EFFECT OF PROCESS PARAMETERS AND OPTIMIZATION OF FORMING TIME OF A1050 H14 ALUMINUM SHEET USING TWO-POINT INCREMENTAL FORMING FOR SUSTAINABLE MANUFACTURING

ẢNH HƯỞNG CỦA CÁC THÔNG SỐ CÔNG NGHỆ VÀ TỐI ƯU HÓA THỜI GIAN TẠO HÌNH CỦA TẤM NHÔM A1050-H14 BẰNG PHƯƠNG PHÁP TẠO HÌNH GIA TĂNG ĐA ĐIỂM HƯỚNG TỚI SẢN XUẤT BỀN VỮNG

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ABSTRACT

Two-Point Incremental Forming (TPIF) offers a flexible and tool-efficient alternative to conventional forming, with strong potential for sustainable manufacturing. This study evaluated the effects of tool diameter (D), step depth (Δz), feed rate (V_{xy}), and spindle speed (n) on the forming time of A1050 H14 aluminum sheets using a Box-Behnken experimental design. ANOVA results showed that V_{xy} and Δz are the most influential factors, while n and D have lesser but still significant effects. The developed regression model demonstrated high predictive accuracy with $R^2 = 0.992$. Using Particle Swarm Optimization (PSO), the optimal process parameters were identified as Δz = 0.83mm, V_{xy} = 1137.51mm/min, n = 1512.99rpm, and D = 14.98mm, achieving a minimum forming time of T = 7.13 minutes. These results highlight the effectiveness of integrating statistical modeling and PSO in optimizing TPIF, supporting enhanced efficiency and alignment with sustainable manufacturing goals.

Keywords: *TPIF, experiment design, metal sheet material, process parameters, forming time.*

TÓM TẮT

Phương pháp tạo hình gia tăng đa điểm (TPIF) mang lại một giải pháp linh hoạt và hiệu quả về dụng cụ so với các phương pháp tạo hình truyền thống, với tiềm năng lớn trong sản xuất bền vững. Nghiên cứu này đã đánh giá ảnh hưởng của đường kính dụng cụ (D), bước tiến theo chiều sâu (Δz), tốc độ chạy dao (V_{xy}) và tốc độ trục chính (n) đến thời gian tạo hình của tấm nhôm A1050-H14, sử dụng thiết kế thí nghiệm Box-Behnken. Kết quả phân tích phương sai (ANOVA) cho thấy V_{xy} và Δz là các yếu tố ảnh hưởng nhiều nhất, trong khi n và D có ảnh hưởng ít hơn nhưng vẫn có ý nghĩa thống kê. Mô hình hồi quy xây dựng được thể hiện độ chính xác dự đoán cao với hệ số xác định $R^2 = 0,992$. Thông qua thuật toán Tối ưu bầy đàn (PSO), các thông số công nghệ tối ưu được xác định là Δz = 0,83mm, V_{xy} = 1137,51 mm/phút, n = 1512,99 vòng/phút, và D = 14,98mm, với thời gian tạo hình tối thiểu đạt T = 7,13 phút. Các kết quả này khẳng định hiệu quả của việc tích hợp mô hình thống kê và PSO trong tối ưu hóa TPIF, góp phần nâng cao hiệu suất và hướng tới mục tiêu sản xuất bền vững.

Từ khóa: *TPIF, thiết kế thí nghiệm, vật liệu tấm kim loại, thông số quá trình, thời gian tạo hình.*

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1. INTRODUCTION

With the manufacturing industry transitioning to eco-friendly practices, sustainable manufacturing has become increasingly important, emphasizing reducing energy use, material waste, and environmental impact while preserving product efficacy [1, 2]. In this context, Incremental Sheet Forming (ISF) has become a feasible substitute for traditional forming techniques, particularly for prototyping and low-volume manufacturing. Among various ISF techniques, Two-Point Incremental Forming (TPIF) presents significant advantages, such as die-less operation, geometric adaptability, and economical implementation. It is appropriate for sustainable and agile manufacturing systems [3, 4].

The selection and optimization of key process parameters strongly influence the forming efficiency of A1050-H14 aluminum alloy in the TPIF process. Specifically, tool diameter, spindle speed, feed rate, and vertical step size significantly affect deformation quality, dimensional accuracy, energy consumption, and material waste, all of which are critical considerations in the pursuit of sustainable manufacturing. Dabwan et al. [5] demonstrated that a larger tool diameter enhances surface quality and reduces sheet thinning during forming. Spindle speed also plays an important role; according to Ghazi et al. [6], a speed of approximately 1500 RPM can provide an optimal balance between formability and thickness control. While feed rate positively correlates with formability, it has an inverse relationship with the residual sheet thickness, thus requiring careful adjustment depending on specific product requirements [6]. Finally, smaller vertical step sizes typically yield improved deformation quality but increase overall processing time, posing a trade-off between efficiency and cost [7].

Although these investigations have established the impact of parameters such as tool diameter, spindle speed, feed rate, and vertical step size on the forming performance of A1050-H14 in incremental forming operations, numerous limitations remain. First, most of these studies are based on the single-point incremental forming (SPIF) method and generally analyze factors in isolation, without thoroughly addressing their intricate interdependencies. These issues can adversely affect the precision and repeatability of the process. Second, the process conditions examined were largely idealized under laboratory environments, which may not sufficiently reflect the variability and constraints of real-world industrial settings.

Therefore, this study intends to analyze the influence of chosen process factors on the forming efficiency of A1050-H14 aluminum sheets, specifically inside the TPIF framework. A complete experimental model is constructed using a statistical design of experiments and regression analysis that integrates multivariable interactions. The ultimate goal is to identify optimal forming conditions that reduce processing time, enhance process performance, and support sustainable manufacturing practices in practical industrial applications.

2. MATERIALS AND METHODS

2.1. Experimental material and equipment

This study utilized an A1050-H14 aluminum sheet measuring 300×300mm^2 and 1.5mm in thickness, which was firmly secured between a movable backing plate and a clamping plate with eight high-strength bolts to avert slippage during the forming process. The sheet assembly was directed vertically by four precisely matched guide rods, incorporated into a custom-designed jig and fixture system (Figure 1). The system was firmly affixed to the worktable of a three-axis CNC milling machine with Typ: eecoMill 635V of Digital Technology Education Centre at LILAMA 2 Technical and Technology College (Figure 2), guaranteeing structural rigidity and positional precision during the forming process [8].

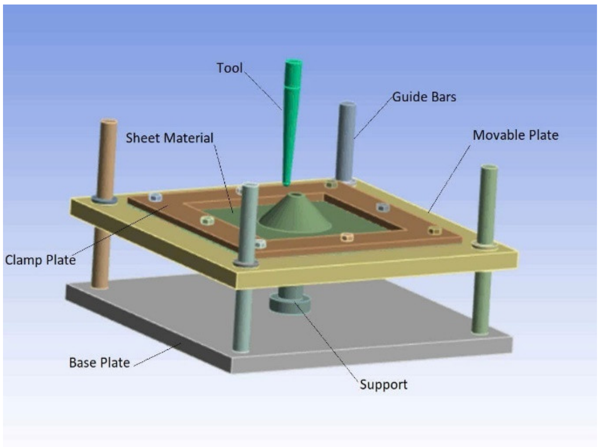


Figure 1. Jig and fixture system

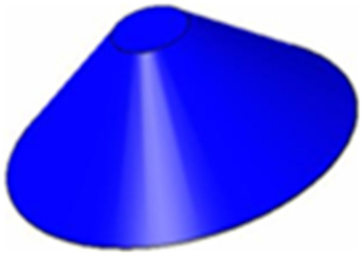
Figure 2. Experiment system for TPISF process

The TPIF process was executed in a layer-by-layer approach utilizing a hemispherical-tipped forming tool that adhered to a predetermined CNC toolpath. To examine the impact of tool geometry on forming properties, interchangeable tool tips with diameters of 6mm, 12mm, and 18mm were utilized, as shown in Figure 3. The forming tool was constructed by welding a hardened steel ball, selected for its outstanding wear resistance, onto the end of a round steel shaft, assuring high durability and uniform geometrical performance throughout the experiments.

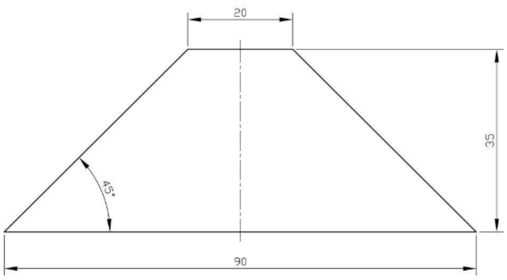
Figure 3. Forming tool

Before each forming attempt, the tool was tested for concentricity and appropriate alignment to ensure uniform forming performance. Lubrication was applied using a composite mixture of solid graphite powder and lithium-based grease in a 1:1 ratio, blended with multi-grade engine oil (SAE 20W-50). This lubricant composition was developed to reduce friction between the tool and the sheet, eliminate localized heat generation, and enhance smooth material flow throughout the forming process.

2.2. Experimental design



(a)



(b)

Figure 4. (a) CAD model of forming product, (b) Geometric profile of forming product

The experiment was developed to examine the effect of various process factors on the shaping time in sheet metal forming, using a frustum-cone shape as the test model, as illustrated in Figure 4. The experimental design followed the Box–Behnken method, a widely used approach for efficiently exploring parameter spaces. Four key process parameters, including depth step (Δz), feed rate (V_{xy}), tool diameter (D), and spindle speed (n), were selected based on previous studies, as stated in Table 1 [8]. These parameters were adjusted at two levels, resulting in 29 experimental runs, as reported in Table 2. The primary response variable for the analysis was the forming time of the product, which was measured in each experimental run. Figure 5 depicts the end products obtained from these testing runs, providing a visual picture of the pieces' final shape and surface quality. This experimental design tries to optimize the shaping process for more efficient production outcomes by investigating the relationship between process parameters and shaping time.

Table 1. Machining parameters for experimental design

No	Machining parameters	Unit	Range of values	
			Low level	High level
1	Depth step (Δz)	mm	0.1	1.5
2	Feed rate (V_{xy})	mm/min	300	1500
3	Spindle speed (n)	rpm	300	1800
4	Tool diameter (D)	mm	6	18

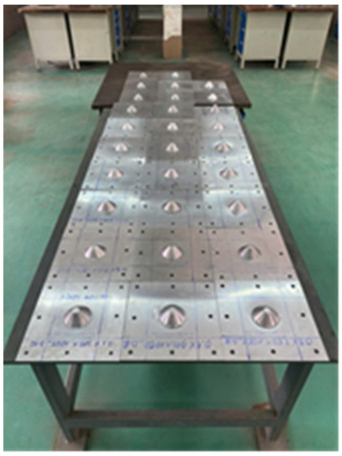


Figure 5. The forming products

Table 2. Design of experiments and results for forming timre (T)

No	Δz (mm)	V_{xy} (mm/min)	n (rpm)	D(mm)	T(min)
1	0.1	300	1050	12	55
2	1.5	300	1050	12	22
3	0.1	1500	1050	12	23
4	1.5	1500	1050	12	18
5	0.8	900	300	6	32

6	0.8	900	1800	6	20
7	0.8	900	300	18	27
8	0.8	900	1800	18	10
9	0.1	900	1050	6	48
10	1.5	900	1050	6	16
11	0.1	900	1050	18	28
12	1.5	900	1050	18	19
13	0.8	300	300	12	48
14	0.8	1500	300	12	16
15	0.8	300	1800	12	22
16	0.8	1500	1800	12	12
17	0.1	900	300	12	52
18	1.5	900	300	12	23
19	0.1	900	1800	12	24
20	1.5	900	1800	12	15
21	0.8	300	1050	6	45
22	0.8	1500	1050	6	18
23	0.8	300	1050	18	30
24	0.8	1500	1050	18	10
25	0.8	900	1050	12	13
26	0.8	900	1050	12	13
27	0.8	900	1050	12	13
28	0.8	900	1050	12	13
29	0.8	900	1050	12	13

2.3. Optimization methodology

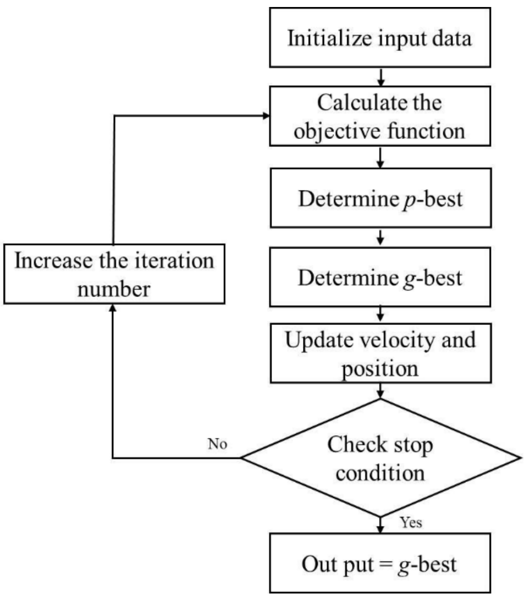


Figure 6. The flow chart of the optimization process based on PSO Alrigirhum [10]

This study uses the Particle Swarm Optimization (PSO) algorithm, a powerful population-based optimization technique inspired by the social behaviors of birds and fish. It operates by initializing a group of particles, each representing a potential solution in a multidimensional search space. These particles iteratively update their positions based on personal best experiences and the best solutions found by their neighbors, effectively balancing exploration and exploitation to converge towards the global optimum [9].

From Figure 6, the PSO algorithm is described step by step as follows:

Step 1: Initialize a population of particles with random positions and velocities in the search space.

Step 2: Calculate each particle's objective function (forming time, T).

Step 3: Update each particle's personal best position (pBest) if the fitness improves.

Step 4: Identify the global best position (gBest) among all particles.

Step 5: Update each particle's velocity and position using PSO equations.

Step 6: Check the stopping condition (e.g., max iterations or minimal improvement).

Step 7: If unsatisfied, return to Step 2; output gBest is the optimal solution.

3. RESULTS AND DISCUSSION

Analysis of Variance (ANOVA) is applied to evaluate the statistical significance of the input parameters' main and interaction effects (Δz, V_{xy}, n, and D) on forming time. Factors are considered significant when p-values are less than 0.05, indicating strong evidence against the null hypothesis. Additionally, each term's percentage contribution (PC) is calculated to quantify its influence on the total variance, providing insight into the relative impact of controllable variables within the regression model.

Based on the results of the ANOVA in Table 3, the regression model demonstrates an excellent fit to the experimental data, with 99.20% of the total variation explained by the model and only 0.80% attributed to error. The input variables, including feed rate (V_{xy}), depth step (Δz), spindle speed (n), and tool diameter (D), all exhibit p-values less than 0.05, confirming their statistically significant influence on the forming time in sheet metal forming. Regarding percentage contribution, V_{xy} emerges as the most influential factor, accounting for 26.38% of the total variation, followed by Δz (23.11%) and n (15.24%). Although D contributes only 5.11%, its effect

Table 3. Analysis of variance (ANOVA)

Source	DF	Seq SS	PC	Adj SS	Adj MS	F-Value	P-Value	Remarks
Regression	14	4896.36	99.20%	4896.36	349.74	123.96	0.000	Significant
Δz	1	1140.75	23.11%	1290.41	1290.41	457.36	0.000	Significant
V_{xy}	1	1302.08	26.38%	779.36	779.36	276.23	0.000	Significant
n	1	752.08	15.24%	335.75	335.75	119.00	0.000	Significant
D	1	252.08	5.11%	261.11	261.11	92.54	0.000	Significant
Δz×Δz	1	417.18	8.45%	648.65	648.65	229.90	0.000	Significant
V_{xy}×V_{xy}	1	204.92	4.15%	317.84	317.84	112.65	0.000	Significant
n×n	1	97.35	1.97%	146.35	146.35	51.87	0.000	Significant
D×D	1	162.16	3.29%	162.16	162.16	57.48	0.000	Significant
Δz×V_{xy}	1	196.00	3.97%	196.00	196.00	69.47	0.000	Significant
Δz×n	1	100.00	2.03%	100.00	100.00	35.44	0.000	Significant
Δz×D	1	132.25	2.68%	132.25	132.25	46.87	0.000	Significant
V_{xy}×n	1	121.00	2.45%	121.00	121.00	42.89	0.000	Significant
V_{xy}×D	1	12.25	0.25%	12.25	12.25	4.34	0.056	Not significant
n×D	1	6.25	0.13%	6.25	6.25	2.22	0.159	Not significant
Error	14	39.50	0.80%	39.50	2.82			
Lack-of-Fit	10	39.50	0.80%	39.50	3.95			
Pure Error	4	0.00	0.00%	0.00	0.00			
Total	28	4935.86	100.00%					
R^2 = 99.20% R^2 (adj) = 98.40% R^2 (pred) = 95.39%								

remains statistically significant (p = 0.000). This has also been emphasized by previous researchers in studies on the incremental forming process of aluminum alloys [11, 12]. The nonlinear (quadratic) terms also show meaningful contributions: $Δz^2$ contributes 8.45%, V_{xy}^2 accounts for 4.15%, and D^2 and n^2 contribute 3.29% and 1.97%, respectively. Interaction terms such as Δz×V_{xy} (3.97%), Δz×D (2.68%), and V_{xy}×n (2.45%) also show significant influence ($p < 0.05$). In contrast, Vxy×D (0.25%) and n×D (0.13%) are statistically insignificant ($p > 0.05$) and can thus be excluded from a reduced model. In conclusion, Δz, V_{xy}, and n play dominant roles in determining forming time and should be prioritized in optimization strategies using Particle Swarm Optimization (PSO).

Furthermore, in statistics, R^2 is the coefficient of determination for regression analysis, which explains the model's goodness-of-fit to the experimental data. According to ANOVA in Table 3 and the assessment of the Response Surface Methodology (RSM) model of T in Figure 7, the R^2 value of T is 0.992, which is very close to 1. It can be seen that the model justifies 99.20% of the total variance.

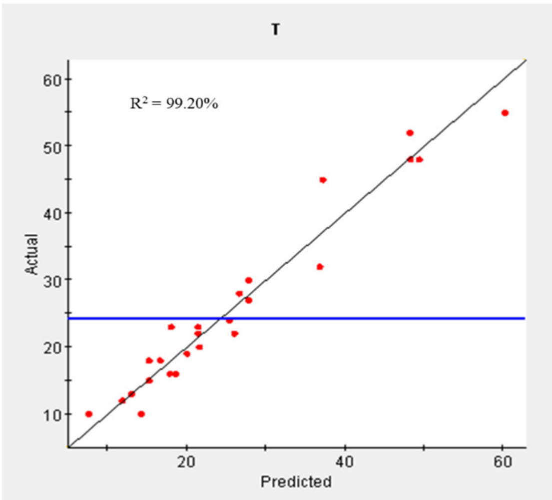
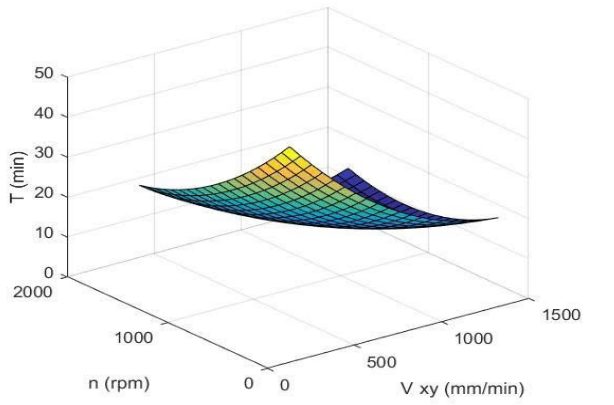


Figure 7. The assessment of the RSM model of T using the coefficient of determination (R^2)

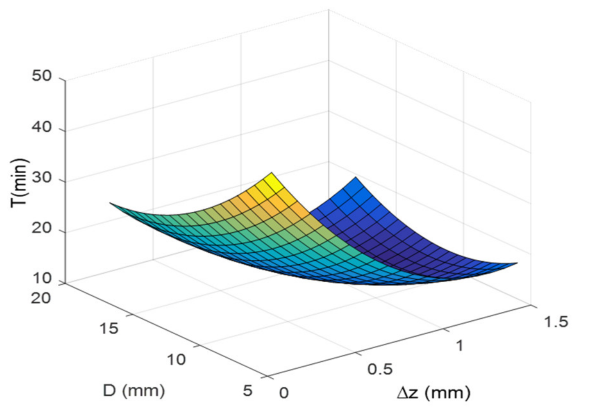
Based on experimental data and employing the Response Surface Methodology, a quadratic mathematical model is developed in this study to predict the forming time (T) during the TPIF process of A1050 H14 aluminum sheets, as follows:

$$T = 164.58 - 88.01\Delta z - 0.08436V_{xy} - 0.04357n - 5.338D + 20.41\,\Delta z\times\Delta z + 1.944.\,10^{-5}\,V_{xy}\times V_{xy} + 0.844.\,10^{-5}\,n\times n + 0.1389\,D\times D + 0.01667\,\Delta z\times V_{xy} + 0.00952\,\Delta z\times n + 1.369\,\Delta z\times D + 1.222.\,10^{-5}\,V_{xy}\times n + 0.000486\,V_{xy}\times D - 0.000278\,n\times D \quad (1)$$

To evaluate the interactive effects of the input process variables on the forming time (T), Three-dimensional response surface plots were constructed based on Equation (1). These plots were generated by simultaneously varying two factors while holding the remaining variables constant at their median levels. All corresponding response surfaces are illustrated in Figure 8.



(a)



(b)

Figure 8. The 3D surface plots for T (other values are maintained at the middle level, respectively)

To comprehensively understand the forming process and its sensitivity to key technological variables, two 3D response surface plots were analyzed to evaluate the interactive effects of process parameters on the forming time (T), as shown in Figure 8. The first plot (Figure 8a) examines the influence of tool rotation speed (n) and feed rate in the XY plane (V_{XY}), while the second (Figure 8b) focuses on the effects of tool ball diameter (D) and vertical step size (Δz). Both models reveal non-linear, highly interactive relationships between the studied variables and the response, offering valuable insights into optimal parameter selection. In Figure 8a, the forming time exhibits a pronounced decrease as both n and V_{XY} increase from their lower bounds, reaching minimum values in the intermediate-to-high ranges of 800 - 1000 mm/min and 1200 - 1400rpm, respectively. This behavior reflects enhanced plastic deformation efficiency and improved material flow, attributable to increased strain rates [13, 14]. However, beyond these optimal values, a slight increase in T occurs, likely due to instability in flow behavior or surface imperfections associated with excessive deformation velocity. Similarly, in Figure 8b, increasing the tool diameter from 5 - 8mm to 12 - 14mm significantly reduces T, owing to a broader contact area and improved stress distribution across the deformation zone. A parallel trend is observed with Δz, where moderate increases (0.8 - 1.0mm) optimize the deformation volume per tool pass and reduce processing time. Nevertheless, exceeding this range ($\Delta z > 1.2$mm) introduces localized stress concentrations and geometric instability, thereby counteracting the gains in efficiency [14]. Both response surfaces exhibit saddle-like geometries, reinforcing that the forming process is governed not by isolated parameter effects but by the synergy between variables. In both cases, time reduction is achieved by balancing deformation volume and material flow continuity. This implies that optimal forming performance cannot be attained by adjusting a single parameter in isolation; instead, a carefully tuned combination, such as moderate-to-high feed rate and rotational speed, along with larger tool diameter and controlled vertical step, must be employed. Therefore, the analyses underscore that minimizing forming time requires a systemic optimization of process parameters that collectively influence deformation kinetics, material flow, and geometric stability. These findings provide a scientific basis for parameter tuning in advanced forming operations, promoting time efficiency and process robustness.

This study employed the PSO algorithm to minimize the forming time (T) by systematically exploring a defined multi-dimensional design space. The optimization problem considered four continuous input variables: tool ball diameter (D), vertical step size (Δz), feed rate in the XY plane (V_{xy}), and tool rotational speed (n), each constrained within realistic process boundaries, as indicated in Table 4.

Table 4. Input variables and constraint ranges for optimization

Input variables	Constraint ranges
Δz (mm)	[0.1 < Δz < 1.5]
V_{xy} (mm/min)	[300 < V_{xy} < 1500]
n (rpm)	[300 < n < 1800]
D (mm)	[6 < D < 18]

After running, the PSO algorithm successfully converged to a global optimum characterized by a minimized forming time T = 7.13min, without violating any design constraints (penalty = 0). The optimal process parameters obtained were D = 14.98mm, Δz = 0.83mm, V_{xy} = 1137.51 mm/min, and n = 1512.99 rpm, as described in Table 5. These values represent a synergistic balance between deformation geometry and strain rate, effectively reducing the number of tool passes and enhancing material flow uniformity. The results demonstrate the robustness and computational efficiency of PSO in navigating complex, non-linear design spaces associated with incremental forming processes. By enabling convergence toward an optimal configuration that minimizes forming time while respecting physical constraints, PSO provides a valuable tool for process engineers aiming to enhance both productivity and process stability.

Table 5. Optimal results by the PSO method

Input variables	Optimal results
Δz (mm)	0.83
V_{xy} (mm/min)	1137.51
n (rpm)	1512.99
D (mm)	14.98
T (min)	7.13

The findings confirm that the integration of ANOVA and PSO offers a practical and sustainability-aligned approach for optimizing TPIF of A1050-H14 aluminum sheets. Through variance analysis, key process parameters (V_{xy}, Δz, n, D) were identified as statistically significant influencers of forming time (T), with feed rate and step depth contributing most prominently to overall variability. The application of PSO enabled rapid convergence toward an optimal parameter set (T = 7.13min) without violating design constraints, effectively minimizing the number of tool passes, reducing cycle time, and improving material flow characteristics. This combined methodology enhances process efficiency and contributes to reduced energy consumption, tool wear, and environmental impact, aligning with the core principles of sustainable manufacturing in modern plastic deformation technologies.

4. CONCLUSION

This study systematically investigated the effect of key process parameters on forming time in the TPIF of A1050 H14 aluminum sheets, focusing on sustainable manufacturing. A Box–Behnken experimental design was applied to explore the influence of vertical step size (Δz), feed rate (V_{xy}), spindle speed (n), and tool diameter (D), followed by the development of a second-order regression model using RSM. Based on the research findings, several conclusions can be drawn as follows:

- The model's accuracy was validated through ANOVA, yielding a high coefficient of determination (R^2 = 99.20%), with V_{xy} and Δz identified as the most influential parameters. In terms of percentage contribution, feed rate (V_{xy}) has the most significant impact, explaining 26.38% of the total variation, with step depth (Δz) and spindle speed (n) following at 23.11% and 15.24%, respectively. Despite its lower contribution of 5.11%, tool diameter (D) still demonstrates a statistically significant effect.

- Subsequently, the PSO was employed to determine the optimal parameter set within constrained design boundaries. The algorithm successfully converged to: D = 14.98mm, Δz = 0.83mm, V_{xy} = 1137.51 mm/min, n = 1512.99rpm, achieving a minimized forming time of T = 7.13 minutes, with no constraint violations.

Overall, integrating statistical modeling and metaheuristic optimization provides a robust framework for enhancing process efficiency in TPIF. The findings contribute to sustainable manufacturing by reducing cycle time, tool wear, and energy consumption, while maintaining deformation stability and surface quality.

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