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Finite element analysis and experimental research on multi-wheel planetary intermittent type spinning mechanism for internally-externally toothed parts with thin-wall cup-shaped

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Abstract. In this paper, a multi-wheel planetary intermittent type spinning process was investigated through finite element analysis(FEA) and process experiment. The spinning deformation mechanism of cup-shaped internally-externally toothed parts was studied by simulating the planetary spinning process. The distribution of the transient stresses in the contact zones between the roller and blank, and the equivalent plastic strains after spinning were analyzed. The location and causes of defects were determined through analyzing three-dimensional stress and equivalent strain. By comparing the distribution of workpiece thickness after spinning with the simulation result, it has indicated that this research is favorable for developing the technological forming criterion to guide the practical manufacture processes.

1. Introduction

The traditional spinning process for parts with the internal teeth alone or external teeth alone has been researched mostly. XU et al. [1] revealed the laws of stress and strain distribution of the longitudinal and hoop ribs in the spinning process by forming the qualified 5A06 alloy samples with ten longitudinal ribs and four hoop combined ribs. Xia et al. [2] discussed the material deformation mechanism, processing failures and spun part defects of the tooth-shaped spinning as a novel spinning processes and analyzed the influence of process parameters on forming quality. XU et al. [3] investigated a multi-pass stagger spinning process of internally toothed gear and analyzed the deformation characteristics and the influences of process parameters. Zhan et al. [4] reveal the forming mechanism of a part with a transverse inner rib during power spinning by established a 3D finite element model. Haghshenas et al.[5]evaluated the equivalent plastic true strain distribution during splined-mandrel flow forming, revealed that the highest strain was located on the workpiece/mandrel interface of the thin wall region near the nose of the internal ribs. Peter G et al.[6] developed a new process of internally geared wheels flow forming, where an externally geared mandrel is fitted into a cup-like work piece. However, the traditional spinning process is unable to form the parts with internal and external teeth simultaneously, the typical workpiece as shown in Figure1. Relevant researches have rarely been conducted.

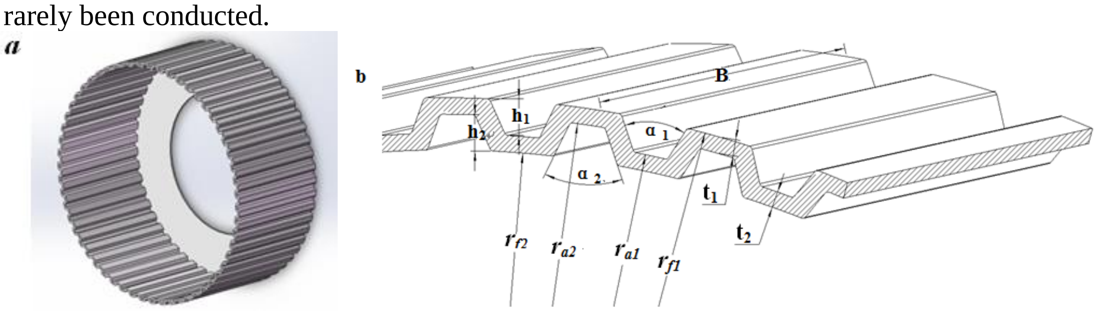

Figure 1. The drawing of internally-externally toothed parts

2. Material and Methods

2.1. The forming principle

Figure2 and Figure3 show the forming principle of multi-wheel planetary intermittent type spinning process. The blank is fixed to the mandrel by the tailstock and rotated intermittently with the mandrel. The two sets of roller bases are distributed symmetrically on both sides of the mandrel, as shown in Figure2. The roller bases are driven by a servo motor along the direction of the groove(external tooth). Each roller bases is equipped with several spinning rollers, which are evenly distributed on the turntable. This paper takes six spinning rollers as an example, as shown in Figure3. The turntable rotates actively after being driven by hydraulic pressure, and the rollers rotate with the turntable. After the rollers contact with the blank, they rotate passively around there center axis and exert pressure on the metal surface of the blank to form instantaneous rapid and sharp plastic deformation. The spindle rotates intermittently to match the turntable rotation and then gradually forms the internally-externally toothed parts.

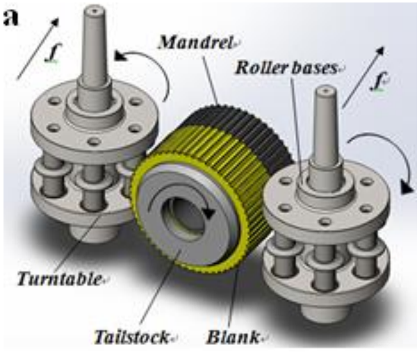

Figure 2. Two sets of roller bases

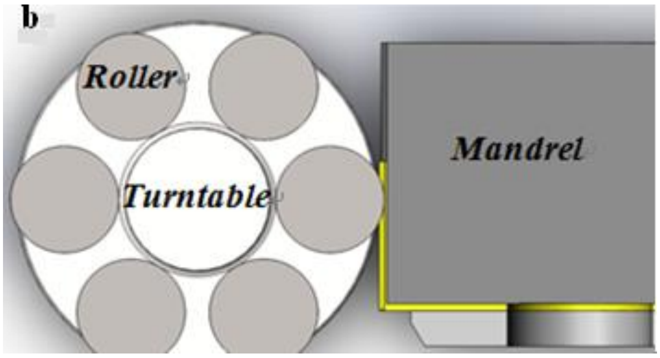

Figure 3. Spinning rollers distributed on the turntable

2.2. Geometric model

To establish the finite element model of the internally-externally toothed parts spinning, it is necessary to research the theories of the finite element deformation and elastoplastic finite element method, especially to analyze the solving method of the elastoplastic finite element with large deformation.

During spinning, the blank and tailstock are fixed together by the glue function in the software. That is to say, the blank and tailstock rotate synchronously by setting the rotating speed of the tailstock, and the blank and tailstock do not rotate relative to each other. The spinning roller bases are evenly distributed on both sides of the mandrel horizontally and symmetrically. Each spinning roller base is equipped with six rollers which are distributed evenly in circumference and revolving around the center of each spinning roller base respectively. The center lines of rollers are perpendicular to the center line of the mandrel. When the spinning roller contacts the blank, the roller revolves around its center line with the help of the friction force produced by the roller and blank. The geometric model is shown in Figure4.

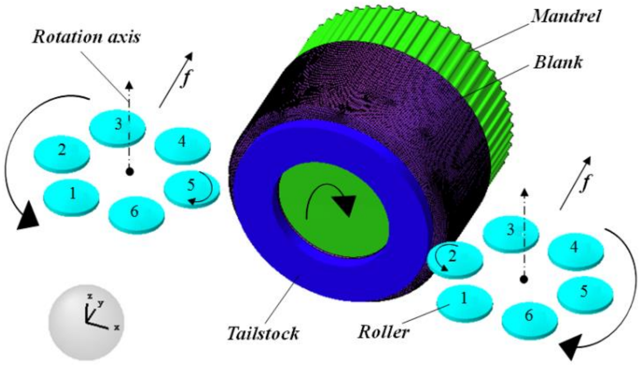

Figure 4. Geometric model

2.3. Elastoplastic FEA model

In the finite element model, the translation and rotation of the rigid spinning roller are realized by defining centroids and exerting displacement constraint on centroids. In order to improve the simulation accuracy, the mesh of the deformation zone is refined. The adaptive re-meshing function is adopted to guarantee the calculation accuracy as well as the computational efficiency. The effect of the material anisotropy on the deformation is ignored and the following hypotheses are adopted: (1) The material is isotropic, homogenous and continuous. (2) The thermal effect between the spinning rollers and blank during spinning is neglected. (3) The gravity and the inertial force are neglected.

The material used in the simulation and experiment was Q235 steel. The material properties were obtained based on the uniaxial tension experiment method of the metal materials at the room-temperature. The relationship between the true stress and strain is $Y=764.6 \in 0.215$, and the mechanical performance parameters are shown in table 1.

Table 1. Material performance

Young's modulus E/GPa	Poisson's ratio μ	Yield strength σs/MPa	work-hardening rate n
206	0.3	258	0.215

3. Distribution of stress

The distribution of stress and the strain in the deformation area is the important basis for analyzing the plastic forming problems correctly [7].The deformation position, range and metal flow in the deformed zone are determined by its stress state during the forming of cup-shaped parts with internal and external teeth. Therefore, it is very important to master the stress and strain states of each deformation area for correctly analyzing the plastic forming problems .

3.1. Transient stresses

Figure 5 shows the contact zone between the spinning roller and the blank is limited to a small part on the outer surface of the internal tooth during the spinning. The plastic deformation will be generated in the contact zone and its surrounding area and constantly pushed forward with the movement of the spinning roller.

Figure 6 shows the stress state of the metal in each contact zone at initial spinning position along the radial, axial and tangential directions, respectively, where the radial, axial and tangential directions correspond to x, y and z directions in the coordinate system. Figure 5 shows that the plastic deformation is generated under the action of compressive stress state in the internal tooth area. In the external tooth area, the elastoplastic deformation is generated at tensile stress state which is indirectly affected by the deformation in the inner contact zone. In the initial spinning stage, the metal in the internal teeth area is easily deformed at the three-way compressive stress state, which is beneficial to the plastic forming of internal teeth. The metal in the external teeth area is formed at the three-way tensile stress state, which is not beneficial to the forming of external teeth. Therefore, the external teeth area of blank is susceptible to crack due to tension at the beginning of the forming.

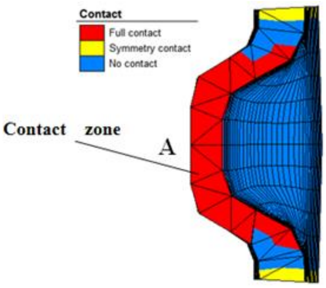

Figure 5. Contact zone

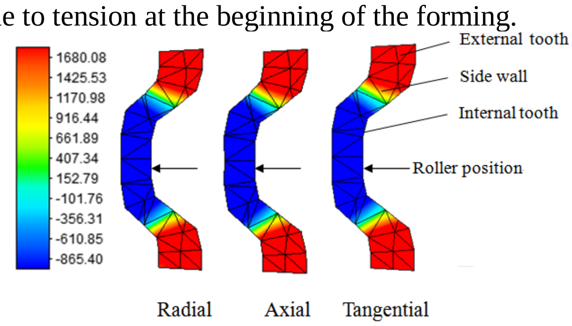

Figure 6. Transient stresses at initial spinning position

3.2. Three-way residual principal stresses

Figure 7 shows the metal stress state of different contact zone along the radial, axial and tangential direction when the roller contacts the blank instantaneously. The radial tensile stress and tangential tensile stress occur in the internal teeth. The axial tensile stress occurs at the outer layer of internal teeth, while the axial compressive stress occurs at the inner layer of internal teeth due to the inner layer deformation is constrained by the mandrel.

Figure 8 shows the three-way residual principal stresses of the workpiece in the 50% cross section after spinning. In the internal teeth area, the distribution of radial stress is evenly, but the axial and tangential stress distributions in the inner layer and outer layer are not uniform. The value of stress in the outer layer is greater than that of the inner layer due to the outer layer metal is contacted by the roller directly during spinning. In the external tooth area, the stress distributions of the inner and outer layer metal are even along the radial direction, but the stress distributions differ obviously along the axial and tangential directions. In the side wall area, the distribution of stress in the inner and outer layer is also not evenly.

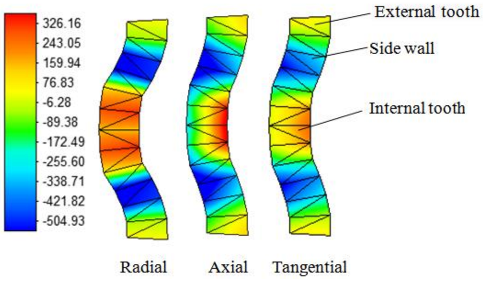

Figure 7. The transient stresses

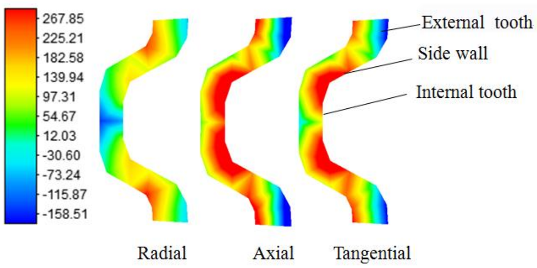

Figure 8. Three residual principal stresses

3.3. Distribution of Equivalent strains

Figure 9 shows the distribution of equivalent strain at cross section after spinning. According to the figure, with the increase of the contact area of spinning roller, the equivalent strain values of each region are increasing. However, the equivalent strain distributions in various regions differ obviously. The equivalent strain value of the internal tooth is obviously greater than that of the external tooth due to the deformation degree of the internal tooth is larger than that of the external tooth. Moreover, in the internal tooth, the strain distributions of inner and outer layer are also different. The equivalent strain value of the inner layer is greater than that of the outer layer due to the inner layer metal deformation is restricted by the mandrel. Figure10 shows the distribution of equivalent plastic strain at axial section after spinning. It shows that the strain distributions of the internal tooth, external tooth and side wall are relatively even along the axial direction, respectively. However, the strain distribution at the same cross section differs obviously.

Figure 11 shows the equivalent plastic strain along axial direction after spinning. It shows that the maximum value of equivalent plastic strain occurs at the inner layer of internal tooth due to it is deformed with the large plastic deformation. The minimum value of equivalent plastic strain occurs at external tooth due to it is deformed with the elastoplastic deformation, mainly elastic deformation. Moreover, in the external tooth and side wall, the difference of the equivalent plastic value at inner layer and outer layer are small.

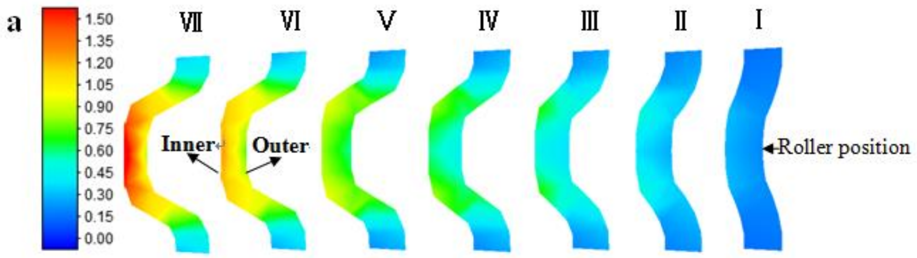

Figure 9. Equivalent plastic strain at cross section

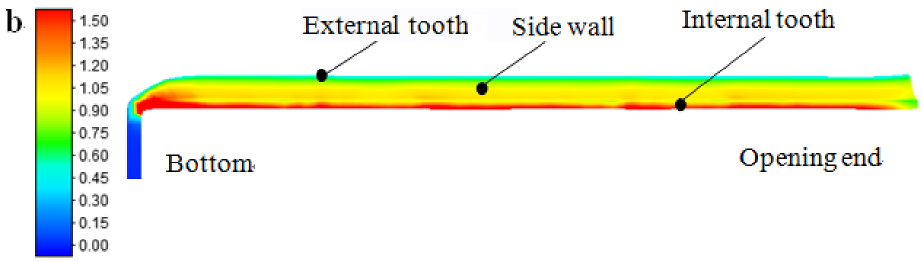

Figure 10. Equivalent plastic strain at axial section

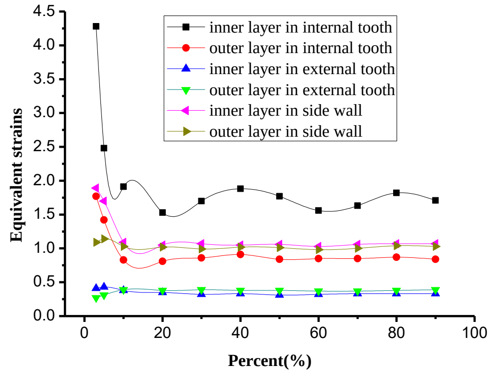

Figure 11. Equivalent plastic strain along axial direction

4. Discussion

To verify the simulation result, the pattern of variation of workpiece thickness during the spinning of internally-externally toothed parts was investigated experimentally. The material and spinning process parameters used in experiment were the same as that in simulation. The experiment is conducted on the CNC spinning machine (as shown in Figure 12).

Figure 12. CNC spinning machine

Figure 13 shows the comparison between the experiment and simulation result. The simulation results include all internal and external teeth, but the length is shortened to reduce the time of simulation calculation. The deviations between the experiment and simulation results are less than 10%. It indicates that the FEA model adopted in this paper can be considered as reliable.

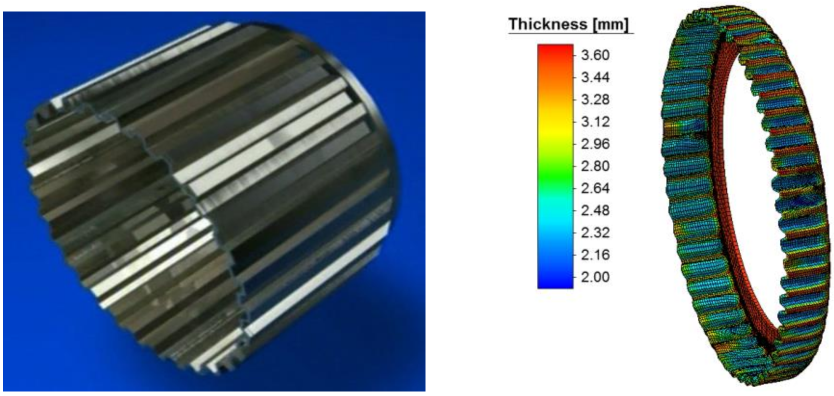

Figure 13. Comparison of experiment and simulation results

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