High sound absorption characteristics of foamed alumina ceramics fabricated by gelcasting-foaming process

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The foamed alumina ceramics with excellent sound absorption performance especially at low frequency were fabricated by gelcasting-foaming process which gelled at room temperature. This process was simpler and more environmental-friendly than conventional gelcasting process because only a very small amount of organics were used and then green bodies could be sintered directly without binder removal process. The effects of foaming agent on porosity, pore size, compressive strength and sound absorption characteristics of the porous ceramics with different air-gap depths were discussed. The results showed that with the increasing of foaming agent content from 0.10 to 0.25 wt %, the porous ceramics had higher porosity, larger pore size, smaller compressive strength and better sound absorption characteristics. But the foaming agent’s effect got less significant than before when it’s amount was more than 0.25 wt %. The sound absorption peak of foamed ceramics shifted towards higher frequency as increasing foaming agent content, but it shifted towards lower frequency as increasing the air-gap depth. And within the data range of this study, increasing porosity could improve the sound absorption characteristic of the ceramics with an air gap. The ceramic with foaming agent content of 0.25 wt % and air-gap depth of 80 mm had the best sound absorption whose maximum sound absorption coefficient and noise reduction coefficient is 0.99 at 400 Hz and 0.79 respectively, and its mean sound absorption coefficient at 50~1000 Hz is ~0.6.

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1. Introduction

Noise pollution¹⁻³ has been a serious environmental problem and many kinds of materials⁴⁻⁸ have been used for restraining noise pollution. Porous materials have become a research hotspot because its complex pore channels have effective energy consumption of sound waves. Park⁹ et al. studied the effect of cell openness foam on the sound absorption behaviors of polyurethane (PU). They found the PU foam with 15% cell openness had better sound absorption performance with the maximum sound absorption coefficient of ~0.9 at 1100 Hz than the foam with double mass density. Han¹⁰ et al. prepared open-celled Al foam by high-pressure infiltration process, and the half-width and maximum value of absorption peak of the optimal foam were 3500 Hz and 0.99 respectively. They found that when there was no air gap between the foams and the rigid wall, the foams with the smallest pore size (~0.5 mm) had the best sound absorption property for viscous and thermal losses, but when there was an air gap, the foams with medium pore sizes (~1.5 mm) had the best sound absorption property because of Helmholtz resonant absorption. Wang¹¹ et al. fabricated a high porous Si₃N₄ ceramics with porosity varied from 70% to 90% and compressive strength varied from 59.9 to 6.7 MPa by a volume-controlled mechanical foaming method. In this report they concluded that both porosity and pore size of porous Si₃N₄ ceramics were closely related to sound absorption coefficient.

Many sound absorption materials have shortcoming in practical application. For instance, organic materials have flammability, poor corrosion resistance, and low intensity; metal materials have poor corrosion resistance, large weight, and high cost. Both organic and metal materials can’t be used in some harsh environments like steel mills and chemical plants. But porous ceramic is an excellent material for sound absorption and practical application since it has good intensity, corrosion resistance, small weight and harmless.

Researchers have studied many methods to prepare porous ceramics but only a few researchers investigated the sound absorption property of porous ceramics. Duan¹² et al. fabricated porous zeolite by high-temperature sintering. They found that the sound absorption coefficient could reach 0.99 when the thickness of sample was 15 mm and the low-frequency absorption range and coefficient of
resonant absorption could be improved by raising the thickness and porosity. Carlesso et al. analysed the sound absorption of near-net-shaped porous alumina/mullite-based ceramics fabricated by freeze gelation combined with sacrificial templating. They concluded that the apertures which connected large pores had a significant improvement on sound absorption properties, making it possible to control the sound absorption properties by changing the template particle content and the solid content in the slurry.

The traditional methods have relatively complex process to make porous ceramics and the process of removing lots of organic additions will produce a large amount of harmful gases and their sound absorption at low frequency of is not good. It limited the application of these sound absorption materials in the areas with low frequency noise like transformer substations, whose noise frequency is mostly blow 1000 Hz. Gelcasting-foaming method is a novel near-net-shape colloidal forming method with mechanical foaming process to prepare foamed ceramic with good composition homogeneity and high performance. Zhang et al. fabricated porous ceramics by gelcasting-foaming method with lots of organic additives and stirred the slurry under N₂ atmosphere. They compared the porous ceramic fabricated by their method and the conventional method and found the ceramics fabricated by their method had better the sound absorption characteristic with the maximum sound absorption coefficient of the porous ceramics was ~0.7. Takahashi et al. prepared porous ceramics with waste resources by gelcasting method with Japanese gelatin as binder. The maximum sound absorption coefficient of the porous ceramics was ~0.75 at 1600 Hz. Potoczêk et al. prepared alumina foams with high porosity by making agarose solutions under overpressure conditions for gelcasting process. The sound absorption coefficient of the porous ceramics with thickness of 18 mm was over 0.7 in the range of 1500–6500 Hz and the maximum sound absorption coefficient is 0.99 at 3000 Hz. But conventional gelcasting process also has lots of organic additives like organic monomer, initiator, gelling agent and catalysts and the additives in green bodies need to be removed before sintering process.

This study aims to prepare foamed alumina (Al₂O₃) ceramics at room temperature by a simpler and more environmental-friendly gelcasting-foaming process. Simpler process makes it easier to control the porosity and pore size with the adjustment of the process parameters. In this process only a single additive was used as both dispersant and gelling agent without other additives. The green bodies were sintered directly without binder removal process since only a very small amount of organics were used and no harmful gas was produced. The sound absorption characteristic of the ceramics is almost close to that reported by Potoczêk, which have the best sound absorption characteristic of the ceramics among the reports the authors have found but more complicated process. But the mean sound absorption coefficient of the porous ceramics in Potoczêk’s report at 500–1000 Hz is ~0.35. And the ceramics in our study have excellent sound absorption performance for low frequency. The mean sound absorption coefficient at 50–1000 Hz of the ceramic with foaming agent content of 0.25 wt % and air-gap depth of 80 mm is ~0.6. Its sound absorption characteristic at low frequency is better than the conventional sound absorption materials, like glass wools. Delany reported the mean sound absorption coefficient at 250–1000 Hz of the fibrous layer material with flow-resistance of 20 CGS units increases from 0.2 to 0.8 with thickness varied from 25 to 100 mm, but the thickness of the sample in our study is just only 20 mm. The effects of foaming agent on porosity, pore size, compressive strength and sound absorption characteristics of the porous ceramics with different air-gap depths were discussed.

2. Experimental procedure

2.1 Ceramic preparation

Al₂O₃ powders were mixed with deionized water (adjusting the pH value to 10 with ammonia) and 0.3 wt % (relative to the weight of alumina powder) Isobam 104# (a copolymer of isobutylene and maleic anhydride, Kuraray Co., Ltd. Osaka, Japan) was used as both dispersant and gelling agent to prepare mixed slurry with 50 vol % solid loading by ball-milling at 250 r/min for 1.5 h. Figure 1 shows that the raw Al₂O₃ powders have uniform shape and concentrated size distribution with an average diameter of 0.584 μm. Subsequently, triethanolamine lauryl

![Fig. 1. (a) SEM morphology and (b) diameter distribution of raw Al₂O₃.](image-url)
sulfate (C_{18}H_{41}NO_{7}S, Usolf Chemical Co., Ltd. Qingdao, Shandong, China), noted as TLS hereafter, with 40 vol% of the aqueous solution was added into the slurry as foaming agent. The contents of TLS was 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 wt% respectively (relative to the weight of slurry), and the mixed slurry was agitated foams at the speed of 750 r/min for 1.5 min to obtain foams by using a kitchen mixer equipped with two agitator blades, then the agitated slurry was poured into a mold. The whole process was finished at room temperature in air. After gelling consolidation and drying at 25 °C for 24 h, the obtained green bodis were sintered at 1500 °C for 2 h with a heating rate of 1.5 °C/min. Figure 2 shows the gelcasting-foaming process of the foamed ceramics and Fig. 3 shows the foamed ceramics after sintering. Similar procedure of preparation and adjustment of performance parameters of the slurry has been reported by Yang19) and Lu.20)

2.2 Characterization

The microstructure of the foamed ceramics was observed by scanning electron microscope (SEM, JSM-7600 F, JEOL Ltd., Japan). The porosity was measured by Archmede’s method. The pore size distribution was analyzed by using software named Image-ProPlus 5.0 (Planetron Inc.). The compressive strength was measured by mechanical testing machine (AG-100KN, Zwick/Roell, Germany). The sound absorption coefficients with different air-gap depths of 0, 20, 40, 60, 80 mm were measured by a sound absorption coefficient measurement system (AWA6290T, Aihua Instrument Co., Ltd. Hangzhou, Chia) equipped with an impedance tube, two microphones, a noise generator and a multichannel digital signal analyzer, as showed in Fig. 4. The complex transfer function was calculated according to the two-microphone transfer-function method. The sound absorption coefficient of the ceramics with 100 mm in diameter, 20 mm in height and 29 mm in diameter, 20 mm in height was measured over a frequency range of 0.2–1.6 and 1.0–6.4 kHz respectively. The two measurement results above were fitted into one curve over a frequency range of 0.2–6.4 kHz.

3. Result and discussion

3.1 Microstructure of foamed ceramics

Figure 5 shows the SEM images of foamed ceramics with different TLS contents. It can be observed that the foamed ceramics consist of lots of open-celled pores, which are interconnected by apertures on the pore walls. Apertures are the connection position of two adjacent
foams. At lower TLS contents, the pores have relatively small pore size and complete spherical structure. When increasing TLS content, the pore size increases and the deformation of foam pores gets more significant.

The reason is that there is a critical micelle concentration (CMC) of the foaming agent TLS. When the concentration of TLS in the slurry is lower than its CMC, increasing TLS content would reduce surface tension of the slurry and make bubbles more stable. It causes that the combination and expansion of small bubbles get easier, leading to the generation of large bubbles. But when the concentration of TLS in the slurry is higher than its CMC, redundant numerators of foaming agent after saturation of the numerators’ surface adsorption could generate colloidal polymer in the slurry and make bubbles more stable. It causes that the combination and expansion of small bubbles get easier, leading to the generation of large bubbles. The apertures would play an important role of the connection of two pores due to the water molecule removal and ceramic particle accumulation.

3.2 Pore characteristics and mechanical properties

The pore size distribution of the ceramics with different TLS contents is illustrated in Fig. 6(a), $d\bar{v}/V$ is the volume fraction of the pores with certain pore size (0–200, 200–400, 400–600, 600–800, 800–1000, 1000–1200 μm) to all the pores. It can be observed that the volume ratio of large pores relative to small pores raises as increasing TLS content with a median particle size ($d_{50}$) of 728, 703, 727, 789, 794, 797 μm corresponding to TLS contents of 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 wt% respectively, which almost conforms to the regulation of the SEM image. When TLS concentration is lower than CMC, large pores are prone to survive because of the raise of stability as increasing TLS content, which shows that the volume ratio of large pores raises as increasing TLS content; when TLS content is higher than CMC, ultra-large pores can’t exist stably because the surface tension stop reducing, which shows the volume ratio of large pores raises slowly at high TLS contents.

Figure 6(b) shows the porosity and compressive strength of the foamed ceramics with different TLS contents. With the increasing of TLS content from 0.10 to 0.35 wt%, the porosity of the foamed ceramics increases from 75.80 to 82.83%. It’s attributed to the generation of bubbles and the increasing of bubble size as increasing TLS content. On the contrary, the compressive strength decreases from 14.01 to 6.05 MPa as increasing TLS content. The reason is that the foamed ceramics have three-
dimension network frame structure and the network frame gets thinner when the porosity is higher and the compressive stress on a single pore get increased as the diameter increasing, resulting in that the foam pores are easier to be broken as increasing TLS content.

3.3 Sound absorption characteristics

The sound absorption characteristics of foamed ceramics is connected with many factors including porosity, pore size distribution, air-gap depth, and sample thickness. In this paper we don’t discuss the effect of sample thickness on the sound absorption characteristics of foamed ceramics due to the limit of the mold. The sound absorption characteristic of the foamed ceramic backed with an air gap is mainly owing to Helmholtz resonator mechanism, which promotes sound absorption performance markedly at low frequency. A Helmholtz resonator is composed of a cavity with a small neck, and it has a definite absorption peak at the resonant frequency of the enclosed air mass in the resonator. The resonant frequency can be calculated by

$$F = \frac{c}{2\pi} \sqrt{\frac{S}{V(l + 0.8d)}} \tag{1}$$

where $F$ is the resonant frequency, $c$ is the velocity of sound, $S$ is the cross-sectional area of the neck, $l$ is the neck length, $d$ is the diameter of the neck, and $V$ is the volume of the cavity.

The sound absorption coefficients as a function of frequency and noise reduction coefficient (NRC) of foamed ceramics with different air-gap depths of 0–80 mm and different TLS contents of 0.10–0.35 wt% respectively are shown in Figs. 7 and 8. NRC is the mean or arithmetic average of the absorption coefficients at the frequencies of 250, 500, 1000 and 2000 Hz. When TLS content is higher than 0.15 wt%, all the ceramics backed with an air gap have excellent sound absorption characteristics in which the maximum value of the peak and NRC can be more than 0.95 and 0.5. Especially for the ceramics with air-gap depth of 80 mm at TLS content of 0.25 wt%, the maximum value of the peak and NRC is 0.99 and 0.79 respectively.

As showed in Fig. 7, the sound absorption peak of foamed ceramics with the same air-gap depth shifts towards higher frequency as increasing TLS content, but the absorption peak with the same TLS content shifts towards lower frequency as increasing the air-gap depth. Ceramics backed with an air gap show different sound absorption performance from that without air gap. When the ceramic is backed without air gap, the maximum absorption coefficients raise as increasing TLS content from 0.10 to 0.20 wt% but decrease from 0.20 to 0.35 wt%; when the ceramic is backed with an air gap, the maximum absorption coefficients raises as increasing the air-gap depth from 20 to 80 mm in TLS content range of 0.10 to 0.20 wt% and nearly remain unchanged in that of 0.20 to 0.35 wt%. Exceptionally, when the air-gap depth increase from 0 to 20 mm, the maximum absorption coefficients decrease in the in TLS content range of 0.10 to 0.20 wt% but raise in that of 0.25 to 0.35 wt%.

Through the observation of SEM images we can know that the apertures on the pore wall form a complex interconnected air channels network among the pores which allow sound waves propagate easily into the material. When the ceramic is backed without air gap, the effect of viscous and thermal losses is dominant on sound absorption, which is more significant at relatively high frequency than low frequency. The sound wave is dissipated via friction while entering the complex interconnected air channels and travelling through the pore aperture. Viscous and thermal losses are positively related to flow resistance, which decrease with the increasing of porosity and aperture size of the ceramics. But the ceramic with high flow resistance, as shown in Fig. 7(a), has high sound reflection and low transmission rates of the incident sound wave because of the low porosity and small aperture size, causing that it’s sound absorption performance is relatively poor as shown in Fig. 7(a). So the ceramics with moderate porosity and aperture and without air gap, as shown in Fig. 7(c), has the best sound absorption characteristic as
When the ceramic is backed with an air gap, it can be regarded as a combination of many Helmholtz resonators, in which the air channels are regarded as the necks with different cross-sectional area and the air gap is regarded as the resonator cavity. It means that the combination has a wide range of sound absorption frequencies but the range will decrease as increasing the air-gap depth. As is seen in Eq. (1), increasing the air-gap depth can be regarded as increasing the resonator cavity, causing that the resonant frequency decreases and the absorption peak shifts towards lower frequency; similarly, increasing TLS content will enlarge the pore size, which can be regarded as increasing the cross-sectional area, causing that the resonant frequency increases and the absorption peak shifts towards higher frequency.

At lower TLS contents (<0.20 wt %), the porosity of the ceramics is less than that of high TLS contents. It means the number of air channels is not enough to maintain high sound absorption rates at each frequency, so the combination of Helmholtz resonators has wider half-peak-width but lower maximum absorption coefficient. In addition, if the porosity and pore size are increased continuously, the sound absorption coefficient should decrease because the number of pores will decrease, but it can’t be completed under the experimental conditions of this study.
As increasing the air-gap depth, the resonant frequencies of Helmholtz resonator get concentrated at low frequency, and the combination has narrower half-peak-width but higher maximum absorption coefficient. At higher TLS contents (>0.20 wt%), the number of pore and aperture is enough for the combination to have high sound absorption rates, so the maximum absorption coefficients nearly remain unchanged as increasing air-gap depth. With the increasing of air-gap depth from 0 to 20 mm, the main sound absorption mechanism changes from viscous and thermal losses to Helmholtz resonator losses. The ceramics without air gap at low TLS contents have high sound absorption rates due to viscous and thermal losses but get inadequate with an air gap due to Helmholtz resonator losses as mentioned above, and this drop will disappear as increasing TLS content.

As showed in Fig. 8, the NRC values for foamed ceramics at the same TLS content raise as increasing air-gap depth. The NRC value at the same air-gap depth raises as increasing TLS content from 0.10 to 0.20 wt% but decreases from that of 0.20 to 0.35 wt%.

The calculation parameters of NRC are the absorption coefficients at the frequencies below 2000 Hz. When the ceramic is backed without air gap, only a part of the peak exists in the range of 0–2000 Hz, and most of the calculation parameter values are small, leading to a small NRC value without air gap. When introducing an air gap between the ceramics and rigid wall, the whole peak shifts towards the range of 0–2000 Hz, the calculation parameter values get larger, and the NRC also get larger with the increasing of the air-gap depth. Increasing TLS content will make the absorption peak without air gap shift towards higher frequency, leading to the decrease of NRC. But when introducing an air gap, the enhancement effect of Helmholtz resonator on sound absorption exceeds the reduction effect of increasing TSL content from 0.10–0.25 wt%, leading to the increase of NRC, but at higher TSL contents (>0.25 wt%), the maximum absorption coefficients nearly remain unchanged and the half-peak-width get narrower leading to the decrease of NRC.

4. Conclusions

This study shows the pore size distribution, porosity, compressive strength and sound absorption characteristics of foamed ceramics fabricated by gelcasting-foaming process. With the increasing of TLS content, the pore size increases because moderately increasing the foaming agent can stabilize the bubbles and benefit the expansion of bubbles, but excessive foaming agent’s effect get less significant. The porosity of the foamed ceramics increases from 75.80 to 82.83% and the compressive strength decreases from 14.01 to 6.05 MPa as increasing TLS content from 0.10 to 0.35 wt% because the pore size increase and the network frame get thin. The foaming agent mostly affect the sound absorption through changing the porosity and pore size. Its high sound absorption characteristic especially at low frequency is due to high porosity, large pore size and the addition of air gap. The ceramics with larger pore size have higher resonant frequency so the sound absorption peak of foamed ceramics shifts towards higher frequency as increasing TLS content. When backed without air gap, the ceramics with low porosity have high sound energy loss for the sound wave entering the ceramics but high sound reflection, and the ceramics with low porosity have the opposite performance. It means that the ceramics with moderate porosity has the best sound absorption characteristic. When backed with an air gap, increasing the porosity is equivalent to increasing the number of Helmholtz resonators, so the sound absorption coefficient increases until the maximum as increasing the porosity, and then it remains unchanged as continuing increasing porosity. Furthermore, the sound absorption coefficient should decrease if continuously increasing the porosity and pore size, but it’s hard to complete under the experimental conditions of this study. The ceramics with higher air-gap depth have lower resonant frequency so the sound absorption peak of foamed ceramics shifts towards lower frequency as increasing air-gap depth. And increasing the air-gap depth could increase the sound absorption coefficient until the maximum and then it remains unchanged as continuing increasing air-gap depth.

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