Effect of Spinning Process Parameters on the Forming Quality of Inner and Outer Teeth Shaped Parts

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Abstract. Deform-3d software was used to conduct numerical simulation on the spinning forming process of inner and outer teeth to study the strain distribution and material flow law during the spinning forming process. The influence of mandrel rotation speed and roller feed speed on the forming quality of inner and outer teeth profile was studied. The results show that the best forming quality of the spinning parts can be obtained under the combination of the process parameters of the mandrel rotation speed of 150r/min and the roller feed speed of 110mm/min. Compared with the experimental results, the maximum relative errors of inner and outer teeth wall thickness were 2.03% and 1.78%, which verified the reliability of the finite element model. The results can provide guidance for the finite element simulation and production of inner and outer teeth spinning forming process.

1. Introduction

Inner and outer teeth shaped parts as the key parts of automobile clutch, the application makes automobile transmission structure more compact, also had to reduce weight, to meet the social demand for vehicles lightweight, because this kind of parts belong to wearing parts at the same time, market demand is big, so the inner and outer teeth shape a variable speed device has broad prospects in[1]. Due to the complex structure of this part, it is difficult to process. The main feature of the traditional processing technology, such as cutting, inserting and broaching, is that the processing process is intermittent cutting, because of its low processing efficiency and high processing cost, which is not conducive to expanding the output of such products [2]. Therefore, in recent years, the forming technology of inner and outer teeth parts has been transformed to plastic forming technology. With the development of the automobile industry and the mechanical industry, in recent years, the requirements for the inner and outer tooth parts not only need higher forming precision, but also put forward the requirements for the forming process itself, such as shortening the manufacturing cycle, saving raw materials and reducing energy consumption. Because the use of plastic forming inner and outer tooth - shaped parts of the process method has become the first choice. In recent years, more efficient, lower consumption and green plastic forming of inner and outer tooth parts have been proposed by scholars all over the world. For example, Lee in Korea designed and developed a rolling
extrusion mold, and analyzed the feasibility of the process through finite element and experiments [3]. Dae-Hoon studied the clearance of the punch and the rolling die in the inner and outer teeth of roll-extrusion, and optimized the clearance value of multiple passes by using numerical simulation [4]. Sun proposed a extrusion forming scheme, and by simulating preforms with different technological steps, different extrusion ratios and different preformed shapes, it was pointed out that the two-part extrusion process was most beneficial to the formed workpiece [5]. The above processes belong to the overall plastic deformation, although to a certain extent to improve the production efficiency and forming accuracy, but there are also large equipment size, mold volume, forming force, mold structure complex problems, which is not conducive to the expansion of production [6].

In order to solve this contradiction, a number of scholars began to study the use of spinning technology to shape the inner and outer tooth shape. Specifically, Xia systematically summarized the new spinning process, among which the inner tooth spinning has attracted much attention due to its low load requirement and simple mold [7]. Xia's research on inner tooth spinning pointed out that under the condition of thin wall thickness, insufficient rotational pressure or poor deformation of materials, the tooth height was unevenly distributed along the axial direction [8]. In addition, Xia also pointed out that offset spinning can improve the forming quality of the inner teeth at the mouth of the workpiece [9]. Xu adopted the multi-pass offset spinning process for the inner gear hub parts, and pointed out that the pre-formed parts formed by secondary drawing and spinning in the first step would be helpful for filling the inner tooth cavity in the second step, and effectively solve the two typical defects of the inner tooth height deficiency and circumferential crack [10]. The above scholars focused on the forming process of the inner teeth, but the distribution of strain and the law of material flow in the spinning of the inner and outer teeth were more complicated than the spinning of the inner teeth. Therefore, in the research content of this paper, the forming process and principle of inner and outer tooth shape parts are emphatically analysed.

2. Construction of 3D Finite Element Model

2.1. Spinning Forming Process

The inner and outer teeth product studied in this paper are shown in Figure 1, which is a typical rotary symmetrical shape with 36 groups of inner and outer teeth. The dimensions of the inner and outer teeth shapes are shown in Table 1.

The process of spinning forming inner and outer teeth is shown in Figure 2. Before forming, the workpiece and mandrel are interlocked, and the workpiece and mandrel rotate together without mutual motion. While forming, the teeth profile of roller and mandrel meets the principle of gear meshing transmission, and the roller has radial displacement, so that the center distance between roller and mandrel is gradually reduced until the target center distance is reached. In this process, the clockwise rotation of the mandrel is defined as forward rotation, and the counterclockwise rotation is defined as reverse. In addition, mandrel speed \( n_m \) and roller feed speed \( v_f \) are important process parameters that affect the forming quality of the inner and outer teeth parts [11]. Therefore, finite element simulation and test of \( n_m \) and \( v_f \) are conducted in this paper to find the optimal combination of process parameters. According to the production experience during spinning forming of inner and outer teeth shaped parts, the values of design process parameters \( n_m \) and \( v_f \) are: \( n_m = 135, 142.5, 150, 157.5, 165 \) r/min, and \( v_f = 100, 105, 110, 115, 120 \) mm/min.
Table 1. Size requirements of inner and outer teeth shapes

| $H_0$ /mm | $H_1$ /mm | $D_{ao}$ /mm | $D_{fo}$ /mm | $D_{ai}$ /mm | $D_{fi}$ /mm | $t_a$ /mm | $t_l$ /mm | $t_s$ /mm | $\alpha$ /° | $R$ /mm |
|-----------|-----------|-------------|-------------|-------------|-------------|---------|---------|---------|---------|---------|
| 45        | 40        | (157.0)     | (151.4)     | 153.0±0.15  | 148.0±0.15  | 2.0     | 1.7     | 1.7     | 60±1   | 2       |

2.2. Finite Element Model

In this paper, Deform-3d is used to simulate the spinning forming process of inner and outer teeth parts. In order to improve the simulation efficiency, the model is simplified, and the effects of material anisotropy, temperature field change and inertial force are ignored. Among them, the material model is elastoplastic deformation, the workpiece material is SPPH440, and the mechanical properties of SAPH440 are shown in Table 2. The friction model adopts shear friction, and the friction coefficient is 0.06. The grid cell type adopted is a tetrahedral grid with special processing, which is easy to realize automatic grid division [12]. The selection of mesh size is based on the principle of ensuring the accuracy and minimizing the operation, and at the same time can accurately reflect the subtle features of the parts. Therefore, four-node quadrilateral cells were used to divide the workpiece into 41,277 nodes and 184,277 cells, and the number of grids was 300,000. The maximum mesh size was 0.6mm, and the minimum mesh size was 0.2mm. Finally, the finite element model of spinning process is shown in Figure 3.

Table 2. Mechanical properties of SAPH440 at room temperature

| $E$/GPa | $\mu$ | $\sigma_b$/MPa | $\sigma_s$/MPa | $n$ | $\delta_\%$ |
|---------|-------|----------------|----------------|-----|-----------|
| 197     | 0.28  | 340            | 554            | 0.137 | 15       |

2.3. Quality Evaluation Indicators

As a special plastic forming method, there is no complete evaluation standard for accuracy and quality at present. In this paper, the teeth thickness $t$ (including outer teeth thickness $t_a$ and inner teeth
thickness $t_f$) after spinning is used as evaluation indicators. The measuring principle of $t_a$ and $t_f$ as shown in Figure 4. The inner and outer teeth shaping a set distance from the bottom of the axial distance of $L$ (Figure 5.), make $L$ is equal to 10 mm, 15 mm, 20 mm, 25 mm and 30 mm, axial section in each place on the outer and inner teeth thickness were measured after five data average, get the forming parts under axial height of the $t_a$ and $t_f$ values.

![Figure 4. Wall thickness measurement diagram](image)

**Figure 4.** Wall thickness measurement diagram

**Figure 5.** Schematic diagram of axial height

3. Simulation of Inner and Outer Teeth Spinning

3.1. Strain Distribution

Figure 6. shows the radial, tangential and axial distribution of the strain of the formed part under the process parameters of $n_m=135$ r/min and $v_f=100$ mm/min. Figure 6. (d), (e) and (f) are the axial cross sections of the formed part with inner and outer teeth when $L=20$ mm.

It can be seen from Figure 6. (a) and (d) that the radial strain distribution of the workpiece is relatively regular, the outer teeth addendum and the inner teeth addendum are divided into negative strain, resulting in material thinning. The arc transition part of the left and right side wall including the inner and outer teeth is a positive strain, resulting in thickening of the material, which reflects the rule of metal flow from the top of the teeth to the two side walls during the spinning process. Figure 6. (a) also shows that the material strain distribution is uniform in all parts of the workpiece's teeth forming part, but the strain at the bottom of the workpiece is the minimum value, indicating that the area with the most severe material thinning is at the bottom deformation area.

As can be seen from Figure 6. (b) and (e), the tangential strain distribution of the workpiece is relatively complex. The outer and inner teeth top regions are positive strain, indicating that the material is stretched. The negative strain on the two side walls indicates that the material is compressed when flowing into the two side walls from the top of the teeth.

It can be seen from Figure 6 (c) and (f), the axial strain of the workpiece increases from the mouth to the bottom, and the maximum strain is concentrated on one side of the inner teeth at the bottom of the workpiece. This is because of the axial flow of the material under the action of the rotary wheel, and in the forming surface of the inner and outer teeth, the inner and outer walls of the preformed blank are respectively subject to the friction resistance of mandrel and roller, which causes the local negative strain. At the bottom of the outer wall, the positive strain is maximized because the material is in a free-flowing state, and the material flows upward and eventually forms a flying edge.
Figure 6. Strain distribution cloud diagram

3.2. Law of Material Flow

It can be seen from the strain analysis that the deformation of the inner and outer teeth in the axial direction is not large, while the deformation in the tangential and radial direction is quite different, so the flow law of the material in tangential and radial direction during the forming is more worthy of attention. Therefore, the axial section at \( L=20 \) mm was selected to analyse the material flow of the inner and outer teeth of the section, and the blue arrow was used to represent the deformation trend vector of the material, so as to analyse the tangential and radial flow characteristics of the material during the spinning forming of the inner and outer teeth. Figure 7 is the schematic diagram of the teeth profile forming process of the inner and outer teeth. Take the forming of No.1 inner tooth and No.2 outer tooth as an example. Figure 7 (a) ~ (d) the four diagrams respectively represent the four stages of teeth forming 1 and 2, which are defined as the meshing stage of inner teeth, the forming stage of inner teeth, the meshing stage of outer teeth and the forming stage of outer teeth. Correspondingly, the inner teeth profile on mandrel and roller is expressed as 1’ and 1” respectively, and the outer teeth profile is 2’ and 2”.
As shown in Figure 7 (a), tooth No.1 enters the meshing stage of inner teeth. At this point, the roller gives the feeding force of the workpiece downward pressure, so the velocity direction of the 1 tooth material is downward, while the 2 tooth material tends to pry upward under the influence of No.1 tooth, so the velocity vector of 2 is upward. It is in the reverse phase at this time, resulting in the flow velocity of $L_1$ side of No.1 tooth is larger than that of $R_1$ side, which also leads to the material first contacted to fill the left rounded corner, and the filling effect is better than that of the right side.

In Figure 7 (b), the No.1 tooth entered the forming stage of the inner teeth. The material at 1 developed from the middle to both sides of $L_1$ and $R_1$. At this time, in the forming of the lateral walls on both sides of $L_1$ and $R_1$, the flow direction of the lateral wall material is different from inner teeth meshing stage, and the flow direction of the material on both sides of lateral wall changes from the rounded corner to the top of the outer teeth. However, at the No.2 tooth, because the No.1 tooth is still forming and has not entered the third teeth forming stage, the upward prying trend of the two materials is more obvious than at the previous stage, so the arrow points upward.

Figure 7 (c) shows that the No.2 teeth enter the outer teeth meshing stage and the formation of the 1 teeth basically ends. At stage three, the material flows downward under the roller feeding pressure on both sides. At the same time, under the influence of roller and mandrel, the material flow velocity at $R_2$ was larger than $L_2$, resulting in a stronger deformation trend on the $R_2$ side to gradually shape the tooth profile on the right side of the outer tooth.

Figure 7 (d) shows that No.2 tooth moved into the inner teeth forming stage. No.2 teeth has basically taken shape to complete at this time and gradually into the subsequent tooth shape, so it can be seen that $L_2$ side materials affected by subsequent tooth forming have been move upward trend, and $R_2$ side material from the roller groove to mandrel tip rounded down direction, the outer teeth profile of the rounded fill full.

**3.3. Simulation Results**

3.3.1. Influence of $n_m$ on Forming Quality. As one of the key process parameters in spinning forming, different $n_m$ has a great influence on the forming quality. According to the values of $n_m$ in section 2.1, different $n_m$ values were simulated with $v_f = 110\text{mm/min}$, and the results were shown in Figure 8.

It can be seen from Figure 8 (a) and (b) that at the same axial height, such as $L=20\text{mm}$, $t_f$ and $t_a$ both show a downward trend with the increase of $n_m$. This is because the $n_m$ increase, and $v_f$ without
change, wheel per unit of radial feed need more contact workpiece, namely the increase of the rotation of the overall number of turns, forcing the material to the inner gear rounded corners for filling, and fill in the required materials from the material flow analysis has provided inside and outside the tooth thickness, so \( t_f \) and \( t_a \) have thinned. However, at the same \( n_m \), such as \( n_m = 135 \text{r/min} \), \( t_f \) and \( t_a \) both have a rising trend with the increase of axial height \( L \). This is because the closer to the mouth of the workpiece, the greater the rebound of the material, resulting in a tendency to increase the thickness of the inner tooth wall far away from the bottom of the workpiece. Five different mandrel rotation speeds were compared, which were within the acceptable size range of \( t_f \) and \( t_a \) (\( t_f = 1.700 \sim 1.775 \text{mm}; \quad t_a = 2.000 \sim 2.075 \text{mm} \)), the higher the \( n_m \), the better the efficiency of production. Therefore, \( n_m = 150 \text{r/min} \) is selected to ensure product quality requirements and better production efficiency.

![Figure 8. Influence curve of \( n_m \) on wall thickness](image)

### 3.3.2. Influence of \( v_f \) on Forming Quality.

Among the key technological parameters of spinning forming, \( v_f \) has a complicated influence on the deformation degree of spinning forming, and has a great influence on the forming accuracy of products. Figure 9 shows the influence of different \( v_f \) on thickness of the inner and outer tooth parts when the \( n_m = 150 \text{r/min} \).

It can be seen from Figure 9 (a) and (b) that at the same axial height, such as \( L = 10 \text{mm} \), \( t_f \) and \( t_a \) both show a downward trend with the increase of \( v_f \). This is because the \( v_f \) increase, and \( n_m \) without change. When the mandrel rotate once a turn, the feed of the roller also increases, which means that the unit pressure of workpiece increases per unit time, making the deformation trend of the inner and outer teeth become larger. This also leads to a greater tendency of material flow, resulting in more material developing toward the inner teeth, resulting in a decrease in the thickness of the wall. When \( v_f \) is the same, \( t_f \) and \( t_a \) both have a rising trend with the increase of \( L \), which is similar to the effect of \( n_m \) on wall thickness, because different axial heights make wall thickness near the mouth of workpiece increase. The influences of five different \( v_f \) on the products were compared. \( v_f = 110 \text{mm/min} \) was selected to facilitate the production of inner and outer tooth-shaped products.
3.4. Test verification

In order to verify the validity of the finite element model, the optimized process parameters $n_m=150$ r/min and $v_f=110$ mm/min were tested, and the sample was prepared as shown in Figure 10. The axial height $L=10$ mm, 20 mm and 30 mm of the test sample were measured, and the wall thickness of the finite element simulation value and the test value were compared, as shown in Figure 11. According to the comparison between the two groups of data, the maximum relative error of $t_f$ is 2.03% and $t_a$ is 1.78%. Therefore, it is considered that the finite element model in this study has good reliability.

4. Conclusion

Based on deform-3D software, this paper established the finite element model of spinning forming of inner and outer teeth parts, analysed the strain distribution and material flow during spinning forming.
of inner and outer teeth parts, studied the law of influence on the forming quality of inner and outer teeth parts under different parameters, and verified the reliability of the model through spinning forming test. The conclusion is as follows:

1) during the spinning forming of the inner and outer teeth, negative strain is generated at the radial top of the inner and outer teeth of the workpiece and the thickness is reduced; The workpiece is stretched by positive tangential strain; Axial positive strain is generated and a flying edge is generated at the bottom of the forming part.

2) At the same axial height, with the increase of mandrel speed and roller feed speed, the wall thickness of inner teeth and outer teeth showed a downward trend; At different section heights, the wall thickness of the inner teeth and the wall thickness of the outer teeth showed an overall rising trend. By comparing the effects of different process parameters on the wall thickness of the formed parts, it is considered that \( n_m = 150 \text{r/min} \) and \( v_f = 110 \text{mm/min} \) have the best effect on the wall thickness and production efficiency of the formed parts with inner and outer teeth.

3) The maximum relative errors of the inner teeth wall thickness and the outer teeth wall thickness were 2.03% and 1.78%, respectively, indicating the reliability of the finite element model.

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References
[1] TIAN Fu-xiang, SUN Zong-qiang, LIU Xiao-ling, et al. Structure and Parameter Calculation of a New Precision Forging Die for Internal Gears [J]. Mold Industry (4):38-41.
[2] ZHUANG zhong. New Technology and Development Trend of Automotive Gear Processing [J]. Automotive Technology and Materials (6):50-54.
[3] Lee J M, Kim B M, Kang C G. A Study on the Cold Ironing Process for the Drum Clutch with Inner Gear Shapes[J]. International Journal of Machine Tools and Manufacture, 2006, 46(6):640-650.
[4] Ko D H, Lee S K, Kwon Y N, et al. Improvement in Dimensional Accuracy of Roll-Die-Formed Clutch Hub Used in Automotive Transmission[J]. International Journal of Precision Engineering & Manufacturing, 2012, 13(2):237-243.
[5] SUN Xiao-long, ZHU Sheng-fa, ZHUANG Xin-cun, et al. Numerical Investigation on Tooth Filling of Clutch Drum Forming Processes[J]. Production Engineering, 2016, 10(1):25-35.
[6] ZHUANG Xin-cun, SUN Xiao-long, XIANG Hua, et al. Compound Deep Drawing and Extrusion Process for the Manufacture of Geared Drum[J]. The International Journal of Advanced Manufacturing Technology, 2016, 84(9-12):2331-2345.
[7] XIA Qin-xiang, XIAO, Gang-feng, LONGLONG Hui, et al. A Review of Process Advancement of Novel Metal Spinning[J]. International Journal of Machine Tools & Manufacture, 85:100-121.
[8] XIA Qin-xiang, YANG Ming-hui, HU Yu, et al. Numerical Simulation and Experimentation Cup-Shaped Thin-Walled Inner Rectangular Gear Formed by Spinning[J]. Journal of Mechanical Engineering, 2006, 42(12):192.
[9] XIA Qin-xiang, SUN Ling-yan, CHENG Xiu-quan, et al. Analysis of the Forming Defects of the Trapezoidal Inner-Gear Spinning[C]. IEEE International Conference on Industrial Engineering & Engineering Management. IEEE, 2009.
[10] XU Wen-chen, ZHAO Xiao-kai, SHAN Debin, et al. Numerical Simulation and Experimental Study on Multi-Pass Stagger Spinning of Internally Toothed Gear Using Plate Blank[J]. Journal of Materials Processing Technology, 2016, 229:450-466.
[11] XIA Qin-xiang. Special spinning forming technology [M]. Beijing: science and technology press. 2017
[12] LIN Xin-bo. Application of deform-2d and deform-3dcae software in simulating plastic deformation of metals [J]. Die technology (3):73-78.