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Investigating the effect of andalusite on mechanical strength and thermal shock resistance of cordierite-spodumene composite ceramics

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ABSTRACT

For increasing working stability of cordierite-spodumene composite ceramics for solar heat transmission pipeline, andalusite was utilized as modified additive to improve mechanical strength and thermal shock resistance of the composite ceramics. The effects of andalusite on densification, mechanical strength, thermal stability, phase composition and microstructure were studied. The experiment results showed that andalusite significantly influenced bending strength and thermal shock resistance of the composite ceramics. Especially, specimen B1 with 5 wt% andalusite sintered at 1400 °C achieved the best performances. The linear shrinkage, water absorption, apparent porosity, bulk density and bending strength were 5.62%, 0.02%, 0.06%, 2.19 g cm^{-3} and 104.94 MPa, respectively. After 30 thermal shock cycles (wind cooling from 1100 °C to room temperature), the residual strength of the specimen increased to 110.65 MPa, accompanying with −5.44% strength loss rate. The XRD and SEM analysis illustrated that mullite grains with short rod-like shape could prevent crack growth of inter-granular fracture to enhance bending strength of the specimens. Furthermore, the generation of β-spodumene grains with low thermal expansion coefficient after thermal shock improved thermal shock resistance of the composite ceramics. It is considered that the cordierite-spodumene composite ceramics with high densification, good mechanical strength and excellent thermal stability can be a potential material for high temperature thermal transmission pipeline in solar thermal power generation.

1. Introduction

Global warming has become a serious problem that needs to be solved urgently in the world. It is reported that the excessive use of conventional energy sources such as petroleum, coal and natural gas caused a huge quantity of CO_2 in the atmosphere [1,2]. The utilization of solar energy is considered as the most effective measures to reduce CO_2 emissions and resolve energy crisis for its cleanest, harmless and inexhaustible [3]. Solar power generation systems are divided into concentrated solar photovoltaic and solar thermal power generation. The solar thermal power generation system with high generating efficiency, low cost and easy conversion has been widely concerned by many researchers at present, which is regarded as the most economically viable technology to impel energy revolution [4,5].

In generally, solar thermal power generation system is constituted by central receiver, heat transport subsystem and thermal storage. The heat transport subsystem plays an important role in the solar thermal power generation. It transmitted heat energy from central receiver into thermal storage to directly affect working stability of the system [6]. In order to increase generating efficiency, plenty of solar thermal power plants have increased the operation temperature up to 800 °C, especially the maximum operation temperature is as high as 1000 °C in DIAPR and 1050 °C in PLVCR-5 [7]. It is indicated that the solar thermal transmission pipeline materials need to have high densification, good mechanical performances and excellent thermal stability to tolerate the high temperature. However, thermal transmission pipelines in traditional power plants usually are fabricated by heat resistant steels such as pearlite, martensite, ferrite and austenitic [8–10]. The alloy steel materials have easy oxidized, poor thermal stability, high creep rate and short service life over 650 °C, which are unsuitable for high temperature transmission pipeline in solar thermal power generation [11]. Therefore, ceramic materials with outstanding mechanical strength, oxidation resistance and heat resistance have been considered as the promising candidate materials for solar thermal transmission pipeline [12].

Cordierite ceramics is widely used in high temperature fields such as catalyst supports, heating elements, burner nozzles, refractory materials and heat exchange for gas turbines for its good corrosion resistance,

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high mechanical strength and excellent thermal shock resistance [13–15]. Unfortunately, dense cordierite ceramics is difficult to fabricate under atmospheric pressure condition by the narrow sintering temperature range and incongruent melting, which seriously hampers the development of the cordierite ceramics [16,17]. Spodumene with low melting point and thermal expansion coefficient has been employed to improve physical performances of ceramic materials [18,19]. In our previous study, the cordierite-spodumene composite ceramics with high densification of 0.29% water absorption, 0.71% apparent porosity and 2.16 g cm^{-3} bulk density was in-situ synthesized [20]. For using as the solar heat transmission pipeline, mechanical strength and thermal shock resistance of the composite ceramics should be further enhanced. Many researches have reported that andalusite is an effective additive to improve thermal stability of the ceramics [21,22]. For instance, Xu et al. [23] prepared the corundum-mullite composite ceramics with 0.15% water absorption, 117.32 MPa bending strength and 2.46% strength loss rate after 30 thermal shock cycles (wind cooling from 1100 °C to 25 °C) by adding 37.31 wt% andalusite. In the research of Wu et al. [24], bending strength of the cordierite composite ceramics increased to 26.20% after 30 thermal shock cycles by the introduction of andalusite. However, few literatures have reported the method to prepare cordierite-spodumene composite ceramics with high thermo-physical performances by the introduction of andalusite.

In order to ensure high generating efficiency of the solar thermal power generation, andalusite additive was introduced to improve physical performances and thermal stability of the cordierite-spodumene composite ceramics for solar heat transmission pipeline in this study. The effects of andalusite on densification, mechanical strength, phase composition, microstructure and thermal shock resistance of the composite ceramics were researched. The improvement mechanism of andalusite on mechanical strength and thermal shock resistance of the cordierite-spodumene composite ceramics was analyzed.

2. Experimental procedure

The starting materials for experiments were γ-Al_2O_3 (under 300 mesh, Shandong Alumina Industry Co., Shandong., China), kaolin (under 300 mesh, China Kaolin Co., Jiangsu, China), talc (under 300 mesh, Guilin Talc Development Co., Guangxi, China) and spodumene (under 300 mesh, Sichuan Tianqi Industrial Co., Sichuan, China). Andalusite (under 300 mesh, Xinjiang Bao'an New Energy-Mineral Co., Ltd., Xinjiang, China) was employed as modified additive. The chemical compositions of the starting materials were listed in Table 1. The designed formulas of the specimens were given in Table 2. The mixtures of starting materials were dry-milled for 60 min by high energy ball milling with alumina grinding balls. After granulating with 5 wt% deionized water and aging for 48 h, the mixtures were uniaxially pressed into cylindrical pellets (Φ30 mm × 5 mm) and rectangular bars (37 mm × 6.50 mm × 6.50 mm) under a pressure of 50 MPa in stainless steel dies. Finally, the specimens were dried at 95 °C for 24 h and pressureless sintered from 1300 °C to 1400 °C for 2 h with a heating rate of 3 °C/min in the silicon-molybdenum furnace.

The chemical compositions of the starting materials were performed by X-ray fluorescence spectrometer (XRF, PANalytical B. V., Almelo, Holland). The linear shrinkages (S_f, %) of the cylindrical specimens after sintering were calculated from the change in diameter by vernier caliper with a resolution of 0.02 mm. The water absorption (Wa, %), apparent porosity (Pa, %) and bulk density (Db, g cm^{-3}) of the rectangular specimens were determined by the Archimedes method. The bending strength (σ, MPa) of the rectangular specimens was measured by a computer controlled electronic universal testing machine (Model RGM-4100, Shenzhen Reger Instrument Co., Shenzhen, China) through the three points bending method. The thermal shock resistance of the specimens under a thermal cycle was described as follow: the specimens were placed in a muffle furnace and heated up to the predetermined temperature of 1100 °C for 30 min, and then were taken out with winding cooling to room temperature. The strength loss rates of the specimens after thermal shock cycles represented the thermal shock resistance. The reported values were available from the average results of five specimens. The phase compositions of the specimens were identified by X-ray diffraction (XRD, D/MAX-III, Japan) technique with Cu Kα (λ = 1.54060 Å) radiation. The morphologies of fractured surfaces of the specimens were observed by scanning electron microscope (SEM, Model JSM-5610LV, Japan) operated at 25 kV. The grains size distribution of crystalline grains was calculated by the Nano-Measure software. The energy dispersive spectroscopy (EDS) was taken at 15 kV and a vacuum of 9.6×10^{-5} Pa. To remove glassy phases at grain boundaries, fractured surfaces of the specimens were etched by 5 wt% hydrofluoric acid solution for 80 s.

Table 2
Designed formulas of the specimens (wt%).

Specimen No.	γ-Al_2O_3	Kaolin	Talc	Spodumene	Andalusite	Total
B0	10.58	43.98	35.44	10	0	100.00
B1	10.05	41.78	33.67	9.5	5	100.00
B2	9.52	39.58	31.90	9	10	100.00
B3	8.99	37.38	30.13	8.5	15	100.00

3. Results and discussion

3.1. Physical performances of the composite ceramics

High temperature thermal transmission pipeline in the solar thermal power generation system need to have high densification to avoid heat loss as far as possible. The performances of linear shrinkage, water absorption, apparent porosity and bulk density are the essential parameters to evaluate densification of ceramic materials, and water absorption below 0.5% is an international standard for high density ceramics [25]. The relationships between linear shrinkage, water absorption, apparent porosity, bulk density and sintering temperature of specimens B0-B3 are revealed in Fig. 1. It was clearly seen that linear shrinkages of specimens B1-B3 were higher than specimen B0 sintered at the range of 1300–1340 °C (for instance, S_f of specimens B0-B3 sintered at 1320 °C were 3.54%, 3.84%, 3.78% and 3.65%, respectively). Because plenty of K^+ and Na^+ ions with strong polarization ability existing in andalusite could reduce the viscosity of high temperature liquid phases. It accelerated grains growth and pores filling to promote sintering of the cordierite-spodumene composite ceramics. Andalusite transformed into mullite and cristobalite over 1340 °C, which was

Table 1
Chemical compositions of the starting materials (wt%).

Starting materials	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	Li_2O	I.L.	Total
γ-Al_2O_3	0.35	97.70	0.02	0.00	0.04	–	0.03	0.33	–	1.49	100.00
Kaolin	48.20	37.99	0.1	0.63	0.07	–	–	–	–	13.01	100.00
Talc	56.99	2.13	0.99	0.09	1.32	30.95	0.01	0.02	–	7.50	100.00
Spodumene	68.47	23.56	0.51	–	0.21	0.20	0.30	0.50	6.25	–	100.00
Andalusite	43.26	50.88	1.11	0.16	1.28	0.14	0.74	0.53	–	1.50	100.00