Three-dimensional FE simulation of cold precision forging of helical gear with the flow relief-hole method

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Abstract. In the present study, billet is designed by utilizing the flow relief-hole principle to improve the dimensional accuracy during the cold precision forging of helical gear. A three-dimensional FE simulation was carried out to analyze the deformation features of billet with different initial diameter of relief-hole under the commercial software DEFORM 3D. When the diameter of relief-hole d0 increases, the forming load decreases and the unfilled portions at the teeth top contacting with the punch increase. The deform mode of relief-hole, the variation trend and the distribution of effective strain are different under different diameter of relief-hole when compression ratio Δs varies.

Introduction

Helical gears are an important transmission component which is wildly used in the most of the mechanical and automotive industry because of their high contact ration, smooth transmission. At present, the vast majority of helical gears are machined from blanks by hobbing, in which large quantities of metal chips as waste are produced and metal streamlines are cut off, thus lowering mechanical properties. Consequently, more and more scholars concentrated on their interesting to product helical gears using precision forming technique owing to its well-known advantages compared with conventional cutting methods, such as the excellent mechanical properties, less material wastage, good tolerance, high productivity and cost savings [1].

Choi et al.developed a new method of cold extrusion for helical gears and analyzed it by using the upper-bound method [2,3]. Lange et al. made a deformation analysis for the cold forging of helical gears by 3D FEM and analyzed the elastic deformation of the die by 3D-BEM [4].Yang investigated the clamping-type forging of helical gears through experiments and analysis by FEM [5]. Jung proposed the extrusion of helical gears by two-step process to reducing the forming load [6]. Feng et al. researched the influenc of different billet geometries on the forming load and the deformation uniformity and optimized the billet geometry during cold precision forging helical gears [7]. However, the effect of billet with relief-hole on the helical gear precision forging process has not been researched in detail.

Due to the inherent complexity of forming processes, the helical gear conventional closed-die forging is of high forging pressure which causes failure, plastic deformation and wear of die. Kondo and Ohga proposed the precision forging method utilizing divided flow, which was effective to reduce the forming load and the die pressure, and improve the filling-up of materials into die cavity [8,9]. When the process on the relief-hole method is applied to forming a helical gear, the relief-hole shrinks as a compression added and finally it is closed up completely. The forging process has to be finished before its complete closure. Therefore, it is very important to decide the initial billet diameter of relief-hole. In this study, the cold precision forging process with relief-hole principle is used to form the helical gear. FE models for cold precision forging process of helical gear with different initial diameter of relief-hole of billet were built. The deform mode of relief-hole, the variation trend and the distribution of effective strain were obtained under different diameter of relief-hole by simulating the cold precision forging helical gears process.

Establishment of 3D FE modeling

According to reference [7], the helical gear used as a component of an automotive transmission is taken as an example. The specification of the helical gear as follows: number of teeth, normal module, normal pressure angle, helix angle and teeth width is 23, 2, 20°, 14°, 17mm, respectively. Billet geometries with six different relief-hole diameters (0mm, 5mm, 10mm, 15mm, 20mm, 25mm, respectively.) were designed. 3D geometrical model of the billet, the upper punch, lower die and sleeve were generated. All the dies are regarded as the rigid bodies and the billet is defined as a deformable body, because the plastic deformation is very large during the cold precision forging of helical gear and elastic deformation is neglected.

The billets with different relief-hole diameters were discretized about 24584 nodes, 120000 tetrahadral elements and 22356 surface polygonal elements. Two different mesh densities were specified for the billet. The outer area of the billet was of a fine density to improve the deformation accuracy in gear teeth area, while the interior zone of the billet had a coarse density to save the simulation time. Automatic remeshing technique was adopted during simulation. The primary die is given constant speed of 10mm/s. The billet is defined as being in contact with all dies at all times. The friction types are constant shear friction and the billet has a constant shear factor of 0.12 with the dies.

The steel used in this study is AISI 4140. Its Young's modulus and Poisson's ratio are 210 GPa and 0.3 respectively, and its constitutive equation is:

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \tag{1}$$

where $\bar{\sigma}$ is the effective stress, $\bar{\varepsilon}$ is the effective plastic strain, $\dot{\bar{\varepsilon}}$ is the effective plastic strain rate, T is the temperature.

Thus, the 3D FE model of helical gears precision forging was establishment as shown in Fig.1.

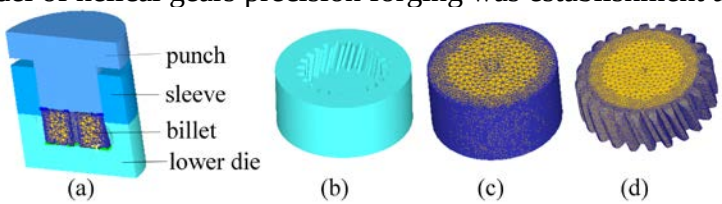

Fig.1 Three-dimensional FE model of cold precision forging of helical gear: a 3D FE model; b cavity; c initial billet; d deformed billet

Results and discussion

Influence of initial diameter of relief-hole on forming load. Fig. 2 gives the variation curves of forming load versus stroke of punch for different initial diameter of relief-hole. It can be seen from Fig.2 that the forming load increases gradually with the increase of stroke and decreases as the diameter of relief-hole d0 increases, and is rapidly accelerated as the relief-hole shrinks and finally approaches its closure. As a result, the downward convex curves appear and arrive the completely filling up steps at their end.

From Fig.2 and reference [7], the cold precision forging of helical gear has experienced three formation stages regardless of the diameter of relief-hole. In spite of similarities of variation trend, some clear differences at the different diameter of relief-hole can be observed from Fig.2. First, the strokes of punch strokes are different because of the difference in the initial billet height. The initial billet height d0=25mm, corresponding punch stroke is the longest. While the initial billet height of design 1, namely without material divided flow, corresponding punch stroke is the shortest.Secondly, the change of forming load is smoother and smaller with the increase of the relief-hole diameter, which will benefit to improve tool life greatly. The cause is the fractional reduction in area of material decreases as the relief-hole diameter increases and is larger and larger monotonously as punch stroke increases in the relief-hole process, and the inward material flow is promoted by the shrinkage of the relief-hole diameter in addition to the outward material flow during the working.

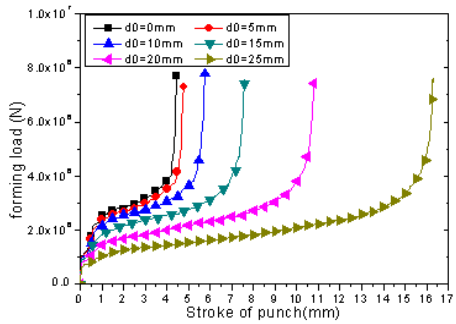

Fig.2 Curves of forming load versus punch stroke under different initial diameter of relief-hole

Figure 3 gives the comparison of the maximum forming load required for the completely filled up at the end the deformed step under different diameter of relief-hole. It can be seen from Fig. 3 that the relief-hole process enable the maximum forming load to get smaller than the process without relief-hole. This means that the process with divided-flow is an effective method to reduce forming load and improve tool life. But, it is also observed from Fig.3 that different relief-hole has a different effect on the maximum forming load F_{max}.When d0 is equal to 5mm, Fmax is the smallest, when d0 is ranged from 10mm to 20mm, the corresponding Fmax decreases as d0 increases and arrives the smallest value at 20mm. But the corresponding Fmax increases as d0 increases when d0 is ranged from 20mm to 25mm.

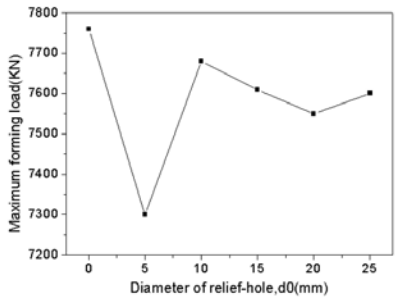

Fig.3 Comparison of the maximum forming load under different initial diameter of relief-hole

Influence of initial diameter of relief-hole on the filling up. Incompletely filling up into the die teeth cavity is one of the main forging defects in cold precision forging of helical gear. The quality of the gear teeth will directly affect the accuracy of dimension and geometry for the final forging part. The minimum distance D_{min} is used here as a measure of the filling up condition, and it can be defined as:

$$D_{\min} = \sqrt{\left(x_{ib} - x_{jd}\right)^2 + \left(y_{ib} - y_{jd}\right)^2} \tag{2}$$

where D_{min} displays the minimum distance from the surface of the billet to the nearest tool, x_{ib}, y_{ib} is the element node i coordinate values on the surface of the billet, x_{jd}, y_{jd} is the element node j coordinate values on the tool surface. The smaller the value of D_{min} is, the more adequate the filling of gear teeth is.

Figure 4 presents the distribution of the minimum distance in forged gear after the cold precision forging for different relief-hole diameter. It can be seen from Fig.4 that the upper addendum region contacting with the punch is not very good filling up. The cause of the characteristic feature is the material flowing resistance is higher under the compression of the punch, and the filling up into the die cavity downward is carried out during the forming. In the process utilizing relief-hole principle, the material flow is divided into a centripetal flow and centrifugal flow. The resistance to the centripetal flow gets smaller with the increase of the relief-hole diameter, which makes the position of the flow division shift inward and is disadvantageous to fill up. Therefore, the unfilled portions increase as the relief-hole diameter increases as shown in Fig. 4.

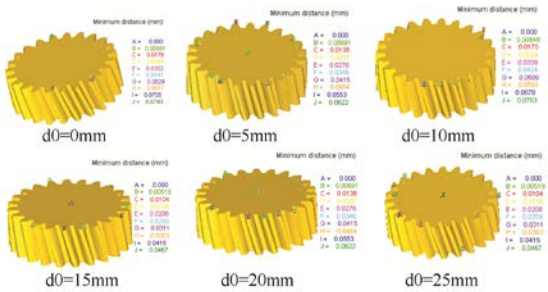

Fig.4 Distribution of the minimum distance in forged gear under different relief-hole diameter

Variation of diameter of relief-hole with compression ratio. Figure 5 shows the variation of diameter of relief-hole with increasing compression ratio Δs, where Δs is the ratio of the height reduction to the punch stroke S(S equals billet height H0 minus product height H). It can be seen that the shape of relief-hole varies with Δs, and the variation trend are different under different diameter of relief-hole. At d0=5mm, the lower material flow inward is faster than the upper material as Δs is greater than 82%, thus relief-hole firstly shrink at the bottom, then the upper material flow inward is faster than the lower material as Δs vary from 82% to 96%, so the contraction of relief-hole is almost the same at Δs=96%, next the upper material flow inward is more faster than the lower material when Δs is larger than 96%, therefore the contraction of relief-hole is more greater at the top, the relief-hole is completely closed at Δs=100% (see Fig. 5a). At d0=10mm, the deform mode of relief-hole is single extrude shape inward near to the downside of the hole and the lower material flow inward is faster than the upper material when Δs is greater than 81%, thus relief-hole firstly shrink at the bottom, then the upper material flow inward is faster than the lower material and the position of the extrude shape gradually moved from the downside to the upside as Δs vary from 82% to 96%, so the position of the extrude shape is in the middle of the hole and the contraction of relief-hole is almost the same at Δs=95%, next the upper material flow inward is more faster than the lower material and the position of the extrude shape is next to the upside of the hole when Δs is larger than 95%, therefore the contraction of relief-hole is more greater at the top, the relief-hole is completely closed at Δs=100%(see Fig. 5b). The deform mode of relief-hole at d0=15mm is similar with the deform mode at d0=10mm(see Fig. 5c). At d0=20mm, the deform mode of relief-hole is also single extrude shape inward, but the location of the extrude shape is in the middle of the hole and flow velocity inward between the lower material and the upper material is almost the same during the whole forging processing (see Fig. 5d). At d0=25mm, the location of the single extrude shape is near to the downside of the hole and flow velocity inward of the upper material is always greater than the lower material during the whole forging processing (see Fig. 5e).

Effective strain distribution under different diameter of relief-hole. The distribution of effective strain at different diameter of relief-hole during the cold precision forging process is shown in Fig. 6. Because of the smaller ratio of height to diameter, the billet undergoes the larger degree of deformation and effective strain is greater at Δs=22% under the conditions of d0=0mm, 5mm, 10mm, 15mm, respectively. Under the action of axial load of the punch and the lower die, the plastic deformation gradually expands along the radial and the gear tooth direction, and the gear shape has already emerged. And the dedendum is extruded by the addendum of the cavity, so the effective strain of the dedendum is larger than that of the addendum at Δs=82%. It can also be seen from Fig.6, the tooth filling is better at d0=0mm, 5mm, 10mm, 15mm than d0=20mm, 25mm, so the effective strain of the billet with 0mm, 5mm, 10mm, 15mm diameter of relief-hole is larger than that of the billet with 20mm, 25mm diameter of relief-hole at Δs=82%. As the deformation progresses, the upside gear shape achieves filling, so the effective strain of the upside is larger than that of the downside at Δs=95%, especially it is much more difference under the condition d0=20mm, 25mm. At the final forging stage at Δs=100%, the total desired strain is achieved in the gear shape area, accordingly the gear shape is filled completely. Moreover, it can also be seen from Fig. 6 that the largest effective strain locates in the downside of the forged gear at d0=0mm, 5mm, 10mm, whereas the largest

effective strain locates in the upside of the forged gear and around the relief-hole at d0=15mm, 20mm, 25mm.

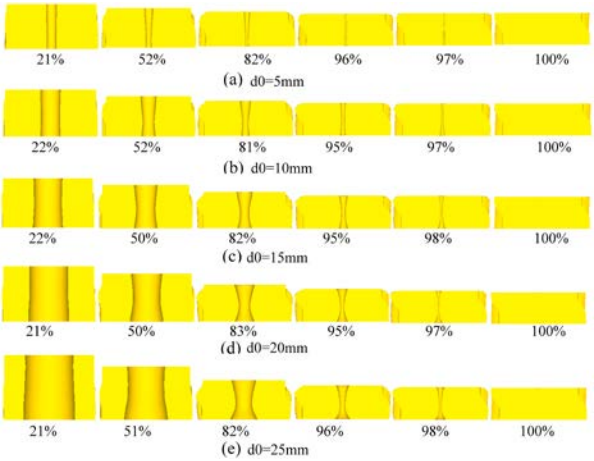

Fig.5 Variation of diameter of relief-hole under different compression ratio Δs

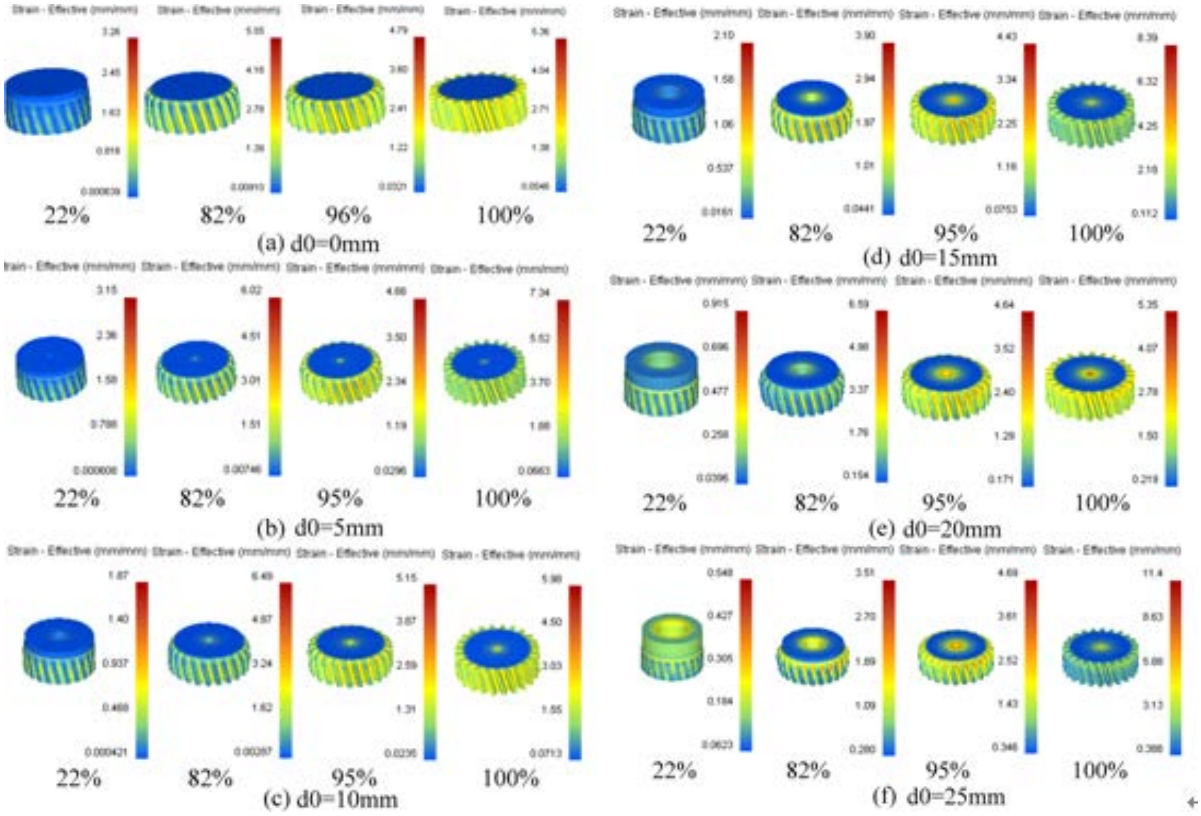

Fig.6 Distribution of effective strain at different diameter of relief-hole

Conclusions

Billet is designed according to the principle of flow of relief-hole, and deformation features for billet with different initial diameters of relief-hole has been analyzed by simulating the helical gear cold precision forging process based on the FE method. The following conclusions can be drawn.

1. The billet with relief-hole can lower the forming load in the cold precision forging process of helical gear. The forming load decreases as the diameter of relief-hole d0 increases, but the maximum forming load required for the complete filling up of the material into the die cavity dose not lower with an increase of the diameter of relief-hole.

2. The unfilled portions increase at the teeth top contacting with the punch when the relief-hole diameter increases. The cause of the characteristic feature is the material flowing resistance is higher under the compression of the punch, the filling up into the die cavity downward is carried out during

the forming. And the resistance to the centripetal flow gets smaller with the increase of the relief-hole diameter.

3. The deform mode of relief-hole and the variation trend are different under different diameter of relief-hole when compression ratio Δs varies.

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