Manufacturing large shafts by a novel flexible skew rolling process

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Abstract

When manufacturing large shafts with multi-specification and small-batch production, both the conventional forging and rolling process bring a high tooling cost due to heavy forging press or large-sized specialized roller. In this study, a novel flexible skew rolling (FSR) process is proposed by adding degrees of freedom to the rollers as compared to the typical skew rolling process. Since each of the FSR rollers has three degrees of freedom (circle rotating, radial rotating, and radial feeding), the FSR process can be divided into four stages: radial rolling, rollers inclining, skew rolling, and rollers leveling. Therefore, the FSR process can produce various shafts with the same rollers via programming different movements. To verify the feasibility of FSR process, a physical investigation corresponding with a numerical simulation for a single-step shaft is undertaken with a Φ80 × 390 mm C45 steel billet. According to the results from physical experiments and numerical simulations, the FSR formed shaft has a maximum deviation of 0.99 mm, and its microstructure and properties have been improved obviously. Moreover, although there is a tendency of the center crack in FSR products as predicted by numerical results, both the transverse and longitudinal sections of the physical shaft are free from central cracking. The major forming defects that existed on the rolled shaft are knurled pockmarks, surface threads, and side cavity, which are the typical defects of the conventional skew rolling and cross-wedge rolling and can be removed by machining. To the authors’ knowledge, this novel process has a good combination of flexible production and less loading, which will be of great engineering significance to reduce the tooling cost in large shafts manufacturing.

Keywords Flexible skew rolling · Large shafts rolling · Forming defects · Forming precision

1 Introduction

Large shafts play an important role in large-elongated axial parts manufacturing and die-forging billets preforming, which are widely used on transportation vehicles, aerospace, construction machinery, and other industrial clusters, such as railway axles [1, 2], truck shafts [3], preforms of turbine blade [4], and railway switches [5]. Up to now, these shafts are generally formed by the forging processes (open die forging [6, 7], radial forging [8–10], and cross-wedge rolling (CWR) process [1, 11, 12]). Nevertheless, the forging process can manufacture various shafts by customized tools but needs a high forging force on account of its characteristic of overall deformation, which results in the heavy tonnage of forging equipment. Conversely, the cross-wedge rolling process can achieve less-loading forming by the regional and progressive deformation but needs large-sized specialized rollers. When manufacturing large shafts in multi-specification and small-batch production, both the forging and rolling processes bring a high tooling cost due to the heavy loading press or the large-sized specialized rollers.

In order to achieve flexible manufacturing, a process of axial feed rolling is early proposed and investigated [13, 14], whose schematic diagram is shown in Fig. 1a. The workpiece is radially compressed via two rollers feeding radially and whereafter axially stretched under the chuck drawing. Therefore, the axial feed rolling process is a flexible production that same rollers can manufacture various multiple-step parts by different roller movements. However, because two rollers are paralleled with each other, the drawing force of the chuck is significantly huge, especially in large shafts manufacturing.

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Another flexible rolling process is the three-roller skew rolling method which can be divided into two types: copy skew rolling (Fig. 1b) and CNC skew rolling (Fig. 1c). Copy skew rolling is originated from the former Soviet Union by Zerikov (1948) [15, 16], in which a copy plate is used to control the motions of tapered rollers. With the development of automatic control technology, Pater et al. [2, 17] used a CNC system to replace the copy unit and successfully accomplished the laboratory experiments of forming two rail axles in a CNC skew rolling mill. Significantly, due to the tapered rollers are inclined to each other, the rolling piece of copy skew rolling and CNC skew rolling can be automatically driven by the axial component of friction, so the drawing force of the chuck can be significantly decreased.

Nevertheless, all above-mentioned processes, whether in axial feed rolling, copy skew rolling, or CNC skew rolling, a chuck is required to draw the workpiece in the axial direction that may cause the following limitations: (1) a considerable amount of chucking allowance is indispensable so that the material utilization is reduced; (2) the maximum length of the rolled shaft is limited by the chuck stroke of the mill.

In this study, a novel flexible skew rolling (FSR) process is proposed by adding degrees of freedom to the rollers as compared to the typical skew rolling process. The aim of this presented paper is to verify the flexibility of this novel FSR process. Firstly, a new type of FSR mill and FSR roller are designed, and their features are detailly introduced. Secondly, an FSR experiment of a Φ80 single-step shaft is
performed to verify the feasibility of FSR process. Thirdly, a corresponding finite element (FE) numerical simulation is conducted to reveal the FSR deformation characteristic. Finally, several types of physical experiments are performed to explore the FSR potential applications and reveal the FSR forming defects.

2 Flexible skew rolling (FSR) process

2.1 Novel process of flexible skew rolling

As shown in Fig. 2, a two-roller FSR process is proposed and patented by the authors [18]. Its rolling device mainly consists of two rollers and two tube guides. Each of the two rollers has three degrees of freedom as circumferential rotating $N_0$, radial feeding $V_0$, and angle adjusting $W_0$. The rotation of angle adjusting $W_0$ is rotating along the radial centerline of the roller that can change the skewing angle between the roller and workpiece. Two tube guides are respectively fixed on the sides of two rollers to restrict the movements of workpiece. By programming the motions ($N_0$, $V_0$, $W_0$) of two rollers in an automatic system, the FSR process can be divided into four stages (Fig. 2b): (1) radial rolling: two leveled rollers have the motions of $N_0$ and $V_0$ and then two rollers knife into the workpiece; (2) rollers inclining: two rollers only have the motion of $W_0$, and the skewing angle $\beta$ is increased to

![Schematic illustration of flexible skew rolling (FSR): (a) process principle; (b) rolling stages [18]](image-url)
target value; (3) skew rolling: two inclined rollers only have the motion of $N_0$, and the workpiece rotates circularly and moves axially; and (4) rollers leveling: two rollers have the motions of $V_0$ and $W_0$ and then back to the original state.

Since the FSR process can be programmed into four stages, the FSR process can flexibly form various shafts without changing the rollers. And according to the above descriptions, the FSR method has the following characteristics: (1) a drawing chuck is unessential because the workpiece can move axially under the action of axial friction; (2) the rolling tooling is relatively simple because only two rollers are needed; and (3) an numerical control system is essential because the movements of two rollers are complex and difficult to control.

2.2 New type of FSR mill and FSR roller

To meet the requirement of the FSR process, a laboratory FSR mill that has three degrees of freedom ($N_0, V_0, W_0$) is developed and designed. Therefore, a new type of multi-freedom rolling mill has been invented and constructed [19]. Its three-dimensional design model is shown in Fig. 3. The physical mill is presented in Fig. 4, and technical specifications are given in Table 1. The FSR mill mainly consists of ten components: a base unit (1), two tube guides (2), two arm stands (3), two angle adjusting systems (4), two rollers (5), two rotational systems (6), a gravity balance unit (7), a radial feeding system (8), a synchronous unit (9), and a servo control system. In the FSR mill, two rotating systems are correspondingly mounted under two arm stands and drive two rollers rotating around its axle. Two angle adjusting systems are fixed on the two arm stands to adjust the skewing angle, respectively. In order to make the radial feeding system synchronous, a synchronous unit worked by two matched gears is used to ensure two arm stands open or close together. The overall dimension of this mill is $1.8 \, \text{m} \times 1.7 \, \text{m} \times 1.6 \, \text{m}$, and its total power is 70 kW, but the maximum billet diameter can be up to 80 mm. The FSR mill has an advantage of compactness structure.

The FSR roller is inspired by the Mannesmann piercing roller [20] but has some developments because all the forming stages need to be considered and the workpiece needs to avoid crack. The FSR roller is shown in Fig. 5 and has a small size and a simple shape. It has a symmetrical structure of a sizing zone in the middle and two forming zones on both sides because the rolling force should be balanced in axis direction during the radial rolling stage. In addition, it is made by the hot-die-material H13, and its hardness is measured as 53 HRC. Besides, the forming zone surface is knurled by a 2-mm knurling knife (CN standard, GB 6403.3). The knurled surface can improve rolling conditions but slightly reduce the surface forming accuracy of rolled product. The geometric parameters of FSR rollers are: diameter $D_0 = 340$ mm, length
$L_0 = 120$ mm, forming angle $\alpha = 20^\circ$, and sizing width $L = 25$ mm.

3 Feasibility experiment of a $\Phi 80$ single-step shaft FSR rolling

3.1 FSR rolling experiment

To verify the feasibility of the FSR process, a physical feasibility experiment of a single-step shaft FSR rolling was undertaken with a $\Phi 80 \times 390$ mm C45 steel billet. The physical experiment was performed at the University of Science and Technology Beijing, China. Because the rolled shaft only has one step, the FSR rolling process simply includes three stages of radial rolling, rollers inclining, and skew rolling. Although not all processes are included, two main forming stages (radial rolling, skew rolling) are contained. Therefore, it can be concluded that the feasibility experiment is reasonable.

The flowchart of rollers’ movements is shown in Fig. 6. At the radial rolling stage, two leveled rollers rotate with a constant speed of $N_0 = 30$ Rpm and feed radially with a speed of $V_0 = 1.5$ mm/s. After the radial rolling stage (10 s later), the gap between the two rollers reaches the target value of 50 mm. During the rollers inclining stage, the inclining angles of two rollers are adjusted into a skewing angle of $\beta = 8^\circ$. At the skew rolling stage, two rollers remain an inclined angle $\beta = 8^\circ$ and rotate at the speed of $N_0 = 30$ Rpm, and the workpiece circumferentially rotates and axially moves under the frictional force.

Prior to the rolling, the billet was preheated to 1050 °C in an electric tube furnace and then immediately transferred to the FSR mill. As shown in Fig. 7, the workpiece is rolled stably during every stage. After FSR rolling, the product was removed and cooled in the air. The rolled shaft is shown in Fig. 8; the reduction ratio of cross-section is greater than 60%.

| Table 1 Technical specifications of FSR mill |
| Parameter                  | Unit | Value |
|----------------------------|------|-------|
| Main rotating motor power  | kW   | $2 \times 30$ |
| Main rotating speed        | rpm  | 0~43  |
| Radial feeding motor power | kW   | 3     |
| Radial feeding speed        | mm/s | 1~5   |
| Angle adjusting motor power| kW   | $2 \times 2.3$ |
| Angle adjusting speed       | °/s  | 1~10  |
| Angle adjusting range       | °    | ±12   |
| Rolling center line range   | mm   | ±0.15 |
| Maximum roller diameter     | mm   | 350   |
| Maximum billet diameter     | mm   | 80    |
| Overall dimensions          | m    | $1.8 \times 1.7 \times 1.6$ |
| Total power                 | kW   | 70    |
| Total weight                | ton  | 5     |
According to the feasibility test, the conclusions can be obtained as follows: (1) the FSR process is feasible and optimistic; (2) numerical control system can achieve the complex movement arrangement of rollers, and the design parameters of FSR mill are appropriate for forming the large shaft parts; (3) the temperature of the workpiece is relatively stable and still in the temperature range of hot deformation.
3.2 Results and discussion

3.2.1 Forming precision

The geometrical dimension of the FSR shaft was acquired by a high-precision 3D scanner and then measured in Geomagic Quality software. As Fig. 9 shows, at the radial rolling stage, the maximum and minimum diameter deviations of the FSR rolled shaft are $+0.8\,\text{mm}$ and $-0.39\,\text{mm}$. Respectively, the deviations of skew rolling stage are $+0.99\,\text{mm}$ and $-0.35\,\text{mm}$. Because the workpiece is restricted by two tube guides, the rolled shaft hardly bends, so that the diameter deviations mainly result from the forming defects of surface threads.

There are some forming defects that appeared on the rolled-shaft as shown in Fig. 9a. The knurled pockmarks exist on the tapered step surface because the rollers’ surfaces were knurled by hatching knurling. In addition, the surface threads, which are formed at the stage of skew rolling, obviously emerge on the rolled rod. The main reason
Fig. 9 The (c) geometric model of the (a) rolled shaft was modeled by a high-precision (b) 3D scanner and their (d, e) dimensional deviations were measured.

Fig. 10 FSR rolled shaft has the defect of side cavity and free from central cracks in macroscale: (a) transverse section; (b) longitudinal section.
for these surface threads may be that the sizing length $L$ is too short or the chamfering angle between the forming and sizing zone of the roller is unreasonable; thus, further research is necessary.

Another observed defect is the side cavity as shown in Fig. 10b, which has a length of 36.8 mm and an angle of 61.2°. It can be explained that the material of the outer sphere flows more rapidly than that of the internal. This defect leads to the waste of the material, but does not affect the quality of products.

Actually, all these observed defects are the typical imperfections in skew rolling [2, 17, 21] and cross-wedge rolling [22–24] and can be removed in later precision machining, so they do not affect the quality of produced shaft.

### 3.2.2 Central quality

Since the skew rolling stage of the FSR process is much similar to the piercing process which has the trend of central cracking, we can anticipate that the central cracks, also called the Mannesmann effect [25], may occur in the workpiece central and reduce the performance of formed parts.

For observing in detail, both the transverse and longitudinal section of the FSR rolled shaft have been dissected and polished. As demonstrated in Fig. 10, it is clearly shown that the rolled shaft is free from any internal defects in the macroscale. Furthermore, its micromorphology is observed by a 200× magnification in the optical microscope. As shown in Fig. 11d, the magnified center is free from visible cracks or holes, which furtherly indicates that the Φ80 mm single-step shaft has no center crack.

### 3.2.3 Microstructure evolution

The microstructure evolution of the deformed metal is one of the most significant indicators to evaluate the mechanical properties of the FSR products. As shown in Fig. 11, four sampling points named P01, P02, P11, and P12 are chosen from the outer and inner region of the unrolled and rolled rod. These samples were polished and etched, and their grain size and micromorphology were obtained in a microscope with 200× magnification.

As Fig. 11 shows, the grain sizes of rolled samples (P11, P12) are smaller than that of unrolled samples (P01, P02),
it can be explained that the grains in outer and inner regions are refined by FSR rolling. Besides, the grains of the outer zone (P11) are obviously refined much greater than these of the inner (P12) because the outer materials have a much larger plastic deformation than central. All these observed results demonstrate that workpiece microstructures can be improved by the FSR process.

3.2.4 Mechanical properties

Testing the mechanical properties is essential to validate whether the FSR process is an optimistic alternative. Therefore, the ultimate tensile strength (UTS) and elongation were employed to characterize the mechanical properties. Four cylindrical testing pieces were extracted from the outer and inner regions of unrolled and rolled rod and tested at room temperature with a drawing speed of 1 mm/min. The sampling positions and testing results are entirely shown in Fig. 12.

In the outer zone, the UTS is significantly enhanced from 624.3 to 670.6 MPa, and the elongation is increased from 28.0 to 31.4%. However, in the center of the shaft, the UTS is slightly reduced, and the elongation is significantly improved. These performances can be explained that the outer materials have experienced a larger deformation which results in the outer grains being greater refined than the inner ones. As for the UTS slight decrease in the central zone, we can think that the rolled bar has a smaller diameter and therefore the faster temperature drops cause the tensile strength to increase. But in general, the overall mechanical properties of the whole shaft are improved after the FSR deformation.

4 Finite element simulation of the feasibility experiment

4.1 FSR finite element modeling

The corresponding FSR FE simulation were performed in the FE software Simufact.Forming, which has been successfully employed in the numerical analysis of cross-wedge rolling process [26, 27] and skew rolling process [2, 28], and their FE results have a good agreement with experimental results. The FSR finite element model is based on the actual situations of the feasibility experiment, and their parameters are the same.

All tools were modeled as ideally rigid bodies, whereas the workpiece was assigned to the properties of a rigid-plastic body. The material of the workpiece is the C45 steel, and its material data were taken from Simufact.Material. The properties (i.e., density, Young’s modulus, and Poisson’s ratio) were set as default. The material model of C45 steel was described with the equation:

$$\sigma_F = 2859.85e^{-0.003125T}e^{(0.00044667T-0.10127)e^{(-0.0000277+0.0008133/\varepsilon)(0.000157-0.002749)}}$$

where $\sigma_F$ is the flow stress (MPa), $\varepsilon$ is the effective strain (-), and $T$ is the temperature (°C).

The friction coefficients between tools and workpiece were formulated by shear model (that of two rollers were 0.8, and two tube guides were 0.2) [2]. The temperature of tools (rollers, guides) was constantly maintained at 300 °C.

![Fig. 12 Mechanical properties of FSR rolled shaft at different locations: (a) positions and dimensions of the tensiled samples; (b) the results of tension tests](image-url)
The initial temperature of workpiece was 1050 °C, and the coefficient of heat transfer between tools and workpiece was 10 kW/m²K [2]. The heat transfer coefficient of the roller to environment was 0.02 kW/m²K, and its heat radiation was 0.75. Besides, the mesh of billet was created by ringmesh mesher, whose element size equals to 6 mm and will be automatically reconstructed if the effective strain increases by 0.4 [2]. The established FSR finite element model is presented in Fig. 13.

4.2 FSR finite element model validating

The FSR FE model was validated by comparing the final geometry parameters of the rolled shaft between the physical and FE results which was used in the study of Zhou [29]. The geometric parameters of FE model and experimentation were measured in the Geomagic Quality software. The comparison results include total length $L$, side cavity angle $\gamma$, minimum diameter $D_{\text{min}}$, and maximum diameter $D_{\text{max}}$ of the rolled bar.

The geometry comparison is shown in Table 2. The maximum relative deviation (relative to physical result) of four geometric parameters is the side cavity angle $\gamma$ with a value equal to 2.1%, and all these deviations are within the 10% range, so that the FSR finite element model can be considered as reliable.

4.3 Results and discussion

4.3.1 Deformation characteristics

In the application of finite element software, the FSR deformation process can be extracted from FE simulation results. As shown in Fig. 14, at the stage of rollers inclining, the workpiece has a slight deformation. Therefore, it can be obtained that the main forming stages of the FSR process are the radial rolling stage and the skew rolling stage. At the radial rolling stage, the workpiece is bit into a groove and deformed on two sides. The metals in contacting zone are radially compressed and axially elongated, and the axial movements of workpiece are at a same speed $V_R$, but with opposite directions. During the skew rolling stage, two rollers contact with the workpiece only on one side, and the rolling workpiece radially rotates and axially feeds automatically under the action of friction component because two rollers are inclined.

In fact, the deformation characteristics of FSR have some similarities to the CWR process which was described in the study of Huang [30]. The workpiece is radially knifed primarily and then stretched axially. The radial rolling stage is similar to the knifing stage in CWR, while the skew rolling stage is similar to the stretching stage of CWR.
Since the area reduction of the rolled shaft is formed by skew rolling, another feature of the FSR deformation is that the major forming stage of the FSR forming is skew rolling stage. To be specific, the shaft is formed by the roller’s forming zone and sized by the roller’s sizing zone. Therefore, the skewing angle $\beta$, forming angle $\alpha$, and sizing length $L$ are extremely important to FSR process.

4.3.2 Central quality of workpiece

According to the experiences of skew rolling and cross-wedge rolling, the Mannesmann hole [25] may occur in the center of FSR workpiece and cause the failure of products. To obtain the evolutions of stress and ductile damage, four transverse sections named S1, S2, S3, and S4 were selected to do a analyze. As signed in Fig. 14, S1 and S3 are the forming sections during the radial rolling and skew rolling stages, while S2 and S4 are the sections after rolling.

Figure 15 shows the distributions of effective stress. At the radial rolling stage, the central materials are exerted two tension stress and one compression stress. More specifically, the radial stress is a compressive stress which gradually reduces from the surface to the center, and the tangential or axial stress is a tensile stress which locally concentrated in the workpiece center.

During the skew rolling stage, the stress distribution characteristics are identical to the rolling stage that two tension stress and one compression stress exist in the central region. Compared to the radial rolling stage, the tangential tension stress and axial tension stress at the skew rolling stage become bigger. The radial stress of the central zone is compressive with a relatively small value of approximately 20 MPa, while tangential stress and axial stress are tensile with the relatively larger value exceeding 40 MPa. Since the stress distribution state of the center is tension in two orientations and one compression in one orientation which may cause the generation of microcracks, it can be concluded that the FSR process is susceptible to central crack.

Three typical damage models were used to predict the damage state in the FSR process (Fig. 16). Cockcroft and Latham [31] considered that the damage value is equal to the ratio of maximal principal stress and effective stress. Oyane [32] proposed a ductile damage model based on the characteristics of porous materials. Ayada et al. [33] held an opinion that ductile fracture only depends on the history of stress triaxiality.

The ductile damages are calculated by the functions demonstrated in Fig. 16. Furthermore, in order to get the damage distribution from FE software, the user subroutine of Simufact.Forming was employed to implement these criteria, so the damage values can unconditionally be updated at every increment and visually analyzed in the postprocessor. As shown in Fig. 16, it can be clearly observed that the ductile damages of three criterions have some common characteristics: (1) there are damage concentrations in the central region; (2) the ductile damages increase evidently at the radial rolling and skew rolling stages. These findings are consistent with the stress distribution conditions analyzed above, so it can be obtained that the FSR process has a trend of central cracking. In addition, although it is shown that there are also some large ductile damages in the outer region, it can be explained that the outer workpiece undergoes the large tensile stress.
However, it is noteworthy that the damage distribution can reveal the trend of central crack which may be occurred under unreasonable parameters, but it cannot be judged that the simulation results are inconsistent with the experiment because the predicted damage value may not reach the fracture threshold value.

### 4.3.3 Axial feeding velocity

The axial feeding velocity of the workpiece directly determines the FSR production efficiency. Four tracking points (P11, P12, P13, and P14) are selected, and their axial velocities are shown in Fig. 17. During the radial rolling stage, the axial feeding velocities of the workpiece from the inlet to outlet side have the same value $V_{R1}$ but in different directions. However, at the skew rolling stage, its value in inlet ($V_{S1}$) and outlet side ($V_{S2}$) is not the same. Quantitative analysis reveals that the axial moving speed of radial rolling stage is relatively small with a value of the approximately 2 mm/s. At the skew rolling stage, the value of axial moving speed has a larger number with an average value of about 28.5 mm/s in the outlet side.

Actually, the axial feeding velocity of the workpiece is affected by rotating speed $N_0$, forming angle $\alpha$, and skewing angle $\beta$. The rotating speed $N_0$ of this study is only 30 rpm, which is relatively low for the skew rolling process. However, the total rolling time is as short as 20 s. It can be concluded that the production of FSR is efficient.
4.3.4 Temperature distribution

The temperature distribution of rolling piece is investigated as shown in Fig. 18. It can be observed that the temperature of the workpiece is relatively stable. Meanwhile, it can be noticed that the temperature increases locally in the working area because the deformation and friction cause heat generation. The surface of the billet has a slight temperature drop, which can be explained that it undergoes a local cooling because the heat is dissipated to the air, but fortunately, the temperature is still in the range of the hot deformation. Moreover, since the temperature drops slowly and the rolling time is short that the workpiece temperature can be stabilized within the hot workability range, the billet of the FSR process needs to be heated only once, which obviously reduces energy consumption.

4.3.5 Rolling force and rotating torque

The force parameters of rolling force and rotating torque are the basic data in equipment design. As shown in Fig. 19, at the roller inclining stage, both the rolling force and rotating torque are very small, which further verify that the workpiece has a very slight deformation at this stage. However, at the forming stages (radial rolling stage and skew rolling stage), the rolling force and torque change correspondingly with relatively large values. Concretely, the rolling force differs little with a value of about...
Fig. 16  Ductile damages of FSR workpiece: (a) Cockcroft and Latham [31]; (b) Oyane [32]; (c) Ayada [33], in which $\varepsilon$ is effective strain, $\sigma_1$ is maximal principal stress, $\sigma_i$ is effective stress, $\sigma_m$ is mean stress, $A$ is a material coefficient (0.424) [34].

Fig. 17  Rolling speed and duration of FSR process
150 kN. The rotation torque of the spindle motor varies greatly with a maximum value approximates to 8700 Nm.

5 Application exploration

The above studies in this paper are based on a simple single-step shaft, but in fact, the shapes of large shafts are diverse. In order to explore the industrial applications, some physical experiments were carried out with different rollers to form various parts in the laboratory (see Fig. 20). Because it can form different shafts by the same rollers, these flexible experiments were conducted conveniently. There were two types of parts being produced: bars and step shafts.

As shown in Fig. 20a, the rollers have different geometries including symmetric rollers and tapered rollers (the tapered roller is generally used in copy skew rolling and CNC skew rolling), and their parameters of sizing length $L$ and forming angle $\alpha$ are also varied in different values. By carrying out the experiments, we found that the tapered roller is not suitable for the FSR process because the step bulge appeared in the radial rolling process due to asymmetric deformation. Besides, the roller material and its heat treatment are very important because the FSR roller stands the high temperature, rapid rotation, and large rolling force. Moreover, the small forming angle $\alpha$ and large skewing angle $\beta$ are favorable for billet feeding, but conversely, it will increase the possibility of central cracking. The large sizing length $L$ can directly reduce the surface threads but will result in the increase of the rolling force. Therefore, a process window needs to be established in further studies.
The shaft with multiple steps is rolled and shown in Fig. 20b. Attention should be paid; there are some forming defects that evidently appeared in the formed products. These defects are summarized and shown in Fig. 20c, in which side cavity, surface threads, pockmarks, and central cracks are the most noteworthy flaws. These defects limit the application of the FSR process and need to be eliminated in future studies.

6 Conclusions

(1) A novel process named flexible skew rolling (FSR) has been proposed and verified through the physical experiment and FE simulation. The FSR process could be expected to produce large shafts with a small equipment and form various shafts without changing the rolling tools.

(2) The FSR rolled shaft has a maximum diametric deviation of 0.99 mm. Although there is a tendency of center cracks as FE results indicate, the actual rolled piece is free from internal cracks, and its microstructure and mechanical properties are improved in overall.

(3) The forming defects of the FSR process are investigated by an exploratory experiment of forming various shafts with different rollers, of which the most noteworthy defects are central cracks, surface threads, and side cavity. The formation mechanisms and optimization methods for FSR defects need to be investigated in further studies.

(4) The deformation characteristics of the FSR process are similar to that of the cross-wedge rolling, in which the workpiece is radially compressed initially and then stretched axially, and the movements of the FSR rollers are much similar to that of the piercing rolling, in which the inclined rollers drive the workpiece to circularly rotate and axially move.

(5) FSR process has an optimistic efficiency with an axial feeding velocity of 28.5 mm/s in outlet side, which is beneficial to keep the temperature relatively stable, so the workpiece needs to be heated only once.

(6) The loading of the FSR process is relatively light that the maximum radial rolling force is about 150 kN and the maximum rotation torque is about 8700 Nm of a Φ80 mm shaft.

Author contribution Longfei Lin: Software, investigation, validation, methodology, writing-original draft. Baoyu Wang: Project administration, supervision, funding acquisition. Jing Zhou: Methodology, writing-reviewing and editing. Jinxia Shen: Data curation, writing-reviewing and editing.
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**Data and material availability** The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed consent** All the authors listed have approved the manuscript that is enclosed.

**Consent to participate** Applicable.

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