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ORIGINAL ARTICLE

Research on gear tooth forming control in the closed die hot forging of spiral bevel gear

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Abstract To improve the tooth forming quality of forging spiral bevel gear, a systematic hot forging method for spiral bevel gear is proposed in this paper, which helps to improve some defects in the traditional forging methods, such as the insufficient gear tooth corner filling, the high forming load, and the low die service life. With Deform-3D, the simulation analyses of the closed die structures are carried out to reveal the effects from the tooth forming process parameters, which are including the forging temperature, the strike speed, the die preheating temperature, and the friction coefficient. For further meliorating the addendum of tooth toe-end filling situation, an improved forging process with tooth preformed is presented. Thereinto, the excess material is reserved at the tooth toe-end position in preformed stage, so that the material flow velocity at the tooth toe-end area synchronizes with that at tooth heel-end area. Compared with the traditional process by the numerical analysis, the improved process can not only reduce more than 6% of the forming load but also relieve the sharp rising trend of finish forging load. Finally, the effectiveness of the improved process is verified through the forming experiments, and the results are in good agreement with the simulation ones, which can provide the theories foundation for enhancing the forging quality and decreasing the scrap rate of the forged spiral bevel gear.

Keywords Spiral bevel gear · Closed die · Hot forging · Process parameter · Tooth preformed

1 Introduction

Spiral bevel gear, with the excellent meshing performance and the outstanding transmission efficiency, is widely applied to the transmission system of intersecting axes or crossed axes [1, 2]. Due to the complexity of meshing surface, the spiral bevel gear machining is not an easy work. As we know, the traditional machining method of spiral bevel gears is face milling/face hobbing [3], which must rely on a special machine tool. Meanwhile, there are some shortcomings in the traditional machining, such as

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the high materials and energy consumptions, the low production efficiency, and the environmental pollution, especially for reduced tooth fatigue strength [4] because of cutting off the continuous flow line. The keys of traditional machining is that the milling process is carried out after isothermal normalizing and the milling allowance of gear tooth is huge, so that the balance of internal stress field is broken and the tooth surface occurs deformation, resulting in reduced accuracy of spiral bevel gear after press quenching and carburization.

Precision forging, as a green manufacturing technology, could be seen as a perfect means to improve the machining gear and to resolve the problems mentioned above. For spur/helical gear and straight bevel gear, the precision forging has achieved remarkable development [4–10]. However, due to the complex geometrical shapes, the spiral bevel gear forging process has been difficult to break. High forming load in the forging process and the insufficient filling of tooth corner have become the main factors restricting the forging form of spiral bevel gear, and the high reject rate of forging blank is also the barriers impeding the industrialization of forging spiral bevel gear.

To improve the problems of precision forging, the studies on forging spiral bevel gear become ever more active. Lai [11] have focused their attentions on the metal flowing laws of gear tooth forming. Wang et al. [12, 13] studied the effects of process parameter on forging spiral bevel gear. Luo et al. [14] and Chen [15] studied the forming process based on the numerical simulation, and they developed an optimized process employing divided flow method. Feng et al. [16] investigated the influence of optimized preformed shape on forming load for forging spiral bevel gear. Deng et al. [17] designed the workpiece geometry of cold rotary forging spiral bevel gear to reduce the forming load via the finite element method. Zhu et al. [18] presented different three models and analyzed the forming quality of rotary forging by finite element method. Zhao et al. [19] carried out the force of lift-out process of spiral bevel gear with small cone angle by ADAMS. Song et al. [20] analyzed the forming process of forging spiral bevel gear using closed die. Yang et al. [21] declared the impacts of preheating temperature and precision forging speed on die wear by rigid-plastic finite element. Gao et al. [22] studied the service life estimation method of the tooth die by using the modified Archard theory. Luo et al. [23] discussed the influences of process parameters on tooth life with rigid-plastic finite element.

All of these research works provide good references for the research on forging spiral bevel gear. So, the process parameters can be included as follows: the forging temperature, the blank shape, the striking velocity, and the friction condition, and the usual method for solving the forming load and quality is divided flow [14, 15, 24].

Table 1 Process parameters combination

	Forging temperature/°C	Die preheating temperature/°C	Strike speed/mm/s	Friction coefficient
C1–1	950	250	200	0.3
C1–2	980	250	200	0.3
C1–3	1100	250	200	0.3
C2–1	980	200	200	0.3
C2–3	980	300	200	0.3
C3–1	980	250	150	0.3
C3–2	980	250	250	0.3
C4–1	980	250	200	0.15
C4–2	980	250	200	0.45

But, there are rarely reports on improving the forging process by designing the tooth profile of preformed blank, and the processes mentioned above would be ineffective if the whole process consistency and the manufacturing cost were considered. In this paper, a systematic hot forging forming method about spiral bevel gear is proposed to solve the problems of forming load and insufficient filling. Firstly, the tooth forming process based on the closed die structure is simulated by Deform-3D, and the influence rules of process parameters on the tooth forming are analyzed. Secondly, to obtain sufficient material filling for forging blank, an improved forging process characterized by the tooth preformed is proposed. With the numerical simulations of the traditional process and improved process, the physical fields (such as the effective stress/strain, the material flow velocity, the forging temperature, and the forming load) are compared and analyzed. Finally, the experiments are also used to verify the rationality of the simulation process and the effective of the improved process. We expect that this method can provide an effective technical reference for the forging spiral bevel gear.

Table 2 Parameters of specified spiral bevel gear

Parameters	Value
Number of tooth	39
Module/mm	5.69
Pressure angle/°	22.5
Spiral angle/°	29.433 R.H
Face width/mm	32
Outside diameter/mm	222.28
Whole tooth depth/mm	10.42
Face angle/°	78.617
Pitch angle/°	77
Roof angle/°	72.85
Outer cone distance/mm	113.87

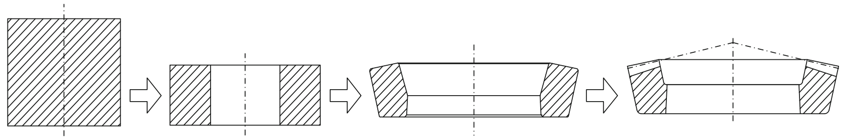


Fig. 1 Forging process for spiral bevel gear blank

2 Formation rules of gear tooth

2.1 Process parameters

For the gear forging using the closed die, the process parameters [11, 25, 26] influencing the tooth forming include the forging temperature, the strike speed, the die preheating temperature, and the friction coefficient. The control of above parameters has a direct effect on the forging quality of gear precision forging, so these are the beginning of our study. In order to revealing the tooth forming rules of process parameters in spiral bevel gear hot precision forging, the traditional method is employed, for example, one parameter is usually set as constant, while the others are set as variables. Thus, different combinations of parameters are constituted, as shown in Table 1, the combination C3–3 and C4–3 are same with C1–2.

In our work, the numerical simulation of gear forging is conducted using Deform-3D, and Table 2 shows the geometric parameters of spiral bevel gear. The gear material is 20CrMnTiH. To reduce the calculating time of CPU, the gear blank is seen as rigid-plastic in forging, and the dies are considered to be rigid body. One ninth of the gear blank are discretized with tetrahedral elements into 161,847 cells and 34,446 nodes, which can ensure that the simulation has better accuracy and convergences.

2.2 Forging process and closed die structure

In consider of the metal oxide generated in reheating stage, the forging process referred is designed to include the preformed forging, the shape rolling, and the finish forging, as shown in Fig. 1, and the blank is only heated once in the whole process. For the process, it is found that the most important phase is the shape rolling. After the shape rolling, the gear blank is similar with that of the finish forging. Thus, the forming load of finish forging can be decreased on account of less deformation.

Figure 2 shows the closed die structure of finish forging, and forging spiral bevel gear requires four elements: upper punch, tooth die, counter punch, and container die. The upper punch and tooth die are attached to the moving ram, and the container is attached to the stationary machine bed. The guide device of upper and counter punch ensures the symmetry of the gear blank. At the last moment of the finish forging, the tooth die is moved into the container die. For prolonging the service life of tooth die, an extra metal chute is designed in edge of the container die, and the excessive metal along back cone can be easily faced off in post-forging operation.

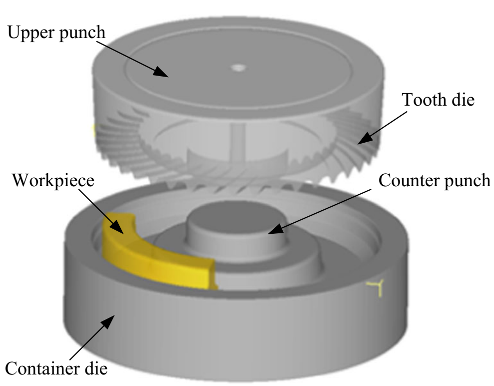


Fig. 2 Forging dies schematic of forging spiral bevel gear

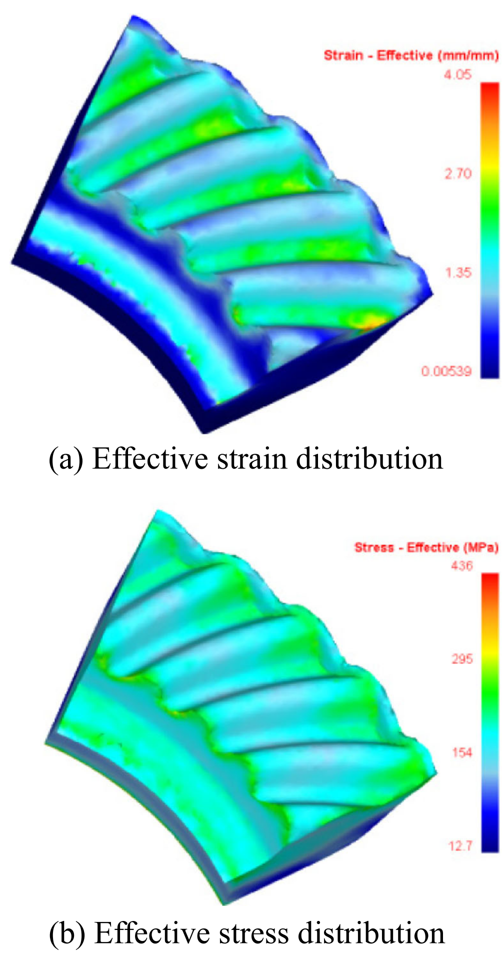


Fig. 3 Effective strain/stress distribution of forging blank. **a** Effective strain distribution. **b** Effective stress distribution

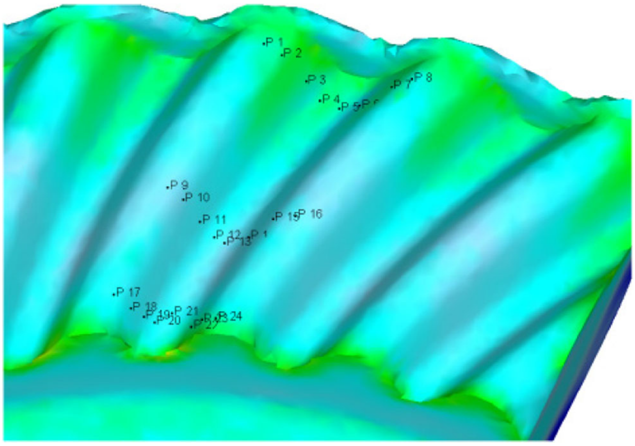


Fig. 4 Schematic location of points

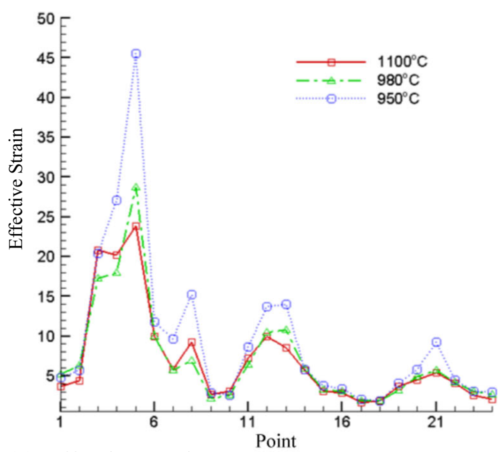
2.3 Simulation results and discussion

The distributions of effective strain and stress in the last stage of finish forging are shown in Fig. 3. The maximum strain and stress often locate at the toe-end and heel-end of tooth. In order to analyze the deformation of gear tooth, eight points are selected at each position of the toe-end, heel-end, and middle of tooth space (i.e., P1, P2..., P24), as shown in Fig. 4. Through the comparative analysis of the effective stress and strain of these points, the influences of process parameters on the forming of spiral bevel gear should be analyzed further.

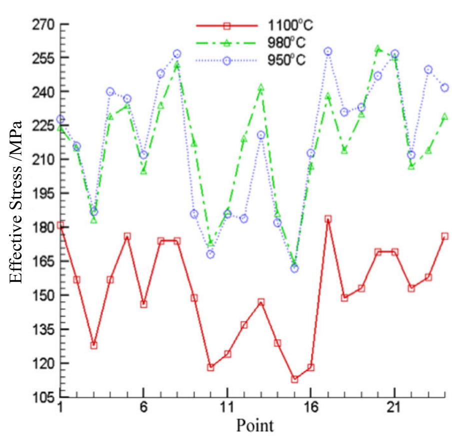
2.3.1 Effects of forging temperature

Figure 5 shows the effective strain and stress at the reference points with different forging temperatures.

From Fig. 5a, it can be found that the higher the forging temperature, the smaller the stress and strain of the forging part. Due to the flash formed by the excessive metal moving along the back cone, the maximum strain appears at the dedendum of heel-end. For different forging temperatures, the change of strain located at selected points are not obviously except the points of dedendum, which illustrates that the material deformation of tooth surface is not sensitive to temperature. Meanwhile, we find that the strain of the same reference point of the

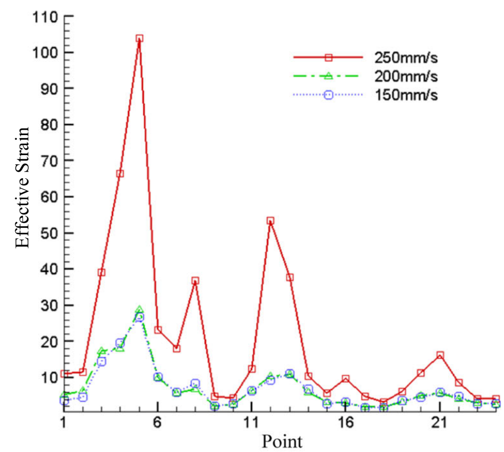


(a) Effective strain

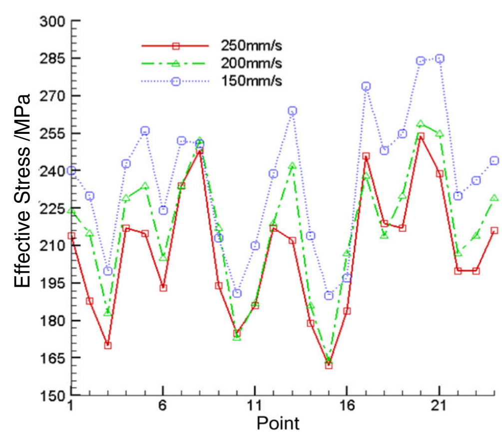


(b) Effective stress

Fig. 5 Effective strain and stress of forging temperature. **a** Effective strain. **b** Effective stress



(a) Effective strain



(b) Effective stress

Fig. 6 Effective strain and stress of strike speed. **a** Effective strain. **b** Effective stress toe-end and middle of tooth is close at 980 and 950 °C; however, the strain of dedendum varies drastically at 950 °C, which should be avoided. In Fig. 5b, the stresses of addendum and dedendum with different forging temperatures are larger than that of other positions. But, the stresses of the reference points at 1100 °C are the lowest than those of at 950 and 980 °C, respectively. In general, the improvement of forging temperature can reduce the stress of the forging part effectively, especially at the dedendum of heel-end. It can also improve the force of the heel-end of tooth die and reduce the occurrence of fracture failure of tooth die.

2.3.2 Effects of strike speed

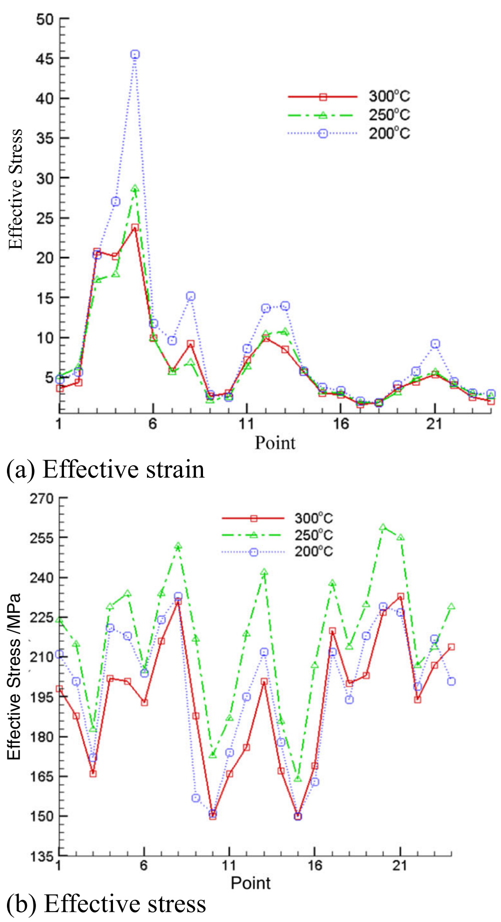
The comparative analyses of the effective strain and stress of forging part with three strike speeds are shown in Fig. 6.

It is clearly observed that the faster the strike speed, the greater the strain of the reference points, and the smaller the stress of those points. At any strike speed, the strain of addendum is less than that of dedendum, and the stress of dedendum is greater than that of addendum. The maximum strain is located at the heel-end of tooth, which indicates that the materials of tooth heel-end flow much faster to form flash in the final forging stage, resulting in the tooth toe-end is filled sufficiently. For the strike speeds 150 and 200 mm/s, the strains of same reference point are little different. In summary, the stress of the forging gear blank is decreasing with the increase of the strike speed. Considering the structure of the tooth die, a higher strike speed should be selected in practical production.

2.3.3 Effects of die preheating temperature

Figure 7 shows the comparative analyses of the effective strain and stress of forging part under different die preheating temperature.

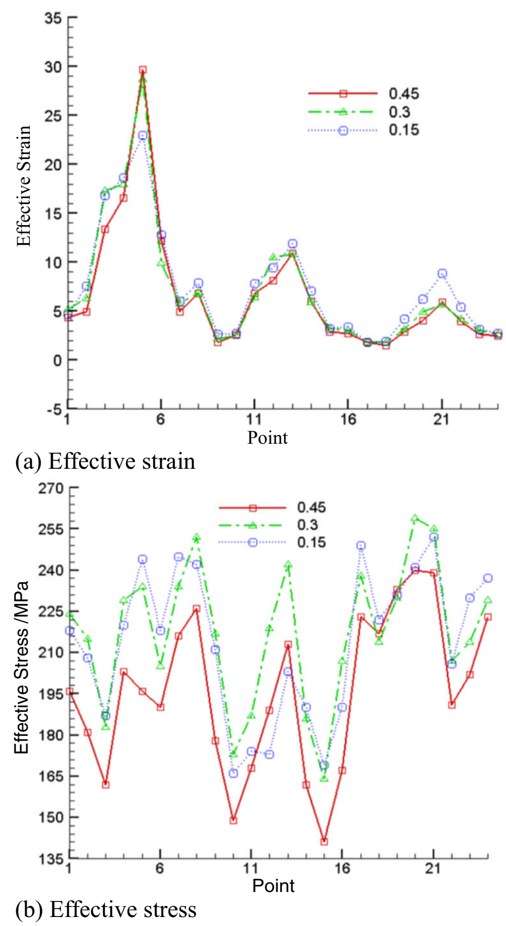
It can be seen from Fig. 7a that the increased die preheating temperature can cause the strain relief for forging part, which is especially obvious at the dedendum of heel-end, and the strain of the dedendum of heel-end is the largest than those of other positions. From the middle of tooth to the toe-end, the strains at the same reference



(a) Effective strain

(b) Effective stress

Fig. 7 Effective strain and stress of die preheating temperature. **a** Effective strain. **b** Effective stress



(a) Effective strain

(b) Effective stress

Fig. 8 Effective strain and stress of friction coefficient. **a** Effective strain. **b** Effective stress

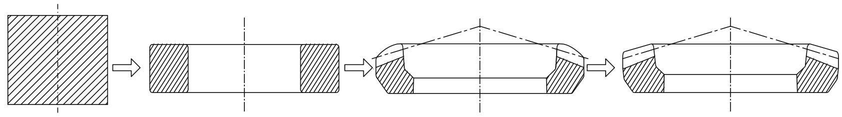


Fig. 9 Improved forging process for spiral bevel gear blank

point positions of forging die are consistent under the three different preheating temperatures. This indicates that the high die preheating temperature benefit to material filling. In Fig. 7b, the stress of the middle tooth surface is the smallest. When the die preheating temperature is 300 °C, the stress of the reference point of the tooth heel-end is the smallest, and when the die preheating temperature is 250 °C, the stress is the biggest, which is due to the improvement of the preheating temperature making for the flow of material. In short, the die preheating temperature is better to take between 250~300 °C, which will benefit to quicken metal flow and increase the service life of dies.

2.3.4 Effects of friction coefficient

The effective strain and stress of reference points under different friction coefficient are shown in Fig. 8.

It can be seen from Fig. 8a that the little friction coefficient can improve the flow performance of materials, so that the strain of the reference point is larger. Because the flash locates at tooth heel-end, the strain at the area is larger than that of other positions. Figure 8b shows that the larger the friction coefficient, the greater stress of the forging part, which illustrates that the metal flow performance of the heel tooth and toe tooth is bad, and the deformation resistance of the material is large. Good lubrication condition not only ensures that the tooth corner is filled ideally but also reduces the forming load effectively. Thus, it is necessary to choose little friction coefficient to improve the wear of tooth die.

2.4 Best process parameter combination

Based on the conclusions of section 2.3, the optimum process parameters are defined as follows: the deformation temperature of forging is 980 °C, the striking speed is 250 mm/s, the die preheating temperature is 250 °C, and the friction factor is 0.15.

3 Improved process

With the developments of computer-aided design and CNC machining technology, the manufacture of the die cavity has a good flexibility, so that the design and process methods can be conformed to the design intention of engineer.

From the deformation effects of the forging gears mentioned in section 2, it can be seen that the filling of tooth toe-end is more difficult than other positions under any process parameter. With the increase of outside diameter of spiral bevel gear, the problem becomes particularly prominent. Therefore, the key work is to solve the scrap rate problem due to the insufficient filling of tooth toe-end.

Firstly, the unimproved process (i.e., Fig. 1) is defined as process A, and the improved process is seen as process B (i.e., Fig. 9). Then, for the process A, the teeth of gear blank are formed in the finish forging stage. According to the simulation results, the tooth heel-end is filled firstly along the tooth width direction (i.e., Fig. 10, the areas besprinkled with green nodes represent the contact areas between the tooth die and

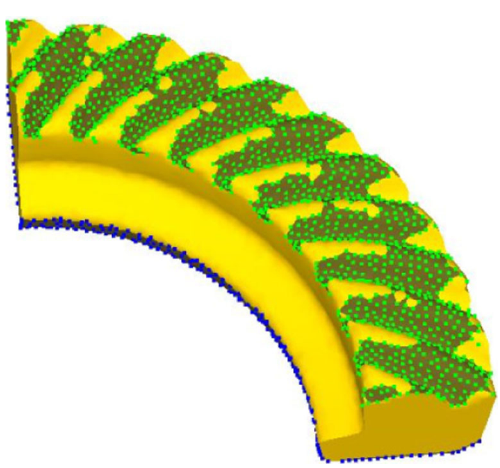


Fig. 10 Metal filling pattern along tooth width of PA

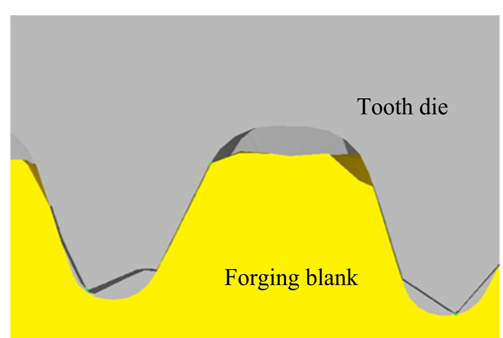


Fig. 11 Metal filling pattern along tooth profile of PA

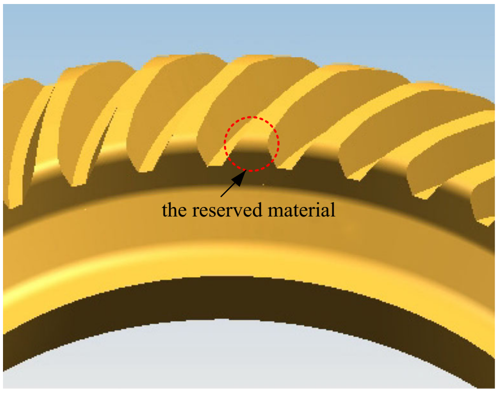


Fig. 12 3D diagram of preformed gear. **a** Metal flow pattern of PA. **b** Metal flow pattern of PB

Table 3 Parameters of specified spiral bevel gear

Parameters	Value
Number of tooth	41
Module/mm	10.588
Pressure angle/°	22.5
Spiral angle/°	34.3833 R.H
Face width/mm	61
Outside diameter/mm	434.1
Whole tooth depth/mm	17.14
Face angle/°	80
Pitch angle/°	49.6
Roof angle/°	76.35
Outer cone distance/mm	220.68

the gear blank), and the tooth toe-end is filled lastly due to the resistances from the friction force and air lock of the closed tooth die cavity. Meanwhile, the material flows along the surface of tooth die cavity, and the metal contacted with the die cavity surface flows slowly than that of other regions, as shown in Fig. 11. In the final stage of tooth filling, the forging load increases sharply due to the closed space of tooth toe-end.

To reduce forming load, the step-by-step forming process is used in the tooth forming, and the preformed gear blank is designed, as shown in Fig. 12. In the final forging stage, the tooth thickness of the finish forging blank is thicker than that of the preformed blank, and when preformed, blank is placed on the finial tooth die, the space between the preformed tooth, and the tooth die cavity always exist; therefore, the frictional resistance can be ignored until that the metal contacts with tooth die surface, and the purpose of reducing the forming load is achieved. In general, the method of improving tooth toe-end corner filling substance is that some materials at tooth toe-end are reserved in preformed stage. As a result, the pattern of process A flowing from the tooth middle region to the tooth toe-end can be changed, as shown in Fig. 13. Thereinto, the flow velocity of the material located at the both tooth ends is basically the same, so that the addendum of tooth toe-end is filled well, as shown in Fig. 13b. From the optimized route mentioned above, the design scheme of tooth die can be conducted for preformed stage in process B.

4 Results and discussion of improved process

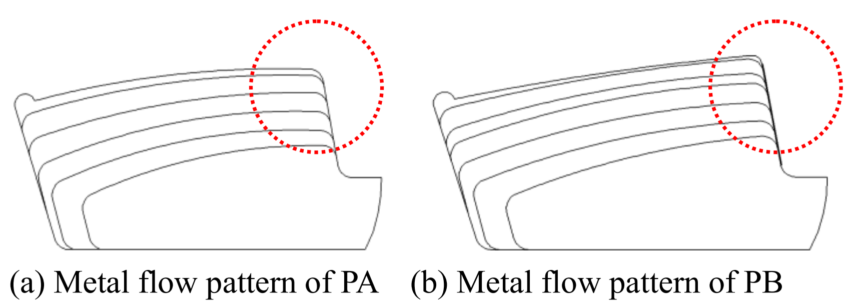
4.1 Simulation procedures

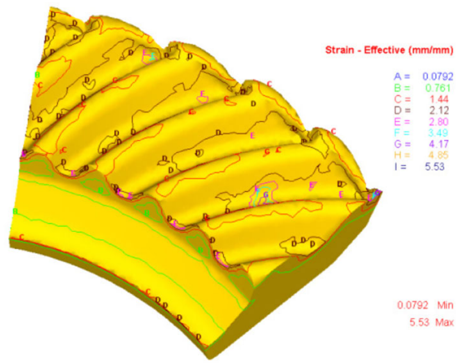
In order to reflect the effectiveness of the improved process, the much more bigger outer diameter is chosen, where it is 434 mm, and the geometric parameters are listed in Table 3. The gear material is 20CrMnTiH. For increasing the accuracy of simulation and decreasing the calculating time, the gear blank is defined as rigid-plastic, and the dies are considered as rigid. The temperature of forging and die preheating are 980 and 250 °C, respectively. The strike speed is 250 mm/s, and the heat transmission coefficient is 5.

4.2 Effective strain

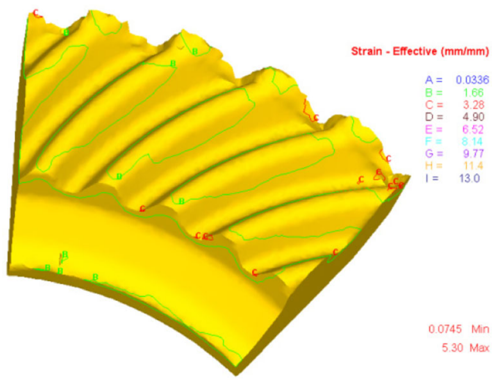
Figure 14 illustrates the distributions of the effective strain in the finish forging stage. For the process A, the tooth are not formed in the preformed stage, the metal flow is severe in the finish forging stage, so that the strain distribution is not regular, as shown in Fig. 14a. It can be

Fig. 13 Diagram of metal flow pattern of two process



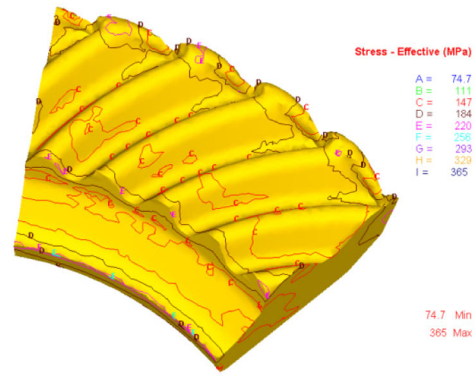


(a) Effective strain of PA

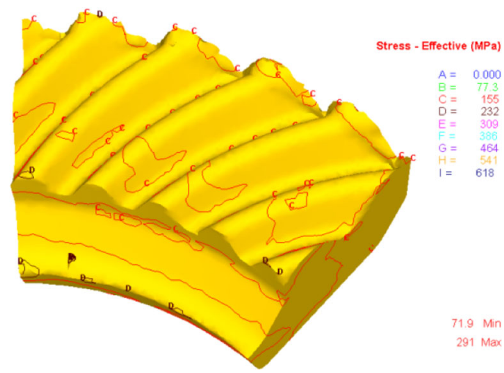


(b) Effective strain of PB

Fig. 14 Effective strain of processes A and B. **a** Effective strain of PA. **b** Effective strain of PB



(a) Effective stress of PA



(b) Effective stress of PB

Fig. 15 Effective stress of processes A and B. **a** Effective stress of PA. **b** Effective stress of PB

found that the strain of addendum is smaller than that of dedendum, that is to say, the metal deformation of addendum is not obvious. Due to the flash formed along the back cone, the strain of tooth heel-end is greater than that of tooth toe-end. From Fig. 14b, it can be seen that the strain distribution of process B is relatively uniform, which indicates that the tooth deformation is relatively gentle, and the force of the tooth die is relatively even.

Moreover, the strain of process B is smaller than that of process A, the maximum strain of the tooth middle is 1.66, and the maximum strain of the tooth heel-end and toe-end is 3.28. Correspondingly, for the process A, the maximum strain of the middle tooth is 4.17, and the maximum strain of each tooth end is 3.49.

4.3 Effective stress

The distributions of the effective stress of the two different processes are shown in Fig. 15.

It can be seen that the stress distribution of process A is not uniform. The stress distribution is different in the tooth toe-end, the middle near tooth toe-end area, and the tooth heel-end. From Fig. 15a, the stress of tooth toe-end is about 200 MPa, the average stress of middle area near toe-end is 147 MPa, and the stress of tooth heel-end is 184 MPa, respectively. The stress distribution of process B is more uniform by contrast, and the stress concentration is mainly distributed in the middle tooth and the tooth heel-end, that is, the average stress is close to 155 MPa.

4.4 Flow velocity

Figure 16 shows the velocity distributions of processes A and B. The velocities of material flowing at both tooth ends are obvious, which indicate that the deformation at last forging moment is the process of flash forming.

From the velocity of tooth heel-end, the maximum velocity in Fig. 16a is 3990 mm/s, and the velocity of the flash area is consistent. Likewise, the maximum velocity in Fig. 16b is 4010 mm/s. In general, the material flow velocity can reflect the corner filling situation,

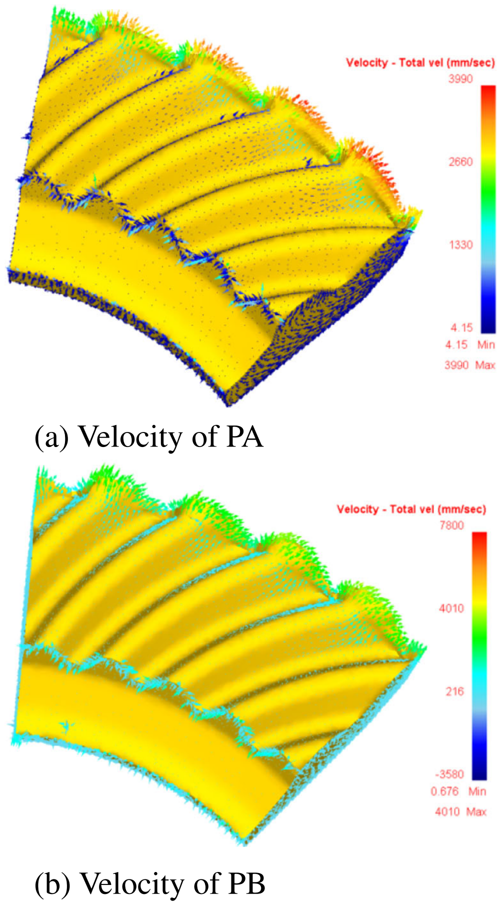


Fig. 16 Velocity of processes A and B. **a** Velocity of PA. **b** Velocity of PB

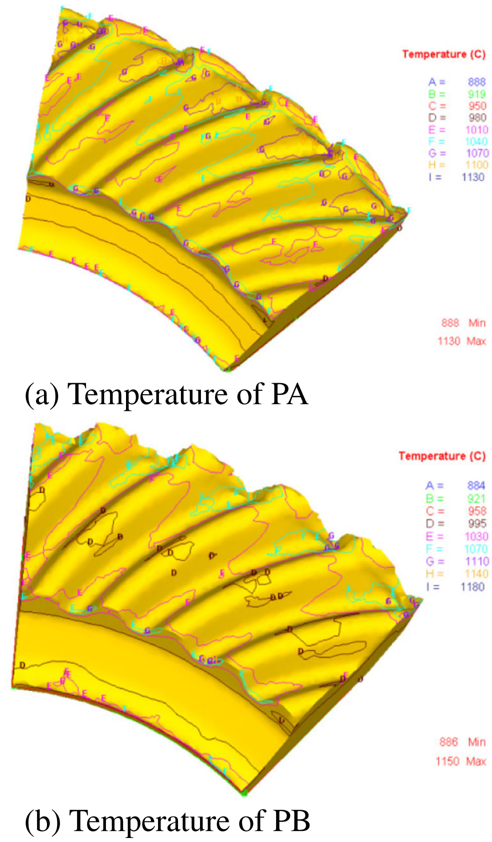


Fig. 17 Temperature of processes A and B. a Temperature of PA. b Temperature of PB

only when the material flows fast, the corner can be filled easily. In Fig. 16a, the average velocity of tooth toe-end is about 382 mm/s, and the average velocity in Fig. 16b is about 416 mm/s, that is to say, the process B has a good driving performance for the material filling tooth toe-end corner.

4.5 Forging temperature

The distributions of the forging temperature for the processes A and B are shown in Fig. 17. Local large deformation will cause the material to generate energy, so that the temperature of the forging blank will be increased. It is well known that high temperature is unfavorable to the service life of tooth die.

From Fig. 17a, the temperature of dedendum is the highest than that of other positions. For the process A, the maximum average temperature of dedendum is about 1100 °C, and the maximum average temperature of tooth toe-end is about 1070 °C. For the process B, the maximum average temperature at dedendum of tooth heel-end is about 1080 °C, and the maximum average temperature of tooth toe-end is about 1070 °C. The results show that process B can reduce the temperature of tooth heel-end of the forging blank, which is beneficial to prolong the die service life.

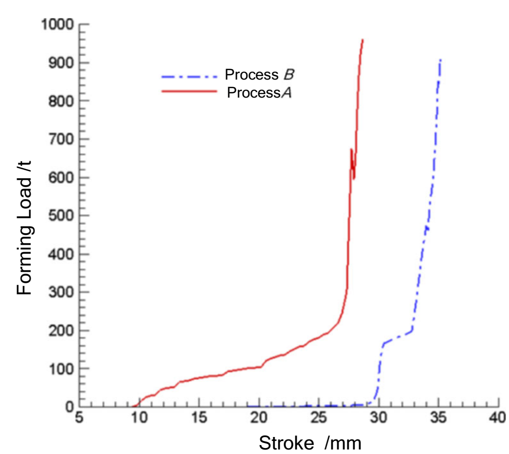


Fig. 18 Forming load of processes A and B

Fig. 19 3 T CNC hammer

4.6 Forming load

The forming loads of two processes in the final forging stage are compared in Fig. 18. The forming loads calculated one ninth of process A and B are 962.57 and 902.35 t, respectively. For the whole gear blank, the forming load of processes A and B are 8663.13 and 8121.15 t. On the other hand, the forming load of process B is about 6.26% lower than that of process A. So that process B can contribute to tap the potential of forging equipment, otherwise, the increasing trend in forming load is smoothly, which does not cause a sharp increase for the load force of die, and it can also help to improve the die service life.

5 Forging trails

According to the proposed process B, die preheating temperature is controlled at 250 ± 10 °C, and the graphite emulsion lubricant should be fully sprayed on the upper and lower surfaces of die cavity before forging. The forging of the preformed blank is carried out by 3 T CNC hydraulic hammer, as shown in Fig. 19. The finish forging is carried out by 25MN electric screw press, as shown in Fig. 20. Before the finish forging, the air gun will blow off the scale on the lower dies to improve the quality of the forged tooth surface.

Figures 21 and 22 show the preformed blank and the final forging blank obtained according to the process B. Resulting from the air lock, there is a little collapse angle at the toe-end addendum of the preformed gear by comparing to Fig. 12, and this situation can be acceptable. In the finish forging stage, the ram of electric screw press hits three times, and the numerical control screen shows each strike force is about 2750 t, so that the total actual forming load is about 8250 t, which is close to 8121.15 t obtained by the numerical simulation. From Fig. 22, the tooth toe-end of the final forging part is filled with a good condition, and it is also in good agreement with the numerical simulation results.

Fig. 21 Preformed blank

Fig. 20 25MN electric screw press

Fig. 22 Finish forging blank

6 Conclusions

In this paper, the 3D rigid-plastic FE model of hot forging 20CrMnTiH alloy spiral bevel gear is established and analyzed utilizing Deform-3D. FE analysis provides detailed information on the forming panorama, the forming load, the effective strain/stress, which can be incorporated into the process design. The following conclusions can be drawn from the results:

(1) The effective stress/strain fields during the forging process of spiral bevel gear are analyzed by the process parameters: the forging temperature, the die strike speed, the die preheating temperature, and the friction coefficient.
(2) From the deformation mechanisms of the forging blank, it can be seen that the deformation of tooth toe-end is difficult for any process parameter.
(3) An improved process plan is proposed in this work. The simulation results show that the improved process scheme has the advantages of the uniform stress distribution, the low forging temperature, and the good metal moving ability at tooth toe-end position. Moreover, the forming load is reduced by 6.26%, and the forming load in the finish forging process is relatively gentle.
(4) Based on the improved process, the forging experiment of spiral bevel gear with an outer diameter of 434 mm is carried out by 3 T CNC die forging hammer and 25MN electric screw press. The results verify the effectiveness of the improved process furtherly.
(5) Compared with the unimproved process, the optimized process needs one more tooth die, which can increase the production costs. For advancing the industrialization of the improved process, the ongoing studies involve prolonging the service life of the tooth die and decreasing the scrap rate.

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