Effects of stirring speed and flux composition on the recycling of aluminium foams

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Abstract
Owing to the excellent performance of aluminium foam in transportation, construction, and aerospace applications, their production has increased rapidly in recent years, leading to the accumulation of an increasing quantity of aluminium foam scrap and used aluminium foams. An efficient recycling process for these products is urgently required for resource conservation and environmental protection. In this study, a flux-covering method is employed to recycle aluminium foams. The effects of stirring speed and flux composition on the recycling process were investigated. An orthogonal test was performed to determine the optimal flux parameters for NaCl, KCl, and NaF. The microstructures of aluminium foams and recycled aluminium were observed using scanning electron microscopy and optical microscope, respectively. Phase compositions of foams, flux, recycled aluminium, and slag were analysed using X-ray diffraction. The results showed that the recovery was improved with increasing stirring speed, and the optimal stirring speed was 150 r min⁻¹; under the present conditions. In addition, the composition of the flux exhibited a significant impact on the recovery. The recovery reached 86.35% when the NaCl, KCl, and NaF concentrations were 15, 15, and 5 wt%, respectively. The mechanisms of recovery improvement were discussed in terms of the primary crystal temperature of flux as well as the thermodynamics and kinetics of the impurity removal.

1. Introduction
Aluminium foams exhibit unique mechanical, thermal, acoustic, and electrical properties [1–15], rendering them attractive in transportation, construction, and aerospace applications [16–26]. Now, aluminium foams have reached the maturity of development in terms of process stability, materials properties and costs required for industrial applications [6, 10]. Meanwhile, owing to the development of high-speed trains, urban railways, light-weight vehicles, and aerospace industry, the demand for aluminium foams is expected to continually increase in the next few years [6]. As a result, the amount of aluminium foam scrap generated during the production and the replacement processes of the aluminium foams will continue to increase. Therefore, recycling aluminium foam is necessary to save natural resources and to comply with legal requirements concerning environmental protection. Compared with aluminium scrap, the aluminium foam has a larger specific surface area and contains more impurities owing to the addition of thickening and foaming agents, which complicate its recycling. The issue of aluminium foam recycling has attracted significant research attention. Ding et al. [27, 28] recycled aluminium foams using a flux-covering method employing NaCl, KCl, and NaF fluxes. NaCl and KCl, the most common fluxes for remelting, are used as covering agents to prevent the combustion of aluminium foam and the further oxidation of molten aluminium in the high temperature furnace, and to remove the inclusion in the foam. NaF can reduce the interfacial tension between molten aluminium and flux and the adhesion work between molten aluminium and impurities, which improve the
Impurity removal effect of the fluxes. Various aspects of the recycling process of aluminium foams, including flux addition, temperature, pre-treatment, and fluoride content, have been extensively studied and reviewed [27–29]. The microstructure and mechanical properties of commercially pure aluminium and recycled aluminium from aluminium foam have been compared and analysed [30–32]. The foam prepared using TiH₂ as a foaming agent has a relatively high content of Ti, and its recycling needs more consideration than that of general aluminium scraps [33]. In addition, secondary aluminium foams have been successfully fabricated using a melt foaming method employing recycled aluminium as raw material [10, 27–29].

Recent publications on the recycling of aluminium foam scrap focus on the recycling process, microstructure, properties, and secondary foaming of recycled aluminium. However, there are few studies on the mechanisms of aluminium foams recycled using flux. Moreover, molten aluminium obtained after the melting process is hard to coalesce owing to the stable oxide barrier layer [36]. To elucidate the process of aluminium foam melting and molten aluminium coalescence, it is necessary to study the recycling mechanisms of the flux-covering method. Therefore, the present study focuses on the mechanism of recycling of the aluminium foam using different flux compositions.

2. Experimental procedures

2.1. Recycling of aluminium foam

In this study, a flux-covering method was used to recycle the aluminium foam scrap fabricated using a melt foaming method with Ca and TiH₂ as thickening and foaming agents, respectively (figure 1(a)). NaCl (analytically pure, Tianjin Tianli Chemical Reagent Co., Ltd.), KCl, and NaF (analytically pure, Tianjin Hongyan Chemical Reagent Factory) were used as the flux. The recycling process is shown in figure 2. First, the aluminium foam scrap (∼300 g) was placed in a graphite crucible; thereafter, NaCl, KCl, and NaF were mixed and placed in the crucible to cover the foams. The mixture was melted in a resistance furnace and stirred for 4 min. The crucible was held in the furnace, and the mixture was separated into slag and molten aluminium. Finally, the crucible was cooled in air to obtain recycled aluminium (as shown in figure 1(b)). During the melting, stirring, and holding process, the temperature of the furnace was controlled at 993 ± 5 K.

For the experiment of the effect of stirring speed on the recovery, the total content of flux (NaCl:KCl:NaF = 2:2:1, i.e., NaCl, KCl, and NaF were 8wt%, 8wt%, and 4wt%) was 20wt% of the aluminium foam scrap based on previous studies [29, 30, 32]. And the same processing parameters, except the stirring speed, were maintained.

2.2. Orthogonal test

An orthogonal test design was used to optimise the flux parameters. NaCl, KCl, and NaF were considered for the orthogonal test, and their levels are listed in table 1. An L₀(3³) orthogonal table has been established in table 2. The subscript ‘9’ in L₉ indicates the number of experiments, which is lower than the possible number of experiments. If all possible parameter groupings were tested, the total number of tests would be 27. In the parentheses, the exponent ‘3’ is the number of factors, and the base ‘3’ represents the number of levels of each factor. The orthogonal experiments were performed based on these factors and levels (table 2), and the process was the same as that in section 2.1.
2.3. Analytical method

Recovery is the most important feature for evaluating the recycling results of aluminium foams. The recovery was calculated using equation (1) [27, 37].
where $P$ is the recovery of aluminium foams; $m_0$ is the mass of aluminium foams; $m_1$ is the mass of recycled aluminium. The microstructure of recycled aluminium obtained at different stirring speeds was observed by optical microscope (OM). The morphology of aluminium foam was characterised using scanning electron microscopy (SEM; Hitachi S4800) integrated with energy dispersive x-ray spectroscopy (EDS). Phase components of aluminium foams, flux, recycled aluminium, and slag were identified using x-ray diffraction (XRD, D8 Advance, Bruker) with a scanning speed of $10^\circ$ min$^{-1}$ and a scanning angle of $10^\circ–90^\circ$.

3. Results

3.1. Morphology of aluminium foam

The microstructure of the original aluminium foam is shown in figure 3. The points analysis of ‘1’ and ‘2’ in figure 3(a) are showed in figures 3(b) and (c), respectively. Surface scanning on the cell wall is showed in figures 3(d)–(f). It can be seen that Al is the matrix of the foam distributed in the cell wall. Ca is mainly distributed at the grain boundaries, while most of oxygen is present on the surface of the pore. The result of Ti is not given because of the less content and inconspicuous distribution of Ti.

3.2. Effect of stirring speed

3.2.1. Morphology analysis

Figure 4 shows the microstructures of recycled aluminium obtained at different stirring speeds. It can be seen that the average grain sizes and the amounts of precipitates at grain boundaries are not significantly different at different stirring speeds. Whereas, the quantities of inclusions show obvious variance. There are many inclusions in the microstructure without any stirring. While, almost no inclusions can be seen at stirring speeds of 50 and 150 r min$^{-1}$. This indicates that stirring has a significant influence on the removal of inclusions. In addition, slags after recycling are observed and the results are showed in figure 5. The slags mainly exist in three forms. The large piece of unmelted aluminium foam is defined as form 1 (figure 5(a)). The slags containing aluminium and small pieces of unmelted aluminium foam are defined as form 2 (figure 5(b)). The slags with smaller particles (negligible aluminium content and unmelted aluminium foam) are defined as form 3 (figure 5(c)). Without any stirring, the slags mainly exist as form 1. When the stirring speeds are 50 and 150 r min$^{-1}$, the slags mainly exist as forms 2 and 3, respectively. The results mean that stirring affects the form of slags.

3.2.2. Recovery

Figure 6 shows the mass of recycled aluminium and the recovery of aluminium foams at different stirring speeds. Without any stirring, the recycling process is ineffective, and the recovery is only 12.3%. The recovery increases...
to 45.1% at a stirring speed of 50 r·min⁻¹, suggesting that stirring is beneficial for enhancing recovery. The maximum recovery (78.5%) is obtained when the stirring speed is 150 r·min⁻¹. Further increasing the stirring speed makes the mixture unstable and prone to splash out of the crucible, thereby reducing the recovery under the present conditions.

3.3. Orthogonal test of different flux composition

In the orthogonal test design, recovery is chosen as the examined index, and the results are shown in Table 2. $K_i$ and $\bar{K}_i$ (i represents three levels, namely, as 1, 2, and 3) are the total and mean values of recovery, respectively, with the same level of i in the same column of the table. $R$ is the range of max ($\bar{K}_i$) and min ($\bar{K}_i$) in the same column. When R increases, the impact of the factor on recovery becomes more significant. As shown in Table 2, based on the R value, NaF has the most significant effect on the recovery of aluminium foams followed by KCl and NaCl.
To understand the influence of each factor on the recovery of aluminium foams, the mean recoveries were obtained using the same level of NaCl, KCl, and NaF. As shown in figure 7, the mean recovery of aluminium foams strongly depends on the level of the same factor, suggesting that the contents of NaCl, KCl, and NaF are important factors affecting the recycling of aluminium foams. The mean recovery is as follows: \( \bar{K}_3 > \bar{K}_2 > \bar{K}_1 \) for NaCl, \( \bar{K}_3 > \bar{K}_2 > \bar{K}_1 \) for KCl, and \( \bar{K}_3 > \bar{K}_2 > \bar{K}_1 \) for NaF. When the contents of NaCl and KCl increase and the content of NaF decreases, the mean recovery increases.

The optimal levels of NaCl, KCl, and NaF are 3, 3, and 1, respectively, i.e., the appropriate contents of NaCl, KCl, and NaF are 15, 15, and 5 wt%, respectively. The optimal parameters evaluated using the examined index point agree with the results of test number 3 in the orthogonal experiment.

4. Discussion

The phase transformation during the recycling of aluminium foams was investigated. Figure 8 shows the XRD patterns of flux, aluminium foam (before recycling), recycled aluminium, and slag (after recycling). The phase components of flux can be confirmed as NaCl, KCl, and NaF due to the flux mixed by NaCl, KCl, and NaF. The major phase present in aluminium foams is Al. Meanwhile, the minor phases of aluminium foams are identified as \( \text{Al}_2\text{O}_3 \) and \( \text{Al}_4\text{Ca} \) due to the oxygen introduced by stirring and the addition of calcium granules as a thickening agent while preparing the aluminium foams. Notably, no distinct diffraction peaks of titanium were observed.

Figure 7. Mean recoveries at the same level of NaCl, KCl, and NaF.

Figure 8. XRD patterns of flux, aluminium foam, recycled aluminium, and slag.
owing to the addition of a small amount of TiH₂ as the foaming agent. The recycled aluminium is mainly composed of Al, and the diffraction peaks of Al₂O₃ and Al₆Ca are not detected. While complex oxides \( (K_aAl_yO_{13.5y/2})_3Na_2Al_yO_{(13.5y/2)} \) and \( (CaO)_3(Al_2O_3)_{11} \), CaF₂, and NaCl are observed in the slag, suggesting that the oxides and other impurities in the aluminium foams interact with the flux to form the slag. Considering that the most critical step in foam recycling is the removal of impurities, the results show that sufficient contact between flux and impurity can ensure a successful recycling process.

Stirring is conducive to the contact between flux and impurity, which facilitates the removal of impurities such as inclusions. In addition, the inclusion concentration can be expressed using equation (2) [38].

\[
\frac{c}{c_0} = \exp(-kt)
\]  

(2)

where \( c_0 \) is the initial concentration of inclusion; \( c \) is the concentration of inclusion at time \( t \); \( k \) is a constant related to the stirring intensity, and the value of \( k \) increases with increasing stirring intensity. According to equation (2), the value of \( c \) decreases with \( k \), i.e., increasing stirring intensity promotes inclusion removal. The reasons explain that stirring can reduce the inclusions in the microstructure of recycled aluminium.

Besides, the aluminium foams recycled using flux without stirring retain the porous structure after a long period of heating. This is because the stable oxides on the surface of pores help to maintain the porous structure. When the stirring speed is 50 and 150 r·min⁻¹, the porous structure of aluminium foams is destroyed, indicating that agitation is conducive to the collapse of pores. This is mainly because stirring improves the fluidity of flux [33] and increases the contact between the flux and aluminium foams. It is well known that an oxide layer is present on the surface of aluminium foams. Stirring can facilitate the removal of the oxide layer and promote the recycling of aluminium foams. Therefore, no large pieces of unmelted aluminium foams are found in the slags obtained at the stirring speed of 50 and 150 r·min⁻¹. The results also prove that the recycling of aluminium foams can be accelerated by stirring. Notably, at a slow stirring speed, parts of aluminium foams may not be fully contacted with the flux, resulting in small pieces of unmelted aluminium foams in the slags. Additionally, several aluminium drops separated by the flux or impurity fail to coalesce at a low stirring speed, leading to small pieces of aluminium in the slag. Increasing stirring speed is conducive to forming complete contact between aluminium foam and the flux and promoting corrosion on oxides by the flux and coalescence of aluminium drops. Therefore, the recovery of aluminium foams at the stirring speed of 150 r·min⁻¹ is significantly improved compared with that at the stirring speed of 50 r·min⁻¹.

Although agitation can promote the removal of impurities, the flux composition is a fundamental factor that determines the removal of impurities. To clearly understand the effect of flux composition on the removal of impurities, the thermodynamics and kinetics of impurity removal are analysed. The thermodynamic and kinetic conditions are obtained using the following equations [38, 39].

\[
\Delta G = \sigma_{M-F} \cos \theta_{M-I}
\]

(3)

\[
W_{M-I} = \sigma_{M-F}(1 + \cos \theta_{M-I})
\]

(4)

\[
\frac{dc}{dt} \propto \omega = \exp(-W_{M-I}/RT)
\]

(5)

where \( \Delta G \) is the change in the Gibbs free energy of the system; \( \sigma_{M-F} \) is the interfacial tension between molten aluminium (M) and flux (F); \( \theta_{M-I} \) is the wetting angle between molten aluminium and impurities (I); \( W_{M-I} \) is the adhesion work between molten aluminium and impurities; \( \frac{dc}{dt} \) is the migration speed of impurities from molten aluminium into flux; \( \omega \) is the probability of impurities leaving the molten aluminium–flux interface. According to equation (3), the thermodynamics are mainly affected by \( \sigma_{M-F} \) and \( \theta_{M-I} \). As the \( \theta_{M-I} \) is generally \( > 90^\circ \), i.e., \( \cos \theta_{M-I} < 0 \), high values of \( \sigma_{M-F} \) and \( \theta_{M-I} \) reduce \( \Delta G \), thereby thermodynamically facilitating the recycling. According to equations (4) and (5), the favourable kinetics are mainly attributed to a decreased \( W_{M-I} \), which is associated with a low \( \sigma_{M-F} \) and a high \( \theta_{M-I} \). Therefore, both \( \sigma_{M-F} \) and \( \theta_{M-I} \) affect the thermodynamics and kinetics, and an increasing \( \theta_{M-I} \) is favourable for the thermodynamics and kinetics of the impurity removal; whereas, the \( \sigma_{M-F} \) has the opposite effect on the thermodynamics and kinetics (i.e., the increasing \( \sigma_{M-F} \) is favourable for the thermodynamics and unfavourable for the kinetics).

The \( \sigma_{M-F} \) and \( \theta_{M-I} \) are closely related to the flux composition, which significantly impacts the thermodynamics and kinetics of impurity removal. In the orthogonal test, the recovery of aluminium foams is more dependent on NaF than NaCl and KCl. The presence of NaF can increase \( \theta_{M-I} \) [40], which benefits the thermodynamics and kinetics of the recycling. In addition, the \( \cos \theta_{M-I} \) is always \( < 0 \); consequently, \( \Delta G < 0 \). Therefore, the impurity removal process can proceed spontaneously based on the thermodynamics. NaF decreases \( \sigma_{M-F} \) [40], which is conducive to the kinetics and explains the accelerated removal of impurities, such as oxides, by NaF. Moreover, the viscosity of the flux [41] is reduced by NaF, prompting the coalescence of aluminium drops and improving the recovery of aluminium foams. However, the results of the orthogonal test show that the recovery of aluminium foams decreases with the content of NaF. This can be explained using the
following factors. As the content of NaF increases, the excessive decrease of $\sigma_{\text{M-F}}$ causes weak separation between molten aluminium and flux, which is unfavourable for thermodynamics. The distribution of the fluxes in the phase diagram of the NaCl–KCl–NaF ternary system [42] and the effect of NaF on the primary crystal temperature of the fluxes are shown in figures 9(a) and (b), respectively. With the increase of the NaF content in the flux, the primary crystal temperature increases distinctly. It is well known that the temperature (particularly the temperature higher than that of aluminium foam recycling) affects the viscosity of the fluxes. The viscosity can affect the recycling process of foams, such as the coalescence of aluminium drops. To clearly understand the effect of the primary crystal temperature on the recycling of aluminium foams, the correlation between the recovery of the aluminium foams and the primary crystal temperature are shown in figure 10. The recovery tends to decrease with the primary crystal temperature, indicating that a high primary crystal temperature has an adverse effect on the recycling of aluminium foams. The results suggest that the amount of NaF in the flux should be appropriately controlled.

Additionally, the recovery of foams is improved with the increase of KCl contents according to the orthogonal experiment results. This is because KCl has wettability and adsorbability to oxides [43, 44]. Moreover, among NaCl, KCl, and NaF, KCl has the lowest melting point and surface tension, which makes it easy to spread and serve as a covering agent [43]. Therefore, increased KCl addition can promote removal of impurities and recycling of aluminium foam. Though NaCl has the minimum effect on recovery, it is still necessary to add NaCl in the flux. The reasons can be explained as follow. First, NaCl has wetting and adsorption effects on oxides, which is similar to KCl [43, 44]. Second, the mixture of NaCl and KCl has more excellent
adsorbability to oxides than a single chloride salt. Third, flux with similar mole fractions of NaCl and KCl has lower primary crystal temperature \([43, 44]\), which is conducive to removal of impurities. It implies that the effect of NaCl on the recovery is not negligible. Besides, according to the phase diagram of the NaCl–KCl–NaF ternary system, the primary crystal temperature of flux can be decreased within limits with the increase of NaCl and KCl contents. It is further evidence that recovery of aluminium foam can be improved with the content of NaCl and KCl increasing.

Based on aforementioned results, the process of impurity removal from aluminium foam can be divided into five stages, and a model is established as shown in figure 11. Initially the porous structure of the aluminium foam is maintained during the heating due to the stable oxides (figure 9(a)). As heating continues, the flux corrodes the oxides on the surface of aluminium foams (figure 9(b)). When the oxides on the surface are constantly corroded by flux, the pores in the foam collapse, and the aluminium drops are besieged by oxides from the surface of pores (figure 9(c)). This stage is difficult to complete without stirring because agitation can accelerate the collapse of pores. Thereafter, the flux maintains close contact with oxides on the surface of aluminium drops and corrodes the oxides. Afterwards, the flux spalls and adsorbs the oxides from the surface of aluminium drops (figure 9(d)). Finally, the oxides are removed by flux, which reduces the resistance of coalescence of aluminium drops and realises the recycling of aluminium foams (figure 9(e)). In the process, collapse of pores, detachment and adsorption of impurities, and coalescence of aluminium drops are the critical steps restricting the recycling of aluminium foam. While considering the recycling of aluminium foam, it is essential to analyse the effect on the critical steps and select appropriate parameters.

5. Conclusions

Aluminium foam scraps were recycled using a flux-covering method. The effects of stirring speed and flux composition on the recycling of aluminium foams were investigated, and the results obtained in this work were listed as follows:

(1) Stirring is conducive to the removal of impurities and reduce the inclusion in microstructure of recycled aluminium. With the stirring speed increasing, the recovery of aluminium foam is improved. An optimal recovery is obtained at a stirring speed of 150 r·min\(^{-1}\) under the present conditions.

(2) NaF has the most significant impact on the recovery of aluminium foams followed by KCl and NaCl. In addition, When the contents of NaCl and KCl increase and the content of NaF decreases, the mean recovery increases. The optimal recovery of aluminium foams is 86.35% when the contents of NaCl, KCl, and NaF are 15, 15, and 5 wt%, respectively.

(3) An impurity removal model of recycling of aluminium foam is established for the first time. Collapse of pores, detachment and adsorption of impurities, and coalescence of aluminium drops are the critical steps restricting the recycling of aluminium foam.

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

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References
[1] Kumar R, Jain H, Sriram S, Chaudhary A, Khare A, Ch V A N and Mondal D P 2020 Lightweight open cell aluminium foam for heat sink and electromagnetic interference shielding properties Mater. Chem. Phys. 240 8
[2] Verma K S, Muchhal D, Panthi S and Mondal D P 2020 Experimental and numerical study of compressive deformation behavior of closed-cell aluminium foam Strength Mater. 52 451
[3] Sathiaiah S, Dubey R, Pandey A, Gorhe N R, Joshi T C, Chilla V, Muchhal D and Mondal D P 2021 Effect of spherical and cubical space holders on the microstructural characteristics and its consequences on mechanical and thermal properties of open-cell aluminium foam Mater. Chem. Phys. 273 12
[4] Pandey A, Muchhal D, Kumar R, Sriram S, Ch V A N and Mondal D P 2020 Flexural deformation behavior of carbon fiber reinforced aluminium hybrid foam sandwich structure Compos. Part B-Eng. 183 1
[5] Rajak D K, Kumaraswamidhas I A and Das S 2018 Investigation of mild steel thin-wall tubes in unfilled and foam-filled, square, and hexagonal cross sections under compression load J. Mater. Eng. Perform. 27 1936
[6] Rajak D K and Gupta M 2020 An Insight Into Metal Based Foams: Processing, Properties and Applications. (Singapore: Springer Nature) (https://doi.org/10.1007/978-981-15-9069-6)
[7] Heim K, Garcia-Moreno F and Banhart J 2018 Particle size and fraction required to stabilise aluminium alloy foams created by gas injection Scripta Mater. 153 54
[8] Heim K, Vinod-Kumar G S, Garcia-Moreno F and Banhart J 2017 Stability of various particle-stabilised aluminium alloys foams made by gas injection J. Mater. Sci. 52 6601
[9] Mukherjee M, Garcia-Moreno F, Jiménez C, Rack A and Banhart J 2017 Microporosity in aluminium foams Acta Mater. 131 156
[10] Banhart J, Vinod-Kumar G S, Kamm P H, Neu T R and Garcia-Moreno F 2016 Light-metal foams: some recent developments Ciência & Tecnologia dos Materiais 28 1
[11] Chaudhary A, Gupta V, Teotia S, Nimanpure S and Rajak D K 2021 Electromagnetic shielding capabilities of metal matrix composites Encyclopedia of Materials: Composites 1 428
[12] Rajak D K, Kumaraswamidhas I A and Das S 2017 Technical overview of aluminium alloy foam Rev. Adv. Mater. Sci. 48 68 (https://ipme.ru/e-journals/RAMS/no_14917/06_14917_rajak.pdf)
[13] Das S, Rajak D K, Khanna S and Mondal D P 2020 Energy absorption behavior of Al-SiC-graphene composite foam under a high strain rate Materials 13 783
[14] Rajak D K, Gavande S A and Kumaraswamidhas I A 2018 Evaluation of mild steel hollow and foam filled circular tubes under axial loading Adv. Mater. Lett. 9 660
[15] Zhang G, Deng B, Liu Q Y, Yang H, Jing M, Hussain S and AlGarni T S 2021 Enhanced areal specific capacity and energy density of solid-state lithium battery by using porous aluminium foam J. Energy Storage 33 7
[16] Sarmadi M, Nassirip R, Razavianf F and Khoshmehranshe B 2021 Synthesis of aluminium foam and its application in reducing noise pollution in a gas power plant under construction Jundishapur J. Health Sci. 13 8
[17] Buonomo B, Pasqua A, Manca O and Nappo S 2021 Entropy generation analysis on heat exchanger in aluminium Foam Ital. J. Eng. Sci. 65 166
[18] Sun M, Fan M, Li L, Xu Z and Yang T 2020 Thermal conductivity of aluminium foam based on 3-D stochastic sphere model J. Heat Transf. 49 823
[19] Koptunov AI, Khokhlov Y Y, Myamin S V and Semistenov DA 2020 Mechanical and operational characteristics of layered titanium-aluminium foam composite materials Inorg. Mater. Appl. Res. 11 238
[20] Zhang X, Wang R, Li X, Lu C, Wang Z and Wang W 2021 Energy absorption performance of open-cell aluminium foam and its application in a landing buffer structure J. Mater. Eng. Perform. 30 6152
[21] Elsheniti MB, Eissa MS, Al-Ansary H, Ordnance Mater. Sci. Eng. 5 2020 Multifunctional FRP-aluminium foam production setup for battery housings of electric vehicles Technol. Lightweight Struct. 4 9
[22] Baumeister J, Weise J, Myslicki S, Kieseritzky E and Lindenberg G 2020 PCM-based energy storage system with high power output using open porous aluminium foams Energies 13 17
[23] Nakamura N, Yokoshima T, Nara H, Mikuriya H, Shiosaki A, Ahn S, Momma T and Osaka T 2021 Polypropylene modification of high sulfur-loaded three-dimensional aluminium foam cathode in lithium–sulfur batteries for high-rate capability J. Electrochem. Soc. 168 10
[24] Pratomo AN, Santos SP, Gunawan L, Widagdo D and Putra IS 2021 Design optimization and structural integrity simulation of aluminium foam sandwich construction for armored vehicle protection Compos. Struct. 276 19
[25] Schmerler R, Gebken T, Kuhn M, Drossel W, Drieder K and Lies C 2020 Multifunctional FRP-aluminium foam production setup for battery housings of electric vehicles Technol. Lightweight Struct. 4 9
[26] Kravchenko K, Gorbunov M, Lovska A, Gerlic J and Kravchenko K 2021 Dynamics and strength of circular tube open windows with aluminium foam filled center sills Materials (Basel) 1412
[27] Ding L, He SY, He DP and Wei YS 2008 Remelting and re-foaming of waste Al foam Ordnance Mater. Sci. Eng. 31 5
[28] Ding L, Wei YS and He DP 2008 Recycling and re-foaming of Al foam Nonferrous Met. Process. 37 22 + 41
[29] Qin J 2010 Study on recycling of scrapped aluminium foam and heat conduction simulation in aluminium foam Unpublished Master’s Thesis (Changsha: Central South University) (https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2011&filename=2010189306.nh&uniplatform=NZKPT&v=PwTv6uvG0NAGizerZjysF5600yud6EGx89_XvVXU-_hY- xAxD1Dx6dOkl5W)
[30] Feng J L et al 2016 Research on recovery rate and mechanical properties of pure aluminium matrix closed-cell aluminium foam Hot Working Technol. 45 75

[31] Feng J L 2016 The study of recovery process on the application feasibility to the recycled aluminium foam Unpublished Master’s Thesis (Tianjin: Hebei University of Technology) (https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201901&filename=1019816220.nh&uniplatform=NZKPT&v=rSKQJ9iEukEOsY_Miovfdr-DAD1MKHVoN-Ue_wcxFm6MUEEIJ34MRZAWXrQ6QMw)

[32] Wang J, Zhao W M, Wang L S, Ding J, Liao W Z and Huang L X 2018 Effect of Cu on the microstructure and tensile properties of secondary aluminium J. Hebei Univ. Technol. 47 75

[33] Jessen K, Friedrich B and Rombach G 2003 Al-foam production scrap-source for recycling Proceeding of the third international conference on cellular metals and metal foaming technology (Berlin, Germany: MIT-Verlag) 543–7

[34] Feng Y, Zhu Z G, Tao N and Zheng H W 2003 Thermal conductivity of closed-cell aluminium alloy foam Acta Metall. Sin. 39 817

[35] Wang H, Zhou X Y, Long B, Yang J and Liu H 2016 Thermal properties of closed-cell aluminium foams prepared by melt foaming technology Trans. Nonferrous Met. Soc. China 26 3147

[36] Meng Q R and Hu Z L 2010 Main performance characteristics of foamed aluminium Nonferrous Met. Process. 39 6

[37] Zhou Q M and Wan L 2007 Research on purifying process for Al scraps by flux Hot Working Technology 36 23

[38] Li P et al 1995 The thermodynamic and kinetic mechanisms of the process of the flux refinement of Al alloys Mater. Sci. Technol. 3 82 (https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD9495&filename=CLKG503.017&uniplatform=NZKPT&v=5xHRtuHSFT1gkGgewbSbwjaxNv60YAw8k3XEWlH677f4Crgp823ytNHiK3Qkrm)

[39] Fu G S and Kang J X 1992 Thermodynamic and kinetic analysis of flux purification of molten aluminium Fujian Association for Science and Technology Proceedings First Acad. Annual Meeting of Youths (Fujian, China: Fujian Science and Technology Press) 294–9

[40] Fu G S and Kang J X 1995 Analysis on the characters of purification in molten aluminium by flux Foundry Technol. 6 23 (https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD9495&filename=ZZJS506.006&uniplatform=NZKPT&v=h58H3TTjLRW5dsB_1biuZIK04vQ0Q2M3e4RpaAYEelUqH0aSyXlmGZKxglGm4X0oK+)

[41] Tenorio J A S, Carboni M C and Espinosa D C R 2001 Recycling of aluminium - effect of fluoride additions on the salt viscosity and on the alumina dissolution J. Light Met. 1 195

[42] Wang Y, Li X, Li N, Ling C, Tang Z and Li Z 2020 Thermal transport and storage performances of NaCl–KCl–NaF eutectic salt for high temperatures latent heat Sol. Energy Mater. Sol. Cells 218 6

[43] Li D C 2003 Interaction of molten NaCl–KCl–Al system and process of aluminium recycling and refining Unpublished Doctor’s Thesis (Shenyang: Northeastern University) (https://docin.com/p/1386289521.html)

[44] Tenorio J A S and Espinosa D C R 2002 Effect of salt/oxide interaction on the process of aluminium recycling J. Light Met. 2 89