Forming Load and Metal Flow of Rotary Forging Process for Spiral Bevel Gear

Wang Huajun[1], Li Yamin[1], Zhang Yang[1],Huang Jing[1,2] and Tang Xuan[1]
[1].School of Material Science and Engineering, Wuhan University of Technology, Wuhan, 430070, China
[2]The First Aviation Academy of Chinese Air Force，Xinyang,464000, China

Abstract *Rotary forging can overcome the shortcoming of cutting machining and reduces the forming load of the precision forging process. In this paper, the rotary forging process of spiral bevel gear was studied using finite element method, deformation and L-t (load–time) curve at every stage was analyzed. Thereby tooth filling phase during rotary forging of spiral bevel gear was obtained. At the same time, the formation of the inside, mid-point and outside at the addendum and dedendum of the convex and concave surface on the blank was also analyzed. As a result, the reason that the outside is difficult to fill was explained. Via theoretical Calculation and the lead specimen test, the rotary forging process of spiral bevel gear was verified which demonstrated the validity of the rotary forging process of spiral bevel gear.*

Keywords *Spiral bevel gear, Rotary forging, Punch, Finite element, Experiment*

1.Introduction

Spiral bevel gear is a core component of the differential，which has the following characteristics: High transmission efficiency, high carrying capacity, driving smoothly and space-saving. Nowadays, its Manufacturing mainly relies on special gear compound cutting machine[1] due to the complexity shape of spiral bevel gear. Comparing with machining, plastic forming can reduce material waste, improve gear strength and service life. However, precision forging of large-diameter spiral bevel gear is very difficult. Rotary forging, which is successive partial plastic forming, can decrease the forming load of spiral bevel gear[2] [3].

Finite element simulation can be used to verify the validity of the initial design and confirm the new ideas. In recent years, some scholars make use of finite element (FE) methods to study on the plastic forming process of gears. Soo-Young Kim studied on cold forging and heat treatment process for manufacturing of precision helical gear[3]. In order to reduce the forming load, Sung-Yuen Jung studied on the two-step extrusion of helical gear [5]. The rotary forging process of straight bevel gear was studied by Cheng Peiyuan [6]. J.J.Sheu studied on the rotary forging process of spur gear and found the ways to improve die life [7][8]. Han Xinghui studied the deformation characteristics of cold rotary forging of the ring workpiece[9]. Finite element simulation has become an important tool to develop and improve gear plastic forming. Because the tooth curve and metal flow of spiral bevel gear are complex，the die often fails from fracture. Die failure and difficulty in filling become the key technology of rotary forging process of spiral bevel gear[10][11]. In order to investigate some problems about metal flow, die stress and load change during rotary forging of spiral bevel gear, FE model of rotary forging process is established and rotary forging course of spiral bevel gear is simulated and analyzed in this paper.

2.FE model of rotary forging process for spiral bevel gear

Taking an automobile differential device spiral bevel gear as the example, the rotary forging process of spiral bevel gear was studied. Forging shape of gear components is shown in Fig. 1 and the blank shape shown in Fig. 2 .The blank material was AISI-1045.

Fig.1.The rotary forging model of spiral bevel gear

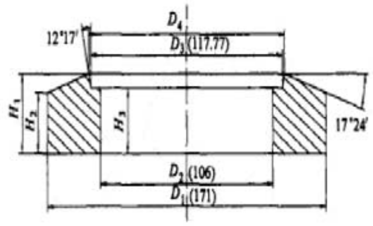


Fig.2.The blank of spiral bevel gear

Fig. 3 shows the finite element model of the rotary forging process for spiral bevel gear. The blank was fixed on the centre of die and the deformation on inner wall was constraint, so the gear was formed by the punch. The constant friction model was adopted for the contact between punch and blank as well as die and blank, and the friction coefficient was 0.12.

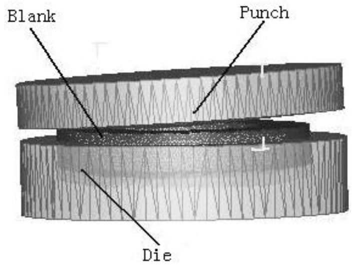


Fig.3.The FE model of spiral bevel gear for rotary forging

3.Analysis of rotary forging Load

3.1load-time curve

The load-time curve during rotary forging process of spiral bevel gear was shown in Fig.4. The figurowed that spiral bevel gear forming process is divided into three phases: free upsetting stage, tooth filling stage, tooth corner filling stage.

1) Free upsetting stage: From the beginning up to 1.5sec; because of the existence of the gap between the blank and die, the deformation at this stage is equivalent to free upsetting process. The forming load increases quickly and the maximum load was 1×10^6N.

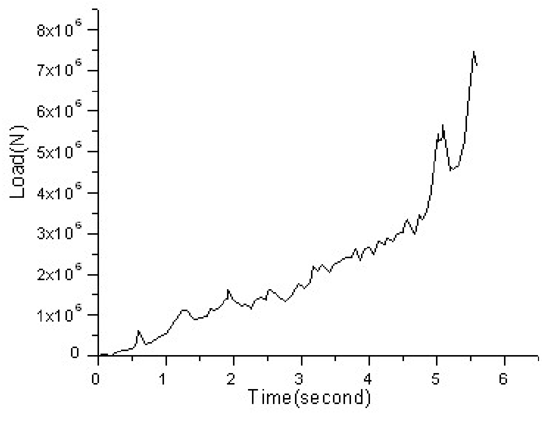


Fig.4.The load –time curve of rotary forging

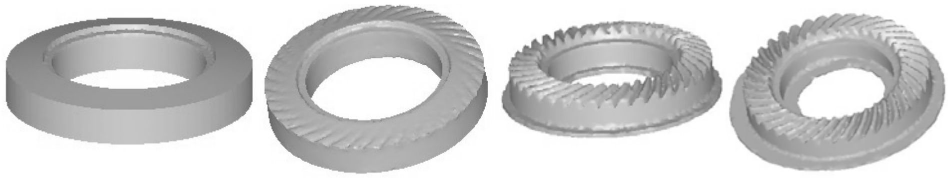
2) Tooth filling stage: From 1.5sec to 4.5sec. Some metal close to the die tooth moves into the tooth impression. Other metal flows back axially or horizontally due to the obstruction of tooth impression. Deformation at this stage is equivalent to forward extrusion with small

cone angle; the tooth profile forms gradually. The load increase slowly and the maximum load is 3×10^6N.

3) Tooth corner filling stage: From 4.5sec to 5.6sec; metal overcome friction resistance and move into the tooth corner. The load surge and the maximum load is 7.5×10^6N. This stage is a decisive stage during forming, for it determines the tonnage of forging equipment, prefabricated blank and precision die shape and so on.

3.2The deformation process of rotary forging

Fig.5 shows the deformation of blank during the rotary forging process, which is obtained from the simulation. As shown, the blank deformation begins from the outside section near the middle, followed by a steady teeth body filling with a uniform flash at the outer and inner edge as shown in Fig.5c. Finally, while metal flows into the tooth corner, the flash becomes thinner and larger because the gap between the punch and the die reduces.



(a) 0sec (b) 1.5sec (c) 4.5sec (d) 5.6sec

Fig.5.The deformation process of rotary forging

3.3The distribution of effective strain

The distribution of effective strain on the blank at the final stage is shown in Fig.11. It can be seen that greatest effective concentrates on the inner and outer lateral flashes. The width of the outer flash is 9.5mm and the inner flash is 8.5mm by measure. Effective strain can reflect the forming load approximately. Thus, large lateral flash consumes large forming road at the final stage of rotary forging process, which causes the load increase to 7.5×10^6N sharply. So reduce the flash area at the final forming stage is necessary.

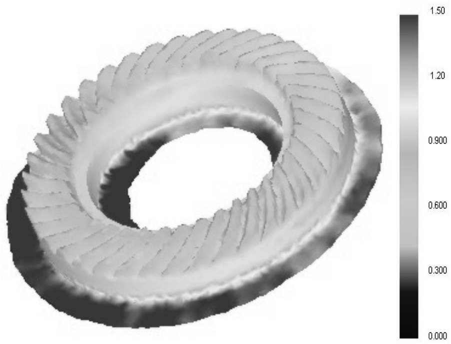
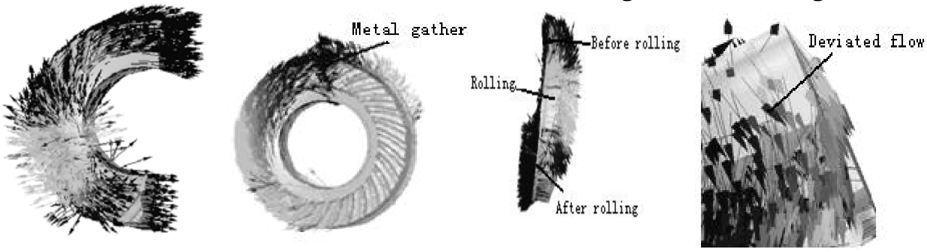


Fig.11. Effective strain of work piece

4.The metal flow

4.1 The overall flow of metal

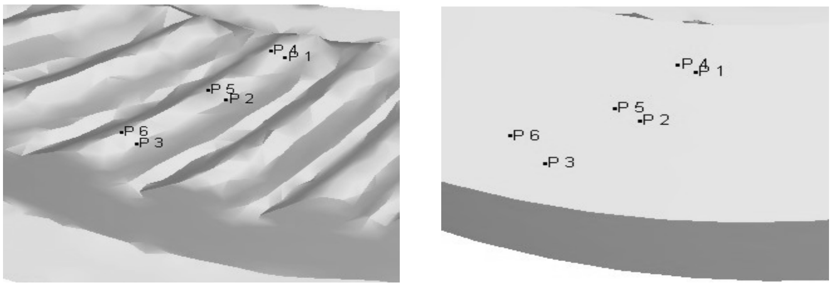
In the forming process, the metal flows along the circumferential direction shown in Fig.6. The circumferential size becomes large and the axial size becomes small. At the area which rolling part contacted with punch , both sides metal was squeezed like a wedge then flow circumferentially and gathered to the opposite of the wedge, as shown in Fig.6b. One side of the wedge, metal flows towards the die; the other side metal flows towards the punch, as shown in Fig.6c. Metal being rolled flows complexly and the tooth shape was changed, which lead to a deviation between the direction of metal flow and feeding, as shown in Fig.6d.



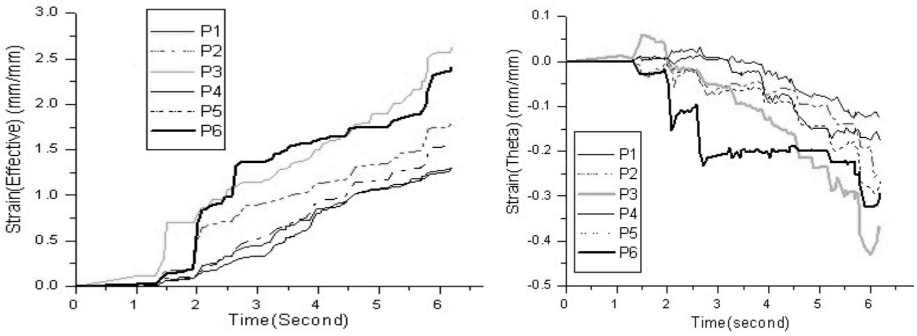
(a) Cross-section (b) Top view (c) Side view (d) Wedge section

Fig.6. Total velocity

4.2 Metal deformation at the addendum



(a) The selected points on the formed part (b) The tracking points on the initial blank



(c) The tangential strain (d) The effective strain

Fig.7. Deformation of the selected points at the addendum

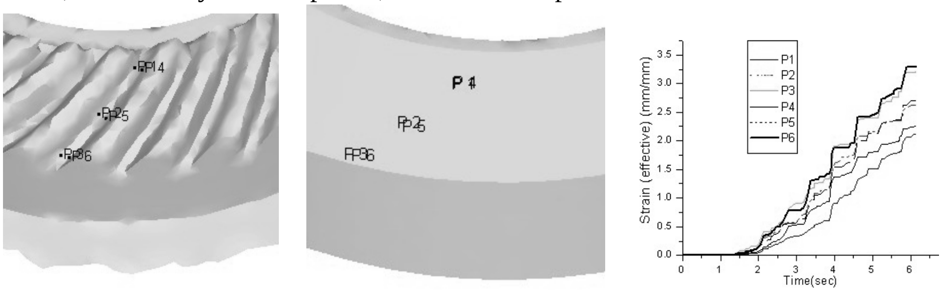
The convex and the concave shapes of a spiral bevel gear are dissimilar. In order to study the deformation of the convex and concave surface at the addendum, some points are selected: P1, P2, P3, the inside, mid-point, outside points at the convex surface, respectively; corresponding to them , P4, P5, P6, the inside, mid-point and outside at the concave surface, as shown in Fig.7a.

After tracking their position and plastic deformation, the selected points at the addendum of the convex and concave can be found on the cone surface of the blank, as shown in Fig.7b, and the points at the outside of the concave and convex produce the largest tangential displacement relatively than others, followed by the mid points, and the inner points are the smallest shown in Fig.7c.

Effective strain of the selected points is shown in Fig.7d which consists with tangential strain trend. The outside portion is difficult to fill except increasing the load.

4.3 Metal deformation at the dedendum

The same method was used to analyze the deformation at the dedendum, some points were selected: P1, P2, P3, the inside, mid-point, outside points at the convex surface, respectively, corresponding to them, P4, P5, P6, the inside, mid-point, outside points at the concave surface, as shown in Fig. 8a. Fig.8b shows the points on the initial blank, and it can be found that they are all under the cone surface of the blank. As Fig.8c shows, the points at the outside of the concave and convex surfaces produce the largest effective strain, relatively than others, followed by the mid points, and the inside points are the smallest.



(a)The selected points on the formed part (b)The tracking points on the initial blank

(c)The effective strain

Fig.8.The deformation of the selected points at the dedendum

5.Theoretical calculation and Forming test

5.1 Theoretical Calculation

The width of the outer flash is 9.5mm by measure and the inner flash is 8.5mm. So the outer radius of the blank is 95mm, and the inner radius is 44mm. Radius values are inputted into the formula of contact surface area ratio of circular pieces during rotary forging process [2], and obtained (Formula 1）.

$$\begin{aligned}\lambda &= (0.4\sqrt{Q} + 0.14Q\ )(1.01 - 0.31\frac{r_1}{R_1}) \\ &= (0.4\times\sqrt{\frac{1.5}{2\times 95\times tg3^\circ}} + 0.14\times\frac{1.5}{2\times 95\times tg3^\circ})\times(1.01 - 0.31\times\frac{44}{95}) \\ &= 0.1527\end{aligned} \qquad (1)$$

Inputting λ into the calculating load formulation [2], it was obtained:

$$\begin{aligned}P &= \lambda F K\sigma_s \\ &= 0.1527\times 3.14\times(95^2 - 44^2)\times 1.9\times 903 \\ &= 5.83\times 10^6 N\end{aligned} \qquad (2)$$

Where λ is the contact surface ratio, F is the contact surface, Q is the relative feeding, K is the coefficient of upsetting.

Load-time curve of rotary forging for spiral bevel gear (fig.4) shows that the stable forming force was about 6×10^6 N, the theoretical value is 5.83×10^6N according to formula (2). The forming force based on the FE simulation is close to the theoretical calculation. This fact shows that the FE simulation about the rotary forging process for spiral bevel gear is successful.

5.2 Forming test

In order to verify the validity of simulation, a test was done using lead as the test material. The blank shape is shown in Fig.2, and its volume designed by equal volume method. The forming process during rotary forging was shown in Fig.9. It can be found that the tooth filling process and the flash deformation obtained by simulation show good agreement with that obtained by the test. Tooth is full-profile, which demonstrates that the rotary forging process of a spiral bevel gear is feasible.

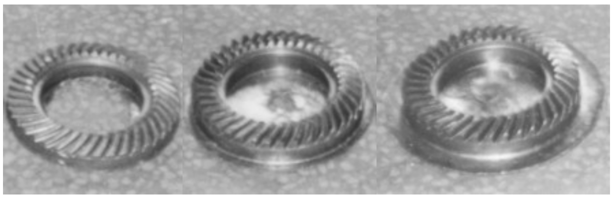


Fig.9.The experiment of tooth filling process

6.Conclusion

Spiral bevel gears have different convex and concave shape, long and spiral teeth, so the rotary forging process of spiral bevel gear is a complicated engineering. In this paper, the rotary forging process of spiral bevel gear was studied using DEFORM-3D and test methods. Through the study on the rotary forging process of spiral bevel gear, the deformation and load at every stage and the tooth filling characteristics are obtained. The main results of specific studies are as follows:

(1) During the rotary forging process of spiral bevel gear, the course of metal-filled cavity is divided into three stages and at the final stage the flash is large and the load is excessive.
(2) The largest strain at the outside points is the reason why it is difficult to fill totally at the outer portion.
(3) Via theoretical calculation and the lead specimen test, the feasibility and validity of the rotary forging process for spiral bevel gear was verified.

Acknowledgements

The research is supported by the Scientific Foundation for Hubei in China (2007ABA214) and the Fundamental Research Funds for the Central Universities (2010-ZY-CL-046).

References

[1] ZENG Tao. Spiral bevel gear design and processing Harbin: Harbin Institute of Technology Press,1989
[2] PEI Xinghua, ZHANG Meng , HU Yamin. Rotary Forging. Beijing: Machinery Industry Press, 1991.
[3] Soo-Young Kim, Satoshi Kubota and Masahito Yamanaka. 'Application of CAE in cold forging and heat treatment processes for manufacturing of precision helical gear part.'[J] Journal of Materials Processing Technology. 2008,201(1-3) : 25~31.
[4] Wang G.C, Zhao G. Q. 'Simulation and analysis of rotary forging a ring workpiece using finite element method'[J]. Finite Elem. Anal. Des. 2002,38 (12): 1151~1164
[5] Sung-Yuen Jung, Myung-Chang Kang and Chul Kim. 'A Study on the Extrusion by a two-step process for manufacturing helical gear'[J]. The International Journal of Advanced Manufacturing Technology. 2008,41: 684~693.
[6] CHENG Peiyuan, HU Rui and HUA Lin. 'Finite Element Analysis of Rotary Forging in Straight Tooth Bevel Gear'[J]. Hot Working Technology. 2006,35(21) : 65~68.
[7] J.J. Sheu and C.H.Yu. 'The die failure prediction and prevention of the orbital forging process'[J]. Journal of Materials Processing Technology. 2008,201(1-3) : 9~13.
[8] J.J.Sheu and C.H.Yu. The Cold Orbital 'Forging Die and Process Design of a Hollow Ring Gear Part'[C]. Proc. Of the The 35th International MATADOR Conference. Taipei (2007) 111~114.
[9] Han Xinghui, Hua Lin.'3D FE modeling of cold rotary forging of a ring workpiece' Journal of Materials Processing Technology.2009,209(12-13):5353~5362.

[10] M.H.Sadeghi，T. A. Dean. ‘Precision Forging Straight and Helical spur Gear’ [J]. Journal of Materials Processing Technology,1995,45(1-4) : 25-30..

[11] Li Yamin，Wang Huajun，Wang Xueyang，Zhu Chundong. ‘Die fracture of bevel gear in the rotary forging process’[J].China Metal Forming Equipment & Manufacturing Technology.2009,89(4):89-92.