Experimental Investigation of Effective Parameters on a New Incremental Tube Bulging Method using Rotary Tool

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Abstract: Nowadays, dieless and flexible sheet forming methods are gaining much interest in prototyping and low production. In this research, a new method is developed to change the cross-sectional area of metal tubes in a longitudinal direction without using special dies. This technique is based on the force applied by a rotary tool to the inside/outside surface wall of a tube. The forming tool is mounted on a CNC milling machine and moves spirally with a specific pitch. In order to study the effects of process parameters on the product quality, a full factorial design of experiments was designed and performed. The input parameters were the feeding depth, forming pitch and tool velocity. Three responses including roughness, minimum thickness and production time were precisely measured for this purpose. The results showed that surface quality and minimum thickness is reduced with increasing the forming pitch and feeding depth. Tool rotational velocity does not have a significant effect on the forming parameters except for production time. Using a multi-objective response optimization, forming pitch of 0.25 mm, feeding depth of 1.25 mm and velocity of 800 mm/min were found to be the best configuration.

Keywords: Dieless tube Forming, Feeding Depth, Forming Pitch, Thinning

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1 INTRODUCTION

In recent years, many researches have been performed on a new sheet forming process known as incremental sheet forming. Numerical control is used in incremental forming to gradually form a shell shape on the sheet. A rotary tool forms the desired shape on a sheet by incremental moving over it. The process is performed in a free space, i.e. there is no contact between the sheet and the matrix. Since the forming is local and incremental, and the forces are concentrated at the contact interface of tool and sheet, formability could be increased [1]. The process is economical due to its flexibility since no specific die is required for each shape. Its only shortcoming is its long production time and relatively low surface quality, so it can be an alternative for stamping and spinning processes in case of rapid prototyping.

Ji and Park [2] studied incremental forming of AZ31 magnesium sheets at elevated temperatures. Li et al., [3] developed a model to predict the required forming forces for incremental forming of sheet metals. Ambrogio [4] investigated high-speed incremental forming of titanium sheets in order to reduce the forming time. Hamilton and Jeswiet [5] studied the effect of tool rotational velocity and feed rate on sheet thickness and surface quality. Wen et al., [6] studied the onset of buckling and distortion in flanging of holes in aluminum sheets using incremental forming. Tube-made products have also many applications in industries such as aerospace and automotive. Tube products with variable sections are usually formed by hydroforming technique. Korkolis and Kyriakides [7] analyzed the deformation of tubes in axisymmetric bulging considering the effect of anisotropy, and calibrated the anisotropic yield functions using experimental results.

Chu and Xu [8] developed a mathematical equation to predict necking and prevent bursting during the tube hydroforming. They also studied buckling and wrinkling defects, and showed that buckling usually occurs in long thin tubes. In another study, they [9] developed process window diagrams for axisymmetric bulging to determine the safe ranges for internal pressure and axial force to produce non-defective products. Seyedkashi et al., [10] investigated the effects of tube dimensions on the required loading path for axisymmetric tube bulging, and determined the optimal path using simulated annealing optimization method. In recent years, axisymmetric hydroforming at high temperatures was also investigated. Hashemi et al., [11] studied the effect of temperature on thickness distribution of the final product in warm tube hydroforming. Seyedkashi et al., [12] optimized the loading profile for bulging of AA6061 tubes at elevated temperatures. They showed that the expansion ratio was increased about 36% by proper selection of load curves at 300℃. Hydroforming process is an expensive technology with other limitations such as a need for high pressure hydraulic system, and special clamping and sealing. In order to enhance the process flexibility and eliminate the cost of equipment, several researches have been conducted on incremental tube forming. Yang et al., [13] studied the dieless incremental hole-flanging process for producing branched tubes. They showed that the formable branch depends on the initial tube diameter and branch diameter.

Teramae et al., [14] studied the incremental tube burring of T-tubes and the effect of anisotropy coefficient on the thickness distribution of the part. Wen et al., [15] characterized four incremental tube forming methods, including axisymmetric expansion/reduction of tube ends, tube wall grooving, and hole flanging. Cao et al., [16] showed that the angle of tool axis has a great effect on the edge buckling in hole-flanging of aluminum sheets. Hussain et al., [17] investigated the effect of initial hole size on the formability in hole-flanging process. They concluded that an appropriate span of initial hole size should be selected for producing the flanges with higher lengths.

The purpose of this research is to form metal tubes incrementally into an axisymmetric bulge by using an innovative system which is less expensive and more flexible. This novel system was proposed based on a rotary tool designed for any geometries and conditions. A rotary tool moves spirally inside a tube and gradually bulges it with desired length, diameter and shape. The tool path is controlled using a CNC milling machine. The main effects and interactions of the feeding depth, forming pitch and tool velocity are investigated on the final minimum thickness, surface finish and total production time. Finally, the optimal production conditions are proposed to obtain the minimum thinning and maximum surface finish.

2 METHODOLOGY

The nature of this process is in such a way that there is no limitations for the final shape even asymmetrical cross-sections such as squares or polygonal. Fig. 1 shows the position of the tube in the fixture, and a sample route of the forming tool. At the beginning of the process, two ends of the tube would be fixed due to their placement inside the upper and lower clamps. Then, the tool moves to the top of the tube to set the zero point.

The tool moves to the starting point tangent to the inner surface of the tube according to the programmed CNC G-code. Then, the first pass begins with the first feed. The tool is fed radially which is called here the "feeding depth", and moves spirally along the tube axis. At the end of the first pass, a favourite part of the tube bugles equal to the feeding depth. The bulging should be performed only on the free length of the tube, i.e. the portion which is not covered by the fixture or clamps. Because of this free portion between the upper and lower clamps, various shapes can be created by changing the tool path. The linear velocity of the tool is kept constant during the process.

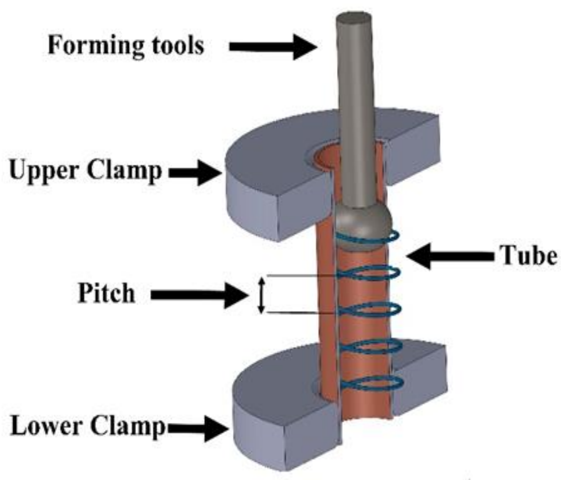

Fig. 1 Schematic of the process components

The axial distance travelled by means of one circular movement of the tool is called the "forming pitch". After the first iteration, the tool rapidly returns to its initial position without making contact with the inner surface of the tube. Higher expansion ratios can be obtained by applying further feeding depth and spiral movement.

3 EXPERIMENTAL EQUIPMENT

In this study, C11000 copper tubes with an initial outer diameter of 22 mm and thickness of 0.8 mm are formed for experimental verification. Fig. 2 shows the engineering stress-strain diagram of the utilized copper tubes. For incremental tube bulging process, a laboratory fixture and a forming tool were designed as shown in Fig. 3. Radius of the tool is 3 mm as shown in this figure.
The setup is fixed on the table of a Kitamura CNC milling machine with the forming tool mounted within the spindle. Three screws are used to connect the upper and lower clamps. The tube is put inside the fixture from the upper clamp. The tool path is defined by a G-code written according to the predetermined parameters.

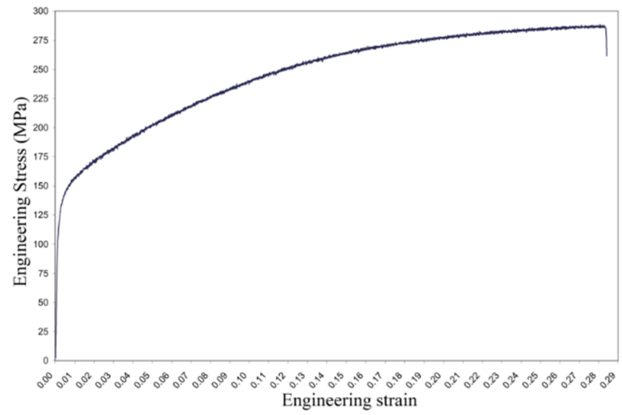

Fig. 2 Engineering stress-strain diagram for Cu C11000

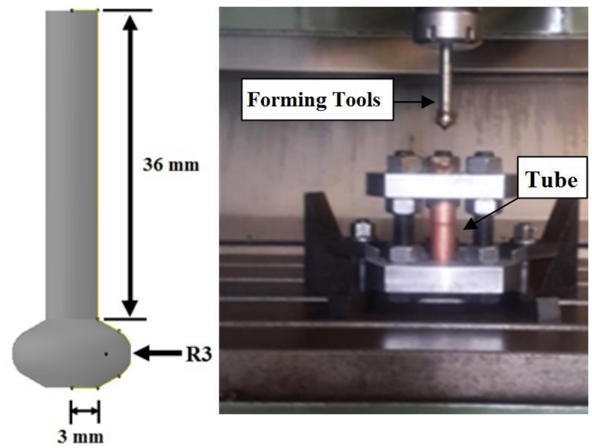

Fig. 3 (a) the forming tool, (b) experimental setup

4 DESIGN OF EXPERIMENTS

The aim of this research is to study the effect of the process parameters on final product quality including surface roughness, wall thickness and total production time. Three effective parameters are involved; feeding depth (mm), forming pitch (mm) and tool velocity (mm/min). A full factorial design of experiments (DOE) has been used in order to fully understand and predict the effects of these parameters. The parameters and their related levels are shown in Table 1. The number of experiments will be equal to 33=27. The number of iterations required for complete forming can be calculated by dividing the amount of final bulge to the feeding depth. The amount of feeding depth is decided to be constant in each iteration in this research. But it can be selected higher in the first iterations for rough forming and less in final iterations for higher accuracy. The center of a 22 mm diameter copper tube is to be bulged to reach to 28mm; i.e. six iterations are required with the feeding depth of 0.5 mm. It should be noted that a completely randomized design (CRD) is used to reduce the effect of potential noises during the process.

Table 1 Transitions selected for thermometry

Parameter	Level 1	Level 2	Level 3
Pitch (mm)	0.25	0.5	1
Velocity (mm/min)	400	600	800
Feeding depth (mm)	0.5	1	1.25

The results for the three responses (surface roughness, minimum wall thickness and total production time) are presented in Table 2 for all of the parts produced based on the DOE. All of the specimens are shown in Fig. 4. The samples were cut to half using wire cut in order to measure the thickness distribution in the longitudinal direction. The thickness was measured by a digital micrometer with 0.001 mm accuracy. Roughness of the inner surface of all specimens was measured using a roughness tester shown in Fig. 5.

Table 2 Surface roughness, minimum thickness and total production time obtained from experiments

	Pitch [mm]	Depth [mm]	Velocity [mm/min]	Thickness [mm]	Time [min]	Rz [μm]
1	0.25	1.25	400	0.421	27.21	2.306
2	0.5	1.25	800	0.376	10.2	3.759
3	0.5	1.25	400	0.377	20.34	3.76
4	1	1	800	0.344	6.17	3.886
5	0.5	1.25	600	0.375	13.45	3.788
6	0.5	1	400	0.365	23.1	2.518
7	0.25	0.5	400	0.398	89.44	1.98
8	1	1	400	0.346	12.27	3.741
9	1	1	600	0.344	8.2	3.88
10	0.25	0.5	600	0.399	59.54	2.043
11	0.5	1	800	0.364	11.39	2.691
12	0.5	0.5	600	0.358	30.27	2.364
13	1	1.25	400	0.349	10.37	4.154
14	1	0.5	400	0.339	23.31	2.785
15	1	1.25	800	0.348	5.22	4.244
16	0.25	1	400	0.41	47.3	2.054
17	0.25	1	800	0.407	23.48	2.415
18	0.25	1.25	600	0.42	18.15	2.231
19	0.25	1	600	0.407	31.42	2.279
20	0.5	1	600	0.367	15.29	2.665
21	0.5	0.5	400	0.359	45.34	2.31
22	0.5	0.5	800	0.358	22.54	2.397
23	0.25	1.25	800	0.421	13.42	2.454
24	1	1.25	600	0.349	7.07	4.23
25	0.25	0.5	800	0.398	44.59	2.15
26	1	0.5	600	0.338	15.45	2.915
27	1	0.5	800	0.337	11.52	3.05

Fig. 4 Formed specimens using the rotary tool

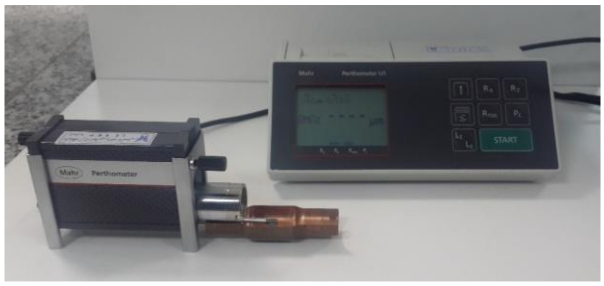

Fig. 5 Roughness measuring

5 RESULTS AND DISCUSSION

Statistical analysis is performed to understand the main effects and interactions of effective parameters during the forming process. The final aim is to determine their optimum range in order to produce a product with minimum thinning and surface roughness. The part with minimum thinning has the highest mechanical strength. In this process, due to a direct contact of the forming tool with the inner surface of the tube and hence higher friction forces, the quality of internal surface decreases which affects the product's service life. Optimization of the input parameters is of utmost importance in order to produce a product in a reasonable time with least thinning and surface roughness which highly affects the production cost. Analysis of variance (ANOVA) method is used as a useful statistical method to scientifically interpret the interaction of parameters. ANOVA results are statistically valid when the data have normal distribution and the variances are equal. These assumptions were verified by investigation of normal probability versus residual plots for all three responses which are shown in Fig. 6.

5.1. Effects of parameters on surface roughness

The surface roughness of the final product at the forming area is one of the most important outputs in the process. Initial tubes were produced by extrusion, and their primary average surface roughness (Rz) was 0.57 micrometers. Surface roughness was measured at the center of all tubes.

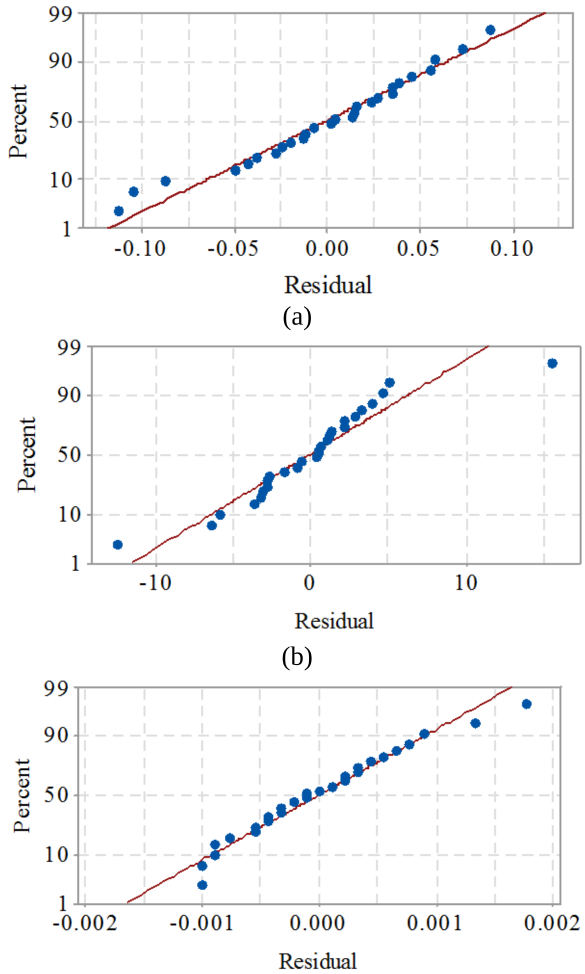

Fig. 6 Normal probability plots for a) roughness, b) production time and c) thickness

Degrees of freedom, adjusted sum of squares and mean squares obtained by analysis of variances for the products roughness are presented in Table 3. According to the selected confidence level of 95%, a prerequisite for a model to be significant is that the amount of its p-value be less than 0.05. According to the ANOVA table for roughness values, the forming pitch among the studied input parameters has the highest effect (with 59.63 % contribution) on the surface finish, while tool velocity has the least importance (with 0.73% contribution). It is shown that the forming pitch, feeding depth and their interaction have a high significance. On the other hand, the 2-way interactions of pitch×velocity and depth×velocity, and the 3-way interaction of pitch×depth×velocity are not significant; hence, were excluded from the analysis.

Fig. 7 shows the main effects of the forming pitch, feeding depth and tool velocity on the surface roughness. With the increase of the forming pitch along the tube axis, the surface quality of all samples is decreased. This increase in roughness is comparable to the change of surface roughness in the machining process. With the increase of the feeding rate, the distances between the peaks increases, hence the roughness increases. According to the results, increasing the feeding depth also increases the surface roughness because it results in the increase of the peak heights. Since the process is performed at room temperature and the material is not so sensitive to the strain rate, the tool velocity also has no significant effect on the product quality.

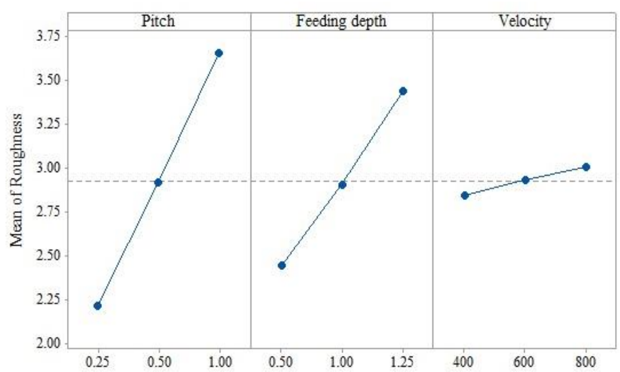

Fig. 7 Main effect plots of pitch, feeding depth and tool velocity on surface roughness

Table 3 ANOVA table for surface roughness

Source	DF	Seq SS	Contribu-tion %	Adj SS	Adj MS	p-value
Pitch	2	9.3515	59.63%	9.3515	4.67576	0.00
Depth	2	4.4404	28.32%	4.4404	2.22019	0.00
Velocity	2	0.1152	0.73%	0.1152	0.05761	0.00
Pitch×depth	4	1.7073	10.89%	1.7073	0.42683	0.00
Error	16	0.0669	0.43%	0.0669	0.00418	

As seen in Fig. 7, change of the tool velocity does not considerably affect the surface roughness. So, it can be concluded that this parameter could be increased as much as possible to reduce the total production time. Fig. 8 shows the interaction between the feeding depth and forming pitch over the final surface finish. The interactions of velocity with pitch and depth are not significant based on the ANOVA results; therefore, were not studied.

As seen in Fig. 8, the minimum surface roughness is obtained with a forming pitch of 0.25mm and feeding depth of 0.5mm, while the maximum roughness is obtained with a pitch of 1mm and depth of 1.25mm. However, it is clear from the slope of the curve that the effect of the pitch on surface roughness is much higher than the effect of depth.

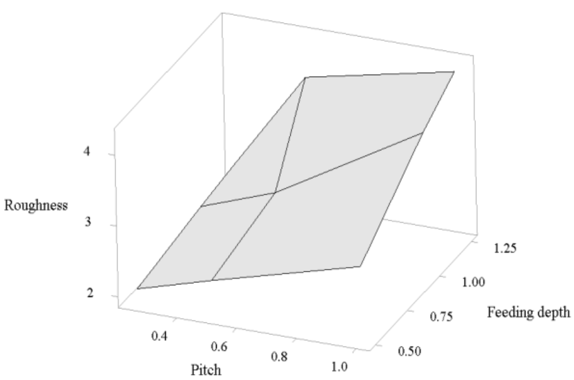

Fig. 8 Interactions between the forming step and depth for surface roughness

5.2. Effects of parameters on minimum thickness

The other goal of this study is the rapid production of final product with maximum bulge without rupture. The thickness distribution shows that the maximum thinning occurs at the bulge corners in all of the specimens. This is due to higher tensile strains at this zone. This position is shown in Fig. 9.

Table 4 presents the ANOVA table for minimum thickness. It is shown that the forming pitch has the most significant effect on the thinning percentage with a 93.28 % contribution among all of the input parameters.

As seen in Fig. 10, by increasing the forming pitch, the minimum thickness at the bulge corner is decreased. It means that the product quality is reduced. In this process, at first, the forming tool moves radially to the specified value to make the bulge, and then moves spirally along the tube axis. So, the tube surface is under bending at the penetration time in order to take the tool shape. The areas around the bending zone are under tension. There is not much thinning in the contact area of the tool corner with the tube because of high friction, but tube is under the utmost tension around this area, and thinning occurs. When the higher pitch is involved, there is less contact between the tube and the tool at the bending zone. So, the tensile strain increases resulting in higher thinning percentage (Fig. 11).

Fig. 9 Position of the maximum thinning

Table 4 ANOVA table for surface roughness

Source	DF	Seq SS	Contribution %	Adj SS	Adj MS	p-value
Pitch	2	0.019723	93.28%	0.019723	0.009861	0.000
Feeding depth	2	0.001286	6.08%	0.001286	0.000643	0.000
Velocity	2	0.000007	0.03%	0.000007	0.000003	0.034
Pitch×depth	4	0.000116	0.55%	0.000116	0.000029	0.000
Error	16	0.000013	0.06%	0.000013	0.000001	

On the other hand, when the feeding depth is increased, there is less tension around the tool due to the conformity of tube surface on the tool shape. So, the tensile strain along the tube axis in peripheral direction decreases, which results in less thinning. It is possible to reduce the thinning percentage with decreasing the number of forming steps (with increasing the feeding depth), but it is necessary to mention that the spring back also increases in this case according to the experimental observations. As explained about the effect of the tool velocity on surface roughness, it has also no significant effect on the thinning percentage due to not having sensitivity to the strain rate.

The effects of forming pitch and depth were also investigated due to their significant interaction effect on the minimum thickness. Fig. 12 shows a decrease in the thickness with increasing the forming pitch and feeding depth, so the number of forming steps has to be increased in order to achieve less thinning. It can be seen that the minimum thickness is obtained with the forming pitch of 1mm and feeding depth of 0.5mm, while the maximum thickness is obtained with the forming pitch of 0.25mm and feeding depth of 1.25mm. According to Fig. 12, the effect of feeding depth on the thickness is more significant than the effect of forming pitch. It can be concluded that increasing the feeding depth is a better solution for speeding up the process than increasing the forming pitch.

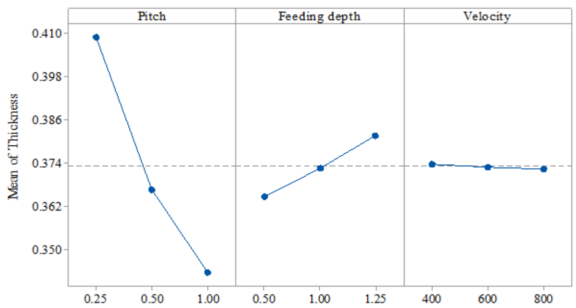

Fig. 10 Main effects of pitch, depth, and velocity on the thickness

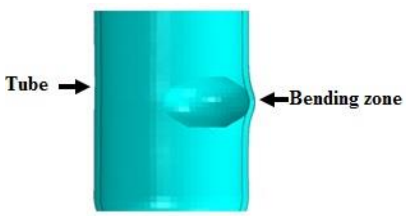

Fig. 11 Contact area of tool tip radius with the tube

5.3. Effects of parameters on production time

The effects of process parameters on the production time were also studied because the production time should also be kept as minimum as possible to reduce the costs and increase the production rate. Since there is no contact between the tool and the inner surface of the tube between each iteration, the tool moves back to the start point with maximum speed. This duration is a non-productive time. On the other hand, the forming time in which the tool is in contact with the inner surface of the tube is a productive time. So, the total production time includes both the productive and non-productive times. Fig. 13 shows the nonlinear effect of pitch, feeding depth and tool velocity on total production time.

According to Table 5, which represents the ANOVA results for the production time, in addition to all three main effects of studied parameters, the interaction of pitch×depth is also significant and has to be considered. The most important parameter is the forming pitch with a 38.85 % contribution, and then feeding depth, tool velocity and interaction of pitch×depth with 29.7%, 13.62%, and 11.16 % contributions, respectively.

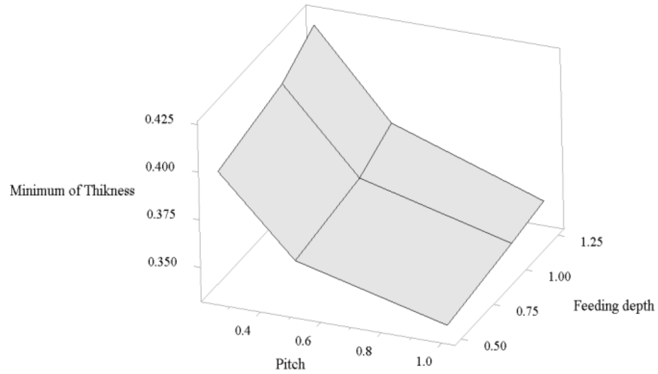

Fig. 12 Interaction of forming pitch and depth on the minimum thickness

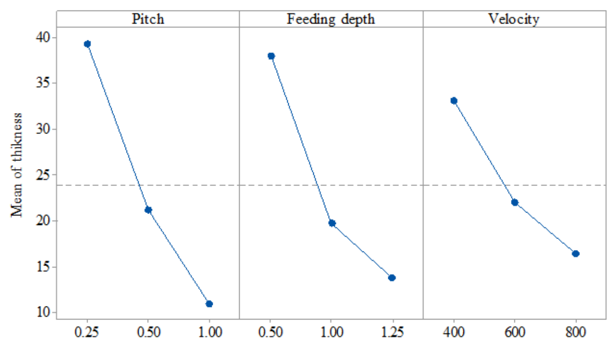

Fig. 13 Main effect plots of pitch, depth, and velocity on total production time

As expected, the production time is reduced by increasing the depth and pitch. According to Fig. 14, the least amount of production time belongs to the pitch of 1 mm and depth of 1.25 mm, while the maximum working time is obtained with the pitch of 1 mm and depth of 1.25 mm. With the pitches close to 1 mm, the change of feeding depth has no considerable effect on the production time, while the effect is significant when utilizing small pitches.

Table 5 ANOVA table for the production time

Source	DF	Seq SS	Contribution %	Adj SS	Adj MS	P-Value
Pitch	2	3703.1	38.85%	3703.1	1851.57	0.000
Feeding depth	2	2830.5	29.70%	2830.5	1415.27	0.000
Velocity	2	1297.9	13.62%	1297.9	648.97	0.000
Pitch× depth	4	1063.5	11.16%	1063.5	265.87	0.002
Error	16	636.1	6.67%	636.1		

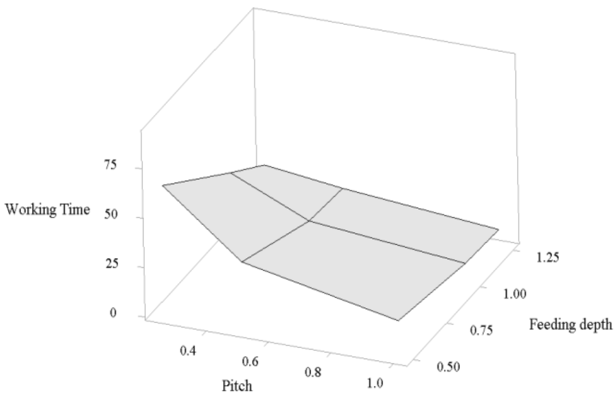

Fig. 14 Interaction of the forming pitch and feeding depth on production time

5.4. Selection of optimal levels

The goal of optimization in this process is to minimize the amount of thinning percentage, surface roughness and production time. But in practice, it is not possible to gain the optimal amounts for all of the responses due to the reverse effects of process parameters on each response, i.e. improvement of one response such as surface roughness has an inevitable negative effect on another one such as production time.

Therefore, the next step is to select the optimal levels to obtain the maximum desirability; i.e. all responses achieve an acceptable level of satisfaction. Response optimization tries to identify the best combination of the input variables that jointly optimize a single response or a set of responses. Individual desirability (d) evaluates how the settings optimize a single response, while composite desirability (D) evaluates how the settings optimize a set of responses. Desirability has a range of zero to one. One represents the ideal case. Eq. 1 shows their relation.

$$D=(d_1 d_2 ... d_m)^{1/m} \quad (1)$$

Optimality evaluation is performed using "response optimizer" in Minitab software. Fig. 15 shows the optimal levels for each parameter based on this method. With regard to all three responses, a composite desirability (D) of 0.9096 is obtained with input variables set of 0.25 mm, 1.25 mm and 800 mm/min for pitch, depth, and velocity, respectively. Individual desirability (d) is also presented in Fig. 15.

It is seen that d-values are also higher than 0.8 for each single response. Based on the response optimization results, the minimum roughness obtained by selected setting is 2.4077 µm, while the minimum obtained production time and maximum thickness are 10.4633 min and 0.4201 mm, respectively.

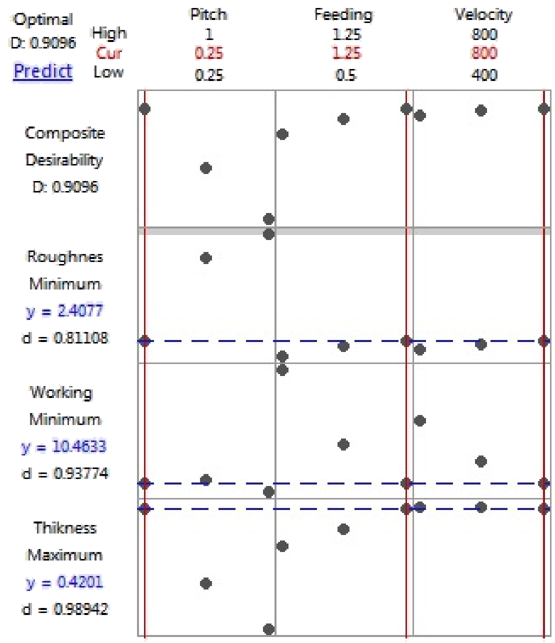

Fig. 15 Result of response optimization.

6 CONCLUSION

This paper presents a new method developed for forming and rapid production of tubes by a rotary tool without use of a specific die. Tool path determines the cross-section shape. The experimental study was performed on an axisymmetric tube bulging, and the effects of process parameters including the forming pitch, feeding depth and tool velocity were examined on the final product surface roughness, wall thickness and production time. According to the obtained results, the surface quality of the final product -as the most important output- and the minimum thickness at the corner are reduced by increasing the forming pitch. With increasing the feeding depth, surface roughness increases while less thinning is obtained. Tool velocity does not have much effect on the forming parameters except working time.

- The minimum roughness occurs at 0.25 mm pitch and 0.5 mm depth, while the maximum roughness is obtained with 1 mm pitch and 1.25 mm depth. The minimum thickness is obtained at 1 mm pitch and 0.5 mm depth, while the maximum thickness at with 0.25 mm pitch and 1.25 mm depth

- The least production time happens with 1 mm pitch, 800 mm/min velocity and 1.25 mm depth, and the highest production time with 0.25 mm pitch, 400 mm/min velocity and 0.5 mm depth.

- The maximum thinning was observed at the bulging corner. This is due to the friction force with the fixture which prevents full feeding of the tube into the bulge.

- After response optimization, the minimum roughness, production time and maximum thickness are happened to be 2.4077 µm, 10.4633 min and 0.4201 mm, respectively. These values are obtained with settings of 0.25 mm forming pitch, 1.25 mm feeding depth and 800 mm/min velocity.

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