A New Method of Manufacturing Hollow Shafts via Flexible Skew Rolling

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Abstract. The existing rolling process of large and long axle parts, such as the cross wedge rolling (CWR) process, requires special molds and larger equipment. Flexible skew rolling (FSR) hollow shafts with mandrel is a near net-shape rolling technology which can achieve the diversified production of rolled parts without special molds. It has significant advantages such as small equipment tonnage, small die size, low rolling load, simple process adjustment, and especially suitable for multi-variety and small-batch production. This paper proposes hollow train shafts formed by FSR with mandrel. Reasonable parameters were selected for experiments, and the forming process was calculated by finite element (FE) software. The experimental results are consistent with the simulation results, indicating that the FE model is reliable. The rolling force and rolling torque are analyzed by simulation. Finally, the microstructure of different positions of the rolled-piece is analyzed, and the microstructure of the rolled part is refined. It is provide a feasible scheme for the rolling of large hollow shaft parts.

Keywords. FSR, hollow shaft, variable diameter, microstructure.

1. Introduction
Currently, high-speed train axles generally use thick-walled hollow axles instead of solid axles, which can not only reduce the unsprung mass of the train, but also reduce the wheel-rail force under high-speed running conditions, and improve the braking and acceleration of the train performance. Hollow structure is also conducive to later flaw detection.

The solid shaft drilling process destroys the metal fibrous structure and reduces the axle load of the hollow shaft [1]. Roll forming as a net forming process can avoid material waste and metal flow lines damage. Bartnicki [2] investigated the influence of process parameters on the stable rolling of hollow shaft in CWR. Ji et al. [3] investigated the effect of process parameters and forming mechanism on the ovality of the hollow shaft of CWR without mandrel. Peng et al. [4] verified that double-wedge CWR can roll large and long thick-walled hollow shafts. Uranker et al [5, 6] investigated the failure conditions of the hollow shaft by CWR. In order to control the dimensional accuracy of the inner diameter of the hollow part, rolling with mandrel is put forward. Yang and Huang [7, 8] investigated the influence of process parameters on the non-circularity of hollow shafts with mandrel. Zheng et al. [9] revealed the mechanism of the hollow shaft by multi-wedge synchrostep cross-ridge rolling (MSCWR). The CWR process requires special molds and the size of large and long shaft parts is limited. Multi-wedge rolling can shorten the length of the mold, but the formed part is easy to be
elliptical and the accuracy error is large. Pater [10] described a skew rolling process with three rollers for a hollow Ti6Al4V alloy shaft and proved that the skew rolling process is suitable for forming hollow long axles. Zhang et al. [11] investigated the forming results of thick-walled hollow parts with equal diameter at small section shrinkage by three-roll skew rolling.

FSR with two rollers, as a semi-net-shaped hollow shaft technology, which is not limited by the size of the mold, and the parts can be formed in multiple passes. Based on the previously studied process parameters of FSR hollow shafts with equal inner diameter [12], this paper proposed FSR hollow train shaft.

2. Simulation Model Establishment and Experimental Setup

2.1. Method and Numerical Modeling

The Geometric model of hollow axle with a variable inner diameter is shown in figure 1, the part requires multi-pass forming and the technological process of FSR is shown in figure 2. Firstly, the initial hollow bar with an outer diameter of 60 mm and an inner diameter of 30mm was heated in the furnace and transferred to the rolling mill. Firstly, one end of the rolled piece is formed with a mandrel with a diameter of 16mm, then the rollers are leveled and size the forming surface. The other end of the rolled piece is shaped in the same way.

![Figure 1. The rough hollow axle (unit: mm).](image1)

![Figure 2. The process flow diagram of FSR hollow axle.](image2)

The FE simulation of FSR hollow axle with a mandrel was carried out in the Simufact. The FE model of FSR hollow shaft with mandrel is shown in figure 3, which includes two rollers, two guiding tubes, one workpiece and a mandrel. The material of workpiece is steel 40Cr, one is widely used in shaft parts. The stress and strain curves of 40cr steel utilized in the numerical calculation is taken from previous studies [13], and parameters are presented in table 1.
Figure 3. The FE of FSR the hollow shaft part with mandrel.

Table 1. Experimental testing arrangement.

| Parameter                               | Value                      |
|-----------------------------------------|----------------------------|
| Speed of roller (Rpm)                   | 30                         |
| Contact heat transfer coefficient(kW/(m²·K)) | 40                         |
| Heat convection coefficient with air (W/(m²·K)) | 100                       |
| Friction factor                         | 0.8                        |
| Initial workpiece (mm)                  | Φ60-Φ30-200                |
| Mandrel diameter (mm)                   | 16                         |
| Initial element number of workpiece     | 26112                      |

2.2. Experimental
The hollow shaft is formed on the FSR mill and the experimental equipment is shown in figure 4(a). The roller is presented in figure 4(b). The cone angle of the roll is 20°, and the sizing section is 30mm. In order to better bite the workpiece, the forming surface is knurled to increase friction. In the process, the hollow bar was heated to 1050 °C and formed.

Figure 4. Laboratory equipment: (a) FSR mill, (b) The roller.

3. Results and Discussion
According to the previously studied process parameters of FSR hollow shafts with equal inner diameter, the rolling process parameters of hollow shaft are designed, and the experiment proves that the FSR railway hollow shaft part is feasible. The following is an analysis of the forming accuracy, forming force and microstructure properties.
3.1. Analysis of Dimensional Accuracy of Rolled-Piece

The roundness of the two ends of the rolled piece is measured, and the rolled-piece has no ellipse. The hollow axle was obtained in laboratory testing on the FSR mill as shown in figure 5 (a), the simulation result was presented in figure 5 (b). The fluctuation of the inner and outer diameters along the axial direction was compared as shown in figure 5 (c). The experimental results are consistent with the simulation results, indicating that the FE model is reliable.

![Image](a)

![Image](b)

Figure 5. Forming Precision comparison of experimental and simulation results.

The average value of the inner diameter and outer diameter of the stable rolling section of the experimental rolled-piece was obtained, as shown in table 2. The relative error (RE) between the experimental value and the design value is calculated with the equation (1). The diameter of the rolled part at both ends is slightly larger than the value of roller gap, indicating that the diameter of the rolled piece has grown after skew rolling. The diameter of the sized part can reach the required diameter. Therefore, it is necessary to choose reasonable parameters to improve the forming accuracy of the rolled parts.

\[
RE = \left(\frac{D_i - E_i}{D_i}\right) \times 100\%
\]

Table 2. Cross section dimension of rolled-piece.

| Forming zone | Average inner diameter (mm) | RE(100%) | Average outer diameter (mm) | RE(100%) |
|--------------|----------------------------|----------|----------------------------|----------|
| I            | 21                         | 16.6     | 42                         | 4.7      |
| II           | 18                         | 0        | 40.5                       | 1.25     |
| IV           | 18                         | 0        | 40.5                       | 1.25     |
| V            | 21                         | 16.6     | 42                         | 4.7      |

3.2. Load Analysis of Rolling Process

Figure 6 presents the force and torque changes of the workpiece during the rolling process. During the entire rolling process, the rolling force curve fluctuates many times, corresponding to the different forming stages of the hollow axle during the rolling process. In the first stage, one end of the
rolled piece is reduced to the target length by skew rolling with the rollers swing angle, then rollers are flattened for sizing and unloaded. Similarly, in the second stage, the other end of the rolled piece is formed.

![Figure 6. Load and torque distribution during rolling.](image)

3.3. Microstructure Analysis
Metal deformation will cause changes in the microstructure of the rolled part. The microstructure of different positions of the rolled-piece is presented in figure 7. The microstructure of the rolled piece is refined by the action of the rollers and the mandrel under high temperature. The grain refinement is due to the dynamic recrystallization of the metal in the rolling process. The action of rollers and the mandrel makes the workpiece deform to a critical strain to trigger the dynamic recrystallization mechanism. The grains will grow up on the austenite temperature as the temperature rises. The P1 point and p2 point have the largest amount of deformation, while the temperature is lower, so its grains are the smallest.

![Figure 7. The microstructure of hollow axle.](image)

4. Conclusion
In this paper, the new process of FSR is used to form the reduced scale train axle shaft, and the result is verified through experiments and simulations.

(1) The dimensions of the rolled axles are basically controllable. In order to improve the application of the FSR in production, reasonable parameter selection is required.
(2) The grains of the rolled piece are refined under the action of the rollers and the mandrel, which can improve the performance of the rolled piece.

The FSR for producing small batches of multi-variety billets is a good choice. The research results lay a theoretical foundation for the short-process and low-cost realization of accurate forming of hollow axles.

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References
[1] Romanenko V P, Stepanov P P and Kriskovich S M 2018 Production of hollow railroad axles by screw piercing and radial forging Metallurgist 61 873-877.
[2] Bartnicki J and Pater Z 2004 The aspects of stability in cross-wedge rolling processes of hollowed shafts Journal of Materials Processing Technology 155 1867-1873.
[3] Ji H C, Liu J P, Wang B Y, Lin J G and Tang X F 2016 The process parameters effect of ovality in cross wedge rolling for hollow valve without mandril MATEC Web of Conferences.
[4] Peng W F, Zheng S H, Chiu Y J, Shu X D and Zhan L H 2016 Multi-wedge cross wedge rolling process of 42CrMo4 large and long hollow shaft Rare Metal Materials and Engineering 45 836-842.
[5] Urankar S, Lovell M, Morrow C, Li Q and Kawada K 2006 Development of a critical friction model for cross wedge rolling hollow shafts Journal of Materials Processing Technology 177 539-544.
[6] Urankar S, Lovell M, Morrow C, Li Q and Kawada K 2006 Establishment of failure conditions for the cross-wedge rolling of hollow shafts Journal of Materials Processing Technology 177 545-549.
[7] Huang X, Wang B Y, Lin J G and Zhu C B 2017 Effect of mandrel diameter on non-circularity of hollow shafts in cross wedge rolling Procedia Engineering 207 2376-2381.
[8] Yang C P and Hu Z H 2016 Research on the ovality of hollow shafts in cross wedge rolling with mandrel The International Journal of Advanced Manufacturing Technology 83 67-76.
[9] Zheng S H, Shu X D, Han S T and Yu P H 2019 Mechanism and force-energy parameters of a hollow shaft’s multi-wedge synchrostep cross-wedge rolling Journal of Mechanical Science and Technology 33 2075-2084.
[10] Z Pater, T Bulzak and J Tomczak 2016 Numerical Analysis of a skew rolling process for producing a stepped hollow shaft made of titanium alloy Ti6Al4V Archives of Metallurgy and Materials 61 677-682.
[11] Zhang S, Shu X D, Xu C, Wang J T and Xia Y X 2020 Simulation and experiment of reduction of equal-diameter hollow shafts with three-roll skew rolling Procedia Manufacturing 50 183-186.
[12] Cao X Q, Wang B Y, Zhou J, Shen J X and Lin L F 2021 Exploratory experiment and numerical simulation investigation on a novel flexible skew rolling of hollow shafts The International Journal of Advanced Manufacturing Technology 116 3391–3403.
[13] Chen L, Sun W Y, Lin J, Zhao G Q and Wang G C 2019 Modelling of constitutive relationship, dynamic recrystallization and grain size of 40Cr steel during hot deformation process Results in Physics 12 784-792.