Experiment and simulation of SiC particle-reinforced aluminum matrix composites fabricated by friction stir processing

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Abstract
The influence of the pre-implanted reinforced particles on the temperature field and the flow field of the processed zone directly determines the microstructure and properties of the aluminum matrix composites fabricated by friction stir processing (FSP). However, the differences in the characteristics of processed materials, especially the effect of pre-implanted reinforced particles on the flow of plastic materials, have rarely been reported. In this study, the temperature distribution of the processed zone was obtained by experimental measurement and numerical simulation. The model of the effect of the SiC particles as reinforced particles on the temperature field and the flow field of the processed zone was established. The influence of the SiC particles on the flow of plastic materials during the FSP was further investigated. The refinement, particle size, and distribution of the SiC particles in the processed zone of the FSPed multi-pass composites were also discussed in detail. The microhardness of the processed zone was also tested and discussed. The results showed that the temperature field at the contact interface between the SiC particles and the matrix in the processed zone was not continuously distributed. Due to the collision and hindrance of the reinforced SiC particles, the flow direction of plastic materials in the processed zone had been changed many times during the flow process. The initial average particle sizes of the SiC particles have a significant effect on the flow path of the processed plastic material. The microhardness of the processed zone of the FSPed specimens is significantly higher than that of the matrix.

Keywords Friction stir processing · Aluminum matrix surface composites · Reinforced particles · Temperature field · Flow path lines

1 Introduction

Research reports show that some of the properties of composites fabricated by friction stir processing (FSP) are better than those of composites fabricated by conventional methods. The reinforced particles are not only uniformly distributed but also refined during the FSP. FSP has become an effective technology for surface modification of materials and fabrication of surface composites [1]. The microstructure and mechanical properties of the composites are directly affected by the process parameters of the FSP. Most of the previous efforts have focused on the development of process parameters to obtain sound composites. Salehi et al. [2] and Luo et al. [3] believed that the uniform distribution of reinforced particles could be achieved by optimizing the FSP process parameters. The homogeneous and grain refinement imparted by FSP to the composites improves the strength and ductility of the composites [4]. A single-pass FSP is usually not enough to promote the uniform distribution of the reinforced particles. However, the uniformity of distribution of pre-implanted reinforced particles generally improves with increasing number of FSP passes when multiple passes of FSP is employed [5]. Husain and Mishra successfully fabricated aluminum matrix composite (AMC) using multi-pass friction stir processing (MPFSP) with SiC nanoparticles and investigated the microstructure and mechanical properties.
of multi-pass FSP/SiC of AA6082-T6 [6]. Sivanesh et al. reported that multi-pass FSP improved the microstructure and phase composition of the processed zone so that the hardness, surface roughness, tensile strength, and wear resistance of the processed material were improved [7]. Ashish et al. also put forward similar views [8]. Javad et al. used the response surface method to evaluate the effects of processing parameters such as rotational speed, traverse speed, shoulder-to-pin diameter ratio, and number of FSP passes on the microstructure and mechanical properties of the FSPed composites [9].

The thermal history and material flow during the FSP process are essentially determined by the process parameters of the FSP. Therefore, studying the effects of FSP process parameters is helpful to further understand and regulate the FSP process. A three-dimensional finite element based transient thermal model was used to predict the thermal history during FSP of AA5052 by Chintalu et al. [10]. Nazanin et al. used DEFORM 3D finite element commercial package V.11 to simulate the effect of pin shape on temperature distribution, which provided a basis for tool structure optimization [11]. In order to better understand the process of FSP, Kayode et al. applied molecular dynamics (MD) to simulate FSP of aluminum alloy 6061-T6 and explain the microscopic details of the thermodynamics that occur during the FSP process [12]. Compared with the finite element model, the friction model modified by Bahman et al. successfully simulated the partial sliding/sticking condition and made the stress patterns consistent. In addition, they successfully predicted the material flow, heat flux, equivalent plastic strain and temperature distribution of the processed material [13]. In order to better understand the effect of process parameters on temperature gradients, Shamanian et al. established a 3D thermo-mechanical model based on the finite element method to study the evolution of the microstructure and mechanical properties of the processed materials due to changes in process parameters [14].

The thermal cycle associated with the FSP determines the generation of different microstructures, which results in different mechanical properties of the composites. To better develop post-processing cooling control, the development of complex mixed microstructures of processed materials under controlled conditions was studied by Julian et al. [15]. Stubblefield et al. adopted a fully coupled thermo-mechanical meshless approach to simulate and analyze a solid-state layer-by-layer additive manufacturing process and revealed temperature and strain rate gradients across the entire deposition process [16]. Arora et al. developed a heat flow model to simulate the temperature history during FSP of magnesium alloys, and the temperature history was further utilized for the estimation of grain growth rate and final average grain size of the FSPed specimen [17]. The published literature reports mainly focus on the thermal history of the matrix, but there are few reports on the effect of reinforced particles on the temperature field when FSP is used to fabricate particle-reinforced composites [18].

The formation of the microstructure of the processed material is not only affected by the thermal history but also directly related to the flow of the material during the FSP. Therefore, material flow during the FSP is one of the research focuses currently. Tutunchilar et al. used the DEFORM-3D software to develop a 3-D Lagrangian incremental finite element method (FEM) simulation of FSP. They extracted three-dimensional results of material flow patterns in the center, advancing side (AS) and retreating side (RS) using the point tracking method, and predicted the stir zone shape, defect types, powder agglomeration, and temperature rise [19]. Wang and Mishra performed a simulation analysis using finite element methods focusing on superplastic forming in the FSP process and calculated the pressure schedule, the overall forming time and the final thickness distribution in the formed component [20]. A procedure combining computational fluid dynamics modeling/Monte Carlo simulation was implemented to predict grain refinement during FSP of an Al–Mg alloy by Khodabakhshi et al. [21]. Hamilton et al. established a coupled numerical model for the FSP of AlSi9Mg aluminum alloys using a tool without a pin. They investigated the flow patterns and temperature distribution of the processed material and further elaborated the relationship between the thermal history and material flow during the FSP [22]. There are obvious differences in mechanical and thermal properties between reinforced particles and matrix, but the differences between reinforced particles and matrix are often ignored in previous studies. Therefore, further study is needed taking into account the different characteristics of the processed materials, especially the influence of pre-implanted reinforced particles on the flow of plastic materials.

Based on literature, it is clear that the process variables of FSP vary with the changes of the processed material and that the perfect combination of FSP process variables controls the refinement and uniform distribution of the pre-implanted reinforced particles. In the early studies, the influence of process variables on the microstructure and properties of FSPed composites has been extensively studied. However, due to the characteristics of the processed material, especially pre-implanted reinforced particles, the effects on the flow of plastic materials are rarely reported. Thus, this study established a model of the influence of SiC particles as reinforced particles on the temperature field and flow field of the processed zone and investigated the influence of SiC particles on the flow of plastic materials during the FSP. This study also discussed the particle refinement in detail, as well as the size and distribution of SiC particles in the processed zone of the FSPed multi-pass composites. The
microhardness of the processed zone of the specimens was also tested and discussed.

2 Experimental

The commercial AA6061 aluminium alloy sheets with the size of \(200 \times 200 \times 8 \text{ mm}^3\) were selected as the matrix in the FSP experiment, and the chemical composition of AA6061 aluminium alloy is listed in Table 1. Some small holes with a diameter of 3 mm and a depth of 5 mm were drilled on the surface of the AA6061 aluminium alloy sheets along the FSP direction, and the interval between holes was 5 mm, as shown in Fig. 1. The \(\beta\)-SiC particles were filled in the holes and compacted before the surface composites fabricated via FSP. The initial average particle sizes of the \(\beta\)-SiC particles used in this experiment were 40 \(\mu\text{m}\) and 20 \(\mu\text{m}\), respectively. The purity of the \(\beta\)-SiC particles is more than 99%. The volume fraction of the SiC particles in the particle-reinforced composites was calculated using the following expressions [23]:

\[
\text{Actual volume fraction} = \left(\frac{\text{Volume of holes}}{\text{Projected area of tool pin} \times \text{Length of aluminum plate}}\right) \times 100
\]

The volume fraction of the SiC particles is 17.41%. A portion of mechanical and physical properties of the AA6061 aluminium alloy and \(\beta\)-SiC particle are shown in Table 2 [24, 25].

An integrated tool made of H13 steel was selected as the FSP tool for the experiment in this study. The design diagram for the tool is shown in Fig. 2. In order to study the influence of FSP process parameters on the heat input in the FSP process, the \(K\)-type thermocouple was used to measure the instantaneous temperature of the processed zone in this paper. The thermocouples used in the experiment were compared and calibrated by using the double probe technique and standard thermocouples. A number of temperature detection points were set in the interior of the work-piece to be processed, and a small hole with a diameter of 1.5 mm and a depth of 2.7 mm was drilled at each detection point. Before the FSP experiment, the \(K\)-type thermocouple was put into the small hole, and then the thermocouple in the small hole was fixed with high-temperature solid adhesive to prevent the thermocouple from falling off due to vibration during the FSP. The schematic diagram of the thermocouple placed on the cross-section of the work-piece was shown in Fig. 3. The AA6061 aluminium alloy added with SiC particles was subjected to 4 passes of FSP with different process parameters. The FSP process parameters are listed in Table 3.

Microhardness of the FSPed composites specimens was evaluated by using Vickers hardness test under the load condition of 200gf and with 10 s dwell time. The microhardness readings were taken at an equal interval of 1 mm in both the AS and RS.

3 Numerical modeling

During the FSP, the temperature of the material in the processed zone on the work-piece is changing all the time. Assuming that the processed material has isotropic properties, then

| Table 1 | Chemical composition of AA6061 aluminium alloy (wt%) |
|---------|------------------------------------------------------|
| Material | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Ti  | Al  |
| 6061    | 0.6 | 0.35| 0.27| 0.15| 1.0 | 0.25| 0.25| 0.08|

Fig. 1 Schematic illustration of the friction stir process
the governing equation describing the transient temperature field \( T(x, y, z, t) \) of the processed zone can be expressed as [26]:

\[
\rho c \frac{\partial T}{\partial t} - (k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2}) - Q = 0
\]  

(2)

where \( \rho \) indicates the density of the material (\( \text{kg/m}^3 \)); \( c \) represents the specific heat capacity of the material (\( \text{J/(kg·K)} \)); \( T \) is thermodynamic temperature (\( K \)); \( t \) is time (\( s \)); \( k_x \), \( k_y \), and \( k_z \) are the heat conductivity coefficient (\( \text{W/(m}^2\cdot\text{K}) \)) of the processed material along the direction of \( x, y \), and \( z \) respectively. \( Q = Q(x, y, z, T) \) indicates the heat source density (\( \text{W/m}^3 \)) inside the processed work-piece. In addition, \( \rho, c, k_x, k_y, \) and \( k_z \) are all functions of temperature.

Both the processed work-piece and the FSP equipment are at room temperature before the FSP is carried out. In the FSP process, the time when the tool just touches the work-piece is defined as the initial time of analysis and calculation [27], namely:

\[
T(x, y, z, t)|_{t=0} = T_0(x, y, z)
\]  

(3)

where \( T_0(x, y, z) \) is the temperature distribution of the work-piece in the initial state (\( t = 0 \)), that is, the ambient temperature.

The heat flux boundary conditions at the contact surface of the shoulder and pin of the tool with the processed work-piece are shown as follows:

\[
k \frac{\partial T}{\partial n} |_\Gamma = q_w(x, y, z, t)
\]  

(4)

The boundary conditions for the thermal convection between the work-piece and the air (or other surrounding fluids) and between the work-piece and the backing plate are expressed as:

\[
k \frac{\partial T}{\partial n} |_\Gamma = \gamma (T_w - T_f)
\]  

(5)

where \( \gamma \) represents the thermal convection coefficient; \( T_w \) indicates the temperature of the surface of the processed work-piece; \( T_f \) is the temperature of the backing plate and the air (or other surrounding fluids).

During the FSP, the continuous flow of plastic materials follows the mass conservation equation, which is expressed in differential form as:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

(6)

where \( u, v, \) and \( w \) are the velocity components of the plastic material flow in the \( x, y, \) and \( z \) directions, respectively.

According to Newton’s second law, the momentum equations (Navier–Stokes equations) of plastic materials along the \( x, y, \) and \( z \) directions can be deduced as follows:

\[
\begin{align*}
\rho \left( V - V_0 \right) \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + w \frac{\partial u}{\partial z} &= -\nabla p - \nabla \tau + \rho G \\
\rho \left( V - V_0 \right) \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= -\nabla p - \nabla \tau + \rho G \\
\rho \left( V - V_0 \right) \frac{\partial w}{\partial x} + \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &= -\nabla p - \nabla \tau + \rho G
\end{align*}
\]  

(7)

### Table 2

| Material  | Hardness | Density \( \rho \) | Shear strength | Tensile strength | Elongation [%] | Elastic modulus | Specific heat capacity \( c \) | thermal conductivity coefficient \( k \) | Thermal expansion coefficient \( \alpha \) |
|-----------|----------|---------------------|---------------|-----------------|----------------|----------------|------------------------|-----------------|----------------------|
| AA6061    | 30 (HBS) | 2700                | 205           | 276             | 25.0           | 72             | 896                    | 237             | 2.32 \( \times 10^{-5} \) |
| SiC       | \( \geq 90 \) (HRA) | 3200                | —             | —               | 410            | 472 – 1267      | 120 – 180              | 4.5 \( \times 10^{-6} \) |

### Table 3

| Case | Traverse speed \( \text{(mm/min)} \) | Rotational speed \( \text{(r/min)} \) | Plunge depth \( \text{(mm)} \) | Plunge pressure \( \text{(MPa)} \) |
|------|---------------------------------|-------------------------------|------------------|----------------------|
| 1    | 60                              | 800                           | 0.2              | 13                   |
| 2    | 60                              | 950                           | 0.2              | 13                   |
| 3    | 60                              | 1300                          | 0.2              | 13                   |
| 4    | 80                              | 950                           | 0.2              | 13                   |

Fig. 2 Design drawing of the FSP tool made of H13 steel (mm)
where $V$ represents the flow velocity of the plastic material, $V_0$ represents the velocity of the tool, $\nabla$ means the gradient operator, $G$ indicates gravity, $\varepsilon$ indicates the strain rate of plastic material, $\eta$ is the viscosity coefficient of the non-Newtonian fluid.

According to Fourier’s law of heat conduction and the principle of conservation of energy, and then introducing shear stress, the energy conservation equation with temperature $T$ as the variable can be deduced as follows:

$$
\frac{\partial \rho c T u}{\partial x} + \frac{\partial \rho c T y}{\partial y} + \frac{\partial \rho c T w}{\partial z} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} + u \tau \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} + v \tau \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} + w \tau \right)
$$

In this paper, it is stipulated that the processed material follows the Von. Mises yield criterion and related flow laws. The results of research show that the viscosity coefficient of plastic materials is related to temperature and strain rate and it can be calculated by the following equation [24, 28]:

$$
\eta = \frac{1}{3 \beta} \ln \left( \frac{\varepsilon \exp \left( \frac{E}{RT} \right)}{A} \right)^{-1/3} + 1 + \left( \frac{\varepsilon \exp \left( \frac{E}{RT} \right)}{A} \right)^{-2} \ln \left( \frac{\varepsilon \exp \left( \frac{E}{RT} \right)}{A} \right)^{-1/3}.
$$

Table 4: Material constants and property values of aluminum alloy Al6061 and SiC

| Parameter                  | Value          |
|----------------------------|----------------|
| Material constant, $A$     | 15.997 s⁻¹     | 31.0 s⁻¹ |
| Material constant, $n$     | 3.55           | 4.38    |
| Material constant, $Q$     | 14,500 J mol⁻¹ | 337,246 J mol⁻¹ |
| Material constant, $\gamma$| 0.045 MPa⁻¹    | 0.0118 MPa⁻¹ |
| Material density, $\rho$   | 2770 kg·m⁻³    | 3200 kg·m⁻³ |
| Material solidus temperature, $t$ | 855 K | 2973 K |
| Material yield strength (> 550 K), $\sigma_y$ | 20 MPa | 35 MPa |

where $A, \beta$, and $\varepsilon$ are constants related to materials; $E$ is activation energy; $R$ means universal gas constant. The constants and properties of the material were determined according to the literature and related experimental results, as shown in Table 4 [24, 29].

At present, there is no published report about the accurate study of the temperature field and flow field when the reinforced particles were implanted in the aluminum alloy by slotting or perforating. If the material in the processed zone in the FSP process was treated as a homogeneous composites, it would not be much different from the FSP of a single phase material, and it was difficult to accurately determine the physical parameters of the material in this zone. However, for the micro local processed zone, the FSP process of the reinforced particle and the matrix is actually the FSP process of dissimilar materials. Therefore, this paper borrowed the physical model of friction stir processing of dissimilar materials to study the temperature field and flow field of the reinforced particles and matrix in the FSP process. The initial average particle sizes of the $\beta$-SiC particles used in this experiment were 40 µm and 20 µm, respectively. However, such small particles could not be established in the simulation model. In addition, the influence of the reinforced particles with too small particle sizes on the temperature distribution may not be significantly displayed due to their sizes too small. In order to clearly show the influence of $\beta$-SiC particles on the temperature field in the FSP process, the particle size of $\beta$-SiC particles was enlarged properly in the simulation. In the first simulation analysis, it is assumed that...
that the initial particle size of SiC particle is 1 mm (particle A), and its particle size is refined to 0.5 mm (particle B) after FSP, as shown in Fig. 4.

4 Results and discussion

4.1 The temperature field of the aluminum matrix surface composites fabricated by FSP

Figure 5 describes the temperature distribution on the surface and cross-section of the work-piece when the SiC particle-reinforced aluminum matrix surface composites were fabricated by FSP. On the upper surface of the work-piece, the temperature distribution is asymmetry, that is, the temperature on the AS is slightly higher than the temperature on the RS, as shown in Fig. 5a. The reason for the asymmetry of the temperature distribution on the surface of the work-piece is that the surface of the tool between the tool and the processed material moves at a higher relative speed and a higher shear rate on the AS than that on the RS. This leads to an increase of heat generated between friction surfaces, so the temperature on the AS of the tool is higher than that on the RS. Figure 5b shows the distribution of temperature on the cross-section of the processed zone perpendicular to the direction of travel of the tool, which further illustrates that the distribution of the internal temperature of the work-piece is also asymmetrical consistent with that on the surface of the work-piece. The specific heat capacity of the AA6061 aluminum alloy and SiC is significantly different, and the thermal conductivity of the two materials is also significantly different, as shown in Table 2. This difference results in a significant difference in the temperature rise and heat conduction between AA6061 aluminum alloy and SiC during FSP, so that the distribution of temperature around the SiC particles in the FSP processed zone is significantly different from that of the AA6061 aluminum alloy, as shown in Fig. 5c. The local abrupt change of temperature distribution is similar to the discontinuous change of temperature at the interface of dissimilar metals during the friction stir welding (FSW).

Figure 6 shows the comparison between the real-time temperature and the temperature of simulated calculated at the detection point on the work-piece during the FSP. The difference between the two results was small and both reflected the same change law of the temperature at the detection point, which confirmed that the established FSP model was reasonable, and the results of simulation could illustrate the actual distribution of the temperature in the FSP process. It is worth noting that the simulated temperature is slightly higher than the measured temperature. This is mainly because in the simulation calculation, it is assumed that the reinforced particles and the matrix are compacted and pore-free, while in the actual FSP process, there are pores between the SiC particles as well as between the SiC particles and the matrix. The existence of pores reduces the initial density of the processed zone, which leads to the weakening of the friction stirring effect between the processed material and the tool. Therefore, the heat generated by friction stirring is naturally reduced, so that the value of the measured temperature is slightly lower than that of the simulated temperature.

It is particularly emphasized that in order to show the effect of the pre-implanted reinforced particles on the temperature distribution during the FSP more clearly, the particle size of the pre-implanted reinforced particles in the simulation model is much larger than that in the actual FSP process. The size of the pre-implanted reinforced particles will affect the temperature at the specific detection point, but it has no effect on the revealed temperature distribution and the trend of temperature changes. Therefore, the results of simulation can accurately clarify the distribution of temperature during the FSP and the influence of pre-implanted reinforced particles on the distribution of temperature.

4.2 Surface macromorphology of the processed zone

Figure 7 presents the surface macromorphology of the processed zone of the FSPed specimens when the initial average particle size of SiC particles is 40 μm. Figure 7 illustrates that under the parameters of the rotational speed
of 800 rpm and the traverse speed of 60 mm/min, the surface of the processed zone had the worst formability, the surface roughness was coarse and some wear debris was generated on the surface, as shown in Fig. 7a. However, the processed surface has the best formability when the rotational speed of the tool is 950 rpm and the traverse speed is 60 mm/min. The surface is flat and smooth and with no obvious machining defects. There are a small number of flash on both sides of the processed zone, and the flash on the RS is more than that on the AS, as shown in Fig. 7b.

The surface of the processed zone presents different morphologies when using the same tool under different process parameters. This is because when using the same tool for FSP, different FSP process parameters determine the more or less heat input in the FSP process, which leads to the process parameters in the FSP process have a significantly influence on the forming results of the surface. With the same tool, the heat input in the FSP process increases accordingly as the rotational speed increases or the traverse speed decreases. The surface forming results are the best when the heat input results in the material being processed to a suitable degree of plasticization, as shown in Fig. 7b. When the rotational speed of the tool is low, due to the low rotational speed, the heat generated by friction between the tool and the material in the processed zone is not enough, and the degree of plasticization of the material in the processed zone is not sufficient. A part of the processed material that was not completely plasticized during the FSP was extruded by the friction force applied by the tool, which resulted in the generation of wear debris and the formation of rough surface, as shown in Fig. 7a.

In addition, comparing the surface topography of the processed zone under different process parameters, it can be found that the flash on the RS is always more than that on the AS. This is mainly because the processed material is stirred...
by the tool and produces a flow velocity relative to the tool, and the flow velocity on the RS is faster than that on the AS. During the FSP, the plasticized processed material is forced to flow with the rotation of the tool. The plastic material on the AS flows to the RS and is blocked by the shoulder of the tool, which leads to the generation of flash.

4.3 Refinement and distribution of the SiC particles in the FSP processed zone

As mentioned earlier, there was a difference in the temperature between the SiC particles and the matrix, which resulted in a difference between the degree of deformation and flow velocity of the SiC particles and the matrix. This difference made the particle size and distribution of the SiC particles changed with the change of FSP parameters. Figure 8 depicts the micromorphology and distribution of SiC particles in FSPed composites using four passes and different process parameters when the initial average particle size of SiC particles is 40 μm. The white phase in the figures is SiC particle. The SiC particles were dispersed throughout the processed zone and the SiC particles were fragmented and redistributed. When the rotational speed and traverse speed of the tool were relatively slow, the particle size of the SiC particle was larger and unevenly distributed (Fig. 8a). The SiC particles were significantly refined and uniformly distributed as the rotational speed of the tool increased (Fig. 8b). However, when the rotational speed of the tool was too fast, the size of the SiC particles became larger again and the distribution was not uniform (Fig. 8c). In addition, increase in the travel speed of the tool also resulted in an increase in the size of the SiC particles and a decrease in the uniformity of the distribution (Fig. 8d). Prater reported that the strong effect of stirring of the tool and the severe plastic strain of the processed material caused the ceramic particles to refine and lead to changes in their size and shape [30]. During the FSP, the tool is not only traversing relative to the work-piece but also rotating at high speed. These movements lead to serious plastic deformation, crushing, stirring, mixing, and refinement of the processed material in the processed zone.

Figure 9 shows the microscopic morphology and distribution of SiC particles in FSPed composites when the initial average particle size of SiC particles is 20 μm. When the rotational speed and traverse speed of the tool were 800 rpm and 60 mm/min, respectively, the particle size and distribution of SiC particles in the FSPed composites were non-uniform, as shown in Fig. 9a. Figure 9b shows that when the rotational speed of the tool is decreased and its traverse speed is increased (ω = 950 rpm, u = 60 mm/min), the number of large particles of SiC particles decreases and the distribution remains non-uniform. When the rotational speed of the tool is increased and its traverse speed is kept constant (ω = 1300 rpm, u = 60 mm/min), the particle size and distribution of the SiC particles are relatively uniform. When the rotational speed of the tool is increased and its traverse speed is kept constant (ω = 1300 rpm, u = 60 mm/min), the particle size and distribution of the SiC particles are relatively uniform, as shown in Fig. 9c. Figure 9d illustrates that when the rotational speed of the tool is 950 rpm and its traverse speed is 80 mm/min, the SiC particles exhibit agglomeration and uneven distribution due to the large traverse speed of the tool.
Comparing and analyzing Figs. 8 and 9, it can be seen that in addition to the rotational speed and traverse speed of the tool, which have a significant impact on the morphology and distribution of SiC particles in the FSPed composites, the initial average particle size of the pre-implanted SiC particles also significantly affects the morphology and distribution of SiC particles in the processed zone. When the SiC particles with an initial average particle size of 40 μm were pre-implanted, after the SiC particles were refined and redistributed by the tool in the FSP process, the average particle size of the SiC particles in the FSPed composites was larger than that with the initial average particle size of the pre-implanted SiC particles was 20 μm under the same FSP process parameters, and the uniformity of the SiC particle distribution in the former composites was correspondingly worse than that of the latter.

According to the above analysis, the influence of the initial particle size on the microstructure and properties of the FSPed composites should be taken into account when selecting the pre-implanted particle material, and the particle with a smaller average particle size should be preferred as the reinforcement phase. At the same time, the smaller the average particle size of the reinforced particles, the larger the specific surface area of the reinforced particles, and the better the reinforcing effect of the reinforced particles. However, if the particle size of the reinforced particles is too small, the agglomeration of the reinforced particles is easy to occur during the FSP process, which is not conducive to the dispersion and distribution of the reinforced particles, so how to promote the dispersion and distribution of the reinforced particles becomes the key to the successful fabrication of FSPed composites [31]. Therefore, it is necessary to pay more attention to the optimization of FSP process parameters while preferentially selecting small particle size particles as the reinforcement phase.
In addition, the SiC particles became core–shell structured particle due to the diffusion phenomenon between the particles and the matrix, where the shell was the diffusion layer [32], as shown in Fig. 10a. This difference in structure leads to obvious differences in the deformation and flow rate of the SiC particles and the matrix in the FSP process, and this prevents the SiC particles from flowing synchronously with the matrix. In the subsequent flow process, the SiC particles were refined due to the influence of various forces, as shown in Fig. 10b. Since the SiC particles continue to be applied with unbalanced forces after being broken, they were further refined and dispersed, as shown in Fig. 10c. The refined and dispersed SiC particles were enveloped by the plastic matrix material and then flow. The flow velocity of the SiC particles was slower than that of the matrix during the entire FSP process. As the FSP process continues, a part of the SiC particles that had been refined would be refined again according to the process shown in Fig. 10. At the same time, due to the discontinuous temperature distribution and the structural difference, the flow velocity of the SiC particles during the entire FSP process was lower than that of the matrix, which further promoted the uniform distribution of the refined SiC particles in the processed zone. With the increase of the pass number of FSP, the degree of refinement and homogenization of SiC particles also increases. At the same time, the defects such as micropores and holes in the processed zone are also reduced accordingly [33].

4.4 Effect of the SiC particles on the flow path lines of particles of the processed material

The particle size and distribution of the SiC particles were the final result of deformation and flow of the SiC particles. The result was directly determined by the flow status of the SiC particles and the matrix during the FSP. In order to observe the flow of the SiC particles and matrix during the FSP, the flow path lines of the particles of processed material in the FSP process were observed on the basis of the simulation results of the temperature field, as shown in Fig. 11. Figure 11 describes the flow path lines of the processed material particles during the fabrication of SiC particle-reinforced aluminum matrix surface composite by
FSP. The different colors of the flow path lines were used to distinguish different material particles. The value of the color bar on the left side of the figure was used to indicate the ID of the material particles. Figure 11a shows the flow path lines of the material particles around the A, B particles and the tool, while the flow path lines of the material particles around the A, B particles and on the surface of the pin are mainly described in Fig. 11b. Figure 11 shows that the flow path line of the processed material particle presents a complex three-dimensional spatial curve during the FSP. This is mainly due to the forced movement of the particles caused by the effect of friction and stirring applied by the tool and the effect of collision with other material particles during the flow process.

In particular, the flow path lines of the processed material particles around the SiC particles had been changed many times, as shown in Fig. 11b. In order to more clearly clarify the influence of the pre-implanted SiC particles on the flow path lines of the surrounding processed material particles during the FSP, the processed material particles around the A and B particles were directly selected as the research object based in Fig. 11. In the process of flow, the flow direction of the processed material particles was changed many times due to the collision and obstruction of A and B
particles, tool surface and surrounding particles of processed material. After the particles of processed material left the A and B particles, the flow direction of this part of material particles was forced to change again during the subsequent flow process because of the collision and obstruction of the surrounding particles of processed material, as shown in Fig. 12.

In addition, the particle sizes of A and B particles are much larger than that of matrix materials, which leads to the flow velocity of the A and B particles to be slower than that of the surrounding plastic material particles during the FSP. In the process of being entrapped by the surrounding plastic material to flow, the obstructive effect of the A and B particles force the flow direction of the surrounding plastic material to change, and the degree of change varies with the change of FSP parameters, as shown in Figs. 8 and 9. Since the flow of plastic materials is affected by the collision and obstruction of the reinforced particles, the flow path lines of plastic materials with pre-implanted reinforced particles are more complex than that of plastic materials without pre-implanted reinforced particles during the FSP.

It should be pointed out that in order to clearly show the influence of the reinforced particles on the flow path lines of the material particles during the FSP, the particle sizes of the A and B particles were magnified many times in the simulation. However, in the actual FSP process, the particle size of SiC particles became very small after being refined and flowed together with the matrix, that is, the refined reinforced particles became a part of the complex flowing material flow shown in Figs. 11 and 12. Therefore, the flow path lines in Figs. 11 and 12 not only shown the flow trajectory of the matrix but also reflected the flow trajectory of the refined SiC particles.

The influence of A and B particles on the flow path lines of the surrounding plastic material indicated that the difference in the properties of the two materials resulted in the difference in flow velocity between the particles of two materials during the FSP of the dissimilar materials. In other words, the collision and obstruction of one kind of material particles would inevitably change the flow direction of another kind of material particles, which made the flow path lines of the material particles in the processed zone more complicated, as shown in Figs. 11 and 12. The more
complicated the flow path lines of the particles of processed material became, the more fully the processed material was stirred and mixed in the processed zone, which was beneficial to the more uniform distribution and densification of the particles of different phases in the surface composites fabricated by FSP. Therefore, the suitable selection of reinforced materials and FSP process parameters is the key factor to regulate the quality of FSP processed zone.

In order to further investigate the influence of the particle size of the reinforced particles on the flow path of the processed plastic material, in the next experiment under the condition that the other process parameters unchanged, the particle size of the reinforced particle A was reduced from 2 to 0.4 mm and modified its name to C particle. At the same time, the particle size of the reinforced particle B was reduced from 1 to 0.2 mm and its name is modified to D particle. Figure 13 depicts the flow path lines of the processed material particles around the surface of the pin and the reinforced particles. Figure 14 shows the results of the simulation analysis when only the effects of particles C and D are considered. According to Figs. 13 and 14, under the same conditions of other process parameters, with the decreases of particle size of reinforced particles, the influence of reinforced particles on the flow path of the processed plastic material is correspondingly decreased. This is mainly due to the difference in flow velocity between the reinforced particles with a smaller particle size and the plastic material is reduced, so that the obstacle of the reinforced particles to the flow of the plastic material is reduced. In addition, the reduction of in the size of the reinforced particles also reduces the frequency of the particles being collided by other material particles. It should be emphasized that the influence of the particle size of reinforced particles on the flow path of the processed plastic material depends on a variety of factors, such as the rotational speed and traverse speed of the tool, the types of the processed materials and the reinforced particles, the structure and size of the tool, etc. Therefore, the influence of the reinforced particles on the flow path of the processed plastic material is a result of a comprehensive influence of multiple process parameters. This conclusion is also demonstrated by the results shown in Figs. 8 and 9.

According to the above-mentioned analysis, after the reinforced particles are refined, the process parameters must be optimized in order to make the reinforced particles evenly
distributed in the matrix. For example, multi-pass FSP schemes with different process parameters are used [6].

4.5 Microhardness distribution of the processed zone

Figure 15 shows the average microhardness distribution of the processed zone of 6061 aluminum alloy pre-implanted with SiC particles and processed with FSP. The results show that the microhardness of the processed zone after adding SiC particles is higher than that of the base metal. After the 6061 aluminum alloy is processed by FSP, the microhardness of the processed zone is quite different. The microhardness value of the stir zone (SZ) is the highest, while the microhardness values of the thermomechanically affected zone (TMAZ) and heat affected zone (HAZ) are relatively low, but their microhardness is higher than that of the base metal (BM). Figure 15 depicts that the average microhardness of the SZ is the highest when the rotational speed of the tool is 950 rpm and the
traverse speed is 60 mm/min, and its average microhardness is about 77HV, which is about 1.6 times that of the BM. Under the parameters of the rotational speed of 950 rpm and the traverse speed of 80 mm/min, the average microhardness of SN is about 65HV, which is about 1.4 times that of the BM.

The increase in microhardness of the processed zone of the FSPed sample is the result of the combined effect of particle reinforcement and fine-grained strengthening. The grain size of the processed zone of the FSPed specimen is significantly refined, which is mainly attributed to two reasons. First, the material in the processed zone during the FSP process is subjected to continuous effects from the pin and the shoulder of the tool, including shearing and extrusion crushing. Under the combined effect of severe plastic deformation and frictional heat, the strain generated by deformation not only stores the strain energy for metal recrystallization but also provides enough energy for recrystallization, which promotes the occurrence of dynamic recrystallization and leads to the processed material forms fine equiaxed grains [34, 35]. Second, the SiC particles added into the matrix are equivalent to the second phase. The SiC particles have a strong pinning effect on the migration of grain boundaries, which not only hinders the migration of grain boundaries but also inhibits the grain growth, so that the SiC particles further refined the grain of the processed material [36].

5 Conclusions

In this study, the aluminum matrix composites was fabricated using 6061 aluminum alloy plate as the matrix and SiC particles as the reinforced particles by FSP technology. The effects of pre-implanted SiC particles on the temperature field and the flow field of the processed zone was studied. The refinement, particle size, and distribution of the SiC particles in the processed zone of the FSPed multi-pass composites were also discussed in detail, as well as the microhardness of the processed zone of the FSPed multi-pass composites. The results could be summarized as follows:

- The combination of process variables controls the temperature field and the flow field in the fabrication of SiC particle-reinforced aluminum matrix surface composites by FSP, and it determines the refinement and uniform distribution of the SiC particles. The optimum process parameters in this experiment are: \( \omega = 950 \text{ rpm, } \mu = 60 \text{ mm/min.} \)
- The specific heat capacity and thermal conductivity between the 1060 aluminum and the SiC are significantly different, which results in the temperature field at the interface between SiC particles and the matrix in the FSP processing zone present a discontinuous distribution, and also causes a difference in the flow velocity between the SiC particles and the matrix.
- The flow direction of the plastic material changes several times due to the collision and hindrance of the reinforced SiC particles. The initial average particle size of the SiC particles has a significant effect on the flow path of the processed plastic material. Selecting appropriate process parameters is beneficial to the refinement and uniform distribution of the processed material particles.
- The microhardness of the processed zone of the FSPed composites is significantly higher than that of the matrix due to the combined effect of particle reinforcement and fine-grained strengthening.

Author contribution Jingming Tang: study design, investigation, writing—original draft, and writing—review and editing. Qichao Deng: data analysis and writing—review and editing. All authors read and approved the final manuscript.

Data availability The measurement data are available from the corresponding author on request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Miracle DB (2005) Metal matrix composites—from science to technological significance. Compos Sci Technol 65(9):2526–2540. https://doi.org/10.1016/j.compscitech.2005.05.027
2. Salehi M, Saadatmand M, Aghazadeh MJ (2012) Optimization of process parameters for producing AA6061/SiC nanocomposites by friction stir processing. Trans Nonferrous Met Soc Chin 22(5):1055–1063. https://doi.org/10.1016/S1003-6326(11)61283-1
3. Luo XC, Kang LM, Liu HL, Li ZJ, Liu YF, Zhang DT, Chen DL (2020) Enhancing mechanical properties of AZ61 magnesium alloy via friction stir processing: effect of processing parameters. Mater Sci Eng A 797:139945. https://doi.org/10.1016/j.msea.2020.139945
4. Akbar H, Yousef M, Masoud R, Samad G (2019) Development of Cu-TiO2 surface nanocomposite by friction stir processing: effect of pass number on microstructure, mechanical properties, tribological and corrosion behavior. J Alloys Compd 783:886–897. https://doi.org/10.1016/j.jallcom.2018.12.382
5. Zhao HL, Pan Q, Qin QD, Wu YJ, Sa XD (2019) Effect of the processing parameters of friction stir processing on the microstructure and mechanical properties of 6063 aluminum alloy. Mater Sci Eng A 751:70–79. https://doi.org/10.1016/j.msea.2019.02.064
6. Husain M, Mishra RS (2021) Effect of multi-pass friction stir processing and SiC nanoparticles on microstructure and mechanical
properties of AA6082-T6. Advances in Industrial and Manufacturing Engineering 3:100062. https://doi.org/10.1016/j.aim.2021.100062

7. Sivanesh PM, Elaya PA, Arulve S (2020) Development of multi-pass processed AA6082/Slip surface composite using friction stir processing and its mechanical and tribology characterization. Surf Coat Technol 394:125900. https://doi.org/10.1016/j.surfcoat.2020.125900

8. Ashish KS, Nagendra KM, Amit RD, Shashi PD, Ambuj S, Manish M (2021) Experimental investigations of A359/Si3N4 surface composite produced by multi-pass friction stir processing. Mater Chem Phys 257:123717. https://doi.org/10.1016/j.matchemphys.2020.123717

9. Javad M, Salman N, Hamed JA (2020) Statistical modelling and optimization of friction stir processing of A390–10 wt% Si C compo-cast composites. Measurement 165:108166. https://doi.org/10.1016/j.measurement.2020.108166

10. Chintalu RS, Padmanaban R, Vignesh RV (2021) Finite element modelling of thermal history during friction stir processing of AA5052. Mater Today Proc 46:7452–7458. https://doi.org/10.1016/j.matpr.2021.01.105

11. Nazanin H, Ali RE, Mohammad RA (2021) Finite element simulation of deformation and heat transfer during friction stir processing of as-cast A291 magnesium alloy. J Mater Res Technol 14:2998–3017. https://doi.org/10.1016/j.jmrt.2021.08.087

12. Kayode O, Olufayo OA, Akinlabi ET (2019) Preliminary studies on molecular dynamics simulation of friction stir processing of aluminium alloys. Key Eng Mater 796:155–163. https://doi.org/10.4028/www.scientific.net/KEM.796.155

13. Bahman M (2021) A modified friction model and its application in finite-element analysis of friction stir welding process. J Manuf Process 72:29–47. https://doi.org/10.1016/j.jmapro.2021.10.008

14. Shaminan M, Mostaen H, Safari M, Dezfooli MS (2017) Friction-stir processing of Al-12%Si alloys: grain refinement, numerical simulation, microstructure evolution, dry sliding wear performance and hardness measurement. Metall Res Technol 114(2):213. https://doi.org/10.1016/j.metall.2016066

15. Julian A, Julian E, Barbara C, WilliamMaghalâães PM, Johnnatan R, Haroldo P, Antonio R (2019) Physical simulation as a tool to understand friction stir processed X80 pipeline steel plate complex microstructures. J Mater Res Technol 8(1):1379–1388. https://doi.org/10.1016/j.jmrt.2018.09.005

16. Stubblefield GG, Fraser K, Phillips BJ, Jordon BJ, Allison PG (2021) A meshfree computational framework for the numerical simulation of the solid-state additive manufacturing process, additive friction stir-deposition (AFS-D). Mater Des 202:109514. https://doi.org/10.1016/j.matdes.2021.109514

17. Arora HS, Singh H, Dhindaw BK (2012) Numerical simulation of temperature distribution using finite difference equations and estimation of the grain size during friction stir processing. Mater Sci Eng A 543:231–242. https://doi.org/10.1016/j.msea.2012.02.081

18. Yang X, Zhang RX, Dong P, Yan ZF, Wang WX (2022) A study on the formation of multiple intermetallic compounds of friction stir processed high entropy alloy particles reinforced Al matrix composites. Mater Charact 183:11646. https://doi.org/10.1016/j.matchar.2021.11646

19. Tutunchilar S, Haghpanah M, Besharati Givi MK, Asadi P, Bahemat P (2012) Simulation of material flow in friction stir processing of a cast Al-Si alloy. Mater Des 40:415–426. https://doi.org/10.1016/j.matdes.2012.04.001

20. Wang Y, Mishra RS (2007) Finite element simulation of selective superplastic forming of friction stir processed 7075 Al alloy. Mater Sci Eng A 463(1–2):245–248. https://doi.org/10.1016/j.msea.2006.08.118

21. Khodabakhshi F, Derazkola HA, Gerlich AP (2020) Monte Carlo simulation of grain refinement during friction stir processing. J Mater Sci 55:13438–13456. https://doi.org/10.1007/s10853-020-04963-2

22. Hamilton C, Stanislav WM, Stanislav D (2015) A simulation of friction-stir processing for temperature and material flow. Metall Mater Trans B 46:1409–1418. https://doi.org/10.1007/s11663-015-0340-z

23. Sathiskumar R, Murugan N, Dinaharan I, Vijay SJ (2013) Characterization of boron carbide particulate reinforced in situ copper surface composites synthesized using friction stir processing. Mater Charact 84:129–138. https://doi.org/10.1016/j.matchar.2013.07.001

24. Sheppard T, Jackson A (1997) Constitutive equations for use in prediction of flow stress during extrusion of aluminum alloys. Mater Sci Technol 13:203–209. https://doi.org/10.1179/mst.1997.13.3.203

25. Thomas WM, Nicholas ED (1997) Friction stir welding for the transportation industries. Mater Des 18:269–273. https://doi.org/10.1016/S0261-3069(97)00062-9

26. Zhang W, Roy GG, Elmer JW, Debroy T (2003) Modeling of heat transfer and fluid flow during gas tungsten arc spot welding of low carbon steel. J Appl Phys 93:3020–3033. https://doi.org/10.1063/1.154074

27. Nandan R, Roy GG, Debroy T (2006) Numerical simulation of three-dimensional heat transfer and plastic flow during friction stir welding. Metall Mater Trans A 37:1247–1259. https://doi.org/10.1007/s11661-006-1076-9

28. Brandon AM, Yu J, Yen C (2013) Numerical simulation and experimental characterization of friction stir welding on thick aluminum alloy AA2139-T8 plates. Mater Sci Eng A 585:243–252. https://doi.org/10.1016/j.msea.2013.07.073

29. Zhang JQ, Shen YF, Li B, Xu HS, Yao X, Kuang BB, Gao JC (2014) Numerical simulation and experimental investigation on friction stir welding of 6061–T6 aluminum alloy. Mater Des 60:94–101. https://doi.org/10.1016/j.matdes.2014.03.043

30. Prater T (2011) Solid state joining of metal matrix composites: a survey of challenges and potential solutions. Adv Manuf Process 26:636–648. https://doi.org/10.1007/s10426914.2010.49205

31. Liu ZY, Xiao BL, Wang WG, Ma ZY (2014) Analysis of carbon nanotube shortening and composite strengthening in carbon nanotube/aluminum composites fabricated by multi-pass friction stir processing. Carbon 69(2):264–274. https://doi.org/10.1016/j.carbon.2013.12.025

32. Tang JM, Shen YF, Li JP (2019) Investigation of microstructure and mechanical properties of SiC/AI surface composites fabricated by friction stir processing. Mater Res Express 6:065576. https://doi.org/10.1088/2053-1591/ab3775

33. Vipin S, Ujjwal P, Manoj K (2015) Surface composites by friction stir processing a review. J Mater Process Technol 224:117–134. https://doi.org/10.1016/j.jmatprotec.2015.04.019

34. Mishra RS, Ma ZY (2005) Friction stir welding and processing. Mat Sci Eng R 50(1):1–78. https://doi.org/10.1016/j.mser.2005.07.001

35. Ma ZY, Pilchak AL, Williams C (2008) Microstructural refinement and property enhancement of cast light alloys via friction stir processing. Scripta Mater 58(5):361–366. https://doi.org/10.1016/j.scriptamat.2007.09.062

36. Ran G, Zhou JE, Xi SQ, Li PL (2006) Microstructure and morphology of Al-Pb bearing alloy synthesized by mechanical alloying and hot extrusion. J Alloys Compd 419(1):66–70. https://doi.org/10.1016/j.jallcom.2005.09.057

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