



Investigating the Impact of Process Parameters on Thinning and Formability in Aluminum Alloy AA 1050 Incremental Sheet Metal Forming



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HIGHLIGHTS

- Nine specimens were fabricated with different processing parameters using a CNC machine
- Investigating the influence of Spindle speed, Feed, tool diameter, and step down on the maximum thinning and formability
- The dominant factor affecting Maximum thinning is the spindle speed large effect

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ABSTRACT

ISMF is a potential manufacturing technology that uses progressive deformation to create complicated shapes. ISMF produces sheet metal consecutively using targeted tool movement. This innovative method increases component precision, material waste reduction, and design flexibility. A tool is moved along a set path over a flat metal sheet while twisting forces are applied to get the needed shape. SPIF could be used in the medical equipment, aerospace, automotive, and building industries, but it is only profitable in certain situations because it is slower than other sheet-forming methods. SPIF-based die-less making makes it easier to shape. To make cone-shaped structures with SPIF, the spindle speed (1000, 1500, and 2000 RPM), feed rate (200, 400, and 600 mm/min), tool width (8, 10, and 12 mm), and step-down (0.2, 0.4, and 0.6 mm) at the specimen interface were all changed. For aluminum alloy AA 5010, the maximum thinning (mm) and formability (%) were the important mechanical qualities. The L9 orthogonal array was used for a complete look at these qualities. Making high-quality cones using a computer numerically controlled machine was the aim of this research. (CNC) machine. The important factors affecting engineering and forming quality were studied using the Taguchi and analysis of variance methods. The most influential factor on maximum thinning was the rotational speed followed by the feeding, which is inversely proportional to it. In contrast, the most effective factor on the formability is the feeding followed by the rotational speed, which is directly proportional to it. It was discovered that a spindle speed of 1500 revolutions per minute (RPM), a feed rate of 200 millimeters per minute (mm/min), a tool diameter of 10 millimeters (mm), and a step down of 0.4 millimeters provide the least amount of maximum thinning (mm) and formability (percent).

1. Introduction

Traditionally, sheet metal components are produced using dies and punches. However, These techniques can be highly expensive, making them only useful for bulk production. With the growing demand for customized products, process flexibility, and shorter production times, finding more efficient manufacturing methods and more efficient manufacturing [1] For industrial applications to be economically feasible, they often require large quantities. Unfortunately, stamping processes fail to meet the demand for forming by flexibility. It is clear that current metal stamping methods can only remain viable in modern production if more adaptable and cost-effective technologies are developed. In a study by Kim and Park [2], several process variables' effect on aluminum sheets' formability Maan and Hamdan [3], created a feature-based manufacturing cost estimator that might assist a person in estimating the cost of a part with little understanding of a manufacturing process. Likewise, Geelink et al. [4] gave users of computer-aided process planning systems a general framework to describe feature categories for sheet metal components. A feature-based approach can also make it simple to record conceptual design information. Behera et al. [5] proposed A taxonomy of sheet metal features based on location, orientation, and process criteria such as failure limits and the curvature sign. However, this taxonomy cannot be effectively utilized without algorithmic implementation [6]. Systematically

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assessing thickness fluctuation and process parameters for incremental sheet metal forming. The quantity, speed, tool path, and rolling direction of the forming passes.

The suggested systematic method uses the design of experiment (DOE) to conduct experiments and response graph, main effect plot, normal probability plot, ANOVA, and predictive model generation to analyze findings and uncover process parameter effects. The number of forming passes and tool motion direction relative to the rolling direction determine the most incremental sheet metal forming thickness. Tool route type, number of passes, and travel orientation effect forming thickness. Hussain's et al. [7] work proposed a novel method for determining the limits of metal sheet thinning in negative forming. The researcher also investigated the influence of the generation of a part's curvature on the formability sheet of aluminum. In Hamdan et al. at work [8], trials comparing and analyzing the surface finish of a traditional rigid tool and an oblique roller ball tool found that the oblique roller ball tool provides a superior surface quality. In Shanmuganatan and Kumar study [9], the effect of tool rotation, tool diameter, pitch, and wall of angle on the formability of A2024 in single-point incremental forming was experimentally studied. The forming depth of conical frustums with a constant wall angle decreases with increasing step size but increases with increasing tool rotation speed. Asghari's et al. work [10] proposed grey analysis using four parameters to establish their effect on two-point incremental forming's minimum thickness, spring back, and surface irregularity.

Sometimes, there is a lack of consensus on the effect of specific process parameters on the quality of the formed component, and the results published in the specialized literature are often at odds with one another. [11], the author studied experiments on polycarbonate. A previous study analyzed polymeric sheet formability and failure mechanisms, including necking and fracture, in conventional and incremental sheet forming (ISF) processes. The experiment examines tool diameter, feed rate, spindle speed, and step down. The study examines how these traits affect formability and failure. There was fracture, twisting, and crazing. Failure usually happens via fracture without necking (mode I crack opening) in SPIF circumstances. All tests entail twisting and breaking. Crazing increases spindle speeds, and twisting increases step-down values. Thermoplastic SPIF failure modes were studied using SEM and integral temperature analysis [12]. The KUKA KR210 industrial robot was selected as the process execution equipment in this experiment to evaluate the dimensional correctness of a truncated cone geometry created by SPIF. Due to its formability, the trials used DC04 mild steel, which is used in the automotive and other industries. This fixes the issues with the discontinuous z-level contouring toolpath.

The truncated cone-shaped pieces formed the incremental step size (0.5 or 1 mm) and wall angle (50 or 60 degrees). This research evaluates geometric correctness and finds that wall angle affects geometrical deviance. Hui and Hengan [13], studied an analytical model that predicts forming forces throughout incremental sheet forming (ISF). Vertical and horizontal forces are estimated by modeling the contact region, thickness distribution, and strain components. The projected force history matches deformation-induced force component variations. This illuminates material deformation mechanisms and their relationship to forming force parameters during the ISF process. Murugesan and Jung [14] proposed an optimization method for process parameters in ISMF of AA3003-H18 alloy. This strategy was developed as part of this investigation. The authors optimized the tool path, speed, and step down by using a Taguchi method that considered many criteria at once. Coman and Mazurchevici [15] analyzed the context of an incremental sheet metal forming process. This study investigated how the thinning of aluminum was affected by the presence of various parameters. The authors adding more levels of parameters had a considerable influence on thinning. Ben Said and Mars [16] researched how the various tool path techniques affected the thinning and formability of the material. They concluded that using a spiral tool path method reduced the amount of thinning that occurred and increased formability. The study [17], reported on the consequences of the thickness thinning and mechanical properties.

The scientists discovered that reducing the pace at which the material was formed led to reduced thinning and greater mechanical properties. The research [18] found how heat treatment affected the thinning and formability of High-Strength aluminum alloys while ISMF was being performed. They concluded that the right kind of heat treatment might improve formability and cut down on thinning. Limpadapun and Kesvarakul [19] found the importance of lubrication to the ISMF process was the primary focus of this research. According to the findings, using the right lubricant lowered the amount of friction, which minimized the amount of thinning. Schmitz and K Bremen han [20] researched how the geometry of the tools used in the ISMF process affected the thinning and formability of aluminum alloys. They concluded that a tool with a smaller diameter would lead to less thinning and improved formability. In this work [21], improving geometric accuracy in double-sided is presented to improve accuracy and reduce thinning that occurs during the ISMF process. The scientists optimized their work with a mix of genetic algorithms and gradient descent approaches to get optimal results. This study examined the effects of spindle speed (RPM), feed rate (mm/min), tool diameter (mm), and step down (mm) on vertical machining center forming quality and maximum thinning rate. The Taguchi design of experiments was used to investigate incremental sheet metal forming (ISF) and optimize input parameters for high-quality products. Despite earlier ISF research, the study also sought the input parameters that minimized forming load and thickness. Process and material factors of incremental forming need to be addressed.

2. Experimental Measurements and Methods

The CNC vertical processing machine used in this research has the following specifications: Features a 450 mm, 350 mm, and 350 mm working range from C-tek Machine Works with a FANUC control system. Precision in position: 0.01 mm; power consumption: 15KVA repeatability: 0.05 mm, Spindle Speed Range - 80–8000 RPM. The rod shape formation tool with a hemispherical head and a 12-millimeter diameter was fastened into the Milling machine's spindle. After setting up the blank holders, the sheet metal was put onto the lower blank holder and the worktable for the simple pass, using the upper blank holder as a press. Here, we consider distinct parameters such as spindle rotation, axial feed rate, and X, Y feed rate. Figure 1B illustrates

the experimental setup and assembly fixture. We selected the parameters shown in Table 1 for direct study. The shape-containing Conical Cups shown in Figure 1A were framed using the part program.

The fixture's primary function was to support the workpiece while forming securely. As forming generates a great deal of localized stress, gripping is crucial. The clasp had a metallic structure. The sheet metal was fastened between the fixture's base and the fastening plate using steel fasteners. It was decided to construct the fixture with four components. The first piece to be bolted was the base. Because of vibrations and forces, it was determined to be 15 millimeters thick. The remaining four components are 25 mm-thick rectangular rods that rise vertically from the base plate to provide a framework for supporting the workpiece. UG-NX was used for designing and creating three-dimensional models of the component. The fixtures were fabricated according to the final shape specifications shown in the figure. The design and manufacture of the 8, 10, and 12 mm diameter tools were based on the conical shape requirements. The SPIF process of the aluminum alloy AA 5010 will be investigated for its critical industrial applications in sheet metal forming.

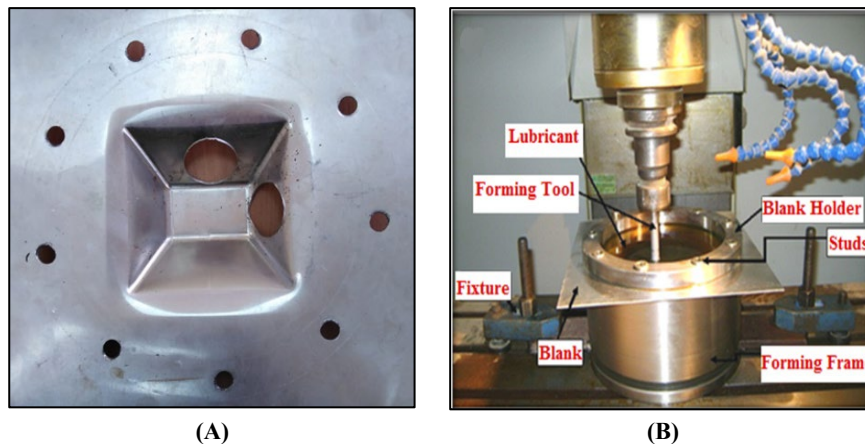


Figure 1: A) Specimens after ISMF Process, B) Experimental setup (die and blank holder)

Table 1: Parameters and Levels

Parameters	Spindle speed (RPM)	Feed (mm/min)	Tool diameter (mm)	step down (mm)
Level 1	1000	200	8	0.2
Level 2	1500	400	10	0.4
Level 3	2000	600	12	0.6

3. Taguchi Experimental Design Method and Analysis of Variance (ANOVA)

This technique relies on two groups; the first is an "orthogonal array (OA)" matrix that incorporates the number of samples based on the number of levels for the controlling parameters, and the second is the signal-to-noise ratio (S/N). The term 'signal' refers to the required values (mean) of the outputs' characteristics, while 'noise' refers to the unneeded values. Calculating (S/N) ratios varies according to objective functions, i.e., a characteristic quantity. The procedure was developed using MINITAB16. Variance analysis (ANOVA) could be applied to the experimental results to determine the influence of forming variables on residual stresses throughout the process. In analysis, the ratio between mean square errors and residual is referred to as the F-ratio, and it is used to determine the significance of a parameter. F ratio corresponds to 95% confidence levels in operation variable calculations. P values represent the significance levels of each parameter [22].

4. Process Parameters

SPIF Aluminum alloy AA 5010 thickness (1mm) with dimensions (250 mm X 250 mm) to measure the maximum thinning and formability (%) in the current work. In the existing investigation, spindle Speed (RPM), tool Diameter (mm), Feed (mm/min), and step down (mm) are individually controllable Process parameters.

5. Results and Discussion

Using the Taguchi Method, the aforementioned technique was able to establish the optimization parameters to attain the final answer for industrial aids and product quality. The findings were put into a table for the sake of further discussion. Based on the information in Table 2, it was concluded that the material can be utilized in various industrial settings. Table 3 During data analysis, the normalized values are obtained by transforming values measured on distinct scales into a single scale, and the normalized matrix is found by employing a mechanism that does the same thing. In Table 2, the normalized values are tabulated. Priority weights are assigned to each response created on the influence on forming yield. For the remaining responses, such as maximum thinning and formability (%), lesser values are preferable (as they tally to the LB criterion of "lower is better").

Consequently, the minimum value of the recorded value is considered the positive ideal solution, while the maximum value represents the negative ideal solution. The positive and negative ideal solutions are calculated and listed in Table 2. It is evident from the tabulations in Tables 3 and 4 that parameter 1 and 2 has the highest ranking. Consequently, the input parameter

corresponding to the best maximum thinning is a spindle Speed of 1000 RPM, step down of 0.4 mm, Feed of 400 mm/min, and tool diameter of 8 mm, Table 2, as shown in Figures 2 and 3.

Table 2: Readings of experimental outputs

No.	Speed (RPM)	Feed (mm/min)	Tool dia (mm)	Step down (mm)	Maximum Thinning	Formability
1	1000	200	8	0.2	14.64	36.9
2	1000	400	10	0.4	13.20	35.1
3	1000	600	12	0.6	17.84	27.0
4	1500	200	10	0.6	22.64	43.2
5	1500	400	12	0.2	15.12	35.1
6	1500	600	8	0.4	18.56	27.0
7	2000	200	12	0.4	13.04	37.8
8	2000	400	8	0.6	12.24	35.1
9	2000	600	10	0.2	15.44	27.0

Table 3: ANOVA results for Maximum Thinning

Source of variance	DOF	Sum of squares	Variance	P(%)
speed	2	42.35	21.18	48.39
Feed rate	2	25.0	12.5	28.54
Tool dia	2	6.9	3.45	7.91
Sidestep	2	13.3	6.6	15.16
Total	8	87.52		100

Table 4: ANOVA results for Formability

Source of variance	DOF	Sum of squares	Variance	P(%)
speed	2	7.7	3.9	3.00
Feed rate	2	234.54	117	90.99
Tool dia	2	7.7	3.9	3.00
Sidestep	2	7.7	3.9	3.00
Total	8	257.8		100

In plastic forming processes, the maximum thinning accurately depicts the impact of deformation on free-surface roughening. Consequently, this measure was utilized in this study. The maximum thinning is determined by the maximum spindle speed, average feed rate, tool diameter, and step down, which are determined by the maximum spindle speed, average feed rate, tool diameter, and step down, respectively. The plastic deformation of the sample about Max spindle speed, Average Feed, tool diameter, and step down is equivalent to the formability of the sheet metal, which is measured by its capacity to withstand deformation without developing defects. As shown in Figures 2 and 3, the maximum thinning is sustained by the same parameter, and formability is the elastic recovery associated with the material's behavior.

Figure 2 shows that feed rate, step down, and tool diameter affect sheet material thinning in incremental sheet forming. Depending on process parameters, material qualities, and tooling circumstances, these variables may not always affect maximum thinning. Figure 2A shows sheet incremental forming. Accelerating the spindle speed can result in greater strain rates and shorter tool-to-sheet contact times. The sheet may thin and experience more plastic deformation due to the increased strain rate. However, there are restrictions on how much spindle speed may be raised without harming the forming process. Comprehensive process parameter analysis is needed to optimize sheet incremental forming maximum thinning. Figure 2B detects the effect of feed rate on thinning in a forming process. Simulate the forming process for different feed rates, keeping other parameters constant. Apply the appropriate tool path and load conditions to mimic the experimental setup.

Figure 2D shows the effect of step down (the amount the tool penetrates the sheet in each incremental step) can likewise thin the sheet. Each incremental tool movement causes greater distortion and material flow with a bigger step-down, increasing thinning. As with feed rate, the step down is limited by machine mechanical restrictions and the material being produced. Sheet incremental forming maximum thinning depends on tool diameter. Figure 2C shows a bigger tool diameter may deform more material and generate narrower sections in each incremental step. However, tool geometry and sheet material interaction are also important. The tool form, edge radius, and surface polish affect material flow and thinning. In sheet incremental forming, increasing feed rate, step down, and tool diameter typically thins the sheet, although practical limits exist. Process instabilities, material fractures, and other quality concerns might result from excessive parameter values. Therefore, these parameters must be optimized depending on the material, machine, and forming needs, considering thinning levels, process stability, and component quality. Experimental testing and numerical simulations help determine how these characteristics affect thinning in a forming process.

Figure 3 shows the increased spindle speed, feed rate, step down, and tool diameter in sheet incremental forming may increase sheet material formability. The link between these parameters and formability is complicated and depends on material qualities and process circumstances. Figure 3A Increased spindle speed improves formability and strain rates. Higher spindle speeds improve material deformation in less time, improving plasticity and formability. There are limits to how far the spindle speed may be raised before causing tool wear or vibrations. Figure 3B Increased feed rate improves material flow and reduces tool sticking, improving formability. It also improves deformation smoothness and uniformity. However, large feed rates can increase forces and vibrations, reducing process stability. Step down (tool penetration depth) can increase deformation in each

incremental step, enhancing formability. Figure 3C increases material flow and deformation, improving shape change and formability. Figure 3D shows step-down has practical limits based on machine capabilities and material properties, like other factors. Sheet incremental forming can benefit from bigger tool diameters.

A bigger tool deforms and shapes more material by covering more sheet area. Deformation can be distributed more uniformly, minimizing localized thinning and enhancing formability. Tool geometry—shape, edge radius, and surface finish—should be carefully studied to reduce formability issues. Increasing these factors can improve formability, but there are trade-offs. Material fractures, high stresses, and poor surface quality can result from excessive spindle speed, feed rate, step down, or tool diameter. Tune these parameters based on material, machine capabilities, and desired form output. Experimental testing and numerical simulations should establish the best settings for increased formability, considering the material's behavior, process stability, and formability needs.

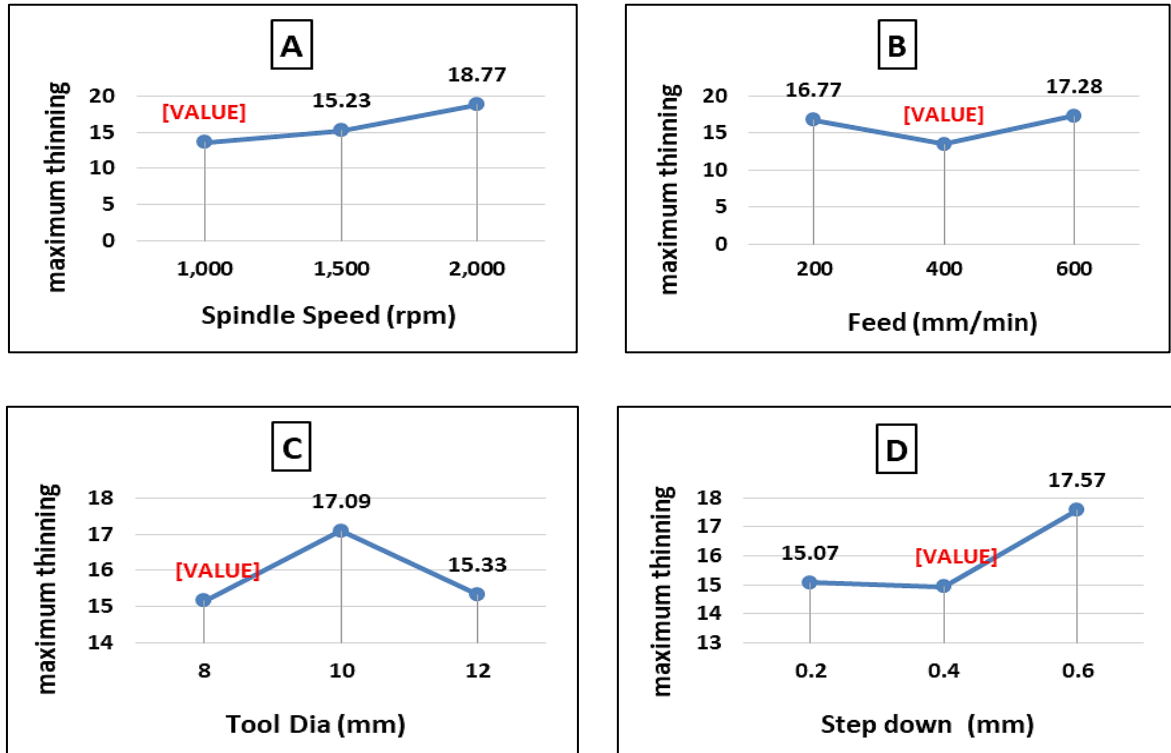


Figure 2: Mean effect plot for Maximum Thinning A) Effect of spindle speed on max thinning, B) effect of feed rate on max thinning, C) effect of tool dia on max thinning, D) effect of step down on max thinning

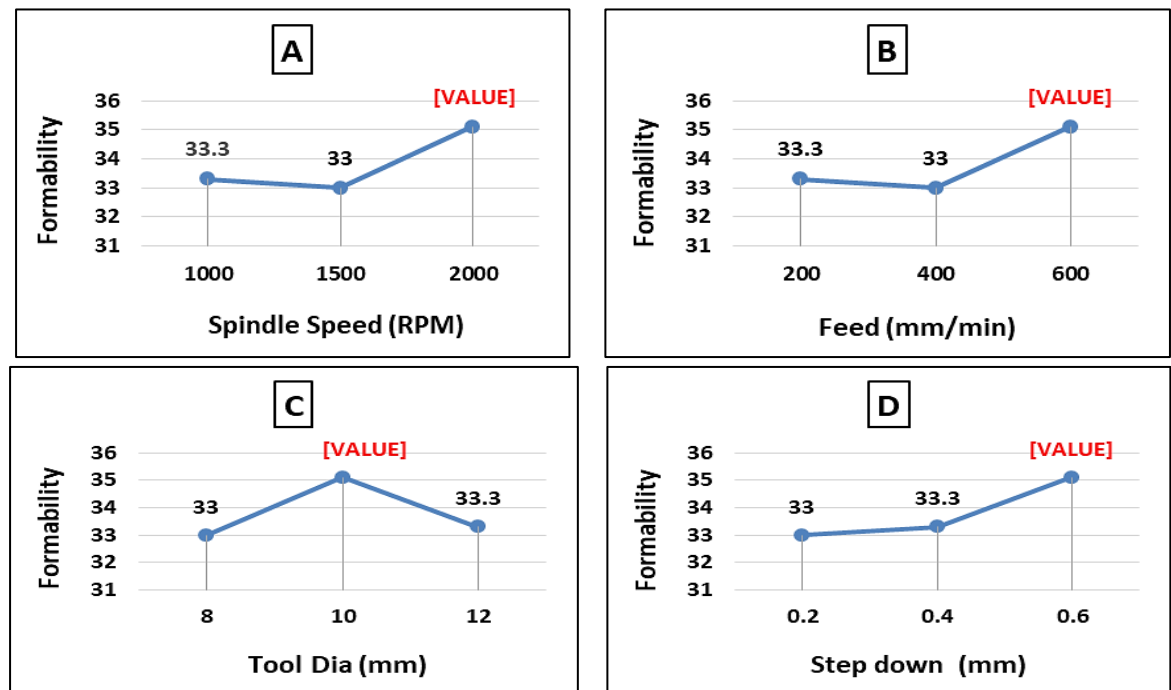


Figure 3: Mean effect plot for Formability A) effect of spindle speed on Formability, B) effect of feed rate on Formability, C) effect of tool dia on Formability, D) effect of step down on Formability

6. Conclusion

This work investigated the influence of four process factors— speed of spindle, feed rate, tool diameter, and pitch on the feature of parts. In conclusion, raising spindle speed in sheet incremental forming can increase thinning, but it is only one of several aspects to consider to optimize the process. A comprehensive strategy addressing several aspects is needed to achieve targeted thinning levels while preserving process stability and quality. Sheet incremental forming feed rates can increase strain rates and sheet material deformation. Plastic deformation can promote thinning. The feed rate can only be increased so much before it impacts process stability and quality. Rapid feed rate increases can create excessive stresses and vibration, causing tool wear, surface roughness, or failure. The quality of the parts was evaluated based on maximum thinning (mm) and formability (%). It was determined that the part geometries had a cone-like shape. It has been discovered, through Taguchi's utilization of the TOPSIS approach to analyze the acquired response value, that the parameter that has the most significant impact on response is. It was discovered that a spindle speed of 1500 revolutions per minute (RPM), a feed rate of 200 millimeters per minute (mm/min), a tool diameter of 10 millimeters (mm), and a step down of 0.4 millimeters provide the least amount of maximum thinning (mm) and formability (percent). The conclusion was that the experimental effects were equivalent to the expected values and lie within the confidence interval.

Author contributions

Conceptualization, S. Ghazi, A. Bedan and M. Salloom; software, S. Ghazi; validation, S. Ghazi, A. Bedan and M. Salloom; formal analysis, S. Ghazi, A. Bedan and M. Salloom; investigation, S. Ghazi, A. Bedan and M. Salloom; resources, S. Ghazi; data curation, S. Ghazi; writing—original draft preparation, S. Ghazi; writing—review and editing, S. Ghazi; visualization, S. Ghazi; supervision, A. Bedan and M. Salloom. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the study design, collection, analyses, interpretation of data, manuscript writing, or publishing the results.

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