Research on deformation mechanism and load effects of three-roller bending process for large gear teeth profile

Zhiyan Feng · Shengdun Zhao · Liangyu Fei · Hongtu Xu · Hao Zhou

Received: 18 October 2021 / Accepted: 21 February 2022 / Published online: 23 March 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Aiming at the problems of a large amount of material cutting waste or large forming load when large gear profile forming adopts overall cutting or precision forging process, this paper proposed a three-roller bending process (TRBP) for large gear teeth profile, and analyzed the deformation mechanism of the rack bending, meanwhile the gear chain for roll forming was designed. Finite element analysis (FEA) was carried out to numerically simulate the load effects of both the precision forging process and the TRBP for the large gear teeth profile in 17CrNiMo6. The effects of deformation force and strain of TRBP for large gear teeth profile were analyzed. The results showed that as the deformation temperature and speed increase, the deformation force and strain required by the gear profile gradually change. And the reasonable parameter of TRBP is around 750°C of deformation temperature and 0.5mm \cdot s^{-1} of speed. Compared with the precision forging process under the same boundary conditions, the deformation force of the gear profile TRBP has decreased by about 99% which could significantly reduce the tonnage requirement of deforming equipment.

Keywords Large gear · Teeth profile · Rack · Bending process · Gear chain

1 Introduction

Gear is one of the most widely used parts in the mechanical transmission systems of aerospace, aviation, navigation, vehicle, and other industries, which has the advantages of high power, high efficiency, high reliability, etc. [1]. Correspondingly, due to the high dimensional accuracy and shape complexity of gears, manufacturing and processing have certain difficulties [2]. The traditional processing methods include cutting processing and no cutting processing.

Cutting processing [3, 4] includes forming method and generative methods like gear milling, hobbing, grinding, etc. No cutting processing means plastic forming method [5, 6], including rolling [7], extrusion [8, 9], forging [10], and so on. At present, these methods have been widely used in the processing of small- and medium-sized gears, but the processing of large gear teeth profiles has always been difficult.

Large gear refers to a gear with a large modulus or large size, which has the characteristic of strong transporting capacity. The usual processing method is cutting [11]. However, cutting large gears requires special machine tools and cutters, which results in high costs, numerous waste [12], and having low fault tolerance. Emelyanov et al. [13] studied the influence of changes in tool axis angle when large-module gears were machining. Klocke et al. [11] analyzed gear hobbing of large-module gears using simulation and machining trials.

The problem of small batches of production and high costs drove researchers to make more researches in cutting tools and optimization of process flow, and also allows scholars to explore the possibility of plastic forming processes for large gears. Choi et al. [14] studied the method of reducing gear forging pressure by using precision forging instead of close-die forging and the accuracy of the gear
obtained met the industrial standard. Groche and Fritsche [15] did research on the method of flow manufacturing for internal gear. Hu et al. [16] simulated three different designs of die to research on insufficient corner filling of cold forging for spur gears. Jung et al. [17] studied a two-step extrusion process for helical gear to reduce forming load. Khodaee et al. [18] studied the effects of blank geometry when rolling large-module gears. Yadav and Singh [2] studied the magnetorheological forming for gear profile with high shape accuracy. Liu [19] used Deform software to simulate the precision forging process of a large gear with module of 20 and number of teeth of 60. Through the design of mold shape and process flow, the forming load was reduced to 4200 t.

In the past, gear processing, especially plastic forming, for large gears has seldom been researched and the design of the processes was mostly based on experience. Aiming at the problems of numerous cutting waste during cutting processing or high forming load during plastic forming when processing large gear teeth profile, this article proposed a new forming process—three-roller bending process (TRBP) for large gear teeth profile, which introduces the process that the rack was formed into an outer ring gear through a bending process, and then welded to the core. This process has many advantages: the processing of racks is much easier than that of large gears. There is no necessity to make special equipment for the forming needs of large gears and to use a large tonnage press, which can reduce the cost greatly. Besides, the strength requirement of large gear teeth is very high, so that superb materials and effective heat treatment processes are needed. Meanwhile, the core is in the shape of a cylinder which means ordinary steel can meet the strength requirements. This gear processing method allows the teeth and core materials to be different, thereby reducing cost further. For the TRBP of large gear teeth profile proposed in this paper, the bending deformation mechanism of the straight rack was analyzed, and the gear chain for the rack bending process was designed. FEA was used to numerically simulate both the TRBP and precision forging process for large gear teeth profile, which provided a theoretical basis for further research of processing trial.

2 Three-roller bending process of large gear

2.1 Bending deformation mechanism of rack

In order to study the novel gear forming process, the deformation mechanism of tooth profile under the condition should be deduced first, so as to lay a good foundation for the technological design. The characteristic of asymmetrical section bending like a rack is that the geometric neutral layer and the strain neutral layer do not overlap [20]. The gear studied in this paper is a large gear model, whose basic parameters are shown in Table 1. The index circle diameter is the product of the modulus and the number of teeth, which equals 600 mm. In another word, the curvature is 1/300. Therefore, it belongs to the problem of the small curvature of the plane. This paper derived the change of gear teeth profile by analogy to channel steel.

2.1.1 The basic assumptions

(1) Assumption of pure bending of the plane. The external force acts in the main inertia plane of the centroid of the rack, causing it to undergo elastoplastic deformation under the action of bending moment, and there is no torsion caused by shearing force.

(2) Assumption of constant volume. The volume of the rack remains unchanged before and after bending, and the position of the geometric neutral layer remains unchanged.

(3) Assumption of conventional material model. The rack is a continuous homogeneous elastic-plastic body. The elastic deformation meets Hooke’s law, and the plastic deformation is consistent with tension and compression.

2.1.2 Geometric model

Since the strain of the tooth bottom reaches its maximum when the rack is purely bent, the rack is simplified as shown in Fig. 1. The width is \( H \). The height is \( B \). The half-tooth tip thickness is \( t_1 \), and the half-tooth root thickness is \( t_2 \). The slope of the tooth surface is approximate 1:3. The rack thickness at the root of tooth is \( d \). The position of the geometric neutral layer is \( z_e \), which can be calculated from Eq. 1:

\[
e_1 = \frac{e_{11}A_1 + e_{12}A_2}{A_1 + A_2} \tag{1}
\]

Where \( e_{11} \) is the geometric neutral layer of the trapezoid part; \( A_1 \) is the corresponding area. Similarly, \( e_{12} \) is the geometric neutral layer of the rectangle part; \( A_2 \) is the corresponding area. And they can be calculated by the parameters mentioned above.

Table 1 Parameters of the gear studied in this paper

| Modulus | Teeth number | Pressure angle/° | Material       |
|---------|--------------|------------------|---------------|
| 5       | 120          | 20               | 17CrNiMo6     |
The equivalent strain neutral layer is introduced, the position of which is \( \varepsilon_3 \) from the bottom of the rack. The radius of curvature after bending is \( \rho_3 \), and the corresponding curvature is \( K_3 \). The distance from the strain neutral layer to the bottom of the rack is \( e_4 \), while to the elastoplastic boundary point being \( e_5 \). The radius of curvature of the geometric neutral layer before bending is \( \rho_0 \), and the corresponding curvature is \( K_0 \), while after bending being \( \rho \), and the corresponding curvature being \( K \). Strain can be obtained:

\[
\varepsilon = (z - e_1)\left(K - K_0\right) + \delta
\]

Where \( \delta = \frac{K_0}{K} - 1 \). And with boundary conditions being:

\[
\varepsilon_{z=e_4} = 0 \quad \text{and} \quad \varepsilon_{z=e_5} = \frac{\sigma_z}{E},
\]

\( e_4 \) and \( e_5 \) can be solved:

\[
e_4 = \frac{(e_1 - e_3)(r + e_3)}{r + e_1} + e_1
\]

\[
e_5 = \frac{\sigma_S(r + e_3)}{E}
\]

Where \( r (r = \rho - e_1) \) is the radius of curvature of the bottom plate after the rack being rolled.

In Fig. 2, suppose the positive tension is \( F_1 \) and the negative pressure is \( F_2 \), which are the integrals of tensile stress and compressive stress in the section. The strain neutral layer may be within the tooth height \((e_4 + e_5 \geq d)\), or it may be below the tooth \((e_4 + e_5 < d)\). In this article, its position is below the tooth. In this case, \( F_1 \) and \( F_2 \) can be obtained:

\[
F_1 = \int_{e_4}^{e_4 + e_3} HE\varepsilon_3 dz + \int_{e_4}^{d} H(D_{e_4} + \sigma_0) dz + \int_{d}^{B} 2t(D_{e_4} + \sigma_0) dz
\]

\[
= HE \int_{e_4}^{e_4 + e_3} \frac{z - e_3}{r + e_3} \varepsilon_3 dz + H \int_{e_4 + e_3}^{d} \left(D_{r + e_3} \frac{z - e_3}{r + e_3} + \sigma_0\right) dz
\]

\[
+ 2 \int_{d}^{B} \left(t_1 + \frac{B - z}{3}\right) \left(D_{r + e_3} \frac{z - e_3}{r + e_3} + \sigma_0\right) dz.
\]

2.1.3 Stress and strain

The bilinear hardening model [21] is shown in Fig. 2 to describe the problem of small curvature bending of the rack. And the stress is:

\[
\sigma = \begin{cases} 
D\varepsilon - \sigma_0 & \varepsilon < -\varepsilon_E \\
E\varepsilon & -\varepsilon_E \leq \varepsilon \leq \varepsilon_E \\
D\varepsilon + \sigma_0 & \varepsilon > \varepsilon_E
\end{cases}
\]

Where \( D \) is the plastic tangent modulus, \( E \) is the elastic modulus, \( \sigma_0 \) is the intercept stress, and \( \varepsilon_E \) is the plastic strain at demarcation point.

The equivalent strain neutral layer is introduced, the position of which is \( \varepsilon_3 \) from the bottom of the rack. The radius of curvature after bending is \( \rho_3 \), and the corresponding curvature is \( K_3 \). The distance from the strain neutral layer to the bottom of the rack is \( e_4 \), while to the elastoplastic boundary point being \( e_5 \). The radius of curvature of the geometric neutral layer before bending is \( \rho_0 \), and the corresponding curvature is \( K_0 \), while after bending being \( \rho \), and the corresponding curvature being \( K \). Strain can be obtained:

\[
\varepsilon = (z - e_1)\left(K - K_0\right) + \delta
\]

Where \( \delta = \frac{K_0}{K} - 1 \). And with boundary conditions being:

\[
\varepsilon_{z=e_4} = 0 \quad \text{and} \quad \varepsilon_{z=e_5} = \frac{\sigma_z}{E},
\]

\( e_4 \) and \( e_5 \) can be solved:

\[
e_4 = \frac{(e_1 - e_3)(r + e_3)}{r + e_1} + e_1
\]

\[
e_5 = \frac{\sigma_S(r + e_3)}{E}
\]

Where \( r (r = \rho - e_1) \) is the radius of curvature of the bottom plate after the rack being rolled.

In Fig. 2, suppose the positive tension is \( F_1 \) and the negative pressure is \( F_2 \), which are the integrals of tensile stress and compressive stress in the section. The strain neutral layer may be within the tooth height \((e_4 + e_5 \geq d)\), or it may be below the tooth \((e_4 + e_5 < d)\). In this article, its position is below the tooth. In this case, \( F_1 \) and \( F_2 \) can be obtained:

\[
F_1 = \int_{e_4}^{e_4 + e_3} HE\varepsilon_3 dz + \int_{e_4}^{d} H(D_{e_4} + \sigma_0) dz + \int_{d}^{B} 2t(D_{e_4} + \sigma_0) dz
\]

\[
= HE \int_{e_4}^{e_4 + e_3} \frac{z - e_3}{r + e_3} \varepsilon_3 dz + H \int_{e_4 + e_3}^{d} \left(D_{r + e_3} \frac{z - e_3}{r + e_3} + \sigma_0\right) dz
\]

\[
+ 2 \int_{d}^{B} \left(t_1 + \frac{B - z}{3}\right) \left(D_{r + e_3} \frac{z - e_3}{r + e_3} + \sigma_0\right) dz.
\]
Where intercept stress \( \sigma_0 = \sigma_3 \left( 1 - \frac{D_1}{D} \right) \). With the condition being \( F_1 + F_2 = 0 \) and parameters of the rack being substituted, \( e_3 = 9.347 \text{mm} \) can be worked out. Then the strain \( \varepsilon_3 \) at the tooth root can be calculated in Eq. 4 which is 0.08. The simulation of the rack bending process by FEA is shown in Fig. 3. The simulation result of the strain at the tooth root and the transition circle is 0.103, which is roughly consistent with the calculated result. The difference may be caused by the simplification of the theoretical model. However, the strain of the tooth profile does not increase linearly according to the calculation. The reason is that the mutation of the local shape of the plate leads to that the local material can not flow in accordance with the conventional theory, whereas the tiny deformation of the tooth shape is required by this novel gear forming process, which can ensure the accuracy of the rack after being bent.

2.1.4 Further simulation of tooth profile change

From the results of the previous section, it is acknowledged that the deformation of the tooth profile is very small, making it difficult to deduce the precise change of the involute tooth profile when the rack is bent. Therefore, the tooth profile change relationship is summarized through image processing by refining the mesh of the tooth profile. The shape of tooth profile before and after the rack bending is shown in Fig. 4 where the shape before bending is shown as mesh while that after bending being shown as strain cloud.

The tooth profile was identified and extracted in Matlab, \( z = d \) in Fig. 1 was taken as the origin of the abscissa, and the rate of tooth thickness change (the ratio of the deformation to original length at the same height) was taken as \( y \) to fit the changing relationship of the tooth profile.

Fitting the rate of change with a quadratic curve, the relationship of the tooth profile change can be obtained:

\[
y = 9 \times 10^{-8} z^2 + 7.9 \times 10^{-5} z + 0.0031
\]

(8)

Combining Sect. 2.1.3 and Eq. 8, the tooth profile of the rack corresponding to the involute gear can be obtained inversely, which provides a theoretical basis for the design and processing of the rack—the first step of TRBP.

2.2 TRBP for large gear teeth profile

2.2.1 Introduction of three-roller bending process

The process of using plate bending equipment to roll flat plates into cylindrical parts with different curvatures has the advantages of high efficiency and low cost, and has a wide range of applications in today’s industry. Among them, the most used plate bending process is TRBP, whose schematic diagram is shown in Fig. 5.

The research on the bending process involves the design and manufacture of bending equipment, the formulation of process parameters, and the realization of automatic control. Among them, the process parameters are as follows: the target radius of bending is \( R \), the diameter of the upper roller is \( D_1 \), the diameter of the lower roller is \( D_2 \), the distance between the lower rollers is \( a \), and the distance of the upper roller moving down is \( l \). From Fig. 5 parameter \( d \) can be obtained:

\[
(R - l)^2 + \left( \frac{a}{2} \right)^2 = R^2
\]

(9)
However, the bending of the blank is affected by many aspects, such as the thickness ratio of the blank, material and springback, etc. According to the research of Gandhi and Raval [22] and other scholars, when the plate is bent, the distance of the upper roller moving down and the bending target radius satisfies the empirical equation shown in Eq. 10, and the process parameters of the rack bending in this paper are also set according to this.

\[ l = P_0^Q R^{2 \times 10^{-5}} a - S \]  

(10)

Where \( P, Q, S \) are all parameters related to the diameter of the lower roller. \( P = 0.198 \left( \frac{D_2}{2} \right)^{-0.2582} \), \( Q = 2.1199 \left( \frac{D_2}{2} \right)^{-0.0057} \), \( S = 1.133 \left( \frac{D_2}{2} \right)^{-0.0373} \).

Based on the above analysis, the gear bending process proposed in this paper is divided into four steps: (1) rack design and processing; (2) rack bending; (3) the end of the rack being welded to get the outer gear ring; (4) the outer ring gear and the core being welded together to form the target gear. This paper mainly studies the first and second steps. The bending process model of the rack is shown in Fig. 6. The rack to be formed is used as a blank, and a gear chain is used as matching support to realize the bending of the rack.

The bending process of the rack is similar to it of the plate which is divided into three steps: pre-bending, bending, and final bending. The pre- and final bending processes are to roll the end of the rack. The process of rack bending is shown in Fig. 7. Where (a) is feeding, (b) is pre-bending, (c) is pressing and rolling, (d) is bending, (e) is bending and rolling, (f) is final bending, (g) is bottom welding, and (h) is core welding.

2.2.2 Design of the gear chain for bending process of rack

The fit between the rack and gear chain is not the traditional involute gear fit, but the shape of the tooth top of the gear chain is the same as the bottom of the rack tooth, and the rest is a straight line tangent to the transition circle of the rack tooth, as shown in Fig. 6b. Surface contact can minimize the pressure on the tooth bottom when the rack is bent under the same forming force, and the top of the rack will not bear the force when exposed to the gear chain gap, which can better ensure the shape of the rack tooth not be destroyed. As a locally rigid-flexible body, gear chains can be reused in the bending process of the rack, and the partial tooth section can be replaced if it is damaged locally, without causing extra cost waste.
During the forming process of a gear chain, the bent rack will be partially covered between the two lower rollers, which will require the distance between the tooth pitches to increase. A part of the process is shown in Fig. 8. Where $R'$ is the radius of curvature of the line connecting the pin centers when the gear chain is wrapped, $\theta$ is the angle between the center of two pitch pins and the center of the ring gear, and $b_1$ is the tooth pitch before wrapping when $b_2$ is which after wrapping. When $\theta$ is small, it can be obtained from the figure.

$$b_2 = \theta R'$$  \hspace{1cm} (11)

For the gear studied in this article, $R' = 318 \text{mm}$, $\theta = 3^\circ$, and $b_2$ can be solved as 16.65mm. And $b_1$ is known as 16.21mm, it can be obtained that $\Delta b = 0.44 \text{mm}$. Therefore, the pin and the pin hole are designed as a clearance fit, and the clearance is 0.22mm to meet the requirement of no movement interference during actual processing.

2.2.3 Plan for numerical simulation

In order to verify the correctness of the TRBP for the large gear teeth profile proposed in this paper, precision forging and TRBP are used to simultaneously deform the large gear teeth profile, and the corresponding comparative analyses of load effects were carried out. The process parameters used in the numerical simulation process are shown in Table 2. Among them, the TRBP is compared with multiple sets of

Fig. 7 Flow diagram of the TRBP for the rack

Fig. 8 Partial detailed schematic diagram of the TRBP for the rack
deformation temperature and speed simulations, and the boundary conditions with the best deforming effects of TRBP were set for precision forging as a comparison.

| Table 2 Process parameter of the numerical simulation |
|------------------------------------------------------|
|                                 | Three-roller bending | Precision forging |
| Mold preheating temperature/°C | 250                  | 250              |
| Deformation temperature/°C     | 250/500/750/1000     | 750              |
| Deformation speed/mnm⁻¹         | 0.2/0.3/0.4/0.5/0.6/0.7/0.8 | 0.5 |

3 Numerical simulation of three-roller bending process of large gear tooth profile

On the basis of the previous design, a 3D model was built, and FEA was carried out to simulate the process of rack bending. In order to improve the simulation efficiency, make the following settings: (1) using a rigid plastic material model, the workpieces are isotropic during deformation; (2) ignore inertial forces; (3) the ambient temperature is set to 25°C, and the friction model is set to Tresca, while the friction coefficient being 0.3.

Because the gear chain is a locally rigid-flexible body, it cannot be simulated in finite element software, and the main purpose of this simulation is to solve the state of the transmission chain.
blank rack in the forming process. Therefore, a rack with the same shape as the gear chain is used for the simulation instead of the gear chain. The process of simulation according to Sect. 2.2 is shown in Fig. 9, where (a) is feeding, (b) is pre-bending, (c) is pressing and rolling, (d) is bending, (e) is bending and rolling, and (f) is final bending. The process parameters do not strictly satisfy the Eq. 10, and the simulation results are obtained by multi-step iteration.

The orthogonal simulation of TRBP of large gear teeth profile was carried out and the result is shown in Fig. 10. It can be seen that the deformation force decreases gradually with the increase of temperature, while the strain decreases first and then increases. It is speculated that the further softening of the material leads to the surge of strain. Therefore, the most suitable forming temperature for 17CrNiMo6 in this process is $750^\circ C$. Furthermore, it can be seen that the deformation force decreases with the increase of deformation speed at high temperature. The strain tends to increase but fluctuation exists. It can be inferred that the mesh division being not fine enough results in the deviation of calculation. Combining Fig. 10a and b, it can be concluded that the deformation temperature being $750^\circ C$ and the deformation rate being $0.5 \text{mm} \cdot \text{s}^{-1}$, the novel TRBP for large gear teeth profile achieves the best deforming effects. The minimum deformation force is $2.367t$ and the strain is 0.2118. The strain cloud diagrams of the corresponding simulation results are shown in Fig. 11. The figure shows that the maximum strain occurs at the root of the tooth while the tooth shape was being well protected. In addition to the simulated points of stress mutation, the deformation strain remained near 0.1, which also verified the accuracy of the simulation in Sect. 2.1.3.

4 Numerical simulation of precision forging process of large gear tooth profile

The optimal boundary conditions of TRBP were given in the previous section, so the precision forging of the large gear was simulated being compared at the same deformation temperature and speed. The schematic diagram of the concave die used in the precision forging of large gears is shown in Fig. 12a. The deforming process is divided into the import stage, forming stage, and the truing stage. According to the gear studied in this article, the concave die is designed as Fig. 12b, and the diagram for assembly is shown in Fig. 12c and d.

The simulation result is shown in Fig. 13. During the axial precision forging process, the maximum forging force is $200t$ and the maximum strain is above 11. The part of blank outside the mating surfaces of the upper and lower molds will produce a certain degree of axial flow without shearing, and the material will eventually be difficult to fill the corner of the concave mold cavity well. The tooth forming result is worse than that of TRBP, and further processing will be needed.

5 Result

Through the novel TRBP for large gear teeth profile designed in this paper, the deformation force of a large gear with modulus of 5 and diameter of 600mm reduced from above $200t$ using precision forging to $2.367t$ at deformation...
temperature of 750°C and speed of 0.5 mm·s⁻¹, which is nearly 99%, meanwhile the accuracy of tooth shape gained was much better. The simulation results confirmed the feasibility of the novel process. And for further study, experiments would be carried out to validate the TRBP for large gear teeth profile.

Fig. 12 Diagram of the model for large gear precision forging

(a) Diagram of the concave die
(b) 3D model of the concave die
(c) Diagram of the assemble model
(d) 3D assemble model
6 Conclusion

- Aiming at the problem of consumptions of machining or large deformation force and insufficient corner filling of plastic forming, this paper proposed a novel TRBP for processing large gear teeth profile. The feasibility of the process was discussed, the deformation mechanism of the rack during bending was analyzed and verified with the FEA method, and the gear chain and its tooth profile required for the TRBP were designed.

- The three-roller plate bending process was studied and TRBP for large gear teeth profile was designed by analogy, meanwhile the appropriate process parameters were calculated. The FEM software was used to numerically simulate the precision forging process and the TRBP for large gear teeth profile. The effects of deformation force and strain field in the process of teeth deformation were analyzed.

- The simulation of load effects of deformation force and strain during the TRBP for the rack verified that the process is theoretically feasible. Compared with the plastic forming method of precision forging, the forming force of which required for hot extrusion at deformation temperature of $750^\circ C$ and speed of $0.5 \text{ mm} \cdot \text{s}^{-1}$ is $200 \text{t}$, the proposed TRBP theoretically reduces the deformation force by $99\%$, greatly reducing the cost in terms of equipment size and tonnage, meanwhile the deforming result is also way better. Furthermore, as the modulus of large gears increases, the equipment tonnage required for precision forging will be greatly increased, which will further reflect the advantages of this process.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

1. Li D, Zhang S, Yang X, Ma H, Sun S (2020) Numerical investigation on roll forming of straight bevel gear. Int J Adv Manuf Technol 1–21
2. Yadav RD, Singh AK (2019) A novel magnetorheological gear profile finishing with high shape accuracy. Int J Mach Tool Manuf 139:75–92
3. Chen Y, Hu Y, Lyu, Y, He G (2020) Development of a form milling method for line gear: principle, CNC machine, cutter, and testing. Int J Adv Manuf Technol 1–11
4. Bouzakis K-D, Kombogiannis S, Antoniadis A, Vidakis N (2002) Gear hobbing cutting process simulation and tool wear prediction models. J Manuf Sci Eng 124(1):42–51
5. Tomov B, Gagov V (1999) Modelling and description of the near-net-shape forging of cylindrical spur gears. J Mater Process Technol 92:444–449
6. Alves M, Rodrigues J, Martins P (2001) Cold forging of gears: experimental and theoretical investigation. Finite Elem Anal Des 37(6–7):549–558
7. Wu T, Wang G, Li J, Yan K (2018) Investigation on gear rolling process using conical gear rollers and design method of the conical gear roller. J Mater Process Technol 259:141–149
8. Koenig W, Fan J, Seibert D (1993) Recent developments in the extrusion of helical gears. Int J Mach Tool Manuf 33(4):599–614
9. Çan Y, Altunbalik T, Akata HE (2005) A study of lateral extrusion of gear like elements and splines. J Mater Process Technol 166(1):128–134
10. Lee Y, Lee S, Lee C, Yang D-Y (2001) Process modification of bevel gear forging using three-dimensional finite element analysis. J Mater Process Technol 113(1–3):59–63

Author contributions Zhiyan Feng did the research and wrote the manuscript. Shengyun Zhao provided the idea and the funding. Liangyu Fei, Hongtu Xu, and Hao Zhou revised the manuscript.

Funding This work was supported by the Joint Fund for Aerospace Advanced Manufacturing Technology Research Key Program (Grant No.U1937203).
11. Klocke F, Brumm M, Weber G (2015) Simulation based design for large module gear machining with indexable inserts. Procedia CIRP 33:470–475
12. Gao Z-S, Li J-B, Deng X-Z, Yang J-J, Chen F-X, Xu A-J, Li L (2018) Research on gear tooth forming control in the closed die hot forging of spiral bevel gear. Int J Adv Manuf Technol 94(5–8):2993–3004
13. Emelyanov S, Chevyelcov SA, Chistyakov PP (2015) A method of processing of involute profiles of large-module gear wheels. In: APPL Mech Mater, vol. 698, pp 546–551. Trans Tech Publ
14. Choi J, Choi Y (1999) Precision forging of spur gears with inside relief. Int J Mach Tool Manuf 39(10):1575–1588
15. Groche P, Fritsche D (2006) Application and modelling of flow forming manufacturing processes for internally geared wheels. Int J Mach Tool Manuf 46(11):1261–1265
16. Hu C, Wang K, Liu Q (2007) Study on a new technological scheme for cold forging of spur gears. J Mater Process Technol 187:600–603
17. Jung S-Y, Kang M-C, Kim C, Kim C-H, Chang Y-J, Han S-M (2009) A study on the extrusion by a two-step process for manufacturing helical gear. Int J Adv Manuf Technol 41(7–8):684–693
18. Khodaei A, Melander A, Haglund S (2018) The effects of blank geometry on gear rolling for large gear modules: experiments and finite element simulations. IEEE Access 6:33344–33352
19. Xiuxia L (2017) Research on the new technology for plastic forming process of large gear. Master’s thesis, Yanshan University
20. Yin J, Liang R (2016) Theoretical analysis of neutral layer deflection in pure bending of asymmetrical section beam. Journal of Yanshan University 40(5):413–418425
21. Zhao J, Yin J, Ma R, Ma L (2011) Springback equation of small curvature plane bending. Sci China Technol Sci 54(9):2386–2396
22. Gandhi A, Raval H (2008) Analytical and empirical modeling of top roller position for three-roller cylindrical bending of plates and its experimental verification. J Mater Process Technol 197(1–3):268–278

**Publisher’s Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.