Numerical study of sheet-bulk forming process of high strength steel 16MnCr5

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Abstract. The sheet-bulk metal forming (SBMF) technology provides a new processing method for gears. This manufacturing technology is greatly affected by process parameters, deformation conditions and material properties. Defects such as holes, tearing and insufficient filling of materials are easy to occur during forming process. In order to understand the mechanism of this process, finite element modelling and simulations are carried out on the sheet-bulk forming of gears. Equivalent stress and material flow are analyzed by combining point tracking method. The mechanism of incremental sheet-bulk forming of gears technology is clarified. The phenomenon of insufficient filling of initial teeth caused by restricting material flow is emphatically explained.

1. Introduction
In recent years, with the rapid development of plastic processing technology, a new process combining sheet metal forming and volume forming is called sheet-bulk metal forming technology. Compared with common plastic forming processes such as metal cutting, stamping and forging, SBMF has the advantages of low cost, high material utilization rate, long service life of the die and few process links. However, SBMF technology is greatly affected by process parameters, deformation conditions and material properties. Therefore, it is necessary to study the forming mechanism of SBMF and explore the specific laws of force and deformation and material flow.

Isik et al. [1] proposed that the crack during forming may occur under the condition of non-planar shear when studying sheet volume forming. Wernicke et al. [2] conducted numerical simulation and experimental research on different strain paths, thus determining the influence of strain hardening and damage defects on the bearing capacity of gears. Peter et al. [3-5] established an analysis model of progressive forming gear along the direction perpendicular to the thickness of the plate when studying the plate volume forming technology. Hirt et al. [6] developed a new rolling process to produce uniform surface ribs in plates.

The current research on SBMF process is mainly concentrated on the experimental investigations of the basic process. The numerical study on this material processing method is rarely reported in literature. This study aims to conduct numerical simulations of high strength steel 16MnCr5 to form gear-type part and investigate the feasibility and mechanism of SBMF process.

2. Analysis of finite element simulation results
2.1. Equivalent stress
Fig 1(a) is the equivalent stress nephogram in the first gear forming process. In Fig 1(a) the equivalent stress is mainly distributed in the tooth groove and the tooth side surface, and the stress near the tooth
top is small, with the maximum equivalent stress reaching 113MPa. The main reason is that the tooth groove and tooth side surface are obviously squeezed by the double wedge punch during the forming process. On the whole, in the process of forming the first tooth, the equivalent stress is distributed annularly, with the tooth groove and tooth side surface being the most obvious, while the equivalent stress decreases gradually along the radial inward direction.

In Fig 1(b) the equivalent stress curves of the edge of the tooth slot, the side surface of the double wedge punch and the center position of the tooth slot basically coincide. When the displacement of the punch is 0 to 0.710mm, the equivalent stress increases sharply. When the displacement of the punch increases from 0.710mm to 3.38mm, the equivalent stress basically does not change, and the three curves are approximately horizontal. At the top of the tooth, the equivalent stress also increases significantly with the displacement of the punch at the beginning. When the displacement is about 0.142mm, the equivalent stress curve oscillates slightly, but the overall change trend has been very gentle. At the position of the circular plate near the tooth, the equivalent stress oscillates significantly in the initial and middle stages of the forming. The equivalent stress decreases and rises greatly around the displacement of the punch of 0.852mm and 1.7mm. At the later stage of the forming, the equivalent stress at this position is similar to the tooth crest and rises slowly.

Figure 1. (a)Equivalent stress during first tooth formation (b)Point tracking analysis results of equivalent stress.

![Figure 1](image1)

Figure 2. Material flow at first tooth simulation steps of 80.

Figure 3. Material flow at first tooth simulation steps of 94.

2.2. Material flow

When the forming of the first tooth enters the later stage, the flow speed of the metal material under the tooth top and outside the punch has been increased, the volume transfer process of the workpiece material from the tooth root to the tooth top is slightly accelerated, and the mold cavity is further filled with sheet metal. However, since the first tooth is extruded by the left and right punch wedges at the same time, the flow of the metal material under the top of the tooth is obviously restricted by the adjacent non-deformed material at the beginning[4]. Therefore, the flow speed of the metal material under the top of the tooth rises slowly during the whole forming process of the first tooth, which leads to insufficient filling of the first tooth and defects. Fig 2 and Fig 3 are the material flow nephogram of the first tooth at the later stage of forming. The number of simulation steps are 80 and 94.
Different from the first tooth, the metal material flow on one side of the double wedge punch has changed from the constrained material flow to the free material flow. As shown in Fig 4, in the early and middle stages of forming the second tooth, although the material at the punch is severely squeezed, the deformation amount is large, and the material flow speed is maximum. At this time one side of the punch has become a free space. The flow of the material is no longer restricted, which makes the metal material under the tooth top play a major role in filling the cavity and have a larger flow speed in the early stage. The speed rises rapidly with the increase of the displacement of the punch, thus reducing the possibility of insufficient filling and easy generation of defects during forming of the first tooth.

In Fig 7, the second tooth is in the late stage of forming. Due to the free flow of metal material, the flow speed of metal material under the tooth top is higher than the first tooth during forming. The increase is more obvious with the increase of punch displacement, which creates advantages for the transfer of plate volume from the tooth root to the tooth top and makes up for the defect of insufficient filling of the second tooth during forming.

2.3. Point tracking analysis of material flow
Consider selecting three key points for point tracking analysis of material flow, as shown in Fig 5. In Fig 6 the edge position of the tooth groove where P2 is located is obviously squeezed by the punch at the beginning, so the flow speed of the metal material at P2 increases sharply in the small range of the punch displacement of about 0 to 0.142mm. In the large range of the punch displacement of 0.142mm to 3.38mm, the flow speed of the metal material near the tooth top mainly filling the mold cavity
gradually dominates. The flow speed of the material at P2 decreases slightly. The curve (green dotted line) starts to show a downward trend and oscillates slightly. However, the material velocity near the tooth top where P1 plays a major role in filling the mold cavity increases with the displacement of the punch during the whole forming process. Although the material velocity curve (red thick solid line) oscillates in the whole range of 0 to 3.38mm, it shows an overall upward trend, thus contributing to the filling of the mold cavity during tooth forming. However, as the material flow on the side of the double wedge punch is restrained by the adjacent non-deformed material during the first tooth forming, the material flow speed at P3 position will not increase after rising within a small range of 0 to 0.142mm, and will remain at a lower speed level and drop slightly in the later period. The material flow speed curve (blue thin solid line) is basically horizontal within a range of displacement of 0.142mm to 3.38mm, with slight oscillation and drop. This prevents the flow velocity of the metal material near the tooth top where P1 is located from rising again at the later stage of forming, thus causing the forming defect due to insufficient filling of the mold cavity.

Acknowledgments

This study used 16MnCr5 as a new material to complete the numerical simulation of incremental sheet-bulk forming of gears. The forming mechanism of this process is clarified and the defects in the forming process are analyzed. The following important points are summarized:

- The filling property of teeth depends on the flow speed of metal material under the top of teeth.
- The flow rate of the metal material under the top of the second tooth increases continuously during the whole forming process due to the larger free flow advantage of the material, thus realizing good filling of the mold cavity.
- When the second tooth is formed, the lateral free flow of the material is remarkable. The restricted flow is dominant in the early stage. The indentation is single punch extrusion. Hence, the die load under the same displacement is about half of that of the first tooth extrusion.

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