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Original Research Article

New forming possibilities in cross wedge rolling processes

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ABSTRACT

The paper describes limitations in the process of cross wedge rolling (CWR). The problem of necking (rupture) of a shaft step is discussed in detail. In addition, the paper also overviews the state of the art of modelling the cross wedge rolling process by the finite element method-based software, Deform-3D. Next, the paper presents methods for increasing effectiveness in two types of CWR: cross wedge rolling where axial flow of metal is blocked and cross wedge rolling with upsetting. The proposed rolling methods are then verified numerically by Deform-3D. Finally, the presented solutions are verified in experimental tests of a rolling process for producing a lever (with blocked axial flow of metal) and for an upset rolling process for producing a driving shaft.

1. Introduction

Cross wedge rolling (CWR) is an advanced metal forming technique for producing preforms (for press forging) or finished-formed stepped axes and shafts. This process is based on the use of wedge-shaped tools mounted either on the rolls or on flat (or concave) rolling mill plates.

The growing interest in CWR can be attributed to numerous advantages of this process such as high efficiency, reduced material consumption (generally, material losses in CWR do not exceed 10%), improved product strength, eco-friendliness, low energy consumption and low manufacturing costs [1]. The popularity of CWR is reflected in numerous publications devoted to this process, the most significant of which are survey publications. For instance, Fu and Dean [2] provided an overview of early studies on CWR (until the 1990s), focusing on the principle of the CWR process, development of machines for CWR, workpiece deformation, applications of CWR and the use of the CAx software in design of CWR processes. Pater [3] summarized the studies on CWR conducted from 1993 to 2010, focusing on the modelling of CWR processes (by engineering analysis methods and finite element method) as well as the development of new CWR methods, methods for producing non-axis-symmetric parts, hollow parts and shafts with eccentric steps, techniques for cold rolling and for producing parts made of non-ferrous metals and their alloys.

Despite the above-mentioned advantages, the CWR process is not free from shortcomings. The main limitation of this forming technique is the difficulty regarding the design of tools ensuring production of defect-free products. According to Johnson and Mamalis, three types of defects can be distinguished in parts produced by CWR [4]:

- incorrectly shaped cross-section mainly due to the occurrence of uncontrolled slipping in the rolling process;

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- eternal defects, mainly traces left by wedges (usually in the form of spiral grooves), necking (rupture) of the workpiece step and overlap;
- internal defects such as shrinkage porosity and material cracking.

Numerous research studies were conducted in recent years to discover solutions for eliminating the aforementioned defects from occurring in the CWR process. However, these studies almost exclusively dealt with the problem of uncontrolled slipping [5–7] and material cracking in the axial zone of the workpiece [8–11]. Still, there are no studies dealing with the problem of workpiece step necking (rupture), which occurs when forming at a high cross sectional reduction R_p. In light of the above, the authors of this paper decided to investigate this problem.

2. Necking (rupture) of a workpiece step

Fig. 1 presents a schematic design of the CWR process and its main parameters: the forming angle α, the spreading angle β, the billet diameter d_0 and the length l of the step being rolled. The tools used in CWR have three basic zones: a knifing zone (sinking of the wedge in material at a rolling depth Δr), a forming zone (spiral development of reduction over the entire step length l) and a sizing zone (removal of shape defects caused in the previous stages of the process).

The main measures of material processing in the CWR process are the reduction ratio δ and the cross-sectional reduction R_p calculated with the following formulas:

$$\delta = \frac{d_0}{d} \tag{1}$$

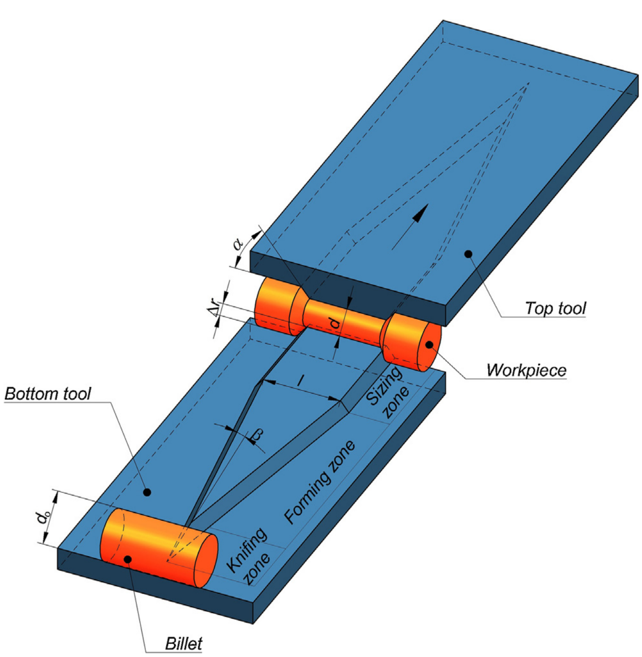

Fig. 1 – Schematic design of a typical CWR process; the most important parameters of the process are marked in the figure.

$$R_p = \frac{d_0^2 - d^2}{d_0^2} \cdot 100\% = \left(1 - \frac{1}{\delta^2}\right) 100\%. \tag{2}$$

Step necking (rupture) occurs when tensile stresses in the step reach the value of yield stresses in material. What promotes the formation of this defect in CWR is the use of wedges with large angles α and β. According to the experimental results reported by Fu and Dean, necking does not occur when the angles meet the condition [12]:

$$\tan\alpha \ \tan\beta \le 0.08. \tag{3}$$

The above condition does not however take into account material processing which is an important parameter of the CWR process as it affects occurrence of the above-mentioned defect. This parameter was considered as part of more complex conditions describing rolling without necking developed by:

- Tsukamoto et al. [13]

$$\frac{\sqrt{2\tan\alpha \ \tan\beta}}{\pi} \left(1 + \sqrt{\frac{1}{\delta}}\right) (\delta - 1) \le 0.2; \tag{4}$$

- Hayama [14]

$$R_p < 1 - 4\left(2 + \pi \tan\alpha \ \tan\beta + \frac{\sqrt{1.5\pi \cot^3\alpha \ \cot\beta}}{\zeta}\right), \tag{5}$$

  where ζ denotes the load coefficient, the values of which are listed in tables in the above work by Hayama [14];

- Pater et al. [15] who used the relative rolling stroke c

$$c = \frac{\pi\delta \tan\alpha \ \tan\beta}{\delta - 1} \tag{6}$$

and distinguished two conditions, i.e.:

for $c \le 1$

$$\frac{4\delta}{3\pi} \frac{p_n}{\sigma_p} \cos\beta \sqrt{\frac{3}{1 \pm \frac{d_0}{d_R}} c \frac{\delta - 1}{\delta}} \left[1 - \sqrt{\left(\frac{1 + c\delta - c}{\delta}\right)^3} - c\frac{\delta - 1}{\delta}\right] < 1, \tag{7}$$

for $c > 1$

$$\frac{4\delta}{3\pi} \frac{p_n}{\sigma_p} \cos\beta (\delta - 1) \sqrt{\frac{3}{1 \pm \frac{d_0}{d_R}} \frac{\delta - 1}{\delta}} < 1. \tag{8}$$

In Eqs. (7) and (8), d_R denotes the roll diameter (in the case of flat wedges: $d_R = \infty$), and p_n/σ_p is the relative pressure on contact surface which can be calculated using the equations given by Pater [16].

Nowadays, the occurrence of product necking (rupture) in CWR can be best predicted by the use of FEM. This method enables careful examination of specific forming cases and adoption of suitable measures to counteract the above defect. This usually involves introducing changes in the design of the rolling process and adopting a two-stage rolling process where the shaft step prone to necking is first formed into an intermediate diameter (wedge 1) and only then finished-formed (wedge 2). To follow the rolling pattern shown in Fig. 2, it is, however, necessary to use longer tools, which means