The Influences of Process Parameters on the Preparation of Closed-cell Aluminum foam by Friction Stir Processing

Qiu Pang

Wuhan University of Science and Technology

Zhengjian Wu

Wuhan University of Science and Technology

Zhili Hu (✉ zhilihuhit@163.com)

Wuhan University of Science and Technology

Research Article

Keywords: Aluminum foam, Friction stir processing, Numerical simulation, Microstructure

Posted Date: July 21st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-710772/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on February 23rd, 2022. See the published version at <https://doi.org/10.1007/s00170-022-08935-5>.

The influences of process parameters on the preparation of closed-cell aluminum foam by friction stir processing

Qiu Pang^{1, 2, 3}, Zhengjian Wu³, Zhili Hu^{3*}

¹Key Laboratory of Metallurgical Equipment and Control Technology of Ministry of Education, Wuhan University of Science and Technology, Wuhan, 430081, PR China

²Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, 430081, PR China

³ Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan 430070, PR China

*Corresponding author: Zhili Hu

Tel.: +86 27 87856773; fax: +86 27 87856733.

E-mail: zhilihuhit@163.com

Abstract

In the present investigation, the closed-cell Al foam was fabricated by friction stir processing (FSP) combined with heat treatment. The influences of process parameters on microstructures of closed-cell Al foam precursor were investigated by optical metallographic microscope and scanning electronic microscope (OM/SEM). Fluent CFD software was developed to simulate the temperature field and flow field in friction stir processing. The cupping test values were compared for base metal and different weld passes. The results show that the welding speeds have little effect on the mixing of powder in the stir zone because of the relatively small welding heat input. However, the pore size and pore morphology are highly sensitive to change in the rotating speeds. When the welding speed is 50mm/min and the rotating speed is 2000rpm, the powder ring is continuous and uniform due

to sufficient plastic deformation and flow. When the foaming time is 110s, the expansion rate of the whole foam increases rapidly, and the diameter of the pore is uniform. Numerical simulation shows that the welding heat mainly comes from the shoulder of the stirring head and the welding temperature peak appears near the stirring pin. The maximum flow velocity appears at the outer edge of the shaft shoulder in which the aluminum matrix is softened preferentially. When the rotating speed increases to 2000r/min, the velocity of the outermost edge of the shaft shoulder increases by 59.96%, and the maximum temperature at the stirring pin reaches 491 °C which is consistent with the experimental results. The formability of the joint interface is improved. The cupping test values increase with the increase of deformation temperature. Especially the cupping test value of foamed preform is close to that of base metal at 450 °C.

Key words: Aluminum foam; Friction stir processing; Numerical simulation; Microstructure.

1. Introduction

Closed-cell aluminum foams are a new integrated functional material with unique structure and properties ^[1,2]. Compared to solid metals, they hold excellent properties such as light weight, large specific surface area, high specific strength, low effective thermal conductivity and good energy absorption performance. Therefore, they may be used in aerospace, automobile transportation, military and other fields ^[3,4].

At present, due to the pore structure characteristics of closed-cell aluminum foam, the foam pore is easy to collapse after deformation. The application scope of aluminum foam structural parts is greatly limited. Generally speaking, aluminum foam forming methods are mainly divided into two types. The first is that the preform is foamed before forming. The second is that the preform is formed before foaming. Due to the special 3D pore structure of aluminum foam, the sheet metal forming process

which is dominated by tensile and shear deformation shows obvious poor formability. Therefore, the first approach is mainly applied to flat components ^[5-7]. For the second process route, whether the hot pressing powder metallurgy technology or the powder composite/cladding rolling technology, essentially speaking, aluminum powder, foaming agent and stabilizer particles are all used to prepare closed-cell aluminum foam. The preparation process is complicated, and the mechanical properties are unsatisfactory ^[8,9].

Friction stir processing (FSP) is a novel solid-state process to modify microstructures and their properties through high strain rate deformation ^[10,11]. At present, the friction stir processing has made some achievements in the research of particle reinforced aluminum matrix composites. The dispersion of reinforced particles in Al matrix increases as the number of passes increase. In recent years, FSP route has been developed for fabricating the precursor of Al foam ^[12-14]. The stabilization agent powder can be mixed into the die casting plates to fabricate the precursor by intense plastic deformation and stirring of pin tool. Then the porous aluminums are successfully obtained by heat treatment of the precursor ^[15,16]. However, till to present, the effects of process parameters on microstructures of closed-cell Al foam precursor are not analyzed in detail. Numerical studies on the flow field and temperature field in friction stir processing are not effectively combined.

In this study, the closed-cell Al foams are successfully obtained by using friction stir processing and post-weld heat treatment. The microstructures of the Al foams are investigated with different process parameters. The numerical models are developed to predict the temperature field and the material flow in FSP process. The influences of process parameters on the temperature field distribution and material flow of the prefabricated foam are revealed. Simultaneously, the material flow and heat transfer during the FSW process are analyzed. The cupping test of Al foam precursor is also carried out. The

effects of deformation temperature and welding passes on the bulging properties of Al foam precursor are investigated.

2 Experimental procedure

The material used in the experiment was a 1.5mm thick 7075-O aluminum alloy plate, and its main chemical composition was shown in Table 1. The closed-cell Al foams were prepared by multi-pass friction stir processing. The foaming agent was TiH_2 powder with particle size of $45\mu\text{m}$. The stabilizer was Al_2O_3 powder with particle size of $1\mu\text{m}$. At first, the 1wt% TiH_2 and 2wt% Al_2O_3 powder were mixed with the planetary ball mill at a speed of 250rpm for 90min. Then the mixed powders were spread evenly between two 7075-O aluminum alloy plates. The process diagram was shown in Figure 1. The different welding speeds (50, 100 and 200 mm/min) and rotation speeds (800, 1200, 1600 and 2000 rpm) were used for multi-pass friction stir processing. The samples were cut into $20\text{mm}\times 20\text{mm}$ by line cutting machine, and then the precursors were foamed by heat treatment furnace. According to the literature ^[17], the foaming temperature was selected as 680°C .

Table 1 Chemical composition of 7075-O aluminum alloy (wt.%)

Element Type	Zn	Mg	Cu	Mn	Si	Fe	Cr	Ti
7075-O	5.0-6.2	2.0-2.8	1.1-2.0	0.29	0.41	0.49	0.19-0.27	0.20

The microstructure of closed-cell Al foam and the distribution of TiH_2 and Al_2O_3 powder in the matrix were analyzed by optical metallographic microscope (OM) and scanning electron microscope (SEM/EDS) respectively. The influences of different process parameters on the morphology of closed-cell Al foams were investigated in detail. In addition, the cupping test of Al foam precursor was carried out by using the servo pressure test system. The test conditions included the sample size for 90 mm diameter, deformation speed 5 mm/s and deformation temperature (25°C , 300°C , 400°C , 450°C ,

475°C). The effects of deformation temperature and welding passes on the bulging properties of Al foam precursor were studied.

Fig.1 Schematic illustrations of closed-cell Al foam precursor by multipass friction stir processing

3 Numerical simulation

Fluent CFD software was used to solve the numerical simulation in friction stir processing. The finite volume method (FVM) combined CATIA and ICEM surf software was utilized to construct the welded joint model. The temperature field and flow field of FSW precursor were employed to study the joint quality. A particle tracing method was proposed for analyzing the flow of TiH_2 and Al_2O_3 powder in preformed billet. A schematic illustration of FSW process and its geometrical model features for numerical simulation was shown in Fig. 2. In order to simplify the FSW model, the effects of tool shoulder concavity and tool tilt angle were ignored. The calculated domain size of the model was 80mm×50mm, and two 7075 aluminum plates (2×1.5mm) were superimposed. The grid division process was carried out in ANSYS ICEM CFD software. The grid size of the model was set as 2mm, and the model grid division was shown in Fig. 3.

Fig. 2 A schematic of FSW process and its corresponding geometrical model

Fig. 3 Mesh view of the cylindrical threaded pin wall embedded in the plates

The flow of TiH_2 and Al_2O_3 powder in the preformed billet was analyzed by particle tracing method during FSP. The tracking particles were added to the CFD model as part of the pre-simulation setup.

Since the particle flow direction was opposite to the welding direction, 630 tracer particles were evenly distributed in the ZY plane which was in front of the axis of the agitator pin, as shown in Figure 4.

Fig.4 Tracking powder process diagram

In different coordinate axes, the momentum conservation equation of material flow satisfied:

$$\frac{\partial(\rho u)}{\partial t} + \rho \left((u - u_{weld}) \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} \right) \quad (1)$$

$$\frac{\partial(\rho v)}{\partial t} + \rho \left((u - u_{weld}) \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right) \quad (2)$$

$$\frac{\partial(\rho w)}{\partial t} + \rho \left((u - u_{weld}) \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z} \right) \quad (3)$$

where p was the pressure, μ was the material viscosity, and V_{weld} was the welding speed.

In this simulation, the material flow process involved heat generation and heat dissipation. Therefore, the fluid flow system should meet the law of conservation of energy:

$$\frac{\partial(\rho C_p w)}{\partial t} + \rho C_p \left((u - u_{weld}) \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + S_v \quad (4)$$

where C_p was the specific heat capacity of the material, T was the absolute temperature, k was the thermal conductivity, and S_v was the viscous dissipation caused by the plastic deformation of the shear layer during the plastic flow of the material.

The velocity and thermal boundary conditions were the main considerations in the simulation of friction stir processing. Its velocity boundary condition could be expressed as:

$$\begin{cases} u = (1 - \delta)(\omega r \sin \theta - V_{weld}) \\ v = (1 - \delta)\omega r \cos \theta \\ w = \frac{\psi \omega}{2\pi} \end{cases} \quad (5)$$

where u , v and w are the relative speeds in x , y and z directions respectively, and ψ are the stirring needle thread.

The thermal boundary condition could be expressed as:

$$-k \frac{\partial T}{\partial z} = \varepsilon_r \delta_r (T^4 - T_0^4) + h_{Al} (T - T_0) \quad (6)$$

where ε_r was the thermal radiation coefficient, δ_r was the Stefan-Boltzmann constant, h_{Al} was convective heat transfer coefficient, k was the thermal conductivity of the material, T_0 was the ambient temperature.

4 Results and analysis

4.1 The effect of different process parameters on the microstructure of closed-cell Al foam precursor

Fig. 5 shows the cross-sectional morphologies of closed-cell Al foam precursor at the different welding speeds. The welding speeds are varied from 50, 100 and 200 mm/min in Fig. 5(a). According to the morphology of the Al foam precursor in Fig. 5(a), the entire sample retains a good surface. The typical "onion ring" morphology appears at the different welding speed at constant rotation speeds 2000 rpm. The width of stirring zone decreases gradually with the increase of welding speed. Simultaneously, an obvious banded structure appears in the mixing area in Fig. 5(a). However, there is no significant difference in the overall morphology of the section. The results prove that the welding speeds have little effect on the plastic material flow velocity in the stir zone because of the relatively small welding heat input.

Fig. 5(b) illustrates the cross-sectional morphologies of closed-cell Al foam at the different rotating speeds. The rotating speeds are 800, 1200, 1600 rpm and 2000 rpm, respectively. It can be seen that the pore size and morphology is highly sensitive to change in different rotating parameter ^[18]. The foaming agent TiH_2 and stabilizer Al_2O_3 powder in the interlayer aren't mixed evenly with the aluminum matrix at the rotational speed of 800 rpm and 1200 rpm. There is obvious stratification between the powder and the aluminum matrix. With increasing the rotating speed of the shaft shoulder, more material generates flow in the counter clockwise direction. The mixed powder is gradually integrated into the aluminum matrix, and the radius of the mixing area gradually increases. When the welding speed is 50mm/min and the rotating speed is 2000rpm, the mixing powder in the aluminum matrix is subjected to the strong rotating of the stirring pin. Simultaneously, sufficient plastic deformation and flow occur in the welding zone. Therefore, the powder ring is continuous and uniform, as shown in Fig. 5(a).

Fig.5 Cross-section morphologies of closed-cell Al foam precursor at different process parameters

Fig. 6 shows the SEM morphology and EDS analysis of the mixing area of closed-cell Al foam precursor at welding speed of 50 mm/min and rotational speed of 2000 rpm. It can be seen that the gray area is Al matrix, and the small white particles are TiH_2 . The Al_2O_3 powder as gray cloudlike region is distributed almost uniformly in the precursor. In addition, the frictional force has resulted in the uniform flow of fusion zone. The experimental results prove that TiH_2 and Al_2O_3 mixed powders can be uniformly mixed in aluminum matrix by strong high-speed rotation of stirring head and multipass welding.

Fig.6 The cross-section SEM image and the EDS maps of the relevant elements in the Al foam

precursor at welding speed of 50 mm/min and rotational speed of 2000 rpm

4.2 The effect of different foaming time on the microstructure of closed-cell Al foam

Fig. 7 shows the cross-section photographs of closed-cell Al foams fabricated at 680°C. The micrographs illustrate the qualitative assessment of the cellular structures evolution for Al foam precursor at different foaming time. It can be seen that the uniformity and compactness of Al foam precursor have great influence on the morphology of Al foam. When the foaming time is 60s, the foaming effect is poor. There is more than 90% of the area without foaming. Very small pores appear in the welding area of the prefabricated joint after 90s. Simultaneously, the number of pores at the bottom of the welding area is greater than that at the top. With the extension of the foaming time, part of TiH_2 powder begins to release gas, and the pore size in the welding area gradually increases.

When the foaming time is 110s, the expansion rate of the whole foam increases rapidly, and the bubble pores at the bottom tends to be round and the pore structure is uniform in Fig. 7. At 138s, TiH_2 powder completely releases the gas, and the pores are distributed in the whole section. However, the size of the pores is not uniform. Some uniform round pores are connected with each other to form the whole pores. In the range of 280s-751s, the circular pores appear collapse due to the further extension of the foaming time. In addition, partially collapsed pores gradually shrink and merge at the bottom. The results show that the foaming process of the precursor starts from the bottom and then goes up. Finally, the pores merge with each other and gradually expansion. The bottom pores appear to collapse into compaction.

Fig. 7 Morphology of cross section of closed-cell Al foam after foaming for different time at 680°C

4.3 Numerical simulation of temperature field of closed-cell Al foam precursor in FSW process

Fig. 8 presents numerical simulation of the temperature distribution at top surface of the workpiece at different rotating speeds with constant welding speed of 50mm/min. The process parameters of the simulation were selected with 800, 1200, 1600, and 2000 rpm, respectively. As it can be seen, the welding temperature peak appears near the stirring pin, which is distributed in a "bowl shape". In addition, the temperature decreases gradually with the increase of the distance between the stirring head center. The closed-cell Al foam precursor in the weld line area undergoes higher velocity and deformation than in the external side.

At the same time, the rotating speed has great influence on the temperature field of the foam precursor during the welding process. When the rotating speed increases from 800rpm to 2000rpm, the temperatures increase by 130°C. In particular, when the rotating speed is 2000rpm, the maximum temperature at the stirring pin reaches 491°C. It indicates that the welding temperature of the stirring head increases gradually with the increase of rotating speed. This is because that the increases of the rotating speed of the stirring head generate a lot of heat by the friction, which improves temperature of the welding joint. The heat affected zone of aluminum alloy is softened heavily.

Fig. 8 Numerical simulation of the temperature distribution at top surface of the workpiece at different rotating speeds with constant welding speed of 50mm/min

Fig. 9 shows the simulated temperature field of transverse cross-section of the welding seam at different rotating speeds with constant welding speed of 50mm/min. It can be seen that the variation of temperature is found to be different on the advancing (AS) and the retarding sides (RS). The temperature on the advancing side is higher than that on the retreating side. Simultaneously, the profile of the temperature distribution is non-symmetric on both sides of the stirring pin, which is effected by changing the FSW processing parameters. The maximum temperature is obtained near the tool shoulder. The results prove that the amount of heat generation mainly comes from the friction between the shoulder and workpieces.

In the friction stir welding process, the high temperature plastic metal in the viscoelastic zone is extruded to the backward side by the rotation of stirring head, which causes sufficient plastic deformation and flow of the metal in the welding zone. When the rotational speed is 800rpm, the simulated temperature field of the cross section of the joint is only 361 °C. The main reason is that the friction between the mixing head and the sample generates less heat. The thermal convection between

the workpiece and the surrounding environment is small, which makes it easy to stratify in both the upper and lower plates as shown in Fig. 5. The interface temperatures of the joint increase rapidly with the increase of the rotation speed. When the rotational speed is 2000rpm, more heat is generated and the maximum temperature value is obtained for 491 °C. The material in this temperature range is softened and reaches the plasticized state under the extrusion and shearing action of the thread. Fig. 10 illustrates a comparison between the experimental temperature result and the numerically calculated one. The result shows that the simulation value matches well with the experimental one.

Fig. 9 The simulated temperature field of transverse cross-section of Al foam precursor joint at different rotational speeds with constant welding speed of 50mm/min

Fig. 10 A comparison between experimental result and finite element analysis (FEA) result

4.4 Numerical simulation of material flow field of closed-cell Al foam precursor in FSW process

Fig. 11 illustrates the numerical simulation of material flow of Al foam precursor joint with 800,

1200, 1600 and 2000 rpm in 50 mm/min welding speed, respectively. It can be seen that material flow occurs mainly on the upper surface. It is because that the tool pin plays a leading role in the plastic material movement. At the same time, the material flow velocity on the retreating side (RS) is slightly higher than that on the advancing side (AS), which is consistent with the literature reported by Morisada et al ^[19]. At the pin side surface, due to the action of the threaded pin, the material moves downward and reflows when it reaches the bottom, and the trajectory is a semicircular motion. Therefore, the materials in the weld area undergo multiple rotation and extrusion because of the forced driving effect of the thread.

Firstly, the aluminum matrix at the outer edge of the shoulder is preferred to soften due to the frictional shear force of FSW process, and a plastic softening zone is formed. Then most of the soften layer particles are spiraled from the advancing side to the retreating side due to the intense stirring action of the pin. Moreover, the linear velocity of the shoulder decreases with increasing the distance from the axis. The plastic flow of weld metal in the vicinity of the shoulder area increases gradually with increasing rotational speed. The material flow velocity of the outermost edge of the shaft shoulder increases by 59.96%, when the rotating speed increases to 2000 rpm. The powder mixing ring has a large diameter, which is consistent with the experimental result in Fig. 5.

Fig. 11 Numerical simulation of material flow of Al foam precursor joint at different rotation speeds

800, 1200, 1600 and 2000 rpm at constant welding speed 50mm/min

Fig. 12 shows the heat flow at the tool-workpiece interface for different rotation speeds 800, 1200, 1600 and 2000rpm. The magnitude of heat flow increases gradually from the center of the tool axis to the outer edge. In addition, due to the effective contact area of the thread, the heat flow is distributed periodically at pin side-workpiece interface. It is evident that the heat flow is proportional to the relative velocity. The maximum occurs at the edge of the tool shoulder. Simultaneously, the heat flow value increases gradually with the increase of rotation speed. Especially the heat flow is increased 1.5 times when the rotating speed is increased from 800 rpm to 2000 rpm. The results show that more heat is generated at the tool shoulder and effectively improve material flow.

Fig. 12 Calculated heat flow at tool-workpiece interface for different rotation speeds 800, 1200, 1600 and 2000 rpm

Fig. 13 shows the streamlines and velocity field of the simulated material flow near the tool at different rotation speeds at constant welding speed 50mm/min. It can be seen that the material flow in the stirring zone increases as the rotation speed increases. Since the rotation direction of the tool is counter clockwise, the soften material under the extrusion action gradually extends outward.

Simultaneously, the material flow region is expanded as the speed of rotation increases. The direction of plastic flow of weld metal is consistent with the rotation direction of the tool. When the rotating speed is between 800rpm and 1200rpm, the backward side metal has not been filled due to the small welding heat, and the plastic flow capacity of the material is poor. The plastic flow capacity of the material is improved gradually with the increase of rotation speed. Especially when the welding speed reaches 2000rpm, the gap caused by rotation is completely filled at the forward side. The formability of the joint interface is improved.

Fig. 13 Streamlines and velocity field of joint interface at different rotation speeds 800, 1200, 1600 and 2000 rpm with constant welding speed 50mm/min

4.5 Numerical simulation analysis of tracking particles in closed-cell Al prefabricated foam

Fig. 14 shows the tracking particle concentration of joint interface at different rotation speeds. The tracking particles are initially arranged on the welding area during the simulation. In the initial stage, the Al matrix is not softened and the particles are mainly squeezed by the pin tool. Then a plastic softening layer is formed and the particles start to flow under the action of the stirring pin. As can be seen from the figure, the numerical simulation of tracking particles presents blue areas, covering the

whole preformed powder ring in Fig. 14(a). Simultaneously, the total particle concentration gradually increases with the increase of the rotational speed. Due to obvious stratification at the joint interface, the highest concentration of powder tracking particles is 0.0096kg/m^3 at the rotation speed of 800 rpm and the welding speed of 50 mm/min.

As the welding speed increases, the heat input improves and the material flow velocity increases. The maximum concentration of powder tracking particles increases separately to 0.0116kg/m^3 and 0.0137kg/m^3 , when the rotation speed increases from 1200rpm to 1600rpm in Fig. 14(b) and (c). In addition, the blue area is gradually replaced by the green area in the numerical simulation process. When the rotation speed is 2000rpm, the highest concentration of powder tracing particles is 0.0123kg/m^3 in Fig. 14(d). The red area with high particle concentration is gradually increased by numerical simulation, which almost covers the prefabrication area.

Fig. 14 Tracking particle concentration of joint interface at welding speed of 50mm/min and different rotation speeds (a) 800 rpm, (b) 1200 rpm, (c) 1600 rpm, (d) 2000 rpm

Fig. 15 illustrates the forming limit curves of aluminum foam specimens at different deformation temperatures. It can be seen that the wall thicknesses of the cupping samples are the uniform symmetrical distribution, which increase gradually from the top to the transition zone. For the base metal, the cupping test value of 7075 aluminum alloy sample is 27 mm at room temperature. Although the temperature increases continuously, the cupping test value does not fluctuate greatly and the curve

is gentle in Fig. 15(b). As for the aluminum foamed preforms, the plasticity of the sample is enhanced and the cupping test values increase obviously with the increase of deformation temperature and weld passes. When the deformation temperature reaches 400 °C, the temperature is close to the solid line of 7075 aluminum alloy. For 3 pass welds, the plasticity of the material is qualitatively changed and the cupping test values gradually decrease. However, for 17 pass welds, the cupping test values increase with the increase of deformation temperature. Especially the cupping test value of foamed preform is close to that of base metal at 450 °C.

Fig. 15 The cupping test values of foam specimens at different deformation temperatures

5 Discussion

The ANSYS Fluent CFD software is used to solve numerical simulation of the temperature field and flow field of friction stir processing. The particle tracking model of joint interface is also developed at different rotating speed. The heat flow coupling model in FSW stage is established for simulation of heat transfer process. The plastic deformation and material flows of the foaming agent TiH_2 and the stabilizer Al_2O_3 in the stirring area are analyzed under the action of the high-speed rotating of the stirring pin. The numerical simulation results show that there are great differences in temperature field distribution and plastic flow of stirring head at different welding parameters. The temperature on the advancing side is significantly higher than that on the retreating side. Therefore, the plastic flow on the advancing side is much better than that on the retreating side.

In the welding process, the welding heat mainly comes from the shoulder of the stirring head due to friction between the stirring pin and aluminum matrix. In addition, during the high-speed rotation of the stirring head, the maximum flow velocity appears at the outer edge of the shaft shoulder, and the aluminum matrix at the outer edge of the shaft shoulder is softened preferentially. With the prolonging of welding time, the softening zone of aluminum matrix gradually increases, and the material reaches the state of plastic flow. As the stirring head moves forward, the high temperature plastic metal is continuously extruded from the advancing side to the retreating side by the rotating motion of the stirring pin, and the material in the welding zone has sufficient plastic deformation and flow. At the same time, the plastic flow capacity and the concentration of powder tracking particles can be effectively improved by increasing the rotating speed of the stirring head.

When the welding process parameter is 50/2000, the temperature field and heat flow of the outer edge of the contact surface between the shaft shoulder and substrate are the maximum and the highest values are 491 °C and $6.20 \times 10^6 \text{ W/m}^2$, respectively. In addition, the heat flow on the surface of the shaft shoulder decreases with the decrease of the radius from the shaft center. When the rotating speed of the stirring head increases from 800rpm to 2000rpm, the flow speed at the outer edge of the shaft shoulder increases by 59.96%, and the maximum concentration of powder tracking particles increases by 28.1%, which is beneficial to the uniformity of the welded joint. Therefore, the simulation results reveal that the shifting tool leads to a better powder distribution, which is consistent with the experimentally acquired.

6 Conclusions

In the paper, the closed-cell Al foams are successfully obtained by using friction stir welding and post-weld heat treatment. The influences of process parameters on microstructures of closed-cell Al

foam precursor were evaluated by experiment and numerical simulation. The following conclusions can be drawn:

(1) The Al foam precursor retains a flat surface. The typical "onion ring" morphology appears under different welding and rotation speeds. Especially, when the welding speed is 50mm/min and the rotating speed is 2000rpm, sufficient plastic deformation and flow occur in the welding zone. TiH_2 and Al_2O_3 mixed powders can be uniformly mixed in aluminum matrix by multipass welding.

(2) In the foaming process at 680°C , the foam pores first appear at the bottom and then expand upwards with the extension of the foaming time. When the foaming time is 110s, the expansion rate of the whole foam increases rapidly, and the pores with highly spherical are homogeneously distributed.

(3) The numerical simulation analysis shows that the temperature decreases gradually with the increase of the distance between the stirring head center. When the rotational speed is 2000rpm, the maximum temperature value is obtained for 491°C . The highest concentration of powder tracing particles is 0.0123kg/m^3 . The material reaches the plasticized state under the extrusion and shearing action of the thread.

(4) As for the aluminum foamed preform, the wall thicknesses of the cupping samples are the uniform symmetrical distribution. The plasticity of the sample is enhanced and the cupping test values increase obviously with the number of weld passes. The cupping test value of foamed preform for 17 pass welds is close to that of base metal at 450°C .

Author contribution Qiu Pang conceived the theory, designed experiments, and wrote the paper.

Zhengjian Wu helped with the experiments. Prof. Zhili Hu initialized and supervised the research.

Funding This work was supported by the by the Hubei Key Laboratory of Advanced Technology for Automotive Components fund (XDQCKF2021007), National Natural Science Foundation of China (51775397, 52075400, 51805393), 111 Project (B17034), Major Program of Science and Technology Program of Hubei Province (2020BAB140), Innovative Research Team Development Program of Ministry of Education of China (IRT17R83).

Availability of data and material Not applicable.

Declarations

Ethics approval The authors conducted their work from research proposal to publication in line with best practices and codes of conduct of relevant professional bodies.

Consent to participate All authors have approved to participate.

Consent for publication The manuscript is approved by all authors for publication.

Competing interests The authors declare no competing interests.

References

- [1] Banhart J (2013) Light-metal foams-history of innovation and technological challenges. Adv. Eng. Mater. 15: 82–111.
- [2] Gibson LJ, Ashby MF (1997) Cellular Solids: Structure and Properties. Cambridge University Press, Cambridge New York.
- [3] Jang W, Hsieh W, Miao C, Yen Y (2015) Microstructure and mechanical properties of ALPORAS closed-cell aluminium foam. Mater. Charact. 107: 228–238.
- [4] Su BY, Huang CM, Sheng H, Jang WY (2018) The effect of cell-size dispersity on the mechanical properties of closed-cell aluminum foam. Mater. Charact. 135: 203–213.

-
- [5] Roohi AH, Naeini HM, Gollo MH, Soltanpour M, Bruschi S, Ghiotti A (2018) Forming of closed-cell aluminum foams under thermal loadings: experimental investigation. *Int J Adv Manuf Technol* 95: 3919–3928.
- [6] Zhang M, Chen CJ, Brandal G, Bian D, Yao YL (2016) Experimental and numerical investigation of laser forming of closed-cell aluminum foam. *J Manuf Sci E* 138: 021006.
- [7] Hangai Y, Kawato D, Ando M, Ohashi M, Morisada Y (2020) Nondestructive observation of pores during press forming of aluminum foam by X-ray radiography. *Mater. Charact.* 170: 110631.
- [8] Shiomi M, Fukaya T (2014) Forming of aluminum foams by using rotating mold. *Procedia Engineering* 81: 664–669.
- [9] Chen SG, Chen HB, Sun ZZ, Li RY, He WF (2014) The U-bending forming of aluminum foam sandwich panels. *Appl. Mech. Mater.* 477-478: 1432–1439.
- [10] Heidarzadeh A, Mironov S, Kaibyshev R, Cam G, Simar A, Gerlich A (2021) Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution. *Prog. Mater. Sci.* 117: 100752
- [11] Azizieh M, Pourmansouri R, Balak Z, Kafashan H, Mazaheri M, Kim HS (2017) The application of friction stir processing to the fabrication of magnesium-based foams. *Arch Metall Mater.* 62(4): 1957–1962.
- [12] Papantoniou IG, Kyriakopoulou HP, Pantelis DI, Athanasiou-loannou A, Manolakos DE (2018) Manufacturing process of AA5083/nano-gamma Al_2O_3 localized composite metal foam fabricated by friction stir processing route (FSP) and microstructural characterization. *J Mater Sci* 53(05): 3817–3835.
- [13] Yamamura K, Kawada N, Nishihara T (2010) Formation of local metallic foam of aluminum alloy

-
- using friction stir processing. *J Jpn I Met* 74: 55–60.
- [14] Matsumoto R, Mori S, Otsu M, Utsunomiya H (2018) Formation of skin surface layer on aluminum foam by friction stir powder incremental forming. *Int J Adv Manuf Technol* 95 (5-8): 1853–1861.
- [15] Hangai Y, Takada K, Fujii H, Aoki Y, Aihara Y, Nagahiro R (2020) Foaming of A1050 aluminum precursor by generated frictional heat during friction stir processing of steel plate. *Int J Adv Manuf Technol* 85(2): 84–87.
- [16] Pang Q, Hu ZL, Song JS (2019) Preparation and mechanical properties of closed-cell CNTs-reinforced Al composite foams by friction stir welding. *Int J Adv Manuf Technol* 103(5-8): 1036–1042.
- [17] Pang Q, Yu HY, Hu ZL (2020) Study on friction stir welding process of closed-cell CNTs/Al composite foam. *Rare Metal Mat Eng* 49(8): 2845–2854.
- [18] Hangai Y, Utsunomiya T, Hasegawa M (2010) Effect of tool rotating rate on foaming properties of porous aluminum fabricated by using friction stir processing. *J Mater Process Tech* 210(02): 288–292.
- [19] Morisada Y, Fujii H, Kawahito Y, Nakata K, Tanaka M (2011) Three-dimensional visualization of material flow during friction stir welding by two pairs of X-ray transmission systems. *Scr. Mater* 65:1085–1088.