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Research Article

Effect of Incremental Forming Parameters and Annealing Condition on Principal Strain Distribution and Formability During Straight Groove Forming

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ABSTRACT

Incremental forming is a highly flexible sheet metal forming process that enables the production of complex components without the need for specialized molds or dies. In this study, the effects of key process parameters—including tool rotational speed, vertical step size, annealing condition, and tool movement direction—on the formability of aluminum 3105H14 sheets were systematically investigated through experimental testing. A Taguchi design of experiments was employed to efficiently examine the influence of these parameters on the maximum forming depth, principal strain distribution, and thickness variation. The results indicate that vertical step size and annealing condition are the most significant factors affecting sheet formability. A maximum forming depth of 10.5 mm and a minimum sheet thickness of 0.584 mm were achieved with a vertical step size of 0.25 mm, spindle speed of 2000 rpm, and tool movement parallel to the rolling direction. Annealed sheets exhibited higher principal strains in intact regions, confirming the positive influence of heat treatment on material ductility. Furthermore, increasing spindle speed enhanced frictional heating, further improving material formability, while forming direction primarily affected strain distribution and localized thinning.

1. Introduction

Incremental forming is a general term that refers to processes in which deformation occurs gradually, and the forming tool progressively covers the entire sheet surface [1]. Based on this definition, various types of incremental forming processes exist, including rotational forming, single-point incremental forming (SPIF), and two-point incremental forming (TPIF) [2]. In SPIF and TPIF, the desired sheet metal geometry is generated using a tool with a spherical or semi-spherical end [3]. Typically, the tool is attached to CNC machines

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or robotic arms, and increasing the degrees of freedom in the robotic system enhances the dimensional accuracy and surface quality of the final workpiece [4]. During each step, the forming tool penetrates into the sheet, usually by 0.1–1 mm, following the desired contour to produce the intended shape. The tool then retracts and follows the next contour in a stepwise manner until the final geometry is achieved [3]. Several parameters significantly influence the outcomes of incremental forming, including vertical step size, tool diameter, feed rate, tool rotational speed, initial sheet thickness, and friction between the tool and sheet. Due to its flexibility, incremental forming can produce complex geometries with a single tool, minimizing the need for dedicated dies and thereby reducing production costs compared to conventional forming methods [2]. Various geometries can be manufactured using a single forming tool with minimal changes to the setup, which substantially decreases production costs compared to other metal forming processes such as stamping [5], rubber-pad forming [6], roll forming [7], and hydroforming [8]. Because of these advantages, the use of incremental forming for product manufacturing has gained significant attention in recent years. Considering the considerable influence of sheet mechanical properties and process parameters on product quality, much research in this field has focused on investigating these aspects. Incremental forming was first proposed in 1967 by Leszak [9] and later was proven to be achievable by Keitazawa et al. [10]. The effects of the most important parameters on formability of incremental sheet forming (ISF) have been widely investigated in literature. Rezaei and Honarpisheh [11] obtained the forming limit diagram (FLD) of CP-Ti/St12 sheets in the SPIF and investigated the effect of layer arrangement on the FLDs. Gheysarian and Honarpisheh [12] optimized process parameters in SPIF of Al/Cu bimetals, optimizing the tool diameter, vertical step, tool path and layer arrangement on surface roughness and forming force. Alinaghian et al. [13] measured residual stress in SPIF of Al/Cu bimetals, using the incremental hole-drilling method to obtain residual stress distributions. Multi-response optimization of SPIF was performed by Honarpisheh et al. [14], who used a hyperbolic shape to form the Al/Cu bimetals. In 2013, Xu et al. [15] demonstrated that the mechanism varies with tool rotational speed. A series of experiments were conducted with tool rotational speeds ranging from 0 to 7000 rpm for AA5052-H32 aluminum alloy sheets. The results showed that at low rotational speeds (0-1000 rpm), friction is the most influential factor affecting formability. Xu et al. also found that at high rotational speeds (2000-7000 rpm), the thermal effect on material properties becomes the dominant factor influencing formability. In 2022, Z. Cheng et al. [16] employed ultrasonic-assisted vibration (UV) combined with multi-stage sheet forming to investigate its effects on the forming process, thickness distribution, and stress-strain distribution through experimental tests and finite element (FE) simulations. The results revealed that the use of ultrasonic vibration significantly reduced forming forces and greatly improved plastic deformation due to the increased equivalent plastic strain. It was also discovered that implementing UV at an appropriate forming stage could achieve more desirable formability and thickness distribution. In 2022, Shafeek et al. [17] investigated the effects of multipoint incremental forming (MPIF) on the formability and failure mechanisms of titanium grade 2 sheets. The main parameter selected for this study was step depth, while the feed rate was kept constant. The results indicated that, at a constant feed rate, an increase in tool speed and step depth leads to reduced formability. When sheets were formed at 300 rpm and 0.2 mm step depths, formability and major true strain reached their highest level. In MPIF, due to the larger contact area between the sheet and forming tool, better formability can be obtained. Kim et al. [18] examined the double-pass incremental forming method to evaluate formability through thickness distribution and concluded that this method leads to better formability compared to single-pass forming. Durante et al. [19] studied two different types of tools namely hemispherical headed and ball ended to improve the surface roughness of the sheet. They revealed that using a hemispherical headed tool results in greater surface roughness compared with a ball-ended tool. Maresh et al. [20] developed an artificial neural network (ANN) to predict the forming force based on various input parameters, including step-down size, tool feed rate , spindle speed (RPM) wall angle, metal thickness and lubricant density . Kumar and Gualti [21] applied the Taguchi method and analysis of variance (ANOVA) to investigate the impact of different factors on the surface roughness of deformed parts. They indicated that the optimal experimental condition for achieving minimum average roughness were: tool diameter (15.6 mm), tool shape (hemispherical), forming oil viscosity, sheet thickness (0.8 mm), wall angle (60˚), step size (0.2 mm), tool rotation (1000 rpm), and feed rate (1500 mm/min). In 2021, San Zhang et al. [22] investigated the effects of various factors on spring back in magnesium alloy (MG) sheets. They found that forming temperature, forming angle, step depth and sheet thickness are the main significant factors influencing springback, while, tool diameter has a much smaller effect compared with the other parameters. Raju et al. [23] examined failure mode in multi sheet single point incremental forming of sheet metal. They found that sheet failure occurs due to the combined effects of shear and brittle mode. During this process, the main stress develops at the base of the part, adversely affecting the process. This stress also contributes to wall thickness variation. Therefore, it is crucial to modify some parameters to reduce this stress, as demonstrated in various studies [24, 25]. Lubricant is another influential factor affecting formability. Vahdani et al. [26] studied MoS_2, graphite powder, and both graphite-based and copper-based anti-seize lubricants. They examined the effects of these four different lubricants, along with the influence of step-down size, feed rate and electric current on the surface finish of Ti-6AI-4V sheets. Their results indicated that lubricant type is the most influential factor on formability, followed by electric current. Frikha et al. [27] explored incremental forming of grade 2 α titanium for biomedical purposes. Their research introduced a new multistep process that improved both material formability and geometrical accuracy. Yamashita et al. [28] studied the effect of tool path on the deformation behavior using the finite element method. They suggested that to achieve a better shape, the tool path should start from one of the product’s corners. Otherwise, it is preferable for the tool to move simultaneously in horizontal and vertical directions to obtain a more uniform thickness distribution.

Recent progress in incremental sheet forming has shown that auxiliary energy inputs and data-driven methods can strongly influence formability, thickness distribution, and geometric accuracy. Ultrasonic-assisted ISF (UISF) has been found to reduce forming forces, improve material flow and thickness uniformity, and delay crack initiation in straight-groove and multi-stage experiments, making it a promising route to enhance formability [29-31]. In parallel, machine-learning approaches have recently been employed to predict geometric errors (such as the pillow effect and wall profile) and to adapt toolpaths, substantially improving forming accuracy in SPIF and ISF processes [31, 32] presented a combined experimental and numerical analysis of thinning mechanisms in AA3003-H14 during SPIF, confirming the dominant role of wall angle and the moderate influence of step size on thickness reduction. Their findings also validated finite element predictions of localized deformation. Finally, careful experimental determination of fracture forming limits, for instance, using digital image correlation (DIC) and fracture-forming-loci methods, has clarified how principal strains and loading paths govern crack initiation in sheet forming these findings provide the motivation for employing principal-strain mapping and thickness measurements in the present work [34].

It is worth mentioning that one of the limiting factors in the incremental forming process is the occurrence of fracture during the process. Therefore, modeling fracture is one of the crucial aspects of this process. A common approach for estimating fracture initiation involves using ductile fracture criteria, which, due to their independence from the loading state during deformation, can be a suitable option for application in the incremental forming process.

Based on the ductile fracture mechanism, Renhao et al. [35] investigated the formability limitations for

AA1050-H111 aluminum sheets in the incremental forming process. Furthermore, fracture modeling in incremental forming process was examined by Mirnia et al. [36], who applied the modified Mohr-Coulomb criterion to predict the fracture initiation. According to their results, applying a nonlinear damage function into this criterion enhances the accuracy of fracture modeling.

Despite numerous research conducted in the field of incremental forming, the influence of the rolling process and heat treatment on principal strain limits in different regions of the final sample, along with their maximum values, and the effects of process parameters on critical strain variations has not been thoroughly explored. Understanding this aspect plays a key role in developing and improving ductile fracture criteria for application in incremental forming. Therefore, in this study, the incremental forming of a straight groove under different process conditions was investigated, and the impact intensity of process variables was evaluated using a combination of experimental tests and numerical methods. The effects of parameters such as spindle speed, vertical step size, heat treatment, and deformation direction on groove depth, as well as the range, and distribution of principal strains, and thickness distribution, were investigated. The primary objective was to determine how the rolling process and its direction affect the formability of aluminum 3105H14 sheets, considering the impact of process parameters.

A straight groove toolpath was defined on the CNC machine to evaluate sheet formability in this process. The sheets were rolled to assess the extent to which rolling direction influences formability. Incremental forming was then performed in two directions: parallel and perpendicular to the rolling direction. Additionally, three different vertical step sizes were utilized to provide a more comprehensive understanding of the process.

2. Materials and Methods

2.1. Mechanical properties of the sheet

In this study, aluminum 3105-H14 sheet was utilized, with dimensions of 2 × 1000 × 1000 mm. This sheet type exhibits excellent corrosion resistance, good formability, and weldability. Uniaxial tensile tests were performed using a universal testing machine (Instron, 100 kN capacity) at room temperature under displacement control, with a crosshead speed of 1 mm/min, corresponding to a strain rate of approximately 1×10^{-3} s^{-1}. The specimens were prepared according to ASTM E8/E8M standards, with a gauge length of 50 mm and a width of 12.5 mm. Elongation to fracture was recorded automatically by the testing system. Four tensile test specimens were prepared, representing different orientations, and some were annealed prior to testing. The configuration of the tensile test specimen and the testing machine is illustrated in Fig. 1.

The resulting engineering stress–strain curves for all orientations and annealed conditions are presented in Fig. 2. It should be noted that the uniaxial tensile testing machine used for material characterization had limited resolution in the very low-strain elastic region, which prevented precise determination of Young’s modulus. However, because the present study focuses on plastic deformation and formability, this limitation does not affect the conclusions.

2.2. Sheet preparation and annealing

For the incremental forming experiments, aluminum 3105-H14 sheets with dimensions of 700 × 1000 millimeters were used. To investigate the effect of rolling direction on formability, the sheet thickness was

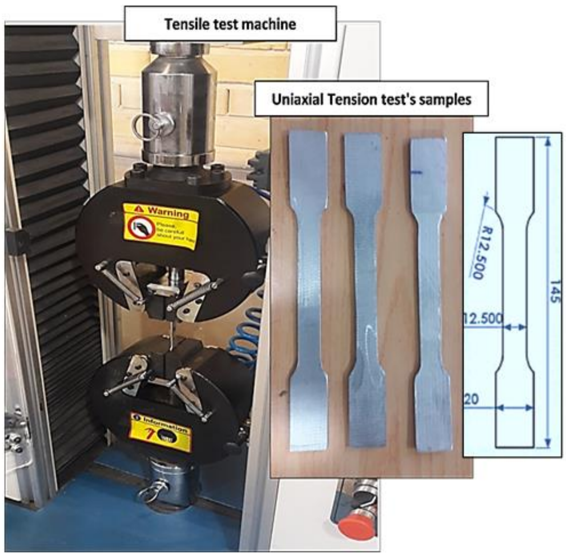

Fig. 1. Tensile test specimen and tensile testing machine (dimensions in mm).

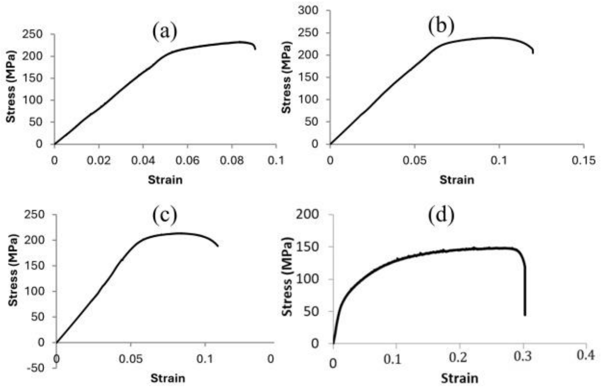

Fig. 2. Stress–strain curves of the aluminum 3105-H14 sheet for different conditions: (a) parallel to rolling, (b) perpendicular to rolling, (c) at a 45° angle to the rolling direction, and (d) annealed state.

reduced from 2 mm to 1.8 mm using a single-pass cold rolling process, corresponding to a 10% thickness reduction. Rolling was performed under standard laboratory conditions without additional lubrication, and the rolling speed was maintained at approximately 2 m/min, consistent with parameters used in similar studies on aluminum alloys.

After cutting the sheets to the desired dimensions, some samples were annealed for stress relief. The annealing temperature of 345 °C was selected to effectively relieve residual stresses in rolled 3105-H14 aluminum sheets while avoiding excessive grain growth or deterioration of mechanical properties. Preliminary tests conducted at 345 °C for 1, 2, and 3 hours demonstrated that hardness stabilized at 30 Brinell after 3 hours, confirming that residual stresses were effectively relieved and the material response had stabilized. Accordingly, all annealed samples in this study were treated at 345 °C for 3 hours. It is worth noting that the selected annealing temperature of 345 °C for 3105-H14 aluminum sheets was based on the ASM Handbook, which indicates that this alloy can be effectively annealed at this temperature to relieve internal stresses without requiring a specific soaking time or controlled cooling rate [37].

2.3. Forming tool and die design

The forming tool is a critical component in the incremental forming process, as it directly contacts the sheet and significantly affects surface finish, machining forces, and formability limits. Owing to the considerable friction generated at the interface between the sheet and the tool, the tool is commonly designed with spherical or semi-spherical geometries and fabricated from materials exhibiting high wear resistance, hardness, and excellent machinability. In this study, a spherical tool made of Mo40 steel with a diameter of 10 mm and a hardness of approximately 58 HRC was used, ensuring minimal wear and consistent forming performance throughout the experiments.

During incremental forming, a die is used to hold and apply deformation on the sheet. In this case, a die was employed, consisting of a black holder onto which the sheet was clamped to prevent displacement during forming. The black holder included several screw locations to secure it to the die. Additionally, some screw locations were used on the inner part of the black holder to act as fixators for the sheet, allowing the screws to pass through the holes created in the sheet. Since the incremental forming process involved a straight groove tool path, the black holder was designed with a groove-like cavity, and the size of the cavity was slightly larger than the tool being used.

2.4. Incremental forming process

In the incremental forming process, the forming tool follows a predefined path to create the final formed piece. In this study, the tool path was generated using a CNC milling machine. For all experiments, the feed rate of the forming tool was kept constant at 1500 mm/min to focus on the effects of vertical step size, spindle speed, annealing conditions, and forming direction on formability and thickness distribution.

The initial sheet metal, along with the incremental forming process equipment and the final sample are shown in Fig. 3.

2.5. Measurement techniques

The measurements related to the experimental tests (strain and thickness distribution) were carried out using a VMM (Vision Measuring Machine) device. The device used in this study was an Easson C-3020 model. The experimental equipment for the annealing process (oven) and the measuring instruments are shown in Fig. 4.

All experimental measurements were repeated three times at each location, and the average values were reported to minimize the influence of laboratory errors. The VMM device offers a repeatability of 2 µm and a resolution of 1 µm, resulting in a measurement uncertainty of less than 1.5% for thickness and 2% for principal strains.

3. Results and Discussion

3.1. Effects of process parameters on groove depth

In incremental forming, several parameters influence the product quality, including forming limit, maximum forming depth, forming thickness distribution, and force behavior. In this study, the effects of spindle speed, vertical step size, heat treatment, and deformation direction were investigated with respect to these factors. The obtained results were quantitatively evaluated and analyzed.

The formed parts from the experimental tests of the direct groove incremental forming process were examined. In this process, the tool moves linearly back and forth across the sheet while incrementally penetrating in steps defined by the vertical step size (as listed in Table 1). This stepwise penetration continues until fracture occurs, which is defined as the point at which a visible crack extends through the entire sheet thickness, resulting in separation along the tool path. The CNC machine stops once this stage is reached. Fig. 5 illustrates the direct groove process performed on the aluminum 3105-H14 sheet.

In the present research, the effects of spindle speed, vertical step size, and tool movement direction on groove depth and formability were investigated. For each parameter, four different levels were considered, as listed in Table 1. Additionally, two different tool movement directions (parallel and perpendicular to rolling path) were adopted to separately study their influence on groove depth and formability.

In conducting the experimental tests, a design of experiment (DOE) approach combined with numerical analysis were utilized. Four influential factors affecting the response were defined, and different levels were assigned to each factor (Table 1). This resulted in a total of 16 experimental design points. It is worth noting that the Taguchi method was employed to develop the experimental design in this study. To determine the design of experiment, analyze the results, and identify influential parameters, MiniTab software was used, which is one of the most common statistical analysis software available. Table 2 presents the experimental combinations generated using the Taguchi method, along with the corresponding results for the maximum forming depth (before fracture) of the aluminum 3105 sheets.

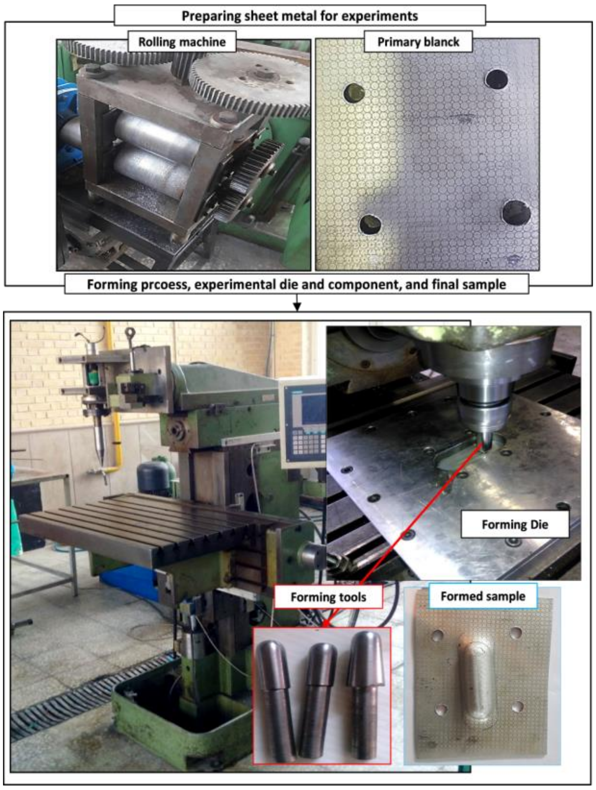

Fig. 3. Experimental equipment for the incremental forming process; initial sheet dimensions: 700 × 1000 mm.

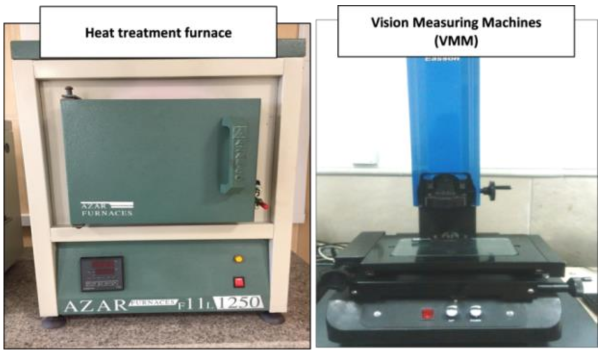

Fig. 4. The annealing oven and the measuring instruments.

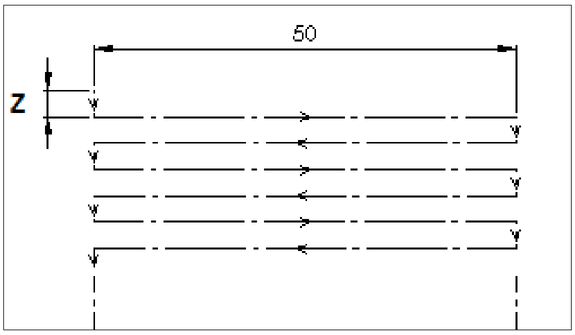

Fig. 5. Tool path during incremental forming process. The tool moves linearly back and forth across the sheet while incrementally penetrating according to the vertical step size until complete fracture occurs (dimensions in mm).

Table 1. Process variable values

Variable	Level 1	Level 2	Level 3	Level 4
Spindle speed (RPM)	1000	1400	1700	2000
Vertical step (mm)	0.25	0.5	0.75	1
Tool direction	Parallel and perpendicular to the rolling path			
Heat treatment	Annealed and non-annealed sample			

To further analyze and investigate the results and to identify the factors affecting the process, analysis of variance (ANOVA) was performed. The experimental design was first implemented to examine the effects of the selected process parameters on groove depth, and the results of the direct groove tests for the maximum and the corresponding experimental conditions are summarized in Table 2.

Table 3 presents the analysis of variance (ANOVA) for the maximum forming depth of the aluminum 3105 sheet. If the value of P-value is less than 0.05, it indicates that the significant that the corresponding input parameters has a statistically significant influence on the process response. Based on the results presented in Table 3, the most influential parameter on the maximum forming depth is the vertical step size and the annealing conditions. The coefficient of determination (R^2) was found to be 93.55%, demonstrating the model's compatibility with the data obtained from experimental results.

The main effects plots are useful to determine the optimal conditions and observe the impact of input variables on the output response. Fig. 6 illustrates the main effects plots for the maximum forming depth. In this figure, four plots are shown, where the horizontal axis represent the mean values of the input parameters (vertical step size, spindle speed, annealing conditions, and forming direction), while the vertical axis represents the average maximum forming depth. According to Fig. 6, the annealed sheet demonstrates superior formability compared to the non-annealed conditions. Increasing the vertical step size leads to a reduction in formability, whereas increasing the spindle speed enhances formability due to the higher friction and the resulting heat generation during the process.

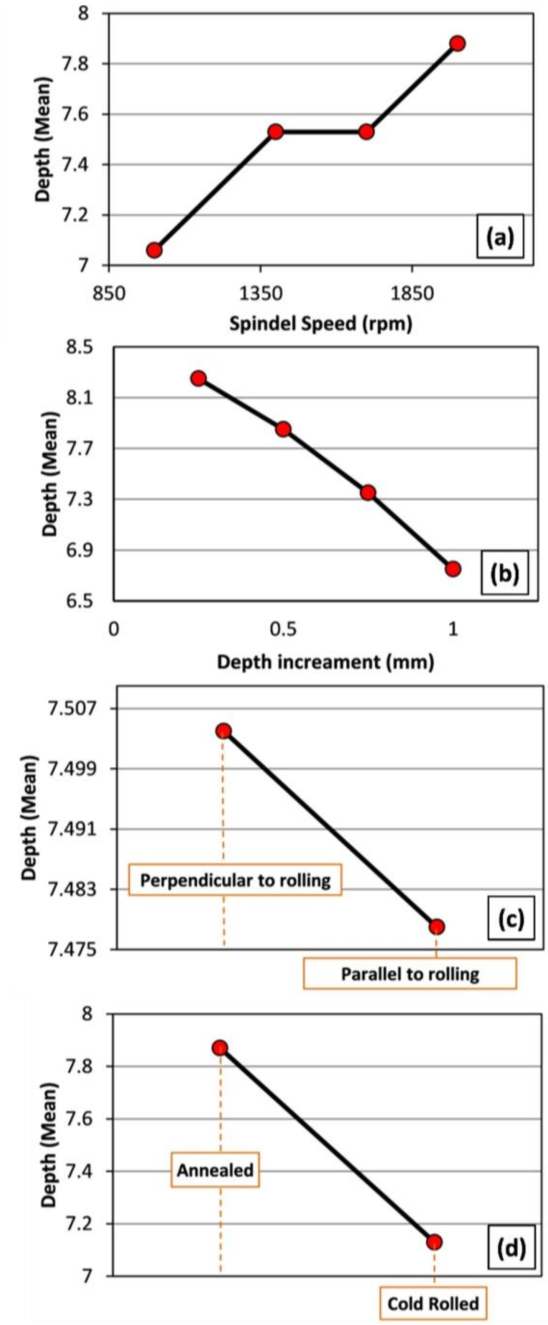

Fig. 6. The impact of input parameters on the maximum forming depth: (a) spindle speed, (b) vertical step size, (c) forming direction, and (d) heat treatment.

Table 2. Design of experiments for maximum depth

Test number	Experiment parameters				Output
	Spindle speed (rpm)	Step down (mm)	Forming tool direction	Heat treatment	Maximum depth (fracture limit)- (mm)
1	1000	0.25	Perpendicular to the rolling	+	8.30
2	1400	0.25	Perpendicular to the rolling	+	8.50
3	1700	0.25	Parallel to the rolling	-	7.80
4	2000	0.25	Parallel to the rolling	-	8.83
5	1000	0.5	Parallel to the rolling	+	8.03
6	1400	0.5	Parallel to the rolling	+	7.90
7	1700	0.5	Perpendicular to the rolling	-	7.24
8	2000	0.5	Perpendicular to the rolling	-	8.02
9	1000	0.75	Perpendicular to the rolling	-	6.44
10	1400	0.75	Perpendicular to the rolling	-	7.03
11	1700	0.75	Parallel to the rolling	+	7.90
12	2000	0.75	Parallel to the rolling	+	7.80
13	1000	1	Parallel to the rolling	-	5.50
14	1400	1	Parallel to the rolling	-	6.60
15	1700	1	Perpendicular to the rolling	+	7.10
16	2000	1	Perpendicular to the rolling	+	7.40

Table 3. Analysis of variance for maximum depth

Source	Degree of freedom	Seq. sum of squares	Adj. mean squares	P-value	Percentage contribution
Step down	3	5.5175	1.8392	0.001	56.8
Spindle speed	3	1.3252	0.4417	0.038	13.6
Annealing condition	1	2.2500	2.2500	0.002	23.1
Forming direction	1	2.2500	2.2500	0.872	23.1
Error	7	0.6269	0.0896	-	6.4
Total	15	9.7222		-	1
R^2= 93.55%			$R^2(adj)$= 86.18%		

The values of principal strains generated in the outer layer of the formed part can be used as an indicator to evaluate changes in formability during the process. To determine these strains, circular grids were marked on the sheet surface prior to forming. After deformation, the grids transformed into ellipses, and the major and minor axes were measured using a vision measuring machine (VMM, Easson C-3020) with a repeatability of 2 μm and a resolution of 1 μm. The principal strains were then calculated based on the measured axes.

According to the results shown in Fig. 7, the process parameters have a significant influence on the distribution of principal strains across different regions, the permissible deformation range, and the strain at fracture. In general, with an increase in the range of variation, necking and fracture are delayed, resulting in enhanced formability. Fig. 7 illustrates the effect of annealing and spindle speed on the values of principal strains and the onset of fracture. The results show that annealing and higher spindle speed lead to increased principal strains in the intact regions and the point of fracture, confirming the influence of process variables on the forming limit in incremental forming process. It should be noted that the influence of spindle speed on formability partially arises from the thermal effects induced by tool–sheet friction. Higher spindle speeds increase local temperature, which softens the material and promotes deformation, resulting in greater principal strains and larger maximum forming depth. Although direct temperature measurements were not conducted, the observed trends in strain and thickness distribution implicitly reflect the influence of these thermal effects.

The observed increase in principal strains ultimately affects sheet thinning in critical regions. Hence, after understanding the influence of variables on the loading path and the resulting changes in the range of principal strains, the final limits and validations of these effects were further examined by quantitatively analyzing thinning calculations.

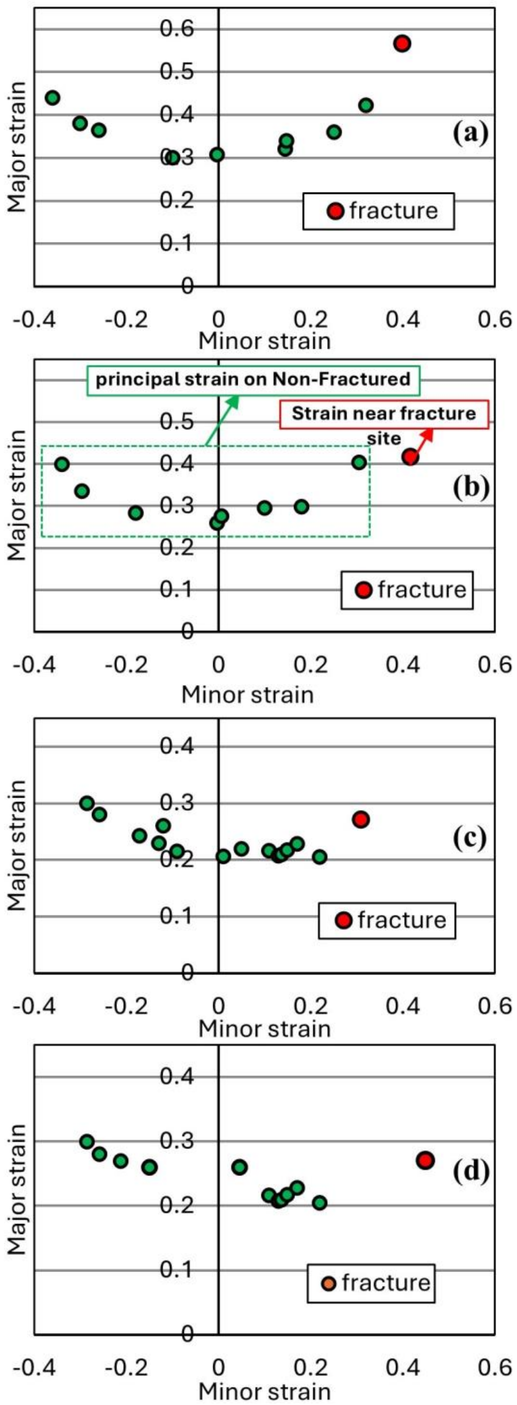

Fig. 7. Distribution of principal strains in the formed samples under different conditions: (a) annealed, spindle speed: 1400 rpm, vertical step size: 0.25 mm, perpendicular to rolling direction, (b) non-annealed, spindle speed: 2000 rpm, vertical step size: 0.25 mm, parallel to rolling direction, (c) annealed, spindle speed: 1700 rpm, vertical step size: 0.75 mm, parallel to rolling direction, (d) annealed, spindle speed: 2000 rpm, vertical step size: 0.75 mm, parallel to rolling direction.

For thickness measurements, the formed sheets were cut along the groove using a wire-cut method, and thickness at multiple locations along the path was measured using a magnification device, as illustrated in Fig. 8. This procedure enabled precise evaluation of both the strain distribution and localized sheet thinning in the formed regions.

The thickness distribution and reduction were determined for all experimental tests and the thickness distribution curves for two representative cases are displayed in Fig. 9. It is evident that at a spindle speed of 2000 rpm, the minimum sheet thickness occurs at a distance of 10.5 mm from the starting point, with a value of 0.602 mm. Fracture was also initiated at this location. Conversely, at the spindle speed of 1700 rpm, the minimum sheet thickness occurs at a distance of 10 mm from the starting point, with a value of 0.669 mm. Under these conditions, further thickness reduction beyond this level is not achievable. These findings suggest that a greater reduction in sheet thickness corresponds to improved formability. In essence, the greater the reduction in sheet thickness, the higher the inferred formability of the sheet. The results clearly indicate the influence of spindle speed in enhancing formability within the examined process. In other words, under these conditions, the maximum achievable forming depth increases with higher spindle speed, indicating improved formability. This trend was consistently observed across all experimental tests. By analyzing the thickness distribution curves, the minimum achievable thickness under different conditions was determined. Table 4 summarizes the obtained minimum thickness values for the direct incremental forming process under various conditions.

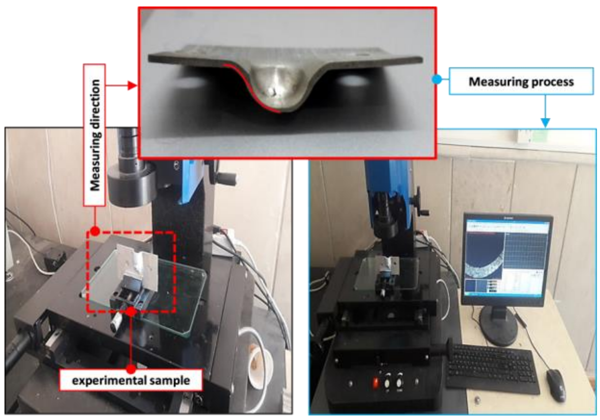

Fig. 8. Thickness measurement process: the sheet is cut perpendicular to the tool path at the midpoint of the groove using a wire-cut method, and thickness is measured along this cross-section.

Table 4. Minimum thickness obtained from straight groove experiments

Test number	Experiment parameters				Output
	Spindle speed (rpm)	Step down (mm)	Forming tool direction	Heat treatment	Minimum thickness (mm)
1	1000	0.25	Perpendicular to the rolling	+	0.601
2	1400	0.25	Perpendicular to the rolling	+	0.584
3	1700	0.25	Parallel to the rolling	-	0.669
4	2000	0.25	Parallel to the rolling	-	0.602
5	1000	0.5	Parallel to the rolling	+	0.625
6	1400	0.5	Parallel to the rolling	+	0.650
7	1700	0.5	Perpendicular to the rolling	-	0.771
8	2000	0.5	Perpendicular to the rolling	-	0.628
9	1000	0.75	Perpendicular to the rolling	-	1.002
10	1400	0.75	Perpendicular to the rolling	-	0.823
11	1700	0.75	Parallel to the rolling	+	0.651
12	2000	0.75	Parallel to the rolling	+	0.668
13	1000	1	Parallel to the rolling	-	1.120
14	1400	1	Parallel to the rolling	-	0.969
15	1700	1	Perpendicular to the rolling	+	0.796
16	2000	1	Perpendicular to the rolling	+	0.764

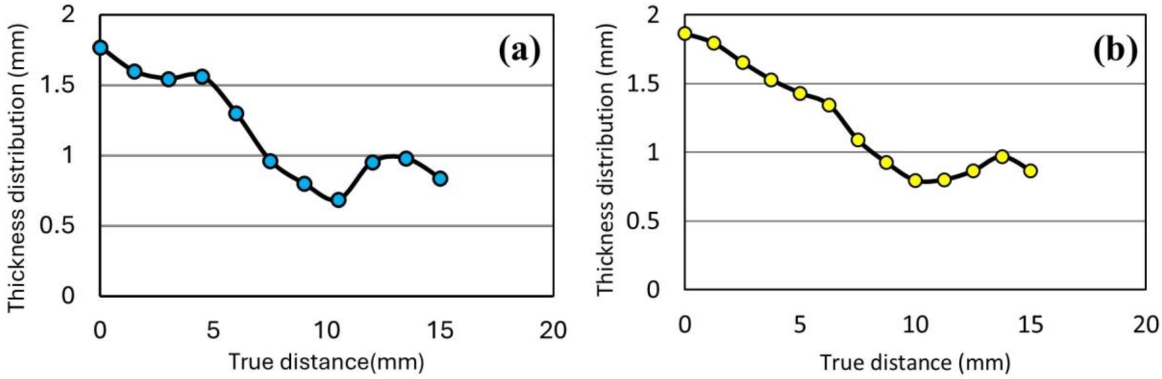

Fig. 9. Thickness distribution along the cross-section of the formed sheet: (a) non-annealed, spindle speed 2000 rpm, vertical step size 0.25 mm, forming direction parallel to rolling direction; (b) non-annealed, spindle speed 1700 rpm, vertical step size 0.25 mm, forming direction parallel to rolling direction. Measurements were taken along the cross-section perpendicular to the tool path at the midpoint of the groove.

Table 5 presents the analysis of variance (ANOVA) for the maximum thickness reduction in the incremental forming process. The analysis yielded aa correlation coefficient of 94.39%.

Based on the ANOVA results, the p-values for vertical step size, spindle speed, and annealing condition are all below 0.05, indicating that the null hypothesis of no significant relationship can be rejected. However, the p-value for forming direction exceeds 0.05, suggesting that the forming direction does not significantly affect the maximum thickness reduction. Although the forming direction (parallel vs. perpendicular to rolling) does not show a statistically significant effect on maximum thickness reduction (Table 5), its role is more pronounced in the distribution of principal strains and the resulting forming limit diagrams. Specifically, forming parallel to the rolling direction produced slightly more favorable strain paths and higher fracture strain, consistent with previous findings on anisotropy in rolled aluminum sheets. Therefore, while the forming direction may not strongly influence thickness reduction, it still affects local strain evolution and the fracture limit in the incremental forming process.

Fig. 10 illustrates the main effects of each parameter on the maximum thickness reduction and formability. The horizontal axis represents the input parameters values, while the vertical axis indicates the minimum thickness. According to the results, reducing the vertical step size, increasing the spindle speed, performing the annealing process, and forming parallel to the rolling direction all lead to an increase in the formability of the sheet in this process. Although the overall stress state in

Table 5. Analysis of variance for maximum thickness reduction.

Source	Degree of freedom	Seq. sum of squares	Adj. mean squares	P-value	Percentage contribution
Step down	3	0.210667	0.070222	0.001	53.6
Spindle speed	3	0.061828	0.020609	0.019	15.7
Annealing condition	1	0.096877	0.096887	0.001	24.6
Forming direction	1	0.000014	0.000014	0.948	0.004
Error	7	0.021947	0.003135	-	5.6
Total	15	0.39332	-	-	100
R^2= 94.39%			$R^2(adj)$= 87.98%		

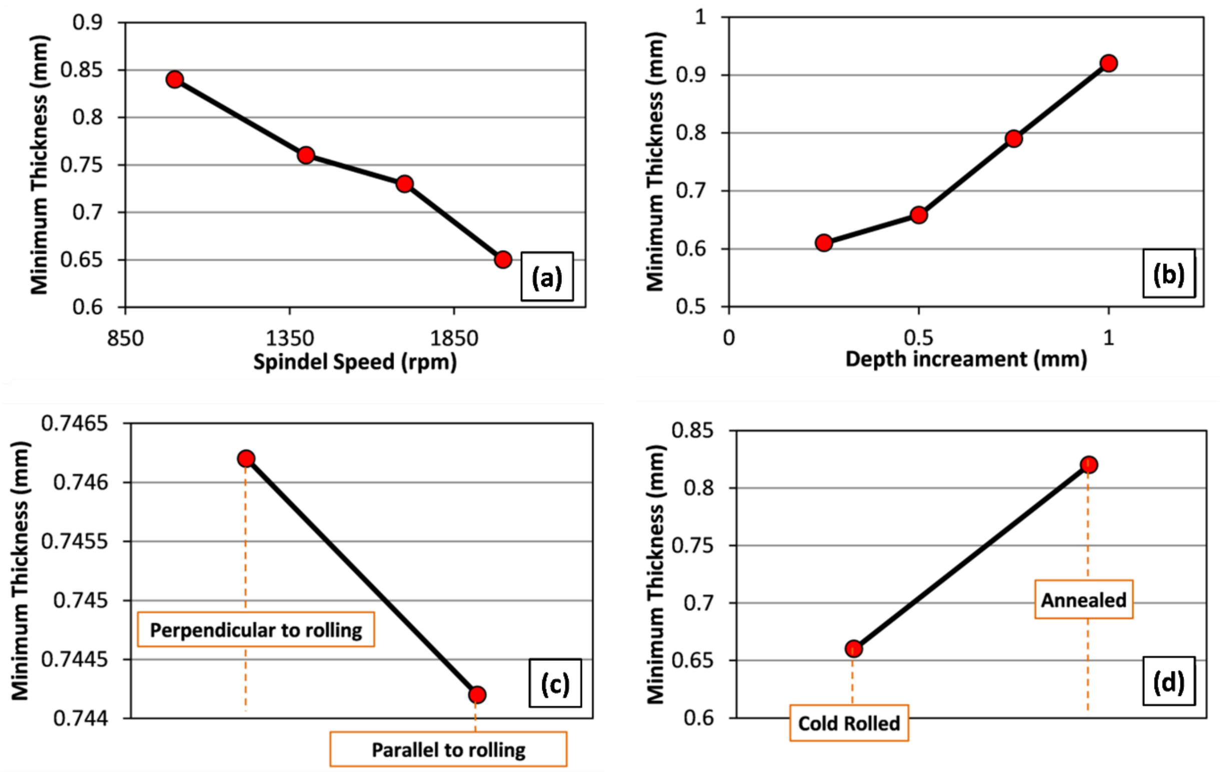

Fig. 10. The effect of process parameters on minimum thickness.

the sheet remains similar during the incremental forming process for the cases considered, the local forming limits differ due to variations in strain distribution, material orientation, and tool–sheet interactions. Therefore, the current research indicates that fracture modeling in this process requires modifications to the fracture criterion function, and provide a valuable foundation for such future modeling efforts.

In comparison with earlier studies, our findings are generally consistent with literature, yet they provide some novel quantification. For example, Wang et al. [38] reported for AA2024 sheets that increased forming temperature and optimized process parameters significantly improve the forming limit, which resonates with our observation that annealing and higher spindle speeds increase principal strains and failure depth. Zhu et al. [39] demonstrated that sheet posture/extrusion direction affects thickness uniformity and forming quality in CNC incremental forming, which aligns with our findings on how forming direction parallel versus perpendicular to rolling influences strain distribution, though in our case forming direction has a smaller impact on thickness reduction. Similarly, Kilani et al. [40] found that step size has a predominant effect on thinning and forming force in SPIF, supporting our conclusion that vertical step size is among the most influential factors. Finally, the work on Al1050 (evaluation of thickness distribution in SPIF) also shows that step depth is dominant in wall thickness reduction, matching our results in Table 5 [41]. These comparisons reinforce the validity of our experimental results and highlight that while forming direction plays a role particularly in strain paths and forming limit, its effect on thickness reduction may often be secondary compared to step size or heat treatment. While these trends agree with prior literature, the present work is distinct in addressing AA3105-H14, quantifying anisotropy effects through ANOVA, and the coupling annealing with rolling direction to reveal new insights into thickness distribution and strain paths.

4. Conclusions

In this study, the incremental forming process of aluminum 3105H14 sheet was investigated using a combination of experimental tests and numerical evaluations. The Taguchi experimental design method was employed, and a total of 16 experiments were conducted to examine the effects of influential process variables such as spindle speed, vertical step size, annealing conditions, and forming direction on maximum forming depth, forming limit, and sheet thickness distribution. The main findings can be summarized as follows:

- Vertical step size and annealing condition have the most significant effect on formability and sheet thickness. Smaller step sizes, specifically 0.25 mm, and annealed sheets resulted in a maximum forming depth of 10.5 mm and a minimum sheet thickness of 0.584 mm, indicating better material ductility and reduced fracture susceptibility.
- Increasing step size from 0.25 mm to 0.75 mm reduced the maximum forming depth by approximately 22–28%, highlighting its dominant influence.
- In the forming limit diagram, a larger diagram range corresponds to higher formability. The highest formability limit was achieved under the following conditions: vertical step size of 0.25 mm, spindle speed of 2000 rpm, and forming direction parallel to the rolling direction. Under these specific conditions, the material has the best formability, allowing for more extensive deformation without reaching its forming limit.
- Tool movement parallel to the rolling direction increased principal strains by 8–12% compared with perpendicular movement, demonstrating the effect of rolling texture on formability.
- Increasing spindle speed from 1400 rpm to 2000 rpm increased the maximum forming depth by 7–10% and reduced localized thinning by 2–3%, due to enhanced frictional heating and material ductility
- As the maximum forming depth increases, the minimum sheet thickness resulting from the incremental forming process decreases. In this study, the minimum achieved sheet thickness after incremental forming was 0.584 mm. Vertical step size and annealing conditions were the most significant impact on final minimum sheet thickness, while forming direction had a minor effect on the final thickness, but a more noticeable impact on strain distribution and forming limit behavior.

Authors' Contributions

A. H. Neshastegir Kashi: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing

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

H. Talebi-Ghadikolaee: Conceptualization, Methodology, Data curation, Investigation, 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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