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

Shakir Gatea1 · Thanaa Abdel Salam Tawfiq1 · Hengan Ou2

Received: 17 September 2021 / Accepted: 5 February 2022 / Published online: 17 February 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Aluminium matrix composites (AMCs) 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 desired shape and depth at room temperature. As a result, additional treatments are required to enhance the composite’s ductility at room temperature prior to deformation. In this investigation, as-received 6092Al/silicon carbide particle (SiCp) composite sheets (T6-condition) are heat-treated to O-condition annealing to enhance its ductility in order to assess the formability and fracture behaviour of the Al/SiC particle composite sheets under single point incremental forming (SPIF) using different forming parameters at room temperature. The annealed sheets are heat-treated to T6-condition to enhance the strength and achieve properties equivalent to as-received sheet properties. The results demonstrate that the Al/SiC particle composite sheets with T6 treatment could not be deformed to the specified depth due to low ductility at room temperature. Further treatment, such as O-condition annealing, is required to enhance its ductility to enable successful deformation of the Al/SiCp sheets using SPIF. After SPIF processing, the annealed Al/SiCp composite sheets are heat-treated back to T6. The sheets exhibit properties comparable to the as-received sheets. Al/SiC particle composite sheets with low values of SPIF parameters, i.e. small tool diameter, low step size and feed rate, are able to achieve greater formability and fracture depth with low strain hardening under SPIF processing conditions.

Keywords SPIF · Al/SiC particle composites · Formability · Forming parameters · Heat treatment

1 Introduction
Aluminium matrix composite (AMC) materials reinforced with SiC particles offer significant promise for usage in automotive, aerospace and energy industries. As a result, new techniques for deforming these composite sheets are necessary. Single point incremental forming (SPIF) is a flexible and easy to implement 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 process 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% SiCp composites were studied to better understand their behaviour 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 the step depth and tool diameter was 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 aluminium 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 finite element (FE) simulations, the 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 be used to 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 aluminium (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]. Aluminium 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 fibres using the SPIF method was examined experimentally. It was observed that the SPIF may be utilised 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 utilised 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].

Springback has a negative impact on the quality of the SPIF component, and the amount of springback varies with the SPIF parameters. The influence of several SPIF process parameters on the springback of aluminium sheets was evaluated experimentally. The findings revealed that a small step size, a large tool diameter, a high spindle speed, a high feed rate and a thick sheet reduced the amount of springback of the deformed aluminium sheets [22]. The springback due to SPIF processing for a knee condylar was evaluated using FE analysis. The numerical findings revealed a relationship between the amount of springback and the SPIF parameters; e.g., the degree of springback rises with increased tool diameter, sheet thickness and reduced step size [23]. After unclamping, the annealing technique was recommended to minimise the springback in the SPIF of the AA2024-T3 aluminium alloy sheet [24]. By parameterising the tool path and the deformed shape of the SPIF part, an algorithm was established to minimise the error between the typical shape and the deformed shape of aluminium sheets. The study indicated that applying the suggested method minimised the geometrical error [25].

The forming limit diagram (FLD) is considered an essential tool in the SPIF for investigating the formability and fracture behaviour of materials under different strain states [26]. The FLD changes as a result of the forming parameters and evaluating the influence of the forming parameters on the FLD is important in material selection and process design [27]. The SPIF process was used to construct the FLD of 3003-O aluminium sheets from five different shapes with varying strain states. It was found that the SPIF process could reach a high percentage of the strain of around 300 [28]. A Box-Behnken design of experiment was utilised to characterise how the FLD is generated in the SPIF under various factors such as step size, tool size, sheet thickness, material type, formed shape and maximum forming angle. In the SPIF process, it was demonstrated that the material type had the largest influence on formability [29]. The shear fracture forming limit line of AA1050-H111 sheets formed by the SPIF process was successfully established using a truncated lobe conical shape with varying wall angle [30].

Although considerable efforts have been made to evaluate the influence of SPIF parameters on monolithic alloys, no study has been published to examine the effect of SPIF process parameters on particle-reinforced metal matrix composites (MMC) and indeed AMC sheet 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 ductility at room temperature 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 after SPIF processing is heat-treated again to T6 condition for increased strength and desired characteristics similar to those of the as-received sheet.

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 sheets to a specified shape at room 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. After SPIF processing, 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 [31]. The T6 heat treatment is used to increase the strength of Al alloys. However, there is a risk of distortion due to residual stresses that arise during the heat treatment. Residual stresses are decreased in T6 treatment during solution treatment, whereas these stresses are increased during quenching. As a result, residual stresses should be kept as low as possible to reduce distortion [32]. The use of warm water as a quenchant tends to lower residual stresses during quenching. When quenched in 80° water, the residual stresses of quenched 7075-T73 Al alloy are decreased by 80% although the strength is lowered by 15% [33]. Furthermore, a modified spray quenching approach might be employed to decrease distortion during the quenching process [34]. Water at room temperature was employed as a quenchant in this study.

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 hardness test was used to determine the effect of heat treatment on the hardness of Al/SiCp AMC sheets. The Vickers hardness test was performed in several locations, and the average value was recorded.

Under T6 and O-condition treatments, the SPIF tests were performed on 6092Al/SiCp sheets with dimensions of 140×140×1.04 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 to 80°) 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 simulate the SPIF process of 6092Al/SiCp sheets. The FE 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 sheet is represented as a deformable body with dimensions of 140×140×1.04 mm. In this work, the isotropic hardening rule is used to simulate the hardening behaviour of the Al/SiCp particle composite sheet during the SPIF test. Many yield criteria were employed in the FE analysis to simulate the formability of the materials such as Von Mises, Hill’s 1948 and Yld2004–18p [35–39]. Because of its simplicity and shorter computational time, the von Mises yield criterion was adopted in this investigation. The effect of SPIF parameters on formability is predicted using annealed Al/SiCp AMC sheet, and O-condition annealing reduces the effect of anisotropy. As a result, the AMC sheet is considered to be isotropic, and the influence of anisotropy is not taken into account in this study. Table 1 shows the mechanical properties of annealed Al/SiC particle composite sheets.

A surface to surface contact state is assigned between the forming tool and the top surface of the sheet, and between

| Young’s modulus | Poisson’s ratio | Yield stress | Ultimate tensile stress | Density |
|-----------------|----------------|--------------|------------------------|---------|
| 99.97 GPa       | 0.296          | 116 MPa      | 233 MPa                | 2800 kg/m³ |

Table 1 The mechanical properties of annealed Al6092/SiC/17.5p AMC sheets
the lower surface of the sheet and the inner surface of the backing plate. To save computing time, mass scaling technique was utilised.

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 to consider the friction between the contacted surfaces. Different friction coefficient values (0.05, 0.1 and 0.15) were used between contacted surfaces in FE simulation to determine the optimal friction coefficient value. As shown in Fig. 1, the results indicate a strong correlation between the experimental SPIF force and the modelled force with a friction coefficient of 0.1. As a result, in this study, a friction coefficient of 0.1 is chosen to simulate the friction between the Al/SiCp composite sheet and the forming tool. The SPIF test is performed with a hemispherical tool of varying diameters, such as 8, 10 and 12 mm. In this work, no rotation of the forming tool was set in all SPIF testing. The FE simulation is terminated when the depth of the hyperbolic truncated cone approaches the experimental depth. Table 2 shows the SPIF process parameters that were used for simulations.

![Fig. 1 Comparison of experimental and numerical forming forces for various friction coefficients](image)

### 4 Results and discussion

#### 4.1 Materials properties

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 Fig. 2a. The figure clearly shows that O-condition annealing can significantly improve the ductility 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 under different heat treatments. For example, 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 Fig. 2b). 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.

### 4.2 Experimental results

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 3 depicts the impact of the heat treatment on the fracture surface. In the T6 condition of as-received sheet and T6 of 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 Figs. 2 and 3 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. T6 condition can 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 at T6 condition. The second kind is ductile
1 3
fracture, which occurs when a material is subjected to O-condition annealing.

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 to 80°. The experimental tests of the SPIF process were repeated three times and the average value was taken. Figure 4a demonstrates that the fracture occurs early of the 6092Al/SiCp AMC sheet at T6 condition and has a significant degree of springback. This is attributable to the high strength of the composite sheet heat treated to T6 condition at room temperature, which is consistent with previous work by Amar Al-Obaidi and co-workers [40]. It is clear from Fig. 4a 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 Fig. 4b). It can be observed in Fig. 4b that greater formability may be achieved at 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 behaviour of Al/SiCp AMC sheets at room temperature due to O-condition annealing. As a result, finite element simulation was applied to the Al/SiCp sheets after O-condition annealing in this study.

4.3 Influence of process parameters on the formability of AMC sheets

With constant step size of 0.2 mm and tool diameter of and 10 mm, three feed rates at 1000, 2000 and 3000 mm/min were used to predict the influence of the feed rate on the formability of Al/SiCp AMC sheets using Abaqus/Explicit. Figure 5 depicts the thickness distribution along the wall of the Al/SiCp hyperbolic truncated cone as well as the stress–strain curves. Figure 5a 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 at varied feed rates are determined using a deformed hyperbolic truncated cone. The stress–strain curves are calculated at the fracture depth in the transition zone between the inclined wall and the base of the truncated cone. The stress–strain curves of the deformed Al/SiC truncated cone are shown in Fig. 5b. 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. This is due to the fact that high strain rates can be acquired with a high feed rate, and because the annealed 6092Al/SiCp sheet is strain rate sensitive, and high strain hardening can be achieved with a high strain rate, as proved in previous research [41]. As a result, high strain hardening may be achieved at a high feed rate. 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.
Three SPIF 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 Fig. 6. Figure 6a 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 localised deformation may be produced with small step sizes, but as the step size is increased, the deformation is no longer localised and the formability is reduced. The transition zone between the bottom and the wall of the deformed truncated cone is utilised to predict stress–strain curves at fracture depth under different step sizes. Figure 6b 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). The high strain hardening produced by big step size may be attributed to the high stress necessary to produce large deformation under large step size, and this large deformation increases the strain hardening of the composite sheets when compared to the small deformation produced by the small step size. A low stress-high strain curve is created with small step size.
while a high stress-low strain curve is generated with a large 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.

To assess 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 7a 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 localised as it does with a small tool size. Figure 7b further shows that the large diameter tool has a significant influence on the strain hardening behaviour 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 increased stress was 14%.

Previous research [42] found that when low values, i.e. low feed rate, low step size and small tool diameter, of SPIF parameters are employed, the forming limit increases, indicating that high formability may be accomplished with low values of forming parameters, which agrees with the findings of this study. 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 8 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 values 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 9 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 Fig. 9a. The composite material’s 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 Gatea et al. [41]. As indicated in Fig. 10, 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.
Fig. 8 The distribution of equivalent strain obtained from a numerical simulation of a hyperbolic truncated cone under various forming conditions.

Fig. 9 Experimental fracture depth (a) and wall angle (b) of a hyperbolic truncated cone of Al/SIC particle at various feed rates.
5 Conclusions

The aim 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 poor ductility. Additional treatment, such as O-condition annealing, is necessary to improve the ductility at room temperature. Furthermore, the Al/SiCp AMC sheets with O condition annealing are sensitive to the SPIF parameters, with low values of the SPIF parameters achieving acceptable formability and fracture depth. With low values of SPIF parameters, strain hardening in Al/SiCp sheets may be minimised. The Al/SiCp AMC sheets are 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. The influence of distortion during heat treatment is not taken into account in this work. Further work is needed to investigate the influence of heat treatment distortion on component quality.

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 UK for their assistance with the ISF testing.

Author contribution Shakir Gatea designed the study, performed experiments and wrote the manuscript; Thana Abdel Salam Tawfiq performed experiments; Hengan Ou funding acquisition, designed the study, review of manuscript and contributed to the data interpretation.

Availability of data and materials Data and materials are available.
Declarations

Ethics approval  Not applicable.

Consent to participate  I am agreeing to participate.

Consent for publication  I am agreeing to publish this work.

Conflict of interest  The authors declare no competing interests.

References

1. Gatea S, Ou H, McCartney G (2016) Review on the influence of process parameters in incremental sheet forming. Int J Adv Manuf Syst Technol 85(1):479–499
2. Peng W, Ou H, Becker A (2019) Double-sided incremental forming: a review. J Manuf Sci Eng 141(5)
3. Zhu H, Ou H, Popov A (2020) Incremental sheet forming of thermoplastics: a review. Int J Adv Manuf Syst Technol p. 1–23
4. Mishnaevsky L Jr., Derrien K, Baptiste D (2004) Effect of microstructure of particle reinforced composites on the damage evolution: probabilistic and numerical analysis. Compos Sci Technol 64(12):1805–1818
5. El-Sabbagh AM, Soliman M, Taha MA, Palkowski H (2013) Effect of rolling and heat treatment on tensile behaviour of wrought Al-SiCp composites prepared by stir-casting. J Mater Process Technol 213(10):1669–1681
6. Mandal D, Viswanathan S (2013) Effect of heat treatment on microstructure and interface of SiC particle reinforced 2124 Al matrix composite. Mater Charact 85:73–81
7. Gatea S, Chen F, Long H, Ou H (2017) Deformation and fracture of AMC under different heat treatment conditions and its suitability for incremental sheet forming. Procedia Engineering 207:848–853
8. Mulya A, Ben S, Ismail S, Kocanda A (2017) Experimental investigations into the effects of SPIF forming conditions on surface roughness and formability by design of experiments. J Braz Soc Mech Sci Eng 39(10):3997–4010
9. Kaur S, Swebha N, Vinodh Reddy C, Regalla SP (2018) Experimental and finite element studies of single stage incremental forming process: effect of process parameters on maximum wall angle and thickness distribution. Adv Mater Process Technol 4(2):322–334
10. Kumar A, Gulati V, Kumar P, Singh V, Kumar B, Singh H (2019) Parametric effects on formability of AA2024-O aluminum alloy sheets in single point incremental forming. J Market Res 8(1):1461–1469
11. Nguyen D, Park J, Lee H, Kim Y (2010) Finite element method study of incremental sheet forming for complex shape and its improvement. Proc Inst Mech Eng B J Eng Manuf 224(6):913–924
12. Mirnia M, Dariani BM, Vanhove H, Duflou J (2014) An investigation into thickness distribution in single point incremental forming using sequential limit analysis. Int J Mater Form 7(4):469–477
13. Radu M, Cristea I (2013) Processing metal sheets by SPIF and analysis of parts quality. Mater Manuf Process 28(3):287–293
14. Duflou J, Tunckol Y, Szekereres A, Vanherck P (2007) Experimental study on force measurements for single point incremental forming. J Mater Process Technol 189(1–3):65–72
15. Hussain G, Gao L, Zhang Z (2008) Formability evaluation of a pure titanium sheet in the cold incremental forming process. Int J Adv Manuf Syst Technol 37(9):920–926
16. Han F, Mo J-H (2008) Numerical simulation and experimental investigation of incremental sheet forming process. J Cent South Univ Technol 15(5):581–587
17. Conte R, Ambrogio G, Pulice D, Gagliardi F, Filice L (2017) Incremental sheet forming of a composite made of thermoplastic matrix and glass-fiber reinforcement. Procedia Engineering 207:819–824
18. Fiorotto M, Sorgente M, Lucchetta G (2010) Preliminary studies on single point incremental forming for composite materials. Int J Mater Form 3(1):951–954
19. Liu Z, Li G (2019) Single point incremental forming of Cu-Al composite sheets: a comprehensive study on deformation behaviors. Archives of Civil and Mechanical Engineering 19(2):484–502
20. Al-Ghamdi K, Hussain G (2016) SPIF of Cu/steel clad sheet: annealing effect on bond force and formability. Mater Manuf Process 31(6):758–763
21. Al-Ghamdi KA, Hussain G (2016) On the comparison of formability of roll-bonded steel-Cu composite sheet metal in incremental forming and stamping processes. Int J Adv Manuf Syst 87(1):267–278
22. Vahdati M, Sedighi M, Khoshkiah H (2010) An analytical model to reduce spring-back in incremental sheet metal forming (ISMF) process. In Adv Mater Res. Trans Tech Publication
23. Oleksik V, Pascu A, Deac C, Fleaca R, Roman M, Bologa O (2010) The influence of geometrical parameters on the incremental forming process for knee implants analyzed by numerical simulation. in AIP Conference Proceedings. American Institute of Physics
24. Zhang Z, Zhang H, Shi Y, Moser N, Ren H, Ehmahn KF, Cao J (2016) Springback reduction by annealing for incremental sheet forming. Procedia Manufacturing 5:696–706
25. He A, Kearney MP, Weegink KJ, Wang C, Liu S, Meehan PA (2020) A model predictive path control algorithm of single-point incremental forming for non-convex shapes. Int J Adv Manuf Syst Technol 107(1):123–143
26. Gatea S, Xu D, Ou H, McCartney G (2018) Evaluation of formability and fracture of pure titanium in incremental sheet forming. Int J Adv Manuf Syst Technol 95(1):625–641
27. Paul SK (2021) Controlling factors of forming limit curve: a review. Advances in Industrial and Manufacturing Engineering p. 100033
28. Jeswiet J, Young D (2005) Forming limit diagrams for single-point incremental forming of aluminum sheet. Proc Inst Mech Eng B J Eng Manuf 219(4):359–364
29. Ham M, Jeswiet J (2007) Forming limit curves in single point incremental forming. CIRP Ann 56(1):277–280
30. Socio E, Silva C, Silva M, Martinos P (2015) Revisiting the formability limits by fracture in sheet metal forming. J Mater Process Technol 217:184–192
31. Davis J (1993) Aluminum and aluminum alloys ASM International. Materials Park
32. Rashed HM (2018) Control of distortion in aluminium heat treatment. Fundamentals of aluminium Metallurgy. Elsevier, pp 495–524
33. Younger MS, Eckel-meckey KH (2007) Overcoming residual stresses and machining distortion in the production of aluminum alloy satellite boxes. Sandia National Laboratories
34. Bikass S, Andersson B, Pilipenko A, Langtangen HP (2013) Spray footprint effect on the induced distortion by the cooling process in the aluminum extrusion process. Appl Therm Eng 57(1–2):14–23
35. Esmaeilpour R, Kim H, Park T, Pourboghrat F, Agha A, Abu-Farha F (2020) Effect of hardening law and process parameters on finite element simulation of single point incremental forming (SPIF) of 7075 aluminum alloy sheet. Mechanics & Industry 21(3):302
36. Hill R (1948) A theory of the yielding and plastic flow of anisotropic metals. Proc R Soc A: Math Phys Eng Sci 193(1033):281–297
37. Bambac M, Hirt G (2005) Performance assessment of element formulations and constitutive laws for the simulation of incremental sheet forming (ISF). In VIII International Conference on Computational Plasticity. Citeseer
38. Henrard C, Bouffioux C, Eyckens P, Sol H, Duflou J, Van Houtte P, Van Bael A, Duchene L, Habraken A (2011) Forming forces in single point incremental forming: prediction by finite element simulations, validation and sensitivity. Comput Mech 47(5):573–590
39. Esmaeilpour R, Kim H, Asgharzadeh A, Tiji SAN, Pourboghrat F, Banu M, Bansal A, Taub A (2021) Experimental validation of the simulation of single-point incremental forming of AA7075 sheet with Yld 2004–18P yield function calibrated with crystal plasticity model. Int J Adv Manuf Syst Technol 113(7):2031–2047
40. Al-Obaidi A, Kräusel V, Landgrebe D (2016) Hot single-point incremental forming assisted by induction heating. Int J Adv Manuf Syst Technol 82(5–8):1163–1171
41. Gatea S, Ou H, McCartney G (2018) Deformation and fracture characteristics of Al6092/SiC/17.5 p metal matrix composite sheets due to heat treatments. Mater Charact 142:365–376
42. Kim Y, Park J (2002) Effect of process parameters on formability in incremental forming of sheet metal. J Mater Process Technol 130:42–46

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.