Producing hollow shafts in a new horizontal mill by novel flat-knifing cross-wedge rolling with single guide

Longfei Lin1 · Baoyu Wang1,2 · Jinxia Shen1 · Tao Liu1

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Abstract
To meet the requirement of lightweight, an increasing number of solid shafts are designed to be hollow in transportation industry. In this study, a novel method of flat-knifing cross-wedge rolling (FCWR) with single guide is proposed including a modified roller, a horizontal mill, and a single-guide structure, and its key problems are studied by numerical simulations and experimental tests. A mathematical model of FCWR roller is established, which reveals that the wedge length of rollers is effectively reduced by modifying knifing wedge from normalized roller. Furthermore, a horizontal multifunctional mill is invented and constructed to carry out the FCWR experiment with single guide. According to the results from the numerical simulations and corresponding experiments, it is observed that the typical defects of hole expansion and knifing groove are absolutely avoided because the improved flat-knifing wedge produces a radial force to shrink the inner hole and avoid the deformation concentration of the outer surface during knifing stage. Moreover, the single-guide rolling performed in the horizontal mill efficiently improves rolling stability because the workpiece is restricted into a smaller workspace. To the authors’ knowledge, all these integrated improvements of FCWR roller, single-guide rolling, and horizontal mill are innovative, which are of great engineering significance to manufacture hollow shafts on account of the advantages of avoiding forming defect, reducing roller diameter, improving rolling stability, and simplifying mill structure.

Keywords Flat-knifing cross-wedge rolling · Horizontal cross-wedge rolling mill · Multifunctional rolling mill · Single-guide rolling · Hollow shaft rolling

1 Introduction
Since hollow shafts have advantages of lightweight structure, low rotating inertia, and convenient flaw detection, more and more solid parts are designed to be hollow such as railway axles [1], engine valves [2], and truck shafts [3]. Up to now, these hollow shafts are mainly formed by forging, extrusion, and drilling so that it generally has the limitations of material waste and low production efficiency.

Cross-wedge rolling (CWR), a near-net shape metal manufacturing process with high production efficiency and low material consumption, has an extensive application in solid
shafts including large-elongated parts (e.g., automobile camshafts, stepped shafts) and die-forging preforms (e.g., engine valves, connecting rods, double-ended spanners) as reviewed by Hu et al. [4] and Pater et al. [5]. Hu et al. [4] pointed out that they have established more than 300 production lines worldwide with an estimated production value of more than $200 million per year and highlighted that the weight of CWR products has over 400,000 tons with an amount of 2 billion pieces per year in China. However, although CWR has been successfully used on solid shafts, it is less common on hollow shafts.

Compared with forging, extrusion, and drilling process, CWR of hollow shafts has advantages of high efficiency, no lubricant, and less loading. Researchers have been concerned about its applications. Huo et al. [6] presented a CWR process for high-speed railway axles and predicted the microstructure and ductile damage at hot forming. Ji et al. [2] proposed to manufacture hollow valve preforms by CWR and investigated the influence of process parameters. Yang et al. [3] developed a process of CWR hollow axle sleeve and studied the elliptical behavior of inner hole. Pater et al. [7] presented a conception of the three-roller cross rolling process of hollow rail axles and found that the walls of formed steps are thickened. Peng et al. [8] used a multi-wedge CWR without mandrel to produce hollow high-speed railway axle and reached a conclusion that the double-wedge CWR for large and long thick-walled hollow shafts is feasible.

To establish a reliable technique for rolling hollow shaft, CWR without mandrel was early proposed and investigated. Bartnicki and Pater [9, 10] analyzed the numerical simulation results and found that the thinner wall thickness may cause the slipping and flattening of billet and concluded that the three-roller CWR can improve rotation conditions. Urankar et al. [11] proposed a dimensionless crushing parameter to predict forming limit of the hollow products, and the defect of hole expansion was shown in their study. However, CWR without a mandrel has a common shortcoming that its inner hole is unable to be regularly formed because the hole is formed randomly.

A process of CWR with mandrel was proposed to control the dimensions of inner hole, and researches have been done to improve its forming performance. Neugebauer et al. [12] proposed two ways to control the movements of mandrel: fixed or free mandrel. Landgrebe et al. [13] modified the typical CWR via adding a drilling mandrel; therefore, a hollow shaft can be directly rolled from a solid billet. Shen et al. [14, 15] used a compensated mandrel to produce hollow shafts with a variable inner diameter. Recently, based on the volume consistency principle, Shen et al. [16] established a theoretical model to predict the critical mandrel diameter. However, many of these researches focused on mandrel design and parameter optimization, but paid less attention to roller modification.

In normalized CWR with mandrel, as shown in.1, although inner hole can be controlled, it brings about the defects of hole expansion and knifing groove [17–20]. Hole expansion exists on the inner hole while knifing groove on the outer surface. These defects reduce the utilization of materials and increase the cost of post-processing. Ji et al. [17] employed variable stretching angle to avoid hole expansion, but it made roller design complicated. Wilson [21] proposed a flat-knifing wedge in hollow shafts three-roller cross-wedge rolling. In engineering practice, skilled workers generally solve the hole expansion by chamfering knifing wedge [22]. Actually, both hole expansion and knifing groove occur in the knifing position of rolled shafts. Therefore, modifying the shape of roller on knifing zone is of great significance.

In this study, a novel flat-knifing cross-wedge rolling (FCWR) with single guide for hollow shafts (Fig. 1b) is proposed whereby modifying roller and mill from the base of normalized cross-wedge rolling (NCWR), which has the advantages of avoiding the defects of hole expansion and knifing groove, reducing the diameter of rollers, improving rolling stability, and simplifying mill structure.

In order to study the new process systematically, its key points are investigated by numerical simulation and experimental research. Firstly, the new process of FCWR with single guide is described in detail. Secondly, the mathematical model of FCWR roller is established, and the length reduction is calculated and visually presented. Thirdly, numerical simulations are conducted to compare the NCWR and FCWR process from the aspects of defect formation mechanisms, workpiece deformation characteristics, and influences of new parameter. At last, corresponding physical FCWR experiments are performed to verify the FE results, and the advantages and disadvantages of these improvements are discussed.

2 Flat-knifing cross-wedge rolling with single guide

2.1 Novel process principle

The process principles of normalized cross-wedge rolling (NCWR) with two guides and flat-knifing cross-wedge rolling (FCWR) with single guide are shown in Fig. 2. They have the same deform mechanism that two wedged rollers are parallel to each other and rotate in the same direction, and the cylindrical hollow billet is deformed into a stepped hollow shaft under the action of roller whereby wedged rollers move tangentially relative to each other. But there are some improvements in this study: (1) the knifing wedge of FCWR roller is flatted, while that of NCWR is sharpened; (2) different from NCWR which has a vertical structure,
Fig. 1 Contrast between two methods for hollow shafts: (a) normalized CWR and (b) flat-knifing CWR.

Fig. 2 Process principle: (a) NCWR with two guides and (b) FCWR with single guide.
FCWR process changes into a horizontal arrangement that can achieve single-guide rolling under gravity; and (3) by single-guide rolling, FCWR workpiece is steadily restricted into a smaller workspace. As a result, the novel process is estimated to have the following advantages:

- The defects of hole expansion and knifing groove can be absolutely avoided.
- The diameter of two rollers can be evidently shortened.
- The mill can be simplified into single-guide structure.
- The rolling stability can be improved.

### 2.2 New type of horizontal multifunctional mill

In order to achieve the technical objective of single-guide rolling, a laboratory mill with a horizontal structure is indispensable. Up to now, the traditional CWR mills commonly have a vertical structure [4, 5], which apparently cannot meet the requirement of this study.

Therefore, a new type of rolling mill is invented and constructed by the authors [23]. The freedom of this mill has been increased by two angle adjusting systems, one radial feeding system, and a synchronous unit (worked by two matched gears). Its 3D model is shown in Fig. 3, the mill is presented in Fig. 4, and the technical specifications are given in Table 1.

![Fig. 3 Geometrical model of the horizontal multifunctional mill [23]](image1)

![Fig. 4 The constructed horizontal multifunctional mill [23]](image2)

This mill is characteristic of multiple freedom degree because it has several movements of circumferential rotating, radial feeding, and angle adjusting, and thus, it can be used for different types of laboratory rolling tests such as longitudinal rolling, cross rolling, and skew rolling. In this study, this mill can be used in cross-wedge rolling when two skewing angles are adjusted to 0.
All the motions of this mill are directly driven by servo motors that mill structure is compact. As signed in Fig. 3, two C-type frames are used to enhance mill strength; the automation system is controlled by an accurate servo drive which is programed in PLC language. All these features may take this type of mill advantages of compact structure, high strength, and high precision, so that it can be expected to be industrially applied as thread rolling mill, ball rolling mill, and CWR mill.

### 2.3 New type of flat-knifing roller

Roller modification is a main innovation of this paper. In the hope of mathematically describing the FCWR roller in detail, both the geometrical models of FCWR and NCWR roller are designed and shown in Fig. 5 with a plane layout way.

There is an obvious difference observed in the figure that the knifing zone of NCWR roller is designed as a V-shaped wedge, while FCWR roller is a flat wedge with a width of $B$. Further, the FCWR roller only changes the wedge shape in the knifing zone, and their configurations are identically divided into three sections as knifing zone, stretching zone, and sizing zone. Figure 6 shows that their contact models (extracted from the A-A view of Fig. 5) between roller, mandrel, and workpiece of FCWR and NCWR roller are the same on stretching zone. To make an analysis, on the one hand, the main deformation of FCWR rolling occurs in stretching zone, where FCWR has the same contact model with NCWR. On the other hand, FCWR process has the same sizing zone with NCWR. In conclusion, these modifications have not changed the process parameters of the NCWR, so that both NCWR and FCWR may have the same process parameters such as forming angle $\alpha$, stretching angle $\beta$, and mandrel diameter $d_m$.

In order to mathematically compare FCWR and NCWR roller, the calculation of wedge length is a basic work, which needs to be undertaken primarily.

At the knifing zone, notwithstanding the different geometries, the wedge lengths of FCWR and NCWR roller are equally formulated as Eq. 1, where $h$ is the height of wedge, $\alpha$ is forming angle, and $\beta$ is the stretching angle.

$$L_{N1} = L_{F1} = h \cot \alpha \cot \beta$$

At the stretching zone, because the initial position of FCWR wedge has a straight section, $L_{N2}$ is obviously longer than $L_{F2}$, and they are respectively calculated by Eq. 2 and Eq. 3, where $L$ represents the sizing width (signed in Fig. 5) and $B$ represents the knifing width.

$$L_{N2} = 0.5L \cot \beta$$

$$L_{F2} = 0.5(L - B) \cot \beta$$

| Parameter                         | Unit | Value     |
|-----------------------------------|------|-----------|
| Power of main rotating motor      | kW   | $2 \times 30$ |
| Speed of main rotating            | rpm  | 0~43      |
| Power of radial feeding motor     | kW   | 3         |
| Speed of radial feeding           | mm/s | 1~5       |
| Power of angle adjusting motor    | kW   | $2 \times 2.3$ |
| Speed of angle adjusting          | %/s  | 1~10      |
| Range of angle adjusting          | $^\circ$ | 12        |
| Maximum diameter of roller        | mm   | 350       |
| Maximum diameter of billet        | mm   | 80        |
| Overall dimensions                | m    | 1.8×1.7×1.6 |
| Total power                       | kW   | 70        |
| Total weight                      | Ton  | 5         |

![Fig. 5](image_url) Configuration and major parameters of NCWR and FCWR roller

![Fig. 6](image_url) Contact model of roller, mandrel, and workpiece at the stretching stage
Since the geometries at sizing zone of NCWR and FCWR are the same, they have the same sizing length which can be formulated by Eq. 4, where \(D_0\) and \(D_1\) are the outer diameter of the workpiece before and after rolling.

\[
L_{N3} = L_{F3} > 0.25\pi(D_0 + D_1)
\]  

(4)

Because the length of each zone is determined through the above equations, the length reduction \(L_R\) can be calculated by Eq. 5.

\[
L_R = 0.5B\cot\beta
\]  

(5)

For a purpose of a more intuitive comparison of the wedge length of roller, their formulas are summarized in Table 2. It can be concluded that the lengths of knifing wedge and sizing wedge of NCWR and FCWR roller are equal in value, while FCWR stretching length is shorter than that of NCWR.

In order to visually reveal the relationship between wedge length reduction and process parameters, a three-dimensional graphic has been drawn as expressed in Fig. 7. The length reduction \(L_R\) is only related to stretching angle \(\beta\) and knifing width \(B\), which increases with the increase of \(B\) and \(\beta\) in range of 200 ~ 800 mm. Take an example of the roller used in the experiment of later study: \(\beta = 2^\circ\) and \(B = 18\) mm; its wedge length reduction reaches up to 257.7 mm.

### 3 Parameter ranges and research schemes

Considering process parameters will directly affect the success of this novel process, the ranges of major parameters are discussed and summarized based on the previous research of NCWR hollow shafts [16, 17, 24].

(1) The workpiece reduction \(\eta\). Workpiece reduction reflects deformation degree and the flattening of workpiece. In the case of hollow billet with thin wall, the large \(\eta\) makes the rolling piece undergo serious flattening deformation and then the rolling status is unstable, so that the products become elliptical finally. In addition, when the hollow billet has a thick wall, the rolled piece has a better resistance to flattening deformation, and the roundness of the rolled products is improved under the condition of a larger \(\eta\) because of the good flow of axial metal. Using the multi-pass rolling can be a way to improve the workpiece reduction, but it makes the process implementation more complex. In the one-pass rolling, the workpiece reduction \(\eta\) is expressed and ranged as Eq. 6.

\[
0.2 < \frac{D_0 - D_1}{D_0} < 0.4
\]  

(6)

(2) The forming angle \(\alpha\). Forming angle is an important roller parameter, which directly determines the contact surface of forming area and then affects the metal flow. For the reason that hollow billet is more prone to elliptical and then the axial flow of the metal may become worse, the forming angle of the hollow shaft rolling is generally greater than that of solid shafts, whose value is usually derived as follows:

\[
30^\circ < \alpha < 50^\circ
\]  

(7)

(3) The stretching angle \(\beta\). Stretching angle is another important tool parameter. Increasing its value is beneficial to decrease the length of roller but enlarges the tangential deformation of the workpiece. As a result, it is easy to cause oval deformation. Therefore, the stretching angle for hollow shafts is generally smaller than solid shafts; its range is:

\[
1.5^\circ < \beta < 4.5^\circ
\]  

(8)

(4) The mandrel diameter \(d_m\). The mandrel is used to control the shapes and dimensions of inner hole. When its

| Table 2 Mathematical comparison of the wedge lengths of NCWR and FCWR roller |
|---------------------|---------------------|---------------------|---------------------|
| Type | NCWR | FCWR | Comparison |
| Equation | \(L_{N1} = h\cot\alpha\beta\) | \(L_{F1} = h\cot\alpha\beta\) | \(L_{N1} = L_{F1}\) |
| | \(L_{N2} = 0.5L\cot\alpha\beta\) | \(L_{F2} = 0.5(L - B)\cot\alpha\beta\) | \(L_{N2} > L_{F2}\) |
| | \(L_{N3} = 0.25\pi(D_0 + D_1)\) | \(L_{F3} > 0.25\pi(D_0 + D_1)\) | \(L_{N3} = L_{F3}\) |
| Length reduction | \(L_R = 0.5B\cot\beta\) | | |

3.0 Springer
diameter is too small, mandrel will unable to contact inner hole and out of service. And when its value gets too large, it makes the rolling wall thin seriously and wall deformation become severe; thus, billet cannot rotate normally. Its value is usually designed as Eq. 9, in which \(d_0\) is the initial diameter of inner hole.

\[
0.5d_0 < d_m < 0.9d_0
\]

(9)

The knifing width \(B\). Knifing width is a new parameter which only exists on FCWR roller. On the basis of previous explorations (discussed in later sections), larger knifing width allows for less length of wedge but increases workpiece ellipticity, rolling force, and rotating torque. Its value is generally selected as:

\[
10\text{mm} < B < 40\text{mm}
\]

(10)

On the basis that the selection ranges of main parameters have been determined, a research scheme combined FE simulations and experimental tests has been worked out as demonstrated in Table 3. The FE simulation is adopted to compare the distinction on NCWR and FCWR from the aspects of defect mechanisms, deformation characteristics, and influences of new parameter. Correspondingly, the physical FCWR tests are conducted to verify the FE results and reveal the advantages and disadvantages of FCWR process.

4 Numerical simulations of NCWR and FCWR with single guide

4.1 Finite element modeling

Preliminary feasibility study was done by numerical simulations. Both NCWR and FCWR finite element (FE) models were established. It should be pointed out that the FE model of NCWR and FCWR only changed the rollers, while other parameters such as billet dimensions, rolling temperature, and mandrel dimensions stayed the same. The FE scheme and parameter were carried out according to Table 3.

\[
\sigma_F = 2589.85e^{-0.003125T}e^{(0.00004466T - 0.10127)}e^{(-0.00001T + 0.0000157957)}
\]

(11)

The friction coefficients between tools and workpiece were modeled by Shear model (two rollers were 0.8, guide and mandrel were 0.2) [28]. The temperature of tools (rollers, guide, and mandrel) was constantly maintained at 300 °C [28]. According to the study of Shen [15] and Ji [2] in hollow shaft cross-wedge rolling, the initial temperature of workpiece was 1050 °C, and the coefficient of heat transfer between tools and workpiece was 10 kW/m²K [28]. Besides, the mesh of billet was created by ringmesh mesher, whose element size equals to 1.4 mm, and will be automatically reconstructed if the effective strain increases by 0.4 [28]. Both the NCWR and FCWR rollers rotated at the same speed of 6 rpm.

4.2 Comparison of forming defects

Four FE results with the parameters of \(D_0 = 50\text{ mm}, d_0 = 30\text{ mm}, \alpha = 45^\circ, \beta = 2^\circ, d_m = 22\text{ mm}, \) and \(B = 18\text{ mm}\) were extracted from the software postprocessor and shown.

| Parameter symbol (unit) | Billet inner diameter \(d_0\) (mm) | Mandrel diameter \(d_m\) (mm) | Knifing width \(B\) (mm) | Method |
|-------------------------|-----------------------------------|-------------------------------|------------------------|--------|
| NCWR                    | 30                                | None                          | None                   | FE     |
|                         | 30                                | 22                            | None                   | FE     |
| FCWR                    | 30                                | None                          | 18                     | FE, test |
|                         | 30                                | 22                            | 14, 18, 22             | FE     |
|                         | 30, 28, 26, 24                    | 22, 20.5, 19, 17.6            | 18                     | Test   |

Besides, \(D_0 = 50\text{ mm}, \alpha = 45^\circ, \beta = 2^\circ, \Delta = 6\text{ mm}, T = 1050\text{ °C}, \) and \(d_m/d_0 = 0.73\)
in Fig. 8. With the help of the numerical simulation, the shape of rolling workpiece can be acquired at every moment.

At the middle of knifing stage, all the workpieces do not contact mandrel. But at the end of knifing stage, there is a difference that FCWR workpiece contacts mandrel, while NCWR does not. Considering the values of mandrel diameters are the same, it can be concluded that the radial deformation of inner hole in FCWR process is more serious than that in NCWR during the whole knifing stage.

The defects of hole expansion and knitting groove primarily appear on the NCWR shafts at the middle of stretching stage regardless of the fact that whether it has mandrel or not (Fig. 8c). But in the case of FCWR shafts at this stage, these defects are completely absent. Inversely, there is a hole shrinkage on the FCWR shaft without mandrel. As a result, we can get the FE conclusion that (1) no matter with or without mandrel, NCWR rolled shafts universally have the defects of hole expansion and knitting groove; (2) FCWR process without mandrel has a defect of hole shrinkage; and (3) the FCWR process with mandrel has a good geometric accuracy on outer and inner surface. The conclusion optimistically verifies the technological assumptions; as a result, the FCWR with mandrel was adopted on hollow shafts forming in later studies.

4.2.1 Hole expansion

Since hole expansion is a major defect in this study, it is necessary to reveal its formation mechanism from aspects of contact surface, loading states, and the shape of inner hole (Fig. 9). Their process parameters are as follows: $\alpha = 45^\circ$, $\beta = 2^\circ$, $h = 6$ mm, $D_0 = 50$ mm, $d_0 = 30$ mm, $d_m = 22$ mm, and $B = 18$ mm.

The contact surface of workpiece was drawn by Boolean subtraction operation in CAD software, which has indicated the difference of deformation morphology between NCWR and FCWR. As shown the Fig. 9a, under the same forming angle $\alpha$ and stretching angle $\beta$, the main difference between NCWR and FCWR contact surface is that there is a rectangle contacting zone on the middle of FCWR workpiece.

Based on the drawn contact surface, the loading states can be acquired as Fig. 9b shows. At the NCWR knifing stage, because AB and BA segments individually produce an axial component on the side of knitting position, the inner hole is tensioned in axial direction and then expanded radially. But in FCWR process, the added BB segment provides a radial force during the knifing stage that promotes the radial flow of the metal, and thus, the inner hole is shrunk. Eventually, FCWR hole contacts with the mandrel, while NCWR does not (Fig. 9c).

In short, the small inner hole is helpful to avoid the defect of hole expansion. When the minimum diameter of the inner hole is equal to the mandrel diameter, the defect of hole expansion can be avoided. FCWR process has an added radial force during knitting stage, which is helpful to the radial flow of the metal and then shrink the inner hole, so that the defect of hole expansion can be avoided in principle.
4.2.2 Knifing groove

Another defect concerned in this study is the knifing groove, which typically appears on the CWR shafts regardless of the fact that whether they are hollow or solid [18, 19]. According to engineering practice, this defect can be avoided via chamfering the knifing wedge. Obviously, this method cannot solve this defect at design stage. The geometric appearances of NCWR and FCWR workpiece are compared in Fig. 10. Their process parameters are as follows: $\alpha = 45^\circ$, $\beta = 2^\circ$, $h = 6$ mm, $D_0 = 50$ mm, $d_0 = 30$ mm, and $B = 18$ mm.

The knifing groove initially appears on the NCWR shaft at the end of knifing stage and then remains until the end. It can be explained that deformation concentration exists on NCWR knifeing area which makes the metal of surface undergo a severe local deformation. As a result, a groove appears on the NCWR shaft at the end of knifing stage and then remains until the end. The ovality of inner hole, an observation section selected from the axial center of the workpiece is contrastively compared in Fig. 11 ($\alpha = 45^\circ$, $\beta = 2^\circ$, $h = 6$ mm, $D_0 = 50$ mm, $d_0 = 30$ mm, $d_m = 22$ mm), which demonstrates that, as the knifing width $B$ increases, the ovalization of inner hole becomes serious.

The ovality of inner hole has a negative effect on rolling stability. When the ovality of inner hole is too large, the radial deformation of workpiece will be unstable. Under this situation, even if rollers are rotating normally, the slipped billet cannot rotate regularly. Hence, considering elliptical hole is bad for rolling stability, the value of knifing width should not be too large.

4.3 Effect of new parameter

4.3.1 Hole ovality

The novel process introduces a new process parameter named knifing width $B$. Since it has an influence on the ovality of inner hole, an observation section selected from the axial center of the workpiece is contrastively compared in Fig. 10 (a) contact surface, (b) loading states, and (c) hole shape.
Fig. 10 Geometry comparison between NCWR and FCWR workpiece: a end of knifing stage, b middle of stretching stage, and c end of stretching stage.

Fig. 11 Relationship between knifing width and hole ovality (end of knifing stage): (a) $B=14\ mm$, (b) $B=18\ mm$ and (c) $B=22\ mm$

Fig. 12 Relationship between knifing width: a rolling force and b rotating torque.
knifing width $B$ increases, the maximums of rolling force and rotating torque rise as well.

Based on the above analysis, it can be concluded that large knifing width deteriorates the ellipse of hole and increases rolling force and rotating torque.

4.4 Formation of the inner hole

The formation of inner hole is a critical problem of hollow shaft rolling, which directly influences the forming accuracy and the rolled-wall performance. A cross-section is selected from the axial center of workpiece and observed at different rolling stages as Fig. 13 shows.

Because mandrel diameter $d_m$ is only 0.73 times of billet hole diameter $d_0$, as mentioned in Table 3, the mandrel is away from the inner hole and out of work at the initial stage. However, as rolling process goes on, the inner hole becomes elliptical, and then workpiece is beginning to contact the mandrel. Latterly, under the double action of mandrel and rollers, the ovality of inner hole becomes smaller and smaller and finally grows into round.

The strain distribution of the workpiece is also obtained in Fig. 14. Initially, the billet has local strain at the contacting zone with a small value. But at the hole sizing stage, both the outer and inner of billet undergo a large strain with a value approximately 1.7, which has demonstrated an important advantage of FCWR with mandrel—the wall of workpiece is rolled by external roller and internal mandrel that the properties of rolled wall can be improved effectively.

5 Experiments of FCWR with single guide

5.1 Rolling experiments

The experiments of FCWR hollow shafts with single guide were performed at the University of Science and Technology Beijing in the new type of horizontal mill.

Fig. 13 Formation of the FCWR hole: (a) initial status, (b) begin of workpiece flattening, (c) begin of mandrel contacting, (d) begin of hole sizing, (e) middle of hole sizing, and (f) end of hole sizing
Experimental tools consisted of two FCWR rollers, several mandrels, and one guide as shown in Fig. 14.

The process parameters of physical experiments corresponded to those of numerical simulations as shown in Table 3. The guide was mounted between two rollers and downwardly offset from roller center line with a 28-mm distance.

The rolling experiments were conducted as Fig. 15 shows. Prior to the rolling, the billet was preheated to 1050 °C in an electric tube furnace and then immediately transferred to the mill, and the transfer time is strictly limited to 5 s. During the rolling stage, the billet was rotated and deformed under the action of rotating wedges of rollers. After the rolling, the rolled product laid on the top of the guide, and then hollow shaft was gained.

By the FCWR tests, it can be observed that the workpiece was rolled stably, which has verified the feasibility of the FCWR process and new horizontal multifunctional mill. The produced hollow axles of FCWR rolling tests are cut and shown in Fig. 16a, and its shot peening products are shown in Fig. 16b. These hollow shafts are free from the typical defects of hole expansion and knifing groove. However, it raises a new question that the rolled shaft cannot be automatically ejected from the mill that a manual transfer is needed.

### 5.2 Results and discussion

#### 5.2.1 Validation of the FEM results

A verification method of geometric comparison is employed in this study. The geometries of inner holes are compared to verify the FEM results in consideration of the fact that its shapes are related to the flow behavior of material, rolling temperature, friction state, and so on.
Two groups of experiments including without and with mandrel are compared in Fig. 17.

The shape of rolled shafts of experimental tests has a good agreement with FE results. In the rolling process without mandrel, both physical and FE shafts have a defect of hole shrinkage on knifing position. But under the circumstance of having a mandrel, this defect is improved, and both physical and FE shafts have a uniformed inner diameter.

The maximum and minimum diameters of inner holes are used for quantitative verification. The minimum inner hole diameter of FCWR without mandrel appears on the knifing position with a value equal to 17.95 mm of physical shaft and 17.66 mm of FE result, and its maximum hole diameter is equal to 20.43 mm in physical test and 21.26 mm in FE result. The maximum relative deviation (relative to physical result) of four comparative diameters is 4% which is lower than 10%, so the FE results are reliable.

### 5.2.2 Advantages and disadvantages

Beside the validation experiments, some deformation tests were carried out with varied values of hole diameters. Simultaneously, the mandrel diameters were changed accordingly as \( dm/d_0 = 0.73 \). The other process parameters stayed the same as \( D_0 = 50 \text{ mm}, \alpha = 45^\circ, \beta = 2^\circ, h = 6 \text{ mm}, B = 18 \text{ mm}, \) and \( T = 1050^\circ \text{ C} \). The rolled shafts are presented in Fig. 18.

By observing the geometric appearances, we can find that all the rolled pieces are free from knifing groove and hole expansion. Therefore, a conclusion can be gained that the new process can absolutely avoid the forming defects of knifing groove and hole expansion. However, as shown in the Fig. 18d, the material cracking occurs on the inner wall of the rolled piece, which is the typical defect of hollow shaft rolling as analyzed by Tomczak [29] and ask for a deeper study in future.

Moreover, these hollow shafts have a good forming accuracy. For example, the right-angle steps are precisely rolled, and the typical limitations are absent, such
as spiral-grooved surface [15, 18] and ellipse of formed shafts [19, 20]. These experimental performances indicate that single-guide rolling can improve rolling stability.

The grain size of rolled part is one of the most significant indicators, which decides the mechanical properties of the hollow products. The microstructure morphology of the rolled shaft is obtained in a microscope with 200 times magnification. As Fig. 19 shows (α = 45°, β = 2°, h = 6 mm, D₀ = 50 mm, d₀ = 30 mm, dₘ = 22 mm, B = 18 mm), the grain sizes of the rolled regions (P1, P2) are significantly smaller than those of unrolled region (P3), which can be explained that the grains are refined under FCWR deformation. Besides, the grain size at the knifing position (P1) is smaller than that at the stretching position (P2), which is consistent with the distribution of strain shown in Fig. 17d, and can be considered that the knifing zone has a larger deformation than the stretching zone.

Although this new process has the above advantages, there are some disadvantages as well. As shown in the numerical simulations and physical experiments, the rolled shaft cannot be automatically ejected from the mill, so a new discharging device is needed. Besides, FCWR process deteriorates the ellipse of hole and increases rolling force and rotating torque.

5.2.3 Application to the solid shafts

For solid shafts, the FCWR advantage of avoiding hole expansion is no longer necessary. However, it also brings the advantages of avoiding knifing groove and reducing the perimeter of rollers.

The major considerations for solid shafts rolling are whether billet can rotate normally and whether central cracks can be avoided. On the one hand, because a BB section (shown in Fig. 9b) is added at the knifing zone, the friction conditions at knifing stage are improved theoretically because the contacting area increases. On the other hand, the trend of central cracking is relieved because the added radial compression-force is beneficial to metal bonding. And when it comes to stretching and sizing stage, the deformation of NCWR and FCWR is the same. Therefore, it can be estimated that this novel FCWR process can be used for solid shafts under the condition of reasonable knifing width.

6 Summary and conclusions

In this paper, a novel process of flat-knifing cross-wedge rolling (FCWR) with single guide was proposed to manufacture hollow shafts, including a CWR roller, single-guide
rolling, and a horizontal multifunctional mill. The following conclusions are obtained:

1. The defects of hole expansion and knifing groove are absolutely avoided because FCWR roller produces a radial force to shrink the hole and avoids the deformation concentration of outer surface during knifing stage.

2. The single-guide rolling can be realized by workpiece axis offset from the center line of two rollers and can improve the rolling stability and simplify the mill structure.

3. The flat-knifing roller reduces the wedge length in the range of 200–800 mm.

4. The process of flat-knifing cross-wedge rolling with single guide brings the shortcomings of non-automatic ejecting, hole ellipse, and the increasement of rolling force and rotating torque.

Availability of data and materials  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.

Consent to participate  Applicable.

Consent for publication  Applicable.

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

Conflict of interest  The authors declare no competing interests.

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