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STUDY ON ROLL-CUTTING FORMING METHOD OF CONICAL END BLANK FOR CROSS WEDGE ROLLING (CWR) WITHOUT STUB BAR

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Using conical end blanks is an effective method to improve the concave defects of cross wedge rolling, while the common method to get conical end blanks is machining, still causing material loss. Aimed at this situation, this paper proposes a roll-cutting forming method of conical end blanks based on metal-plastic forming. In order to clarify the roll-cutting forming mechanism of the conical end, the displacement field and strain field variation during the forming process of the conical end are analyzed based on finite element simulation analysis, and the metal flow during the roll-cutting process is obtained. Moreover, the conical end blank formed by roll-cutting is sent to cross wedge rolling, the results verify the feasibility of roll-cutting conical end blank used for cross wedge rolling without stub bar.

Key words: cross wedge rolling, roll-cutting, end-face cavity, conical end blank,hot bar

INTRODUCTION

Cross wedge rolling is a rotary near-net forming method for shaft parts. Due to its good rolling performance, high production efficiency and low energy consumption, it is widely used in the production of various shaft parts [1]. End-face cavity is the common defect which restricts the near-net forming of the cross wedge rolling [2]. Some researches have been done to suppress the generation of end-face cavity. Pater [3] proposed that the end of the bar is machined into a cone in advance, which could compensate for the unsynchronized flow of the surface metal and the core metal during the rolling process, thereby the end-face cavity is suppressed. Zeng Jian [4] furtherly found that the depth of end-face cavity is proportional to the cone angle, and the end-face cavity can be suppressed by suitable cone angle. Yang Cuiping [5] also found that the blank with proper conical end not only saves material, but also avoids the risk of central damage at shaft ends. All these researches demonstrate that using conical end blanks is an effective method to improve the concave defects of cross wedge rolling. However, the prefabrication of the conical end is based on machining in these researches, which caused material loss. Hence a roll-cutting forming method of conical end blank based on metal-plastic forming is proposed in this paper. The rest of the paper is organized as follows. Section 1 presents the theory of roll-cutting for conical end blank. Section 2 demonstrates the roll-cutting forming mechanism of the conical end. Section 3 describes the finite element simulation analysis experiment of cross wedge rolling using the conical end blank formed by roll-cutting. Section 4 summarizes the study .

THEORY OF ROLL-CUTTING FOR CONICAL END BLANK

The schematic diagram of roll-cutting for conical end blank is shown in Figure 1. The bar heated to cross-wedge rolling temperature is clamped by a fixture. Two cutting tools arranged symmetrically rotate around their own axis while revolve around the hot bar. The wedge blades of the cutting tools spin into hot bar step by step due to the compound motion, making the bar generates radial compression, tangential expansion and axial extension at the roll-cutting area. Finally, the bar is cut into two pieces with conical end, forming conical end blank. Since metal flowing causes the axial movement of the bar dur-

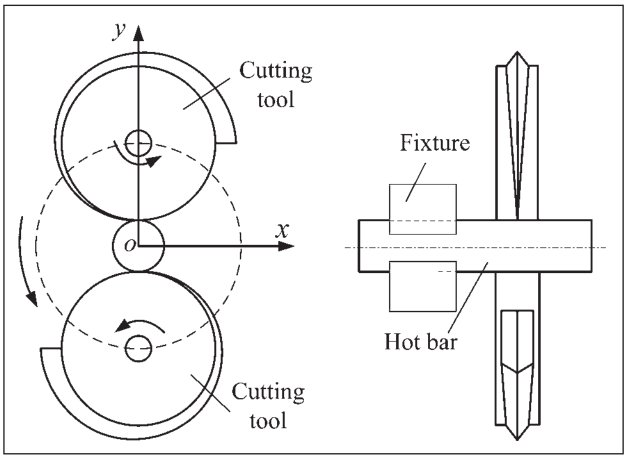

Figure 1 The schematic diagram of roll-cutting for conical end blank: (a) front view; (b) left view

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ing roll-cutting, the bar has only one degree of freedom to move axially under the constraints of the fixture.

The function of the wedge blade can be divided into two stages: the wedge extension stage and the precision forming stage, as shown in Figure 2. In the wedge extension stage, with the increase of wedge width and wedge height, the large deformations, including radial compression, tangential expansion and axial extension, occur continuously when roll-cutting. The structural parameters of the wedge blade at this stage are determined by the forming angle α, the stretching angle β and the wedge height h. In the precision forming stage, the wedge height and the forming angle of the wedge blade remain unchanged, and the widening angle is 0, so that the cutting end is rounded to get high quality conical end. In addition, in order to avoid the radial metal stacking in the roll-cutting area, cylindrical bosses are set on both side of the wedge blade. During the roll-cutting process, cylindrical bosses roll on the surface of the bar to promote the axial flow of the metal. The structural parameters of the cutting tool satisfy the following relationships:

$$\begin{cases} \theta_1 = \dfrac{L_1 \times 180}{\pi r} \\ \theta_2 = \dfrac{L_2 \times 180}{\pi r} \\ L_1 = h \cot\alpha \cot\beta \\ 0 < L_2 < 2\pi r - L_1 \\ d > \dfrac{2h}{\tan\alpha} \end{cases} \quad (1)$$

Where, L_1 is the length of the wedge extension stage, L_2 is the length of the precision forming stage, θ_1 is the central angle of the wedge extension stage, θ_2 is the central angle of the precision forming stage, β is the stretching angle, r is the base radius of the cutting tool, d is the width of the cylindrical boss, and h is the wedge height. The radius of the cylindrical boss is smaller than the base radius of the cutting tool by 0,2 mm - 0,5 mm to make the metal flow easily.

ROLL-CUTTING FORMING MECHANISM OF THE CONICAL END

Finite element simulation analysis model of roll-cutting

Figure 3 shows the finite element model of roll-cutting in DEFPRM - 3D. The function of the fixture is

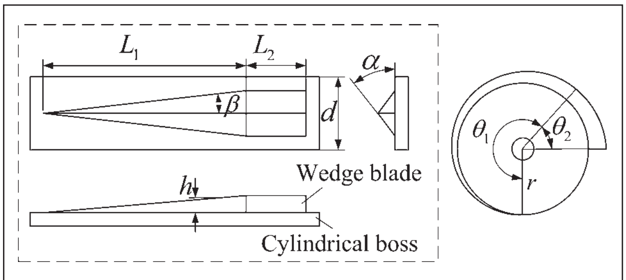

Figure 2 Sketch of the roll-cutting tool

Table 1 **The structural parameters of the cutting tool**

Forming angle α / °	52 °
Stretching angle β / °	7 °
Maximum wedge height h / mm	20,5 mm
Base radius of the cutting tool r / mm	150 mm
Length of the wedge extension stage L_1 / mm	500 mm
Length of the precision forming stage L_2 / mm	150 mm
The width of the cylindrical boss d / mm	50 mm

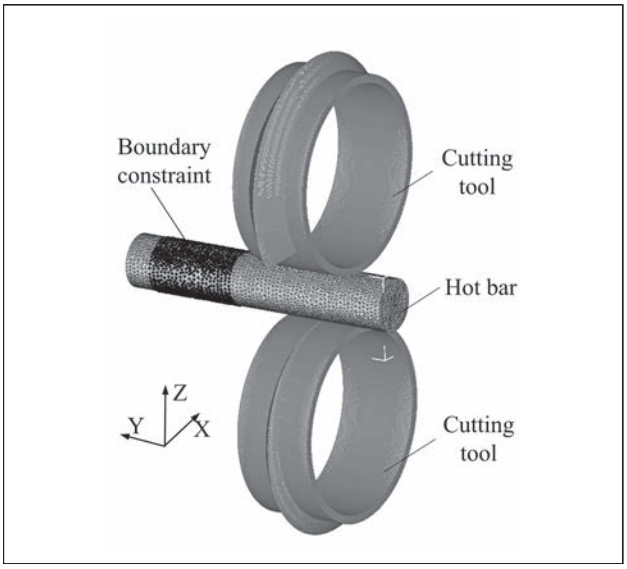

Figure 3 Finite element model of roll-cutting

realized by setting the bar boundary constraint in the software (the red part in Figure 3). Because the bar material mainly exhibits ductile fracture at the end of the roll-cutting process, the Normalized Cockcroft - latham ductile fracture criterion is selected in the software. The material of the bar is AISI1045(45 steel) and the diameter of the bar is 40 mm.The elastic modulus E is 206 GPa, Poisson's ratio v is 0,3, and the temperature of the bar is 1 050°. The bar is divided into 50 000 tetrahedral element meshes. Table 1 shows the structural parameters of the cutting tool.

Analysis of the forming process

Going through both of the wedge extension stage and the precision forming stage, the hot bar is cut into two pieces with conical end, forming conical end blank. As shown in Figure 4, the bar continuously undergoes radial compression, tangential expansion and axial extension at the wedge extension stage.At this stage, as the conical wedges are pressed against the bar, the bar will produce metal ridges on both sides of the conical wedge. The raised metal gradually moves away from the cutting area along the cylindrical boss until the end of the wedge extension stage.When the process enters the precision forming stage, the blank no longer deforms greatly. More,the conical wedge gradually rolls the formed surface into a conical shape. The ridged metal on the circumference of the blank end is further rolled into a cylindrical shape along the tangential direction by the cylindrical boss. Finally, the required conical end blank can be obtained.

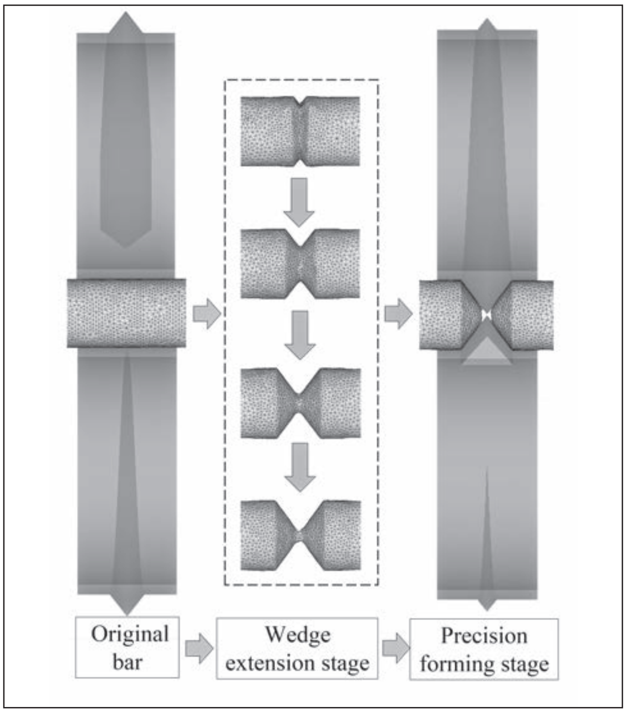

Figure 4 Roll-cutting forming process

Analysis of displacement field

In order to analysis the forming of the conical ends, 11 tracking points are set uniformly in the radial direction of the cross section of the bar. The initial position of each point before roll-cutting and the final position after roll-cutting are shown in Figure 5.

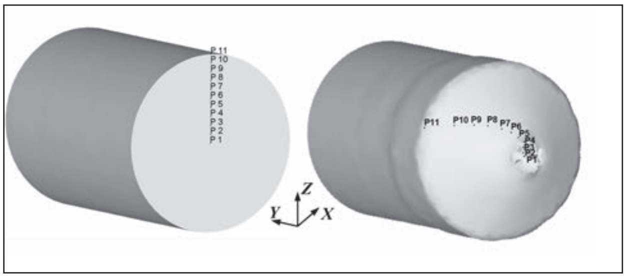

Figure 5 Positions of the tracking points before and after roll-cutting

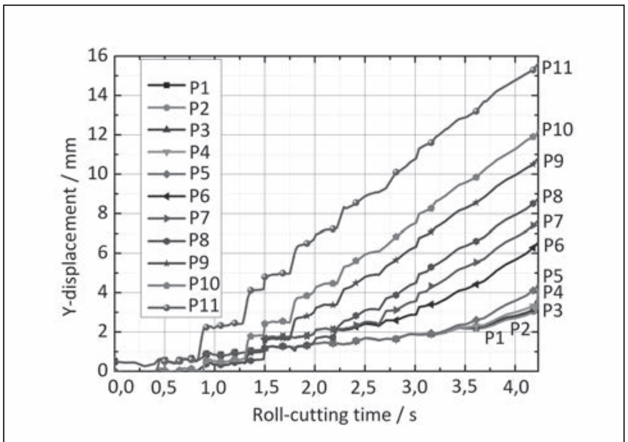

Figure 6 Y-axis directional displacement

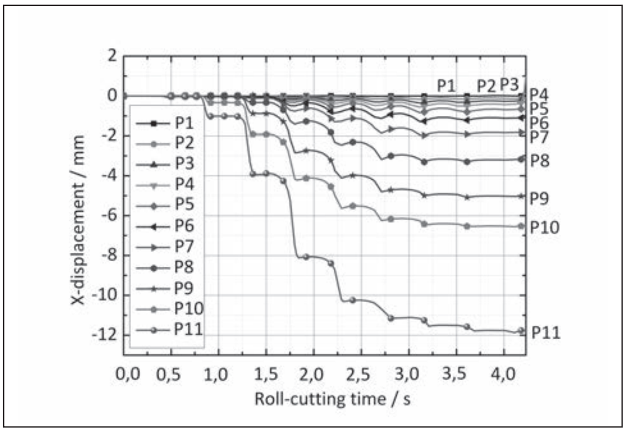

Figure 7 X-axis directional displacement

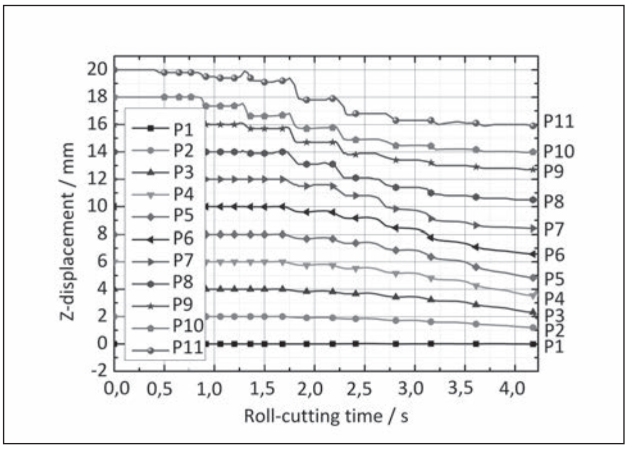

Figure 8 Z-axis directional displacement

From the displacement variation of each point (P1 - P11) during roll-cutting in the Y direction in Figure 6, it can be seen that the outer metal displacement is larger than that of the center metal, and the flow velocity is relatively faster. From the displacement variation of these points in the X and Z directions in Figure 7 and Figure 8, it can seen that the closer to the core of the bar, the smaller the angle of rotation of the point around the bar axis, and the smaller the displacement.

In order to analysis the forming of the conical end, the radial coordinates and the axial coordinates of each tracking point after roll-cutting are projected onto a plane (as shown in Figure 9). It is apparent from the figure that the oblique line of the end face after roll-cutting is substantially identical to the theoretical oblique line of the conical end face in most points. The deviation in the P1 - P4 is because the bar material is gradually pulled off at the end of the roll-cutting process, causing the conical tip has an irregular shape. In addition, it can be seen from the figure that the distance between point P11 and bar axis is larger than the radius of bar 20 mm. This is caused by the gap between the cylindrical boss and the bar. During the roll-cutting process, the metal in the roll-cutting area extends outward radically until it contacts the cylindrical boss and then flows along the axis. At the end of the roll-cutting process, the axial protuberance appears as shown in the Figure 5.

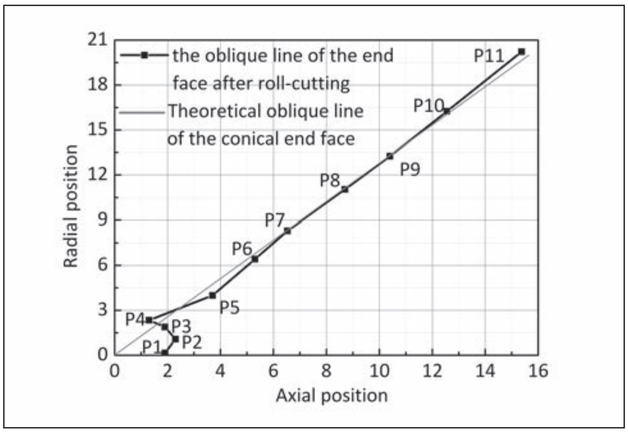

Figure 9 Projection of the end location of the tracking points

Analysis of strain field

In order to clarify the metal flow law furtherly and explain the interaction between the cutting tool and the bar,the strain distribution during roll-cutting process is analyzed in this section.

At the beginning of the wedge extension stage as shown in Figure 10, local strain gradually appears in the contact area between the bar the and tool under the action of extrusion and friction of the wedge blade. Since the cylindrical boss makes the raised metal flow along the axial and tangential directions, the equivalent strain of the raised metal in this area is the largest. Next, with the continuous downward pressure of the wedge blade, the equivalent strain of the cutting area of the metal increases gradually along the circular motion direction of the tool, and decreases gradually along the inside of the blank.

Under the continuous action of the cylindrical boss, the equivalent strain of the metal that contacts with it tends to be the same in the circumferential direction. Due to the long interaction time between the raised metal and the tool in the end corner region, the equivalent strain reaches the maximum in the wedge extension stage. The equivalent strain decreases gradually along the radius from the circumference to the center of the circle and toward the distal end in the axial direction due to the cutting force of the tool and the metal flow resistance of the blank itself. Lastly,the deformation of roll-cutting area decreases with the end of the wedge extension stage.

At the initial of the precision forming stage, the axial extrusion force of the tool on the bar causes the bar reach the ductile fracture criterion. At this point, the bar is broken into two parts, the tip of the end cone becomes irregular shape. Then the equivalent strain of the center metal becomes smaller. At this stage, the equivalent strain varies very little due to the metal at the cutting area is no longer deformed in large quantities.

It can be seen from the entire strain distribution that the equivalent strain of metal mainly occurs in the contact area of the bar and the tool during the roll-cutting process.

SIZE COMPARISON OF END-FACE CAVITY

It can be seen from the above, the conical end obtained by roll-cutting is different from the ideal conical end. In order to verify the feasibility of the roll-cutting conical end blank used for cross wedge rolling without stub bar, cross wedge rolling simulation experiments are conducted in this section.

The finite element model of cross wedge rolling shown in Figure 11 is established in DEFORM - 3D, in which the forming angle of the die is set at 27 °, the broadening angle is 8 ° and the section shrinkage rate is 51 %. With the same rolling parameters, three different kinds of blanks, including roll-cutting conical end blank, ideal conical end blank and flat end blank, are all rolled, and the end-face cavities after rolling are compared.

Figure 12 shows the end-face cavities from three different blanks after cross wedge rolling. Compared with the shaft 1 got by rolling roll-cutting conical end blank, the shaft 2 got by rolling ideal conical end blank has a tip. This is the tip of ideal conical end, which is not exist in roll-cutting conical end. But the end-face cavities of the shaft 1 and the shaft 2 are almost identical, and both are very smaller than the end-face cavities of

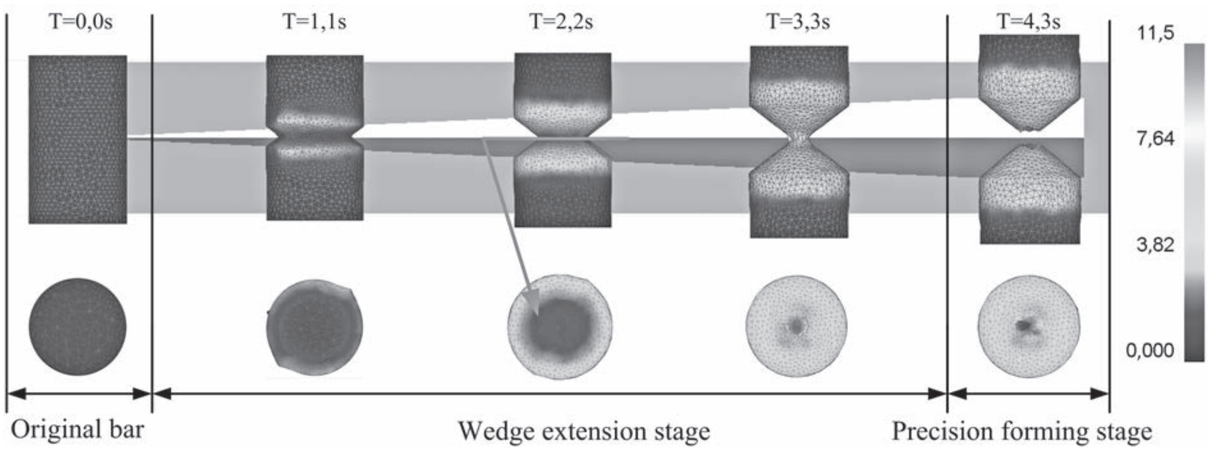

Figure 10 Equivalent strain distribution during the roll-cutting process

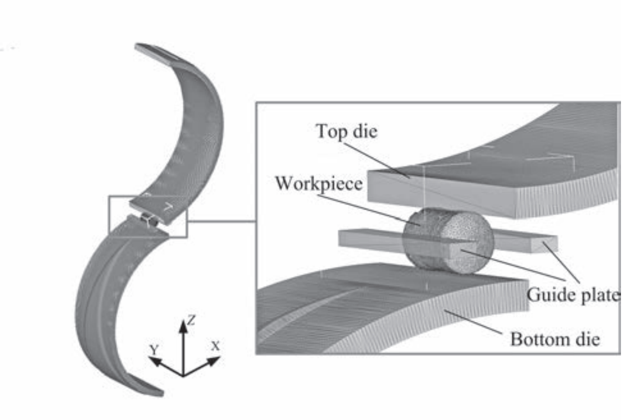

Figure 11 Finite element model of cross wedge rolling

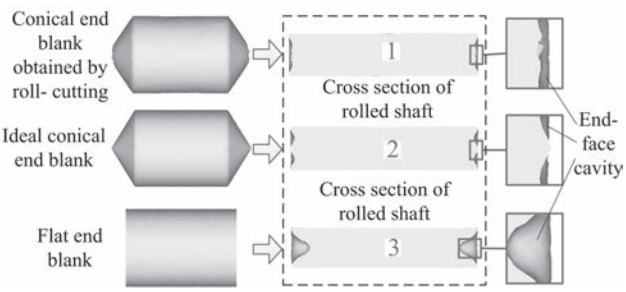

Figure 12 Size comparison of end-face cavities

the shaft 3 got by flat end blank. The above results verify it is feasible to use the roll-cutting forming method to produce conical end blank for cross wedge rolling without stub bar.

CONCLUSIONS

(1) For the purpose of prefabricating conical end blank and applying it to cross wedge rolling without stub bar, the roll-cutting forming method of the conical end blank is put forward in this paper. The theory of roll-cutting forming process together with the structural design of the cutting tool is expounded.

(2) The mechanism of roll-cutting forming conical end blank is clarified by analyzing the displacement field and strain field at cutting area during the roll-cutting process.

(3) The size comparison of the end-face cavities from three different kinds of blanks after cross wedge rolling is conducted. The conical end blank obtained by roll-cutting has almost the same suppressed end-face cavity effect as the ideal end blank. This study provides a reliable theoretical method for the realization of the cross wedge rolling without stub bar.

Acknowledgements

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Note: The professional translator for the English language is Q. Q. Yan, Zhejiang, China