top and bottom of the mold respectively. Such conditions make cleaning the residual powder inside the ceramic mold complicated cavities very difficult. Besides, the low density and high porosity of alumina ceramics made by LPBF usually result in low strength due to low powder bed packing density, which means that the post-treatment techniques are needed to enhance the mechanical properties of the alumina ceramics[4,5]. Infiltration is a method that can fill micro-pores of ceramic green body with ceramic slurry, thus improving the density of ceramic parts. But the solid loading of ceramic slurry has a significant influence on the infiltration effect. The infiltration efficiency would be decreased if the solid loading is too low, while the cavity would be blocked if the solid loading rises too high, so how to design an optimal ceramic slurry and infiltration scheme is another problem.

2 Experimental procedure

Once the printed specimens were cleaned, the first vacuum infiltration was applied to enhance their densities. The specimens were firstly placed in a vacuum container and the pressure was kept under − 0.08 MPa, then the ceramic slurry was pumped into the container until the specimens were fully immersed. The specimens were kept immersed under vacuum for 30 min to achieve uniform infiltration. After the specimens were dried, they were subjected to debinding and pre-sintering in a furnace. The debinding and pre-sintering process was: the specimens were heated up to 600 ℃ with a rate of 1 ℃/min and held for 2 h to remove binder completely, and then were directly heated up to 1200 ℃ with a rate of 2 ℃/min and held for 4 h. Afterward, the specimens were cooled in the furnace to room temperature. In order to further improve the mechanical properties of the ceramic for casting purposes, the specimens needed to undergo the second vacuum infiltration and final-sintering. The second vacuum infiltration followed the same protocol as the first vacuum infiltration. The final sintering process was: the specimens were heated up to 1600 ℃ with a rate of 5 ℃/min and held for 2 h, and then cooled in the furnace to room temperature.

3 Result and discussion

The effects of solid loading of ceramic slurry on properties of infiltrated green bodies and pre-sintered bodies are shown in Fig. 1. The weight increasing ratio increases as the solid loading increases, indicating that introducing fine alumina powder is an efficient way to promote material density. The weight increasing ratio of the 20 vol% ceramic slurry is 22.24 %, which is almost four times as large as that of the counterpart treated with pure silica sol (5.05 %).
Different from the properties discussed above, solid loading of the ceramic slurry does not have significant impact on the pre-sintering shrinkage. All the specimens show low shrinkage rates below 1.4 % along different directions, and specimens infiltrated with ceramic slurries which contain fine alumina powder have even lower shrinkage rates around 1 %. It can also be found that the shrinkage rate along the Z-axis direction is just slightly larger than the shrinkage rate along the X/Y direction during this stage, which means the shrinkage anisotropy is not significant. Due to the low pre-sintering temperature (1200 ℃) and low sintering activity of the coarse spherical alumina powder, the thermodynamic conditions of mass transfer and particle rearrangement between the coarse alumina particles cannot be fulfilled.

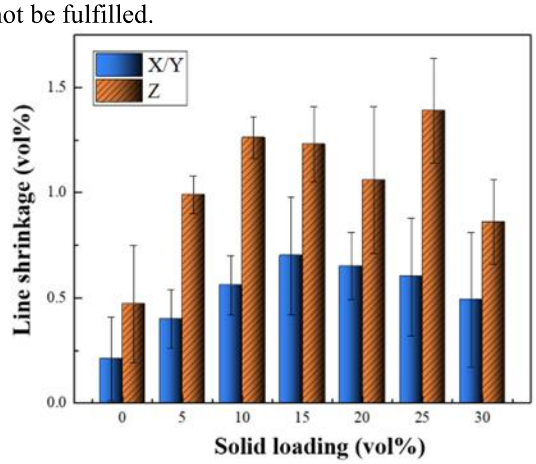

Figure 1 Effects of fumed silica suspension solid loading on line shrinkage of LPBF-fabricated ceramic mold

The overall shape of the casting mold is intact, and there are no obvious cracks and other defects on the outer surfaces. However, cracks can be found inside the ceramic mold, and some trapped bubbles can be seen inside the bonding joint. To verify the feasibility of this process, casting experiment is conducted and a nickel-based superalloy turbine blade is successfully fabricated. The turbine blade is basically intact and the cracks in the ceramic mold did not lead to fatal failures. Also, no noticeable metal leakage can be seen around the bonding joint, proving that the bonding process is feasible for casting superalloy turbine blade.

4 Conclusion

CMCS with low sintering shrinkage and adequate properties was prepared by LPBF and its feasibility for casting superalloy turbine blade was successfully verified. The CMCS model was split into two parts for the convenience of cleaning residual powder. Ceramic slurry with high solid loading (≥25 vol%) is not suitable due to low infiltration efficiency and clogging phenomenon, and the ceramic slurry with 20 vol% is determined to be optimum for both first and second infiltration. After final-sintering, alumina-based material with low sintering shrinkage (1.51–2.03 %), adequate apparent porosity (30.82 ± 0.01 %) and room-temperature strength (13.03 ± 2.90 MPa) is obtained. The two parts of CMCS were bonded by a ceramic binder with adequate strength (9.72 ± 1.34 MPa), and no obvious cracking was found at the interface. Finally, the potential to cast superalloy turbine blades was demonstrated by a cast case using the CMCS.

Acknowledgments

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