Numerical Modeling of Cross - Wedge Rolling of Hollowed Shafts

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Abstract. In this article, the results of numerical calculations and experimental work of the cross-wedge rolling (CWR) processes of hollowed shafts, realized with mandrels and without them, are presented. The results of numerical calculations for the CWR process of three rolls were also provided. On the basis of the calculations it was stated that the method of forming with the use of three rolls is the most appropriate for forming of hollowed shafts. This because in this process there is no excessive and irremovable ovalization of the normal cut, often observed in the process of rolling with two tools.

INTRODUCTION

The main application of CWR process is the fabrication of stepped shafts or axles. In spite of the fact that this technology has many advantages, it is not widely applied in industrial conditions. This results from the limits connected with the designing and manufacturing processes of tools which guarantee the stability of the rolling process. Tools stability can be violated by necking of rod, uncontrolled slipping or by internal fractures (usually in the axial parts of the material). The spoilage present in the first two cases is easily noticeable and it does not require additional control operation. However, the elimination of the internal cracks needs to be detected by special procedures e.g. defectoscopy.

In the CWR processes tubes can be used as a charge as well. The basic advantages of this application include the diminution of material consumption and the elimination of risk of internal cracks inside the billet. The application of hollowed charge results in a small diminution of the mechanical characteristics. This process can be also limited by irremovable ovalization of cross section of workpiece.

In this work the results of the numerical analyses of the CWR processes of hollowed parts are shown. This analysis focuses mainly on the influence of the technology parameters on the process stability.

NUMERICAL MODEL OF THE CWR PROCESS OF HOLLOWED SHAFTS

The analysis of the CWR process of hollowed shafts was made using commercial software MSC.SuperForm 2002, based on the finite element method (FEM). This software allows for the numerical simulations of metal forming processes in the condition of plane, axi-symmetrical or 3D state of strain. In order to simplify calculation of such complex processes as CWR, constant value of friction factor on the contact surface workpiece-tool is assumed. Additionally, the tool fillet radii is omitted and it is assumed that the tool is rigid.

Worked out geometrical model of the process for one of taken into consideration cases is shown in schema (Fig. 1). The model consists of two flat wedge tools (moving in the opposite directions with the same speed 0.06 m/s) and the charge modeled by 8-noeds, hexagonal elements. The research were made for the cases of forming from the tubes with external diameter d_0 = Ø30 mm and internal diameters d_w = Ø9; Ø12; Ø15; Ø18 mm. The cases in which the external diameter was reduced to d= Ø26; Ø24; Ø22; Ø20 mm were analyzed. The main geometrical parameters of tool (forming angle α = 20°÷40°, spreading angle β = 6°÷10°) were changed during the calculation.

In the calculations it was assumed that formed material is commercially pure lead, for which the flow curve is presented in the equation [1]:

$$\sigma_p = 25.35\,\varepsilon^{0.249}\,\dot{\varepsilon}^{0.065}, \qquad (1)$$

where: σ_p - flow stress, ε – strain, $\dot{\varepsilon}$ - strain rate.

The rest parameters taken into calculation include: density ρ = 11200 kg/m^3, Young modulus E = 18000 MPa and Poisson coefficient ν = 0.42. The choice of the material model was dictated by the possibility of the verification of numerical calculations in the laboratory conditions.

Due to the presence of slipping phenomenon on the surface of contact between tool – formed material, in the calculation the model of constant friction

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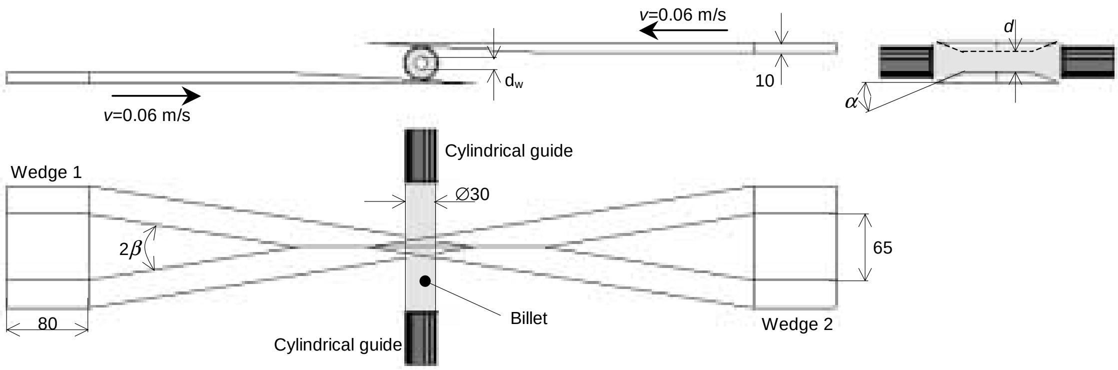

FIGURE 1. Geometrical model of the CWR process of flat wedges

depended on the slipping ratio was used as in the equation:

$$\tau = m\,k\,\arctan\left(\frac{v_p}{a_p}\right)\frac{v_p}{|v_p|}, \qquad (2)$$

where: m – friction factor (assumed limiting value m = 1.0); υ_p – vector of slipping velocity; a_p – coefficient a few times lower than slipping velocity (assumed a_p=0.1% of wedge speed).

EXPERIMENTAL RESEARCH

The forming process of hollowed shafts by CWR method was realized in the laboratory conditions using flat wedge laboratory rolling mill LUW-1. This rolling mill has a hydraulic motion which allows to form with working tool speed v_N = 0.06 m/s (for each wedge) and with the maximal tool moving force F =39 kN. More elaborate description of the rolling mill and the applied measuring system is shown in paper [2].

In the laboratory research billets from commercial pure lead with identical dimensions (comparing with theoretical analysis) were used. In the rolling processes six pairs of forming wedges were applied. They allowed to make the verification with forming angle α = 20°; 30°; 40° and spreading angle β = 6°; 8°; 9° and 10°. Three of the tool sets used in the experimental verification are shown in the Fig. 2. Besides, the samples of hollowed shafts made by CWR method are shown in the Fig. 3.

RESULTS AND DISCUSSION

The application of FEM method allows for e.g. precise observation of material flowing during the CWR process. In Fig. 4 changes of the shape of chosen normal cut of workpiece are shown. The changes are numerically predicted for two cases of forming of shafts on the same diameters d = ∅20 mm. Basing on these results the changes of shape of normal cut of workpiece during the CWR process can be observed. Such an analysis shows that in the first of the given

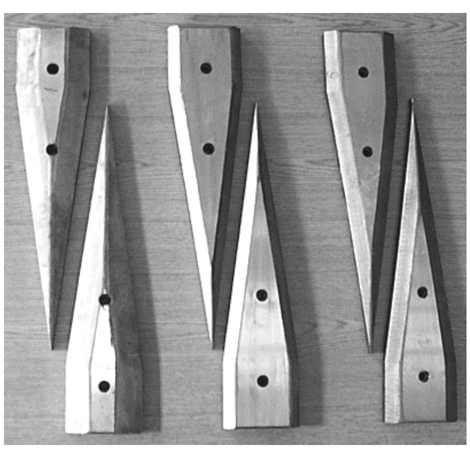

FIGURE 2. The example of tool sets used in experimental work

FIGURE 3. Hollowed shafts formed in the CWR process of flat wedges

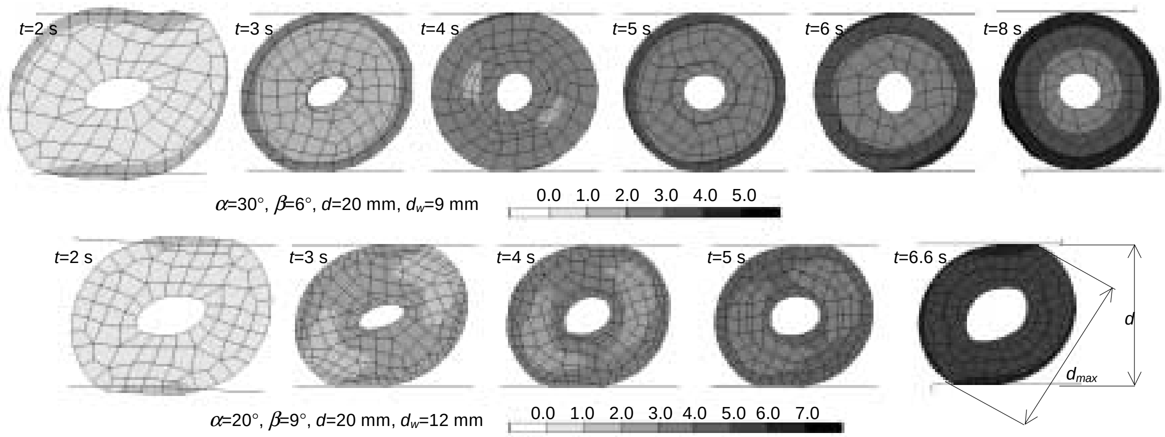

FIGURE 4. Progression of shape and distribution of the strain in the normal cut of hollowed shafts formed without mandrel, at time given in the figure

processes (with $\alpha = 30°$, $\beta = 6°$ and $d_w = \varnothing 9$ mm) just after half forming time the needed circular cut was obtained. However, in the CWR process $\alpha = 20°$, $\beta = 9°$ and $d_w = \varnothing 12$ mm the normal cut undergoes the ovalization which is irremovable till the end of the CWR process. It should be noticed that in the process in which the cut has the circulars shape the distribution of strain has the character of layered rings which is typical for the CWR processes. In the process in which considerable ovalization due to repeated bending of walls takes place, the obtained strain is the same in the whole thickness of the workpiece's wall. It is worth mentioning that the assumed in both presented cases of forming geometrical angles α, β are typical for CWR processes of full shafts. These angles guarantee obtaining of products with the circular normal cuts. The results of numerical analysis show that it is impossible to directly implement rules connected with CWR of full products in the area of hollowed ones. These rules should be worked out during the separate experimental works.

The measurement of the ovalization of normal cut of workpiece can be parameter Δ calculated as:

$$\Delta = d_{\max} - d \, , \quad (3)$$

where: d_{max} - the maximal diameter of workpiece after rolling, d - the nominal (assumed to obtain) diameter of workpiece see Fig. 4.

In the table 1 the results of calculations and experimental works, which aimed at describing the influence of basic parameters on Δ parameter are shown. The analysis of the results proves that the increase of the forming angle α favors the decrease of ovalization. This assumption is consistent with Celikov's suggestions according to whom in the CWR processes the forming angle $\alpha = 45°$ should be applied. However, the influence of the rest of analyzed parameters on Δ parameter (spreading angle β and diameter of rolled workpiece d) is irregular.

Ovalization of the normal cut of workpiece, present in the CWR processes, is the effect of the extensive compression of workpiece in the radial direction. This compression, according to German researchers' suggestions [3] can be limited by the application of the floating mandrel, placed inside the shaft. In order to

TABLE 1. Ovalization parameter Δ determined for the CWR process without mandrel (measurements in millimeters)

d_w= 15 mm		α=20°				α=30°				α=40°			
		d=26	*d*=24	*d*=22	*d*=20	*d*=26	*d*=24	d=22	*d*=20	*d*=26	*d*=24	*d*=22	*d*=20
β=6°	FEM	1.4	1.5	1.7	2.1	1.6	0.3	0.2	0.4	0.4	0.9	0.7	0.7
	Exp.	---	---	---	---	1.3	0.7	0.4	1.1	---	---	---	---
β=8°	FEM	1.3	1.3	1.1	1.2	1.1	0.4	0.6	1.3	0.3	0.6	0.5	0.3
	Exp.	1.7	1.4	0.9	1.1	0.8	0.1	0.3	1.6	0.5	1.0	0.6	0.3
β=10°	FEM	0.4	1.0	1.5	1.7	0.4	0.5	0.9	1.3	0.6	0.9	1.1	0.8
	Exp.	---	---	---	---	0.9	1.1	1.4	1.7	---	---	---	---

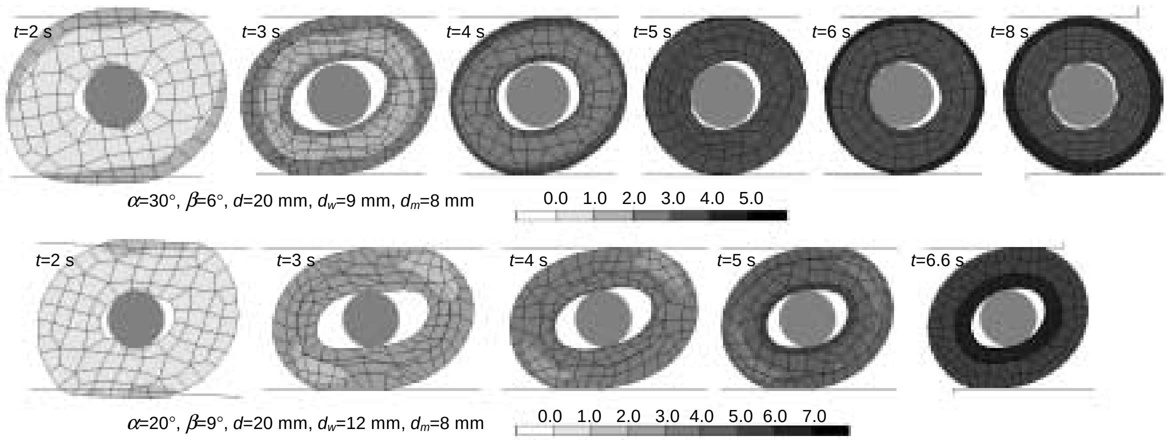

FIGURE 5. Progression of shape and distribution of the strain in the normal cut of hollowed shafts formed with mandrel, at time given in the figure

verify such an assumption, the authors of this paper analyzed the CWR process in which the floating mandrel with external diameter $d_m=\varnothing 8$ mm was used. In Fig. 5, progression of shape of workpiece normal cut, formed in the floating mandrel with identical parameters as in the case of the analyzed earlier rolling processes without mandrel is presented. Comparison of the results of calculations for both CWR methods (rolling with mandrel and without it) shows that the use of mandrel does not limit the ovalization of the normal cut. This is because the mandrel by limiting the material flow in the direction perpendicular to the tool surface, at the same time increases the presence of this flow in the tangent direction (consistent with the direction of rolling). Hence, the ovalization of the normal cut grows. However, the results of calculations showed that the use of mandrels in the CWR processes of hollowed shafts can be explained by the possibility of determining wall thickness of the formed shaft. The example of successful interference on the wall thickness during the CWR process of hollowed shafts is demonstrated in Fig. 6. In this figure, the thickness of walls obtained during rolling with mandrel and without it is also compared.

It seems that the application of the three-rolling CWR method, in the place of the method using two tools, is an effective way of preventing the ovalization of the normal cut of hollowed part. In order to confirm this assumption, the numerical simulations of the CWR process with the use of three rolls (where α =20°, β = 12° - see Fig. 7) were made. It should be noticed that with these parameters of wedges in the CWR processes, realized with the use of two tools, an irremovable ovalization of cut takes place. In the result of calculations, it was stated that in all analyzed cases of rolling with three rolls (when d_w= ∅18, ∅15, ∅12 and ∅9 mm) the desirable circular shape of workpiece normal cut was obtained. In Fig. 8 the calculated changes of workpiece normal cut for rolling processes of shafts with the smallest and the largest wall thickness are put together.

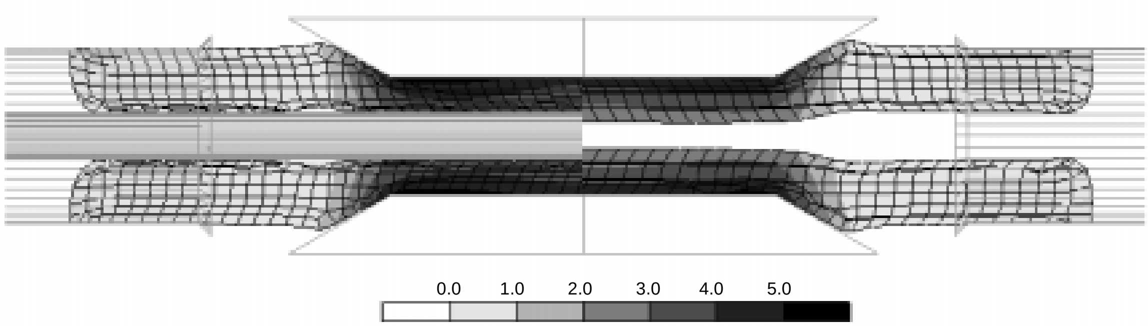

FIGURE 6. Calculated distribution of strain in longitudinal cuts of workpiece formed with mandrel and without it, where α=30°, β=6°, d=20 mm, dw=9 mm, d_m=8 mm

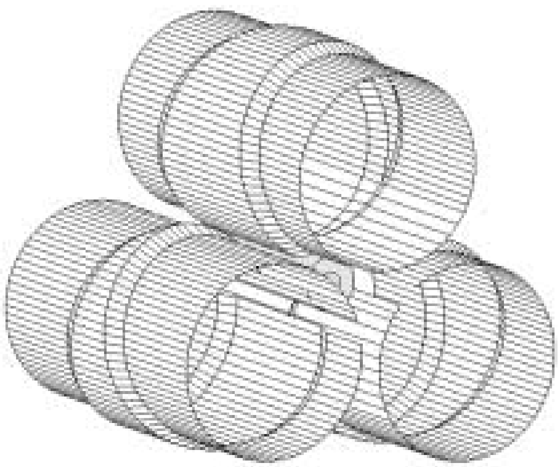

FIGURE 7. Geometrical model of the CWR process of three wedges

The finite element method (FEM) can be successfully used for valuating the forming force, the knowledge of which is necessary for the proper designing of the CWR processes. In Fig. 9, the maximal values of the forming force calculated and measured in the rolling process of wedges with angles: α =30°, β=8° are presented. The analysis of data shown in this figure indicates conformity of the results of calculations and experimental work. Moreover, the increase of the wall thickness of charge in a significant way increases the forming force.

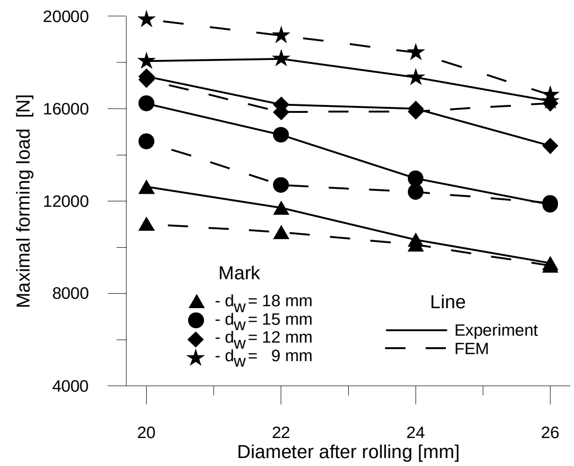

FIGURE 9. Values of the maximal forming forces determined for CWR process without mandrel, where: α=30°, β=8°

SUMMARY

In this article, the calculations of the numerical analyses and experimental work of the CWR processes of hollowed shafts, realized with mandrels and without

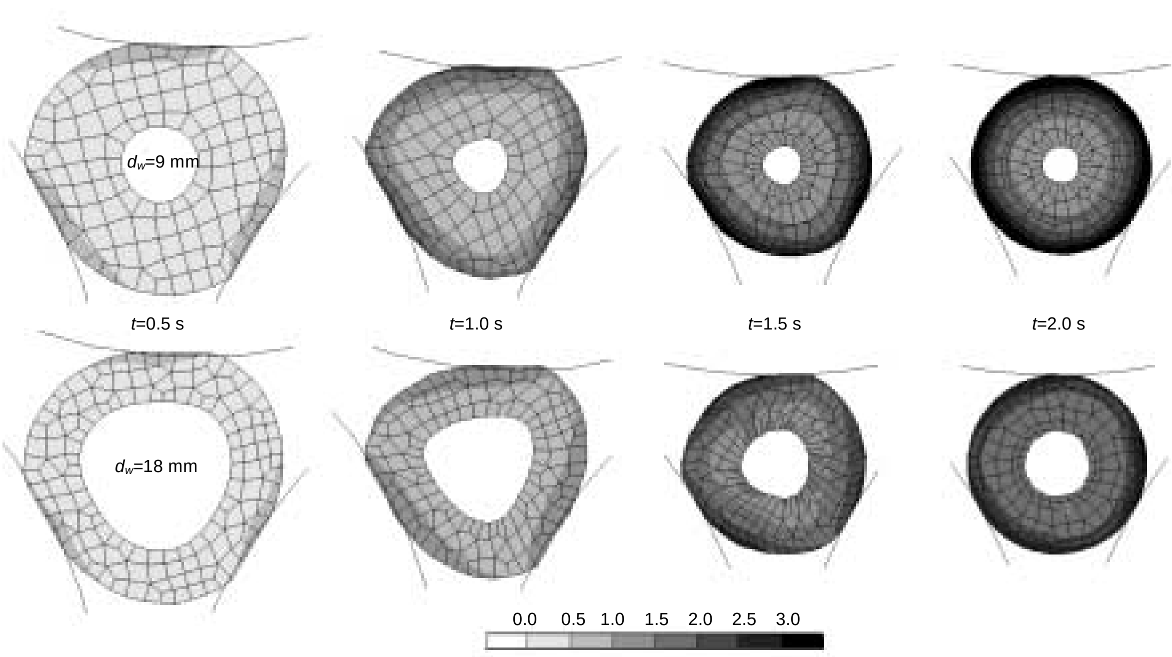

FIGURE 8. Progression of shape and distribution of the strain in the normal cut of hollowed shafts formed with three rolls, at time given in the figure

them, are presented. On the basis of these analyses it was stated that in these CWR processes (as opposed to rolling of full charge) very often excessive and irremovable ovalization of the normal cut appears. It was also claimed that for CWR processes with two tools there exist such pairs of angles: forming α and spreading β at which this ovalization is removable. However, numerical value of these angles depends on the rest of parameters in the process, such as the charge wall thickness or the reduction of billet diameter. Each time this value should be determined on the basis on calculations. Generally, it can only be stated that during designing of wedges for the two - tool CWR method, the maximal values of forming angles α should be assumed. In the result of calculations, the application of three wedges in the CWR processes of hollowed shafts was regarded as necessary. In this method of rolling, there is no undesirable ovalization of normal cut. Hence, during tool designing, rules for the rolling processes of full charges can be used.

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