

Preparation and characterization of $\text{SiC}_p/2024\text{Al}$ composite foams by powder metallurgy

LI Ai-bin, XU Hong-yu, GENG Lin, LI Bin-ling, TAN Zheng-bin, REN Wei

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

Received 9 July 2012; accepted 13 August 2012

Abstract: $\text{SiC}_p/2024\text{Al}$ composite foams were manufactured by powder metallurgical methods using foaming agent CaCO_3 in order to enrich the foam fabrication process and promote its development and extensive application. The effects of CaCO_3 and SiC volume fractions on the foaming behaviours were investigated by means of SEM and Magiscan-2A image analysis technique. The influence of SiC content on the compressive behaviour was analyzed using Gleeble 1500 thermal simulation testing machine. The experimental results show that with increasing the foaming agent, the porosity and pore dimension increase first and decrease later. With increasing the reinforcement content, the porosity and pore dimension decrease. The compressive curves reveal that the introduction of SiC particles can improve compressive yield strength and energy absorption capacity. Meanwhile, it is found that $\text{SiC}_p/2024\text{Al}$ composite foams are the brittle foam materials.

Key words: aluminum composite foams; foaming agent CaCO_3 ; powder metallurgical method; foaming behaviour; compressive behaviour

1 Introduction

Closed-cell aluminum foam materials are a kind of structural and functional materials becoming increasingly important for the applications in the aerospace and automobile because they possess high specific stiffness, high specific strength, and extraordinary energy absorption [1,2].

Recently, metallic foams have received extensive interest. YANG et al [3] investigated the effect of TiH_2 on the preparation of closed-cell aluminum foam and its compressive behavior. However, the cell structure of metallic foams is irregular and the cell size is inhomogeneous due to low viscosity of metal melts [4,5]. Meanwhile, aluminum foams exhibited relatively low compressive strength [6,7], consequently restricting their applications. In order to increase the viscosity of metal melts and improve their strength, the addition of ceramic particles is a good approach. Many researches reported the effect of ceramic particle addition on both foaming and compressive behaviors [8–10]. KENNEDY and ASAVAVISITCHAI [11] researched the effects of TiB_2 particle addition on the expansion, structure and mechanical properties of PM Al foams. DAOUD [12]

investigated the compressive response and energy absorption of foamed $\text{A359-Al}_2\text{O}_3$ particle composites. These above investigations are mainly focused on the composite foams fabricated by direct foaming method or powder metallurgical method using the foaming agent TiH_2 . Recently, there have been limited reports on the composite foam fabrications using CaCO_3 foaming agent by direct foaming [13,14] rather than powder metallurgical method. Therefore, it is necessary to research the preparation and characterization of aluminum composite foams by PM using CaCO_3 in order to enrich the foam fabrication process and promote its development and extensive application.

In the present work, $\text{SiC}_p/2024\text{Al}$ composite foams were manufactured by powder metallurgical methods using foaming agent CaCO_3 . The foaming behaviours with different contents of CaCO_3 and SiC particles were analyzed, and then the effects of SiC content on the compressive behaviour and energy absorption capacity were characterized.

2 Experimental

In the present work, 2024 Al alloy powders of 30 μm , SiC particles of 10 μm and CaCO_3 powders of 12 μm

were selected as the matrix, reinforcements and foaming agent, respectively. The precursor materials containing SiC particles and CaCO_3 were fabricated by powder metallurgy method followed by hot extrusion. Firstly, these raw materials were blended for 12 h, then were sintered at 550 °C under 20 MPa for 2 h. Finally, the sintered precursors were extruded at 450 °C with an extrusion ratio of 16:1.

The precursor materials were foamed in a tube furnace at 700 °C for 10 min by the decomposition of CaCO_3 into CaO and CO_2 phases. In order to investigate the effects of the contents of the foaming agent and reinforcement on the foaming behaviors, the content of CaCO_3 foaming agent was chosen to be 1.5%, 2%, 2.5% and 4% (volume fraction), and the volume fraction of SiC particles was selected to be 0, 5% and 10%. The foam microstructures were investigated by means of SEM, and the pore size was characterized by Magiscan-2A image analysis technique. The foam porosity was determined using Archimedes' principle. Quasi-static compression experiments of $\text{SiC}_p/2024\text{Al}$ composite foams were tested on a Gleeble 1500 thermal simulation testing machine, and then the quasi-static compression behaviour and energy absorption capacity were analyzed.

3 Results and discussion

3.1 Effect of CaCO_3 content on foaming behaviour

In order to investigate the effect of foaming agent on the foaming behavior, Figs. 1 and 2 show the

macroscopical and microscopical micrographs of 10% $\text{SiC}_p/2024\text{Al}$ composite foams fabricated with different contents of CaCO_3 , respectively. Obviously, below 2%, the pore size and area increase with increasing CaCO_3 content. Above 2%, the uniformity of pore structure gets worse, and more pores interconnect to form a gap. Meanwhile, Fig. 3 characterizing quantitatively the porosity and pore diameter shows that both pore diameter and porosity increase first and decrease later with increasing CaCO_3 content. It is found from the above characterization results that higher or lower contents of foaming agents cannot enhance the porosity. Consequently, the optimum content of foaming agent is determined to be 2%.

Generally, the foaming agents must undergo thermal decomposition and generate gas pressure in the Al matrix sufficient to overcome atmospheric pressure and cause foaming. With increasing CaCO_3 content, the decomposed gas content increases, consequently enhancing the foam porosity and size. When CaCO_3 content is larger, the decomposed gas bubbles escape, accordingly reducing the foam porosity and size. Therefore, the optimal content of foaming agent is determined to be 2% in the present work.

3.2 Effect of SiC particle content on foaming behaviour

In order to research the effect of reinforcement content on foaming behaviour, Fig. 4 shows the microscopical morphologies of 2024Al, 5% $\text{SiC}_p/2024\text{Al}$ and 10% $\text{SiC}_p/2024\text{Al}$ foams. Large pores are clearly

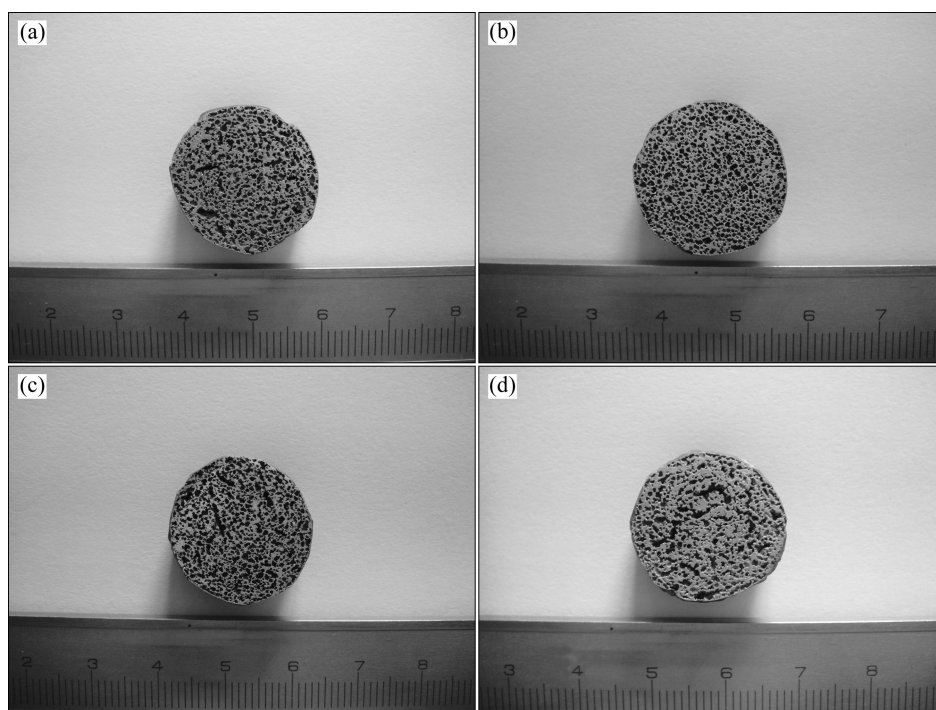


Fig. 1 Macroscopical images of 10% $\text{SiC}_p/2024\text{Al}$ composite foams fabricated with different CaCO_3 contents: (a) 1.5%; (b) 2%; (c) 2.5%; (d) 4%

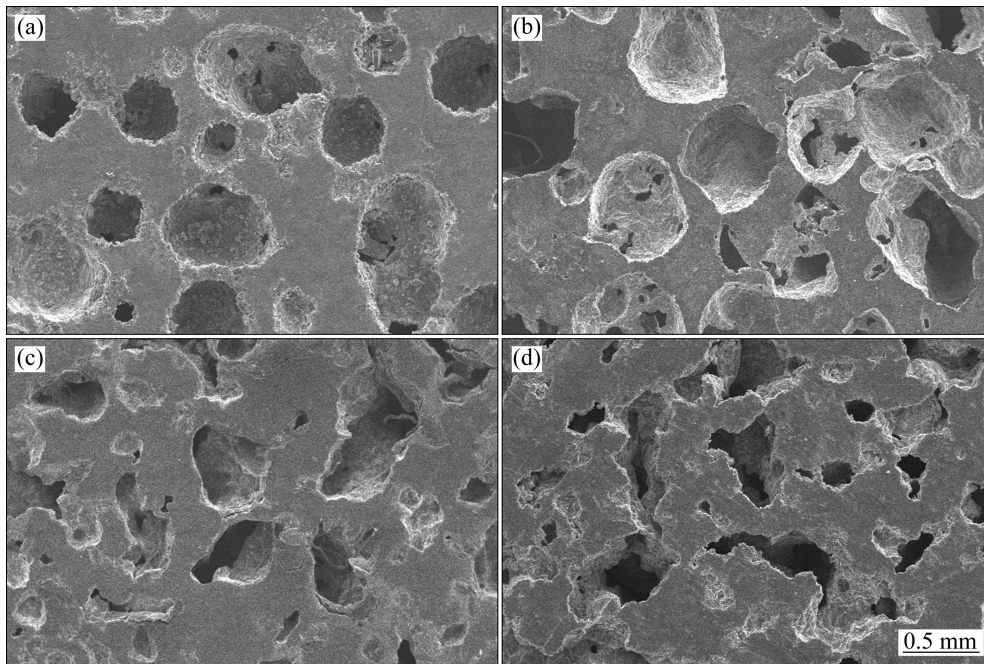


Fig. 2 SEM images of 10%SiC_p/2024Al composite foams fabricated with different CaCO₃ contents: (a) 1.5%; (b) 2%; (c) 2.5%; (d) 4%

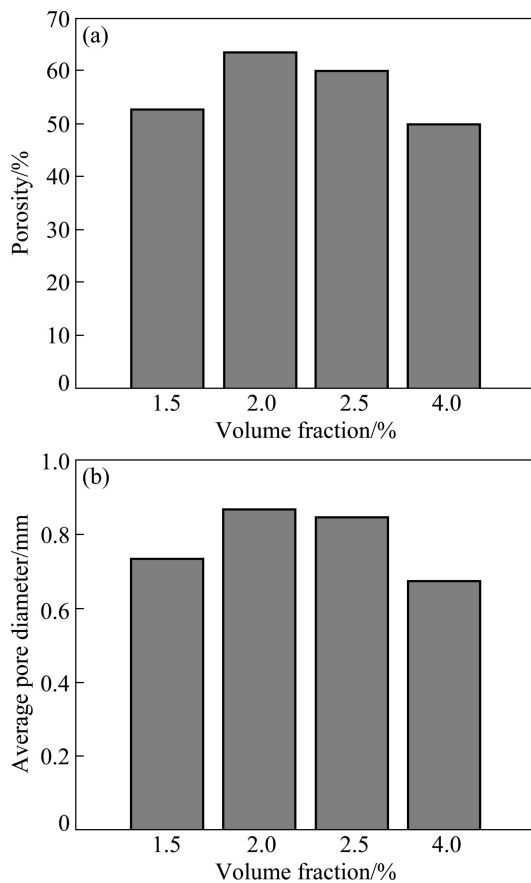


Fig. 3 Variation of porosity (a) and pore diameter (b) for 10%SiC_p/2024Al composite foams with CaCO₃ foaming agent content

observed in pure Al foam, as shown in Fig. 4(a). This is because pure Al foam is ease to interconnect. When

5%SiC particles are introduced into Al matrix, the foam interconnection phenomena are improved in foam composite, and the pore diameter becomes small in Fig. 4(b). At 10%, the pores exhibit spherical shape, and pore structure becomes homogeneous in Fig. 4(c).

In order to analyze the effect of SiC content on the foaming behaviour, Fig.5 characterizes quantificationally the variation of the porosity and pore diameter with particle content. It can be seen that with increasing the SiC particle volume fraction, the foam porosity decreases slightly, and the pore diameter reduces significantly. It is known that the introduction of ceramic particles plays a critical role on liquid foam stabilization through enhancing melt viscosity and increasing surface viscosity of the cell faces [9]. Under the same foaming parameters, the addition of SiC particles can increase melt bulk viscosity. Moreover, this viscosity increases with the increase of the particle content. As compared with Al compacts, the resistance of the movement of the gas–liquid interface increases, and the drainage of liquid foam reduces. Therefore, the presence of SiC particles can improve the liquid foam stabilization and reduce the foam interconnection phenomena, inducing the pore diameter to become small and stable [8,9].

3.3 Effect of SiC particle addition on compressive behaviour and energy absorption

Figure 6 shows the quasi-static compressive curves with different reinforcement contents. It can be seen that similar to 2024Al foam, the compressive curves of composite foams exhibit three distinct regions: linear

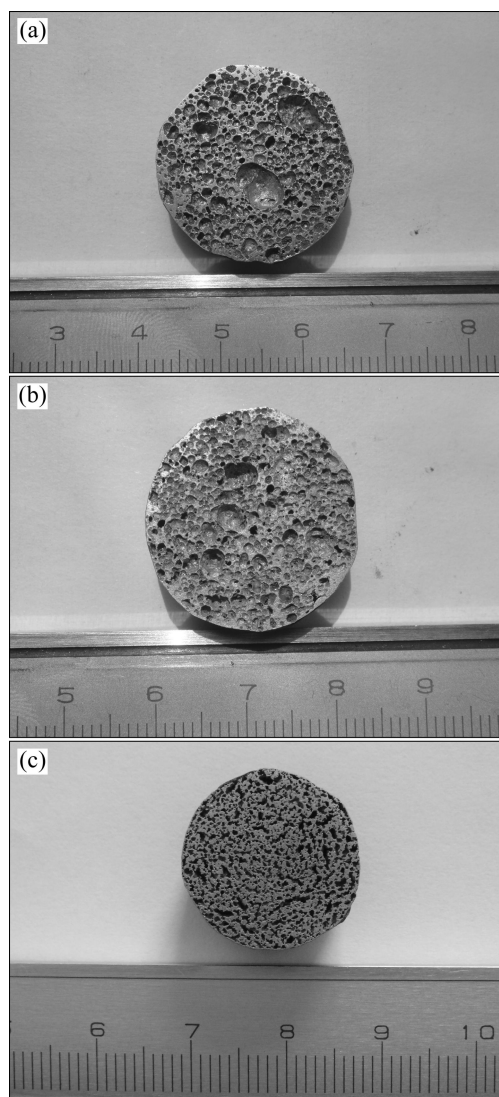


Fig. 4 Micrographs of 10%SiC_p/2024Al composite foams fabricated with different SiC particle contents: (a) 0%; (b) 5%; (c) 10%

elastic region, collapse region and densification region. Different from the smooth compression curve of 2024Al foams, the yield platform of the compressive curve of the composite foam indicates the jagged fluctuations, suggesting that due to the addition of SiC particles, this material is changed from the plastic foam into the brittle foam. Meanwhile, with increasing the particle content, the stress plateau exhibits more significant serration, namely they become more brittle. The main reason is that SiC particles in the cell walls change the deformation mechanism of the cell walls [14]. During the collapse of composite foam, the parts of cell walls with SiC particles produce suddenly brittle rupture, and the stress also reduces suddenly. With increasing the compressive strain, other cell walls continue sudden rupture, and the stress also decreases constantly. Consequently, the typical serration plateau is formed in the compressive

stress—strain curve of the composite foam. Therefore, the composite foams are brittle foams. The similar compressive behaviours of composite foams were reported in Ref. [13,14].

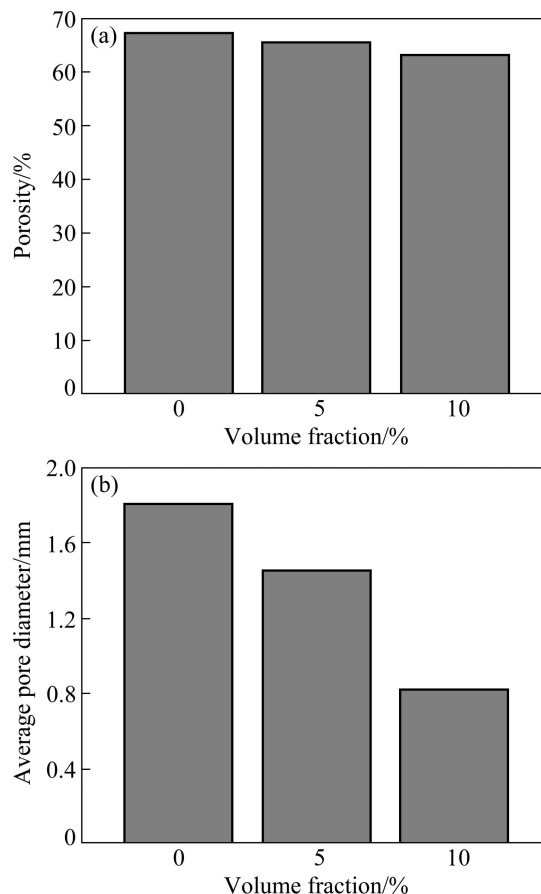


Fig. 5 Variation of porosity (a) and pore diameter (b) of foams with SiC particle content

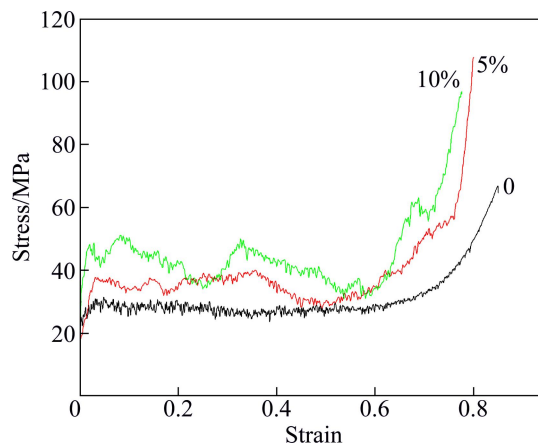


Fig. 6 Quasi-static compressive curves with different SiC reinforcement contents

Table 1 lists the compressive results with different particle contents. With increasing the particle content, the yield stress increases. When the porosity is about 67%, the mean plateau stress of 10%SiC_p/2024Al foam is

about 48.2 MPa, and it is 16.6 MPa larger than that of 2024Al foam. Generally, the compressive strength of metal foams depends not only on the pore size but also on the porosity [15]. Particle reinforced composite foams include three aspects: alloy matrix, particles and pores. The compressive strength of composite foams depends on load transfer strengthening and the strengthening effect due to thermal mismatch increased dislocation density [12]. Under similar foam porosity and diameter, the volume fraction of reinforcement introduced into the metal matrix affects significantly the compressive strength. Increasing SiC volume fraction can enhance the load transfer strengthening and strengthening effect due to thermal mismatch increased dislocation density, accordingly enhancing the contribution of the SiC particles to compressive strength.

Table 1 Results of quasi-static compressive tests with different SiC reinforcement contents

Materials	Porosity/ %	Diameter/ mm	Yield stress/ MPa	Plateau length/ %	Absorbed energy/ (MJ·m ⁻³)
Foam 2024Al	69.1	1.441	31.6	0.704	22.1
5%SiC/2024Al	68.4	1.257	37.7	0.696	24.8
10%SiC/2024Al	67.0	1.012	48.2	0.691	26.8

From the compressive test data, the energy absorption during the compression can be calculated by integrating the area under the stress—strain curve [1]:

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (1)$$

where W is the absorbed energy per unit volume, σ is the compressive stress and ε is the strain.

Table 1 also lists the absorbed energy up to densification strain, which is defined as the strain corresponding to the end of the stress plateau of foam materials. The compressive strength obviously changes with SiC particle content in spite of no apparent variation of plateau length. It can also be seen from Table.1 that with increasing the particle content, the energy absorption capacity enhances. This indicates that SiC particles contribute to energy absorption capacity due to the contribution of SiC particles to compressive strength. It is generally accepted that metallic foams can dissipate energy by the yielding, buckling, fracture of the cell structure, the friction between the cell wall fragments, and sticky flow of the gas trapped in the foams. Besides these above factors, for composite foams, the debonding energy of reinforcement/matrix interface is responsible for the additional energy absorption [16]. As reported in Ref. [12], an additional energy for the composite foams is absorbed due to the presence of the particles in the cell wall. Therefore, the introduction of SiC particles can

enhance energy absorption capacity.

4 Conclusions

1) SiC_p/2024Al composite foams are successfully manufactured by powder metallurgical methods using foaming agent CaCO₃.

2) The pore diameter and porosity increase first and decrease later with increasing the foaming agent content.

3) The pore diameter and porosity decrease with increasing the SiC particle content.

4) The presence of SiC particles can improve the liquid foam stabilization and reduce the foam interconnection phenomena, inducing the pore diameter to become small and stable.

5) With increasing SiC particle content, both compressive yield strength and energy absorption capacity increase. Meanwhile, SiC_p/2024Al composite foams are brittle foam materials.

References

- [1] HIDEO N. Fabrication, properties and application of porous metals with directional pores [J]. *Progress in Materials Science*, 2007, 52: 1091–1173.
- [2] GOKHALE A A, KUMAR N V R, SUDHAKAR B, SAHU S N, BASUMATARY H, DHARA S. Cellular metals and ceramics for defence applications [J]. *Defence Science Journal*, 2011, 61: 567–575.
- [3] YANG Guo-jun, YU Hai-jun YAO Guang-chun. Effect of TiH₂ on preparation of closed-cell aluminum foam and its compressive behavior [J]. *Transactions of Nonferrous Metals Society of China*, 2006, 16: 1442–1445.
- [4] ATTIA M S, MEGUID S A, TAN K T, YEO S C. Influence of cellular imperfections on mechanical response of metallic foams [J]. *International Journal of Crashworthiness*, 2010, 15: 357 – 367.
- [5] KADOI K, NAKAE H. Relationship between Foam stabilization and physical properties of particles on aluminum foam production [J]. *Materials Transactions*, 2011, 52: 1912–1919.
- [6] MU Y L, YAO G C, LIANG L S, LUO H J, ZU G Y. Deformation mechanisms of closed-cell aluminum foam in compression [J]. *Scripta Materialia*, 2010, 63: 629–632.
- [7] SAID M R, TAN Chee-fai. The response of aluminium foams under quasi-static loading [J]. *Chiang Mai Journal of Science*, 2008, 35: 241–249.
- [8] PRAKASH O, SANG H, EMBURY J D. Structure and properties of Al–SiC foam [J]. *Materials Science and Engineering A*, 1995, 199: 195–203.
- [9] GUDEN M, YUKSEL S. SiC-particulate aluminum composite foams produced from powder compacts: foaming and compression behavior [J]. *Journal of Materials Science*, 2006, 41: 4075–4084.
- [10] WANG Yong, ZU Guo-yin, LI Bing, YAO Guang-chun. Study on compressive property of aluminum foam with particle-reinforced Al alloy matrix [J]. *Journal of Functional Materials*, 2008, 7: 1174–1180.
- [11] KENNEDY A R, ASAVAVISITICHAI S. Effects of TiB₂ particle addition on the expansion, structure and mechanical properties of PM Al foams [J]. *Scripta Materialia*, 2004, 50: 115–119.
- [12] DAOUD A. Compressive response and energy absorption of foamed A359–Al₂O₃ particle composites [J]. *Journal of Alloys and*

- Compounds, 2009, 486: 597–605.
- [13] LUO Yan-ru, YU Si-rong, LI Wen, LIU Jia-an, WEI Ming. Compressive behavior of $\text{SiC}_p/\text{AlSi9Mg}$ composite foams [J]. Journal of Alloys and Compounds, 2008, 460: 294–298.
- [14] YU Si-rong, LIU Jia-an, LUO Yan-ru, LIU Yao-hui. Compressive behavior and damping property of $\text{ZA22}/\text{SiC}_p$ composite foams [J]. Materials Science and Engineering A, 2007, 457: 325–328.
- [15] KOZA E, LEONOWICZ M., WOJCIECHOWSKI S, SIMANCIK F. Compressive strength of aluminium foams [J]. Materials Letters, 2003, 58: 132–135.
- [16] LIU J A, YU S R, HU Z Q, LIU Y H, ZHU X Y. Deformation and energy absorption characteristic of $\text{Al}_2\text{O}_3/\text{Zn}-\text{Al}$ composite foams during compression [J]. Journal of Alloys and Compounds, 2010, 506: 620–625.

粉末冶金法制备 $\text{SiC}_p/2024\text{Al}$ 泡沫复合材料的表征

李爱滨, 许虹宇, 耿林, 李斌玲, 谭镇斌, 任伟

哈尔滨工业大学 材料科学与工程学院, 哈尔滨 150001

摘 要: 为了丰富泡沫材料制备工艺、推动其快速发展与广泛应用, 以 CaCO_3 为发泡剂采用粉末冶金法制备 $\text{SiC}_p/2024\text{Al}$ 泡沫复合材料。采用 SEM 和 Magiscan-2A 图像分析仪研究了 CaCO_3 发泡剂和 SiC 颗粒的含量对发泡行为的影响, 并且通过 Gleeble 1500 热模拟机分析了 SiC 颗粒的含量对压缩性能的影响。结果表明: 随着发泡剂的增多, 孔隙率和孔径先增加后减小。随着增强体含量的增加, 孔隙率和孔径都减小。压缩曲线揭示加入增强体可以改善压缩屈服强度和吸能能力。 $\text{SiC}_p/2024\text{Al}$ 泡沫复合材料显示为脆性泡沫材料。

关键词: 泡沫铝基复合材料; CaCO_3 发泡剂; 粉末冶金法; 发泡行为; 压缩行为

(Edited by HE Yun-bin)