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Research on Deformation Mechanism and Load Effects of Three-roller Bending Process for Large Gear Teeth Profile

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Abstract

Aiming at the problems of 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 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 changes. And the reasonable parameter of TRBP is around **750°C** of deformation temperature and **0.5mm · s⁻¹** of speed. Compared with the precision forging process under 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 mechanical transmission system of aerospace, aviation, navigation, vehicle and other industries, which has the advantages of high power, high efficiency and 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 method like gear milling, hobbing and 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 profile has always been difficult.

Large gear refers to a gear with 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 on the influence of changes in tool axis angle when large-module gears were machining. Klicke 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 on 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 et al.[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 on a two-step extrusion process for helical gear to reduce forming load. Khodae et al.[18] studied on the effects of blank geometry when rolling large-module gears. Yadav et al.[2] studied on 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 4,200t.

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 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 shape of 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 to 600mm. In another word, the curvature is 1/300. Therefore, it belongs to the problem of small curvature of the plane. This paper derived the change of gear teeth profile by analogy to channel steel.

Table 1: Parameters of the gear studied in this paper

Modulus	Teeth Number	Pressure Angle/ $^{\circ}$	Material
5	120	20	17CrNiMo6

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 reach its maximum when the rack is purely bent, the rack is simplified as shown in Figure 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 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_c , which can be calculated from equation 1:

Fig. 1: Schematic diagram of the model of the rack simplified to two half-teeth

$$e_1 = \frac{e_{11}A_1 + e_{12}A_2}{A_1 + A_2} \quad (1)$$

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.

$$\begin{aligned} e_{11} &= \frac{(B-d)(2t_1+t_2)}{3(t_1+t_2)} + d \\ e_{12} &= \frac{d}{2} \\ A_1 &= (t_1+t_2)(B-d) \\ A_2 &= Hd \end{aligned} \quad (2)$$

2.1.3 Stress and strain

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

$$\sigma = \begin{cases} D\varepsilon - \sigma_0 & \varepsilon < -\varepsilon_E \\ E\varepsilon & -\varepsilon_E \leq \varepsilon \leq \varepsilon_E \\ D\varepsilon + \sigma_0 & \varepsilon > \varepsilon_E \end{cases} \quad (3)$$

Where D is the plastic tangent modulus, E is the elastic modulus, σ_0 is the intercept stress, and ε_E is the plastic strain at demarcation point.

Fig. 2: Stress and strain diagram for pure bending

The equivalent strain neutral layer is introduced, the position of which is e_3 from the bottom of the rack. The radius of curvature after bending is ρ_ε , and the corresponding curvature is K_ε . 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 ρ_0 , and the corresponding curvature is K_0 , while after bending being ρ , and the corresponding curvature being K . Strain can be obtained:

$$\varepsilon = (z - e_1)(K_\varepsilon - K_0) + \delta \quad (4)$$

Where $\delta = \frac{K_\varepsilon}{K} - 1$. And with boundary conditions being: $\varepsilon_{z=e_4} = 0$ and $\varepsilon_{z=e_5} = \frac{\sigma_S}{E}$, e_4 and e_5 can be solved:

$$\begin{aligned} e_4 &= \frac{(e_1 - e_3)(r + e_3)}{r + e_1} + e_1 \\ e_5 &= \frac{\sigma_S(r + e_3)}{E} \end{aligned} \quad (5)$$

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

In Figure 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:

$$\begin{aligned}
 F_1 = & \int_{e_4}^{e_4+e_5} HE\varepsilon dz + \\
 & \int_{e_4+e_5}^d H(D\varepsilon + \sigma_0) dz + \\
 & \int_d^B 2t(D\varepsilon + \sigma_0) dz \\
 = & HE \int_{e_4}^{e_4+e_5} \frac{z - e_3}{r + e_3} dz + \\
 & H \int_{e_4+e_5}^d \left(D \frac{z - e_3}{r + e_3} + \sigma_0 \right) dz + \\
 & 2 \int_d^B \left(t_1 + \frac{B - z}{3} \right) \left(D \frac{z - e_3}{r + e_3} + \sigma_0 \right) dz
 \end{aligned} \tag{6}$$

$$\begin{aligned}
 F_2 = & \int_0^{e_4-e_5} H(D\varepsilon - \sigma_0) dz + \\
 & \int_{e_4-e_5}^{e_4} HE\varepsilon dz + \\
 = & H \int_0^{e_4-e_5} \left(D \frac{z - e_3}{r + e_3} - \sigma_0 \right) dz \\
 & HE \int_{e_4-e_5}^{e_4} \frac{z - e_3}{r + e_3} dz
 \end{aligned} \tag{7}$$

Where intercept stress $\sigma_0 = \sigma_S \left(1 - \frac{D}{E}\right)$. With the condition being $F_1 + F_2 = 0$ and parameters of the rack being substituted, $e_3 = 9.347mm$ can be worked out. Then the strain ε_d at the tooth root can be calculated in Equation 4 which is 0.08. The simulation of the rack bending process by FEA is shown in Figure 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.

Fig. 3: Equivalent strain cloud of the rack bending process employing lower die bending

2.1.4 Further simulation of tooth profile change

From the results of the previous section, it is acknowledged that the deformation of 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 Figure 4 where the shape before bending is shown as mesh while that after bending being shown as strain cloud.

Fig. 4: The shape of tooth profile before and after the rack bending

The tooth profile was identified and extracted in matlab, $z = d$ in Figure 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 change relationship of the tooth profile.

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

$$y = 9 \times 10^{-8} z^2 + 7.9 \times 10^{-5} z + 0.0031 \quad (8)$$

Combining section 2.1.3 and Equation 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 Figure 5.

Fig. 5: Schematic diagram of TRBP for plates

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: 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 Figure 5 parameter d can be obtained:

$$(R - l)^2 + \left(\frac{a}{2}\right)^2 = R^2 \quad (9)$$

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

$$l = Pa^Q R^{2 \times 10^{-5}a - S} \quad (10)$$

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

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 Figure 6. The rack to be formed is used as a blank, and a gear chain is used as a matching support to realize the bending of the rack.

Fig. 6: Model of the TRBP for 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 process is to roll the end of the rack. The process of rack bending is shown in Figure 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 rack and gear chain is not traditional involute gear fit, but the shape of the tooth top of the gear chain is as same as the bottom of the rack

Fig. 7: Flow diagram of the TRBP for the rack

tooth, and the rest is a straight line tangent to the transition circle of the rack tooth, as shown in Figure 6b. Surface contact can minimize the pressure on the tooth bottom when the rack is bent under the same forming force, and the tooth top of the rack will not bear the force when exposed to the gear chain gap, which can better ensure the shape of 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 Figure 8. Where R' is the radius of curvature of the line connecting the pin centers when the gear chain is wrapped, θ is the angle between the center of two pitch pins and the center of the ring gear, b_1 is the tooth pitch before wrapping when b_2 is which after wrapping. When θ is small, it can be obtained from the figure.

$$b_2 = \theta R' \quad (11)$$

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 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 analysis of load effects was 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 deformation temperature and speed simulations, and the boundary conditions with the best deforming effects of TRBP were set for precision forging as comparison.

Table 2: Process parameter of the numerical simulation

	Three-roller Bending	Precision Forging
Mould Preheating Temperature/ $^\circ\text{C}$	250	250
Deformation Temperature/ $^\circ\text{C}$	250/500/750/1000	750
Deformation Speed/ $\text{mm} \cdot \text{s}^{-1}$	0.2/0.3/0.4/0.5/0.6/0.7/0.8	0.5

Fig. 8: Partial detailed schematic diagram of the TRBP for the rack

Fig. 9: Flow diagram of the FEA simulation of the TRBP for large gear teeth profile

Fig. 10: Deformation force and the max equivalent strain of the TRBP for large gear teeth profile under different boundary conditions

Fig. 11: Strain cloud diagram of the formed gear through TRBP

On the basis of the previous design, 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, 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 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 Section 2.2 is shown in Figure 9, 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. The process parameters do not strictly satisfy the Equation 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 Figure 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°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 Figure 10a and Figure 10b, it can be concluded that the deformation temperature being 750°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 Figure 11. The figure shows that the maximum strain occurs at the root of the tooth while the tooth shape 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 Section 2.1.3.

3 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 Figure 12a. The deforming process is divided into import stage, forming stage and truing stage. According to the gear studied in this article, the concave die is designed as Figure 12b, and the diagram for assemble is shown in Figure 12c12d.

The simulation result is shown in Figure 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 concave mold cavity well. The tooth forming result is worse than that of TRBP, and further processing will be needed.

Fig. 13: Simulation results of large gear precision forging

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

4 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 $0.5\text{mm}\cdot\text{s}^{-1}$, 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.

5 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 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°C and speed of $0.5\text{mm} \cdot \text{s}^{-1}$ is 200t, 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.

Declarations

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Plate Bending Theory & Asymmetric Section Bending Theory

Gear Chain Design & Three-Roller Bending Process Design of Rack

FEA of TRBP for Large Gear Teeth Profile with High Shape Accuracy and Lower Forging Pressure

Equivalent Strain

Equivalent Strain

Table 1.Parameters of the gear studied in this paper

Modulus	Teeth Number	Pressure Angle/°	Material
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Table 2. Process parameter for numerical simulation

	TRBP	Precision Forging
Mould Preheating Temperature /°C	250	250
Deformation Temperature /°C	250/500/750/1000	750
Deformation Speed /mm·s ⁻¹	0.2/0.3/0.4/0.5/0.6/0.7/0.8	0.5