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Studying the Effective Parameters on Teeth Height in Internal Gear Flowforming Process

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ABSTRACT

The flowforming process is a chipless metal forming process that is used to produce precise thin walled tubes. Manufacturing of internal gears using flowforming process is a difficult-to-achieve, but very interesting process in which the gear may be produced without the need for high forming forces and r high tooling cost. In this study, manufacturing of internal gears using flowforming process is studied. The process has been numerically analyzed and simulated. The plastic behavior of the material, and friction conditions were determined using tensile and friction tests, respectively. Several controlled test were performed to evaluate the validity of simulation results. A comparison of simulation and experimental results indicates very good agreement. Once the simulation is verified, the effects of roller diameter, thickness reduction percentage, feed rate and attack angle on tooth height were obtained using design of experiments (DOE) procedure. According to DOE results, attack angle (α), thickness reduction percentage (T), interaction between roller diameter and attack angle (D×α), and interaction between roller diameter and feed rate (D×f) are the most significant parameters affecting the tooth height. The tooth height increases with increasing the roller diameter and thickness reduction, but decreases with increasing the feed rate and attack angle.

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NOMENCLATURE

D	Roller diameter (mm)	f	Feed rate (mm/rev)
T	Thickness reduction (%)	α	Attack angle (degree)

1. INTRODUCTION

Flowforming, also known as tube spinning, is a novel metal forming method that is used to produce thin-walled high precision tubular products. A tubular workpiece (preform) is held onto a mandrel, and the material can be displaced axially by one or more rollers moving axially along the mandrel. The advantages of flowforming are flexibility, simple tooling, low production cost and low forming loads, which makes it suitable for automotive production [1]. Forming a tube along with internal teeth (such as internal gears) is another application of this process. Internal gears are widely used in defense and aerospace industries as external sun gears of planetary mechanisms due to their compact structure, large torque-to-weight ratio, high gear ratio, reduced noise and vibration, etc. [2]. Gears are generally manufactured via metal cutting processes, which require more time and can lead to material waste. Moreover, gears are subjected to various stress conditions and should be strong enough to withstand these conditions. A gear that is manufactured through metal cutting procedure has poor strength [3]. To overcome this drawback, flowforming can be used for manufacturing of internal gears.

Because of the importance of flowforming in manufacturing the tubular parts including internal teeth, a number of studies have been carried out using theoretical analyses and experimental methods. Groche and Fritsche [4] investigated gear manufacturing using flowforming. They studied the influence of the number of rollers on the force applied to the mandrel teeth. To achieve a uniform distribution of the force on the mandrel teeth, they suggested using a ring instead of a roller. Jiang et al. [5] studied manufacturing of thin-walled tubes

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including internal teeth using ball spinning process. They calculated the influence of thickness reduction on teeth height using the finite element method, and compared the results with experiments. Jiang et al. [6] studied the influences of roller diameter, feed rate and the initial thickness of the tube on the height of teeth using neural networks. Jiang et al. [7] simulated manufacturing of thin-walled tubes with internal teeth using finite element method (FEM). They investigated the influence of the roller diameter on teeth height and surface roughness. Jiang et al. [8] investigated the influence of the number of passes during thickness reduction on teeth height, surface roughness and microstructure of the tube. Haghshenas et al. [9–11] investigated the influences of microstructure, hardness, thickness reduction and strain hardening rate on the plastic strain in metals with FCC structure. Xia et al. [12] analyzed Trapezoidal internal gear production defects, experimentally and numerically. They examined the effect of thickness reduction and direction of rotation of the mandrel on the shape of the gear. Xu et al. [13] studied both experimentally and numerically the multi-stage internal gear production using a plate. They investigated the effect of process parameters on the tooth height and filling rate of the mandrel cavity. The process was applied to ASTM 1035 mild steel using three rollers in two stages. Although the process has received attention from the research community, the application of flowforming to manufacture of internal gears has been a new attempt so far. Achieving the desired teeth is one of the most critical tasks in flowforming of internal gears and the deformation mechanism of teeth in this process is more complex compared with the counterparts with no inner ribs. Moreover, the influence of parameters has not been studied so far.

In the present study, the emphasis is on investigating the influence of process parameters on tooth height in backward flowforming of internal gears using the results of experiment and FEM. In this study, the flowforming process is simulated using FEM, and then the results are validated by experimental tests. This FEM model is used in DOE and determination of parameters affecting teeth height. Finally, the optimum value is predicted. Research methodology is shown in Figure 1.

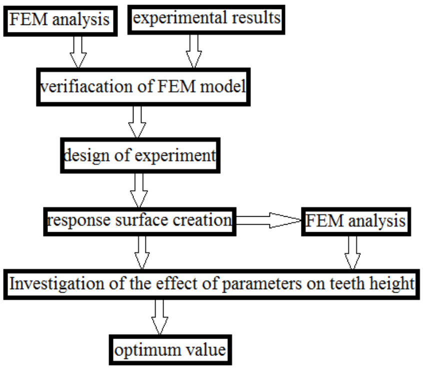


Figure 1. Research methodology in this study

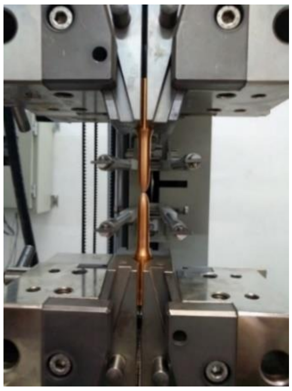


Figure 2. Setup of tensile test equipment

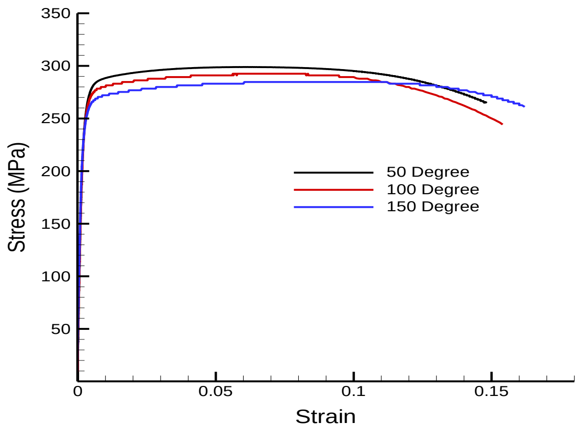


Figure 3. Stress-strain curves of copper workpiece at different temperatures in degrees Celsius

2. Material and method

2. 1. Tensile Test To determine the plastic behavior of the material, tensile testing was carried out using the Zwick/Roell tensile test machine with a maximum load of 600 kN and a servo motor control. The setup is shown in Figure 2. Test samples were prepared according to the ASTM. The tests were carried out with a rate of 20 mm/min at temperatures of 25, 100 and 150ºC. The obtained stress-strain diagrams are presented in Figure 3.

2. 2. Friction Test To determine the friction coefficient, the ring pressure test was carried out at temperatures of 25, 60, 100, and 150ºC. The test samples were rings with a standard geometric ratio of 2:3:6 (thickness, internal diameter and external diameter of 8, 12 and 24 mm, respectively). A Zwick/Roell pressure test machine with a maximum load of 600 kN was used to carry out the tests (Figure 4).

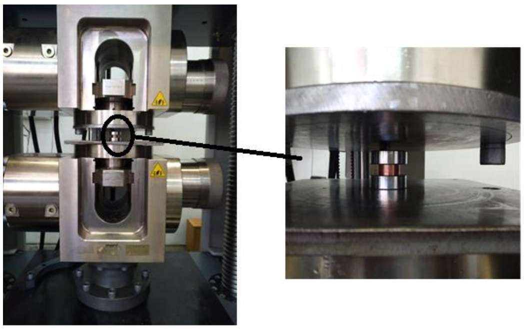


Figure 4. Setup of ring pressure test

2. 3. Flowforming Process

In this study, a backward flowforming was performed using a universal lathe. The preform was a C12200 copper alloy tube with an internal diameter of 13.2 mm and a wall thickness of 2.5 mm (Figure 5). A ball-bearing (deep groove ball-bearing SKF 6203/VA201 with a diameter of 40 mm and a width of 12 mm) was used as the roller. A gear with 20 teeth and an outer diameter of 13.2 mm, which was heat-treated to get the surface hardness of 58 RC, was used as the mandrel (Figure 6). The experimental setup is shown in Figure 7. The gear was complete in four passes of forming. The minimum thickness reduction should be determined so that the plastic metal flow not to be limited to the external surface, which is usually 15% [14]. The primary preform was removed from the mandrel when 25% thickness reduction was achieved. This was repeated in the second step, i.e., another 25% thickness reduction was carried out in the second step. In the third step, the thickness reduction was 20%, and in the fourth step 15%. To evaluate the quality of the gear teeth, it was necessary to section the specimens; this was done using a wire-cutting machine. A video measuring machine (VMM) was used to measure the profile and teeth height of gear in the sectioned specimens. Then, the gear microstructure was investigated.

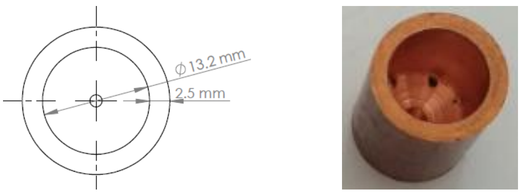


Figure 5. Dimensions of preform

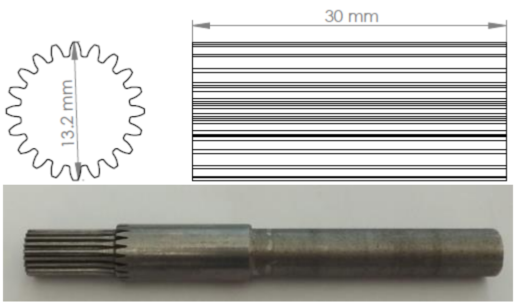


Figure 6. Mandrel used to form internal gear

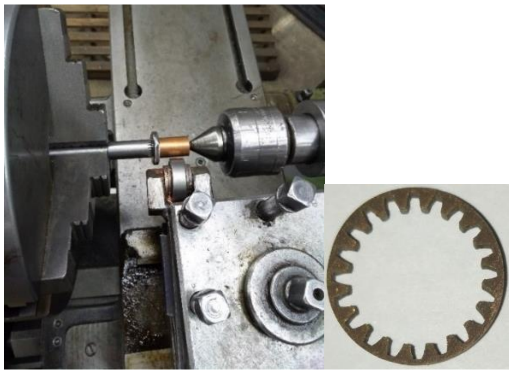


Figure 7. Setup of the experiment and the produced final gear

3. MODELING OF FLOWFORMING PROCESS

The model is shown in Figure 8. In this study, the workpiece material was C12200 copper alloy that is considered an elastic-plastic material (the stress-strain curve is shown in Figure 3). The mechanical properties of C12200 are shown in Table 1. The geometrical dimensions of pre-form, rollers and mandrel are described in Section 2.3. To investigate the effects of friction and temperature on the process a thermo-mechanical analysis was carried out, and 41470 C3D8RT type elements with the ALE formulation were used for

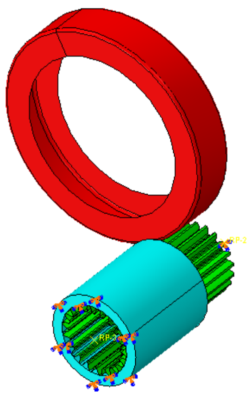


Figure 8. Schematic of backward flowforming in FEM model

TABLE 1. Mechanical properties of copper workpiece

Material	σy(MPa)	σu(MPa)	E(GPa)	υ	ρ(kg/m3)
C12200	227	295	115	0.3	8930

meshing [15, 16]. For simplicity, the mandrel and roller were considered to be rigid. The Coulomb friction model was used to define the contact surfaces, and the friction coefficient was determined according to the friction test (as it is described in Section 2.2). Due to high deformation and complicated contact conditions in the flowforming process, the dynamic explicit solving procedure used because of the numerical robustness and computational efficiency in the case of highly non-linear and large-scale applications [1]. In this analysis, the mass scaling factor was used to reduce the solution time. The process was simulated using FEM software along with some codings. Finally, to validate the simulation model, the tooth height was compared in two experimental and simulation in four steps, which is shown in Table 2.

4. RESULTS

4. 1. Experimental and Simulation Results In this section, the results of simulation and experiments are discussed. The manufacturing of the gear was carried out in four steps and the gear teeth were formed gradually. Figures 9 and 10 present the form and height of a gear tooth in four steps, which was obtained from the simulation and experimental results.

4. 2. Microstructure of Gear Analysis of the microstructure of the gear produced by flowforming helps to understand the deformation mechanism. In this research, samples from the preform and gear (in four passes) were prepared. Microstructures of the samples were obtained using a light microscope, and the results are shown in Figures 11 and 12. As can be seen in Figure 11, the microstructure of the preform consists of equiaxed grains. However, as shown in Figure 12, severe deformation and misaligned orientation of the grains in the gear are quite evident; hence, an inhomogeneous plastic deformation can be inferred. As shown in Figure 12, the grains are oriented in the tangential and radial directions so that the mandrel grooves are snugly filled. In each pass, the amounts of elongation and deformation of the grains are increased until the fourth pass in which the maximum elongation of the grains is achieved.

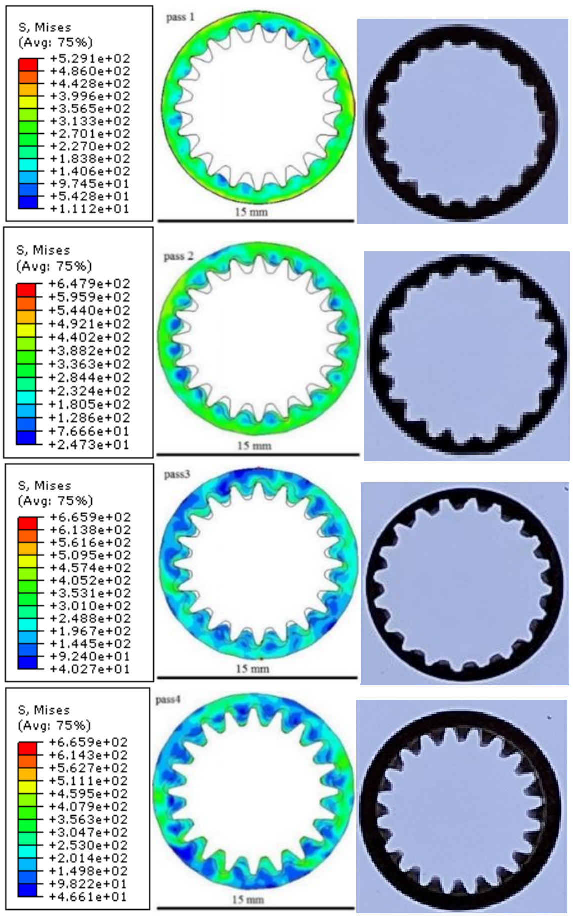


Figure 10. Tooth formation in four steps

TABLE 2. Comparison between Tooth heights in four steps

	Step 1	Step 2	Step 3	Step 4
Simulation	0.44	0.84	1.19	1.35
Experimental	0.5	0.89	1.21	1.35
Error	12%	5%	2%	0

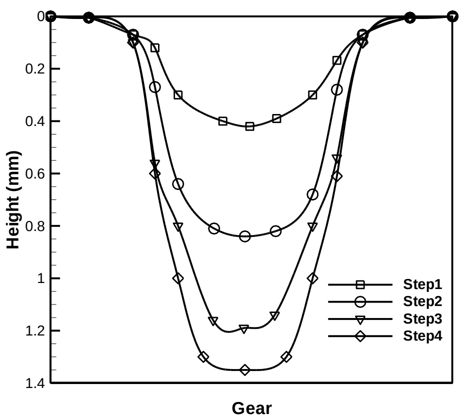
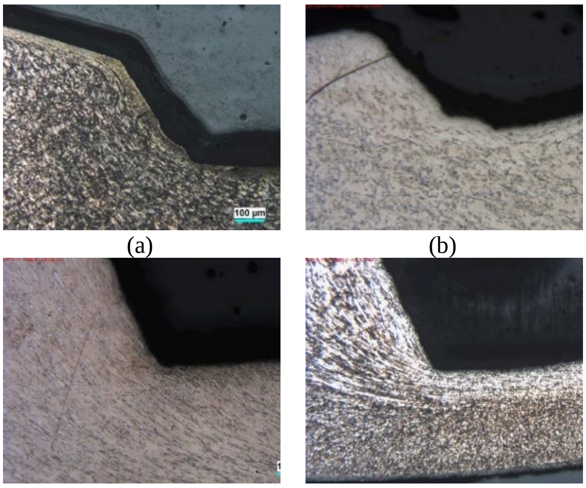


Figure 9. Tooth height at different steps of simulation

Figure 11. Microstructure of preform



(a) (b) (c) (d)

Figure 12. Microstructure of gear, a) Pass 1, b) Pass 2, c) Pass 3, and d) Pass 4

4. 3. Effective Parameters and Statistical Optimization Achieving a specific geometry is important in manufacturing industrial components; thus, the investigation of the influence of each parameter on tooth height is necessary. However, there is no concrete objective function to be used by statistical methods for optimizing the process parameters. Response surface method (RSM) was used to investigate the effect of each parameter on tooth height. Response surface method is a statistical method that is used to model and analyze processes that are affected by several parameters. The goal of this method is to model and optimize the response [17]. In this study, a central composite design (CCD) was applied. In this process, four parameters including roller diameter, thickness reduction percentage, feed rate and attack angle (as shown in Figure 13) are more important than others [1]. The levels of these parameters are given in Table 3. According to the applied method, 31 experiments were considered with α=2.

After doing the tests, the teeth height was obtained for each test, and the ANOVA results were obtained (Table 4). Figure 14 presents the residual distribution of the present study, and the normality of the distribution can be confirmed. A significance level of 95% was selected; that is the results are correct with a confidence level of 95%. Therefore, a parameter is significant if the P-value is less than 0.05.

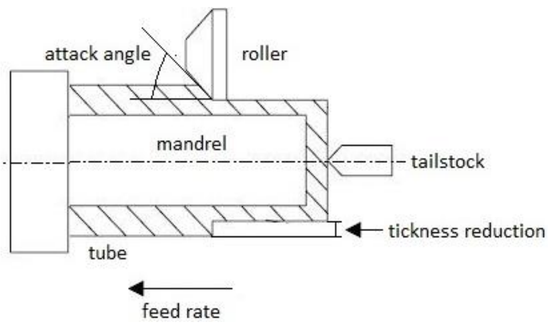


Figure 13. Effective parameters in flowforming process

TABLE 3. Effective parameters and their levels

Parameter	Roller diameter (d)	Thickness reduction (t%)	Feed rate (f)	Attack angle (α)
Low level	20 mm	15%	0.05 mm/rev	20°
High level	60 mm	35%	0.25 mm/rev	60°

TABLE 4. ANOVA table for teeth height

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	0.34517	0.02465	24023.3	0.000
Linear	4	0.27014	0.06753	65804.2	0.000
D	1	0.00003	0.00003	31.62	0.000
T	1	0.05008	0.05008	48794.7	0.000
f	1	0.00265	0.00265	2577.73	0.000
α	1	0.22187	0.22187	216185.5	0.000
Square	4	0.02220	0.00555	5408.29	0.000
D*D	1	0.00040	0.00040	391.79	0.000
T*T	1	0.00818	0.00818	7967.74	0.000
f*f	1	0.00000	0.00000	8.52	0.011
α*α	1	0.01111	0.01111	10821.1	0.000
2-Way Interaction	6	0.04441	0.00741	7211.73	0.000
D*T	1	0.00859	0.00859	8367.28	0.000
D*f	1	0.01111	0.01111	10827.4	0.000
D*α	1	0.01256	0.01256	12238.9	0.000
T*f	1	0.00069	0.00069	668.81	0.000
T*α	1	0.00553	0.00553	5385.69	0.000
f*α	1	0.00039	0.00039	386.19	0.000
Error	15	0.00001	0.00000		
Lack-of-Fit	9	0.00001	0.00000	1.81	0.242
Pure Error	6	0.00000	0.00001		
Total	29	0.34518			

According to Table 4, all parameters and interactions are significant and affect the teeth height. Pareto chart is shown in Figure 15, which expresses the magnitude of the effect of each parameter on tooth height. According to Figure 15, attack angle (α), thickness reduction (T), interaction between roller diameter and attack angle

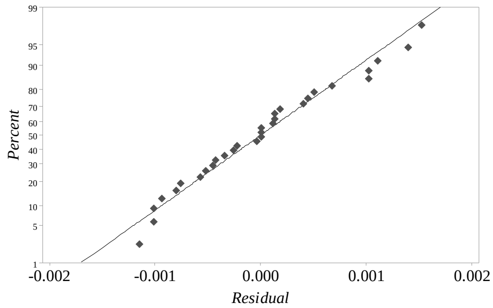


Figure 14. Normal probability of residuals for tooth height

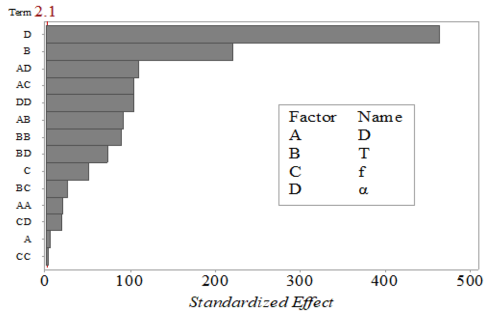


Figure 15. Pareto chart for teeth height

(D×α), and interaction between roller diameter and feed rate (D×f) are, respectively, the most significant parameters affecting the tooth height. In this analysis, R-Sq = 99.99 and R-Sq (adj) = 99.98 that confirm ultra-high accuracy of the model developed using RSM. To investigate the influences of the parameters effective on the teeth height, the main effects and interactions should be investigated precisely. In this section, the influence of each parameter will be discussed. In the analysis of interactions, other parameters were considered in a balanced mode (central point) of tests.

4. 3. 1. Influence of Roller Diameter The influence of the roller diameter on tooth height is shown in Figure 16, which indicates that the tooth height increases with increasing the roller diameter up to 40 mm and decreases with further increase. Additionally, according to the D×T interaction, which is shown in Figure 17, the height increases with increasing the roller diameter at low thickness reductions, but at values above 25%, the height decreases. As the roller diameter increases, the plastic deformation zone increases, and this leads to an increase in material flow beneath the roller and tooth height. However, as the roller diameter increases (more than 40 mm in Figure 16 and at thickness reductions above 25% in Figure 17), the S/L ratio (circumferential contact length (S) to axial contact length (L)) increases, and due to friction, the material flow increases in axial direction. However, to increase the gear height, the axial flow must be reduced. According to the D×f interaction in Figure 18, the increase in feed rate decreases the tooth height because at high feed rates, the material does not remain beneath the roller and tends to escape from underneath it and flow in the opposite direction of the roller axial movement. However, this effect is reversed by increasing the roller diameter. As the roller diameter increases, the contact area becomes larger and the engagement of roller and the workpiece increases, so the material escape from the roller less frequently. Consequently, increasing the diameter of the roller results in a better flow of material in the radial direction and an increased tooth height. According to Figure 19, which shows the D×α interaction, the tooth height increases with increasing the roller diameter.

4. 3. 2. Influence of Thickness Reduction Percentage According to the main effect of thickness reduction percentage (Figure 20) as well as the interactions of T×F (Figure 21), T×α (Figure 22) and D×T (Figure 17), the tooth height increases with increasing the thickness reduction percentage. As the thickness reduction percentage increases, the plastic deformation zone increases, and this causes an increase in material flow and tooth height. In addition, at high thickness reduction, the S/L ratio decreases and the axial flow is restricted. According to the F- value in the Table 4, the interaction of T×f has little effect on the tooth height which is shown in Figure 21.

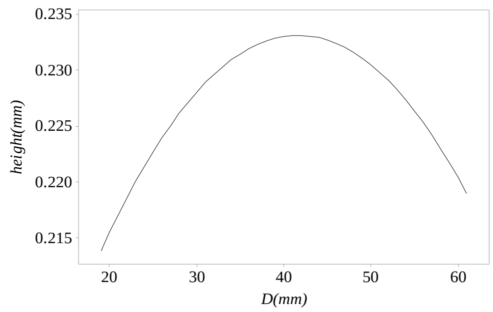


Figure 16. Effect of roller diameter on tooth height

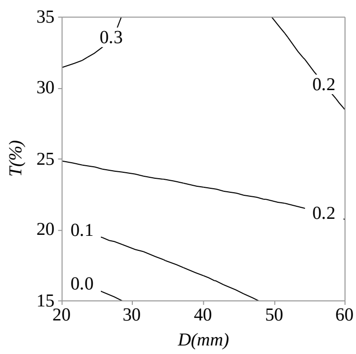


Figure 17. Interaction effects of roller diameter and thickness reduction on tooth height

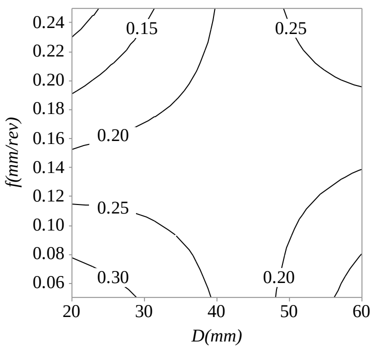


Figure 18. Interaction effects of roller diameter and feed rate on tooth height

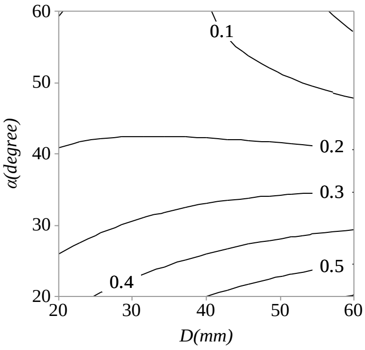


Figure 19. Interaction effects of roller diameter and attack angle on tooth height

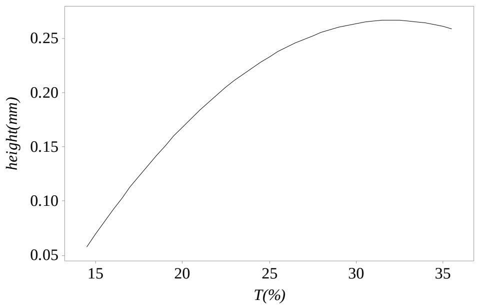


Figure 20. Effect of thickness reduction on tooth height

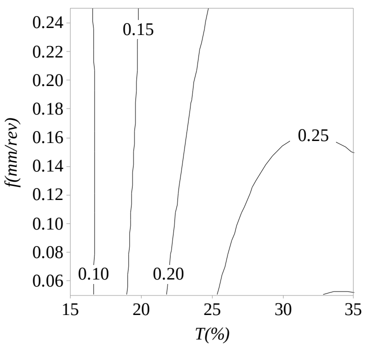


Figure 21. Interaction effect of thickness reduction on tooth height

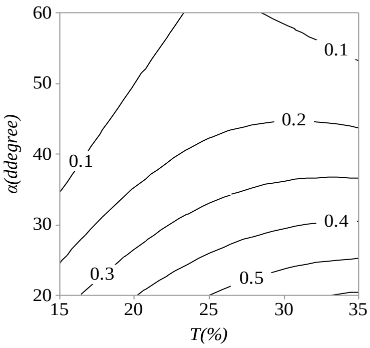


Figure 22. Interaction effects of thickness reduction and attack angle on tooth height

4. 3. 3. Influence of Feed Rate According to Figure 23, increasing the feed rate, reduces the tooth height, as described in Subsection 4.3.1. Increasing feed rate increases the S/L ratio, and due to the friction, the material flow increases in the axial direction and the tooth height decreases. The interaction of D×f and T×f was explained in Subsection 4.3.1 and 4.3.2 respectively. The interaction of f×α Almost no effect on the tooth height as shown in Figure 24.

4. 3. 4. Influence of Attack Angle The influence of attack angle is shown in Figure 25, which indicates that the tooth height decreases with increasing the attack

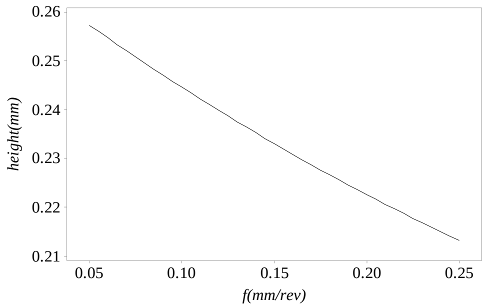


Figure 23. Effect of feed rate on tooth height

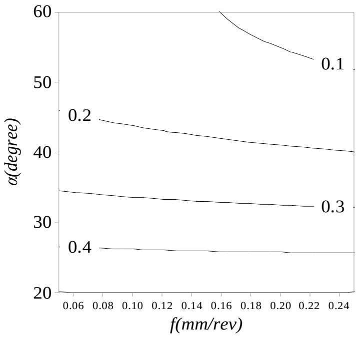


Figure 24. Interaction effects of feed rate and attack angle on tooth height

angle. This effect can also be seen in Figure 19 (interaction of D×α), Figure 22 (interaction of T×α) and Figure 24 (interaction of f×α). If the attack angle is zero, the flow of materials is in the radial direction and increases the gear height. As the attack angle increases, the axial flow of the material also increases, and the gear height decreases.

4. 3. 5. Response Optimization In the previous sections, the parameters affecting tooth height were found. In this section, we can find the situation for optimizing the response by using response optimization. In fact, in this method, from the selected levels, the best settings are set to achieve the desired goal, which is to achieve maximum teeth height. As shown in Figure 26, a maximum tooth height of 0.7272 is obtained for D=20 mm, T=35%, f=0.05 mm/rev and α=20°.

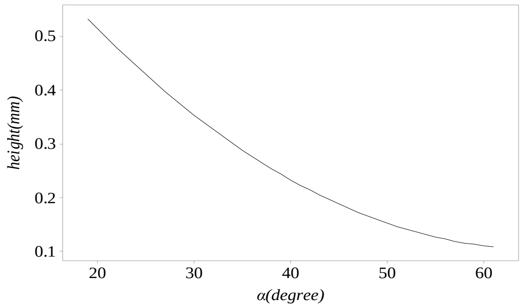


Figure 25. Effect of attack angle on tooth height

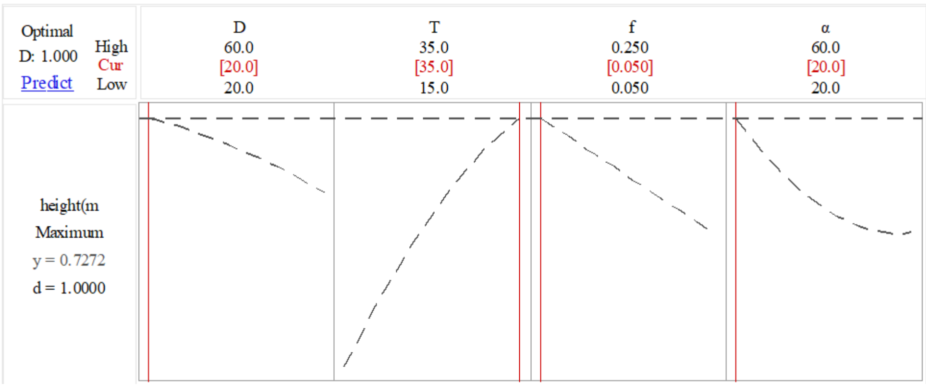


Figure 26. Response optimization plot for tooth height

5. CONCLUSION

The flowforming process is a relatively new method for producing internal gears that is suitable for batch production. In the present study, flowforming process was used to produce an internal gear on a lathe. Then, the process was modelled and the model was verified by comparing the simulation and experimental results. Achieving the desired teeth is one of the most critical tasks in flowforming of internal gears and formability of the tooth depends mainly on roller diameter, thickness reduction, feed rate, and attack angle of the roller. Due to the complexity of the process, the effect of input parameters on tooth height can not be calculated analytically, and therefore the design of experiment method (DOE) was used. By analyzing the process and obtaining the tooth height for each test, the results of the ANOVA analysis were obtained as follows:

- All parameters and interactions affect tooth height. attack angle (α), thickness reduction (T), interaction between roller diameter and attack angle (D×α), and interaction between roller diameter and feed rate (D×f) are, respectively, the most significant parameters affecting the tooth height.
- The tooth height initially increases with increasing the roller diameter up to 40 mm, and then, decreases with a further increase in the diameter.
- The tooth height increases with increasing the thickness reduction.
- The tooth height decreases with increasing feed rate.
- The tooth height decreases with increasing the attack angle.
- A maximum tooth height of 0.7272 is obtained for D=20 mm, T=35%, f=0.05 mm/rev and α=20°.

Predicting the formation and tooth height with statistical and optimization methods (such as ANN), as well as investigating the effect of process parameters on the defects of this process is one of the tasks that can be done in the future.

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Persian Abstract

چکیده

ساخت چرخ‌دنده‌ی داخلی با استفاده از فرآیند فلوفرمینگ، فرایندی جدید است که در آن دندانه‌ها با نیروی کم و بدون نیاز به ابزارآلات پُرهزینه تولید می‌شوند .در این تحقیق، ساخت چرخ‌دنده‌ی داخلی با استفاده از فرایند فلوفرمینگ مورد بررسی قرار گرفته است. این فرآیند به صورت عددی مورد تحلیل و شبیه‌سازی قرار گرفت .چندین آزمایش تجربی برای ارزیابی صحت نتایج شبیه‌سازی انجام شد. مقایسه‌ی نتایج شبیه‌سازی و تجربی نشان‌دهنده‌ی تطابق بسیار خوب بین این نتایج است. پس از تایید نتایج شبیه‌سازی، با کمک روش طراحی آزمایش‌های (DOE) اثرات قطر غلتک، درصد کاهش ضخامت، پیشروی و زاویه‌ی حمله بر روی ارتفاع دندانه بررسی گردید. طبق نتایج تحلیل واریانس(ANOVA)، زاویه‌ی حمله، درصد کاهش ضخامت، اثر متقابل $(D\times\alpha)$ و $(D\times f)$ به ترتیب بیشترین تاثیر را بر روی ارتفاع دندانه دارند. با افزایش قطر غلتک و درصد کاهش ضخامت ارتفاع دندانه افزایش می‌یابد، اما پیشروی و زاویه‌ی حمله اثر معکوس بر روی ارتفاع دندانه دارند.