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ZBIGNIEW PATER*

STRESS STATE IN CROSS WEDGE ROLLING PROCESS

STAN NAPRĘŻENIA W PROCESIE WALCOWANIA POPRZECZNO-KLINOWEGO

The results of a numerical analysis of the cross wedge rolling process (CWR) are presented in the paper. The calculations have been made using the commercial finite element programming package MSC.MARC AutoForge. The FEM model has been validated experimentally. The paper is limited only to the analysis of stress state, performed in order to examine the problem of internal cracks. The hypothesis of the longest elongation has been used in order to present the method of determining the moment of the process, when the material cracks. Besides the above, the calculated distributions of stress coefficient are presented. On their basis, the influence of the basic parameters of the CWR process on the possibility of internal cracks arising has been determined.

W artykule przedstawiono wyniki analizy numerycznej procesu walcowania poprzeczno-klinowego (WPK). Obliczenia wykonano korzystając z komercyjnego pakietu oprogramowania MSC. MARC AutoForge, bazującego na metodzie elementów skończonych. Opracowany model MES zweryfikowano doświadczalnie. W opracowaniu ograniczono się do analizy stanu naprężenia, wykonanej pod kątem problematyki pęknięć wewnętrznych. Do określania momentu procesu, w którym wystąpi pęknięcie materiału wykorzystano hipotezę największego wydłużenia. Ponadto przedstawiono obliczone rozkłady wskaźnika stanu naprężenia. Na podstawie tych rozkładów określono wpływ podstawowych parametrów procesu WPK na prawdopodobieństwo utworzenia pęknięć wewnętrznych.

Notations

E – Young modulus,
M – material constant,
WK – coefficient of stress state,
a_p – coefficient,
d – diameter after rolling,
d_0 – billet diameter,
k – shear yield stress,
l – rolling width,

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m – friction factor,
r_0 – billet radius,
v – wedge shifting speed,
v_p – slippage speed vector,
Δ_r – rolling depth,
α – forming angle,
β – spreading angle,
δ – relative reduction ($\delta = d_0/d$),
ε – effective strain,
$\dot{\varepsilon}$ – strain rate,
ν – Poissons ratio,
ρ – density,
σ_1 – first principal stress,
σ_2 – second principal stress,
σ_3 – third principal stress,
σ_i – equivalent stress,
σ_m – mean stress,
σ_p – yield stress,
σ_v – reduced stress.

1. Introduction

Cross wedge rolling (CWR) is a modern forming method. During the process, the part is made through the action of wedge tools, mounted on rolls or on flat or concave plates of a rolling mill. The CWR method has many advantages comparing with other forming methods (forging, machining, casting). They are the following [1, 2]: high efficiency, better utilization of materials, higher strength parameters of products, easy automation and less harmful for the environment.

In spite of the above advantages, the CWR method is not widely used in industry, mainly because of the difficulties in to designing wedge tools, which can guarantee a stable forming process. The stability of the CWR process might be disturbed by the following: uncontrolled slipping between the tool and the workpiece, necking of the workpiece and internal cracks. Presently in some scientific centers in the world, studies are being performed in order to determine methods of designing wedge tools in such a way that the above defects are eliminated. The numerical method, utilizing the finite elements method, is now often used in those studies [2-6].

The CWR process is first of all determined by the shape of used tools. A typical wedge segment (Fig. 1) consists of the following zones: knifing, forming and sizing. Sometimes a guiding zone is placed after the knifing one. The main geometrical parameters of the CWR process are the following (Fig. 1): forming angle α, spreading angle β, charge diameter d_0, diameter after rolling d, relative reduction δ and rolling width l.

The study reported in this paper includes the results of tests, which have been performed in order to determine the influence of the basic CWR process parameters on the stress state in the rolled workpiece. Basic attention is paid to the problem of determining the moment of internal cracks occurring in rolled parts.

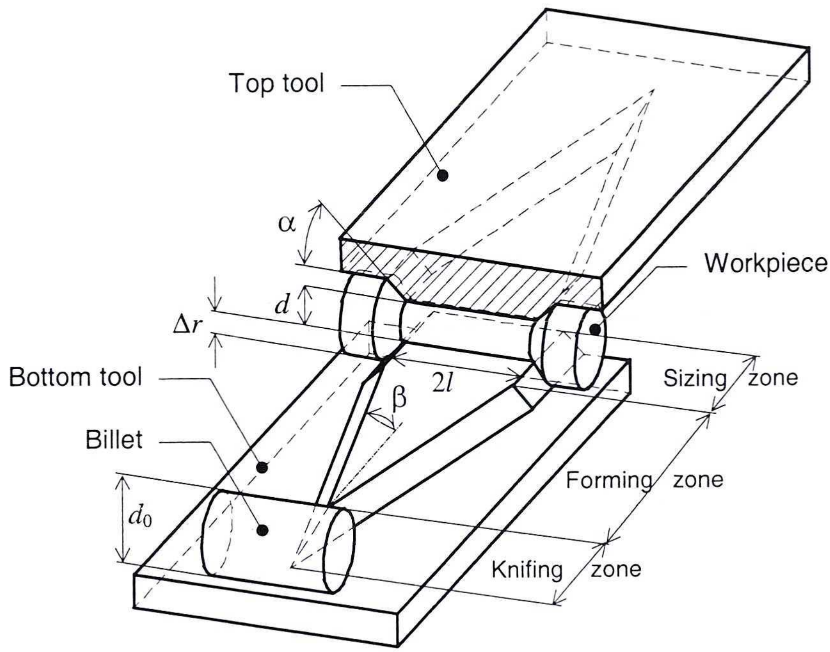

Fig. 1. The scheme of cross wedge rolling process

2. FEM model of the CWR process

The commercial programming package MSC.MARC AutoForge [7] has been used to model the CWR process. The program can be used for the mechanical or thermo-mechanical simulation of metal forming processes, which take place in plane, axial-symmetrical or three – dimensional strain state [8]. In order to shorten the time necessary to perform the calculations, the following simplifications have been used: the friction factor on the material – tool contact surface is constant, the tool material is rigid, the temperature of forming process is constant, tool corner radii are omitted.

Three geometrical models of the CWR process are presented in Fig. 2. The following items are included in the models: billet and tools (flat or convex wedges) moving with the speed of 0.1 m/s each. In order to model the charge, eight-node cubic elements have been used. The additional limitations have been added to the nodes located on the billet symmetrical axis (they can not shift along x and y directions). This has been done in order to determine the charge location and in order to abstain from using guiding strips if using two rolls.

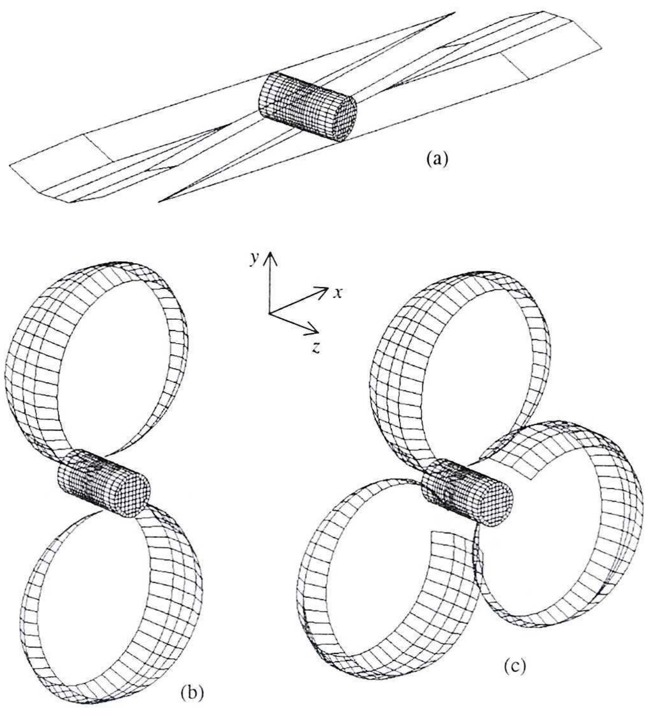

Fig. 2. Geometrical models of CWR process used in the calculations

Numerical simulations of the CWR process have been done for room temperature rolling of aluminum Al 99.8 (A) having the following flow curve [9]:

$$\sigma_p = 127\ (0.0023 + \varepsilon)^{0.261}\,. \tag{1}$$

The other material properties used are: Youngs modulus $E = 70000$ MPa, Poissons ratio $\nu = 0.34$ and density $\rho = 2700$ kg/m^3.

Because the direction of friction forces on the contact surface changes, the constant friction model, depended on the metal slippage speed along the tool, has been used, includes a speed dependent factor according to the following equation:

$$\tau = -\, mk\,\frac{2}{\pi}\,\arctan\left(\frac{|v_p|}{a_p}\right)\frac{v_p}{|v_p|}, \tag{2}$$

where: m is the friction factor, k – shear yield stress, v_p – slippage speed vector, a_p – coefficient smaller than slippage speed. In the analysis it is assumed that $a_p = 0.1\%$ of the tool speed and $m = 1$.

3. Validation of FEM model

In order to verify the numerical calculation results, the distributions of wedge pushing (tangential) load calculated using the finite element method have been compared with those measured experimentally. The load has been measured using a laboratory flat-wedge rolling mill, shown in the Fig. 3. The rolling mill (marked by LUW-1) is hydraulically driven. It makes it possible to form forgings with maximum wedge pushing loads up to 39 kN. Because of that reason that rolling mill can be used to form such products as stepped shafts, made of model materials.

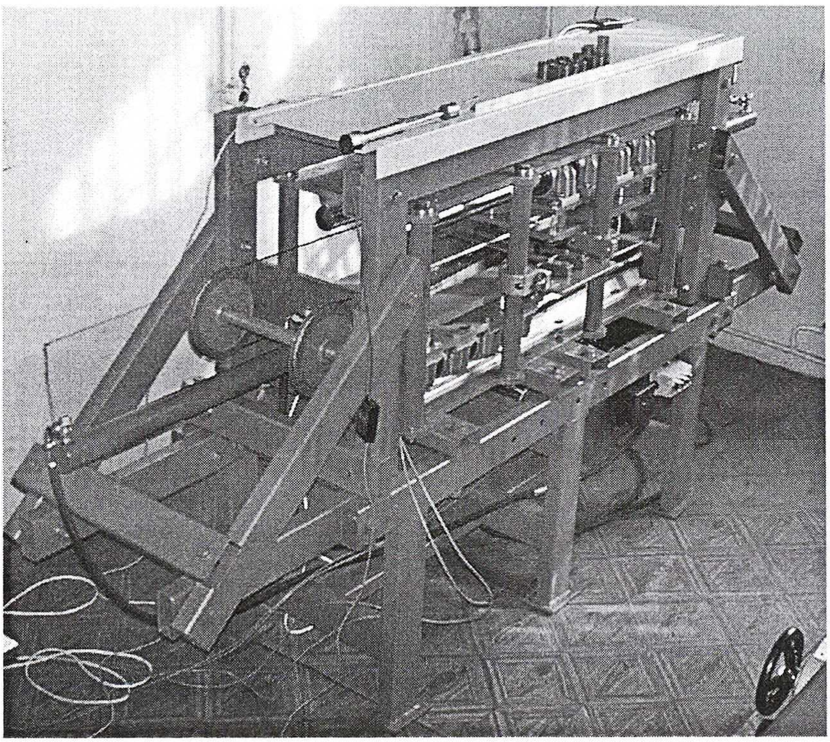

Fig. 3. Laboratory flat-wedge rolling mill LUW-1

For the analysis, upsetting tests have been done using samples made of commercial pure lead, having flow curve determined by the following dependence:

$$\sigma_p = 24.8\ \dot{\varepsilon}^{\,0.088}\,. \qquad (3)$$

The rolling has been performed at room temperature. The samples used for the tests had the following diameters: ∅20, ∅22, ∅24 mm. Their length was equal to 180 mm. All samples were reduced (at wedge shifting speed $v = 0.06$ m/s) to the same diameter of 18 mm. Wedge tool segments have been used in the tests. They had the following dimensions: forming angle $\alpha = 30°$, spreading angle $\beta = 5°$, rolling width $l = 22.7$ mm. Serrations were made on the side surfaces of the wedges in order to minimize the possibility of uncontrolled slippage occurring.

The same parameters as in the experiments with lead have been used in the numerical calculations. Besides that the following material parameters have been taken for the calculations: E = 18000 MPa, ν = 0.42, ρ = 11200 kg/m^3, m = 1.

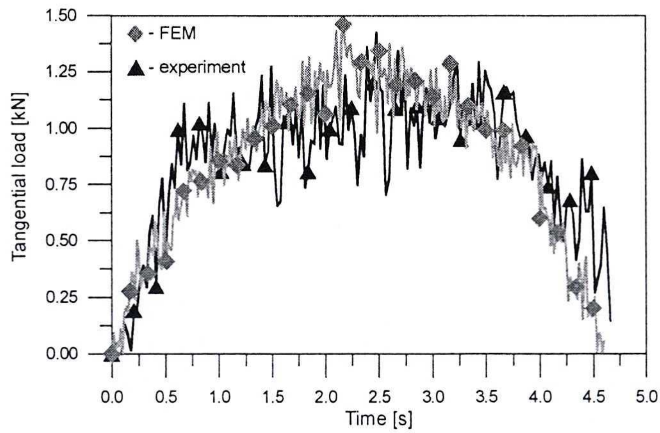

Fig. 4. Experimental and calculated distributions of tangential load for the CWR process at: $\alpha = 30°$, $\beta = 5°$, d_0 = 20 mm, d = 18 mm, ν = 0.06 m/s

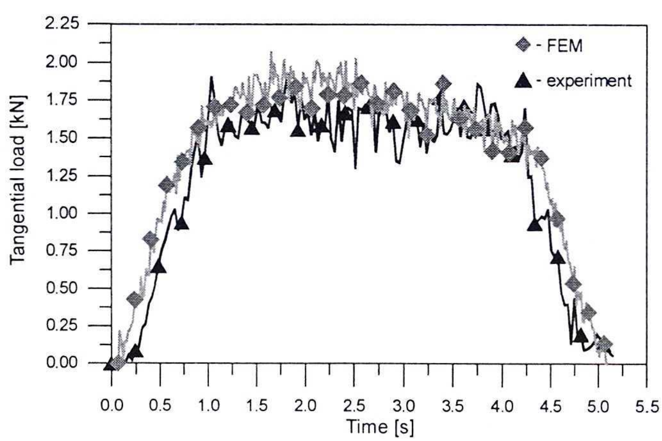

Fig. 5. Experimental and calculated distributions of tangential load for the CWR process at: $\alpha = 30°$, $\beta = 5°$, d_0 = 22 mm, d = 18 mm, ν = 0.06 m/s

The distributions of wedge pushing load are presented in Figs. 4-6. The characteristic feature of those distributions is the local growth of load value on the border of two zones: knifing and forming. That growth is higher where the reduction of the cross section area is

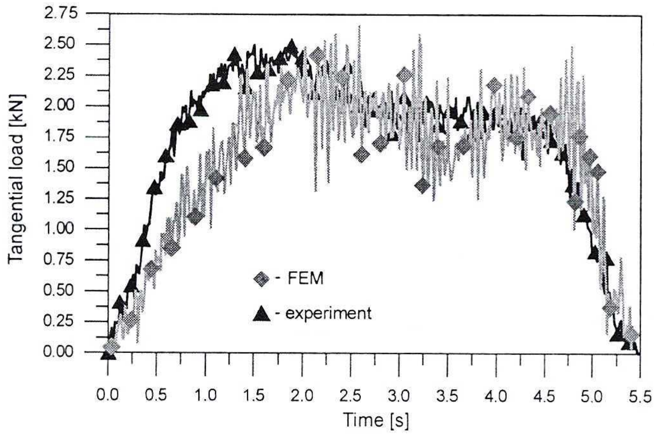

Fig. 6. Experimental and calculated distributions of tangential load for the CWR process at: $\alpha = 30°$, $\beta = 5°$, $d_0 = 24$ mm, $d = 18$ mm, $v = 0.06$ m/s

bigger. It seems that the reason of that is connected with the beginning of material forming with the maximum rolling depth, by the wedge-sizing surface. That phase of the CWR process takes place with the relative maximum slippage [6]. These two facts are the reason of increasing the material-tool contact surface, and as a consequence – increasing the load value. The comparison of load distributions (calculated and measured) showed good compliance, quality and quantity. It is confirmed that FEM method is the proper one for the analysis of CWR processes.

4. Internal cracks in products formed by CWR method

Internal cracks, which come into existence during the CWR process, are the main limiting reason of using that forming technology widely. The shape of cracks depends on the rolling method. In two rolls method and in rolling using flat wedges, the cracks are axial gaps. For three rolls method the cracks are ring longitudinal gaps.

In the first study [10], concerned with defects of cross-rolled rods it is explained, that the cracks are caused by tangential and tensile stresses. The test results presented in the study [11] show that axial and radial tensile stresses cause the cracks. It is also underlined in the study that intensive plastic strains in the central (axial) zone of the cross rolled material also cause the cracks. Celikov and others [12], on the basis of the theoretical analysis, confirmed by the experiments, came into the conclusion that with the increase of rotations of the workpiece a crack occurs when the tensile stresses in the forging exceed the formed material yield point. The authors of the study [13] state that compression, which takes place during the CWR process, causes concomitant tensile stresses, which lead to axial cracks. In 1979, in an overview of scientific-research studies [14] concerning the matter of cracks occurring in cross rolling processes, Thompson and Hawkyard concluded that low-cycle material fatigue causes the cracks. Hayama in the study [15] determined the dependence between the tensile stress and the reduction of cross-section area of the workpiece and presented the requirement for the stability of forming process, without internal cracks occurring as:

$$(0.15 + 0.0038\alpha)\beta^{0.325} \geq M. \tag{4}$$

In the above dependence, the unit of angles α and β is a degree. M is a material constant, with value between 0.35 and 0.4.

Until now the only analysis of stress state in the CWR processes was done by Dong and others [16]. Using the FEM method, the authors traced the changes of the first principal stress σ_1 in the central point and in the middle point of the workpiece. It was concluded that σ_1 stress in the middle point of the forging almost in all studies cases was tensile. In the middle point the first principal stress changed cyclically. The results of Dong and others [16] theoretically confirmed former experiments [17] of the material cracking mechanism during CWR processes.

The numerical calculations done by Dong and others referred only to the phases of wedge knifing and guiding and were limited to the method of rolling using flat tools. Therefore they omitted the influence of many important parameters of the CWR process (for example spreading angle β) on the stress state in formed pieces. In a similar way, the criteria of first main stress used in calculations, does not allow the prediction of a crack occurring in those cases, in which compressive stresses dominate. Because of these reasons, in this study, the complete CWR process is subjected to the analysis and the hypothesis of the longest elongation (elaborated by de Saint Venant [18]) is used to predict the internal cracks occurring. According to that hypothesis, the reduced stress σ_v is equal to:

$$\sigma_v = \sigma_1 - \nu(\sigma_2 + \sigma_3). \tag{5}$$

The internal cracks occur when σ_v stress reaches value of cohesive strength of the formed material.

5. The results of calculations and their analysis

The numerical calculations are done for many CWR methods, choosing the parameters of the process in such a way that it is possible to determine their influence on the stress state. As it is seen from the dependence (5), in order to calculate the reduced stress, it is necessary to know principal stresses. The distributions of those stresses (at points A, B, C, D, E and F located at the cross section of the forging, symmetry plane, initially at 0%, 20%, 40%, 60%, 80% and 100% of r_0 from the axis) are presented on the Fig. 7-9. The analysis of data presented in these figures shows that the least favorable stress state double axis tension with compression is present in axial layers of the material. In the outside layers the principal stresses change cyclically and their sign changes during the rolling process. When those points are located perpendicularly to the tool, the stresses have minimum values. Maximum stresses occur when the points are on radii located parallel to the tool axis. Such a distribution of stresses can lead to fatigue cracks. However, according to the suggestion of Wyrzykowski and others [19], if the number of stress cycles is smaller than several hundred, the cracks are quasi-static. Such an assumption allows the analysis of CWR processes to be based on only the hypothesis of the longest elongation.

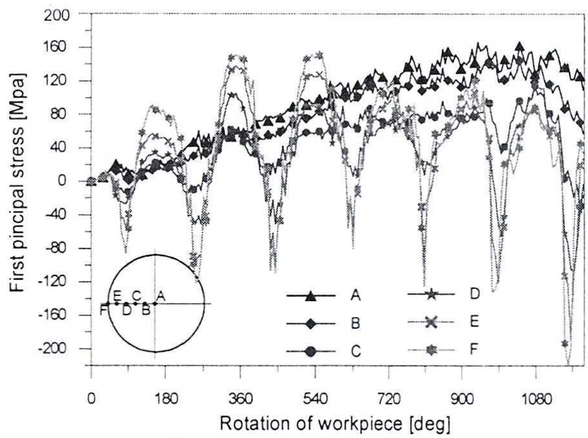

Fig. 7. Distributions of the first principal stress, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

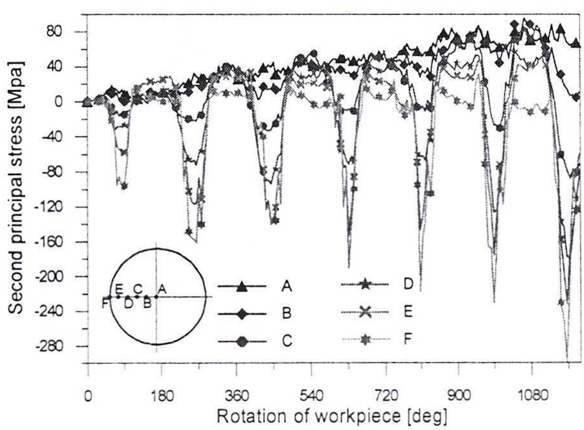

Fig. 8. Distributions of the second principal stress, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta 1.3$

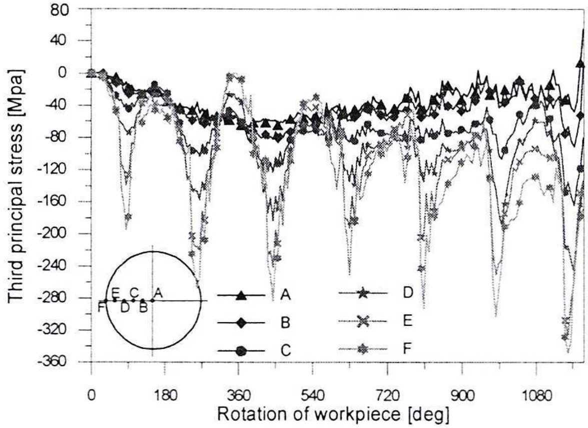

Fig. 9. Distributions of the third principal stress, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta 1.3$

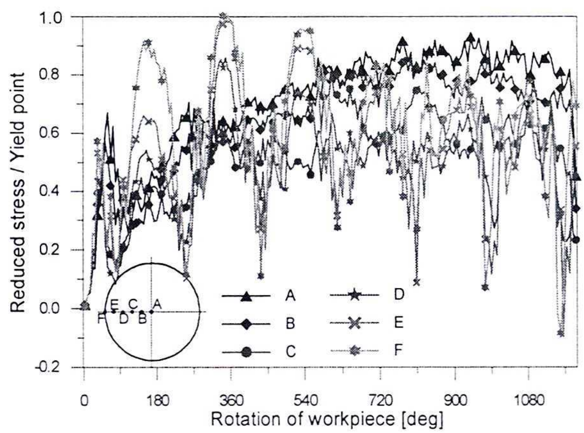

Fig. 10. Distributions of the reduced stress σ_v compared to the yield point, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

Fig. 10 presents the distributions of reduced stresses referred to the yield point of the material, calculated for the analyzed points: A, B, C, D, E and F. According to the calculations, the biggest values of σ_v/σ_p ratio are found in the central layers of the material, which are the most subjected to internal cracks erasing. It can be also underlined that at some points the σ_p stress reaches values close to critical. Such local increments of reduced stresses have been observed during the initial phase of the CWR process (before the workpiece rotates about 2 times) in outside layers of the material. It is suspected that such situation is caused by intensive tension of the outside layers of the material, which is the result of ovalization of the workpiece cross section. After the part cross section again becomes round (of a smaller diameter), those oscillations cease.

It is convenient to use *WK* coefficient of stress state in order to perform the comparison analysis of CWR processes with the reference to internal cracks. The coefficient is determined by the following dependence:

$$WK = \frac{\sigma_m}{\sigma_i}, \tag{6}$$

where: σ_m – mean stress (hydrostatic), σ_i – equivalent stress.

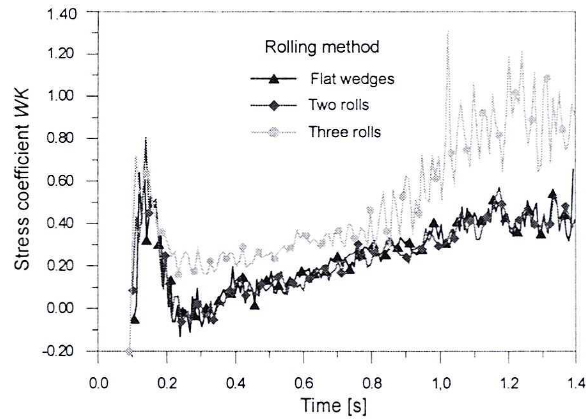

Fig. 11. Distributions of the stress state coefficient in the central point of the workpiece, calculated by FEM for the CWR process, $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0,1$ m/s, $\delta = 1.3$

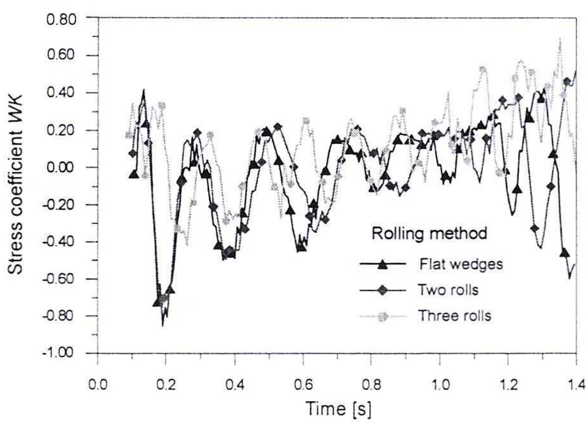

Fig. 12. Distributions of the stress state coefficient *WK* in the point located initially at $0.4r_0$ from the workpiece axis, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

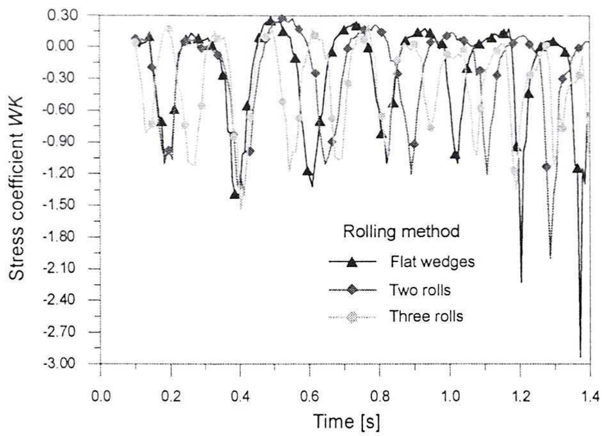

Fig. 13. Distributions of the stress state coefficient *WK* in the point located initially at $0.8r_0$ from the workpiece axis, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

It is generally known that, if $WK > 0$ and the bigger it is, the probability of cohesion loosing in that place of the body is also bigger. If $WK < 0$, the positive mechanism of pores and micro gaps bonding takes place. Such conclusion conforms with energy criterion of Cockroft and Latham [20], according to which the work performed by tension stress only is the essential factor for cohesion disturbance.

Refer to Figs. 11-13 for distributions of *WK* coefficient for various rolling methods calculated for central point and points situated at a distance of $0.4r_0$ and $0.8r_0$ from centre line of the workpiece respectively. Analysing the data included in these Figures, it can be seen that the most adverse situation takes place along centre line of the workpiece. The positive value of strain state coefficient in that area is maintained practically during the whole period of rolling process. We have to emphasize that similar distributions of *WK* coefficient (in central point) have been recorded for all cross wedge rolling processes under analysis. In the initial phase of rolling process – associated with wedge knifing – a local maximum is reached (Fig. 11), followed rapidly by a minimum value. After that the *WK* coefficient gradually increases throughout the forming zone and then stabilizes in sizing phase. It is seen that the three roll process is characterised by most adverse conditions (potential cracking). The positive values of stress state coefficient (two times greater than values calculated for remaining CWR methods) are maintained during whole rolling process. However no difference has been found for the values of *WK* coefficient calculated for two tools (flat wedges or rollers).

In the course of analysis of the influence of initial point position on *WK* coefficient, it should be emphasised that maximum values of that coefficient are reached at the point situated on centre line of the workpiece. *WK* reduces with increasing radial distance. Variable distribution of calculated values of *WK* coefficient should be also mentioned. The distribution is the illustration of existing conditions, i.e. consisting in increasing role of compressive stresses (causing welding of microcracks) at increasing distance from the centre line of the workpiece. Therefore the next sections of the present study have been limited to comparison of *WK* coefficient values calculated in central point (centre line of the workpiece) being characterised by most adverse stress state in view of inner cracks creation. Furthermore, our analysis of basic parameters of CWR process (α, β, δ) has been limited to rolling by means of flat wedges as the method being most commonly used in industry.

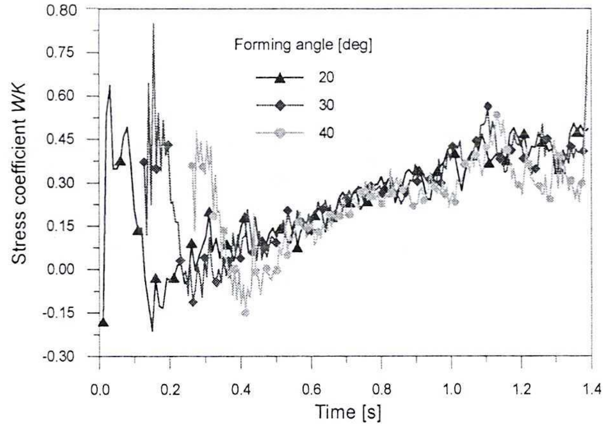

Fig. 14. Distributions of the stress state coefficient *WK* in the central point of the workpiece, calculated by FEM for the CWR process at: $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

The influence of forming angle α on *WK* coefficient value is illustrated in Fig. 14. As shown in the representation, increased values of forming angle α are accompanied by insignificant increase of *WK* coefficient. Besides the above, it is stated, that the lower the forming angle, the longer time of material subjecting to the inconvenient tensile stresses. The idea presented in the analysis [21], that increasing of the forming angle α makes the probability of internal cracks occurring bigger, is confirmed.

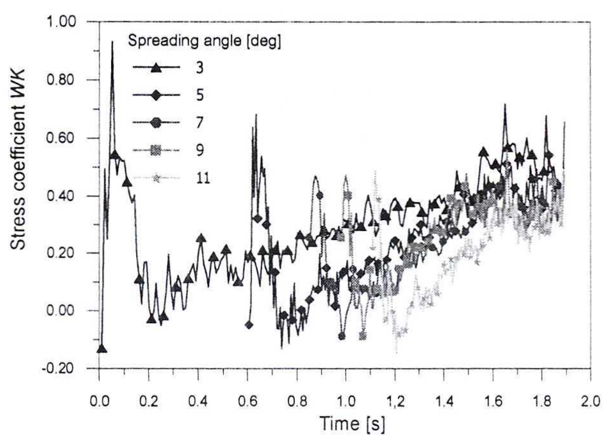

Fig. 15. Distributions of the stress state coefficient *WK* in the central point of the workpiece, calculated by FEM for the CWR process at: $\alpha = 25°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1.3$

The influence of wedge spreading angle β on the value of *WK* coefficient is presented on the Fig. 15. It can be seen that if β is increased, the *WK* coefficient is also increased. Besides, the inconvenient influence of the spreading angle on the CWR process time is seen. According to the calculations, if β is increased from 3° to 9°, the rolling time during which the inconvenient stress state takes place is doubled.

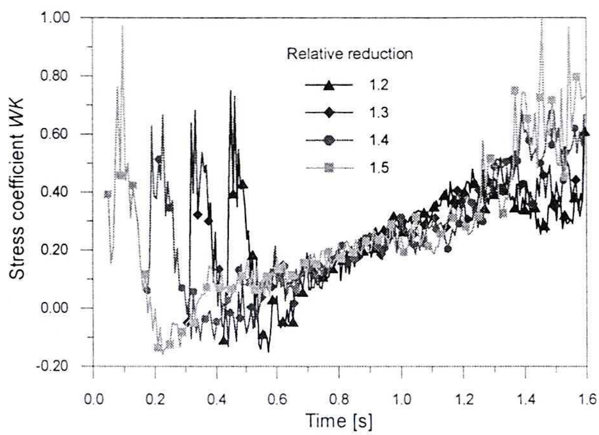

Fig. 16. Distributions of the stress state coefficient *WK* in the central point of the workpiece, calculated by FEM for the CWR process at: $\alpha = 25°$, $\beta = 5°$, $d_0 = 13$ mm, $v = 0.1$ m/s, $\delta = 1$

The similar conclusion can be drawn on the basis of the Fig. 16, presenting the influence of relative reduction δ on the *WK* coefficient. From the data presented on that Figure, it can be concluded, that rise of δ is connected first of all with the elongation of rolling time. Besides that, it is observed that during the final phase of the CWR process (sizing), during the processes with bigger δ, the stress state coefficient has grown inconveniently.

6. Summary

The analysis of the stress state in the parts formed by CWR process is presented in the paper. The commercial program MSC.MARC AutoForge has been used for the calculations. The program allows to simulate the processes of metal forming, which take place in the three – dimensional strain state. The main emphasis is put on the subject of internal cracking in formed pieces. The forecasting method of cracking moments in CWR processes has been explained. The Saint Venant hypothesis of the biggest elongation has been used in calculations.

In order to compare the influence of the main CWR parameters on the possibility of internal cracking occurring, the distributions of stress state coefficient *WK* for different variants of rolling processes have been determined. They are presented on the Fig. 11-16. According to the analysis of the processes, it can be seen that if the of relative reduction

δ grows and the forming angle α as well as the spreading angle β gets smaller, the possibility of internal cracks occurring increases. It has been shown also that such a change of CWR parameters not only causes the growth of *WK* coefficient but also increases the time of the process.

REFERENCES

[1] P. Fu X., T. A. Dean, Past developments, current applications and trends in the cross wedge rolling process. International Journal of Machinery Tools Manufacture Design, Research and Application. **33,** 367-400 (1993).

[2] Y. Dong, M. Lovell, K. Tagavi, Analysis of slip in cross wedge rolling: an experimentally verified finite element model. Journal of Materials Processing Technology. **80-81,** 273-281 (1998).

[3] R. Glaß, F. Hahn, M. Kolbe, L. W. Meyer, Process of partial bulk metal-forming aspects of technology and FEM simulation. Journal of Materials Processing Technology **80-81,** 174-178 (1998).

[4] M. Lovell, Evaluation of Critical Interfacial Friction in Cross Wedge Rolling. Transactions of the ASME-F-Journal of Tribology **123,** 2, 424-429 (2001).

[5] Z. Pater, Examination of the strain state in products of cross wedge rolling. Proc. of the Int. Conference on Advanced Materials and Processing Technologies (AMPT01), Madrid (Spain) September 18-21, 875-882 (2001).

[6] Z. Pater, A. Gontarz, W. Weroński, Selected Problems of Theory and Technology of Cross Wedge Rolling. Ed. LTN, Lublin 2001.

[7] MSC.MARC AutoForge – User's guide. Version 3.1. MSC.Software Corporation 1999.

[8] A. Gontarz, W. Weroński, Forging of Aluminum Alloys: Theoretical and Technological Aspects. Ed. Technical University of Lublin, Lublin 2001.

[9] Z. Gabryszewski, J. Gronostajski, Mechanic of metal forming processes. Ed. PWN, Warsaw 1991.

[10] V. S. Smirnov, The deformation process in cross rolling. Stal **6,** 511 (1947).

[11] P. K. Teterin, Ju. F. Luzin, The mechanism of metal rupture in cross rolling. Stal **10,** 930-933 (1960).

[12] A. I. Celikov, The theory of cross cold rolling on three-roll machine. Vestn. Mashinostroeniya **7,** 49-54 (1961).

[13] V. S. Smirnov, V. A. Lunev, Stress state in cross rolling. Izv. Chern. Metallurgiya **3,** 94-100 (1965).

[14] G. Thompson, J. B. Hawkyard, Crack formation in transverse rolling a review. Proc. of 1st Int. Conf. Rotary Metalworking Processes p. 171-184 20-22 XI 1979 London UK.

[15] M. Hayama, Optimum working conditions in the cross rolling of stepped shaft. Journal of Mechanical Working Technology **3,** 31-46 (1979).

[16] Y. Dong, K. Tagavi, M. Lovell, Z. Deng, Analysis of stress in cross wedge rolling with application to failure. International Journal of Mechanical Sciences **42,** 1233-1253 (2000).

[17] H. Sugiyama, The central cavity of transversely hot rolled shaft. Annals of the CIRP **22/1,** 93-94 (1973).

[18] T. W. Pełczyński, T. A. Pełczyński, Theory of Metal Forming. Part I. Mechanic of Metal Forming Processes. Ed. Technical University of Warsaw, Warsaw 1982.

[19] J. W. Wyrzykowski, E. Pleszakow, J. Sieniawski, Deformation and fracture of metals. Ed. WNT, Warsaw 1999.

[20] M. G. Cockroft, D. J. Latham, A simple criterion of fracture for ductile metals. Nat. Eng. Lab., Report no 240 Glasgow 1966.

[21] Z. H. Hu, X. Xiu, D. Y. Sa, The principles, processes and machines of helical rolling and cross wedge rolling. Ed. Metall. Ind. Press, Beijing 1985.

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