Research Article

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Investigation on the acoustic properties of structural gradient 316L stainless steel hollow spheres composites

<https://doi.org/10.1515/secm-2021-0046>

received May 25, 2021; accepted August 13, 2021

Abstract: In this study, a kind of structural gradient metal hollow spheres composites (SG-MHSCs) were fabricated using two kinds of 316L stainless steel hollow spheres with different diameters and A356 aluminum through the casting method. Then the density of the SG-MHSCs was measured by the direct measurement; the micro-structure of the SG-MHSCs was characterized by the Scanning Electron Microscope. Meanwhile, the acoustic performance of MHSCs was tested by the impedance tube, and the sound absorption and insulation mechanism SG-MHSCs were discussed and analyzed.

Keywords: structural gradient metal hollow spheres composites, acoustic performance, sound absorption and insulation mechanism

1 Introduction

Metal hollow spheres composites (MHSCs) were a kind of closed-cell porous material. Generally, the casting and

powder metallurgy methods can be used to connect the metal hollow spheres (MHSs) and the matrix materials to fabricate the MHSCs [1,2]. Compared with traditional metal foam, the properties of the MHSCs can be designed by choosing the material of MHSs and matrix materials [3]. The aluminum alloys [4–8], magnesium alloys [9], iron, titanium, and zinc [10–14] can be used as the matrix. The mechanical properties of the MHSCs were much higher than those of metal foams through selecting the matrix materials and MHSs and reasonable structural design [15]. Besides, the MHSCs had many good functional properties due to the structure of the MHSs, such as high heat insulation [16], good acoustic performance [17,18], nuclear shielding [19,20], and ballistic performance [21].

It was widely known that the closed-cell metal foams were mostly used in the field of sound insulation due to the closed-cell structure [22]. The sound insulation mechanism was that the sound waves entered the closed-cell metal foams by the refraction and propagated, which caused the air vibration in the pores. Then the vibrating air rubbed against the pores wall, and the sound waves energy was converted into heat energy [23–26]. Due to the closed-cell structure and the rigid sphere' wall structure, the sound waves would be reflected many times by the MHSs when the sound waves passed through the MHSCs. The reflection changed and increased the transmission path of the sound waves in the MHSCs, which hindered the transmission of the sound waves and made the MHSCs have a good isolation effect on the sound waves. Wang et al. [17] made a preliminary exploration on the acoustic properties of the MHSCs and made a simple analysis on the sound absorption and insulation mechanism of the MHSCs. Usually, the acoustic materials can be characterized by sound absorption coefficient and sound transmission loss [27,28]. The absorption coefficient of acoustic materials was studied by analyzing the sound waves energy reflected of acoustic materials. The part of energy consumed by the materials should be considered only, when studying the sound transmission loss of materials. Besides, it was a fast and efficient way to study the sound absorption and insulation

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mechanism of materials by establishing the sound absorption model of materials. Meanwhile, it provided the theoretical support for designing the sound absorption and insulation performance of materials. At present, the application of the MHSCs in the field of sound insulation was rare due to the high production cost of MHSs and the single structure of the MHSCs.

The appearance of functionally graded materials provided a new idea for the application of MHSCs in the field of sound insulation [29,30]. By using the idea of functionally gradient materials, the SG-MHSCs with good acoustic performance were fabricated, which made expanding the application of MHSCs in the acoustic field possible. In order to explore the sound absorption and insulation mechanism of SG-MHSCs, we used the MHSs with different diameters to fabricate the SG-MHSCs, then the density and microstructure of the SG-MHSCs were characterized. Meanwhile, the acoustic properties of the SG-MHSCs were measured, and the sound absorption and insulation mechanism of the SG-MHSCs were analyzed.

2 Materials and methods

2.1 Materials

The MHSs with different diameters and the A356 alloy were chose to fabricate the MHSCs. The MHSs were manufactured by our team, which was sintered at 1,100°C, and the wall porosity was 47.87% [31]. The diameters and wall thicknesses of the MHSs were shown in Table 1.

2.2 Fabrication of the MHSCs

We used the counter-gravity casting method to fabricate the SG-MHSCs, as shown in Figure 1. First, the mold was placed upside down, and the metal fiber grid (MFG) was installed at the bottom of the forming room in the mold, then a graphite support sleeve was installed into the forming room. After that, a certain amount of MHSs with the diameter of 2.88 mm were placed into the forming room.

Second, another graphite support sleeve was put into the mold after the second MFG was put into the forming room, and the third MFG was used to seal the forming room of the mold after a certain amount of MHSs with the diameter of 5.76 mm were put in the forming room. Third, the mold, crucible, and A356 alloy were assembled as shown in Figure 1 and put into the resistance furnace for casting. The process used in the casting process was as follows: the mold was slowly pressed until it reached the bottom of the crucible after the resistance furnace was heated to 710°C and kept 30 min. Then, the mold and crucible were taken out from the resistance furnace after keeping 10 min at 710°C and cooled to the room temperature in the air. Finally, the SG-MHSCs were taken out from the mold. In the experiment, we used MHSs with the same diameter and the above preparation process to fabricate other two kinds of MHSCs. One was the MHSCs fabricated by using the MHSs with diameter of 2.88 mm (MHSCs-2.88), the other was the MHSCs fabricated by using the MHSs with diameter of 5.76 mm (MHSCs-5.76).

2.3 Characterization

2.3.1 Density of MHSCs

The density of the MHSCs was measured by direct measurement [32]. First, the mass and dimension of the regular MHSCs were measured, and then the volume of the MHSCs was calculated. Second, the density of MHSCs was calculated according to the equation (1):

$$\rho = \frac{m}{V}. \quad (1)$$

In the equation (1), the m was the mass of the MHSCs, and the V was the volume of the MHSCs.

2.3.2 Microstructure analysis of the MHSs and SG-MHSCs

We used the Scanning Electron Microscope (SEM, SU-70) with xflash 5010 energy dispersive spectrometer (EDS) to observe the microstructures of the MHSs and MHSCs. The interface between MHSs and matrix was analyzed by the EDS.

2.3.3 Acoustic performance of the MHSCs

The acoustic properties of MHSCs were measured by impedance tube (SW477). The sound absorption coefficient of

Table 1: The diameters and the wall thicknesses of MHSs

No	Diameter (mm)	Wall thickness (mm)
1	2.88 ± 0.02	0.137 ± 0.003
2	5.76 ± 0.05	0.274 ± 0.005

Figure 1: The schematic of fabricating SG-MHSCs.

the MHSCs was measured according to the BS EN ISO 10534-2:2001 and ASTM E1050-98 standards. The sound transmission loss of the MHSCs was measured according to the ASTM E2611-09 standard. In the experiment, we measured the acoustic performance of the MHSCs ($\varnothing 20 \text{ mm} \times 30 \text{ mm}$) in the sound waves frequency range of 1,000–6,300 Hz. Every sample of the MHSCs was measured 6 times, and the average value was taken to make the acoustic performance curves. Besides, when we measured SG-MHSCs, the surface of the MHSs with big diameter in the SG-MHSCs faced the sound source.

3 Results and analysis

3.1 Density of the MHSCs

The density of the MHSCs fabricated in the experiment was measured, and the results were shown in the Table 2. It can be seen from Table 2 that the densities of the MHSCs-2.88, MHSCs-5.76, and the SG-MHSCs were similar

and $1.74\text{--}1.76 \text{ g/cm}^3$, when the volume fraction of MHSs in the MHSCs was 48.50%. Figure 2 shows the photos of the MHSCs-2.88, MHSCs-5.76, and the SG-MHSCs.

3.2 Microstructural analysis

3.2.1 Microstructural analysis of the MHSs

The wall SEM of the MHSs with different diameters was shown in the Figure 3. It could be seen clearly that the wall was composed of the metal particles, pores, and the connections between the metal powder particles. At the same time, the microstructure of the MHSs sintered at the same temperature was almost the same, and there were a lot of pores.

3.2.2 Microstructural Analysis of the MHSCs

Figure 4 shows the distribution of alloying elements around the interface between the MHS and matrix, and

Table 2: Density of the MHSCs

Sample	MHSs			Density of MHSCs (g/cm^3)
	Diameter (mm)	Sintering temperature ($^{\circ}\text{C}$)	Volume fraction (%)	
MHSCs-2.88	2.88	1,100	48.50	1.74 ± 0.03
MHSCs-5.76	5.76	1,100	48.50	1.76 ± 0.06
SG-MHSCs	$5.76 + 2.88$	1,100	48.50	1.75 ± 0.04

Figure 2: The photos of the MHSCs: (a) MHSCs-2.88, (b) MHSCs-5.76, and (c) SG-MHSCs.

Figure 3: The wall SEM of the MHSs sintered at 1,100°C: (a) 2.88 mm and (b) 5.76 mm.

Figure 4: The distribution of alloying elements between the MHS and the matrix, and the results of line scan: (a) the transition layer between MHS and matrix; (b) the distribution of alloy elements around transition layer; and (c) the EDS results at the white line in (a).

the EDS results of white line from bottom to top are shown in Figure 4(a). It can be seen from Figure 4(a) that there was a continuous transition layer between the MHS and the matrix. From Figure 4(b) and (c), it can be inferred that the alloying elements in the MHS diffused into the matrix through the “original interface” between the MHS and the matrix and formed the transition layer, while the Al and Si elements in matrix cannot diffuse to the wall through the “original interface.” Table 3 shows EDS results of transition layer. Combined with Table 3 and related researches [33–36], it can be known that the transition layer was identified as the $\text{Fe}_2\text{Al}_7\text{Si}$ phase. To sum up, we can see that the transition layer was formed between the MHS and the matrix, which made the MHSs isolated from each other. From this point, the MHSCs could be regarded as the closed-cell foam. Figure 5 shows the backscatter image in the matrix and the distribution image of alloying elements. From Figure 5, the morphology of phases in the matrix was mainly the needle-like and block-like. Besides, the elements in the MHSs diffused into the matrix, and the Fe element formed a bright lath phase with Al and Si elements. Meanwhile, the

Si element formed a dark lath phase. According to the related researches [14,26], the bright lath phase was identified as the $\text{Fe}_2\text{Al}_4\text{Si}$ phase, and the dark lath phase was identified as the $\alpha\text{-Si}$ phase.

3.3 Acoustic performance of the MHSCs

Figure 6 shows the sound absorption coefficient and sound transmission loss of MHSCs. It can be seen from Figure 6(a) that the sound absorption coefficient of MHSCs first increased and then decreased with increasing the sound waves frequency and formed sound absorption coefficient peak. However, the sound absorption coefficient of SG-MHSCs was similar as that of the MHSCs-5.76, and lower than that of the MHSCs-2.88, when the MHSCs did not resonate with the sound waves. However, when the MHSCs resonated with the sound waves, the sound absorption coefficient peak of SG-MHSCs was lower than that of the MHSCs-5.76, and higher than that of MHSCs-2.88. It can be seen from Figure 6(b) that the sound transmission loss of MHSCs and the SG-MHSCs first increased

Table 3: The EDS results of transition layer

Area	Al (wt%)	Si (wt%)	Fe (wt%)	Cr (wt%)	Mn (wt%)	Ni (wt%)	Mo (wt%)	Mg (wt%)
Transition layer	65.52	8.32	17.64	6.10	0.45	0.53	1.28	0.02

Figure 5: The phases and the distribution of alloying elements in the matrix.

and then decreased in a certain range with increasing the sound waves frequency and were similar. Meanwhile, the sound transmission loss of MHSCs-2.88 was maximum. Besides, it was also found that the resonance frequency of MHSCs and sound waves moved to the high frequency with increasing the diameter of the MHSs. The resonance

frequency of SG-MHSCs was located between the resonance frequency of the MHSCs-2.88 and MHSCs-5.76.

When the MHSCs did not resonate with the sound waves, the average sound absorption coefficient of MHSCs-2.88 was the highest and 0.19. However, the average sound absorption coefficient of MHSCs-5.76 was 0.12, and the

Figure 6: The acoustic properties of MHSCs: (a) sound absorption coefficient and (b) sound transmission loss.

average absorption coefficient of SG-MHSCs was 0.11. When the MHSCs resonated with the sound waves, the sound absorption coefficient peak of MHSCs-2.88 was 0.39, the sound absorption coefficient peak of SG-MHSCs was 0.44, and the absorption coefficient peak of MHSCs-5.76 was 0.58. Meanwhile, the average sound transmission loss of MHSCs-2.88 was 23.5 dB, which was 15.2% higher than that of MHSCs-5.76 (20.4 dB). The average sound transmission loss of SG-MHSCs was 21.8 dB, which was between 20.4 and 23.5 dB.

4 Discussion

4.1 The sound absorption mechanism of the MHSCs

The relationship among the sound speed (C), wavelength (λ), and frequency (f) of the sound waves was shown in formula (2):

$$C = \lambda f. \quad (2)$$

At the room temperature, the sound velocity was about 340 m/s. In the experiment, the measurement range of sound waves frequency was 1,000–6,300 Hz, and the corresponding wave length was 54–340 mm. Meanwhile, the average diameters of the MHSs were 2.88 and 5.76 mm, respectively. Compared with the wavelength, the diameter of the pores in the MHSs was much smaller. Therefore, the scattering effect on the surface of MHSCs was very weak.

The Figure 7 shows the sound absorption mechanism schematic diagram of MHSCs. It can be seen from the

Figure 7 that the energy of the incident sound waves can be divided into three parts: reflection, absorption, and transmission of the sound waves energy by the MHSCs. When the MHSCs did not resonate with the sound waves, most of the sound waves were reflected, and only few sound waves were absorbed by the micropores and microcracks on the surface of the MHSCs. Besides, the hemispherical hole structure on the surface of the MHSCs can also increase the sound absorption coefficient of the MHSCs by interfering between the sound waves [37,38]. Therefore, the sound absorption coefficient of MHSCs was mainly determined by the number of micropores, microcracks, and hemispherical hollow spheres on the surface of the MHSCs. And the more the number of micropores, microcracks, and hemispherical hollow spheres on the surface of the MHSCs, the higher the sound absorption coefficient of the MHSCs.

For the MHSCs-2.88, due to the much more hemispherical hollow spheres on the surface and a lot of pores in the wall of the MHSs, the average sound absorption coefficient of the MHSCs-2.88 was highest. For the MHSCs-5.76 and the SG-MHSCs, due to the much fewer hemispherical hollow spheres on the surface, the average sound absorption coefficient of the MHSCs-5.76 and SG-MHSCs was lower than that of the MHSCs-2.88. Meanwhile, as the number of hemispherical hollow spheres on the surface of the test sample between the MHSCs-5.76 and the SG-MHSCs was similar, the average sound absorption coefficient of the MHSCs-5.76 and SG-MHSCs had a little difference.

When the MHSCs were excited by the sound waves and vibrated with sound waves at resonance frequency or natural frequency, the sound waves entered MHSCs in resonance mode and propagated. When the sound waves encountered the MHSs in the process of propagation, the

Figure 7: The sound absorption mechanism schematic diagram of MHSCs.

Figure 8: The schematic diagram of sound waves propagation mechanism in MHSCs under resonance condition: (a) at the MHS and (b) in the MHSCs.

sound waves would be reflected and refracted by the MHSs, due to the different acoustic characteristic impedances between the MHSs and matrix. Meanwhile, most of the sound waves would be reflected and changed the direction of transmission, and only a small part of sound waves would enter the MHSs, as shown in Figure 8(a). The reflected sound waves continued to propagate in the MHSCs; a part of the sound waves was reflected into the air and the other part was transmitted through the MHSCs, after many times of reflection by the MHSs. Meanwhile, the propagation path of the sound waves in MHSCs was extended through the reflection of the MHSs, which increased the consumption of the sound waves in the propagation process. However, the sound waves that entered the MHSs cannot propagate out of the MHSs due to the mismatch between the acoustic characteristic impedance of the MHSs and matrix. After repeated consumption by the MHS, the sound waves were absorbed, and the propagation process of sound waves in MHSCs is shown in Figure 8(b).

Therefore, when the sound wave resonated with the MHSCs, the sound absorption coefficient peak of MHSCs was mainly determined by the number of interfaces between the MHSs and matrix in the MHSCs. And the more the interfaces, the more the reflected sound waves, the lower the sound absorption coefficient peak of the MHSCs.

For the MHSCs-2.88, due to the most interfaces between the MHSs and the matrix, the sound absorption coefficient peak of the MHSCs-2.88 was lowest. For the MHSCs-5.76, due to the least interfaces between the MHSs and the matrix, the sound absorption coefficient peak of the MHSCs-2.88 was highest. While the SG-MHSCs were fabricated by the MHSs diameters of 5.76 and 2.88 mm, the number of interfaces in the SG-MHSCs was between the number of the interfaces in the MHSCs-2.88 and MHSCs-5.76; the sound

absorption coefficient peak of the SG-MHSCs was between the sound absorption coefficient peak of the MHSCs-2.88 and MHSCs-5.76.

From the above research results, it can be known that the SG-MHSCs fabricated by different diameters of MHSs can effectively decrease the average sound absorption coefficient and the sound absorption coefficient peak of the MHSCs.

4.2 The sound insulation mechanism of the MHSCs

The attenuation of sound waves propagation in nonideal medium mainly included geometric attenuation, scattering, and absorption loss. The geometric attenuation and scattering did not reduce the energy of sound waves in essence, but changed the direction or mode of sound waves propagation only. The sound waves loss absorbed by the acoustic materials in the process of propagation was that the sound energy was continuously lost due to the absorption of the acoustic material itself. The essence was that the mechanical energy in the form of sound waves was continuously transformed into other kinds of energy. Usually, the sound waves were converted to heat energy. And the main reason of sound absorption was the viscosity of medium, heat conduction, and relaxation effect caused by microprocess. When the sound waves propagated in the viscous medium, it would cause the vibration of the particles in the medium. If the motion speed of the adjacent particles in the medium was different, the internal friction would be generated between the particles due to the relative motion, which hindered the movement of the particles. Thus, the sound energy would be converted into heat energy through the friction and viscous resistance, and the incident sound waves would be attenuated. Meanwhile, when the sound waves passed through the medium, it would make the medium expand and compress. The volume of compression zone would be smaller, so that the temperature would increase, while the volume of expansion zone would be larger, and the temperature would decrease. Thus, a temperature gradient was generated between the expansion zones and the adjacent compression regions, and a part of the heat flowed from the compression zone to the expansion zone, resulting in heat exchange, and the sound energy would be converted to heat energy and consumed [39].

When the sound waves were incident on the surface of the MHSCs, it would excite the air inside the MHSs to vibrate, and the air would move relative to the wall of the

MHSs. Due to the viscosity of the air, the corresponding viscous resistance would be generated in the micropores of the wall, which made the vibrating air continuously converted into heat energy, so that the sound energy would be consumed and attenuated. Besides, when the air was adiabatically compressed, there would be continuous heat exchange between the air-wall-matrix, and the sound energy would be converted into heat energy, which made the sound energy be consumed.

For the MHSCs in the experiment, as the volume fraction of MHSs was 48.50%, the sound transmission loss of the MHSCs-2.88, MHSCs-5.76, and SG-MHSCs had no significant difference. However, due to the difference in content of the interfaces between the MHSs and matrix, the propagation paths of sound waves in MHSCs were different. In the MHSCs-2.88, the interfaces content was the highest, the reflection times of sound waves were the most, and the propagation path was longest, so the sound transmission loss of the MHSCs-2.88 was the highest. In the same way, the MHSCs-5.76 contained the least interfaces, and the sound transmission loss of the MHSCs-2.88 was the lowest. And the SG-MHSCs contained the intermediate quantity of interfaces, so the sound transmission loss of SG-MHSCs was higher than that of MHSCs-5.76 and lower than that of MHSCs-2.88.

5 Conclusion

In this study, we used the MHSs with different diameters to fabricate the SG-MHSCs, then the density and microstructure of the SG-MHSCs were characterized. Meanwhile, the acoustic properties of SG-MHSCs were measured, and the sound absorption and insulation mechanism of the MHSCs were analyzed. Then according to the experimental results, the sound absorption and insulation mechanism of the SG-MHSCs were analyzed, and the conclusions were as follows:

- (1) The density of the MHSCs-2.88, MHSCs-5.76, and the SG-MHSCs was similar and $1.74\text{--}1.76\text{ g/cm}^3$ when the volume fraction of MHSs in the MHSCs was 48.50%.
- (2) The microstructure observation showed that the MHSs and matrix occurred in an alloying reaction and formed a continuous transition layer composed by the $\text{Fe}_2\text{Al}_7\text{Si}$ phases. And the phases in the matrix were $\text{Fe}_2\text{Al}_4\text{Si}$ phase and $\alpha\text{-Si}$ phase.
- (3) When the MHSCs did not resonate with the sound waves, the average sound absorption coefficient of

MHSCs-2.88 was the highest and 0.19. Meanwhile, the average absorption coefficient of MHSCs-5.76 was 0.12, and the average absorption coefficient of SG-MHSCs was 0.11. When the MHSCs resonated with the sound waves, the sound absorption coefficient peak of MHSCs-2.88 was 0.39, the absorption coefficient peak of MHSCs-5.76 was 0.58, and the sound absorption coefficient peak of SG-MHSCs was 0.44.

- (4) The average sound transmission loss of MHSCs-2.88 was 23.5 dB, which increased by 15.2% than that of MHSCs-5.76 (20.4 dB). And the average sound transmission loss of SG-MHSCs was 21.8 dB, which was between 20.4 and 23.5 dB.
- (5) When the MHSCs did not resonate with the sound waves, the absorption coefficient of MHSCs was mainly determined by the number of micropores, microcracks, and hemispherical hollow spheres on the surface of the MHSCs. And the more the number of micro-holes, microcracks, and hemispherical hollow spheres on the surface of the MHSCs, the higher the sound absorption coefficient of the MHSCs.
- (6) When the sound wave resonated with the MHSCs, the absorption coefficient peak of MHSCs was mainly determined by the number of interfaces between the MHSs and matrix in the MHSCs. And the more the interfaces, the more the reflected sound waves, the smaller the sound absorption coefficient peak of the MHSCs.
- (7) When the sound wave was incident on the surface of MHSCs, it would excite the air inside the MHSs to vibrate, and the air would move relative to the wall of the MHSs. Due to the viscosity of the air, the corresponding viscous resistance would be generated in the micropores of the wall, which made the vibrating air continuously converted into heat energy, so that the sound waves energy would be consumed and attenuated.
- (8) From the test results, it can be known that the SG-MHSCs fabricated by different diameters of MHSs can effectively decrease the average sound absorption coefficient and the sound absorption coefficient peak of the MHSCs. However, the sound transmission loss of the SG-MHSCs had no significant improvement.

Funding information: The financial support for this study received from National Key Research and Development Program of China (No. 2017YFE0123500); the National Natural Science Foundation of China (No. 11972128); Foundation of China (No. 0104047).

Conflict of interest: The authors declare that they have no conflict of interest

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