

Effect of alumina fibers on ceramic shell mold properties

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Abstract: Alumina fibers, with an aspect ratio ranging from 9 to 27, were utilized as the reinforcing materials for silica-sol ceramic shell molds, and the impact of different alumina fiber additions on the green bending strength, room- and high-temperature bending strength, and self-weight deformation of ceramic shell molds was investigated. The green bending strength of shell molds is the maximum at an alumina fiber addition amount of 0.2wt.%, reaching 6.20 MPa. Further increases in alumina fiber content do not significantly affect the green bending strength. As the alumina fiber addition amount increases from 0.2wt.% to 1.0wt.%, the bending strength and the resistance to self-weight deformation of the ceramic shell molds at high-temperatures show a pattern of first increase and then decrease. The shell molds after sintering exhibit the highest room-temperature strength of 17.33 MPa and the highest high-temperature strength (18.97 MPa at 1,100 °C; 17.78 MPa at 1,200 °C; and 15.3 MPa at 1,300 °C), and the smallest self-weight deformation of 0.022% at 1,000 °C when the alumina fiber addition is 0.6wt.%. The appropriate amount of fibers in the shell mold matrix consume the energy required for crack growth through mechanisms such as bridging and pulling-out, thereby improving the strength of shell molds. In summary, the comprehensive performance of the shell molds is the best when the fiber addition amount is 0.6wt.%.

Keywords: ceramic shell molds; alumina fibers; bending strength; self-weight deformation

CLC numbers: TG221

Document code: A

Article ID: 1672-6421(2025)06-646-08

1 Introduction

Engine casings, as key load-bearing components of aircraft engines, have been limited by conventional forming technology. As a result, they were typically designed with increased wall thicknesses, simplified geometries, and relied on subsequent machining to achieve intricate thin-walled configurations. As the performance and reliability of aircraft engines continue to improve, the structural design requirements for the next generation aircraft engines with a high thrust-to-weight ratio have become increasingly stringent. A great number of complex structures characterized by high structural efficiency, large sizes, thin walls, and complex geometries are adopted^[1-4]. The ceramic shell mold is an important factor determining the quality of large and complex superalloy casings. Statistical data indicate that defects originating from ceramic shell molds account for 50% to 70% of superalloy casting

failures^[5]. To obtain high-quality superalloy castings with large sizes and complex structures, ceramic shell molds must exhibit high bending strength and low self-weight deformation to withstand the impact of molten metal during casting. Meanwhile, the shell molds need to have sufficient strength to prevent cracking due to the expansion of the wax material during dewaxing^[6-11].

Research works related to strength improvement of fiber-reinforced ceramic shell molds are extensive. Researchers have incorporated organic fibers and inorganic fibers into ceramic shell molds. The organic fibers improve the green bending strength and the permeability of the shell molds^[12-17]. However, the burn out of organic fibers reduces the high-temperature bending strength of the molds. As research progresses, fiber preparation techniques are enhanced. Inorganic fibers, such as glass fibers, zirconium oxide fibers and so on, which can boast high temperature performance and physical and chemical properties, are being used for reinforcing ceramic shell molds^[18-24]. However, the agglomeration of ceramic fibers and their unintended sintering with the shell matrix remain significant challenges in the fabrication of high-performance ceramic shell molds.

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Received: 2024-03-13; Revised: 2024-12-01; Accepted: 2025-02-28

In this study, micron-sized alumina fibers were incorporated into the backup slurry of ceramic shell molds at varying contents. The bending strength and high-temperature self-weight deformation of the resulting shell molds were systematically assessed. The objective was to identify an optimal fiber content that enhances shell strength while minimizing high-temperature self-weight deformation rate. The results are expected to provide a foundation for the development of reinforced ceramic shell molds with improved performance.

2 Experimental procedures

2.1 Materials and ceramic shell mold preparation

Fused white corundum powder, fused white corundum sand, bauxite powder, and gangue sand were used as the refractory materials to prepare ceramic shell molds. The properties of these refractory materials are shown in Table 1. JN-30 colloidal silica was used as the binder, and its typical properties are listed in Table 2. Alumina fibers, with an aspect ratio ranging from 9 to 27, were used as reinforcing material,

and their main components and performance parameters are shown in Table 3. An alcohol solution of a silane coupling agent was prepared for fiber surface pretreatment. The agent was diluted with a small amount of deionized water and well stirred, assure the silane concentration maintained at 0.25% by mass of the total solution. The alumina fibers were then added to the solution and stirred at 110–120 rpm. After being cleaned and filtered, the alumina fibers were subjected to ultrasonic dispersion for 20 min and then dried in an oven. Figure 1 displays the SEM (QUANTA-400) micrographs of alumina fibers before and after pretreatment.

The primary slurry (Layer 1) was prepared using fused white corundum as the filler with a filler-to-binder ratio of 3.5:1, while the transitional slurry (Layers 2 to 4) had a ratio of 2:1. The reinforcement (Layers 5 to 7) and seal (Layer 8) slurries used bauxite as the filler at a ratio of 2.1:1. Six types of back-up (Layers 5 to 8) slurries were prepared by incorporating varying proportions of alumina fibers, specifically 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% by weight. The primary and back-up slurries were separately mixed in a slurry mixer for 12 h, then poured into a L-type mixer for an additional 12 h. Table 4

Table 1: Properties of the refractory materials

Refractory materials	Granularity (mesh)	Main component (%)				Refractoriness (°C)
		Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	Na ₂ O	
Corundum powder	320	≥99.00	<0.30	<0.15	<0.35	2,430
Corundum sand	100, 60	≥98.50	<0.30	<0.16	<0.50	2,430
Bauxite powder	320	≥55.00	≥35.00	<3.00	<1	1,700
Gangue sand	46, 24	≥42.00	≥50.00	<2.00	<1	1,700

Table 2: Typical properties of the binder JN-30 colloidal silica

Na ₂ O content (%)	SiO ₂ content (%)	Density (g·cm ⁻³)	PH	Viscosity (s)	Particle size (nm)
≤0.5	30.5±1	1.19–1.21	9.5–11	≤10	8–15

Table 3: Typical properties of the alumina fibers

Al ₂ O ₃ content (%)	SiO ₂ content (%)	Length (μm)	Diameter (μm)	Refractoriness (°C)
≥95	≤5	10–580	8–32	1,450–1,600

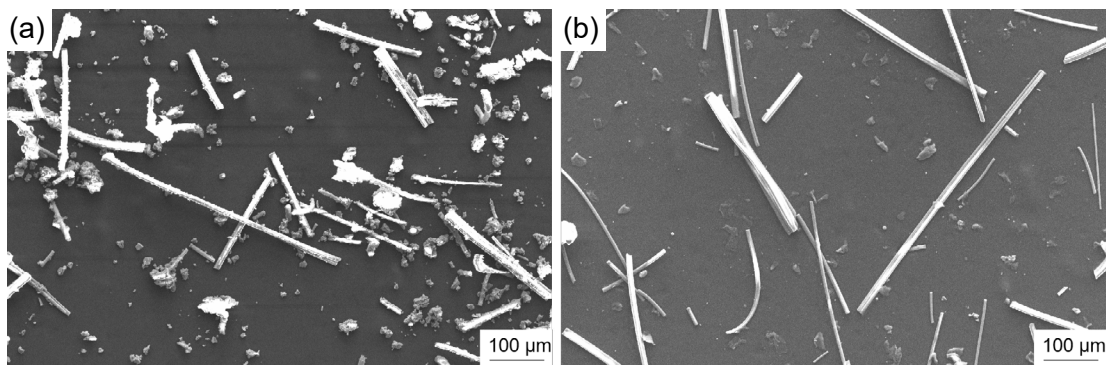


Fig. 1: SEM micrographs of alumina fibers before (a) and after (b) surface pretreatment

Table 4: Ceramic shell molds processing parameters for each layer

Layer	Filler: binder	Viscosity (s)	Fiber content (wt.%)	Drying temperature (°C)	Humidity (%)	Air velocity (m·s ⁻¹)	Drying time (h)
1	3.5:1	35±2	–	22–25	50–70	–	12
2–4	2:1	15±2	–		40–60	6–8	6
5–7	2.1:1	10±2	0, 0.2, 0.4,		40–60	6–8	6
8			0.6, 0.8, 1.0		40–60	6–8	6

summarizes the molding parameters, including humidity, drying temperature and drying time for each layer.

2.2 Experimental method

Five bending strength specimens measuring 40 mm×20 mm×6 mm were prepared for each group, corresponding to different fiber contents, as depicted in Fig. 2. The strength of ceramic shell specimens was tested using a universal testing machine at a loading speed of 6 mm·min⁻¹. The green strength was tested after dewaxing. The high-temperature strength was tested after heating the sintered specimens to the test temperatures of 1,100 °C; 1,200 °C; and 1,300 °C, and holding for 10 min. The bending strength (σ_w) of the specimens was calculated as Eq. (1):

$$\sigma_w = \frac{3PL}{2bh^2} \quad (1)$$

where L is the spanning distance between the two support points of the three-point flexural testing equipment, P is the load at fracture of the specimen, b is the width of the specimen, and h is the thickness of the specimen.

The ceramic shell molds feature a multi-layer heterogeneous structure composed of binder-coated refractory particles, where thermophysical properties vary across layers due to differences in refractory composition, particle distribution, and interlayer bonding. Its own gravity and the stress generated from thermal phase transformation during the preheating process cause the deformation in ceramic shell molds. Five high-temperature self-weight deformation specimens, as shown in Fig. 3, were prepared for each group, corresponding to different fiber contents. The sintered specimens were then placed in a furnace at room temperature and gradually heated to 1,000 °C at a heating rate of 250 °C·h⁻¹. The specimens were held at 1,000 °C for 1 h before being cooled down to below 300 °C and removed from the furnace. They were then cooled to room temperature before measuring the outer diameter of the specimens. The high-temperature self-weight deformation rate of ceramic shell molds can be calculated using the following equation:

$$\delta_{t-\tau} = \frac{A_0 - A_1}{A_0} \times 100\% \quad (2)$$

where $\delta_{t-\tau}$ is the deformation of the specimen at a certain

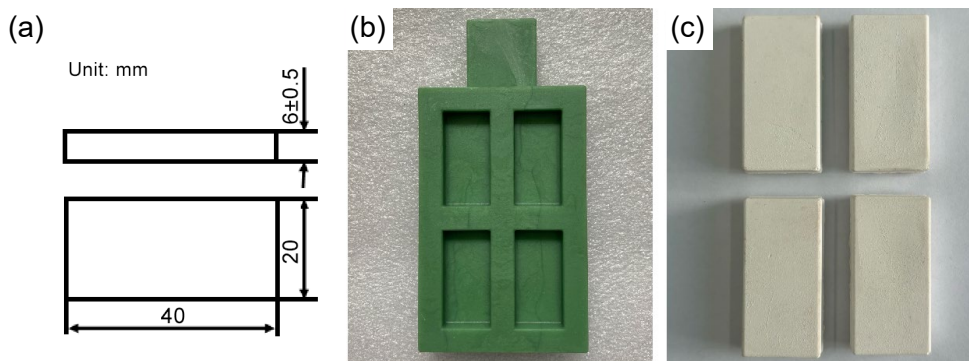


Fig. 2: Sizes of bending strength specimens (a), wax pattern (b), and picture of specimens (c)

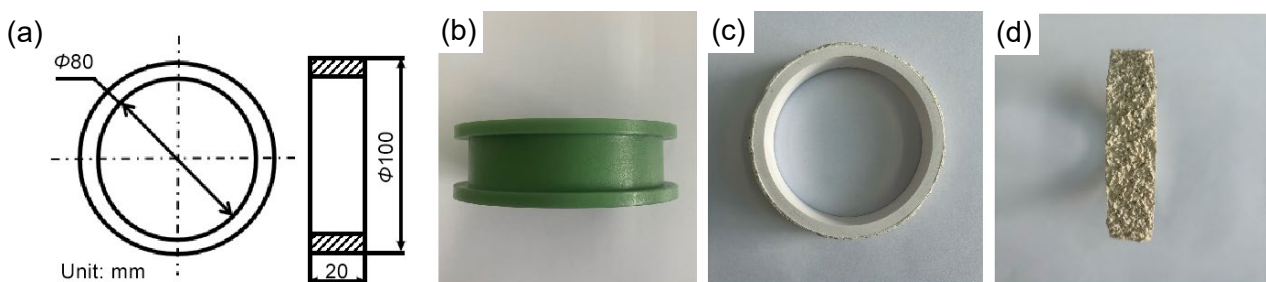


Fig. 3: High-temperature self-weight deformation drawing (a), wax pattern (b), and front (c) and side (d) of ceramic shell mold specimen

temperature t and time τ , A_0 is the original outer diameter of the specimen, and A_1 is the outer diameter of the specimen after deformation.

3 Results and discussion

3.1 Effect of alumina fiber content on green bending strength of ceramic shell molds

Figure 4 illustrates the impact of alumina fiber content on the green strength of ceramic shell molds. The green bending strength of ceramic shell molds is 4.60 MPa without alumina fiber addition. However, when 0.2% of alumina fibers are added, the green bending strength of ceramic shell molds increases to a peak value of 6.25 MPa, which represents a 36% increase. The addition of a small amount of alumina fibers improves the interlayer bonding of ceramic shell molds. Figure 5(b) shows that the interfacial bonding between fibers and silica-sol gel in the reinforced ceramic shell molds forms a supporting skeleton^[25] that strengthens the connection between the refractory powder and the binder. The pinning and connecting force of the fibers in the interlayer play a major role in enhancing cohesion, as these fibers fill the voids in the shell mold interlayer. The improvement in interlayer cohesion correspondingly increases the bending strength of

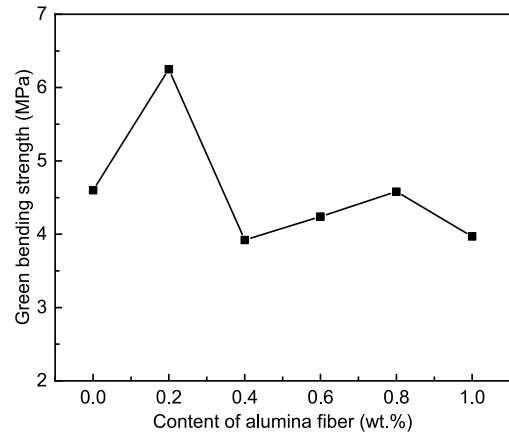


Fig. 4: Effect of alumina fiber content on green bending strength of ceramic shell molds

the green ceramic shell molds when compared to the ceramic shell molds without fiber addition. Further addition of alumina fibers decreases the bonding between the fibers and refractory material, resulting in a reduction of the green bending strength. The bending strength of the specimen with a fiber content of 0.4% decreases to 3.92 MPa, representing a minimal value among the six groups of specimens. Cracks and voids in the green blank increase in interlayer compared with the other samples, as shown in Fig. 5(c). The refractory materials cannot

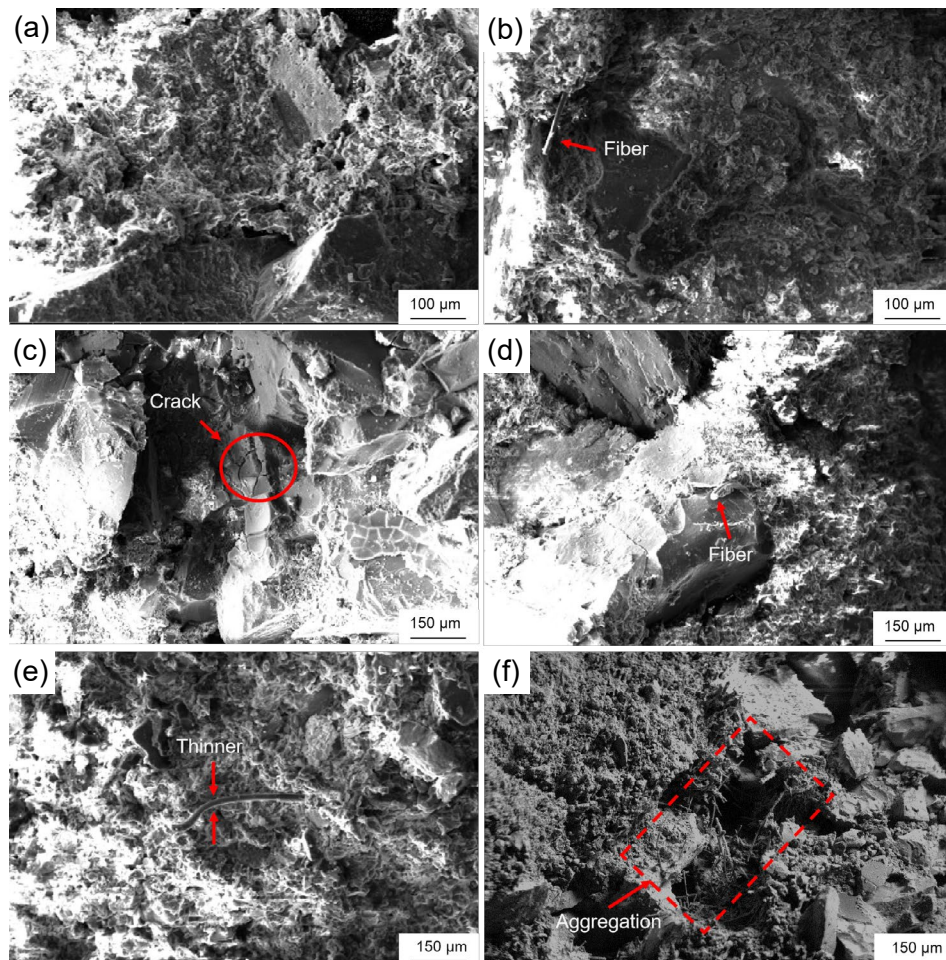


Fig. 5: SEM micrographs of green strength fracture surfaces of shell molds with different fiber contents by weight: (a) 0%; (b) 0.2%; (c) 0.4%; (d) 0.6%; (e) 0.8%; (f) 1.0%

tightly wrap around the alumina fibers when the fiber content is 0.6% and 0.8%, as shown in Figs. 5(d) and (e). Because the fiber agglomerations are not evenly dispersed, the fibers act more as stress concentrators or crack initiators than as reinforcing agent, resulting in a looser shell mold matrix structure. Therefore, although the bending strength of the ceramic shell molds slightly increases with the addition of fibers increases from 0.4% to 0.6% and 0.8%, it still lower than that without fibers. As the fiber content further increases to 1.0%, the bending strength decreases again to 3.97 MPa. This is due to uneven fiber dispersion and agglomeration, the matrix integrity is severely compromised, resulting in a decrease in the ceramic shell mold's green strength, as shown in Fig. 5(f).

3.2 Effect of alumina fiber content on room-temperature bending strength of ceramic shell molds

The sintering process of a ceramic shell mold involves the removal of free water and wax material, followed by a series of complex physical and chemical reactions, ultimately resulting in a dense structure with sufficient mechanical strength. In Fig. 6, the impact of alumina fiber content on the room-temperature bending strength of ceramic shell molds is depicted. The strength of ceramic shell molds without the addition of alumina fibers is

14.65 MPa. Under loading, many cracks initiate within the dense matrix when no fibers are added, as shown in Fig. 7(a). However, with alumina fiber addition, specially as the alumina fiber content increases from 0.2% to 0.6%, the bending strength obviously increases, as shown in Figs. 7(b) to (d). This is attributed to the sintering process, during which the alumina fibers are wrapped by the matrix more tightly. The evenly distributed alumina fibers effectively resist crack growth, absorbing energy during deformation, and thereby

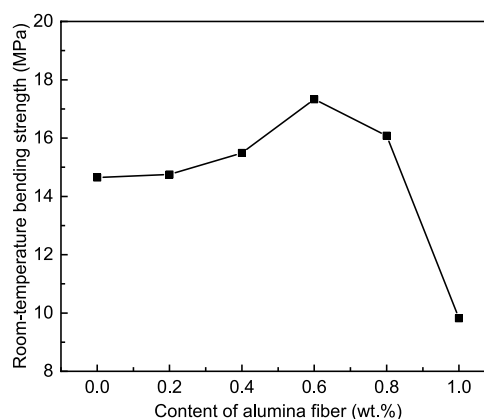


Fig. 6: Effect of alumina fiber content on room-temperature bending strength of ceramic shell molds

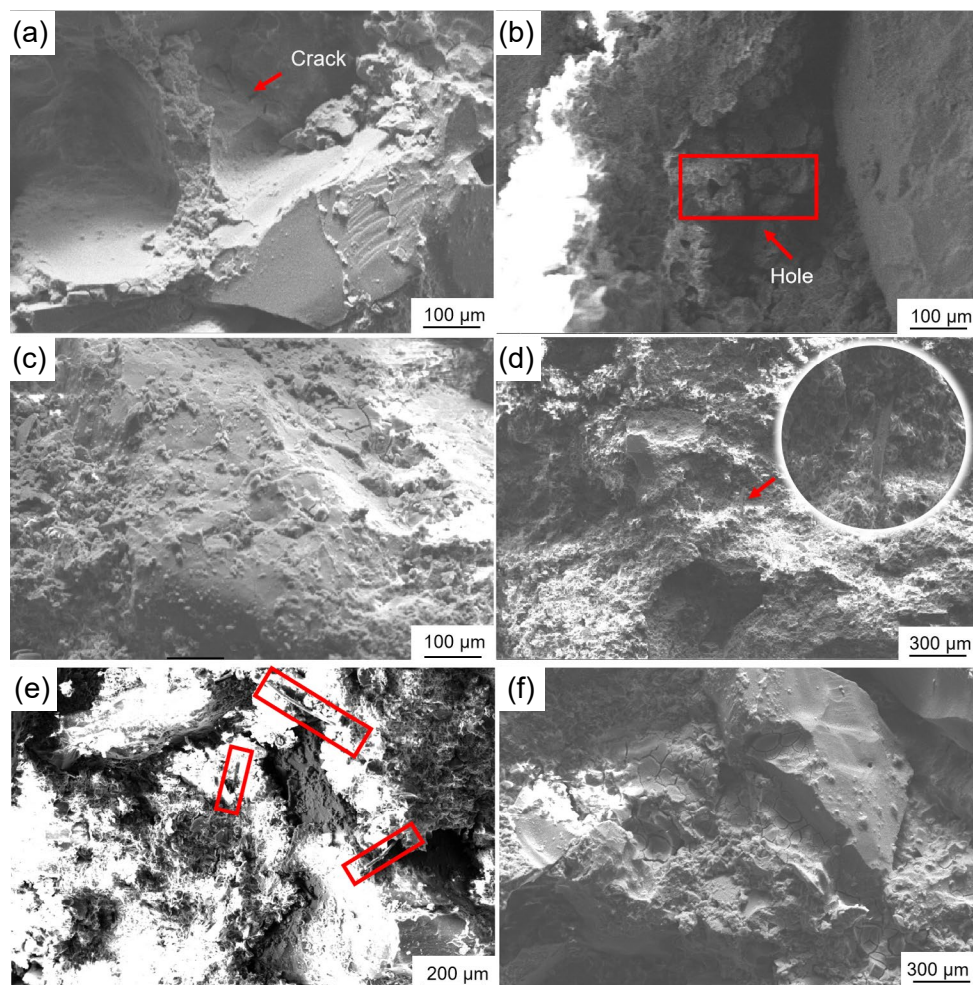


Fig. 7: SEM micrographs of fracture surfaces of ceramic shell molds with different fiber contents by weight: (a) 0%; (b) 0.2%; (c) 0.4%; (d) 0.6%; (e) 0.8%; (f) 1.0%

enhancing the bending strength. At 0.6% alumina fiber content, the bending strength peaks at 17.33 MPa, an 18% increase compared to the specimen without alumina fibers. Further increases in fiber content result in a reduced strengthening effect, as the fiber tends to agglomerate within the matrix [Figs. 7(e) and (f)]. At 1.0% alumina fiber content, the bending strength significantly decreases to 9.82 MPa, its lowest value among the six fiber-reinforced specimens.

3.3 Effect of alumina fiber content on high-temperature bending strength of ceramic shell molds

At high temperatures, the ceramic shell mold experiences internal stress caused by phase transitions and external forces from molten metal during casting. To prevent deformation or damage, ceramic shell molds must have a sufficient high-temperature strength. Figure 8 illustrates the impact of alumina fiber content on the high-temperature strength at 1,100 °C; 1,200 °C; and 1,300 °C. Across all three temperatures, the high-temperature strength of ceramic shell molds exhibits a consistent dependence on alumina fiber content. Specifically, as the alumina fiber content increases from 0.2% to 0.6%, the high-temperature strength gradually increases, peaking at 0.6% alumina fiber content. At 1,100 °C, the bending strength of the molds with 0.6% alumina fibers is 18.97 MPa, representing

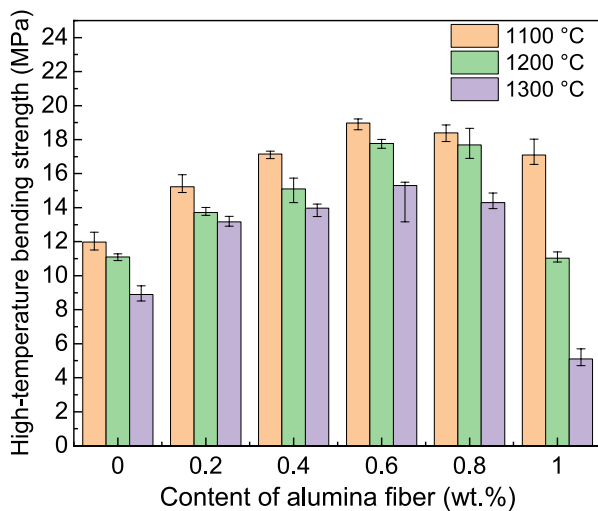


Fig. 8: Effects of alumina fiber content on high-temperature bending strength of ceramic shell molds

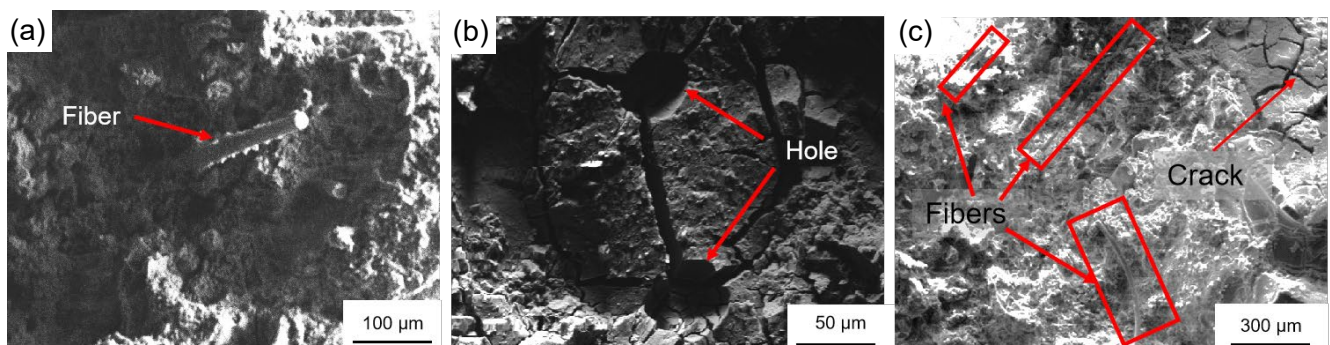


Fig. 9: SEM micrographs of fracture surfaces of ceramic shell molds with 0.6% fibers at different temperatures: (a) 1,100 °C; (b) 1,200 °C; (c) 1,300 °C

a 58% increase compared to the shell mold without alumina fibers. Similarly, at 1,200 °C, the bending strength reaches 17.78 MPa, a 60% improvement over the shell molds without alumina fibers, and at 1,300 °C, it measures 15.3 MPa, representing a 72% enhancement. This indicates that the reinforcing impact of 0.6% alumina fibers becomes more pronounced with increasing the test temperatures. Figures 9(a) to (c) demonstrate that at 0.6% fiber content, the fibers are evenly distributed in the shell mold matrix. As the ceramic shell mold matrix undergoes further sintering and shrinkage, the fibers remain thermally stable and become more tightly wrapped. This tighter wrapping impedes crack growth, leading to greater energy absorption and improved strength. However, once the fiber content reaches 0.8%, the dispersion effect weakens, and the high-temperature bending strength begins to decline. When the fiber content is up to 1.0%, as illustrated in Figs. 10(a) to (c), the fiber aggregation in the matrix leads to the growth of numerous cracks in regions lacking fibers. Stress concentration initiates in areas with fiber aggregation, negatively affecting the integrity of the matrix. The aluminum fiber structure is denser compared to the ceramic shell, and they exhibit different thermal expansion behavior. When the temperature rises, the mismatch of thermal expansion between fibers and matrix can lead to an increase in internal stress^[26, 27]. This stress generates microcracks at the interface, weakening the overall bending strength of the material. Excessive fiber exacerbates this mismatch, thereby increasing internal stress. Moreover, fiber aggregation results in localized weak zones. These areas are more prone to cracking and fracture at high temperatures.

3.4 Effect of alumina fiber content on self-weight deformation of ceramic shell molds

Figure 11 illustrates the impact of alumina fiber content on the high temperature self-weight deformation rate of ceramic shell molds. At 0.2% fiber content, the fiber reinforcement effect is minimal, with the deformation rate similar to that of ceramic shell molds without fibers, approximately 0.090%. As the alumina fiber content increases from 0.2% to 0.6%, the self-weight deformation rate gradually decreases to a minimum of 0.022%, decreases by 76%. Given the high thermal stability of alumina fibers and their physical compatibility with the refractory matrix, uniformly distributed alumina fibers effectively resist shell mold deformation at high temperatures.

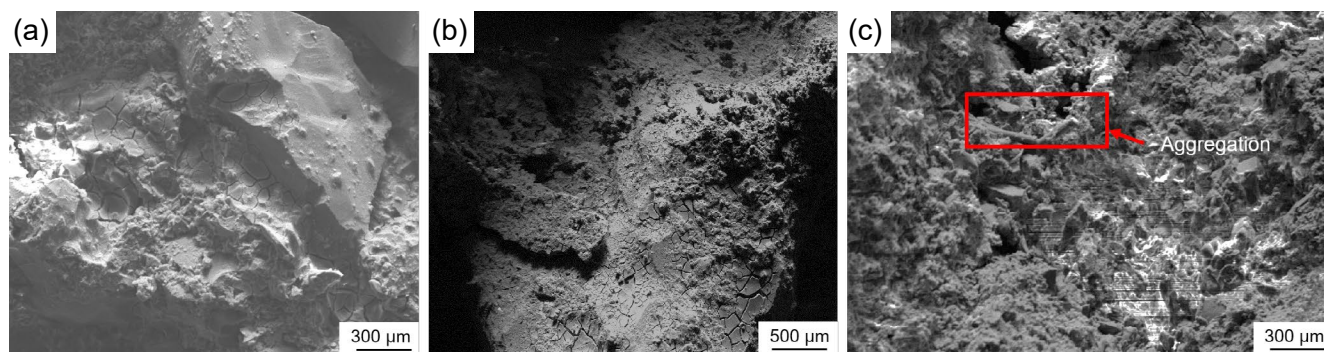


Fig. 10: SEM micrographs of fracture surfaces of ceramic shell molds with 1.0% fibers at different temperatures: (a) 1,100 °C; (b) 1,200 °C; (c) 1,300 °C

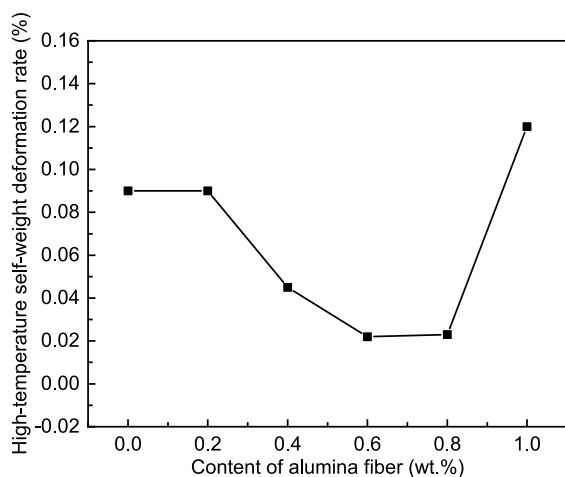


Fig. 11: Influence of fiber content on high-temperature self-weight deformation rate of ceramic shell molds

However, this dispersion effect weakens at 0.8% fiber content, leading to a potential increase in high temperature shell mold deformation. At 1.0% alumina fiber content, the self-weight deformation rate peaks at 0.12%. Uneven distribution of alumina fibers results in a higher self-weight deformation rate compared to shell molds without alumina fibers.

4 Conclusions

Alumina fibers were utilized as the reinforcing material in ceramic shell molds, and were added with varying contents in the back-up slurry. The study examined the green bending strength, room-temperature bending strength, high-temperature bending strength, and high-temperature self-weight deformation of the shell molds under consistent technological conditions. Based on the results of this experimental investigation, the following conclusions are drawn:

(1) When adding 0.2% alumina fibers, the green bending strength of ceramic shell molds reaches its peak value of 6.25 MPa, which is about 36% higher than that of the shell mold without fiber addition. This enhancement is attributed to the pinning and bridging effects of alumina fibers between layers, which improve interlayer cohesion, leading to the green bending strength of the ceramic shell mold.

(2) At an alumina fiber content of 0.6%, the ceramic shell

molds exhibit the greatest enhancement in both room- and high-temperature bending strengths, primarily due to fiber bridging and energy dissipation during the shell bending process. At this fiber content, the room-temperature bending strength of the ceramic shell mold is 17.33 MPa; the bending strengths under high temperature conditions are 18.97 MPa (1,100 °C), 17.78 MPa (1,200 °C), and 15.3 MPa (1,300 °C), respectively.

(3) The uniformly distributed alumina fibers exhibit excellent thermal stability and good physical compatibility with the refractory matrix, and they can effectively inhibit the deformation of the shell molds at high temperatures. When the fiber content is 0.6%, the self-weight deformation rate of the ceramic shell molds decreases to 0.022%, which is approximately 76% lower than that of the fiber-free ones.

Conflict of interest

The authors declare that they have no conflicts of interest.

References

- [1] Pattnaik S, Karunakar D B, Jha P K. Developments in investment casting process – A review. *Journal of Materials Processing Technology*, 2012, 212(11): 2332–2348.
- [2] Fábio J B B, Amico S C, Vedana I, et al. Microwave dewaxing applied to the investment casting process. *Journal of Materials Processing Technology*, 2009, 209(7): 3166–3171.
- [3] Mishra S, Ranjana R. Reverse solidification path methodology for dewaxing ceramic shells in investment casting process. *Materials and Manufacturing Processes*, 2010, 25(12): 1385–1388.
- [4] Todoroki H, Oikawa M, Wang K, et al. Prospects for the control of solidification structures from the viewpoints of weld, hot-workability and near net shape casting. *ISIJ International*, 2008, 48(3): 256–263.
- [5] Wang D, Li J X, Dong A P. Research progress of materials for investment casting molding shells. *Precision Forming Engineering*, 2023, 15(4): 205–216.
- [6] Jones S, Yuan C. Advances in shell moulding for investment casting. *Journal of Materials Processing Technology*, 2003, 135: 258–265.
- [7] Janos E K, Stefan S, Sharon R U, et al. An overview of ceramic molds for investment casting of nickel superalloys. *Journal of the European Ceramic Society*, 2020, 40: 4955–4973.
- [8] Venkat Y, Choudary K R, Das D K, et al. Ceramic shell moulds for investment casting of low-pressure turbine rotor blisk. *Ceramic International*, 2021, 47(4): 5663–5670.

- [9] Jones S, Bentley S A, Marquis P M. Effect of refractory phase separation on investment mould integrity. *British Ceramic Transactions*, 2002, 101(3): 100–105.
- [10] Yu V L, Yu I F, Rykova T P, et al. Thermophysical properties of ceramic materials of molds and cores for casting the heat resistant alloy based blades of gas turbine engines. *Inorganic Materials*, 2014, 5(4): 407–412.
- [11] Kevin L, Stuart B, Stewart T W. A more representative mechanical testing of green state investment casting shell. *Ceramics International*, 2017, 43: 268–274.
- [12] Lu G, Chen Y S, Yan Q S, et al. Carbon-nylon hybrid fibers modified silica sol shell with enhanced flexural strength and heat transfer for investment casting. *Journal of the European Ceramic Society*, 2022, 42(8): 3624–3633.
- [13] Jones S, Yuan C, Lewis K. Organic fibre modified ceramic shell moulding for investment casting. *Materials Science and Technology*, 2013, 18(12): 1565–1573.
- [14] Lü K, Liu X D, Zhao X, et al. Bending strength and fracture surface topography of natural fiber-reinforced shell for investment casting process. *China Foundry*, 2016, 13(3): 211–216.
- [15] Pattnaik S. An investigation on enhancing ceramic shell properties using naturally available additives. *The International Journal of Advanced Manufacturing Technology*, 2017, 91(9–12): 3061–3078.
- [16] Yuan C, Jones S. Investigation of fibre modified ceramic moulds for investment casting. *Journal of the European Society*, 2003, 23: 399–407.
- [17] Li Z H, Man W F, Zhao Y H, et al. Enhanced comprehensive properties of alumina ceramic shells by a pennisetum fiber/ $\text{AlF}_3 \cdot 3\text{H}_2\text{O}$ powder hybrid system. *Ceramic International*, 2024, 50: 43230–43239.
- [18] Zhao H, Yu J B, Lin C X, et al. Effect of Al_2O_3 fibers mixing methods and in-situ formed SiC nanowires on the properties of silica-sol ceramic shells for investment casting. *Ceramics International*, 2023, 49(22): 36391–36404.
- [19] Jiang Y H, Wang Z, Lu D H. Effect of aluminum silicate fiber modification on crack-resistance of a ceramic mould. *China Foundry*, 2012, 9(4): 322–327.
- [20] Zhao Z Y, Lü K, Xiang D L, et al. The influence of calcination temperature and insulation time on the strength of aluminum silicate fiber composite silica sol shell. *Foundry Technology*, 2016, 37(6): 1176–1178. (In Chinese)
- [21] Chen Y S, Lu G, Liao Y, et al. The influence of the mass ratio of nylon alumina mixed fibers in the sanding layer on the properties of silica sol shell. *Journal of Composite Materials*, 2023, 40(6): 3449–3458.
- [22] Ren J, Chen X, Liu Y, et al. Properties of fiber reinforced plaster molds for investment casting. *China Foundry*, 2020, 17(5): 332–340.
- [23] Chen Y S, Lu G, Liao Y, et al. Effects of stuccoing layer nylon-alumina hybrid fibers mass ratios on the properties for silica sol ceramic shell. *Acta Materialiae Compositae Sinica*, 2023, 40(6): 3449–3458.
- [24] Lu Z L, Fan Y X, Miao K, et al. Effects of adding aluminum oxide or zirconium oxide fibers on ceramic molds for casting hollow turbine blades. *International Journal of Advanced Manufacturing Technology*, 2014, 72: 873–880.
- [25] Lü K, Liu X D, Lu Y, et al. The interfacial characteristics and action mechanism of fibre-reinforced shell for investment casting. *International Journal of Advanced Manufacturing Technology*, 2017, 93: 2895–2902.
- [26] Dong R L, Peng Z H, Xiang Y, et al. Research progress in composition and preparation process of alumina fiber reinforced alumina ceramic matrix composites. *Journal of Materials Engineering*, 2023, 10: 27–41.
- [27] Qin G, Zou S, Jiang L, et al. Research progress of silicon carbide fiber reinforced silicon carbide ceramic matrix composites. *Journal of Ceramics*, 2023, 6: 389–407.