Materials Research Express

PAPER

Mechanical behavior of open-cell aluminium foams filled with tin-bronze foams

Qiang Feng1, Changzhong Liao1,2,4, Xueyan Wu1, Qian Zhang1 and Li Yu1

1 Institute of Nonferrous Metal Gradient Materials Preparation and Performance, College of Physics and Engineering, Chengdu Normal University, Chengdu, Sichuan 611130, People’s Republic of China
2 Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, People’s Republic of China
3 School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, People’s Republic of China
4 Key Laboratory of New Processing for Nonferrous Metal and Materials (Ministry of Education), Guangxi Key Laboratory of Processing for Non-ferrous Metallic and Featured Materials, School of Resources, Environment and Materials, Guangxi University, Nanning 530004, People’s Republic of China

E-mail: liaocz29@connect.hku.hk

Keywords: porous materials, powder technology, internal reinforcement, aluminium foams composite

Abstract

The interior pore of open-cell aluminium foams filled with bronze foams is a new method of preparing aluminium foams composite. The voids of bronze foams were fabricated by in situ thermal decomposition of space-holder in a powder metallurgical sintering process. Cu3Sn phase content is observed to increase through phase transformation at the expense of Cu6Sn5 and aluminium-matrix during isothermal aging. The effect of bronze foams porosity on the interface microstructure between aluminium-matrix and the filler has been investigated. The ‘bulge’ shape appears in the compressive stress-strain curve of aluminium foams composite, which is sharply different from single-component metal foams. According to the characteristic of the stress distribution, the stress-strain curves can be divided into 4 stages: quasi-linear region, stress decrease region, plateau stress region and densification region. The effect of bronze foams filler relative density on the first maximum stress and absorbed energy density of aluminium foams composite was also studied. The results suggest incorporating bronze foams in the aluminium foams pores is an effective method to improve the mechanical properties of open-cell aluminium foams.

1. Introduction

Aluminium (Al) foams have traditionally been regarded as good energy-absorbing materials due to their compressive stress-distance curves which rise linearly first and then keep constant. During an impact process where the collision force is below the maximum stress-bearing capacity of an object, the impact energy will be absorbed by Al foams for achieving impact protection. However, it is well known that the mechanical properties of Al foams are worse than expected, which leads to the constraints that limit their application in load bearing [1]. To obtain better properties, Al foams are used as cores of sandwich panels being the panels serve as the solid sheets supporting the loads [2, 3]. The sandwich structure has proved beneficial to improve properties in bending and tension rather than in compression. The main disadvantage of this method lies in the increase in weight and cost. A method of external stainless steel net-shape reinforcements can also improve mechanical properties in bending and tension modes for Al foams without increasing the substantial weight increase and cost. Unfortunately, mechanical properties in compression are not enhanced obviously, the worse external appearance of the foams is observed [4, 5]. To improve the compressive stress-bearing capacity, the method of electro-deposition of alloy was used to enhance Al foams by thickening the struts [6, 7]. However, the improved mechanical properties in compression stress utilizing this approach were unsatisfactory [8, 9].

On the other hand, some researchers paid close attention to filling the incompressible viscous liquid in Al foams pores. More energy would be dissipated when liquid flows through the connected channels, resulting from the friction between the liquid and the cell walls [10, 11]. Silicate rubbers, which have long been regarded as
vibration reducers, cushions and impact energy absorbers, were used to fill the open cells of Al foams. Obviously, filling materials in previous research are all non-metallic with low strength. They improve the absorption energy capacity to some degree and still leave much to be desired. So far, metal foams with stiffer or higher damping have been paid little attention as pore filler candidates for mechanical performance improvement. Tin-bronze alloys are characterized by a relatively low melt point (i.e., Cu₃Sn and Cu₆Sn₅ have a melting point of 676 and 415 °C, respectively)\(^{[12–14]}\), high hardness and good wear resistance. Therefore, the carbamide particles were chosen as the space-holder for preparing the bronze foams in current work. The tin-bronze foams were then used as the pore filler in Al foams utilizing powder sintering method, aiming to reinforce the mechanical properties of Al foams.

2. Experimental

Several steps of mixing have been adopted to prepare open-cell Al foams filled with bronze foams in the present investigation. Firstly, a small amount of Al-phosphate (binding agent) and copper oxide (curing agent) were added in the tin-bronze powder (Shijiazhuang Jingyuan Powder Material Co. LTD.), and then mixed homogeneously. Secondly, both sesbania powder and carbamide particles (diameter ranging from 0.6 to 1.2 mm) were mixed with the previous mixture to get tin-bonze composite with particle size of 1.5 mm approximately. Thirdly, the prepared particles were added as the filler into a mixture of Al-phosphate and Al powder (Xingtai Chuangying Metal Materials Co. LTD. with purity more than or equal to 99.8%). Lastly, the ready-prepared mixtures were uniaxially cold compacted in a cylindrical die cavity with a hydraulic press at a pressure of 300 MPa for 10 min. The preparation process is schematically shown in figure 1. Initial components of the powder were mixed to prepare precursors with identical porosity for Al foams (Al-55.0 vol.% space-holder with compacting volume ratios of carbamide particles to bronze powder at 55:45, 60:40, 65:35 and 70:30, namely, 1#, 2#, 3# and 4#, respectively). The compacted pellets were dried at 200 °C in an evacuated quartz tube for 1 h, followed by heating at 570 ± 10 °C for 2 h, and then cooled to ambient temperature. Volume ratios of space-holder were used to determine the relative densities of the foam structure for both Al foams matrix and bronze foams filler, respectively. The relative densities of all Al foams matrix are the same 0.45, and the relative densities of filler (bronze foams) in Al foams (samples 1#, 2#, 3# and 4#) are 0.45, 0.40, 0.35 and 0.30, respectively.

The x-ray powder diffraction data of the prepared samples were collected on an x-ray diffractometer (BRUKER, D8 Advance) with Cu-Kα radiation (\(\lambda = 1.54056 \text{ Å, 40 kV/30 mA}\)) at room temperature. Both Al-matrix and the interface of Al/bronze foams filler were characterized by an electron microscope (Japan, JEOL JSM-6510LV) in conjunction with energy-dispersive x-ray spectroscopy (EDS). Mechanical property of cylindrical samples (Diameter: 20 mm, height: 20 mm) was performed on a 20 KN servohydraulic universal testing machine with a crosshead speed of 0.001/s at ambient temperature \(^{[15]}\). Each model of the Al foams filled with bronze foams was tested with three parallel specimens. The porosity structure was captured with optical microscopy, and the outer region of the image was cut to evaluate the planar porosity using ImageJ software \(^{[16]}\).
3. Results and discussion

3.1. Morphological analysis

Representative structure of Al foams filled with bronze foams (1#) obtained from the powder sintering process is shown in figure 2(a). The diameter of the porous filler particle is in millimeter scale, and their geometry mainly relies on the distribution of the filler particles in the compacted precursors. A tradeoff between false-negative and false-positive has to be made and the binarized micrograph picture composed of only white (referring as pores) and black (representing Al-matrix) colors is shown in figure 2(b). The result evaluated from the binarized micrograph indicates a planar porosity proportion of 53.0% in Al foams, agreeing with basically the Al foams filler volume of 55.0%.

Figure 2. The Al foams filled with bronze foams 1# for (a) morphology and pore structure micrograph; (b) binarized micrograph.
The foam structure of the open-cell bronze foams filler in Al foams pores (1#) is shown in figure 3. The pores derived from the decomposition of carbamide particles are internally linked almost by the interconnecting pore channels. The pore size ranges from tens to hundreds of microns. Its morphology relies on the carbamide particle distribution during the granulation process. When the volume fraction of carbamide particles reaches a certain level, most carbamide particles would interconnect to form a three-dimensional (3D) continuous through holes. On the other hand, a few internal cracks are starting to appear due to the bronze shrinkage which is likely to intensify with the increasing of void ratio, as shown in figures 3(c) and (d). The 3D curved figure obtained from figure 3(a) with ImageJ software relating to the pixel intensity in pseudo-color images (non-RGB images) is shown in figure 4. The surface plot analysis for sample 1# which characterizes the surface topography of bronze foams is closely associated with surface foam structures, i.e. the pore shape, size and distribution.

3.2. Phase analysis

For sample 1# as shown in figure 5(a), diffraction peaks before annealing are mainly reflected as Al (Fm-3m [No. 225]), AlPO4 (C2221 [No. 20]), carbamide (P-421m [No. 113]), CuSn3 (Cmcm [No. 63]) and Cu6Sn5 (C2/c [No. 15]). The carbamide phase disappears after annealing and Al (Fm-3m [No. 225]), Al2Cu (I4/mcm [No. 140]), CuSn3 (Cmcm [No. 63]) and Sn (I41/amd [No. 141]) are the main phases observed. During sintering, carbamide particles were decomposed thermally, and the pores were formed in bronze-matrix. The appearance of both Al2Cu and Sn after annealing suggests the following reaction:

\[ \text{Cu}_6\text{Sn}_5 + 6\text{Al} \rightarrow 3\text{Al}_{2}\text{Cu} + 4\text{Sn} + \text{Cu}_3\text{Sn} \]  

Therefore, the formation of Cu3Sn is contributed from the expense of both Cu6Sn5 filler and Al. It indicates that the variation of filler matrix is determined not only by atom diffusion but also by the interfacial reaction. Result of Rietveld quantitative phase analysis for sample 4# by MAUD program is shown in figure 5(b) [17, 18]. The value of the profile refinement quality factor (GOF) in the case is 1.52. The phases Al2Cu and CuSn3, with content of 7.34 wt% and 5.85 wt%, respectively were obtained from the sample 4# after annealing, which means Cu3Sn phase become the major component in the filler. This is contributed to the reaction between the Cu6Sn5 and Al-matrix after the isothermal aging. However, the formative Cu3Sn often exhibits more serious volume shrinkage compared to Cu6Sn5, which explains the appearance of internal cracks in the bronze foams [19]. Previous study
has proved a bigger fracture-toughness value of Cu₃Sn than that of Cu₆Sn₅ in both thin films and bulk samples [20, 21]. Therefore, the produced Cu₃Sn may help to improve the mechanical properties of Al foams.

### 3.3. Interface analysis

Figure 6(a) shows the scanning electron microscopes (SEM) results of the interface between the Al foams matrix and the bronze foams filler in sample 3#. Element content in the filler region shown in figures 6(a) and (b) confirms the produced Cu₃Sn phase. The distribution of elements Al, Cu, Sn, O and P near the matrix interface of Al/bronze obtained by EDS mapping is shown in figures 6(c)-(h), respectively. The elements of P and O derived from the addition of AlPO₄, aimed to strengthen adhesion in both bronze and Al-matrix during the sample preparation process. Both the light blue color Cu and the dark blue Sn spread almost all the tested areas (figures 6(e) and (f), respectively). However, element Al with light red color situates only in the local region (figure 6(d)). Combined with XRD analysis, it can be obtained from figures 6(d) and (e) that the Al₂Cu intermetallic distributes mainly in the light red region, as shown in figure 6(c). It can be observed from figure 6 that the number of Al atoms diffused to Cu-matrix side is extremely small compared to Cu to Al-matrix side, ascribed to the higher diffusion coefficient of Cu in Al than that of Al in Cu [22]. Therefore, Cu and Sn atoms from the bronze-matrix diffuse directly to Al-matrix, and the combination of Cu with Al leads to the formation of Al₂Cu. The remained Sn in Al-matrix would be distributed between Al₂Cu and Al-matrix since the Al-Sn is a simple eutectic system with restricted solid solubility [23]. Al₄Cu₉ was identified in some reports of diffusion in friction welded Al/Cu bimetallic joints [24]. It is a remarkable fact that Al₄Cu₉ phase is not observed in the present work, which can be attributed to the transformation of Al₄Cu₉ from Al₂Cu through the slower solid-state diffusion coupled with insufficient diffusion time [25]. Obviously, the increased Cu₃Sn chemical composition originates from the decomposition of Cu₆Sn₅.

Figures 7(a) and (b) exhibit SEM results of the interface between the Al-matrix and the bronze foams filler for samples 1# and 4#, respectively. The combination of the interface was high close for sample 1#. However, some cracks and gaps arise in the local boundary when the carbamide particles volume in the filler reaches 70%, as in sample 4#. The result suggests that the interface bond between Al foams matrix and the bronze foams filler tends to get worse rather than better, which can be attributed to the more apparent volume shrinkage effect of Cu₃Sn with the augmentation of the bronze foams filler porosity [19]. From figures 7(b1)–(b3) where the element distributions of Al, Cu and Sn are displayed, it can be obviously observed that the copper and tin atoms diffuse to the Al side although some cracks and gaps are produced in the local boundary.
3.4. Mechanics property analysis

Figure 8 presents compressive stress-strain curves of the open-cell Al foams filled with different relative density bronze foams without radial constraints. The diagram shape of the stress-strain curves can be divided into four typical main regions, including initial quasi-linear elastic region (I), stress decline region (II), plateau stress region (III) and the densification region (IV), as indicated for sample 1#. It is clear that the stress-strain relationship of the open-cell Al foams composite differs from any other Al foams due to the interaction between the bronze foams filler and pore walls of the Al foams. The densification strain trends to reduce with increasing the relative density of bronze foams filler. In the initial quasi-linear elastic region (I), the increase in maximum stress for the open-cell Al foams composites can be ascribed to the filled bronze foams with strength is much higher than that of Al foams. That is, the lateral deformation of the Al foams cell walls was hindered by the bronze foams filler, which imposed a resistance to the deformation of Al foams cell walls before the plastic deformation of the filler happened.

It can be observed from Figure 8 that the drum shapes present in the stress-strain curves since the stresses increase firstly and then decline when the strain is roughly below 30%, and the stress-strain behavior of the open-cell Al foams composite is in contrast with that of other metallic foams [1]. As the deformation of open-cell Al foams composite beyond the quasi-linear elastic region, the stress drastic declines and 'bulge' shape forms due to the brittleness of the bronze foams filler. Collapse begins at the weakest cross-section in Al-matrix and spreads progressively into the adjacent area. Cu3Sn serves as a major constituent in the filler at the expense of Cu6Sn5 and Al after isothermal aging. However, both Cu6Sn5 and Cu3Sn phases are brittle in nature. Furthermore, Al7Cu is formed near the interface between Al foams matrix and the bronze foams filler in the present work, which may
also decrease the plasticity and ductility. Subsequently, the plateau stress region (III) appears after the bronze foams filler is completely crumbled and collapsed until the densification region (IV) happens. It is evident that the collapsed plateau strength (Region III) of samples 1#, 2#, 3# is similar but higher than that of sample 4#. The phenomenon may be attributed to the stronger influence of the crushed bronze foams on the Al-matrix due to the filler with higher relative density.

The metallic foams with a single component normally is usually divided into three stages, i.e. linear elastic deformation region (I), plateau stress region (II) and densification region (III) [1]. It also can be obtained that the compressive stress-strain curve of Al/Cu bimetallic foams is characterized as five typical stages including two quasi-linear regions, two plateau stress regions and a densification region [26]. The second plateau stress that arises from Cu-matrix is higher than the first one of Al-matrix, suggesting that the gradient-growth plateau stress will benefit the energy absorption capacity. However, a ‘bulge’ shape appears in the compressive stress-strain curve of Al foams composite, which differs markedly from both the single-component metal foams and Al/Cu bimetallic foams. It is well known that the protected objects are constantly subjected to huge external forces, easy to cause damage to the organizational structure. Whereupon, the maximum bearing capacity of the protected object will be weakened at the latter stage and the object will be more vulnerable to injury. Then in the later stage (area III), the reducing of the plateau stress will help to reduce the external force on the protected object, thus avoiding damage. That is to say, the filled bronze foams in the Al foams can improve the plateau stress in the initial plateau stress. Due to the non-durable high plateau stress, no harmful effects will be on the protected objects simultaneously. Therefore, this structural material is expected to be a new kind of anti-collision structural material.

Figure 9 shows the mechanical properties, such as the first maximum compressive strength, plateau stress, the change rate of absorption energy density and absorption energy density were derived from the stress-strain curves. The first maximum stress increases gradually with the augment of the bronze foams filler relative density. The plateau stress according to the arithmetical mean of stress values between 20% ($\varepsilon_1$) and 40% ($\varepsilon_2$) strain was calculated [15] as follows:

$$\sigma_{\text{plateau}} = \frac{1}{\varepsilon_1 - \varepsilon_2} \int_{\varepsilon_1}^{\varepsilon_2} \sigma(\varepsilon) d\varepsilon$$

(2)

Figure 6. SEM morphologies and EDS analysis for the interfaces of Al foams filled with bronze foams of sample 3#. 
The energy absorption density, namely, the area under the stress-strain curve and can be written as:

\[ W = \int_{0}^{\varepsilon} \sigma(\varepsilon) \, d\varepsilon \]  

where \( \sigma(\varepsilon) \) is the compressive stress as a function of the strain \([15]\).

The energy absorption capacity of each structure was defined as the area under the load-displacement curve for up to 50% strain, as shown in figure 9(c). Obviously, the higher the stress plateau, the greater the energy absorption capacity. Energy absorption of the foams is mainly dependent on the buckling, yielding, fracture,
Figure 8. The compressive stress-strain curves of the open-cell Al foams filled with different relative densities of bronze foams.

Figure 9. Mechanical property parameters of the open-cell Al foams composite as function of the relative densities of bronze foams.
friction of cell walls and the interaction between the bronze foams filler and the Al foams pore wall during compressive deformation. Under impact, the energy absorber follows a energy absorption density-strain curve which rises sharply at first and then increases slowly due to the bronze foams filler with hard and brittle. Obviously, the feature of curve suggests that the open-cell Al foams composite is beneficial to improve rapidly the energy absorption capacity at the initial stage.

To better study the influence of bronze foams filler relative density on the change rate of energy absorption capacity at the initial stage (the strain is below 30.0%), linear fitting was made for the slope of the absorption energy density versus strain as shown in figure 9(c). The results of the linear fitting slopes are 22.56, 13.60, 6.12 and 4.27 MJ/m³, respectively. It can be obtained that the relative density of bronze foams filler has a significant effect on the increased rate of the energy absorption capacity when the strain is the range of 0 to 30.0%. The energy absorption density increases with the augment of bronze foams filler relative density, as shown in figure 9(d), indicating that the relative density of filler plays an important role. The high relative density of the bronze foams can effectively increase plateau stress at the initial stage. However, when the deformation degree is the same, the excessive growth load in initial stage acting on the protected object will go against the impact protection. Therefore, choosing bronze foams with the appropriate relative density to fill the pores of Al foams can be favorable for improving energy absorption and avoiding the excessive large initial peak load. The improvement of absorption efficiency will make impact protection more effective and more reliable.

4. Conclusions

The stress-strain relationship and mechanical properties of the open-cell Al foams filled with bronze foams were studied. After isothermal sintering, Cu₆Sn₅ reacts with Al-matrix and Cu₃Sn becomes the major filler in the open-cell Al. The interface microstructure between Al-matrix and the filler is subject to the filler porosity of bronze foams. Because of the brittleness of the bronze-filled material, the drum shape appears in the compressive stress-strain curve of Al foams composite, which is fundamentally different from that of single-component metal foams. The drum-shaped stress-strain curve can be divided into 4 typical stages, i.e. the quasi-linear region, stress decrease region, plateau stress region and the densification region. The first maximum stress, the plateau stress and the absorbed energy density increase with augmenting the bronze foams filler relative density. As a consequence, selecting the bronze foams with appropriate relative density to fill the Al foams is beneficial to improve the mechanical properties of the open-cell Al foams.

Acknowledgments

This research work is supported by China’s Sichuan Science and Technology Program (2019YJ0441), Chengdu Normal University First-class Discipline Construction Major Scientific Research Projects (CS18ZDZ03) and Chengdu Normal University College Students Innovation and Entrepreneurship Training Program Project (S202114389008).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Changzhong Liao  © https://orcid.org/0000-0002-7426-870X

References

[1] Feng Q, Wu X, Guo Y, She J and Xiang Y 2018 The effect of aluminium dihydrogen phosphate on the enhanced mechanical properties of aluminium foams Mater. Trans. 59 922–6
[2] Yan L, Li Y, B, Han B, Chen C, Q, Zhang Q C and Lu T J 2013 Compressive strength and energy absorption of sandwich panels with aluminium foam-filled corrugated cores Compos. Sci. Technol. 86 142–8
[3] Zhu F, Zhao L, Lu G and Wang Z 2008 Deformation and failure of blast loaded metallic sandwich panels-Experimental investigations Int. J. Impact Eng. 35 937–51
[4] Nosko M, Simancik F and Florek R 2010 Reproducibility of aluminium foam properties: effect of precursor distribution on the structural anisotropy and the collapse stress and its dispersion Mater. Sci. Eng. A 527 5900–8
[5] Szlancik A, Katona B, Bobor K, Möllinger K and Orbudov I N 2015 Compressive behaviour of aluminium matrix syntactic foams reinforced by iron hollow spheres Mater. Des. 83 230–7
[6] Bicelli L P, Bozzini B, Mele C and D'Urzo I 2008 A review of nanostructural aspects of metal electrodeposition Int. J. Electrochem. Sci. 3 356–408
[7] Devivier C, Tagliaferri V, Trovalusci F and Ucciaridello N 2015 Mechanical characterization of open cell aluminium foams reinforced by nickel electro-deposition Mater. Des. 86 272–8
[8] Feng Q, Liao C, Peng Y and Zhang S 2020 Strengthening the pore walls of Al foams with surface-alloying technique Surf. Rev. Lett. 27 1950212
[9] Boonyongmaneerat Y, Schuh C A and Dunand D C 2008 Mechanical properties of reticulated aluminium foams with electrodeposited Ni-W coatings Scr. Mater. 59 336–9
[10] Cheng H F and Han F S 2003 Compressive behavior and energy absorbing characteristic of open cell aluminium foam filled with silicate rubber Scripta Mater 49 583–6
[11] Gibson L J and Ashby M F 1997 Cellular Solids: Structures and Properties (Cambridge: Cambridge University Press) 2nd edn.250
[12] Acharya N N 2001 Thermal analysis of slow cooled copper–tin alloys J. Mater. Sci. 36 4779–95
[13] Zhao H Y, Liu J H, Li Z L, Song X G, Zhao Y X, Niu H W, Tian H, Dong H J and Feng J C 2018 A Comparative study on the microstructure and mechanical properties of Cu3Sn and Cu6Sn5 joints formed by TLP soldering with/without the assistance of ultrasonic waves Metall. Mater. Trans. A 49 2739–49
[14] Liu B, Tian Y, Wang C, An R and Liu Y 2016 Extremely fast formation of Cu3Sn intermetallic compounds in Cu/Sn/Cu system via a micro-resistance spot welding process J. Alloys Compd. 687 667–73
[15] Standard I 2011 ISO (International Standardization Organization) 13314: 2011 (E) Mechanical testing of metals–ductility testing-compression test for porous and cellular metals. Ref Number ISO. 13314 (13314), 1–7
[16] Doube M, Klosowski M M, Arganda-Carreras I, Cordelieres F P, Dougherty R P, Jackson J S, Schmid B, Hutchinson J R and Shefelbine S J 2010 Bone: free and extensible bone image analysis in image J Bone 47 1076–9
[17] Patra S, Satpati B and Pradhan S K 2009 Microstructure characterization of mechanically synthesized ZnS quantum dots J. Appl. Phys. 106 034313
[18] Lutterotti L and Gialanella S 1998 X-ray diffraction characterization of heavily deformed metallic specimens Acta Mater. 46 101–10
[19] Yu C, Chen J, Wang K, Chen J Q and Lu H 2013 Suppression effect of Cu and Ag on Cu6Sn5 layer in solder joints J Mater Sci: Mater Electron 24 4630–5
[20] Chen J, Li Y S, Yang P F, Ren C Y and Huang D J 2009 Prospects of biodiesel production from microalgae in India J. Mater. Res. 24 2361–72
[21] Balakrishnan B, Chum C C, Li M, Chen Z and Cahyadi T 2003 Fracture toughness of Cu–Sn intermetallic thin films J. Electron. Mater. 32 166–71
[22] Viňáš J, Vrabeí M, Greš M, Brezina J, Sabadka D, Fedorko G and Molnár V 2018 Restoration of worn movable bridge props with use of bronze claddings. Materials 11 459
[23] Saed T, Abdullah-Zadeh A and Sazgari B 2010 Weldability and mechanical properties of dissimilar aluminium copper lap joints made by friction stir welding J. Alloy Compd. 490 652–5
[24] Qian Y Y, Dong Z G and Gao F 2002 Microstructure development and metallurgical analysis of the Al–Si contact reaction J. Mater. Process. Technol. 122 305–8
[25] Han Y Q, Ben I H, Yao J J, Feng S W and Wu C J 2013 Investigation on the interface of Cu/Al couples during isothermal heating. Int. J. Min. Met. Mater. 22 309–18
[26] Feng Q, Ma S, Liao C, Xie Y and Duan Z 2021 Effects of CuSn33 content on the microstructure and mechanical properties of Al/Cu bimetallic foams Mater. Res. Express 8 016504