EFFECT OF ALUMINA-BASED FIBER ON THE MID-TEMPERATURE STRENGTH OF INTEGRAL CERAMIC MOLD FOR CASTING HOLLOW TURBINE BLADE

GUOQIANG TIAN, ZHONGLIANG LU†, WEIJIAN WAN, KAI MIAO AND DICHEN LI
State Key Laboratory of Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, 710049, China

ABSTRACT: The fabrication process of integral ceramic mold based on stereolithography and gelcasting can eliminate the assembly errors between cores and that between cores and shell in the traditional manufacturing process of ceramic molds. However, the bending strength of the mold at 500°C (mid-temperature strength) drops significantly during pre-sintering because the gel networks surrounded the ceramic particles are burnt off, which often causes the core fracture or shell cracking of the integral ceramic mold. In this paper, short alumina-based fibers were added into the gelcast ceramic slurry to improve the mid-temperature of the ceramic mold. Filling experiment and computed tomography (CT) test were performed to investigate the effect of fiber content and fiber length on the filling ability of ceramic slurry in the cavity with small complex structures. The mid-temperature strengths of the ceramic mold were tested. Microstructures of the ceramic mold sintered at 500°C were observed by scanning electron microscope (SEM). It was found that the filling ability of the ceramic slurry decreased as the fiber length and fiber content increased, however the mid-temperature strength of the ceramic mold increased with the fiber length and fiber content. When 1.5wt% short alumina-based fibers with lengths between 0.5 mm and 1 mm were added, the ceramic slurry could meet the requirement of gelcasting, and the mid-temperature strength of the ceramic mold was improved from 0.78 MPa to 1.65 MPa.

INTRODUCTION

The hollow turbine blade is the key component of high performance generating equipment, the aircraft engine and marine power equipment (Lu et al., 2013). At present, the hollow turbine blade is mainly fabricated via traditional investment casting process (Lu et al., 2013). Production of high quality ceramic mold is a crucial step of the whole process. During the traditional production process of ceramic mold, the ceramic cores and shell are fabricated separately and then assembled together, therefore the position errors between cores and that between cores and shell often occur (Wu et al., 2009). Besides, the production of ceramic molds suffers from high tooling investments for producing wax patterns and ceramic cores (Wu et al., 2009).

The rapid fabrication method of integral ceramic mold (ICM) based on stereolithography (SL) and gelcasting provides a new route for fabricating hollow turbine blade (Wu et al., 2009; Wu et al., 2010). Firstly, a resin mold, containing a resin prototype and a resin shell, was manufactured by SL. Secondly, the ceramic slurry was poured into the resin mold. Under the action of the initiator and catalyst, the slurry was in situ polymerized to form the wet ICM. Thirdly, the water in the wet ICM was sublimated by freeze drying after the resin shell was removed, then the SL resin prototype surrounded by the ICM and the organic monomer polymers within the ICM were burnt out during pre-sintering. Finally, the ICM was prepared successfully after sintering at high

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[†] Author to whom correspondence should be addressed. e-mail: zllu@mail.xjtu.edu.cn

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temperature. Because the resin prototype is used to replace wax patterns, there is no need to manufacture wax-pattern dies, causing a low manufacturing cost. In addition, the ceramic cores and shell are formed together, instead of being assembled together, thus the position accuracy between cores and that between cores and shell can be ensured.

However, during pre-sintering of the ICM, the strength of the molds at about 500°C (mid-temperature strength) drops significantly, as the gel networks formed by acrylamide monomer were burnt off (Miao et al., 2016). The integrity of ICM was maintained only by the particle packing effects, therefore slender structures of the ICM may be broken by gravity. Therefore, the ceramic mold should have a high mid-temperature strength. Many efforts have been made to improve the mid-temperature strength of the ICM, such as adding inorganic binders (Miao et al., 2016), preceramic polymers (Miao et al., 2016), whisker (Lu et al., 2013) or short fiber (Lu et al., 2014). Among these methods, short fiber reinforcing is an effective approach to improve the strength of the ceramic mold. However, the filling ability of the ceramic slurry would become poor when short fibers were added into the slurry. Therefore, effects of short fiber on the mid-temperature strength of the ICM and the filling ability of the ceramic slurry should be studied simultaneously.

In this work, short alumina-based fibers were used as the mid-temperature strengthening phase in ICM by gelcasting. The effects of fiber length and fiber content on the filling ability of the ceramic slurry and the mid-temperature strength of the ICM were investigated simultaneously. The optimum fiber length and fiber content were obtained.

EXPERIMENTAL PROCEDURE

Experimental materials

Commercially available alumina powders (grain size ranging from 2 to 40 μm, supplied by Shandong Zibo Aluminum Inc., Zibo, China) and MgO powders (mean grain size: 40 μm, supplied by Sinopharm Chemical Reagent Co, Ltd, Shanghai, China) were used as the raw materials. Continuous alumina-based fiber bundles Nextel 440 (3M Corporation, St. Paul, MN, USA) were selected to strengthen the ceramic mold. The chemical composition of the fibers is 70 wt% Al_2O_3, 28 wt% SiO_2 and 2 wt% B_2O_3. The continuous fiber bundles were cut into short fiber bundles with the size of 0.5-1 mm, 1-2 mm or 2-3 mm. Then the short fiber bundles were converted into short individual fibers with corresponding sizes under the action of ultrasonic dispersion. For the gelcasting process, acrylamide ($C_2H_3CONH_2$, AM, supplied by Tianjin Kemiou Chemical Reagent Co, Ltd, Tianjin, China) and N,N'-methylenebisacrylamide ($(C_2H_3CONH)_2CH_2$, MBAM, supplied by Tianjin Kemiou Chemical Reagent Co, Ltd) were employed as the monomer and coupling agent, respectively. And sodium polyacrylate (PAAS, supplied by Sinopharm Chemical Reagent Co, Ltd) was used as the dispersant. Ammonium persulphate ($(NH_4)_2S_2O_8$, APS, supplied by Sinopharm Chemical Reagent Co, Ltd) and N,N,N',N' -tetramethylethylenediamine $(CH_3)_2NCH_2CH_2N(CH_3)_2$, TMEDA, supplied by Sinopharm Chemical Reagent Co, Ltd) were used as the initiator and catalyst, respectively. Deionized water was used in the whole work.

Sample preparation

The preparation procedures for testing samples were the same as the references (Wu et al., 2009; Wu et al., 2010). Firstly, resin molds for ceramic sample were fabricated by SPS600B (Xi'an Jiaotong University, China) using photosensitive resin (SPR 8981; Zheng bang Ltd., Zhuhai, China). Then a premixed solution with a concentration of 15% was prepared by dissolving AM and MBAM (in 24:1 ratio) in proper amount of deionized water. The pH value of the premixed solution was adjusted to 11 by strong ammonia after sodium polyacrylate (2.5 wt% of solid powders) was added. Subsequently, all powders, including alumina powders with different particle sizes, MgO powders and short alumina-based fibers with different length, were added into the premixed solution in steps. The component of the composite powders was shown in table 1. By ball-milling for 40 min, the ceramic slurry with high solid loading (60 vol%) was prepared. After degasing for 5 min, the ceramic slurry was poured into the resin molds, then in situ polymerized to form green ceramic bodies under the action of initiator and catalyst. After freeze-drying for 24 h, the green bodies were moved into a furnace, heated to 1000 ºC and kept for 3 hours to remove the polymer.

Table 1. Component of the composite powders

Sample no.	Weight fraction (wt.%)						
	Al_2O_3 (40 μm)	Al_2O_3 (5 μm)	Al_2O_3 (2 μm)	MgO (40 μm)	Short fiber (0.5-1 mm)	Short fiber (1-2 mm)	Short fiber (2-3 mm)
A	51.60	29.10	15.30	4	0	0	0
B	51.10	29.10	15.30	4	0.5	0	0
C	50.60	29.10	15.30	4	1	0	0
D	50.10	29.10	15.30	4	1.5	0	0
E	49.60	29.10	15.30	4	2	0	0
F	50.10	29.10	15.30	4	0	1.5	0
G	50.10	29.10	15.30	4	0	0	1.5

Testing

The ceramic slurry was poured into several resin molds with small structures under vacuum conditions. The structures and sizes of these resin molds were similar with that of the tip part of some types of hollow turbine blades. Then, the filling ability of the ceramic slurry were investigated by detected the internal structure integrity of the wet green tip parts using the micro X-ray imaging system (Y.Cheetah; YXLON, Hamburg, Germany) with a scanning resolution of about 45 μm. The mid-temperature strength of the samples at 500 ºC was tested in a three-point bending test machine (Sino steel Luoyang Institute of Refractories Research Co., Ltd, China) using green ceramic samples of a nominal size of 4 mm × 10 mm × 60 mm. The samples were mounted on a silicon nitride ceramic fixture within the chamber of the testing machine, heated to 500 ºC, and kept for half an hour. Then three-point bending tests were performed. The span length L was 30 mm, and loading speed was 0.5 mm/min. Average bending strengths were obtained from five tests for each condition. The microstructures of the sintered samples were observed by a scanning electron microscopy (Hitachi SU-8010, Japan).

RESULTS AND DISCUSSION

Effect of short fiber on the filling ability of the ceramic slurry

Figure 1 shows the CT images of the wet green tip parts. When adding 1.5wt% short fibers with lengths between 0.5 mm and 1 mm, the small structure of the tip part could be filled perfectly [Fig. 1(a)]. However, when adding 2wt% fibers with lengths between 0.5 mm and 1 mm, small insufficient filling occurred in local area of the tip part [Fig. 1(b)]. The reason should be that, air entrainment occurred as the slurry viscosity increased due to the increasing of fiber content, causing the insufficient filling in the small structure of the tip part. Besides, when adding 1.5wt%

short fibers with lengths between 1 mm and 2 mm or between 2 mm and 3 mm, large insufficient filling was found in both of the two tip parts [Figs. 1(c) and (d)]. The reason should be that, the length of the fiber was larger than the size of the small structures of the tip part, and the flow of ceramic slurry in the small structures was obstructed.

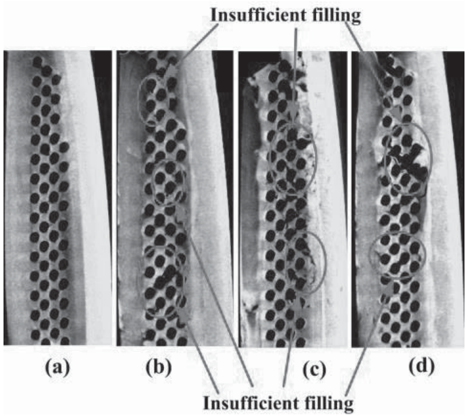

Figure 1. Effect of fiber length and fiber content on the filling integrity of the tip pats of integral ceramic mold

Mid-temperature strength of the ceramic mold

Figure 2 shows the mid-temperature strength of the mold with different fiber content. Here, the fiber length was 0.5-1 mm. As seen in the figure, the mid-temperature strength increased with the fiber content. The mid-temperature strength of the mold was only 0.78 MPa without fiber, however, it reached 1.96 MPa when 2wt% fibers were added. Figure 3 shows the mid-temperature strength of the mold with different fiber lengths. Here, the mass fraction of the fiber was 1.5wt%. It can also be seen that the mid-temperature strength of the mold increased as the fiber length increased. When the fiber length was 0.5-1 mm, 1-2 mm and 2-3 mm, the mid-temperature strength was 1.64 MPa, 2.31 MPa and 2.49 MPa, respectively. Taking into account the filling ability of the ceramic slurry and the mid-temperature strength of the ceramic mold, the fiber content and fiber length was selected as 1.5wt% and 0.5-1 mm, respectively. In this case, the mid-temperature strength of ICM increased from 0.78 MPa to 1.65 MPa.

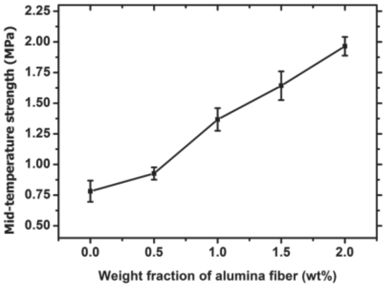

Figure 2. Effect of fiber content on the mid-temperature strength of the integral ceramic mold

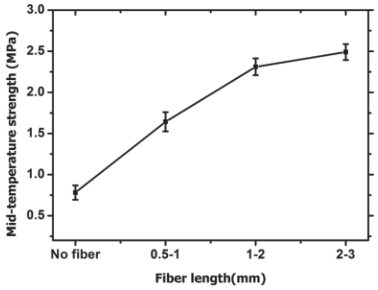

Figure 3. Effect of fiber length on the mid-temperature strength of the integral ceramic mold

The mid-temperature is closely related to the microstructures of the ceramic mold. Figure 4 shows the fracture surface of the ceramic mold sintered at 500 ^{o}C containing 1.5wt% alumina-based fibers with lengths between 0.5 mm and 1 mm. Because the water within the sample was removed during the freeze drying process and the gel networks surrounded the alumina particles were largely burnt off at 500 ºC, many holes were observed in the sample. There were no sintering necks among alumina particles, resulting in the weak binding force between alumina particles. So the bending strength of the ICM at 500 ^{o}C was low. However, the fiber pullout effect occurred during the fracturing process of the sample containing alumina-based fiber, the mid-temperature strength of the ICM was improved. Moreover, alumina-based fiber had much higher strength than the ceramic mold at 500 ^{o}C, which was beneficial to the improvement of mid-temperature strength.

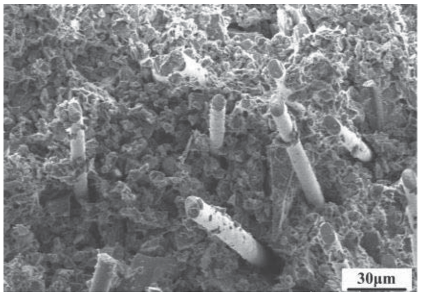

Figure 4. Microstructures of fracture surface of the ceramic mold sintered at 500 ^{o}C

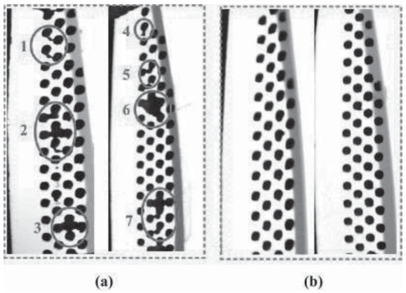

Figure 5. Effect of short fiber on the structural integrity of the tip parts of integral ceramic mold after pre-sintering. (a) Tip parts of the ICM without short alumina-based fibers. (b) Tip parts of the ICM containing alumina-based fibers.

For the tip parts of the ICM without fibers after pre-sintering, fractures appeared in several local areas, such as area 1 to area 7 [Fig. 5(a)]. However, for the tip parts containing 1.5wt% alumina-based fibers with lengths between 0.5 mm and 1 mm, its structural feature was complete after pre-sintering [Fig. 5(b)]. This indicated that the mid-temperature strength of the mold could be effectively improved when adding short alumina-based fibers.

CONCLUSIONS

In conclusion, short alumina-based fibers can improve the mid-temperature strength of the integral ceramic mold significantly. When 1.5wt% alumina-based fibers with lengths between 0.5 mm and 1 mm were added, the ceramic slurry could meet the requirement of gelcasting. Meanwhile, the bending strength of the integral ceramic mold at 500 °C was improved from 0.78 MPa to 1.65 MPa. The alumina-based fibers had higher strength than the mold matrix and the fiber pullout effect occurred as the mold matrix fractured, which were responsible to improve the mid-temperature strength of the integral ceramic mold.

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