

Research Article

Investigating the Effect of Single-Point Incremental Forming Process Parameters with a Hyperbolic Wall Model on the Formability of Aluminum-Polymer Composite Sheets

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ABSTRACT

Single-point incremental forming (SPIF), as a novel method in sheet forming processes, has attracted significant attention, especially for producing lightweight and advanced parts, due to its high flexibility and reduced production costs. This study investigates the effect of process parameters on the formability and fracture of aluminum-polymer multilayer sheets. The sheets consisted of two layers of 1050 aluminum and a polymer layer based on polyethylene modified with maleic anhydride, produced under controlled temperature and pressure conditions. Maleic anhydride, as a compatibilizer, improved interlayer adhesion and enhanced bond stability. Experiments were conducted using a CNC milling machine and a forming tool with a constant diameter of 10 mm. The experimental design was a full factorial, examining the effects of vertical step size, spindle speed, and feed rate on formability depth and fracture angle. Results showed that vertical step size is the most influential parameter affecting the fracture mechanism and formability depth; increasing it from 0.1 to 0.3 mm improved the fracture angle and formability depth. The best process performance was achieved with a combination of a 0.3 mm vertical step size, 1000 rpm spindle speed, and 1000 mm/min feed rate. This research demonstrates that the SPIF process has high potential for forming aluminum-polymer multilayer sheets and can be used as an efficient method for producing lightweight parts.

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1. Introduction

The single-point incremental forming (SPIF) process is one of the advanced sheet forming methods used for manufacturing complex and customized components. Due to its high flexibility, reduced tooling requirements, and relatively low production costs, SPIF has attracted

considerable attention in recent years. Unlike conventional forming processes requiring dedicated dies, SPIF uses a relatively simple forming tool and a computer-controlled toolpath, making it particularly suitable for low-volume production, prototyping, and customized components [1]. The process progressively

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deforms the sheet through localized contact between the forming tool and the sheet while the workpiece is clamped by a fixture. Despite its advantages, limitations such as relatively long forming times, reduced dimensional accuracy, surface quality issues, and localized sheet thinning remain important challenges [1, 2].

The final quality and dimensional accuracy of SPIF components are affected by several factors, including tool geometry, toolpath strategy, process parameters, and sheet material characteristics. Different forming tools and toolpath strategies have been investigated to control forming forces, friction, surface quality, and tool wear [3-5]. In addition, CNC control, numerical simulation, and statistical analysis can assist in implementing complex toolpaths and understanding the effects of process parameters on forming behavior [5-7].

An important aspect of formability evaluation in SPIF is the maximum wall angle that can be achieved before fracture. The maximum wall angle provides a useful indication of the deformation capability and forming limit of a sheet under incremental forming conditions. In variable wall-angle geometries, the wall angle changes continuously along the forming depth, allowing the forming behavior of a material to be evaluated under different wall-angle conditions within a single formed component. This approach provides an effective means of characterizing formability while reducing the need for multiple specimens with different constant wall angles. Kurra and Regalla [8] demonstrated the application of variable wall-angle geometry for evaluating sheet formability in incremental forming and showed the usefulness of this approach for investigating the forming limits of sheet materials.

Multilayer and composite sheets have increasingly attracted attention because combining materials with different mechanical and physical properties can provide a desirable balance between strength, flexibility, corrosion resistance, and weight. In particular, metal-polymer multilayer structures can combine the relatively high strength and stiffness of metallic layers with the low density and deformability of polymeric materials, making them attractive for lightweight engineering applications [6, 7].

Incremental forming of multilayer and hybrid sheets has therefore received increasing research attention. Yeole et al. [9] developed a hybrid composite consisting of a polypropylene matrix and aluminum sheet and reported improved adhesion and flexural strength through-thickness reinforcement. Davarpanah and Malhotra [10] investigated the influence of metal and polymer layer thickness on composite-sheet formability and reported that polymer thickness can significantly affect formability and fracture behavior. Gheysarian and Honarpisheh [11] investigated SPIF of aluminum-copper bimetal sheets and reported that layer arrangement, tool diameter, and toolpath can influence surface quality and thickness distribution. Zhao and Ou [12] introduced a flexible multi-point incremental sheet forming process for multilayer sheets and demonstrated its potential for reducing thinning and improving surface quality.

Honarpisheh and Mohammadi Jobedar [13] investigated the SPIF of Al1050 and Cu C10100 bimetal sheets using a hyperbolic final profile and examined the effects and interactions of process parameters and layer arrangement on fracture depth and wall thickness. Farhadi et al. [14] investigated three-layer Al-PE-Al sheets during two-point incremental forming using a central composite design (CCD) and reported that material arrangement and layer interaction affected the thickness distribution of the multilayer structure. These studies demonstrate the potential of incremental forming for multilayer structures; however, the formability and fracture behavior of aluminum-polymer multilayer sheets under a variable wall-angle geometry remain insufficiently investigated.

In particular, the combined effects of vertical step size, spindle speed, and feed rate on the formability and fracture behavior of aluminum-polymer multilayer sheets have not been sufficiently investigated. In the present study, a variable wall-angle truncated cone with a hyperbolic generatrix was employed as the forming geometry. Unlike the circular-generatrix variable wall-angle geometry commonly used in previous studies, the hyperbolic generatrix provides a continuously varying wall angle along the forming profile. The present study

therefore applies the variable wall-angle concept to an aluminum-polymer multilayer structure and experimentally investigates the effects of vertical step size, spindle speed, and feed rate on formability depth, thickness reduction, and fracture angle.

2. Research Methodology

In this research, the single-point incremental forming (SPIF) process was evaluated for aluminum-polymer multilayer sheets, which represent a class of lightweight multilayer structures whose forming behavior has received comparatively less attention. Since the required multilayer samples were not commercially available, the first stage of the research was dedicated to preparing the multilayer sheets with the desired layer arrangement. This stage was important because the quality of interlayer bonding can affect the subsequent forming behavior. After sample preparation, the main investigation focused on designing experiments and analyzing the effects of key process parameters on formability. For this purpose, the design of experiments (DOE) method was employed to examine the effects of vertical step size, tool spindle speed, and tool feed rate. The target geometry was selected as a hyperbolic profile to investigate the forming behavior of the multilayer sheet along a continuously varying toolpath.

In this study, AA1050 aluminum sheets with a thickness of 1 mm were used as the outer layers of the multilayer specimens. The sheets were cut to dimensions of 180×180 using a guillotine shear. AA1050 was selected because of its good ductility and formability. According to reported data for EN AW-1050A, the elastic modulus is approximately 69 GPa, while the yield strength, tensile strength, and elongation are reported as approximately 20 MPa, 60 MPa, and 25%, respectively [15]. These values are provided as reference properties of AA1050 and were not experimentally characterized in the present study [15].

A fundamental challenge in manufacturing metal-polymer multilayer sheets is obtaining stable bonding between the constituent layers. To address this issue, a maleic-anhydride-grafted polyethylene (PE-g-MA) adhesive was used as the polymeric interlayer and

compatibilizing agent. The material used in this study was Aria Adhesive 4107T242. According to the manufacturer's datasheet, its tensile stress at yield, tensile stress at break, and tensile strain at break are 16 ± 4 MPa, 18 ± 4 MPa, and greater than 300%, respectively [16]. The material is designed as a tie-layer adhesive for multilayer structures and provides adhesion between polyethylene-based materials and polar materials such as aluminum [16].

The layer arrangement in the aluminum-polymer multilayer samples was selected to combine the structural contribution of the aluminum outer layers with the flexibility and low density of the polymeric core, thereby providing a lightweight multilayer configuration. Such weight reduction is particularly relevant to lightweight engineering applications, including aerospace structures, where reducing structural mass is an important design consideration. A three-layer structure consisting of two outer AA1050 aluminum layers and a polymeric core was employed. The aluminum/polymer/aluminum multilayer sheets were fabricated using a hot-pressing process. The aluminum sheets were arranged with the polymer layer between them using a stainless-steel frame to maintain the desired layer configuration and polymer thickness. The assembled layers were placed in the hot press and heated to 150 °C. The assembly was maintained at this temperature for approximately 10 minutes without applying pressure to allow sufficient heat penetration through the multilayer structure. Subsequently, pressure was applied and maintained for 20 minutes at 150 °C to promote bonding between the aluminum and polymer layers. After the pressing stage, heating was stopped and the multilayer specimens were cooled under constant pressure until the temperature reached approximately 50-60 °C.

Fig. 1 shows the forming tool during the SPIF process and the final formed samples.

The SPIF experiments were performed using a three-axis CNC vertical machining center (VMC), model VMC-1000L (Poyakar Co., Iran), equipped with a Siemens 828D CNC controller. The machine provides X, Y, and Z-axis travels of 1020, 520, and 550 mm,

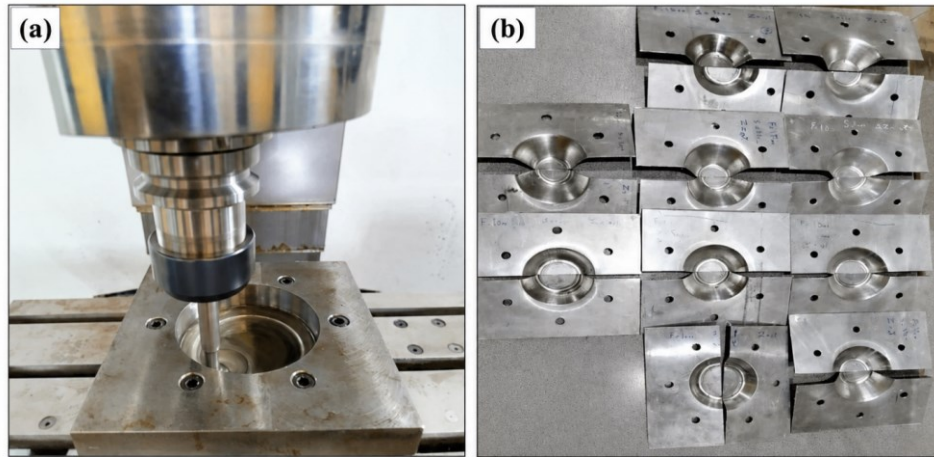


Fig. 1. Experimental setup and formed aluminum-polymer multilayer samples: (a) single-point incremental forming (SPIF) process and (b) formed samples after sectioning for fracture-angle measurement.

respectively, and has a maximum spindle speed of 10,000 rpm. According to the manufacturer's specifications, the positioning accuracy and repeatability are ± 0.01 mm and ± 0.006 mm, respectively [17]. The VMC was used to execute the programmed toolpath and provide controlled movement of the forming tool during the SPIF experiments.

To clearly illustrate the tool movement employed during the SPIF process, the toolpath was generated using PowerMill CAM software. A spiral toolpath strategy was used, in which the forming tool followed a continuous spiral trajectory while progressively moving downward according to the prescribed vertical step size. The schematic representation of the generated toolpath is presented in Fig. 2.

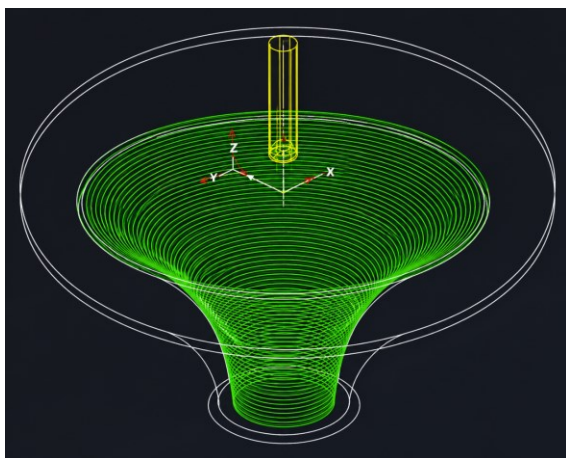


Fig. 2. Schematic representation of the spiral toolpath generated using PowerMill CAM software for the SPIF process.

Design and analysis of experiments were performed using Minitab software. A two-level full factorial design of experiments (DOE) was employed to investigate the effects of three process parameters: tool spindle speed, tool feed rate, and vertical step size. Since each parameter was considered at two levels, the factorial design consisted of ($2^3 = 8$) main experimental runs. The selected levels were a vertical step size of 0.1 and 0.3 mm, a spindle speed of 1000 and 2000 rpm, and a feed rate of 1000 and 1500 mm/min. Two additional experiments at the center levels, corresponding to a vertical step size of 0.2 mm, were conducted for additional verification of the experimental results. Thus, a total of 10 experimental samples were examined. The experimental data were subsequently analyzed using Minitab to evaluate the effects of the investigated process parameters on the measured responses.

Experimental trials involved manufacturing and forming the aluminum-polymer multilayer sheets with a variable wall-angle truncated-cone geometry having a hyperbolic generatrix (Fig. 3).

The fracture angle, β , was defined as the local angle between the tangent to the formed profile at the fracture location and the horizontal reference line, as illustrated in Fig. 3.

3. Results and Discussion

This study investigated the effect of single-point incremental forming process parameters on the

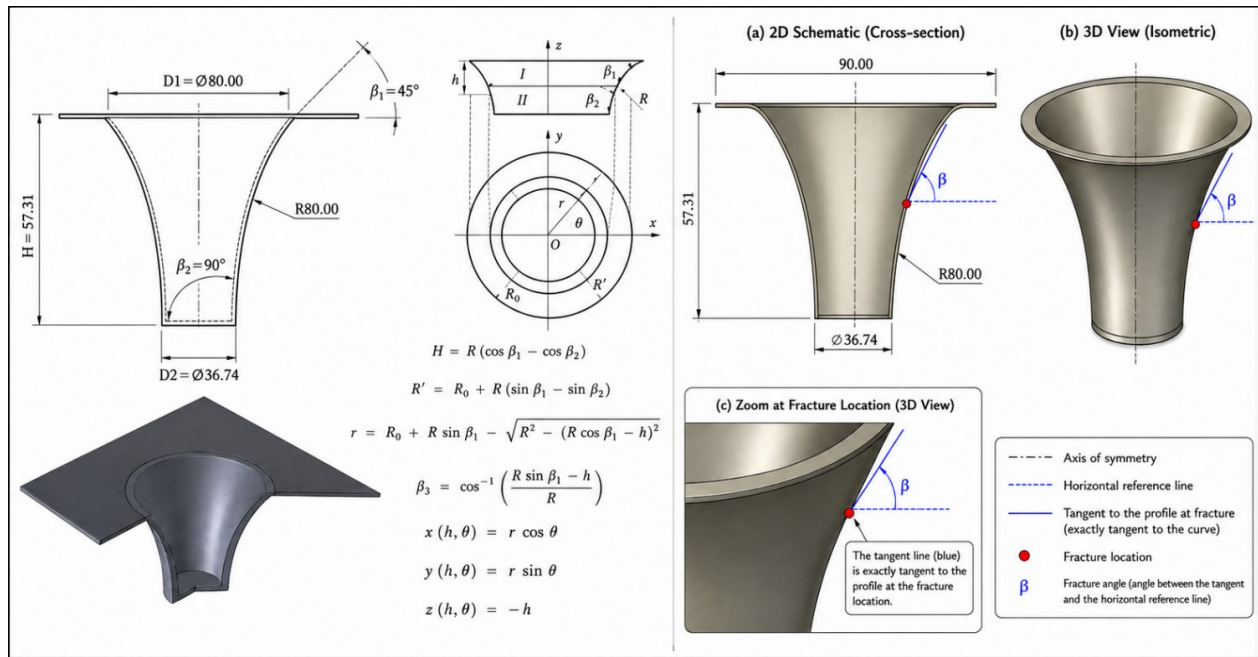


Fig. 3. Schematic representation of the variable wall-angle truncated cone with a hyperbolic generatrix and definition of the fracture angle in the single-point incremental forming (SPIF) process: (a) 2D cross-sectional view of the formed profile, (b) 3D isometric view, and (c) enlarged view of the fracture location showing the tangent to the formed profile and the fracture angle, β .

formability of aluminum-polymer composite sheets. The hybrid sheets consisted of a 1050 aluminum layer and a polyethylene-based maleic anhydride polymer layer as the intermediate and adhesive layer. This research was conducted to achieve a better understanding of the behavior of multilayer sheets in the incremental forming process.

To investigate the effect of the main single-point incremental forming process parameters on the behavior of aluminum-polymer multilayer sheets, the design of experiments (DOE) method with three factors and two levels was used. The selected parameters were tool feed rate (at two levels: 1000 and 1500 mm/min), tool spindle speed (at two levels: 1000 and 2000 rpm), and vertical step size (at two levels: 0.1 and 0.3 mm). A total of eight main experiments were designed and executed. Additionally, two extra experiments with mid-range parameter values (feed rate of 1200 and 1300 mm/min, spindle speed of 1800 and 1500 rpm, and a step depth of 0.2 mm) were considered to allow for supplementary analysis and the plotting of comparative charts in Minitab software.

The results obtained from the experimental investigation under the selected process conditions are presented in Table 1.

3.1. Qualitative analysis of results

The results show that the vertical step parameter has a very significant effect on the final formability depth. Specifically, in all experiments where the vertical step was 0.3 mm (tests 1, 2, 3, and 7), the formability depth was noticeably higher, ranging from 20.82 to 26.54 mm, compared to tests with a 0.1 mm step, where the formability depth ranged from 10.60 to 16.67 mm. This trend indicates that increasing the vertical step within the studied range leads to increased deformation capability of the composite sheet and greater formability depth. This dominant effect can be related to the deformation mechanism of the SPIF process, in which the vertical step directly controls the incremental amount of deformation imposed on the sheet during each tool pass. A smaller vertical step results in a larger number of incremental passes and a more gradual accumulation of deformation, whereas a larger step imposes a greater

Table 1. Results of single-point incremental forming experimental tests

No	Feed rate (mm/min)	Spindle speed (rpm)	Vertical step (mm)	Depth of fracture (mm)	Initial thickness (mm)	Final thickness (mm)	Thickness reduction ratio	Fracture angle (deg)
1	1000	2000	0.3	20.82	2.42	1.63	32.64	62.38
2	1500	2000	0.3	24.56	2.59	1.40	46.00	65.27
3	1000	1000	0.3	26.54	2.50	1.28	48.80	66.78
4	1000	1000	0.1	16.67	2.74	1.61	41.20	59.00
5	1000	2000	0.1	10.60	2.70	1.63	39.64	54.00
6	1500	2000	0.1	15.27	2.53	1.56	38.23	58.00
7	1500	1000	0.3	22.78	2.36	1.32	43.98	63.90
8	1500	1000	0.1	15.90	2.32	1.38	40.50	58.45
9	1300	1800	0.2	21.33	2.20	1.34	39.25	62.80
10	1200	1500	0.2	22.64	2.23	1.16	48.00	63.80

deformation increment at each pass. Within the investigated range, the 0.3 mm step therefore allowed the sheet to reach greater forming depths before fracture. The more pronounced change in formability depth associated with the vertical step, compared with the changes observed for spindle speed and feed rate within the investigated conditions, indicates its dominant influence on the forming response. The intermediate results obtained from tests 9 and 10 further support this trend, as the 0.2 mm vertical step resulted in formability depths between those obtained at 0.1 and 0.3 mm.

The effect of spindle speed is not linear or simple and clearly interacts with other process parameters. For instance, at a vertical step of 0.3 mm and a feed rate of 1000 mm/min (tests 1 and 3), decreasing the spindle speed from 2000 to 1000 rpm increased the formability depth from 20.82 to 26.54 mm. At a feed rate of 1500 mm/min (tests 2 and 7), the same decrease in spindle speed had a reducing effect, decreasing formability depth from 24.56 to 22.78 mm. This contradictory behavior shows that the effect of spindle speed depends on the feed rate level, necessitating the analysis of the interaction between spindle speed and feed rate for accurate interpretation. The effects of feed rate are also not independently describable, and its behavior changes in interaction with spindle speed. For example, under conditions of a 0.3 mm step and a 2000 rpm spindle speed, increasing the feed rate from 1000 to 1500 mm/min (test 1 to test 2) increased formability depth.

However, under conditions of a 0.3 mm step and a 1000 rpm spindle speed, the same increase in feed rate (test 3 to test 7) decreased formability depth. These observations again highlight the importance of analyzing interaction effects over the individual examination of parameters. The trend of changes in fracture angle is similar to the behavior of formability depth. The greater the final formability depth, the higher the fracture angle. For example, tests 2 and 3, which had the greatest depths, exhibited fracture angles of 65.27 and 66.78 degrees. In contrast, test 5 with the lowest depth (10.6 mm) showed the lowest fracture angle (54 degrees). This indicates that the fracture mechanism and separation angle depend on the amount of deformation and accumulated strain in the sheet. Two tests numbered 9 and 10, designed with mid-range parameter values, play an important role in validating the observed trends and evaluating the system's predictive capability. Choosing a vertical step of 0.2 mm (between 0.1 and 0.3 mm) resulted in intermediate formability depths (21.33 and 22.64 mm). This result suggests that formability depth increases systematically and almost linearly with increasing vertical step within the range studied.

3.2. Statistical analysis of results

Preliminary data examination shows that the vertical step parameter plays a dominant role in determining process responses. However, the non-linear behavior of spindle speed and feed rate and their complex variations

in combination with each other reveal the necessity of statistical analysis. Therefore, data analysis was performed using Minitab software and a full factorial design method to accurately examine the main effects and interactions between parameters. The experimental results obtained from the (2^3) full-factorial design were statistically evaluated at a 95% confidence level. The standardized effects of the investigated process parameters were examined using the normal probability plot and Pareto chart, while main-effects and interaction plots were used to examine the effects of individual process parameters and the response trends under different combinations of process parameters. Based on the examination of the effects of process variables on fracture angle (Fig. 4), the normal probability plot of effects showed that among the factors studied, only the vertical step (factor C) was statistically significant at a 95% confidence level, showing a significant deviation from the normal line. In contrast, feed rate (A) and spindle speed (B) factors did not show significant effects within this experimental range.

The findings of the normal probability plot were confirmed by the Pareto chart (Fig. 5), where only the vertical step parameter (factor C) was identified as the most important and influential factor on the fracture angle. This indicates that the vertical step has a higher priority in controlling the fracture angle compared to other studied parameters.

Analysis of the normal probability plot of effects for the thickness reduction response (Fig. 6) showed that, unlike other parameters, none of the main factors (feed rate, spindle speed, or vertical step) had a statistically significant deviation from the normal line within the experimental range. This indicates the lack of an independent and significant effect of these parameters on thickness reduction and reinforces the hypothesis regarding the complexity of thickness reduction behavior, possibly due to interactions or non-linearities.

Fig. 7 shows the interaction plot for the effect of key parameters on sheet thickness reduction in the incremental forming process. The plot indicates that increasing spindle speed from 1000 to 2000 rpm is generally associated with an increase in thickness

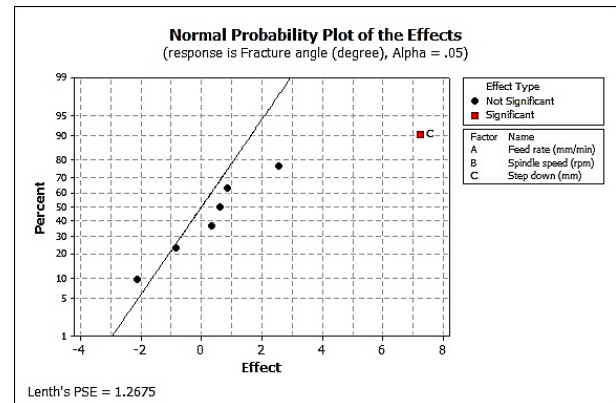


Fig. 4. Normal probability plot of effects for fracture angle.

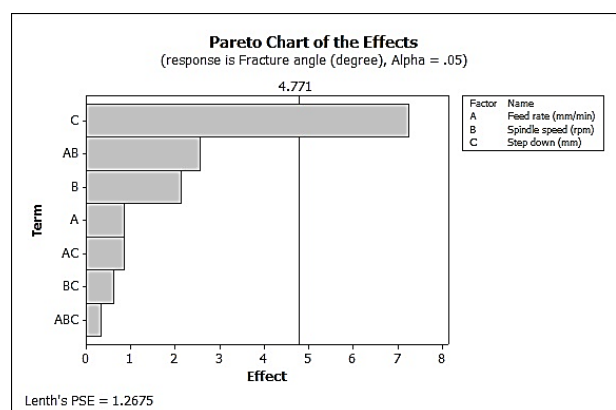


Fig. 5. Pareto chart for examining factor effects on fracture angle.

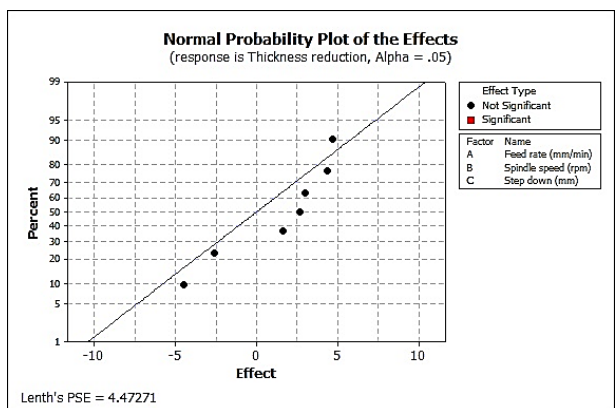


Fig. 6. Normal probability plot for examining factors affecting thickness reduction.

reduction, particularly at lower feed rates. Increasing the vertical step from 0.1 to 0.3 mm also corresponds to an increase in thickness reduction under the investigated conditions. However, these observations represent response trends in the experimental data and are not interpreted as evidence of statistically significant interaction effects. Overall, the plot illustrates the

variation in thickness reduction under different combinations of spindle speed, feed rate, and vertical step.

Based on the interaction plot (Fig. 8), the vertical step was identified as the most effective parameter for the fracture angle of aluminum-polymer multilayer sheets; increasing it from 0.1 to 0.3 mm significantly increases the fracture angle under all conditions. Regarding the effect of feed rate and spindle speed, it was observed that at low feed rates (1000 mm/min), increasing spindle speed (from 1000 to 2000 rpm) leads to a decrease in fracture angle, whereas this trend reverses or weakens at higher feed rates. The observed response trends indicate that higher vertical step values are generally associated with higher fracture angles under the investigated conditions.

The main effects plot for thickness reduction (Fig. 9) shows the gentle slopes of the lines for feed rate, spindle speed, and vertical step, indicating the absence of strong main effects of these parameters on this response; this finding aligns with the normal probability plot results (Fig. 6). In contrast, the main effects plot for fracture angle (Fig. 10) indicates a significant effect of vertical step, such that increasing it from 0.1 to 0.3 mm leads to a clear increase in fracture angle. In this plot, the lines for feed rate and spindle speed have gentle slopes, confirming their statistical non-significance. These results demonstrate the determining role of vertical step in shaping the fracture angle.

Contour plots were generated to illustrate the response behavior and identify regions associated with higher or lower response values. The contour plot for fracture angle (Fig. 11) offers two perspectives: the left plot shows regions of high and low fracture angle based on the combination of spindle speed and feed rate, allowing the response behavior under different parameter combinations to be visually compared. The right plot shows the effect of vertical step on feed rate, indicating that the maximum fracture angle (over 65 degrees) occurs at a vertical step of 0.3 mm and low to medium feed rates, consistent with the significance of the vertical step parameter. However, the contour plot for thickness reduction (Fig. 12) shows a complex and

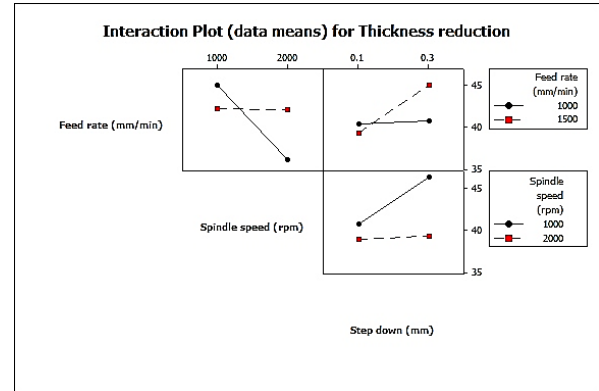


Fig. 7. Interaction plot for examining thickness reduction.

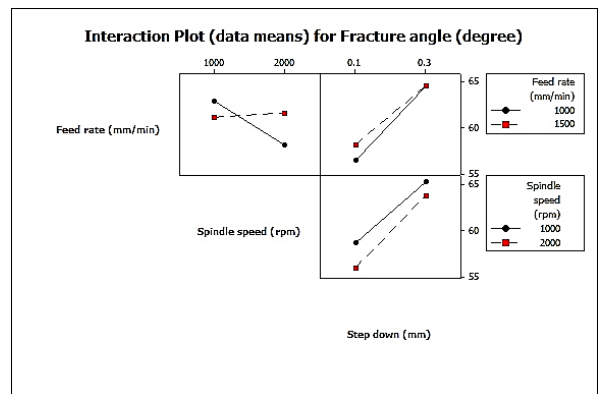


Fig. 8. Interaction plot for examining fracture angle.

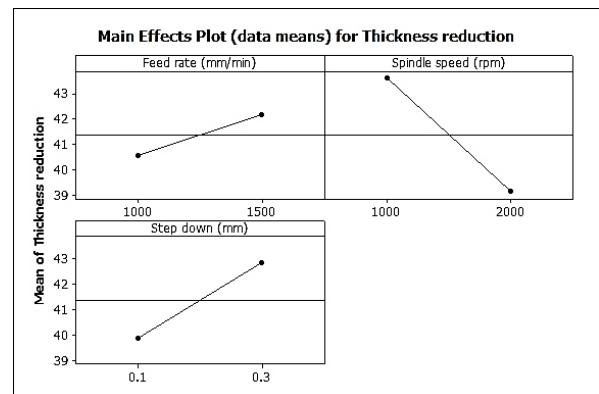


Fig. 9. Main effects plot for examining thickness reduction.

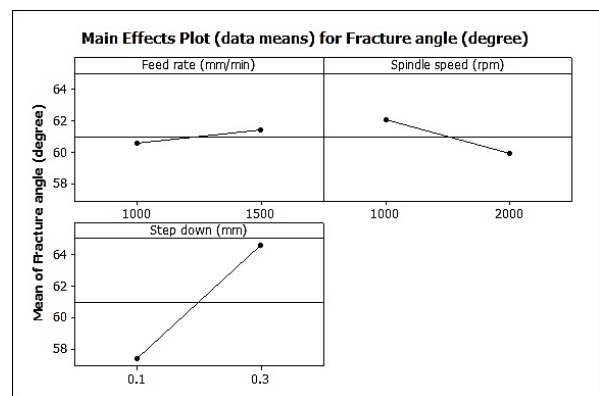


Fig. 10. Main effects plot for examining fracture angle.

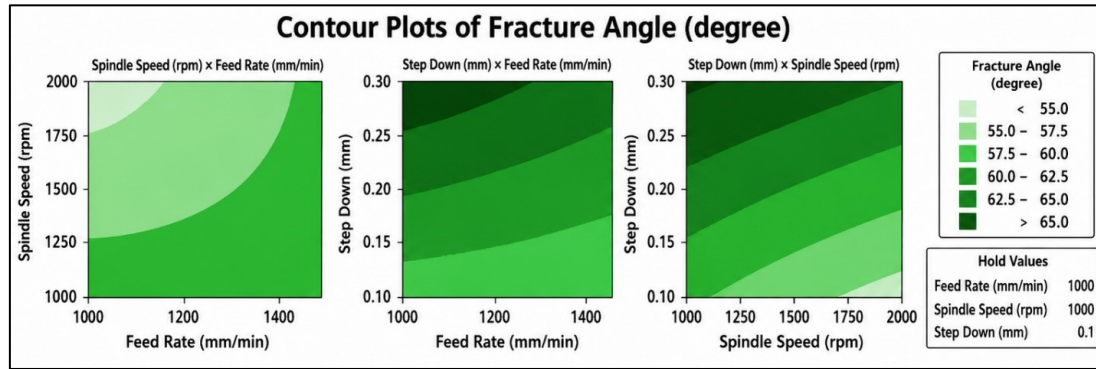


Fig. 11. Contour plot based on fracture angle.

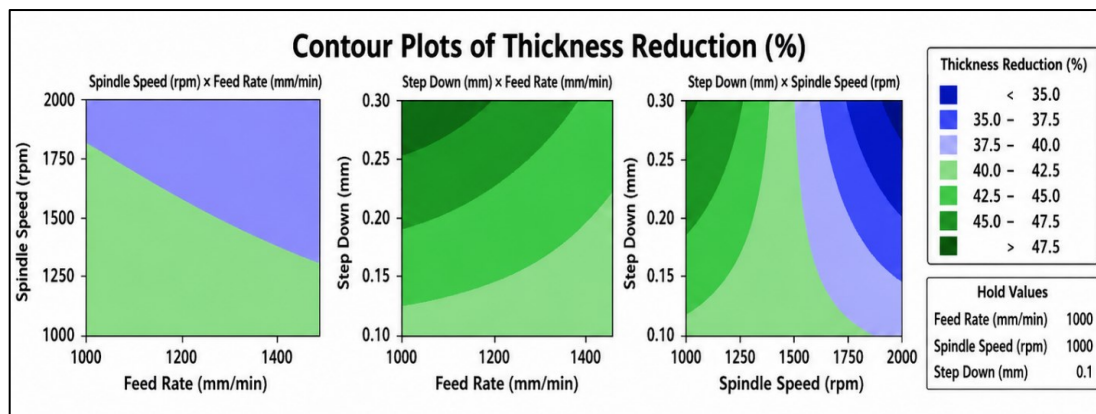


Fig. 12. Contour plot based on thickness reduction.

irregular pattern; the non-linear and scattered behavior of this plot highlights the complexity of the thickness reduction response and the difficulty of identifying a clear response trend within the investigated parameter range.

4. Conclusion

This study investigated the effects of vertical step size, spindle speed, and feed rate on the formability of aluminum-polymer composite sheets during the single-point incremental forming (SPIF) process. Based on the experimental results and statistical analysis, the following conclusions were obtained:

- The vertical step size was the most influential main process parameter affecting the fracture angle. Statistical analysis at a 95% confidence level showed that vertical step size had a statistically significant effect, whereas feed rate and spindle speed did not show statistically significant main effects within the investigated ranges.
- Increasing the vertical step size from 0.1 to 0.3 mm resulted in a clear improvement in formability. The formability depth increased from 10.60-16.67 mm at a vertical step size of 0.1 mm to 20.82-26.54 mm at 0.3 mm, demonstrating the dominant role of vertical step size in the forming behavior of the aluminum-polymer composite sheets. In contrast, the thickness-reduction response showed more complex variations, and none of the investigated main parameters had a statistically significant main effect within the studied range.
- The highest formability depth of 26.54 mm was obtained at a vertical step size of 0.3 mm, spindle speed of 1000 rpm, and feed rate of 1000 mm/min. This condition represents the best-performing experimental condition within the investigated parameter range rather than an optimized condition.
- Overall, the results demonstrate the importance of vertical step size in controlling the formability of aluminum-polymer composite sheets in the

investigated SPIF process. Further studies using a wider range of vertical step sizes, additional process parameters, and repeated experiments are recommended to provide a more comprehensive understanding of the forming behavior of these multilayer sheets.

Authors' contributions

M. M. Babaei Niasar: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing

M. Honarpisheh: Conceptualization, Methodology, Data curation, Formal analysis, Writing - review & editing

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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