Cavity formation in cross-wedge rolling processes

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Abstract

The problem of end-face cavity formation in parts produced by cross-wedge rolling was studied in order to reduce material consumption. The cavity depth was measured by the displacement method. Twenty-one different cases of rolling were analysed by finite element method to determine the effects of process parameters such as the wedge tool angle, the temperature of material, the tool velocity and the reduction ratio on the depth of end-face cavities. Relationships between these parameters are examined in order to establish dependencies enabling quick and simple selection of a concavity allowance in order to remove the cavities. The equations for calculating the concavity allowance were verified in an experimental process for manufacturing ball pins with the use of flat tools. Rolling tests were performed using a billet with its length selected in compliance with the established dependencies. The experimental results demonstrate that the proposed solution is a viable method for end-face cavity removal.

Keywords Cross-wedge rolling · End-face cavity · Concavity allowance · Ball pin

1 Introduction

Cross-wedge rolling (CWR) is an advanced method for producing axisymmetric products such as stepped axles and shafts. It has numerous advantages including high efficiency, low material consumption, high-strength properties and eco-friendliness. Given these advantages, a growing interest can be observed in the use of this metal forming technique in recent years, which is reflected in numerous research works focused on developing the technological potential of CWR and eliminating its shortcomings.

As far as new trends in the use of CWR are concerned, following tendencies can be seen. To shorten the tool length and increase efficiency of the process, multi-wedge tools are used, as this design solution enables the forming of a workpiece by several pairs of tools at the same time. The solution is recommended for the production of considerably long parts such as axle shafts for cars [1] and railway axles [2]. A multi-wedge rolling method has been

proposed for manufacturing balls for ball mills, which makes it possible to manufacture dozens of balls simultaneously [3].

To explore new applications for the CWR technique, researchers have turned their attention to parts that do not have axial symmetry, for example, the application of the CWR technique for manufacturing screw spikes [4] and threaded shafts [5]. An interesting solution was proposed by Zheng et al. [6], who designed rollers with special profile surface for cam forming. Pater devised a cross-wedge rolling process for shafts with eccentric steps, consisting in the use of special guides that act on the billet and change its position while the tool cuts into the material [7]. Products without axial symmetry can also be formed by cross-wedge rolling from billets with non-circular cross sections. The results of a numerical analysis of cross-wedge rolling for billets with a square cross section were reported by Ma et al. [8]. Pater et al. [9] designed a cross-wedge rolling technique for producing balls wherein balls are formed in two stages. First, heads of scrap railway rails are formed into a cylindrical billet. After that, the cylindrical billet is formed into balls with a diameter bigger than that of the billet.

There have been numerous studies on the application of the CWR method for manufacturing hollow parts. The primary failure mode in the rolling of such parts is

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excessive cross-sectional ovalization [10]. This failure mode can be prevented easily by the application of small spreading angles or three rolls in the rolling process [11]. Yang et al. [12] found that the use of an internal mandrel prevents axial metal flow, and, as a result, they were able to produce parts with the intended side wall thickness. By eliminating the failure modes characteristic of CWR processes for hollow parts, Ji et al. [13] were able to design an innovative method for manufacturing hollow valves via cross-wedge rolling and die forging.

The CWR technique is primarily used for forming steel parts. Nonetheless, this technique has been employed to form parts made of nonferrous metal alloys in recent years. For instance, Cakircali et al. [14] and Pater et al. [15] studied the use of CWR in the production of shafts made of titanium alloy Ti6Al4V. Tomczak et al. [16] proposed a solution for producing preforms made of magnesium alloy AZ31, while Pater et al. [17] found that the CWR technique can be used for producing toothed shafts made of aluminium alloy 2618. Mirahmadi et al. [18] conducted numerical and experimental studies to determine parameters of a cross-wedge rolling process allowing for hot forming of shafts made of Nimonic® 80A and Nimonic® 115 superalloys.

Cross-wedge rolling is usually performed as a hot-working process. Nevertheless, it can also be conducted under warm-working conditions. According to Huang et al. [19], decreasing the rolling temperature for steel to 700 °C leads to an approximately three-time increase in the rolling forces along with a significant increase in the mechanical properties of products. Kache et al. [20] proposed an innovative warm cross-wedge rolling process, finding that the application of warm working produces a fine-grained structure. Pater and Tofil [21] studied a cold cross-wedge rolling process for forming V-shaped grooves on the circumference of cylindrical bars. The grooves make it possible to accurately divide the bar into two parts via rotary bending.

As regards other research works investigating the possibilities of increasing the technological potential of CWR, a study on the forming of parts from cylindrical billets produced by plasma-transferred arc (PTA) welding [22] and a study on the manufacturing of microparts for electronics are worth mentioning. The results of the latter were reported by, among others, Wei et al. [23] and Jiang et al. [24] who found that CWR is an effective cold forming process for producing copper parts with a diameter smaller than 1 mm, characterized by high-strength properties.

As already mentioned, the CWR method is not free from disadvantages limiting its use. One of these disadvantages is the generation of end-face discards, which leads to higher material consumption of the manufacturing process. Namely, when the workpiece is deformed by rolling,

cavities are formed on its ends—a defect that must be removed. Consequently, in the final stage of the process (after the sizing operation), the workpiece ends (with cavities) have to be cut off with the side cutters, the design of which has been described in Ref. [25]. New rolling methods have been designed to eliminate this shortcoming, and they can be divided into two groups.

One group includes the methods that focus on preventing a non-uniform axial flow of the metal. This effect can be achieved by making special wedge-shaped grooves on the tools (for restraining the material's surface flow) or by providing the tools with special side guides to totally prevent an axial flow of the material [26, 27]. The application of these solutions reduces the size of cavities and ensures a considerable increase in the cross-sectional reduction in the workpiece in one tool pass [28].

The other group includes the solutions proposing the use of bars (billets) with different shapes of their ends. Guo and Lu [29] discovered that the use of a tapered-end billet significantly reduces the depth of concavity on the end face of the workpiece. Karpov et al. [30] found that the use of tapered-end bars as billet can totally eliminate the above shortcoming. It must, however, be remembered that the cost of a billet with profiled ends may be higher than that of discards generated by cutting off the ends of the workpieces.

Given the above, it is necessary to investigate the effects of CWR process parameters on the size of end-face cavities. The knowledge of these effects will make it possible to design a CWR process that ensures cavity depth reduction. In this respect, it seems important to devise a method for accurate calculation of a concavity allowance, as this will facilitate selection of billet dimensions. The above problems are investigated in this paper.

2 Scope of the analysis

The study involved performing a numerical analysis of a CWR process for producing a stepped shaft by flat tools. The process is shown schematically in Fig. 1. The analysis rested on the assumption that end-face cavity formation primarily depends on the following variables: the reduction ratio δ (where $\delta = d_0/d$), the forming angle α and the spreading angle β (collectively described by $\tan \alpha \tan \beta$), the tool velocity v and the billet temperature T .

The effects of selected variables on the formation of end-face cavities were determined via numerical multi-variant simulations performed in Simufact.Forming. This software had previously been used to build many geometric models of CWR processes, one of which is shown in Fig. 2. All the models consisted of two identical wedge tools and a billet. To accelerate the computations, the

Fig. 1 Schematic design of investigated CWR process and its main parameters

Fig. 2 Geometric model of one investigated CWR case with axial symmetry for $\delta = 1.4$

modelling was done for a CWR process with axial symmetry. The billet had an initial diameter of 40 mm and a length of 90 mm and was assigned with the properties of C45 steel described by the equation:

$$\sigma = 4105.6e^{(-0.003549T)}\varphi^{(-0.0001328T-0.005072)}e^{\left(\frac{-0.00002037-0.0281}{\varphi}\right)}\dot{\varphi}^{(0.0001805T-0.02416)}, \quad (1)$$

where σ is the yield stress, MPa; φ is the effective strain; $\dot{\varphi}$ is the strain rate, s^{-1} ; and T is temperature, $^{\circ}C$.

In all the tested rolling cases, two variables were maintained constant: the temperature of the tools ($150^{\circ}C$) and the coefficient of heat exchange ($10 \text{ kW}/(\text{m}^2 \text{ K})$). In

addition, the constant shear friction law was applied with the friction factor set to 0.95. Other variables of the rolling process (δ , α , β , v , T) were applied in a range suitable for the CWR method, according to Table 1. In total, 21 cases of rolling were modelled in compliance with the schematic shown in Fig. 1.

3 Depth of end-face cavities

The primary objective of the analysis was to determine the effects of selected parameters of the CWR process on the depth h of end-face cavities (Fig. 1). To measure the cavity depth, five measuring points were located at the end face of each billet (see Fig. 3). One of the points (1) was located in the axis of the workpiece, while the remaining four points (2, 3, 4, 5) were located every 90° over the circumference of the workpiece. During rolling, the points changed their location due to, among others, axial elongation. As shown in Fig. 4, which illustrates displacements of these points, their location undergoes considerable changes in the forming stage, becoming stable only at the end of the rolling process (i.e. during the sizing operation). The information about the final axial location of the points suffices to determine cavity depth, calculated as the

Table 1 Parameters of investigated cases of CWR

No.	δ	$\tan \alpha \tan \beta$	$V/(\text{mm s}^{-1})$	$T/^{\circ}C$
1	1.1	0.06	250	1100
2	1.2	0.06	250	1100
3	1.3	0.06	250	1100
4	1.4	0.06	250	1100
5	1.5	0.06	250	1100
6	1.6	0.06	250	1100
7	1.7	0.06	250	1100
8	1.8	0.06	250	1100
9	1.9	0.06	250	1100
10	1.5	0.04	250	1100
11	1.5	0.05	250	1100
12	1.5	0.07	250	1100
13	1.5	0.08	250	1100
14	1.5	0.06	100	1100
15	1.5	0.06	350	1100
16	1.5	0.06	500	1100
17	1.5	0.06	250	950
18	1.5	0.06	250	1000
19	1.5	0.06	250	1050
20	1.5	0.06	250	1150
21	1.5	0.06	250	1200

Fig. 3 Location of points for measuring end-face cavity depth

Fig. 4 Axial displacement of measuring points marked in accordance with Fig. 3, for $\delta = 1.8$

difference between the average displacement of the points located on the circumference and that of the point located in the axis of the workpiece. To obtain relative values, h was referred to d_0 . The final numerical results are given in Figs. 5–8.

The results demonstrate that h/d_0 primarily depends on the applied reduction ratio (Fig. 5), describing the degree of deformation of the material. The increase in δ from 1.1 to 1.9 results in an over three-time increase in h/d_0 (from 0.117 to 0.364). It can also be observed that the increase in the cavity depth is not proportional to δ . At small δ , a more significant increase in h/d_0 than the case with higher

reductions can be observed (when $\delta > 1.6$, the cavity depth does not change to a significant extent). However, it should be stressed that the reduction ratio applied in the analysed CWR process is a result of the ratio between billet diameter and shaft step diameter, which means that it cannot reduce cavity depth if changing the variable during rolling.

Another parameter with significant impact on the depth of cavities is tool geometry defined as the product of the tangents of the forming angle and the spreading angle. The increase in this parameter results in a significant decrease in h/d_0 (Fig. 6), which leads to a more rapid radial flow of the metal due to the application of big α and β . The highest h/d_0 amounts to 0.389 and is obtained with the tools described by $\tan \alpha \tan \beta = 0.04$. This value is 2.1 times the value of 0.183 obtained with the tools described by $\tan \alpha \tan \beta = 0.08$. Therefore, it can be claimed that α and β can effectively reduce the depth of end-face cavities and hence reduce the size of concavity allowance.

The cavity depth can also be decreased by applying lower tool velocities (Fig. 7). The impact of this variable on h/d_0 is still not as significant as that of tool geometry. The results demonstrate that decreasing the tool velocity from 500 to 100 mm/s leads to an approximately 20% decrease in the cavity depth. Nonetheless, it must be noted that tool velocity will have a negative effect on the rolling process, leading to a drastic reduction in its efficiency.

The depth of end-face cavities also depends on the temperature of the billet (Fig. 8). The higher the temperature of the billet is, the easier the deformation of the metal becomes, and the metal is more uniformly deformed over its entire volume. As a result, the value of h/d_0 decreases. As regards the quantitative effects of the billet temperature on h/d_0 , it can be observed that decreasing T from 1200 to 950 °C causes an approximately 30% increase in the cavity depth.

4 Concavity allowance

In CWR, the estimation of concavity allowances is of great practical importance. In general, the size of allowance is determined based on the results of a series of consecutive rolling tests where different length billets are applied, which can be quite troublesome. Therefore, it seems necessary to develop an equation for quick calculation of an allowance, depending on the basic parameters of the CWR process.

Figure 9 shows a schematic illustrating the manner of dividing the volume of the material (billet) into two parts, i.e. the product volume V_p and the end-face discard volume V_s (equal to the volume of the end part of the billet described by a length l). V_s was determined for every

Fig. 5 Relative cavity depth versus reduction ratio for $\tan \alpha \tan \beta = 0.06$, $v = 250$ mm/s and $T = 1100$ °C

Fig. 6 Relative cavity depth versus α and β for $\delta = 1.5$, $v = 250$ mm/s and $T = 1100$ °C

analysed case of the CWR process (Table 1) by calculating V_p with the equation:

$$V_p = \frac{\pi}{4} (d_0^2 l_1 + d^2 l_2), \quad (2)$$

where $d_0 = 50$ mm; l_1 is the length of the central step ($l_1 = 15$ mm); and l_2 is the length of the rolled step calculated as

$$l_2 = l_0 + \Delta x - l_1, \quad (3)$$

where l_0 denotes the billet length ($l_0 = 45$ mm) and Δx denotes the axial displacement of Point 1, initially located in the axis of the workpiece and on its lateral surface (see Figs. 3, 4).

By subtracting V_p from V_0 , V_s can be obtained, which is used for determining the relative concavity allowance, l/d_0 , according to the equation:

$$\frac{l}{d_0} = \frac{4V_s}{\pi d_0^2}. \quad (4)$$

The numerical results are shown in Figs. 10–13. The investigation of the effects of basic parameters of the tested CWR process on the allowance l/d_0 reveals that in terms of quality, it resembles the effect exerted by these parameters on the depth of end-face cavities discussed in the previous section of this paper. In general, increasing $\tan \alpha \tan \beta$ (Fig. 10) and T (Fig. 11) along with decreasing v (Fig. 13) lead to a decrease in l/d_0 . The effect of δ on l/d_0 is even more complex (Fig. 13). With increasing this variable in a range from 1.1 to 1.4, l/d_0 increases too, while increasing δ above 1.4 results in a slight decrease in l/d_0 . This effect can be accounted for by the fact that the increase in δ leads to higher depth and lateral dimensions of the cavity.

Fig. 7 Relative cavity depth versus tool velocity for $\delta = 1.5$, $\tan \alpha \tan \beta = 0.06$ and $T = 1100$ °C

Fig. 8 Relative cavity depth versus temperature for $\delta = 1.5$, $\tan \alpha \tan \beta = 0.06$ and $v = 250$ mm/s

To establish an equation for calculating l/d_0 , the numerical results were approximated. The approximation functions are marked with blue lines in Figs. 10–13. As a result, a dependence was obtained for describing the effect of the investigated variables (α , β , δ , T , v) on l/d_0 expressed as:

$$\frac{l}{d_0} = k_{\alpha\beta} k_v k_T (0.662\delta - 0.208\delta^2 - 0.389), \quad (5)$$

where

$$k_{\alpha\beta} = 1.766 - 12.110 \tan \alpha \tan \beta, \quad (6)$$

$$k_v = 0.3407 + 0.1217 \ln v, \quad (7)$$

$$k_T = 1.6354 - 0.000557T. \quad (8)$$

5 Examples of applications for numerical results

The above equations for calculating l/d_0 were verified in an experimental CWR process for manufacturing ball pins with the use of two tools. A schematic design of this

Fig. 9 Schematic explaining division of billet volume V_0 into V_p and V_s

Fig. 10 l/d_0 versus α and β for $\delta = 1.5$, $v = 250$ mm/s and $T = 1100$ °C

process is shown in Fig. 14. The billet has a diameter of 29 mm, which means that the end steps of the product are formed at $\delta = 1.81$.

Taking account of the fact that increasing the angles α and β leads to minimizing concavity allowance, tools with the spreading angle of 9° and the forming angle of 30° were designed. For such design of the tools, $\tan \alpha \tan \beta$ amounts to 0.914 and is thus higher than the recommended value ($0.04 \leq \tan \alpha \tan \beta \leq 0.08$). For this reason, a numerical simulation was performed to verify whether the tools described by such angles can be used for manufacturing parts with the intended shape.

Fig. 11 l/d_0 versus T for $\delta = 1.5$, $\tan \alpha \tan \beta = 0.06$ and $v = 250$ mm/s

Fig. 12 l/d_0 versus v for $\delta = 1.5$, $\tan \alpha \tan \beta = 0.06$ and $T = 1100$ °C

The numerical modelling was performed via Simufact.Fforming. A geometrical model of the CWR process for producing ball pins was designed (Fig. 15). The material was assigned with the properties of C45 steel, and its model was described by Eq. (1). The material was preheated to 1100 °C, the temperature of the tools was maintained constant at 50 °C, the tool velocity was $v = 300$ mm/s, the friction factor was 0.95, and the coefficient of heat exchange was set to 10 kW/(m² K).

The billet length l_0 was calculated using Eqs. (6)–(8), and the following parameters were obtained: $k_{\alpha\beta} = 0.659$, $k_v = 1.035$, $k_T = 1.023$. Next, using Eq. (5), the relative allowance was calculated and found to be $l/d_0 = 0.089$, which yielded an allowance of 2.5 mm per workpiece end after taking account of the billet diameter. Assuming that

Fig. 13 l/d_0 versus δ for $\tan \alpha \tan \beta = 0.06$, $v = 250$ mm/s and $T = 1100$ °C

the ball pin has a volume of $59,744 \text{ mm}^3$, the required billet length was calculated as 90.5 mm. Increasing this length by the previously calculated allowance, it was finally determined that the billet had to be 29 mm in diameter and 95.5 mm in length.

The numerical results confirm that it is possible to produce ball pins with the designed tools. The examination of the CWR process (Fig. 16) does not reveal the occurrence of any failure modes like uncontrolled slipping or workpiece necking. In addition to this, the numerical findings show no presence of remnants of the cavities on the end face of the ball pin (see Fig. 17). In light of the above, it was determined that the applied CWR process parameters and billet dimensions were correct and experimental rolling tests were performed.

Fig. 15 Geometric model of a CWR process for manufacturing ball pins with two tools

The experiments were performed on a laboratory flat-wedge rolling mill available at the Lublin University of Technology (Fig. 18). The machine has a hydraulic drive and can be used to produce parts with a maximum diameter of 70 mm and a maximum length of 310 mm. The rolling mill is provided with wedge tools with the shape identical to that of the tools used in the numerical simulation.

The billets for rolling were preheated in an electric chamber furnace to the temperature of 1100 °C. After that, they were mounted in the lower tool, and the rolling mill was set in motion. In the last rolling stage, when the ball pins are formed, the workpiece ends with cavities are cut off by the cutters (Fig. 19).

The experimental results demonstrate that the ball pins produced by CWR have the intended shape and are free from both internal and external defects (Fig. 20). The results also reveal that the billet length selected in

Fig. 14 Ball pins produced by CWR with two tools

Fig. 16 Changes in workpiece shape in CWR for ball pins and effective strains

Fig. 17 Ball pins without end-face cavities modelled by finite element method

Fig. 18 Flat-wedge rolling mill (a) available at Lublin University of Technology and lower tool set (b) for manufacturing ball pins with two tools

compliance with the proposed equations is correct—the cutoff discards show the presence of cavities, but they are not punched through.

Fig. 19 Rolling of ball pins. a Positioning of the billet on lower tool; b cutting off workpiece ends

6 Conclusions

1. To minimize concavity allowances in CWR, it is recommended that the tools should be described by the maximum allowable α and β angles and the billet should be preheated to the highest allowable forming temperature.
2. Increasing the tool velocity leads to an increase in the depth of cavities.
3. Concavity allowances can be selected according to Eqs. (5)–(8).
4. The use of FEM ensures that parameters of the CWR process are selected correctly, also in terms of material consumption.

Fig. 20 Ball pins produced by CWR with two tools and their cut off ends in accordance with Eqs. (5)–(8)

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