Numerical and experimental investigation of formability in incremental sheet forming of particle reinforced metal matrix composite sheets

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Abstract

Metal matrix composites (MMCs) have a high strength-to-weight ratio, high stiffness, and good damage resistance under a wide range of operating conditions, making them a viable alternative to traditional materials in a variety of technical applications**.** Because of their high strength, composite materials are hard to deform to a significant depth at room temperature. As a result, additional treatments are required to enhance the composite's room ductility prior to deformation. In this investigation, as-received 6092Al/SiCp composite sheets (T6-condition) are heat treated to O-condition annealing to enhance its ductility in order to assess the influence of single point incremental forming (SPIF) parameters on the formability and fracture behavior of the Al/SiC particle composite sheets at room temperature. Then the annealed sheets are heat treated to T6-condition to enhance the strength and achieve properties equivalent to as-received sheets properties. The results demonstrate that the Al/SiC particle composite sheets with T6 treatment could not be deformed to the specified depth at room temperature due to low room ductility and that further treatment, such as O-condition annealing, is required to enhance the room ductility. When annealed Al/SiCp composite sheets are heat treated to T6, the sheets exhibit properties comparable to the as-received sheets. Al/SiC particle composite sheets with low SPIF parameters may have greater formability and fracture depth with low strain hardening curve.

Keywords*: SPIF, Al/SiC particle composites, Formability, Forming parameters, Heat treatment*

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1. Introduction

Aluminum matrix composite (AMC) materials reinforced with SiC particles offer significant promise for usage in the automotive, aerospace and energy industrial sectors. As a result, new techniques for deforming these composite sheets are necessary. Single point incremental forming (SPIF) is a flexible and easy to implementation sheet forming process, which only requires the use of a CNC milling machine to control the movement of a hemispherical tool and to deform the sheet in following a predefined tool path. Because of the unique characteristics of single point incremental forming, such as flexibility, cost-effectiveness, shortened time-to-market, and increased forming limit, the SPIF is a potential technology that can be developed further as an alternative production approach for composite sheets [1-4]. The impact of T6 treatment on the tensile properties of Al6061 and Al7108/SiCp composites was examined and compared to samples prior to T6 treatment. T6 treatment was shown to enhance the ultimate tensile strength of 6061 and 7108 composites [5]. The microstructure and interface of Al2124/10wt% SiC particle composites were studied to better understand their behavior at high temperatures. The results revealed that a dispersed phase was formed around the SiC particles and also at the grain boundary [6]. Under different heat treatment conditions, the feasibility of using the SPIF to form 6092Al/SiCp sheets was investigated, and it was discovered that the composite sheets may be satisfactorily formed after O-condition annealing [7]. The impact of SPIF process parameters on a maximum forming angle in forming high strength AA5052-H32 alloy sheet has been experimentally examined. The results revealed that when step depth and tool diameter increased, the maximum forming angle decreased [8]. The influence of process parameters on the maximum forming angle was examined in the incremental forming of extra deep drawing steel sheets. The largest impact on the wall angle is affected by the tool diameter, followed by the feed rate and step depth [9].

The SPIF test was used to assess the formability of the aluminum alloy AA2024-O. The formability deteriorated with increased wall angle and step size [10]. To evaluate and enhance the process variables of the incremental sheet forming process using finite element simulations, the tool radius, step size, and friction coefficient were chosen as the key process variables. As a result of the FE simulations, the tool step size was found to be a major component for enhancing the formability of the incremental sheet forming process [11]. A simplified model of the SPIF of a truncated cone capable of estimating the thickness distribution was constructed using sequential limit analysis (SLA). It is proven that the SLA can predict the thickness distribution more precisely and efficiently than the comparable FEA technique [12]. Processing conditions also affect the quality of the SPIF parts made of carbon steel (DC01), stainless steel (304), and aluminum (A1050). Increased tool diameter, feed rate, and spindle speed enhance surface roughness and microstructure of formed components. Increased tool diameter and feed rate, on the other hand, have a negative impact on the component precision [13]. Aluminum Al3003-0 was used in a SPIF experimental test. The formability of the workpiece was seen to deteriorate as the step size was increased [14]. Using a cold incremental forming process, the effect of feed rate on the formability of DIN 1.0037 steel (St 37-2 steel) was studied. The results revealed that as the feed rate was increased, the formability decreased [15]. In order to examine the effect of tool diameter on formability, researchers tested the formability of a Cp Ti sheet in a cold ISF process. It was found that when the tool size was increased, the formability was decreased [16].

The workability of a thermoplastic matrix reinforced with glass fibers using the SPIF method was examined experimentally. It was observed that the SPIF may be utilized to deform the thermoplastic composite sheets [17]. The SPIF process's suitability for deforming composite/metal hybrid sheets was tested experimentally. The results demonstrated that the SPIF process may be utilized to create a composite/metal hybrid sheet component [18]. Numerical, analytical, and experimental studies were used to assess the formability of bimetal composite sheets (Cu-Al composite sheets) in the SPIF process. Surface roughness, formability, and forming force of bimetal composite sheets were discovered to follow similar patterns to single-layer sheets [19]. The SPIF process was used to evaluate the effect of annealing on the formability of Cu-St composite sheets. When the annealing temperature is raised, the formability of the Cu-St composite sheets was improved [20, 21].

The literature clearly shows that attempts have been made to evaluate the influence of SPIF parameters on monolithic alloys, but no study has been published to examine the effect of SPIF process parameters on particle-reinforced metal matrix composites materials. Al/SiC-T6 AMC sheets are hard to deform at room temperature because of their high strength. As a consequence, O-condition annealing is used to improve the room ductility of Al/SiCp AMC sheets in this work. The capability of the SPIF process to deform the Al/SiCp AMC sheets at room temperature is next examined, with a special focus on the effect of SPIF parameters on the formability of the Al/SiCp AMC sheets. Because high strength is important for the AMC materials, the annealed sheet is heat treated again to

T6 condition for increased strength and desired characteristics similar to those of the as-received sheet. This work is done by experimentation and finite element simulation.

2. Experimental testing

Al6092/SiC/17.5p AMC sheets having a thickness of 1.04 mm and received at T6-condition are used in this work. The main feature of Al/SiCp AMC material is its high strength. Nevertheless, due to its high strength, it is difficult to deform the AMC sheet to a specified shape at ambient temperature. As a result, in this research, the as-received 6092Al/SiCp AMC sheets (T6-condition) are heat treated to O-condition annealing to increase its ductility at room temperature, then the annealed sheet is heat-treated to T6-condition to improve the strength again. The heat treatments (O-condition annealing and T6-treatment) were carried out in accordance with the ASM's recommendations.

To evaluate the effect of heat treatment on the mechanical properties of the Al/SiCp AMC sheets, tensile tests were performed using an INSTRON testing machine with the as-received sheet (T6), O-condition annealing sheet, and T6-treatment sheet. ASTM-E8 was used to design and manufacture the tensile specimens. The Vickers test was used to determine the effect of heat treatment on the hardness of Al/SiCp AMC sheets. For 15 seconds, the load was set at 5 kg. The Vickers hardness test was performed in several locations, and the average value was recorded.

Under T6 and O-condition treatments, the SPIF test was performed on 6092Al/SiCp sheets with dimensions of 140 mm ×140 mm × 1.04 mm. To minimise friction between the tool and the Al/SiCp sheet, the Rocol RDT grease compound was employed as lubricant. A hyperbolic truncated cone with varying wall angles (from 22^{o} to 80^{o}) was used to analyse the formability and fracture position in the 6092Al/SiCp sheets. The thickness, fracture depth, fracture wall angle, and stress-strain curves were all related to the findings of the SPIF testing. The tests were carried out at three different feed rates (1000, 2000, and 3000 mm/min), with a tool diameter of 10 mm and a step size of 0.2 mm. The deformed components were sectioned from the middle for two portions to analyse the thickness distribution of the SPIF components along the deformed wall.

3. Finite Element Simulation

In this work, Abaqus/Explicit software is used to do finite element simulation of single point incremental forming. The SPIF process's finite element model is made up of four separate parts: a forming tool, a sheet, a blank holder, and a backing plate. Analytical rigid bodies are used to simulate the forming tool, holder, and backing plate. The Al/SiCp AMC is represented as a deformable body with dimensions of 140 x 140 x 1.04 mm. A surface to surface contact state is assigned between the forming tool and the top surface of the sheet, and between the lower surface of the sheet and the inner surface of the backing plate. To save processing time, mass scaling technique was utilized.

The AMC sheet meshed with a 4-node shell element (S4R). The major goal of this simulation was to predict the deformation of a 6092 Al/SiCp sheet during SPIF, with special attention paid to the effect of the SPIF parameters on the results. The simulation parameters are tool diameter, step size, and feed rate. The Coulombs friction law was used, with a friction coefficient of 0.1 between the Al/SiCp sheet and the tools (forming tool, holder, and backing plate). The FE simulation is terminated when the depth of the hyperbolic truncated cone approaches the experimental depth. Table 1 shows the SPIF process parameters that were used for simulations.

Table 1 The SPIF Process parameters

Parameter	Level 1	Level 2	Level 3
Tool diameter (mm)	8	10	12
Step down (mm)	0.2	0.4	0.6
Feed rate (mm/min)	1000	2000	3000

4. Results and Discussion

The stress-strain curves of the Al6092/SiCp AMC sheet under different heat treatment conditions i.e., as-received sheet (T6), O-condition annealing, and T6 are shown in Figure 1 (a). The figure clearly shows that O-condition annealing can significantly improve the formability of AMC sheets. When the as-received 6092Al/SiCp AMC sheets (T6-condition) are heat treated to O-condition annealing, the elongation to fracture increases by 65%, and the maximum value of stress is reduced by 34%. When O-condition annealed sheets are heat treated to T6 condition, similar characteristics to the as-received sheets can be obtained with a little percentage increase in elongation to fracture (about 5%) and a small percentage decrease in ultimate tensile stress (about 5%).

The Vickers hardness of the Al/SiCp AMC sheets varies with heat treatment type; as-received sheets have a high hardness, which decreases by 58% during O-condition annealing and increases again when the O-condition annealed sheets are heat treated to T6-condition (see

Figure 1 (b)). It can be concluded that there is a good correlation between the stress-strain curve and the hardness of Al/SiCp AMC sheets under different heat treatment conditions and that low stress-high strain and low hardness could be produced with O-condition annealing, which can improve the composite sheet's ductility at room temperature.

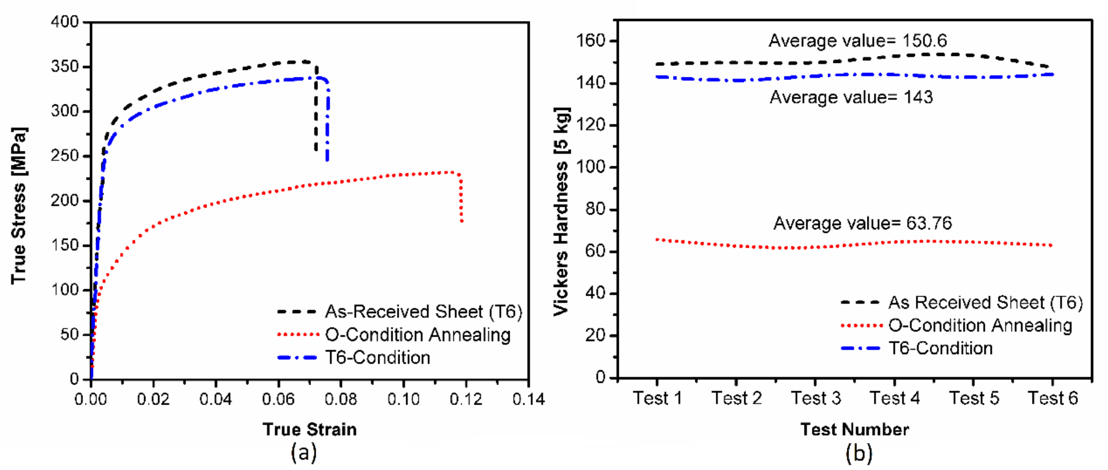

Figure 1 True stress-true strain curves (a) and Vickers hardness (b) of Al6092/SiC/17.5p under different heat treatment conditions.

The morphologies of the fracture surfaces of tensile specimens were examined using a scanning electron microscope (SEM) under different heat treatment conditions (as received sheet (T6), O-condition annealing, and T6-treatment). Figure 2 depicts the impact of the heat treatment on the fracture surface. In the T6 condition of as-received sheet and annealed sheet, the fracture surface exhibits shallow dimples with some broken SiC particles and debonding between the Al matrix and SiCp particles. However, after annealing, a high percentage of dimples were observed on the fracture surface of the tensile specimen. It is clear from Figures 1 and 2 that O-condition annealing can be used to lower the strength of the Al/SiCp AMC sheets and to increase its ductility at room temperature. In conclusion, annealing the 6092Al/SiCp AMC sheets significantly improved their room ductility. T6-condition might be used to regain the strength and mechanical characteristics similar to as-received sheets.
As a result, two types of fracture mechanisms could be observed in this study: the first is a brittle fracture for material treated with T6. The second kind is ductile fracture, which occurs when a material is subjected to O-condition annealing.

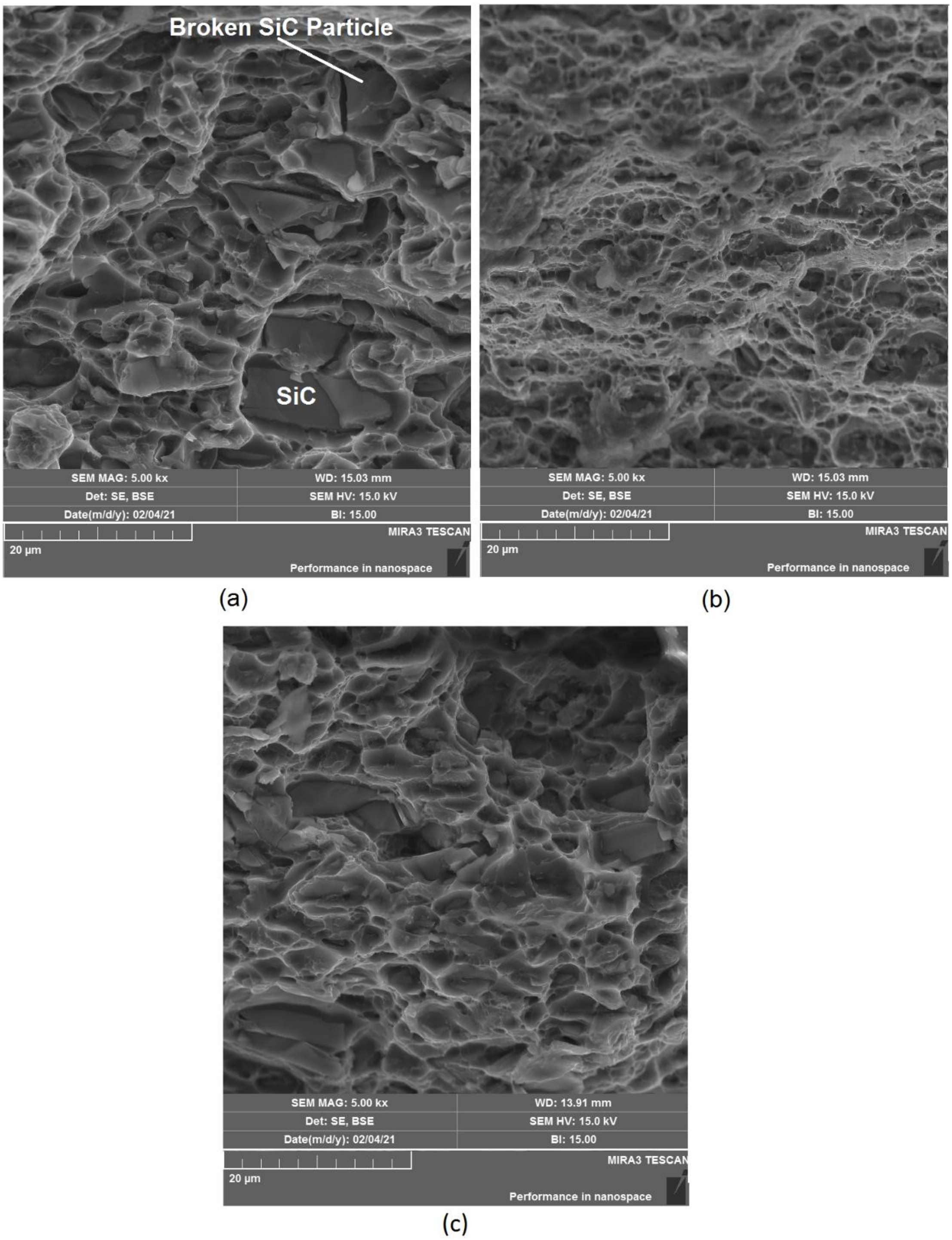

Figure 2 Fractography of 6092Al/SiCp with (a) T6-treament (as received), (b) O-condition annealing, and (c) T6-treatment.

The SPIF experimental tests were performed with T6 and O-condition treatments to deform a hyperbolic truncated cone shape with wall angles ranging from 22^{o} to 80^{o}. Figure 3 (a) shows that the fracture occurs early in the T6 condition and has a substantial amount of springback. It is clear from Figure 3 (a) that without additional treatment, deforming the Al/SiCp AMC sheets at room temperature is difficult. To overcome this problem, O-condition annealing was employed to increase the ductility of the AMC sheets (see Figure 3 (b)). It can be observed in Figure 3 (b) that greater formability may be achieved with O-condition annealing with a little degree of springback. According to the observation, it is necessary to examine the influence of the SPIF parameters on the formability and fracture behavior of Al/SiC AMC sheets at room temperature due to O-condition annealing. As a result, the finite element simulation was applied to the Al/SiCp sheets after O-condition annealing in this study.

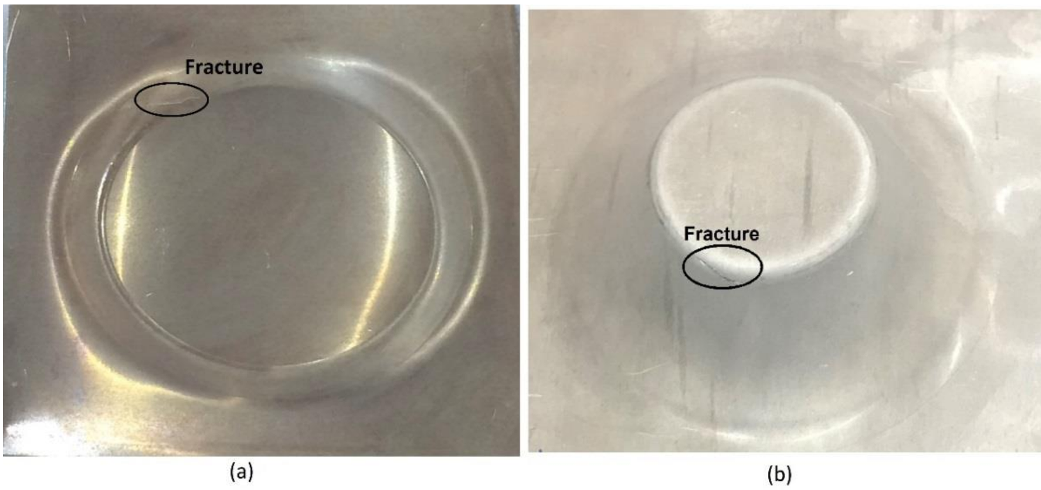

Figure 3 Heat treatment effects on the fracture depth of hyperbolic truncated cone: (a) after T6-treatment; (b) after O-condition annealing.

With constant step size and tool diameter of 0.2 mm and 10 mm, three feed rates at 1000, 2000 and 3000 mm/min were used to examine the influence of the feed rate on the formability of Al/SiCp AMC sheets. Figure 4 depicts the thickness distribution along the wall of the Al/SiCp hyperbolic truncated cone as well as the stress-strain curves. Figure 4 (a) shows that changing the feed rate can alter the thickness distribution, especially when the depth of the truncated cone is increased. The lowest thickness without fracture is reached with a low feed rate (1000 mm/min), since a high forming angle may be produced with a low feed rate. The stress-strain curves of the deformed Al/SiC truncated cone are shown in Figure 4 (b). The figure shows that strain hardening rises with feed rate, and high hardening is obtained with a high feed rate (3000 mm/min). As a result, a high feed rate produces a high stress-low strain curve, whereas a low feed rate produces a low stress-high strain curve. The formability of the deformed cone is enhanced with a low level of feed rate and the equivalent strain is increased by 10% when the feed rate changes from 3000 to 1000 mm/min, while the maximum value of stress is reduced by 6% .

It may be concluded that with a low feed rate, low stress values with high strain values can be obtained, and good formability can be obtained at these stress-strain values. Furthermore, there is a relationship between the thickness distribution and the stress-strain curves, low values of thickness without fracture could be achieved with a low stress-high strain curve.

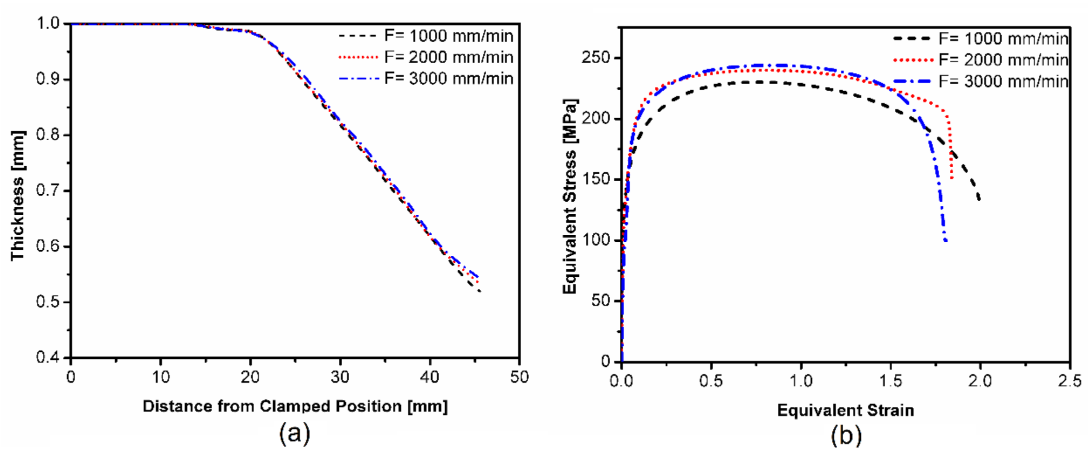

Figure 4 Thickness distribution (a) and stress-strain curves (b) at various feed rates.

Three tests were carried out to determine the influence of step size on the formability of the Al/SiCp AMC sheets at constant tool diameter and feed rate of 10 mm and 1000 mm/min, respectively. The step size was adjusted to three different values: 0.2, 0.4, and 0.6 mm. The effect of step size on the thickness distribution and stress-strain values of deformed Al/SiCp sheets is shown in Figure 5. Figure 5 (a) shows that with a small step size (0.2 mm), low thickness values with more depth may be produced, and these values rise as the step size increases, with the greatest thickness at fracture being seen with a 0.6 mm step size. This is because a localized deformation may be produced with small step sizes, but as the step size is increased, the deformation is no longer localized and the formability is reduced. Figure 5 (b) depicts the stress-strain curves for various step sizes. The figure clearly shows that the step size can affect the strain hardening in Al/SiCp sheets; high strain hardening is generated with a big step size (0.6 mm), while low strain hardening is obtained with a small step size (0.2 mm). A low stress-high strain curve is created with small step size, while a high stress- low strain curve is generated with a big step size. When the step size is raised from 0.2 to 0.6 mm, the effective strain decreases by 23% but the effective stress increases by 5%. It is reasonable to conclude that low stress-high strain curve may be produced with small step sizes, which increases the fracture depth of the SPIF component and improves the formability of the Al/SiCp AMC sheets.

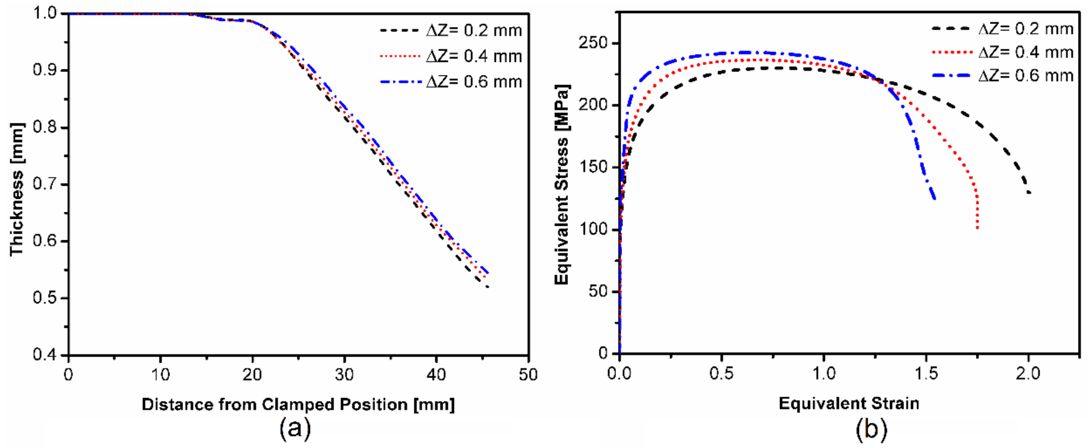

Figure 5 Thickness distribution (a) and stress-strain curves (b) at various step sizes.

To explain the influence of tool diameter on the formability of composite sheets, three sizes of forming tool diameter were used: 8, 10, and 12 mm with constant step size and feed rate of 0.2 mm and 1000 mm/min, respectively. Figure 6 (a) depicts the influence of tool size on the thickness distribution along the wall of an Al/Sicp AMC truncated cone and the stress-strain curves. The tool size clearly has a substantial influence on the thickness distribution and stress-strain curves. When the tool size is small, a low thickness distribution is generated without fracture and this distribution increases as the tool size increases. Formability decreases as tool diameter increases. Because the contact area expands as the tool size rises, the deformation does not remain localized as it does with a small tool size. Figure 6 (b) further shows that the large tool has a significant influence on the strain hardening behavior of the Al/SiCp AMC sheet, the strain hardening increases with tool diameter and the small tool obtaining minimal strain hardening in the composite sheet. With a small tool size, high strain values can be produced, and these values decrease as the tool size increases. When the tool diameter was changed from 8 to 12 mm, the decrease in strain was 27% and the percentage of rising in stress was 14%. When the impact of SPIF process parameters on Al/SiCp AMC sheets is compared, tool size is the most sensitive, followed by the step size and feed rate.

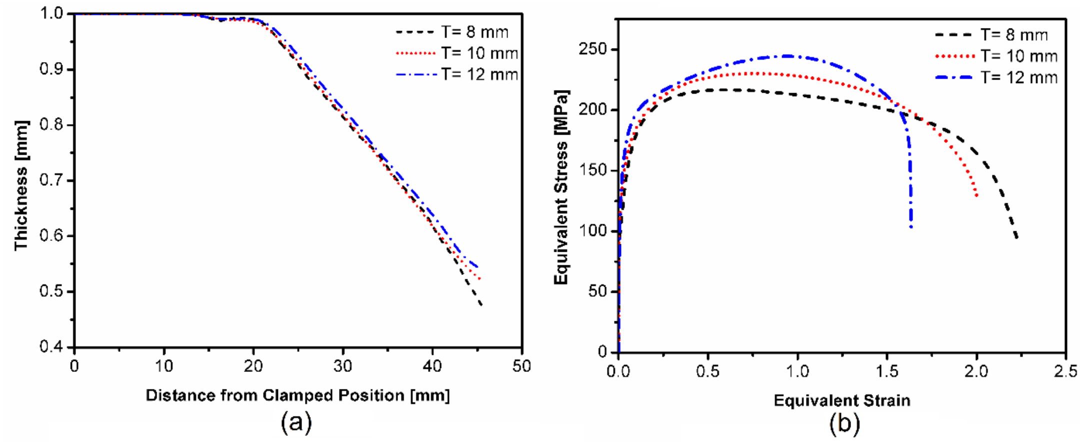

Figure 6 Thickness distribution (a) and stress-strain curves (b) at various tool sizes.

Figure 7 depicts the predicted distribution of equivalent plastic strain on the hyperbolic truncated cone under various conditions. Small values of strain are obtained at the beginning of the SPIF, and these values rise with cone depth, with the greatest value of equivalent plastic strain being in the transition zone between the inclined wall of the truncated cone and the base of the cone. The SPIF parameters may change the maximum value of predicted strain, and high strain (high formability) could be obtained with a low level of the SPIF parameters (step size (Z) = 0.2 mm, feed rate (F) = 1000 mm/min, and tool diameter (T) = 8 mm). The tool size, followed by the step size and feed rate, has a substantial influence on the formability of Al6092/SiCp AMC sheets.

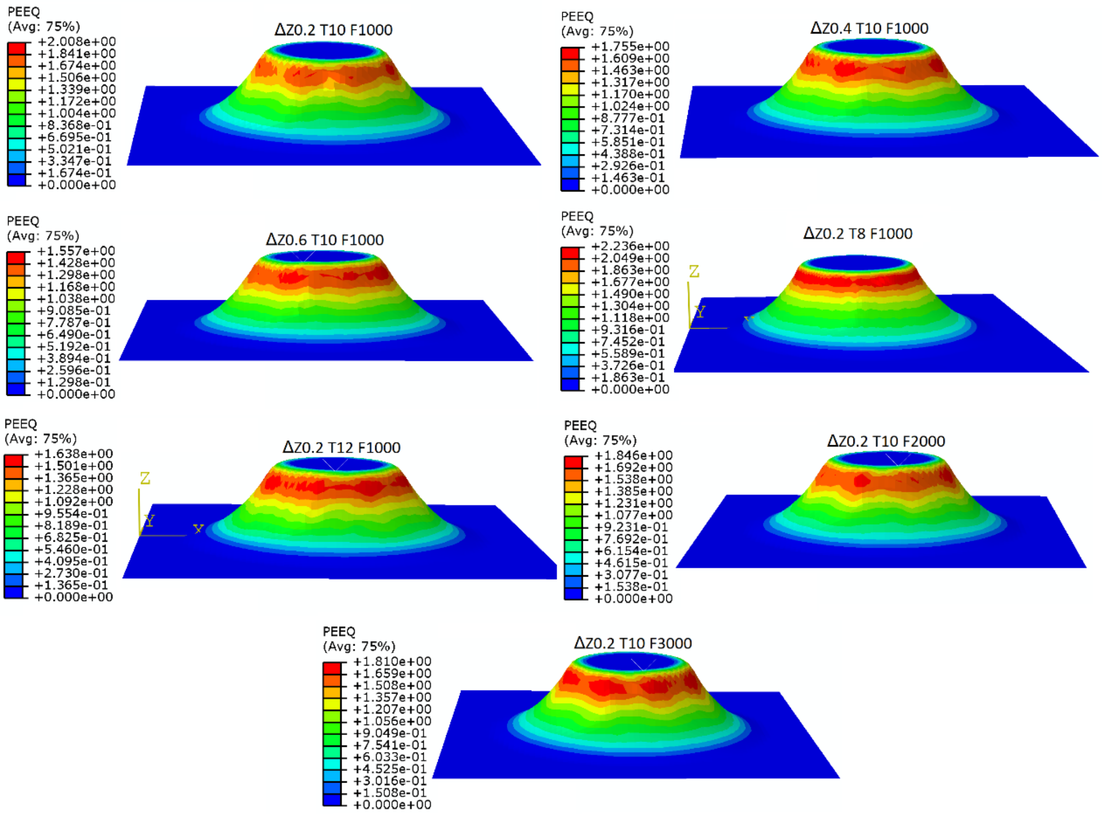

Figure 7 The distribution of equivalent strain obtained from a numerical simulation of a hyperbolic truncated cone under various forming conditions.

Figure 8 depicts the experimental fracture depth and wall angle. According to the figure, greater formability (wall angle) may be achieved with a low feed rate, but fracture occurs early with a larger feed rate, as shown in Figure 8 (a). The composite materials' sensitivity to strain rate may explain the early fracture with a high feed rate. The high strain rate causes stresses in the composite sheets to increase and fracture to occur more quickly, which is consistent with previous studies by Shakir Gatea et al. [22]. As indicated in Figure 9, the predicted thickness was compared to the experimental thickness to validate the FE results. The numerical and measured thickness results from the SPIF experiments have a strong correlation in terms of the thickness distribution of the hyperbolic truncated cone.

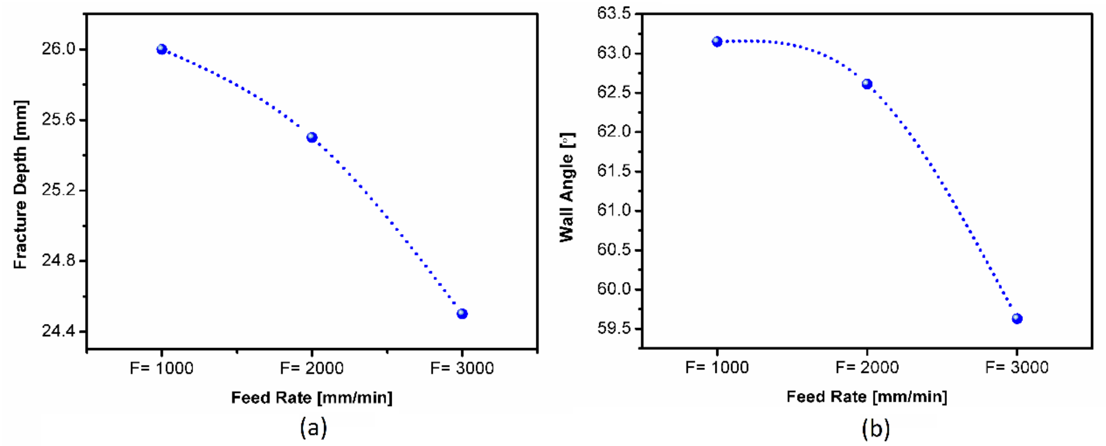

Figure 8 Experimental fracture depth (a) and wall angle (b) of a hyperbolic truncated cone of Al/SIC particle at various feed rates.

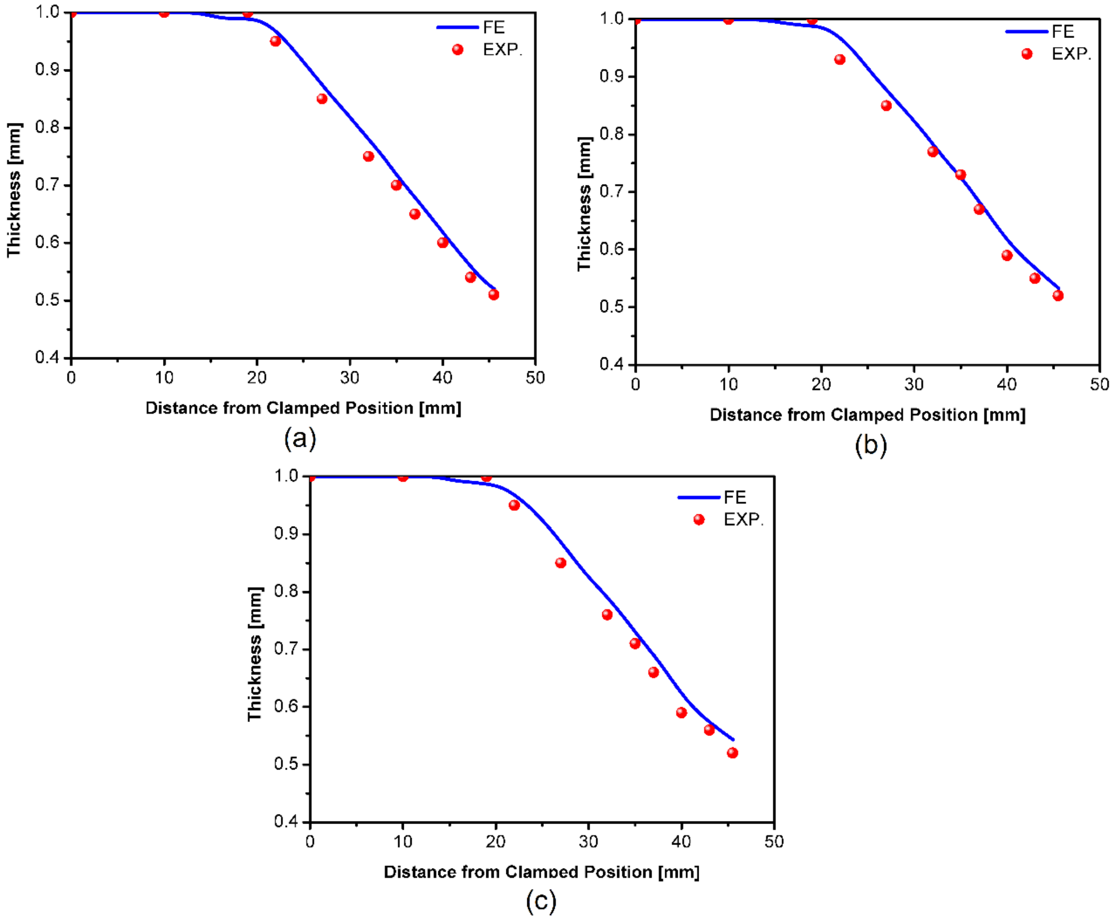

Figure 9 Simulated thickness results of the Al/SiCp hyperbolic cone shape in comparison to the real forming experiment: (a) feed rate 1000 mm/min, (b) 2000 mm/min, and (c) 3000 mm/min.

5. Conclusions

The major goal of this study is to improve the ductility of the Al/SiCp AMC sheets and to investigate the capability of the SPIF process to deform the AMC sheets, with a particular focus on the influence of SPIF parameters on the formability of the AMC sheets under O-condition annealing. The findings revealed that fracture morphology changes depending on the treatment conditions and the Al/SiC AMC sheets with T6 treatment could not be deformed to the specified depth at room temperature because of the poor ductility and that additional treatment, such as O-condition annealing, is necessary to improve the room ductility. Furthermore, the Al/SiCp AMC sheets with O-condition annealing are sensitive to the SPIF parameters, with low levels of the SPIF parameters achieving acceptable formability and fracture depth. With a low level of SPIF parameters, strain hardening in Al/SiCp sheets may be minimised. The Al/SiCp AMC sheets are the most sensitive to tool size in the SPIF process, followed by the step size and feed rate. When annealed Al/SiCp AMC sheets are heat treated to T6, the sheets exhibit properties comparable to the as-received sheets.

Acknowledgements

The authors would like to express their gratitude to Professor Hui Long and Mr. Jamie Booth of the Department of Mechanical Engineering at the University of Sheffield in the United Kingdom for their assistance with the ISF testing.

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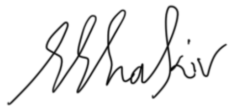
Declarations

Paper title: Numerical and experimental investigation of formability in incremental sheet forming of particle reinforced metal matrix composite sheets incremental forming

Authors: Shakir Gatea, Thana Abdel Salam Tawfiq**,** and Hengan Ou
Funding (Not applicable)
Conflicts of interest/Competing interests (Not applicable)
Availability of data and material (Data and materials are available)
Code availability (Not applicable)
Authors' contributions (Shakir Gatea designed the study, performed experiments, and wrote the manuscript; **Thana Abdel Salam Tawfiq** performed experiments; **Hengan Ou** designed the study and contributed to the data interpretation)
Ethics approval (Not applicable)
Consent to participate (I am agreeing to participate)
Consent for publication (I am agreeing to publish this work)



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PhD