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Research and prospect of flexible forming theory and technology of hollow shaft by three-roll skew rolling

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Abstract

With the rapid development of high-end equipment in aviation, high-speed rail and other fields, the requirements for the necessary shaft foundation parts on the equipment are more stringent. This has resulted in rapid development of the new generation of Three-Roll Skew Rolling (TRSR) flexible forming shaft parts technology. It is an important issue to explore the theory and technology of TRSR flexible forming of hollow shaft and systematically expounding the flexible forming theory of TRSR of hollow axle. Therefore, this paper explores the feasibility of TRSR through the combination of theory and experiment, analyzes the formation mechanism as well as develop macro and micro uniformity law in order to clarify the quality control measures. In order to realize the low-cost forming of hollow axle with short process, the piercing-rolling compound forming (Integrated forming of shape and inner hole of hollow axle) and the multi-roll skew tandem rolling technology for large section shrinkage shafts are innovated. The forming mechanism is verified through the simulation research. Based on the above-mentioned research, it is concluded that skew-rolling composite integrated forming of large hollow shafts, multi-roll skew tandem rolling technology for large section shrinkage shafts and the flexible forming process and equipment of digital TRSR is the future development direction of the TRSR flexible forming technology of hollow shaft. The results provide a theoretical basis and development direction for improving the precision short process, high efficiency and high-quality manufacturing of high-end equipment shaft foundation.

Keywords Hollow shaft · Flexible forming · Three-roll skew rolling · Piercing-rolling compound forming · Multi-roll skew tandem rolling

1 Introduction

Hollow shaft is one of the key basic components on high-speed trains, automobiles, aircrafts and other means of delivery. Compared with the solid shaft, the hollow shaft can not only reduce the material consumption and the weight of the shaft, but also reduce the vibration and improve the bearing capacity of the equipment, which has a good application prospect [1,2]. With the continuous improvement of the requirements for high speed and heavy load of the new generation vehicles, the hollow shaft with lightweight, long fatigue life and high reliability is the key component to achieve this goal. The hollow shaft forming process with short process, high efficiency and high precision is urgently needed to meet the requirements that cannot be met by these traditional forming processes [3]. The present challenges of hollow shaft forming mainly include three aspects. First of all, the shape is very complex, mainly refers to the complexity of the size and characteristics, such as large size hollow shaft (eg, high-speed train hollow axle length is more than 2m, diameter is more than 25cm), multi-step and variable wall thickness hollow shaft (automobile hollow drive shaft, aero-engine turbine shaft, etc.), which makes the traditional processing technology and equipment is difficult to achieve high efficiency and precision demand of such hollow shaft forming. Secondly, the microstructure and properties of difficult-to-form alloy steel are difficult to control after plastic deformation at high temperature over 1000 ° C, which changes very complex under multi-field coupling [4]. Finally, high precision forming size and prefer microstructure and properties are needed. Hollow shaft has two basic dimensional accuracy requirements of outer circle and inner hole, so the synchronous forming of outer circle and inner hole should be made to ensure dimensional accuracy. At the same time, good microstructure and properties should be obtained by controlling process parameters. The coupling superposition of these three challenges makes the manufacturing of high-precision and high-performance hollow shaft extremely difficult. At present, the forming process of large-scale and high-performance hollow shaft mainly includes forging and CWR (cross wedge rolling). The forging hollow shaft technology is to forge the solid bar to the hollow shaft shape, and then process the inner hole through deep hole drilling. The hollow shaft formed by this method has good microstructure and performance, but the process flow is long, the technical difficulty is large, and the material utilization rate and processing efficiency are nonideal [5]. The cross wedge rolling technology of hollow shaft is that the mandrel is first inserted into the bar with a central hole, and then the shape of the hollow shaft is processed on the cross wedge rolling mill, and then the mandrel is extracted. This method has high processing efficiency but the corresponding die size is huge when processing large hollow shafts, so it is not suitable for forming large hollow shafts [6].

The TRSR flexible forming is a metal plastic processing technology that places the heated billet between three uniformly distributed conical rolls, and the billet generates continuous plastic deformation of radial compression and axial extension after local loading, so that the simple billet forms complex stepped shaft parts. Since the variable cross-section shaft can be formed by controlling the center distance of three rolls, the TRSR flexible forming process has the characteristics of no-die and flexible processing, which is very suitable for processing long shaft parts and hollow shaft parts [7]. In the 1970 s, the former Soviet Union researchers used the profiling plate to control the three-roll center distance to roll the seamless steel tube out of the hollow shaft shape. This process is called the profiling skew rolling process, which is the prototype of the TRSR flexible forming technology. However, the application of this process is limited due to the poor universality of the mold [8,9]. Some scholars in China and Poland have improved and proposed a TRSR flexible forming process that can stably roll stepped shaft parts, and conducted a large number of theoretical and simulation studies [10-15]. In particular, Polish researchers have developed a CNC TRSR mill, which has achieved a breakthrough from theory and simulation to experiment and application [16-19]. The research of Chinese scholars on the three-roll skew rolling flexible forming of hollow shaft is at the leading level in this field, especially in the regulation of forming quality and microstructure and performance [20-22].

The authors and research team explored the basic theory and key technology of three-roll flexible forming of hollow shaft, broke through the challenges faced by large long or hollow shaft parts, and promoted the innovative development of three-roll flexible forming technology from small scale to large scale components, from simple structure to complex structure. For large-size hollow shaft and large section shrinkage shaft parts, piercing-rolling compound forming and multi-roll skew tandem rolling technology are developed. This paper mainly introduces the latest progress in technical principle, deformation behavior, defect control and typical application, which provides a theoretical basis and development direction for improving the precision, short process, high efficiency and high-quality manufacturing of high-end equipment shafting foundation parts.

2 Flexible Forming Theory of TRSR for Shaft Parts

2.1 Flexible forming principle of TRSR

Flexible forming manufacturing is the integration of forming processes, digital, automation and information technology. Through the active control of tooling/die with multiple degrees of freedom, the precise forming of components with different shape characteristics is flexibly realized [24]. The TRSR belongs to the flexible manufacturing technology of local loading axial continuous plastic forming, and its basic principle is shown in Figure 1. The three disc rolls are distributed around the billet at 120°, and the axis between roll and billet are deflected at a certain angle (deflection angle θ). The maximum diameter of the roll is D. The included angle between the conical surface of the roll and the rolled piece is the forming angle α. In the rolling process, the three rolls are synchronously rotated in the same direction to drive the rolling piece to rotate. At the same time, the billet is axially fed under the action of the roll due to the existence of the deflection angle, and the three rolls are synchronously radially fed at the step formation to realize the forming of the step shaft. The TRSR flexible forming process has a wide processing range, which is more suitable for forming large shaft parts than the CWR process, and is the development trend of large shaft parts [24].

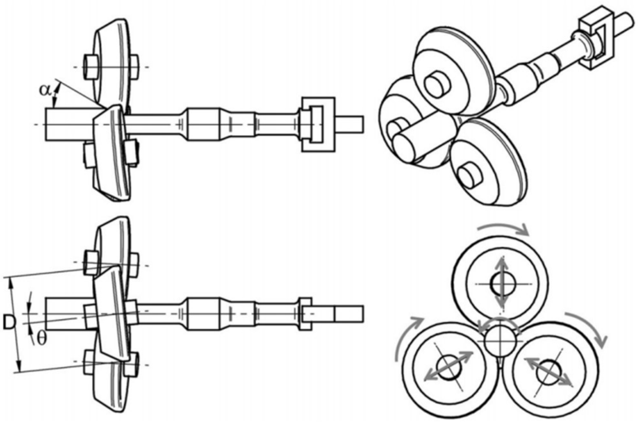


Fig. 1 Principle of three roll flexible forming for shaft parts

2.2 Kinematics Analysis of Three-Roll Skew Rolled Hollow Shafts

Spiral advance is the most obvious motion feature of the three-roll skew rolled shaft. With the equal pitch spiral advance of the straight shaft section and the variable pitch spiral feed of the variable diameter section, the rolled piece rotates and advances until the end of the rolling process. This motion mode can be decomposed into: (1) The axial movement of the chuck clamping rolled piece; (2) Three rolls rotate in the same direction to drive the rolling piece rotation; (3) The axis between roll and work-piece deflect at a certain angle. Fig. 2 shows the velocity vector analysis of any point in the deformation zone during stable rolling [25]. The point O is defined as the rotation center of the roll when the feed angle is adjusted, and the vertical rolling line passing the point O is the rotation axis. The plane composed of rotating axis, rolling line and roll axis is the principal rolling plane and principal roll plane, respectively. Taking any point P in the deformation zone of the TRSR piece as the coordinate origin, the x, y and z axes of the crossing point P are respectively along the rolling direction, the tangential direction and the vertical line of the rolling line. A-A view is the projection perpendicular to the principal plane along the rolling direction, B-B view is the projection perpendicular to the principal plane along the roll axis. β is the feed angle. γ is the angle between the z-axis and the principal plane of the rolling. φ is the angle between the radius of the roll passing through point P and the principal plane of the roll.

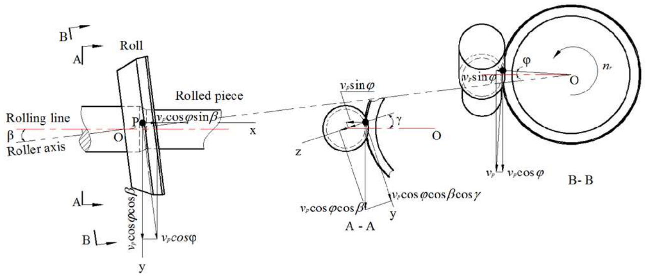


Fig. 2 Velocity vector analysis of any point in the deformation zone of the rolled piece

In the stable rolling stage of the three-roll skew rolled shaft, the point O of the rotation center is set on the interface between the roll cone and the cylindrical table, and point P is taken to be located on the rotating shaft. At this time, the relationship between the rolling speed n_b and the roll speed n_r can be expressed as:

$$n_b = \frac{\rho_{\max}}{r_a} n_r \eta_y \cos\beta \tag{1}$$

Where ρ_{max} is the maximum radius of the roll, r_a is the radius of the exit profile in the deformation zone of the rolled piece. η_y is the slip coefficient of any point P in the deformation zone of the rolled piece in the tangential direction of the rolled piece. The measured value or empirical value of the existing equipment is generally taken as the axial slip coefficient η_x, and the value range is 0.5~1.3 [26].

The guide Z_x and pitch z_x of the rolled piece along the rolling direction can be expressed as:

Z_x:
$$Z_x = 2\pi r_a \frac{\eta_x}{\eta_y} \tan\beta \tag{2}$$

z_x:
$$z_x = \frac{2\pi r_a}{3} \frac{\eta_x}{\eta_y} \tan\beta \tag{3}$$

According to equations (1-3), when ρ_{max}, r_a, n_r and β are constant, increasing the tangential slip coefficient can improve the rolling speed but prolong the rolling time and increase the number of repeated rolling in the deformation zone. Increasing the axial slip coefficient can shorten the rolling time and reduce the repeated rolling times, thus affecting the yield of rolling mill and the forming quality of rolled pieces.

Formulas (4-5) are the guide and pitch calculated without axial traction. In order to improve the forming accuracy, the fixture is used to clamp the rolled piece along the axial direction. The axial velocity of the rolled piece is fixed, and the P point is located on the rotating shaft. At this time, the lead Z_x and pitch z_x of the rolled piece along the rolling direction are:

Z_x:
$$Z_x = \frac{60 u_x r_a}{\rho_{\max} n_r \eta_y \cos\beta} \tag{4}$$

z_x:
$$z_x = \frac{20 u_x r_a}{\rho_{\max} n_r \eta_y \cos\beta} \tag{5}$$

It can be seen from Formulas (4-5) that the method of controlling the pitch isometric or less than a certain value in the variable diameter section is to adjust the axial traction speed of the fixture or the rotational speed of the roll in real time. The axial traction speed of the fixture can be gradually reduced or the roll speed can be increased in the diameter raising section, while the reverse is true in the diameter reducing section.

3 Feasibility of TRSR for Hollow Axle

3.1 Finite element simulation for three-roll skew rolled hollow axle

Hollow axles are the development trend of high-speed train axles with the advantages of saving materials, light-weighting, improving vehicle carrying capacity, facilitating maintenance and flaw detection. The TRSR forming technology of hollow axle is an advanced plastic forming technology, which can replace forging and CWR to manufacture large hollow axle parts. The process of three-roll skew rolled hollow axle is to pull the rolled piece by fixture. At the same time, the friction force between the roll and the rolled piece causes the radial, circumferential compression and axial extension plastic deformation, showing an obvious three-dimensional deformation state. The finite element model of TRSR of hollow axle is shown in Figure 3. The hollow axle of high-speed train is reduced according to the actual size of 1:5 for simulation analysis. The reduced proportion of the hollow axle parts is shown in Figure 4. The initial hollow axle blank is a thick wall hollow pipe with diameter of 52 mm, wall thickness of 10 mm and length of 500 mm.

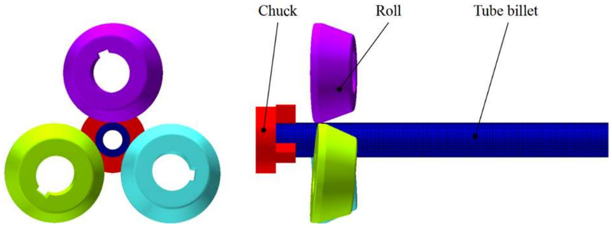


Fig. 3 Finite Element model of three-roll skew rolled hollow axle

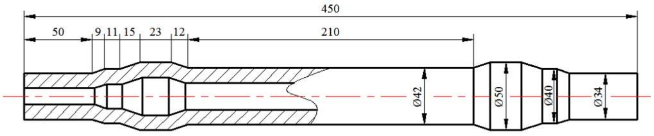


Fig. 4 Hollow axle of high-speed train with proportion of 1:5

According to the shape characteristics of the rolled piece after forming, it can be divided into clamping section, reducing section, straight axis section, lifting section and excess section, as shown in Figure 5. Among them, the clamping section is the contact part between the fixture and the rolled piece, and the material section is reserved to ensure the quality of the rolled piece end forming, both of them need to be removed after formed. Under the condition of 1100°C initial temperature of shaft billet, 20mm/s axial traction speed of fixture and 60rpm roll speed, the TRSR hollow axle obtained by simulation is shown in Figure 5. Where, the A-C are the straight axis, lifting and reducing diameter section, respectively. These three sections are collectively called variable-diameter section.

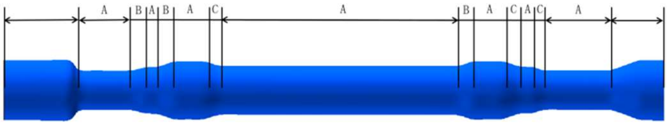


Fig. 5 Divided sections of TRSR hollow shaft

Fig. 6 shows the shape change of variable-diameter section in the forming process. In the lifting section, the billet gradually enters the roll pass along the rolling direction, and the roll cone squeezes the deformation zone along the axial and radial directions, so that the deformation zone of the billet becomes a cone, and then the billet continues to feed in the axial direction. At the same time, the roll radial withdrawal increases the pass, so as to complete the forming of the lifting section of the rolled piece. In the straight axis section, the roll has no radial movement, that is, the roll hole type remains unchanged, the billet is extruded by the roll cone in the axial feed process, so that the billet is axially extended and radially compressed, and the roll finishing section makes the forming area of the rolled piece round, so as to realize the straight section forming of the rolled piece. In the reducing section, due to the radial feed of the roll, the inner hole of the billet gradually shrinks. With the continuous radial feed of the roll, the contact surface continues to increase, and the billet diameter continues to shrink until the rolling of the reducing section is completed.

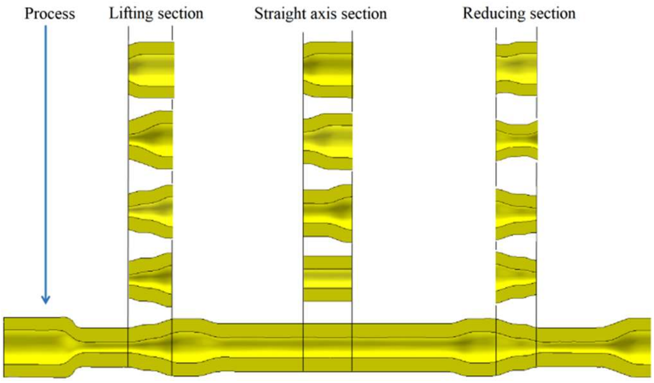
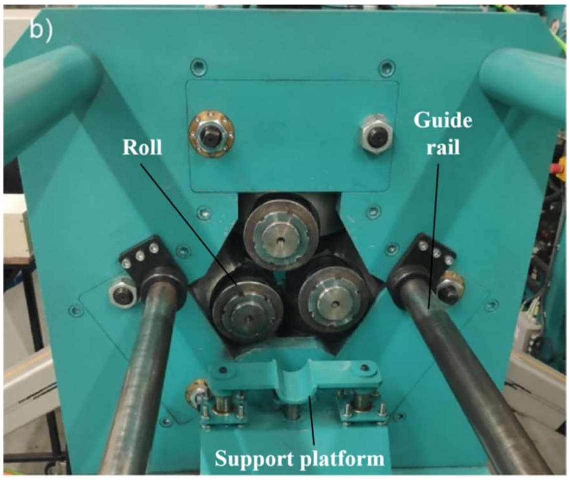


Fig. 6 Morphological changes in different forming stages of three-roll skew rolled hollow axle

3.2 Experiment of three roll skew rolled hollow axle

According to the theory and simulation results, the experiment of three-roll oblique rolling hollow axle is carried out by the numerical control TRSR mill producing by Lublin University of Technology. The experimental equipment is shown in Figure 7 shows the construction of the experimental equipment, where: 1–rack, 2-Drive unit, 3-Support plate, 4-axial displacement element, 5-Powertrain, 6-Blank support unit, 7-Four claw chuck unit, 8-Rolling support unit, 9-Control system.

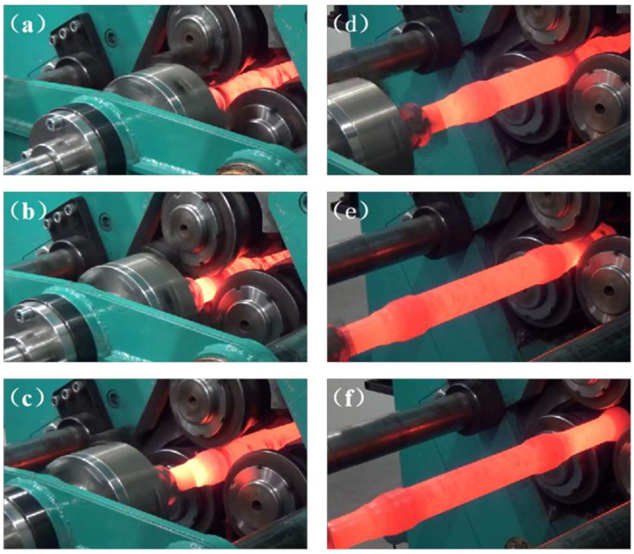
a) TRSR experimental mill



b) Roll System

Fig. 7 CNC TRSR mill and roll system

Figure 8 shows the experimental process of three-roll skew rolled hollow axle. Firstly, the high temperature hollow shaft billets taken from the heating furnace are clamped on the four claw chuck. Then, the rolled piece is inserted into the roll gap by the axial feeding mechanism, and next the roll and fixture move simultaneously to form the hollow axle. The shape is formed by controlling the axial traction speed of the fixture and the radial feed speed of the roll through the control system. Finally, the rolled piece is removed from the fixture and cooled by water. The clamping part and end of the rolled piece will be removed after cooling.



(a) Roll biting stage; (b) Step forming at the front end of rolled piece; (c) Step forming at the maximum diameter stage of rolled piece; (d) Step forming at the axle body of rolled piece; (e) Step forming at rear end of rolled piece; (f) TRSR hollow axle

Fig. 8 1:5 TRSR hollow axles of high-speed trains

Figure 9 shows some hollow axles processed on the NC three roll skew rolling mill. The final shape of the rolled piece meets the design requirements. The shape of the hollow axle formed under different process parameters is consistent, indicating that the three roll skew rolling technology has the advantage of high part processing consistency.

Fig. 9 Test pieces of TRSR hollow axle

The further research on the forming experiment of three roll skew rolling hollow axle shows that the main factors affecting the roundness of the outer contour of the hollow axle are the rolling temperature and the radial compression. The higher the temperature, the smaller roundness of the outer contour of the rolled piece and the larger roundness of the inner hole. The greater the radial compression, the greater roundness of the inner hole and the outer contour. However, under different process parameters, the roundness of the inner hole and outer contour of the hollow axle is less than 8%. The three roll skew rolling technology can better control the roundness error of the rolled piece. The wall thickness distribution of the three roll skew rolling hollow axle is relatively uniform, and the process parameters have no obvious regularity on the wall thickness of the hollow axle. The theory and experiments show that the three roll skew rolling technology has advantages in the forming of hollow axles.

4 Quality control technology for TRSR hollow axle

4.1 Mechanism and control of surface forming quality defects

According to the forming mechanism of three roll skew rolling, the generation mechanism of spiral marks on the surface of rolled piece can be divided into two aspects: on the one hand, the relative position relationship between rolled piece, fixture and roll; On the one hand, it is the influence of process parameters, such as roll rotation speed, fixture axial traction speed, etc. [27-29]. During the process of three roll skew rolling hollow axle, the relative position of roll and rolled piece is shown in Figure 10. The deformation area of the rolled piece fits with the conical surface of the roll. The included angle between the conical surface of the roll and the axis of the rolled piece is the forming angle. The forming angle determines the deformation speed and deformation amount of the rolled piece during stable rolling, and affects the axial traction force of the fixture and the axial force of the roll during the rolling process. The deformation difficulty of the rolled piece increases with the increase of forming angle. Generally, the forming angle cannot exceed 30°. The angle between the roll axis and the axis of the rolled piece is called deflection angle. The deflection angle determines the screw pitch of the axial spiral advance of the rolled piece during stable rolling and affects the axial traction force of the fixture and the axial force of the roll during rolling. The deformation difficulty decreases with increasing the deflection angle, which leads to an increase in the rolling force and results in a larger screw pitch. The smaller the forming angle, the larger contact area between the deformation area of the rolled piece and the conical surface of the roll, and the easier it is to obtain a smooth surface of the rolled piece. The larger the deflection angle is, the easier the deformation of the rolled piece will be. However, at the same time, the variation of the pitch of the axial spiral advance of the rolled piece will cause spiral marks on the surface of the rolled piece, and the deflection angle is generally within ± 10 °.

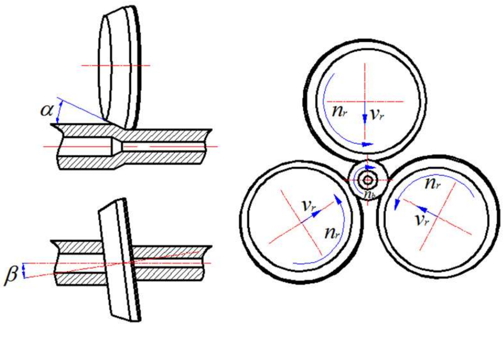
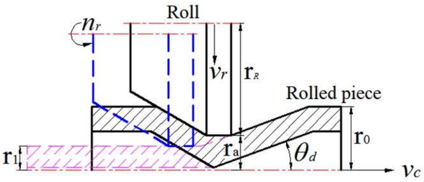
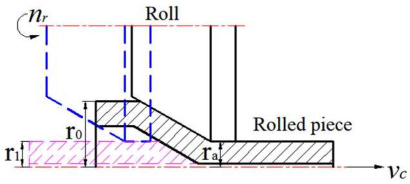


Fig. 10 Relative position between roll and rolled piece during TRSR

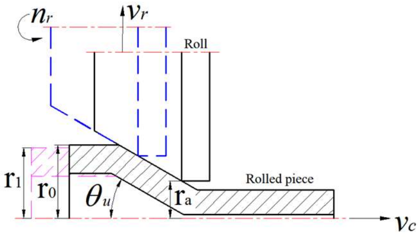
The influence of process parameters on the spiral mark of rolled piece is very complex. The main parameters that affect the spiral mark in different rolling stages are different. The deformation process of three roll skew rolling hollow axle at different forming stages is shown in Figure 11. In the reducing section, plastic deformation occurs in the deformation area of the rolled piece under the joint action of the radial feed of the roll and the axial feed of the fixture. The contact surface between the roll and the forming area of the rolled piece is the tail of the cylindrical section of the roll (i.e. the finishing section of the roll). When the radial feed speed V_r of the roll and the traction speed Vc of the fixture are constant, the pitch on the surface of the rolled piece in the reducing section will change in descending order. At this time, the surface of the rolled piece is very easy to produce gradually dense spiral marks. In the straight axis section, the roll has no radial feed movement, and the rolled piece is fed axially under the traction of the fixture. The main factor affecting the surface quality is the axial traction speed of the fixture. When the axial traction speed is constant, the rolled piece surface will only produce uniform spiral marks. At this stage, the contact surface between the roll and the rolled piece is the cylindrical end of the roll, and the contact area is large, which can improve the spiral marks to a certain extent. In the rising section, the deformation of the rolled piece gradually decreases, and the contact surface between the roll and the rolled piece at this stage is the transition area between the conical surface and the cylindrical surface of the roll, so the spiral mark is not obvious in the reducing section. When the size of the roll forming angle is closer to the conical angle of the rising section, the spiral mark is less likely to appear in the rising section. When they are the same, the surface of the rolled piece will be a smooth conical surface. Fig. 12 shows the maximum height of the spiral mark under different fixture axial speeds and different roll rotation speeds when other process parameters are fixed. Under a certain roll rotation speed, the smaller the fixture axial speed, the smaller the maximum height of the spiral mark. Under a certain fixture axial speed, the larger the roll rotation speed, the smaller the maximum height of the spiral mark, and the maximum height of the spiral mark on the straight shaft section is significantly smaller than that in the reducing section, it shows that the three roll skew rolling hollow axle is more prone to spiral marks in the reducing section. The research shows that selecting a smaller fixture axial speed and a larger roll rotation speed in the process of three roll skew rolling hollow axle can reduce the spiral mark defects and obtain a better surface quality of rolled piece [30].



(a) The reducing section

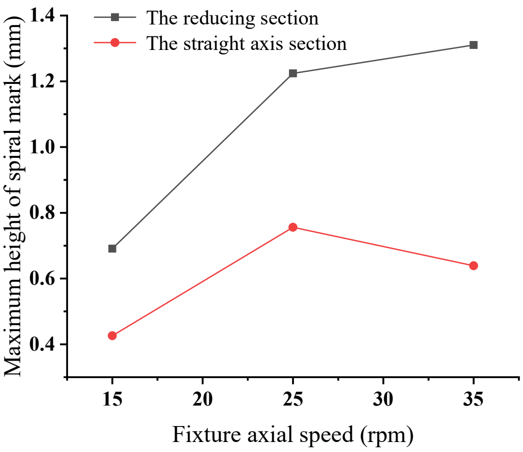


(b) The straight axis section

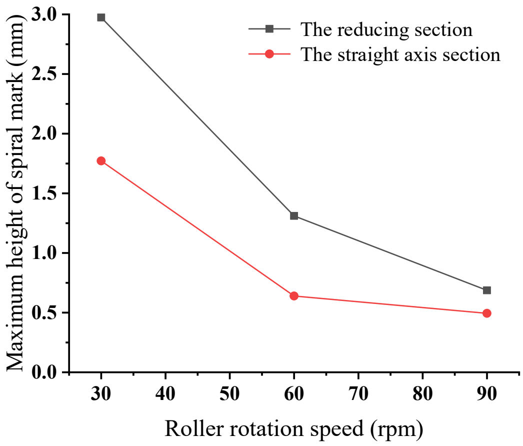


(c) The rising section

Fig. 11 Formation process of three roll skew rolling hollow axle at different forming stages



(a) Maximum height of spiral mark under different fixture axial speeds



(b) Maximum height of spiral mark at different roll rotation speeds

Fig. 12 Maximum height of spiral mark on rolled piece surface

There are many reasons for the formation of spiral mark defects on the surface of rolled piece. Under the condition of reasonable selection of process parameters, the correct design of roll profile is also one of the important methods to eliminate spiral mark defects. At present, the types of forming rolls of three roll skew rolling mainly include disc shape and drum shape, as shown in Figure 13. During the forming process of the disc roll in the reducing section, only the end transition fillet of the roll surface contacts the surface of the rolled piece forming area, so the rolled piece is easy to produce surface spiral marks in the reducing section. In addition, the disc-shaped roll can realize the right angle step shape of rolled piece in the reducing section, but cannot form the right angle step shape of the rising section. During the forming process of the reducing section of the drum roll, the tail cone surface contacts with the forming area of the rolled piece, which can play the role of finishing the surface of the forming area. Therefore, the drum roll can form a smooth surface of the reducing section. Although the drum roll can eliminate the spiral mark of the reducing section, it cannot form the right angle stepped reducing section.

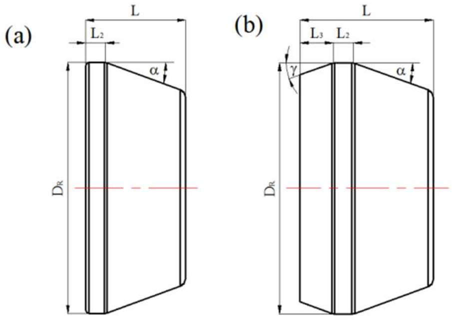
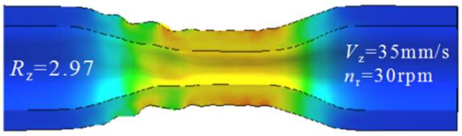
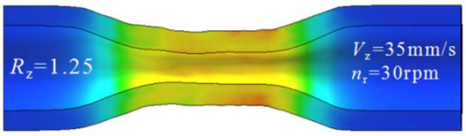


Fig. 13 Roll type：(a) Disc roll; (b) Drum roll

Figure 14 shows the comparison of the surface forming quality of the roll before and after the optimization of the roll shape. It can be seen from the figure that the surface of the rolled piece formed by the optimized drum roll is obviously smoother than that of the disc roll. Under the same process parameters, the maximum height *Rz* of the spiral marks formed by the drum roll is smaller than that of the disc roll. Half of the maximum height of the spiral marks on the surface of the formed rolled piece, indicating that the optimal design of the roll profile can effectively control the surface spiral mark defects of the rolled piece. The comparison of surface forming quality of rolled piece before and after optimization of roll profile is shown in Figure 14. It can be seen from the figure that the surface of the rolled piece formed by the optimized drum roll is obviously smoother than that formed by the disc roll. Under the same process parameters, the maximum height R_Z of the spiral mark on the surface of the rolled piece formed by the drum roll is less than half of the maximum height of the spiral mark formed by the disc roll, indicating that the optimized design of the roll profile can effectively control the spiral mark defects.



(a) Disc roll



(b) Drum roll

Fig. 14 Comparison of forming quality of rolled piece before and after roll profile optimization

4.2 Shape and performance uniformity

4.2.1 Evaluation and influencing factors of wall thickness uniformity

There is a phenomenon of uneven thickness in the axle body. For the rolled piece, the poor wall thickness uniformity will affect the subsequent finishing of the inner hole and outer contour of the rolled piece, and in serious cases, it will lead to the scrapping of the rolled piece. Therefore, the wall thickness uniformity of the axle body must be ensured [31]. In order to facilitate the research on the uniformity of wall thickness, the axle body is taken as the research object. 15 sections are cut at an equal distance in this section. 80 points (40 points on the inner and 40 points on the outer surfaces) are evenly taken on each section. The inner and outer 40 points correspond to each other one by one. The distance between the two points is the wall thickness of the axle body. The point selection method is shown in Figure 15. 40 wall thicknesses can be obtained for each section, and the average value is taken as the wall thickness of this section.

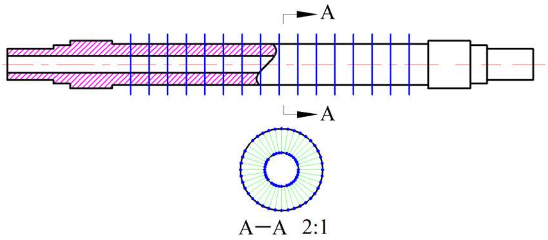


Fig. 15 Point selection method

Suppose the coordinates of 80 points of the selected points of section A-A are (X_n, Y_n, Z_n) (n=1, 2, 3... 80), then the wall thickness tn of the section is:

$$t_n = \sqrt{\left(X_{n+40} - X_n\right)^2 + \left(Y_{n+40} - Y_n\right)^2 + \left(Z_{n+40} - Z_n\right)^2} \tag{6}$$

The average wall thickness of section A-A is T:

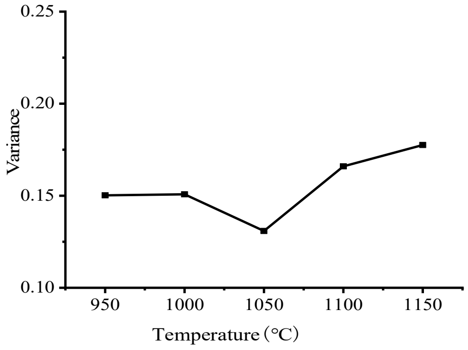
$$T = \frac{1}{40}\sum_{n=1}^{40} t_n \tag{7}$$

In order to evaluate the wall thickness uniformity of rolled piece more intuitively, the 15 sections are selected as the wall thickness variance, and the variance is used to evaluate the wall thickness uniformity of rolled piece. The smaller variance of rolled piece, the better uniformity of rolled piece. The expression of wall thickness variance is as follows:

$$S^2 = \frac{1}{40}\sum_{n=1}^{40}\left(t_n - T\right)^2 \tag{8}$$

Through the research, it is found that among the four process parameters of temperature, fixture axial traction speed, deflection angle and roll finishing section length, fixture axial traction speed and deflection angle have the greatest impact on the wall thickness uniformity. When the fixture axial traction speed is too large, it will lead to the deterioration of the wall thickness uniformity of the rolled piece, and even serious spiral groove marks on the surface of the rolled piece. When the deflection angle is too large, it will lead to serious metal backflow on the surface of the rolled piece, the wall thickness uniformity becomes worse. The influence of different process parameters on the wall thickness uniformity of rolled pieces is shown in Figure 16. During the rolling process, the metal backflow causes the wall thickness of the rolled piece to decrease gradually in the axial direction. This phenomenon can be solved by compensation of the radial feed of the roll or secondary processing.

The results show that the wall thickness uniformity of the rolled piece is the best when the deflection angle is 7°, the length of the finishing section of the roll is 5mm, the axial traction speed of the fixture is 20mm/s-30mm/s, and the rolling temperature is 1050℃. The simulation results of hollow axle under secondary process parameters are shown in Figure 17. At this time, the maximum deviation of rolled piece wall thickness is 0.7mm and the minimum deviation is 0.2mm.



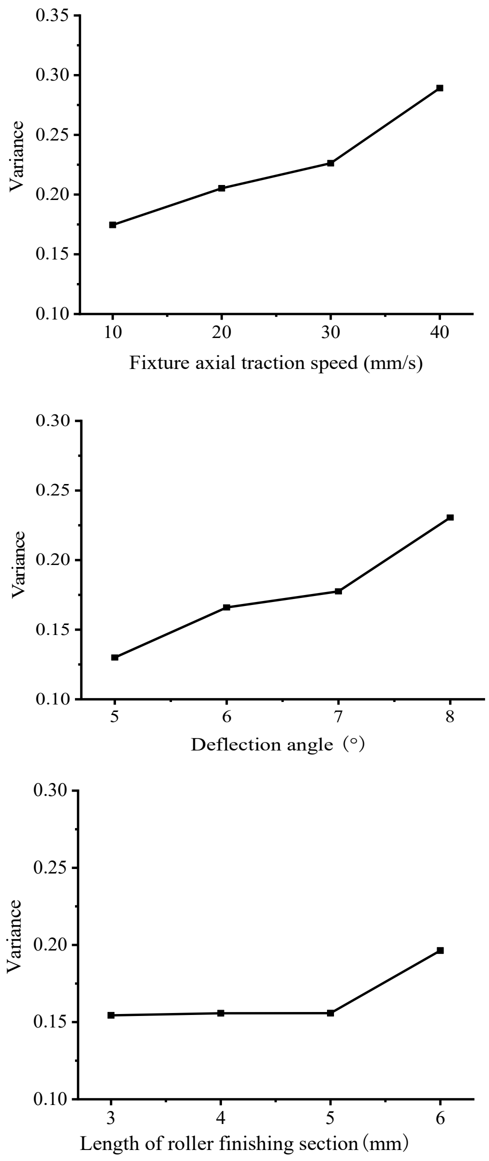


Fig. 16 Wall thickness uniformity under different process parameters

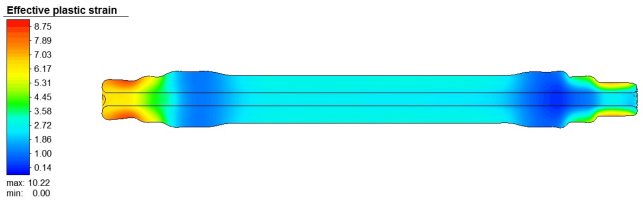


Fig. 17 Simulation results under optimal process parameters

4.2.2 Evaluation and influencing factors of microstructure uniformity

The grain size and its distribution uniformity in hollow axle is one of the most important factors to determine its comprehensive mechanical properties. Specifically, in the rolling process, the higher grain refinement degree and the more uniform distribution of grain size in the rolled piece, the better mechanical properties of the rolled piece [32,33]. In order to facilitate the statistics of the average grain size of rolled pieces, five typical cross sections are taken along the axial direction on the hollow axle, each cross section is divided into three equal parts along the radial direction, and 21 points are uniformly selected on each of the four boundary lines as the research object. The method of taking points is shown in Figure 18.

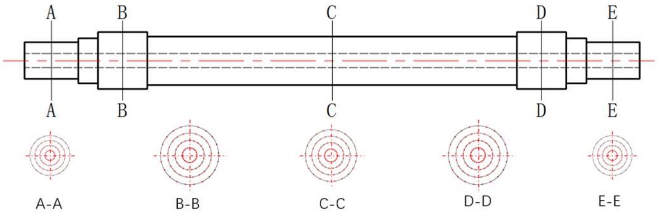


Fig. 18 Statistical sampling method of grain size

The average grain size of the rolled piece is calculated as follows:

$$d_{ave} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}}{mn} \qquad (9)$$

Where: n is the section number; m is the number of statistical points of each section; d_{ij} is the grain size at point i of section j.

The axial and transverse microstructure uniformity of the rolled piece directly determines the properties of the rolled piece. Therefore, the uniformity coefficients S_1 and S_2 are introduced as the uniformity evaluation indexes. The smaller the

S value is, the better microstructure uniformity will be.

$$d_{iave} = \frac{\sum_{j=1}^{n} d_j}{n} \tag{10}$$

$$S_1 = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(d_{ij} - d_{iave}\right)^2}{mn}} \tag{11}$$

$$S_2 = \sqrt{\frac{\sum_{i=1}^{m}\left(d_{iave} - d_{ave}\right)^2}{m}} \tag{12}$$

Where: S_1 and S_2 are the microstructure uniformity coefficients of cross section and longitudinal section of rolled pieces respectively. d_{iave} is the average grain size of the cross section.

Through numerical simulation, it is found that the influence of process parameters on the average grain size of each section is consistent with that on the *S* value of microstructure uniformity coefficient. The specific performance is that it decreases with the increase of deflection angle, decreases with the increase of roll rotation speed, and first decreases and then increases with the increase of rolling temperature. Through orthogonal test, the influence laws of different process parameters on the microstructure uniformity of three roll skew rolling hollow axle can be obtained. The results can be analyzed by range method. The primary and secondary relations of the influence of various process parameters on the microstructure uniformity of three roll skew rolling hollow axle are as follows: roll rotation speed C, deflection angle B, rolling temperature A. If the cross-section uniformity, axial uniformity and grain size are taken as the judgment criteria, the influence order are B>C>A, C>B>A, C>A>B respectively. The combination of process parameters to obtain the optimal microstructure uniformity is that the rolling temperature is 1150℃, the roll rotation speed is 60rad/min, and the deflection angle is 7 °.

The experiment was carried out under the best process parameters of optimal microstructure uniformity. The microstructure morphology of the five characteristic sections on the experimental rolled piece is shown in Fig. 19. The average grain size of the five typical sections is significantly refined, from the initial average grain size of 150 μm, refined to 28~75μm. The comparison between the experimental results and the simulation results of the axial and radial average grain sizes on the five sections is shown in Figure 20. The error between the experimental results and the simulation is within 10%, which verifies the accuracy of the theoretical and simulation analysis [34]. The results provide a theoretical basis for further optimizing the microstructure and properties of three roll skew rolling hollow axle.

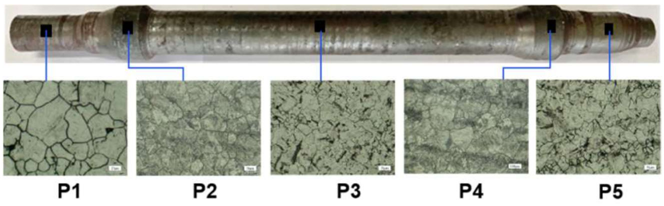
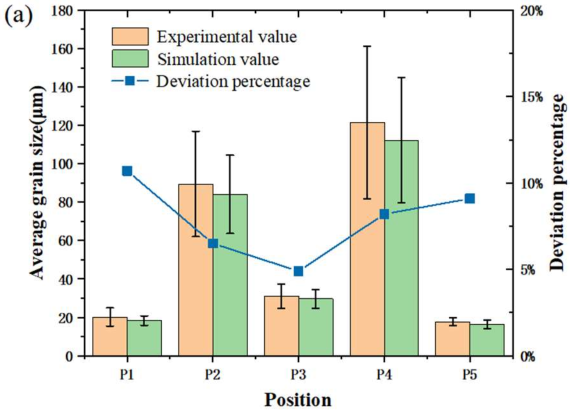


Fig. 19 Microstructure morphology of five typical sections of experimental rolled piece



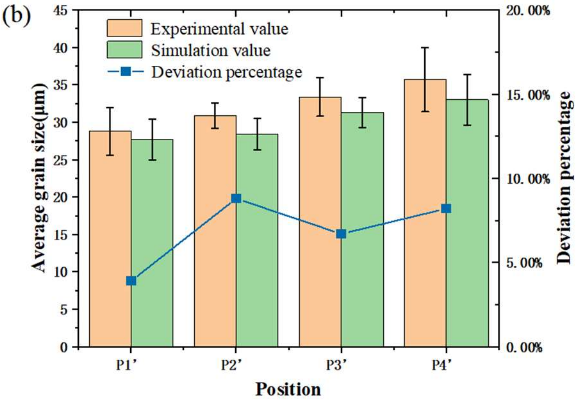


Fig. 20 Comparison of experimental and simulation results: (a) Axial; (b) Radial.

5 Integrated Forming of Shape and Inner Hole of Hollow Axle

At present, the process of forming hollow axle mainly adopts solid bar forging or rolling to form the axle shape, and then machining the inner hole on this basis. This process has long process flow and high cost. In order to realize the short process and low-cost manufacturing of hollow axle, the author and his team innovate the skew rolling and piercing composite process to form the hollow axle: the billet is perforated to form the hollow through the piercing process, and the initial forming of the inner hole of the axle can be completed without machining (short process); The shape of hollow axle is formed by skew rolling with variable roll spacing, and the structural shape forming (flexible forming) can be completed without a die. The basic principle of integrated forming process is shown in Figure 21. The billet is rolled and perforated synchronously between two or three rolls with the same rotation direction and the longitudinal axis intersecting (or inclined) with each other along its own axis for rolling, advancing and reducing deformation [35]. Because the hollow axle rolling through composite technology completes the inner hole forming and step shaft forming in one process, it does not need to drill the inner hole separately in the later stage, which avoids unnecessary waste of materials and effectively improves the utilization rate of materials.

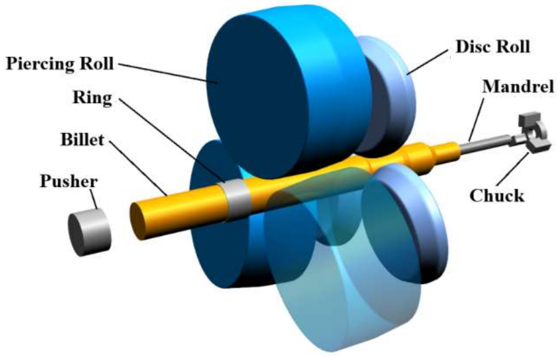
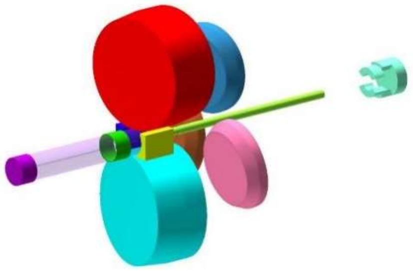


Fig. 21 Principle of Integrated Forming

The finite element model and simulation process of integrated forming of shape and inner hole of hollow axle are shown in Figure 22. The billet is first rolled into a capillary in the piercing part, and then the capillary is rolled into a stepped shaft with a certain size in the rolling part, eliminating the reheating of the capillary, which not only saves energy, but also improves the processing efficiency. It is very beneficial for rolling metals with narrow rolling temperature range. From the final shape, except the material head at the rear of the axle and the spiral lines on the surface of the long axle section need to be removed by machining, the dimensions of other parts are very close to the standard axle, so it is feasible to form the hollow axle by this process.



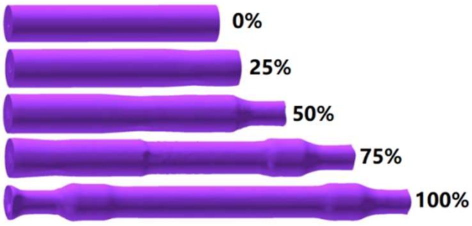


Fig. 22 Finite element model and simulation process of integrated forming

The distribution of equivalent plastic strain of hollow axle is shown in Figure 23. From the figure, it can be seen that the strain mainly occurs on the outer surface of the axle in contact with the roll, the maximum value appears at the place with the maximum reduction of section, and the minimum value appears on the inner surface of the axle. At the same time, it can be seen from the action direction of friction that the material flow direction in the process of forming axle is mainly circumferential flow. Compared with the forging process, the hollow axle formed by this process makes the most of the materials and avoids the waste of materials. The temperature distribution on the surface of hollow axle is shown in Figure 24. It is obvious from the figure that the temperature of the rolled piece in the area in contact with the plug is low. This is due to the heat transfer between the rolled piece and the tool, which leads to the temperature outside the rolled piece being greater than that on the inner surface. At the same time, it can be seen that the temperature of the surface contacted by the rolled piece and the roll is higher than that of the surface contacted by the plug. This is due to the large plastic deformation of the surface contacted by the rolled piece and the roll. The heat generated by the plastic deformation makes up for the heat lost by the rolled piece, so that the temperature of the rolled piece is always kept within the rolling temperature range.

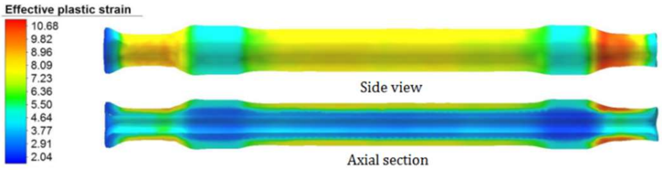


Figure 23 Equivalent plastic strain distribution of hollow axle

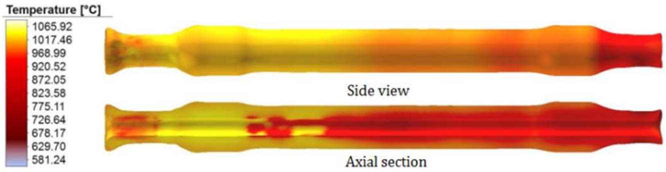


Fig. 24 Temperature field distribution of hollow axle

Through the simulation analysis of hollow axle processed by integrated forming, it can be seen that it is feasible to form hollow axle with this technology; The radial load and axial load are determined by the reduction rate and axial velocity respectively; During the forming process, the temperature of the rolled piece is always within the range of the rolling temperature. This technology improves the rolling efficiency and saves energy at the same time; Because the piercing process and rolling process are completed on one machine, the technology saves the area of the workshop; Due to the existence of tail stock head and surface spiral, the technology needs to be further improved.

At present, the forming of aeroengine turbine shaft (Fig. 25[33]) is a process of precision forging the shape first and then deep machining the hole. This method has the disadvantages of long process and cutting off the metal streamline, resulting in low performance and service life of turbine shaft manufactured in China. The application of piercing and rolling compound forming technology to the forming of aeroengine turbine shaft can effectively solve these problems. The process of piercing and rolling compound forming machining engine turbine shaft is to pierce the solid blank to form the inner hole of the turbine shaft through the piercing process; At the same time, the shape of the turbine shaft is formed by three roll skew rolling process to complete the dieless flexible forming. The technology of piercing and rolling compound forming provides a new idea for realizing the independent production of turbine shaft with high performance and short process, and improving the combat performance of military aircraft engine.

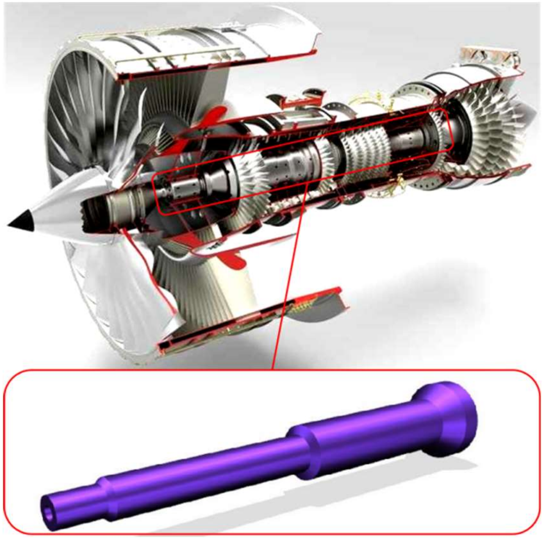


Fig. 25 Schematic diagram of aeroengine turbine shaft

6 Multi-roll skew tandem rolling technology for large section shaft parts

The hollow shaft with large reduction of area refers to the hollow shaft with a reduction of area greater than 75%. As a special form of hollow shaft parts, it has the advantages of material saving, weight reduction and consumption reduction. It also has broad application prospects, such as aerospace, high-speed trains, new energy vehicles, etc. At present, the rolling forming technology of hollow shaft with large reduction of area is mainly divided into cross wedge rolling and three roll skew rolling. However, there is a technical bottleneck in forming hollow shaft with large reduction of area through rolling process. The rolling forming technology of hollow shaft with large reduction of area is a difficult problem that needs to be solved urgently in the direction of hollow shaft rolling forming. In order to break through the limitation of reduction of area in the process of forming hollow shafts by traditional processes, the author and his team put forward the multi-roll series skew rolling process to process hollow shafts with large reduction of area, so as to solve the problems such as large contact surface in the forming area, large rolling load and equipment rolling space of the forging process, while the cross wedge rolling and three roll skew rolling processes are difficult to break through the limitation of 75% reduction of area.

6.1 Principle of multi-roll skew tandem rolling process for hollow shaft with large area reduction

Multi-roll skew rolling is a new process developed based on the theoretical research of three roll skew rolling. The rolled piece rotates, advances and deforms along its own axis between two groups of skew rolling roll systems. The die required for the multi-roll system skew continuous rolling process is composed of two sets of roll systems (the roll system is composed of three rolls distributed at 120 ° around the circumference of the rolled piece) and a clamp for clamping the axial feed of the die. The main parameters of the die include the deflection angle of the roll centerline relative to the workpiece centerline β, Forming angle formed by roll cone generatrix and rolled piece center line α, Roll system spacing between two sets of roll systems λ. Figure 26 shows the principle of local loading axial forming of multi-roll skew tandem rolling. At the initial stage of rolling, the fixture pulls the rolled piece to feed axially at a certain speed. At the same time, the three rolls of the front roll system rotate in the same direction to drive the hollow rolled piece to rotate. Local loading is applied to the rolled piece in the contact area, so that the rolled piece can undergo the thermoplastic forming of radial compression and axial extension, so as to realize the prereduction of the rolled piece. With the rolling process, the three rolls of the post roll system rotate at a certain speed and feed along the radial direction of the rolled piece to realize the secondary reduction of the rolled piece. When the rear roll system reaches the maximum reduction, the two groups of roll systems form a stable continuous rolling relationship until the front roll system and the rear roll system successively complete the reduction process of the specified length.

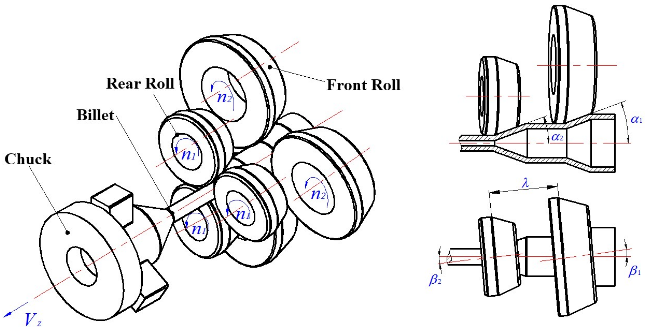


Fig. 26 Principle of local loading axial forming of multi-roll skew tandem rolling

6.2 finite element simulation of multi-roll skew tandem rolling of hollow shaft with large area reduction

The finite element model of the hollow shaft with large area reduction in multi-roll skew tandem rolling is shown in Figure 27. The model is composed of fixture, hollow rolled piece, front roll system and rear roll system. The finite element simulation results of hollow shaft for multi-roll skew rolling are shown in Figure 28. Through the simulation analysis, it can be seen that the stress field and strain field of hollow shaft with large area shrinkage are evenly distributed during the skew rolling process, the maximum equivalent stress is less than 38Mpa, and the equivalent plastic strain gradually decreases from outside to inside along the radial direction, indicating that the multi-roll skew rolling process can further reduce the rolling force and save energy; The deformation of the surface layer is larger than that of the core layer and the inner surface layer. Controlling the forming quality of the surface layer is the key to improve the properties of the rolled piece. The rolling process of multi-roll skew rolling hollow shaft is stable, and the metal material in the transition section of the rolled piece flows smoothly without accumulation. The multi-roll skew rolling has a good effect on forming the hollow shaft with 81% reduction of area. In the process of skew rolling, the metal of the rolled piece mainly flows along the axial direction, and the flow along the radial direction is relatively small. The finite element simulation of multi-roll skew tandem rolling forming of hollow shaft with large area reduction has been carried out successfully, which provides a new process method for solving the problem of difficult rolling forming of shaft parts with large area reduction.

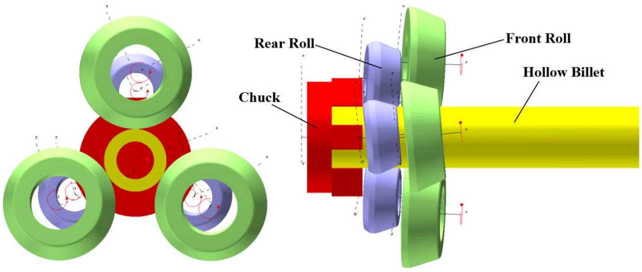
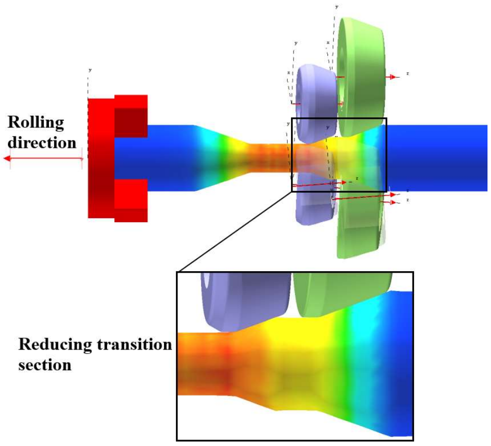
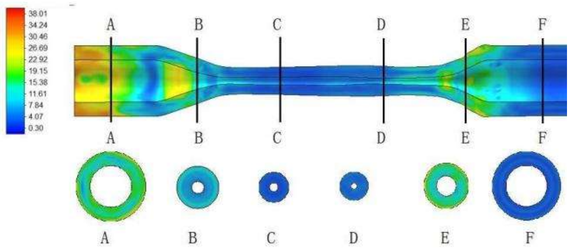


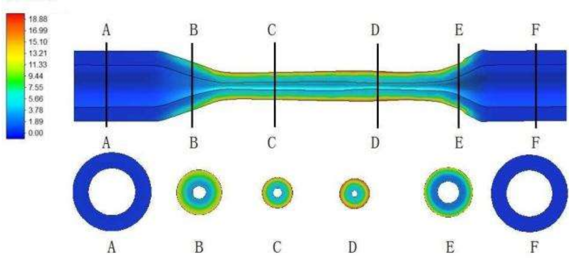
Fig. 27 Finite element model of hollow shaft with large area reduction in multi-roll skew tandem rolling



a) Forming process of hollow shaft with large area reduction



b) Equivalent stress distribution of rolled piece



c) Equivalent plastic strain distribution of rolled piece

Fig. 28 Finite element numerical simulation of hollow shaft with large area reduction in multi-roll skew tandem rolling

The automobile steel solid shaft is heavy, which is difficult to meet the social needs of automobile energy conservation and emission reduction and helping carbon peak and carbon neutralization. Using high-performance aluminum alloy hollow slender shaft with variable cross-section for automobile lightweight instead of steel solid shaft is the development trend of the new generation of automobile lightweight technology. However, the automobile hollow drive shaft belongs to the hollow shaft with large section shrinkage (Fig. 29), which is difficult to process by traditional process. However, the forming of such parts by using this technology has advantages, which can improve the level of China's automobile industry and help carbon to reach peak carbon neutralization.

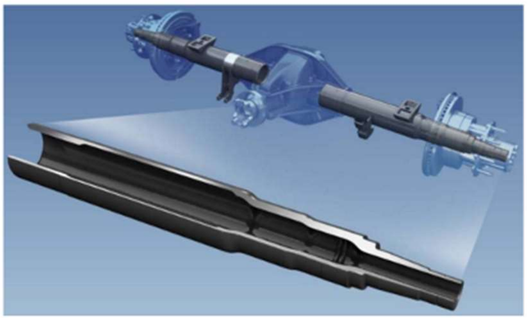


Fig. 29 Automobile hollow drive shaft (half shaft)

7 Development directions and perspectives

Facing the higher demand of the next generation aerospace, new energy vehicles and high-speed train transportation equipment for lightweight, high reliability and long life, the future development direction of three roll flexible forming technology is as follows:

(1) Large hollow shaft parts are formed by piercing and rolling. With the development of heavy-duty trucks and new high-speed trains, there is an urgent need for oversized hollow shaft parts (more than 2m in length). However, due to size constraints, the forging or cross wedge rolling process cannot achieve the integrated forming of large hollow shaft parts, resulting in low processing efficiency and poor consistency of forming quality. At present, the research on piercing rolling compound forming

process is still in its infancy, which can realize the forming of small hollow shaft. Therefore, in the future, it is necessary to develop the theory of piercing rolling compound forming system for large hollow shaft parts, develop a complete set of piercing rolling compound forming equipment and testing equipment, and finally realize the digital, efficient, energy-saving and economic mass production of large hollow shaft parts.

(2) Hollow shaft parts with large area reduction are formed by multi-roll skew tandem rolling. With the development of lightweight structure, the forming method of hollow shaft with large area reduction is developing towards more efficient, precise and flexible. However, when the hollow shaft is formed by the traditional rolling process, the reduction of section generally cannot be greater than 75%, otherwise the rolled piece will produce necking, fracture or surface quality defects, which limits the development and application of hollow shaft products with large reduction of section. The multi-roll skew rolling technology can solve this problem, but the current research only demonstrates the feasibility of multi-roll skew rolling of hollow shaft parts with large area reduction. Therefore, it is necessary to carry out the research on the cooperative control mechanism of multi-roll skew rolling of hollow shaft with large area reduction and realize the manufacturing of hollow shaft parts with large area reduction.

(3) Digital three roll flexible forming process and equipment. At present, the three-roll flexible forming process and equipment have not fully realized the digital control. During the forming process, the process parameters such as the radial displacement of the roll and the axial traction speed of the fixture are all digitally controlled according to the set loading curve. However, the roll speed cannot be adjusted, the forming force can only be detected, and the closed-loop control cannot be realized. Moreover, due to the influence of uncertain factors such as billet performance fluctuation and die wear, the size of formed rolled pieces is sometimes very unsatisfactory. Based on the theory of shape coordination control for three roll flexibles forming of shaft parts, a digital control platform for manufacturing process is built to realize the three roll flexible forming number of shaft parts digital closed-loop precise control.

8 Conclusions

The latest research progress and trend of three-roll flexible forming technology are expounded.It is expounded that the three-roll flexible forming technology is the most effective method for high-efficiency, high-quality and accurate volume forming of shaft parts. It is the development direction to realize the short-process green intelligent manufacturing of shaft parts. The main conclusions are:

(1) The TRSR technology can realize the flexible forming of shaft parts without mold, which overcomes the disadvantage of poor universality of the mold for cross wedge rolling shaft parts.

(2) The integrated forming technology of shape and inner hole of hollow axle can realize the short-process, high-efficiency and high-quality forming of hollow shafts and holes, which solves the problem that the traditional method is difficult to process the inner hole and outer contour of the hollow shaft at the same time

(3) The multi-roll skew tandem rolling technology can realize the forming of hollow shaft parts with large section shrinkage rate, which broadens the application scope of the TRSR technology. It is the best process for forming the hollow parts with large section shrinkage rate.

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Conflicts of interest The authors declare that they have no competing interests.

Availability of data and material The authors confirm that the data supporting the findings of this study are available within the article.

Code availability Not applicable.

Ethics approval This work does not include human and animal; hence, ethical approval from any committee is not required.

Consent to participate This work does not include human and animal; hence, consent to participate in the research is not required.

Consent for publication The authors give the publisher the consent to publish the work.

Authors' contributions Shu Xuedao makes the experimental plans, performs data processing, performs finite element simulations. Zhang Song and Shu Chang writes the paper. Shu Xuedao and Zhang Song determine the direction of the paper and the purpose of the experiment. Wang Jitai,Ye Caoqi and Xia Yingxiang assist to complete the experiment and help revise the paper. Essa Khamis and Pater Zbigniew assist to complete the experiment and check the literature. All authors read and approved the final manuscript.

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