

Research Article

Incremental Forming of Titanium Tubes: An Experimental Study

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ABSTRACT

Incremental forming has emerged as a flexible and cost-effective alternative to conventional tube and sheet forming methods, particularly suitable for low-volume production and prototyping. In this study, an experimental investigation was carried out on the die-less incremental forming of thin-walled titanium tubes to produce a square cross-section at the tube end under room-temperature conditions.

A flexible forming system was developed, consisting of a rotating internal tool mounted on a CNC milling machine, programmed to follow a predefined square path. A full factorial design of experiments (DOE) was employed to analyze the influence of key process parameters—linear feed rate, axial step, and forming depth—on wall thickness and geometric accuracy.

The results showed that increasing the tool speed improved formability due to localized frictional heating and reduced springback, whereas excessive step size led to greater thinning and distortion. Statistical analysis using ANOVA confirmed the validity of the developed models, with high correlation coefficients ($R^2 > 0.93$) between predicted and experimental values. Overall, the proposed die-less incremental forming process demonstrates excellent potential for manufacturing non-axisymmetric tubular components, offering high flexibility, low tooling cost, and good dimensional accuracy.

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1. Introduction

In recent decades, extensive research has been carried out on a novel sheet metal forming process known as incremental sheet forming (ISF). In ISF, a CNC-controlled tool gradually shapes a sheet through localized plastic deformation, layer by layer, without the use of a dedicated die. Since deformation occurs locally and the forming forces are concentrated around the tool–

sheet contact zone, the process offers superior formability compared to conventional stamping [1].

The absence of a die reduces tooling costs significantly and allows the formation of a wide variety of shapes. ISF is particularly suitable for the production of sheet components typically manufactured by stamping but in low-volume or customized quantities. Ji

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and Park [2] studied the high-temperature incremental forming behavior of AZ31 magnesium alloy sheets, while Li et al. [3] developed a predictive model for the forming forces required in incremental forming of metallic sheets. Ambrogio et al. [4] investigated high-speed incremental forming of titanium sheets to minimize processing time, and Hamilton [5] analyzed the effect of tool rotation speed and feed rate on wall thickness and surface quality.

Furthermore, Wam et al. [6] examined buckling and distortion in incremental hole-flanging of aluminum sheets. Tubular components are widely used in industries such as automotive and aerospace. Traditionally, variable-section tubular parts are produced through hydroforming, particularly in axisymmetric bulge geometries. Korkolis and Kyriakides [7] analyzed the deformation behavior of tubes in axisymmetric bulge hydroforming considering anisotropy effects. Chu and Xu [8] developed mathematical relations to predict necking and bursting limits in hydroforming and studied buckling and wrinkling phenomena in thin-walled tubes.

While hydroforming can produce high-quality components, it requires expensive dies, high internal pressures, and complex sealing systems [9–12]. To increase flexibility and eliminate the need for dies, several studies have investigated incremental tube forming (ITF). Yang et al. [13] explored edge-forming processes for branch tube formation and showed that the formability of the branch depends on the initial tube diameter and hole geometry. Trama et al. [14] studied T-branch forming by incremental methods, highlighting the influence of anisotropy on thickness distribution. Wam et al. [15] investigated four incremental tube forming modes—inner diameter expansion, outer diameter reduction, grooving, and hole flanging—and reported significant springback effects due to elastic recovery.

Suresh Kura et al. [16] investigated deep incremental forming, focusing on achieving maximum wall angle and minimum thinning without fracture. Moheddinia et al. [17] numerically compared two different tool paths—constant height and helical—in forming the ends of thin-

walled tubes, showing that feed path significantly affects wall thickness distribution. Seyedkashi et al. [18] experimentally examined incremental tube forming without dies and showed that increasing feed step reduces surface quality but limits corner thinning. Rahmani et al. [19–20] further investigated incremental forming of aluminum tubes using a rotating tool system. Accordingly, this work aims to establish a room-temperature incremental forming process capable of producing a square cross-section at the tube end and to quantitatively assess the influence of key process parameters on dimensional accuracy and thickness distribution for process optimization.

2. Experimental Procedure

The experiments were conducted on titanium tubes with an initial outer diameter of 22 mm and a wall thickness of 1 mm. During forming, the tube was held firmly in place using a four-jaw chuck to prevent displacement, while a precision-fit mandrel was inserted inside the tube to prevent bending or ovalization during deformation. The mandrel was manufactured from hardened alloy steel to ensure high stiffness and to prevent elastic deformation during forming. Its diameter was designed with a 0.05 mm clearance relative to the tube inner diameter. The high mandrel stiffness minimized ovalization and reduced springback, thereby ensuring dimensional accuracy of the formed square section.

Forming was performed on a CNC milling machine, where the forming tool was mounted on the spindle and its motion was precisely controlled through manually programmed G-codes. The ball-end tool was in direct contact with the inner wall of the tube, inducing localized plastic deformation through a combination of rotational motion and feed. The experimental setup and clamping system are shown schematically in Fig. 1.

The forming path followed a square trajectory inside the tube at a constant linear speed. Due to limited material formability, the desired geometry could not be achieved in a single step; therefore, multiple incremental passes were defined. In each step, the tool penetrated radially into the tube and moved along the square path



Fig. 1. Forming milling machine.

before advancing axially for the next pass. A spherical-headed forming tool was used (see Fig. 2).

The forming tool was made of hardened tool steel (HSS-M2) with a diameter of 12 mm and a spherical nose radius of 6 mm. The tool surface was polished to a surface roughness of $R_a \approx 0.4 \mu\text{m}$ to minimize friction and prevent surface galling on the titanium tube. The tool was coated with TiN to reduce adhesion and improve wear resistance.

The forming process involved two key feed parameters:

- Axial step (AS): Incremental feed in the axial direction of the tube (0.25, 0.5, and 0.75 mm).
- Radial step (RS): Incremental feed in the radial (X–Y) direction that defines the square contour (0.3, 0.5, and 0.75 mm).

In this study, the spindle rotational speed was kept constant at 300 rpm during all experiments. The process parameters varied in the DOE included: (1) linear feed rate, (2) axial step (as), and (3) forming depth. The radial step (RS) was kept constant at 0.5 mm and was therefore excluded from the DOE factors.

Appropriate path design plays a crucial role in achieving the desired shape, minimizing distortion, and ensuring uniform thickness. After various trials, it was determined that initiating the forming path from the tube center and progressing along one principal axis yields the most accurate square geometry, as illustrated in Fig. 3. The optimal contact condition occurs when the tool first engages the tube wall from its maximum diameter, improving accuracy and minimizing distortion.

Fig. 4 shows the formed samples used to evaluate geometric accuracy and wall thickness. The measurement

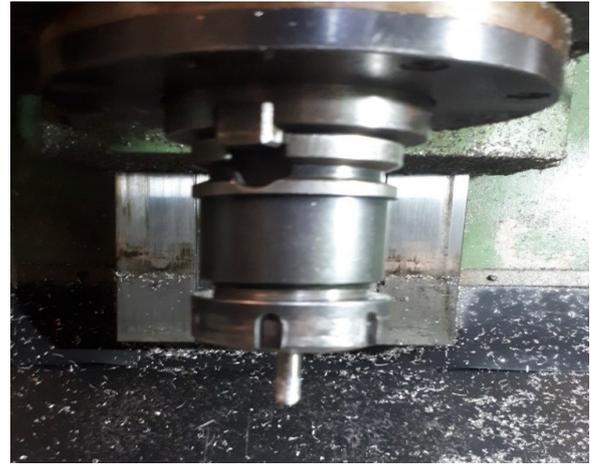


Fig. 2. Forming tool.

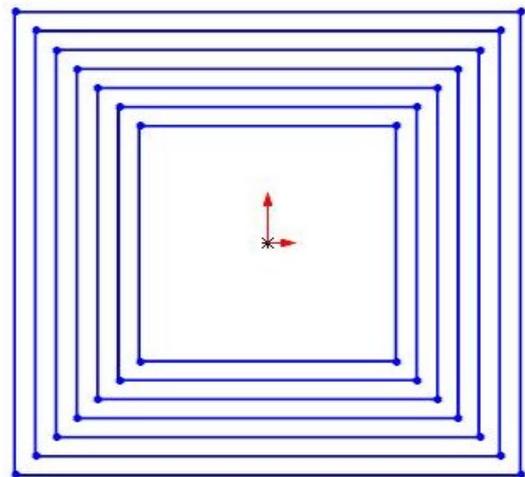
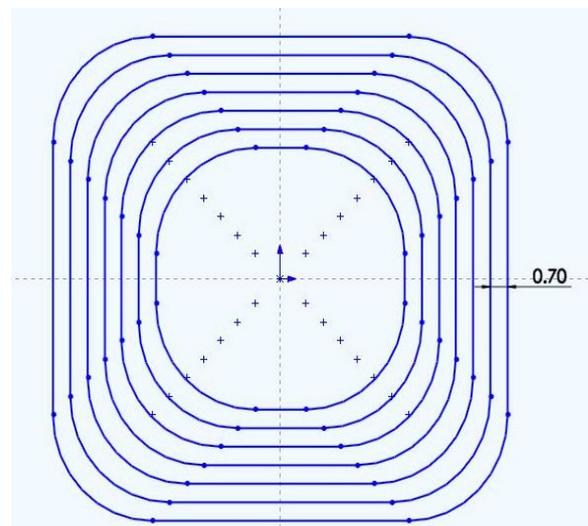


Fig. 3. Up: programmed tool path; down: forming stages up to the final shape.

locations for the side length (a), diagonal (d), and wall thickness (t) are indicated on the specimens. The primary parameters measured were:

- **a:** Side length of the square section (geometric accuracy)
- **d:** Diagonal length (indicating corner radius formation)
- **t:** Wall thickness (representing thinning and structural strength)

A comparison between the initial circular and final square tube sections is presented in Fig. 5.

Each measurement was repeated three times, and the mean value was used; the maximum measurement uncertainty was ± 0.03 mm for wall thickness and ± 0.05 mm for geometric dimensions.

3. Design of Experiments (DOE)

The design of experiments (DOE) is a systematic and efficient method that enables scientists and engineers to study the relationships between multiple input variables and key output responses. It provides a structured approach for data collection and analysis to identify the influence of various factors on a process.

The DOE approach is used to:

- Determine whether one or more factors significantly affect a response.
- Identify possible interactions between factors.
- Model the response behavior as a function of the factors.
- Optimize the response variable.

In this study, a full factorial design was employed, allowing the simultaneous variation of all factors to analyze their individual and interactive effects on the forming quality. Changing all factor levels concurrently rather than one at a time helps reveal potential interactions between parameters.

Three independent process parameters were selected as input factors:

1. Linear feed rate (mm/min)
2. Axial step (mm)
3. Forming depth (mm)

The factor levels were selected based on preliminary trial experiments that identified the practical operating window of the machine and the titanium tube. Levels outside these ranges resulted in either excessive thinning

(for larger steps) or negligible deformation (for smaller steps). Therefore, the final three levels represent a combination of manufacturable and safe operating ranges.

Each factor was tested at three levels, resulting in a total of 27 experimental runs (3^3 design). The experimental design was created using Design-Expert software. The selected levels for each factor are presented in Table 1.

After precise measurement of the fabricated samples, the results were entered into the software for statistical analysis. The measured responses are listed in Table 2. As expected, due to tube wall expansion during forming, wall thinning occurred in all samples, resulting in a final thickness of less than 2 mm.



Fig. 4. Formed titanium tube samples with measurement locations identified: side length (a), diagonal (d), and wall thickness (t).



Fig. 5. Cross-sectional variation of titanium tubes.

Table 1. Full factorial design parameters

Factors	Level 1	Level 2	Level 3
Axial step (mm)	0.25	0.50	1.00
Linear feed rate (mm/min)	400	600	800
Forming depth (mm)	0.5	1.0	1.5

Table 2. Measured results for experimental runs

No.	Feed rate (mm/min)	Axial step (mm)	Forming depth (mm)	a (mm)	d (mm)	t (mm)
1	800	1.00	1.50	27.87	33.69	1.65
2	600	0.50	1.00	28.00	33.19	1.75
3	800	0.50	1.00	28.27	33.47	1.72
4	600	1.00	0.50	28.09	33.43	1.80
5	600	0.25	0.50	28.40	33.60	1.78
6	600	0.50	1.50	28.12	33.70	1.81
7	800	0.50	0.50	27.98	33.45	1.70
8	800	0.25	1.50	28.08	33.45	1.79
9	800	1.00	1.00	28.20	33.40	1.86
10	600	1.50	1.50	28.48	33.59	1.80
11	400	0.50	1.00	28.00	33.05	1.71
12	400	0.25	0.50	27.99	34.73	1.69
13	800	1.00	1.50	28.81	33.70	1.67
14	800	1.50	1.00	28.05	33.94	1.74
15	400	0.50	0.50	28.21	33.17	1.74
16	400	0.25	0.50	28.43	33.15	1.98
17	800	0.25	0.50	28.23	33.06	1.72
18	400	1.00	1.50	27.85	32.94	1.85
19	600	1.50	1.00	27.79	33.22	1.70
20	600	1.00	1.50	27.88	33.34	1.92
21	400	0.25	0.50	28.10	33.14	1.74
22	400	0.50	1.00	27.99	33.39	1.68
23	800	1.00	0.50	28.84	33.81	1.61
24	600	0.25	1.00	27.49	33.30	1.72
25	400	0.50	0.50	27.92	33.28	1.51
26	600	0.25	0.25	28.28	33.10	1.80
27	400	0.25	1.50	28.25	33.77	1.77

The maximum formed diameter was obtained at a feed rate of 400 mm/min, axial step of 0.5 mm, and forming depth of 1.5 mm. The influence of each parameter on wall thickness and geometric accuracy will be discussed in the subsequent section.

Although a full factorial DOE with 27 unique runs was performed, three additional repeated experiments at selected mid-level conditions (600 mm/min, 0.5 mm AS, 1.0 mm depth) confirmed repeatability with variation less than 2%.

4. Results and Discussion

4.1. Effect of process parameters on the side length of the square section

Although temperature was not directly measured, localized heating was inferred based on established correlations in the literature. Several studies (e.g., Kim et al. [16], Göttmann et al. [6]) showed that tool–workpiece friction in incremental forming can raise local temperature by 20–60 °C, which reduces flow stress of

titanium. The observed reduction in springback and improved formability at higher tool speeds in our study is consistent with these previously reported mechanisms.

The influence of forming parameters—namely linear feed rate, feed step, and forming depth—on the side length of the formed square section is illustrated in Fig. 6. As observed, increasing the tool speed results in a larger side length. This can be attributed to localized heating at the tool–tube interface due to friction and plastic deformation, which reduces springback and allows the formation of a larger square geometry.

Conversely, increasing the axial step (feed increment) leads to a decrease in the side length. Larger step sizes cause greater deformation per pass, leading to higher elastic recovery and distortion. A similar trend is observed for forming depth—greater penetration results in increased stretching at the corners of the square cross-section and consequently induces higher distortion.

To statistically validate the observed effects of the process parameter, an analysis of variance (ANOVA)

was performed. The normal probability plot of residuals (Fig. 7) indicates that the residuals are approximately normally distributed, confirming the reliability of the experimental data. The ANOVA results, summarized in Table 3, demonstrate that the model is statistically significant, with an F-value indicating a less than 0.01% probability that the results are due to random error. The p -value < 0.05 criterion was satisfied, and the model exhibited an $R^2 = 0.9993$, confirming the excellent predictive accuracy of the model. Furthermore, the Adeq Precision ratio exceeded 4, validating the adequacy of the signal-to-noise ratio.

The correlation between the predicted and experimental results (Fig. 8) shows that the data points are closely aligned with the diagonal line, further verifying the high precision of the developed model.

The very high R^2 values (>0.99) do not indicate overfitting, as the number of experiments (27 runs) is sufficiently larger than the number of model terms. The

residual plots also show no systematic trend (Figs. 7 and 10), confirming that the model adequately represents the experimental data.

4.2. Effect of process parameters on the diagonal of the formed square (d)

To statistically evaluate the influence of the forming parameters on the diagonal length (d), an analysis of variance (ANOVA) was performed. The results, presented in Table 4, confirm that the model is statistically significant ($p < 0.05$), indicating that the selected process parameters have a substantial effect on the formed diagonal dimension. The obtained R^2 and Adj- R^2 values demonstrate the high accuracy and predictive capability of the developed regression model. Only factors with $p < 0.05$ were interpreted as statistically significant. For other terms, although trends were observed in response surfaces, their effects were not considered statistically significant in the ANOVA table.

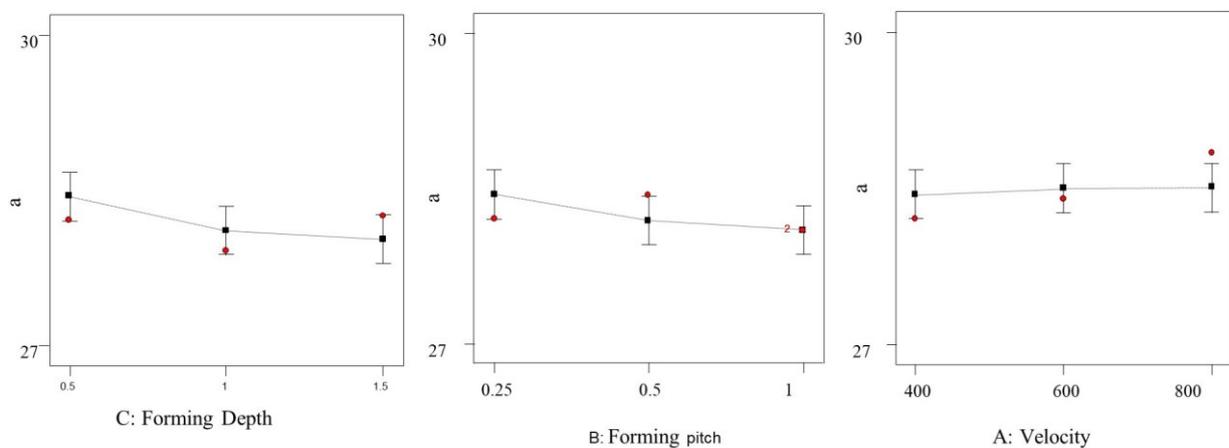


Fig. 6. Effect of process parameters on the formed square side length.

Table 3. Analysis of variance (ANOVA) table for the formed side length

Source	Sum of squares	df	Mean square	F value	p-value (Prob > F)	Remark
Model	1280.28	10	128.03	2223.36	0.0001	significant
A – Velocity	0.23	2	0.115	2	0.18	
B – Forming pitch	269.27	2	134.63	2338.89	0.0001	
C – Forming depth	274.61	2	137.31	2384.55	0.0001	
BC	273.48	4	68.37	1187.15	0.0001	
Residual error	0.4	16	0.0576			
Total	1280.68	26				

Std. Dev.	0.24	R-Squared	0.9990
Mean	26.13	Adj R-Squared	0.9995
C.V. (%)	0.92	Pred R-Squared	0.9993
PRESS	2.60	Adeq Precision	165

Table 4. Analysis of variance (ANOVA) table for the formed diagonal length

Source	Sum of squares	df	Mean square	F value	p-value (Prob > F)	Remark
Model	5.45	18	0.30	5.12	0.0174	significant
A – Velocity	0.54	2	0.27	4.59	0.0532	
B – Forming pitch	1.06	2	0.53	8.97	0.0117	
C – Forming depth	1.34	2	0.67	11.30	0.0061	
AB	0.10	4	0.03	0.45	0.7857	
AC	0.13	4	0.03	0.53	0.7271	
BC	2.08	4	0.52	8.80	0.0073	

Std. Dev.	0.24	R-Squared	0.9294
Mean	33.53	Adj R-Squared	0.7480
C.V. (%)	0.73	Pred R-Squared	-0.0505
PRESS	6.16	Adeq Precision	8.728

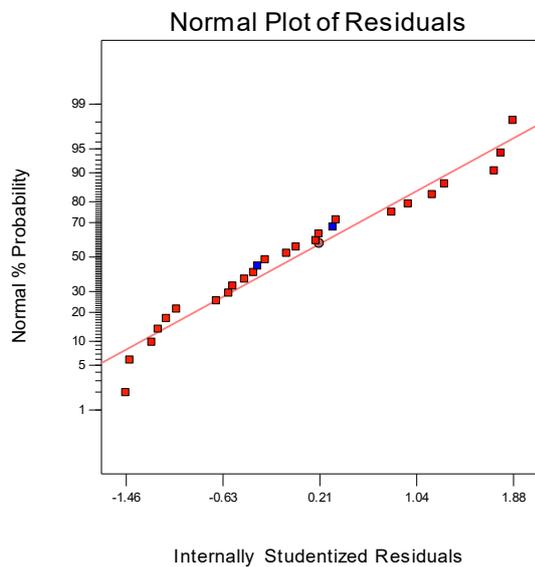


Fig. 7. Normal probability plot versus residuals.

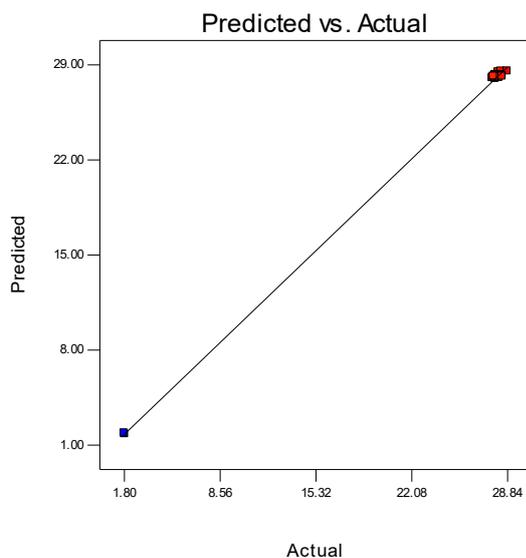


Fig. 8. Predicted versus actual values.

The effect of forming parameters on the diagonal length of the square section is shown in Fig. 9. The diagonal increases with tool speed, confirming that higher rotational speed enhances local temperature and material formability. Therefore, higher speeds within machine limits are recommended for improved square formation.

However, an optimal feed step value was observed—either too small or too large a step size reduced the final diagonal dimension. Increased forming depth also reduced springback by promoting greater plastic deformation in each pass, resulting in a larger and more defined square shape.

The normal probability plot of residuals (Fig. 10) confirms that the residuals follow a normal distribution, ensuring model validity. ANOVA results (Table 4) show that the model is statistically significant with $p < 0.05$ and a high R^2 value of 0.9294, thereby confirming the reliability of the developed regression model.

The comparison between predicted and experimental values (Fig. 11) demonstrates a strong correlation, with the data points lying close to the diagonal line, thereby validating the predictive accuracy of the model.

4.3. Effect of process parameters on wall thickness (t)

An ANOVA was also performed for the wall thickness response (t). As shown in Table 5, the model is statistically significant ($p < 0.05$). Among the main factors, forming depth and axial step show the highest contribution to wall thinning. The model demonstrates

strong accuracy with $R^2 = 0.9299$ and an adequate precision value above the minimum required level.

Wall thickness directly affects the structural integrity of the formed tube—lower thinning corresponds to higher strength and dimensional stability. The effects of

tool speed, axial step, and forming depth on wall thickness are presented in Fig. 12.

The results indicate that higher tool speeds, while beneficial for forming larger diameters and sharper corners, tend to increase wall thinning due to elevated

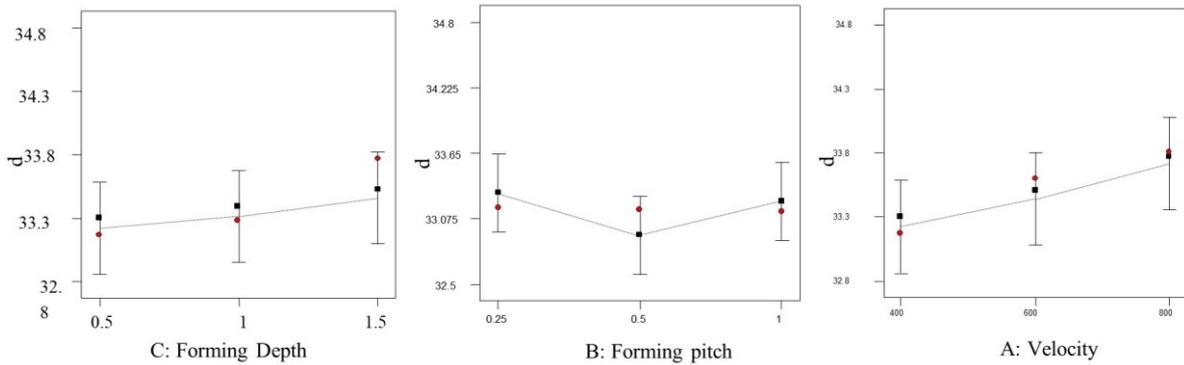


Fig. 9. Effect of process parameters on the diagonal (d).

Table 5. Analysis of variance (ANOVA) table for the formed Square Wall Thickness

Source	Sum of squares	df	Mean square	F value	p-value (Prob > F)	Remark
Model	0.22	18	0.012	5.16	0.0171	significant
A – Velocity	0.020	2	9.845E-003	4.10	0.0664	
B – Forming pitch	0.012	2	6.061E-003	2.52	0.1497	
C – Forming Depth	0.025	2	0.013	5.23	0.0408	
AB	0.036	4	9.043E-003	3.76	0.0611	
AC	0.074	4	0.018	7.66	0.0107	
BC	0.056	4	0.014	5.83	0.0218	

Std. Dev.	0.049	R-Squared	0.9299
Mean	1.75	Adj R-Squared	0.7496
C.V. (%)	2.80	Pred R-Squared	-0.0274
PRESS	0.25	Adeq Precision	9.736

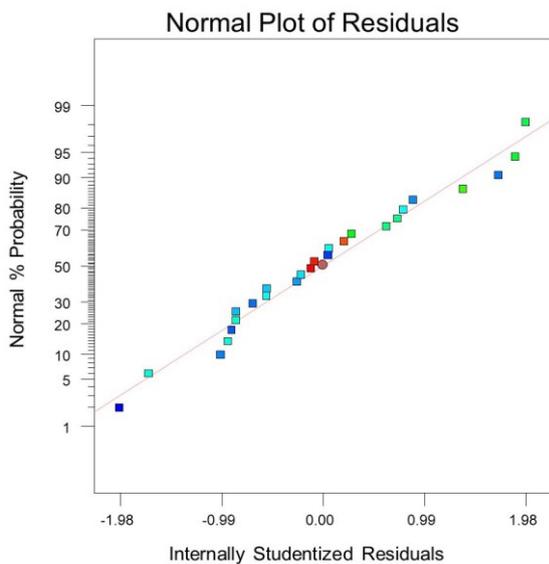


Fig. 10. Normal probability plot versus residuals.

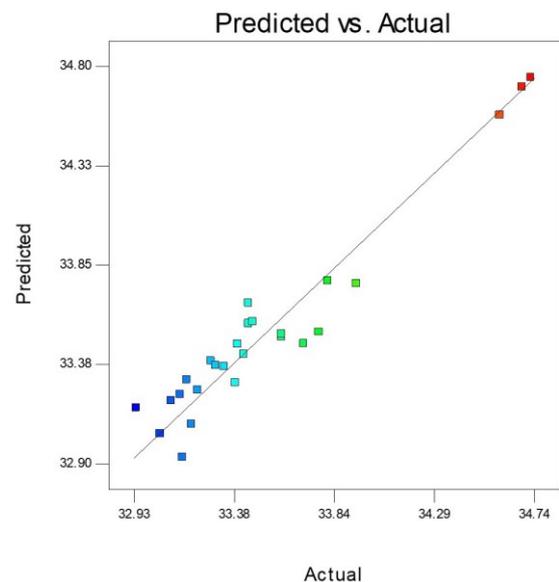


Fig. 11. Predicted versus actual values.

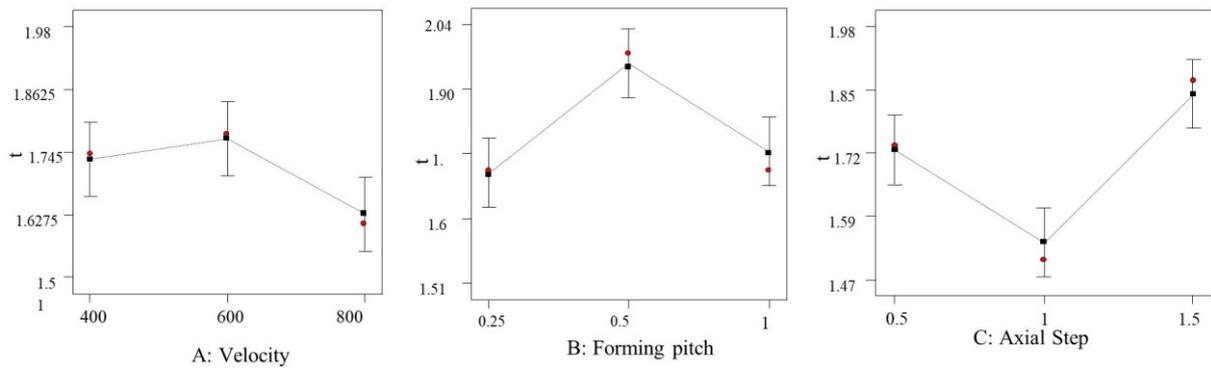


Fig. 12. Effect of process parameters on wall thickness (t)

tensile strain in the tube wall. Hence, achieving larger square dimensions inherently leads to reduced wall thickness.

Optimal axial step and forming depth values were found to minimize thinning; however, excessive increases in either parameter resulted in greater wall reduction due to intensified localized deformation.

The residuals shown in Fig. 13 follow a normal distribution, and an ANOVA was also performed for the wall thickness response (t). As shown in Table 5, the model is statistically significant ($p < 0.05$). Among the main factors, forming depth and axial step show the highest contribution to wall thinning. The model demonstrates strong accuracy with $R^2 = 0.9299$ and adequate precision value above the minimum required level. The predicted versus actual values (Fig. 14) show minimal deviation from the ideal line, reflecting high model precision.

The obtained thinning levels (1.61–1.98 mm) and achievable forming depths are consistent with titanium tube forming studies such as Zhang et al. [13], who reported similar deformation limits in multi-stage incremental forming of Ti-3Al-2.5V tubes.

4.4. Optimization of forming parameters

The primary goal of incremental tube forming is to achieve the desired geometry with minimal tooling cost and lower forming forces. In this study, optimization was conducted using Design-Expert software to obtain the best combination of process parameters that produce the maximum side length and diagonal while minimizing wall thinning.

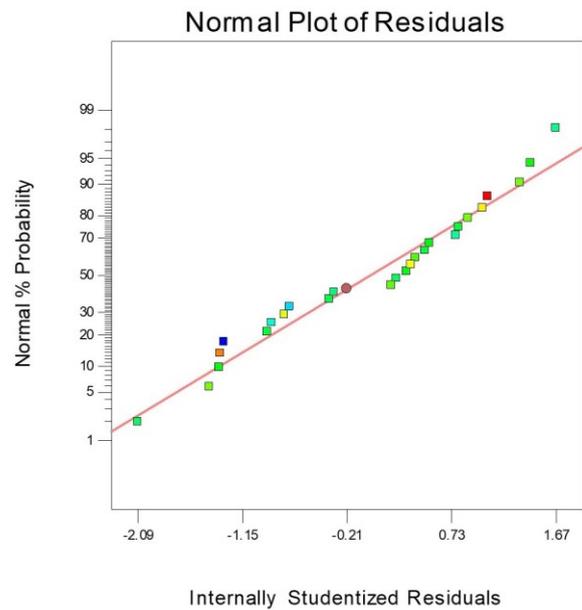


Fig. 13. Normal probability plot versus residuals.

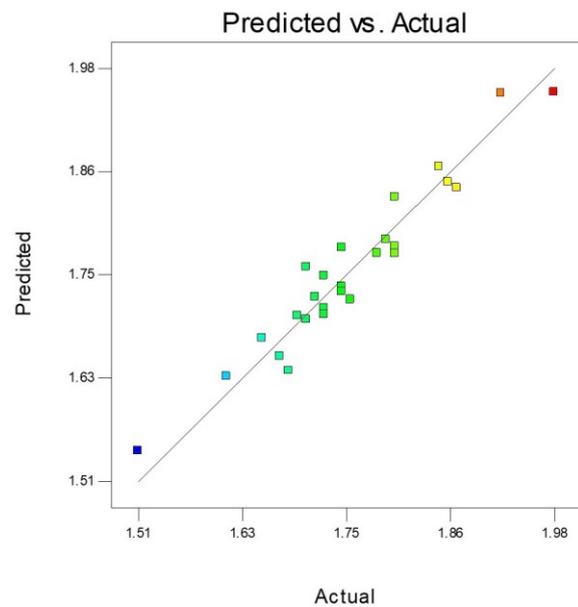


Fig. 14. Predicted versus actual values.

The objective function was defined to simultaneously maximize side length (a), diagonal (d), and wall thickness (t) with equal weighting. The optimal process conditions determined by the software are summarized in Table 6.

The results indicate that the optimal forming parameters for producing a well-defined square cross-section with minimal thinning are:

- Tool speed: 600 mm/min (medium level)
- Axial step: 1.0 mm (maximum level)
- Forming depth: 1.5 mm (maximum level)

These optimized settings provide a balance between

form accuracy and thickness uniformity, yielding a high-quality formed square section at a reduced forming cost.

Compared to hydroforming, the internal-tool incremental forming method offers lower tooling cost and higher geometric flexibility. However, hydroforming provides superior thickness uniformity and deeper forming limits due to hydraulic pressure support. The method used in this work is more appropriate for prototyping and low-volume production where die cost is prohibitive.

Table 6. Optimization results

Number	Velocity	Forming pitch	Forming depth	a	d	t	Desirability	
1	600	1	1.5	28.1304	34.5661	1.76889	0.787	Selected
2	400	1	1.5	28.072	34.7442	1.69833	0.730	
3	800	1	1.5	28.1376	34.6997	1.67278	0.692	

5. Conclusions

This study experimentally investigated the incremental forming of thin-walled titanium tubes to produce a square cross-section at the tube end without the use of external dies. A novel flexible forming system based on an internal rotating tool was developed and implemented on a CNC milling machine. The effects of three main process parameters—tool speed, axial step, and forming depth—on the geometric accuracy and wall thickness of the formed tubes were analyzed using a full factorial design and statistical evaluation through ANOVA. The maximum forming depth was primarily limited by material failure (corner thinning) rather than machine rigidity. Additionally, larger depths may also be restricted by tool design and contact stability.

The main findings of this research can be summarized as follows:

1. Tool speed: Increasing the tool speed enhanced the side length and diagonal of the formed square due to localized heating, which improved material formability and reduced springback. Conversely, higher speeds also led to increased wall thinning because of higher tensile strain in the tube wall.
2. Feed step and forming depth: Both parameters

exhibited significant effects on the accuracy and surface quality. Excessive step size or forming depth caused local distortion and uneven thickness, whereas moderate values improved dimensional precision and uniform wall distribution.

3. Statistical analysis: ANOVA confirmed the validity of the developed regression models, with high R^2 values (0.93–0.99) and p-values below 0.05, indicating strong correlation between predicted and experimental data.
4. Optimization: Based on multi-objective optimization using Design-Expert software, the optimal forming parameters were determined as a tool speed of 600 mm/min, an axial step of 1.0 mm, and a forming depth of 1.5 mm. These conditions resulted in the largest square geometry with minimal wall thinning and high surface quality.

Overall, the results demonstrate that incremental tube forming is a highly flexible and cost-effective method for producing non-axisymmetric tubular components such as square-section ends. The process offers significant potential for applications in aerospace, automotive, and prototype manufacturing, where

lightweight structures and die-less forming are advantageous.

Future work

Industrial application of this process is currently limited by cycle time, thickness non-uniformity, and forming depth constraints. Future work will focus on developing a hybrid warm-forming system with controlled heating, implementing adaptive tool paths to minimize thinning, and conducting numerical simulations for predicting failure.

Authors' contributions

F. Rahmani: Supervision, Investigation, Writing - review & editing

S. J. Hashemi: Formal analysis, Writing – review, Methodology

Conflict of interest

The authors declare that they have no financial or personal relationships that could have inappropriately influenced or biased the work presented in this manuscript.

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