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EXPERIMENTAL AND THEORETICAL ANALYSIS OF THE CROSS – WEDGE ROLLING PROCESS IN COLD FORMING CONDITIONS

ANALIZA TEORETYCZNO-EKSPERYMENTALNA PROCESU WALCOWANIA POPRZECZNO-KLINOWEGO NA ZIMNO

In this paper the analysis of the cross – wedge rolling (CWR) of a V – shaped groove on the bar in cold forming conditions is presented. The rolling tests were made basing on the laboratory stand for CWR at the Lublin University of Technology. However, in the theoretical calculations the analysis was based on the finite element method (FEM) and the commercial software MSC.SuperForm 2005 was used. The worked out model of the CWR process in cold forming conditions was verified by comparing forming forces obtained from numerical simulations and measured in experimental research. Good qualitative and quantitative agreement in the forces values confirmed the rightness of the applied solution. On the basis of the obtained research a more detailed analysis were made: kinematics of material flow, state of strain distribution, increase of the rolled bar diameter, forming forces and disturbance of the rolling stability.
Keywords: Cross wedge rolling, FEM, experiment

W opracowaniu przedstawiono analizę procesu walcowania poprzeczno – klinowego (WPK) na zimno rowka w kształcie litery V na obwodzie pręta. Próby walcowania wykonano w oparciu o stanowisko laboratoryjne do WPK znajdujące się w Politechnice Lubelskiej. Natomiast w obliczeniach teoretycznych bazowano na metodzie elementów skończonych i stosowano komercyjny pakiet oprogramowania MSC.SuperForm 2005. Opracowany model procesu WPK na zimno zweryfikowano porównując siły kształtowania otrzymane z symulacji numerycznej oraz zmierzone w badaniach eksperymentalnych. Dobra zgodność jakościowa i ilościowa w wartościach sił potwierdziła trafność zastosowanego rozwiązania. Na podstawie wykonanych prac badawczych dokonano szczegółowej analizy: kinematyki płynięcia metalu, stanu odkształcenia, zwiększenia średnicy walcowanego pręta, sił kształtowania oraz zakłóceń stabilności walcowania.

1. Introduction

Cross – wedge rolling (CWR) is a modern technology of forming applied mainly in manufacturing of: stepped axes and shafts for automotive industry; isolators cores, preforms for die forging [1]. This process is done mainly in hot forming conditions. However, in the 1980's CWR technology in cold forming conditions was worked out and implemented in industrial conditions. The basic differences between these processes, apart from the temperature of the formed metal, include:

- limiting the CWR technology in cold forming conditions to rolling of small axi – symmetrical parts (maximal diameter smaller than 10 mm);
- applying in the CWR processes in cold forming conditions cooling and lubricating substances (in order to increase the tools durability and remove of material chip);
- lack of technological cuts (serrages) on the side surfaces of the wedges used in the CWR processes in cold forming conditions;
- differences of angles of the wedges used for rolling [2, 3].

In recent years in the Metal Forming and Computer Modelling Department at Lublin University of Technology research have been done on a new technology of round metal bars splitting without discard. It is based on making a V-groove on the bar, and later, on repeated bending of the bar leading to material fatigue cracking. In order to obtain the V-groove on the bar perimeter the CWR method in cold forming conditions was proposed.

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In this paper the results of research work dealing with the process of forming of the V-groove on the bar perimeter by means of the CWR in cold forming conditions are presented. Because of the laboratory stand for CWR, in the research author limited to the rolling method by means of flat wedges. Two cases of groove forming (Fig. 1) were analyzed. In the first case (Fig. 1a), called free CWR, the contact with metal was present in the area of the formed necking. However, in the second case (Fig. 1b), called CWR with compression, tools contacted with the workpiece also outside the forming zone. Additionally, in Fig. 1 the main geometric dimension of the analyzed CWR process are shown.

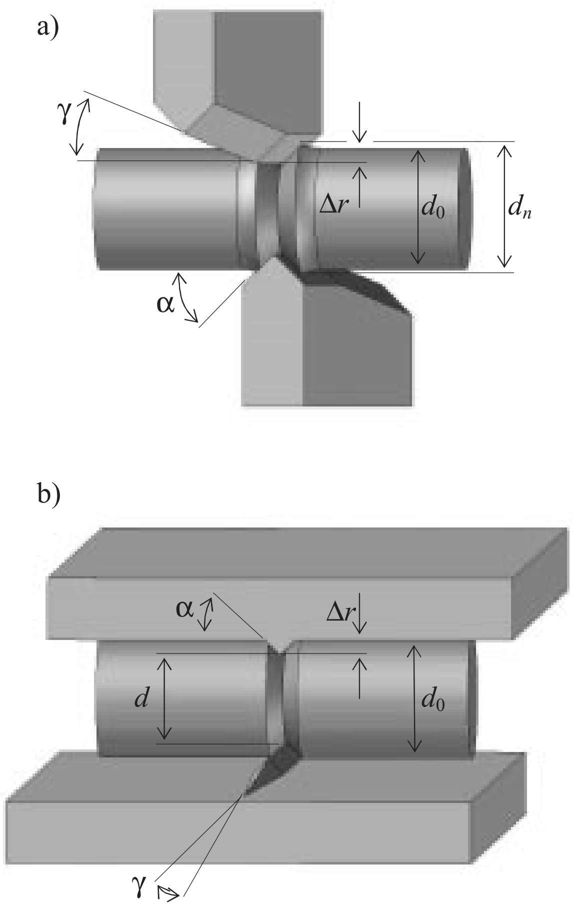

Fig. 1. Analyzed within the scope of research works method of cross rolling of V-grooves on the workpiece circumference: a) local contact (free CWR), b) contact on the tool whole length (CWR with compression)

2. Experimental research

Experimental research were made using the laboratory rolling mill LUW-2 shown in Fig. 2. This machine consists of body, upper and lower slides and driving unit. The rolling mill body was made as a welded construction consisting of two plates supported by rectangular pipes. These plates are connected with each other by means of four double connecting bolts transmitting forming forces during rolling. Driving devices with shafts are fixed to the plates. On these shafts, hydraulically driven slides move, each slide has eight bearings. The upper slide is built from the two plates (upper and lower) connected by means of connecting bolts. Between these plates are placed two force sensors used for measuring of radial force values. The rolling mill driving unit consists of hydraulic unit with hydraulic feeder (driven by electric engine 11kW) and two hydraulic motor operators (with stroke 630 mm) At the maximal pressure 20 MPa it is possible to obtain the power of 39 kN on each motor operator. One of the motor operator is equipped with two pressure converters which allow for determining the wedge squeezing (tangential) force. Necessary for the proper realization of the forming process is the simultaneous slides movement obtained by means of special synchronization linear system. The rolling mill LUW-2 is equipped with a special digital measuring system allowing for registering of main force and kinematical parameters of the CWR process. Apart from forces (tangential and radial), using the worked out measuring system during the CWR process, the slide linear velocity and the rotary speed of the rolled workpiece can be monitored. The measurements of all parameters are synchronized in time and their registration is caused by slide displacement of 1 mm.

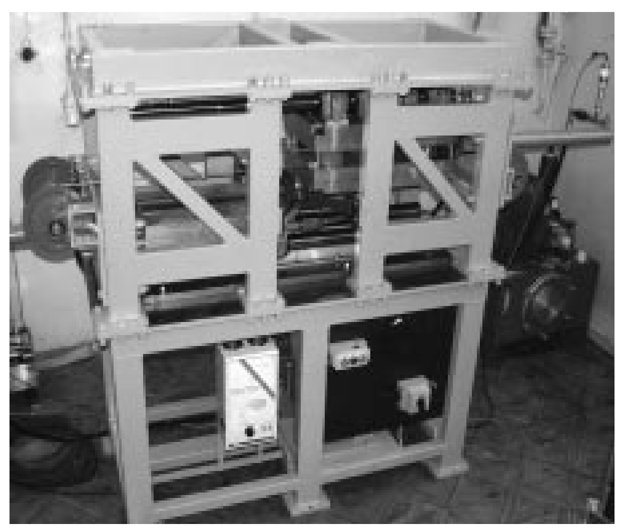

Fig. 2. Laboratory stand LUW-2 for CWR with two flat wedges

In research works were used, specially designed and made for this purpose tools sets Fig. 3. The main element of the set is mounting plate, to which changeable wedges (knives) are fixed, these wedges differ between themselves depending on the value of the forming angle α (angles α = 30°, 40°, 50°, 60° were used). Additionally, due to the application of spacers placed under the wedges, the possibility of regulation of the reducing depth Δr was obtained. In the research the following reductions of depths was used Δr: 1.0 mm, 1.6 mm, 2.0 mm, 2.6 mm, 2.9 mm and 3.5 mm. The whole tools construction was complemented with squeezing plate which, apart the stability of the wedge position, allowed for the contact between the tool and workpiece outside the zone of the formed necking.

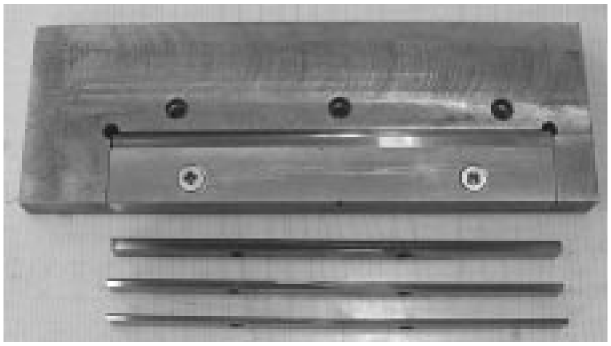

Fig. 3. Tool segment used in experimental research of CWR in cold forming conditions

In the laboratory tests, charges were used of dimensions Ø18 × 250 mm and made from steel C45 type. The flow curve of this steel, at room temperature, was determined by means of plastometric upsetting test on the basis of which the following constitutive equation of the analyzed type of steel was made:

$$\sigma_p = 1041,4\,\varphi_i^{0,201}, \tag{1}$$

where: σ_p – yield stress [MPa]; φ_i – effective strain.

In order to determine the friction conditions present during rolling of product from steel C45 at ambient temperature upsetting test of ring specimen was used. In research ring specimen were applied wit the following dimensions: external diameter d_{z0} = 12,0 mm, internal diameter d_{w0} = 6,4 mm, height h_0 = 6,1 mm. The specimens were upset to different height and the upsetting force was registered at the same time. On the basis of the made tests it was stated that the value of friction factor for friction pair tool steel – steel C45 was m = 0.45.

Rolling tests of V-groove were realized at the rolling tool spacing of 17.8 mm. In this rolling case, in accordance with the schema shown in Fig. 1b, apart from the rolled necking (groove), the bar external diameter was also sized. The research course was as follow. The specimen was placed in the rolling mill feeder. Next, in the special recess, made in the charge front surface, a gauge connected with angular displacement meter (of precision 0.144°) allowing for determining rotary speed of workpiece during rolling was implemented. After starting the rolling mill, the rolling process at given parameters and tools linear velocity v = 0.13 m/s was realized. After rolling, the workpiece was pulled out and the formed V-groove examined. Next, the tools were moved back and the test was repeated. The applied charges allowed for making on their circumference of 3 grooves – Fig. 4.

Fig. 4. Samples with V – grooves obtained in the CWR processes at: α = 50° and Δr = 1.0; 1.6; 2.0; 2.6 and 2.9 mm (from the top)

3. Numerical analysis basing on FEM

For the analysis of the process of rolling of V-groove the commercial software MSC.SuperForm 2005 was applied. Forming according to two cases, shown in Fig. 1, was calculated. In the simulations it was assumed that the grooves were rolled on bars from steel C45. It was also assumed that material model of the formed metal was described by equations (1). In the analysis thermo-mechanical schema of calculations was used assuming that the charge and tools temperature was equal ambient temperature 20°C. At the same time, it was assumed that the coefficient of heat exchange between tools and metal was 20 kW/m^{2}K, and between metal and environment 0.2 kW/m^{2}K. Because of the changes of friction force on the surface of contact between material and tool, in the simulation the model of constant friction dependant from slide velocity of metal (in correspondence wit tool) was used – according to the equation:

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

where: m – friction factor, v_p – slide velocity vector, a_p – coefficient a few orders smaller that slide velocity.

In order to shorter the calculation time in the analysis the following simplifications were assumed: rigid tools; lack of roundness of tools edges; constant friction factor on the surface of contact between material – tool. Moreover, because of the process symmetry, modelling was limited to the part of bar at the one side of wedge.

Considering the mentioned above simplifications a lot of FEM models of the process of V-groove rolling were worked out. Two of them are shown in Fig. 5. Each model consists of billet – bar of diameter Ø30 × 80 mm; symmetry plane and wedges upper and lower moving in the opposite directions. For modelling of bar eight-nods perpendicular elements were applied. Yet, on nods placed in the axis of rotary movement constrains removing movement possibility in the direction perpendicular to the bar axis were given. In Fig. 5 are shown also basic tools geometrical parameters. During calculations the following were changed: wedge lift angle γ (assumed γ = 1°, 2°, 3°, 4° and 5°), forming angle α (assumed α = 25°, 30°, 35°, 45° and 60°) and reduction ratio δ (δ = 1.1; 1.2; 1.3; 1.4 and 1.5, where $\delta = d_0/d$). At each process parameters (γ, α, δ) calculations were made two times assuming local (Fig. 5a) and widened on the bar's whole length (Fig. 5b) contact between the tool and metal. Moreover, numerous calculations were made in which the values of friction factor m were changed. Generally, about a hundred of cases of the rolling process of the V-groove on the bar were simulated.

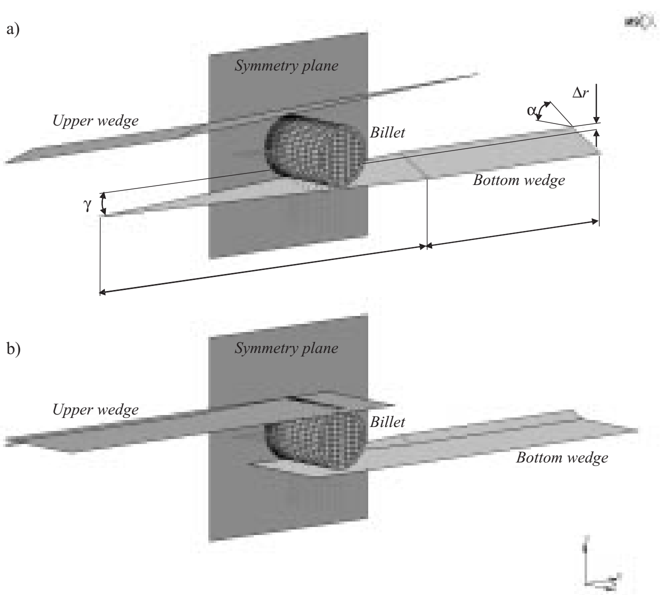

Fig. 5. The worked out FEM models of cross rolling processes of V-grooves on the workpiece circumference, in which there is presence of metal – tool: a) local; b) on whole width of the tool

In order to verify the worked out FEM of the CWR process of V-groove in cold forming conditions the distributions of forming force calculated and measured in experiments (Fig. 6) were compared. The comparison presented in Fig. 6 shows good qualitative and quantitative rightness between the forces courses – calculated and measured during experiments. This fact confirms the usefulness of FEM in modelling of complex processes of metal forming, which include CWR process of V-groove on the bar circumference in cold forming conditions.

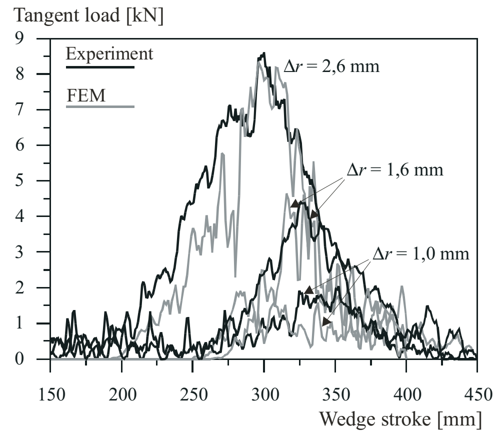

Fig. 6. Comparison of tangent forces (squeezing wedge) calculated by FEM and determined in experiments in the CWR processes when: $\alpha = 50°, \gamma = 1°, d_0$ = 18 mm, material – C45

4. Results of research

Due to the application of FEM it is possible to analyze kinematics of material flow during CWR of V-groove. In Fig. 7 is shown the progression of work-

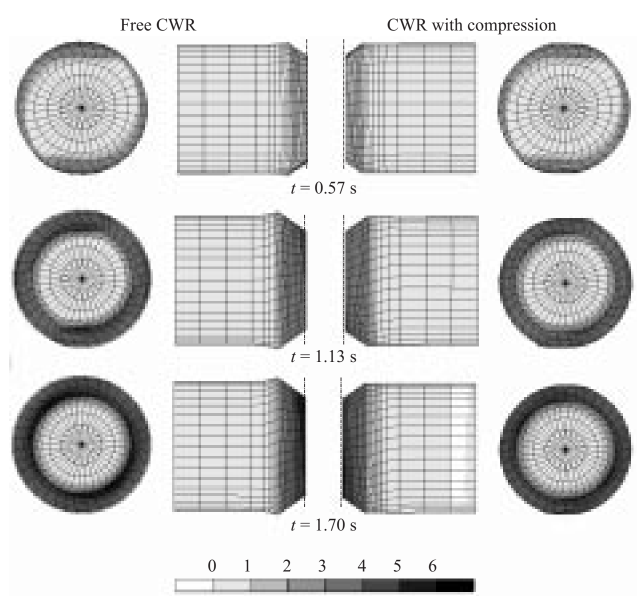

Fig. 7. Progression of shape and distribution of effective strain in parts rolled at: $\alpha = 35°, \gamma = 3°, \delta = 1,3, d_0$ = 30 mm and the time t given in the figure

piece shape in the CWR processes – free and with compression – realized at $\gamma = 3°, \alpha = 35°, \delta = 1.3$ and $d_0 = 30$ mm. From the data presented in this figure results that wedges squeeze into the workpiece making it into rotary movement. The material squeezed by the tools moves in the axial direction. At the same time, in the case of rolling by means of free wedges, a part of the metal is extruded at the wedge's side causing the local increase of workpiece diameter. Squeezing wedges into material also causes the ovalization of the workpiece cross-section, which increases together with the increase of the reduction depth value Δr. After the wedges cut into material on the desired depth, the sizing stage begins, during which ovalization is removed and the desired circular shape of the workpiece cross-section is obtained.

From the comparison of shapes of workpieces obtained in particular rolling schemata results that limiting metal flow outside (present in the CWR process with compression) leads to the increase of ovalization, which effective removal requires application of tools with longer sizing zones. At the same time, this workpiece is elongated in more even way than in the case of CWR free process. Such a conclusion confirms for example the distribution of material flow in the axial direction, determined for the workpiece longitudinal cross-section, shown in Fig. 8. Using the FEM method it is possible to analyze the state of strain in parts, in which, by means of CWR in cold forming conditions, ring shaped wedge groove was formed. From Fig. 7 results that strains in the groove zone have a laminar type distribution (in the form of rings). Yet, the largest strains are present in the external layers and they decrease in the direction of workpiece axis. Such a strain distribution is characteristic also for typical CWR processes, realized in the hot forming conditions.

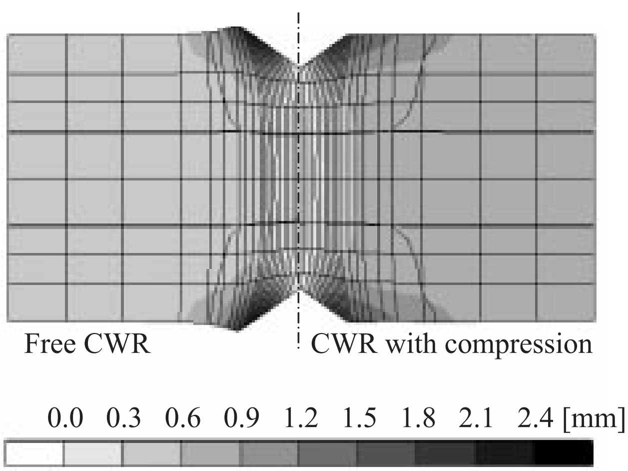

Fig. 8. Displacement of metal in axial direction in parts rolled at: $\alpha = 35°, \gamma = 3°, \delta = 1,3, d_0 = 30$ mm

Next figure shows distributions of effective strain φ_i determined in longitudinal cross-sections of parts rolled at various process parameters. On the basis of the analysis of strain distributions from Fig. 9, the influence of forming angle α and lift angle γ on the value of φ_i can be given. From this analysis results that the increase of angle α leads to a considerable decrease of deformed metal zone and decrease of maximal values of effective strain. Considering angle γ, it can be stated that its value does not influence the size of the strain zone. However, this parameter influences in a considerable way the values of maximal strains present in the workpiece surface layers, which decrease with the increase of γ. Considering the influence of the reduction ratio δ, it can be stated that the increase of this parameter leads to the increase of both strain zone and effective strain value. This is the effect of the increased material flow in the radial direction (in the effect of the increase of the wedge cutting depth) and tangent direction (caused by elongating of the wedge in the cutting zone).

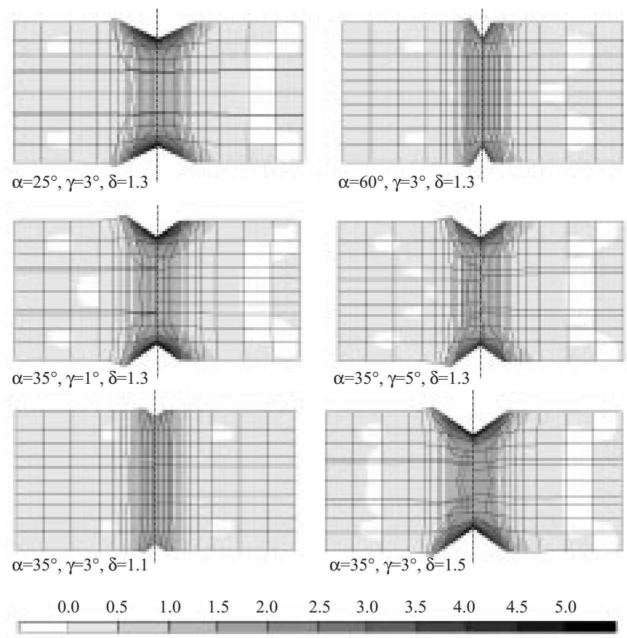

Fig. 9. Effective strain distribution in the longitudinal cross-section of parts formed in the CWR processes: free (at the left form symmetry axis) and with compression (at the right from symmetry axis), at d_0 = 30 mm and m = 0,9

During the rolling process large amount of heat produced in the result of deformation work and friction work are generated. In the results of this process, in the strain zone the metal temperature increases even of 300°C. In Fig. 10 are presented different temperature distributions in workpieces longitudinal cross-sections, on which V-groove is rolled. From the presented distributions it can be read that the largest temperatures are present in the area of the formed top of the groove. Moreover, it was stated that the size of the zone in which metal was heated depends on the CWR process parameters and increases together with the increase of reduction ratio δ. Considering the applied rolling method it can be said that in the CWR process with compression, the heated metal zone is larger than in the case of CWR free process. This is due to both increasing of strain zone size (in which deformation work is changed into heat) and elongating of material – toll contact zone outside the groove (where the friction forces are present). From the experimental research and numerical calculations, it can be noticed that during the CWR free process, material accumulating before the wedge is present; this can be seen in previous figures e.g. Fig. 9 and Fig. 10. In the result of this, the workpiece diameter increase from d_0 to d_n. The increase of the workpiece diameter leads to the increase of metal – tool contact zone, and, in consequence, to the increase of forming forces. The measure of this accumulating in the CWR process is coefficient of diameter increase ξ, defined as $\xi = d_n/d_0$. The coefficient ξ value was determined for the CWR process in hot forming conditions by the author [4] on the basis of the slip line fields method. In this solution it was considered ideal plastic model of the deformed material, which is, however, not acceptable in the case of forming in the cold forming conditions.

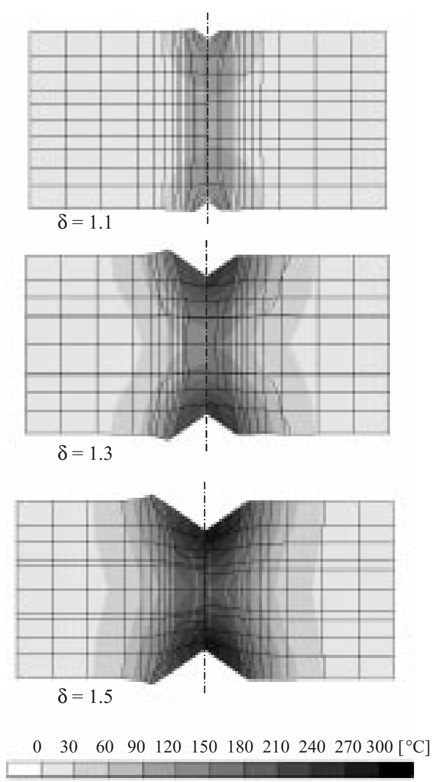

Fig. 10. Temperature distributions in the longitudinal cross-section of parts formed in the CWR processes: free (at the left form symmetry axis) and with compression (at the right from symmetry axis), at d_0 = 30 mm and m = 0,9

On the basis of numerical simulations of the CWR free process, within the scope of this work, the analysis of the workpiece diameter increase phenomenon was made. On the basis of calculations, the quantitative evaluation of influence of the rolling process basic parameters (γ, α, δ) on the final value of diameter increase coefficient ξ is presented – Fig. 11. From the analysis it results that at the assumed reduction ratio δ, the decisive influence on the coefficient ξ has the value of the applied forming angle α.

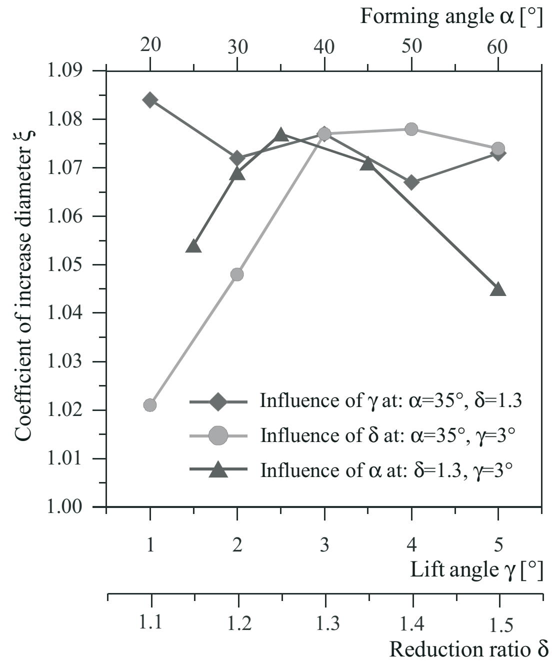

Fig. 11. Calculated by means of FEM the influence of wedge angles (α, γ) and reduction ratio δ on the increase of diameter of parts formed in free CWR at d_0 = 30 mm and m = 0,9

Forces in the process of V-groove rolling are decomposed on 3 components: tangent F_x, radial F_z (forming) and axial F_y – according to Fig. 12. During rolling processes, made in the laboratory rolling mill LUW – 2, components F_x and F_z of rolling force were measured. In Fig. 13 and Fig. 14 are shown registered distributions of these forces in the function of forming angle α and wedge displacement. From the data in Fig. 13, it results that the tangent force increases gradually in the wedge cutting zone (mainly due to the increase of reduction depth Δr), and has maximal values at the border of sizing and cutting zones. Next, the force F_x rapidly decreases in the sizing zone, which is caused by gradual removal of the cross-section ovalization. The character of the radial force F_z course (Fig. 14) in a considerable way differs from the distributions of tangent force F_x at the beginning of rolling. The force F_z oscillates within the range of 4÷15 kN before the workpiece contacts with the wedge. This is due to rotational compression of the workpiece external surface by the mounting plates.

The observed oscillations are the effect of the errors of the rolled bar shape, constituting charge, which has no ideal circular section. In the further stages of the CWR process, the distribution of radial force is analogical to the distribution registered for tangent force.

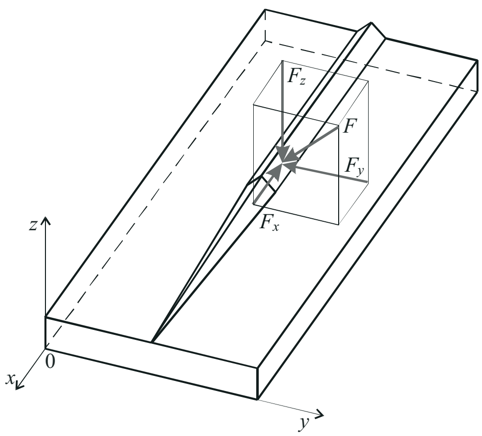

Fig. 12. Decomposition of force F influencing the wedge during CWR process of V- groove on components

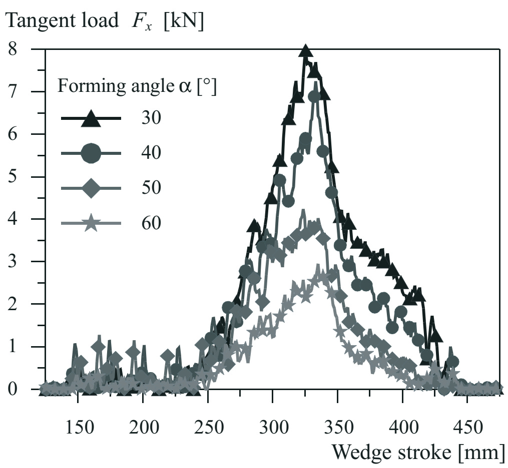

Fig. 13. Distributions of tangent force F_x measured in CWR with compression at: Δr = 2 mm, γ = 1°, d_0 = 17.8 mm

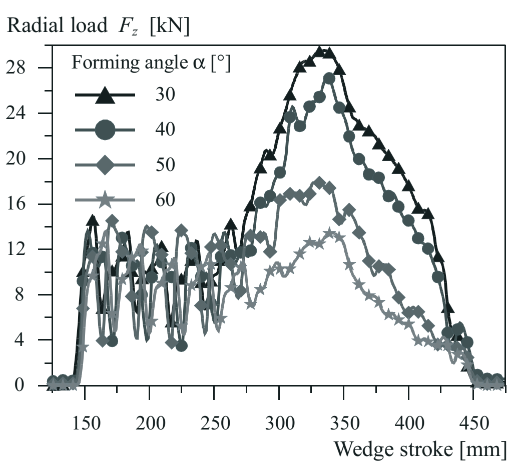

Fig. 14. Distributions of radial force F_z measured in CWR with compression at: Δr = 2 mm, γ = 1°, d_0 = 17.8 mm

From the F_x and F_z courses shown in Fig. 13 and Fig. 14, their dependencies on the forming angle α can be concluded. It can be also stated that the increase of angle α is connected with the decrease of forming forces, which is mainly the result of decrease of material – tool contact surface.

The further Fig. 15 and Fig. 16 illustrate the reduction depth Δr influence (reduction ratio $\delta = r_0/(r_0 - \Delta r)$) on components F_x and F_z of rolling force. Presented on those figures forces courses are very similar to those noticed in the processes realized at constant Δr and different α (Fig. 13 and Fig. 14). As it was expected, the increase of reduction value leads to a considerable increase of components F_x and F_z of rolling force.

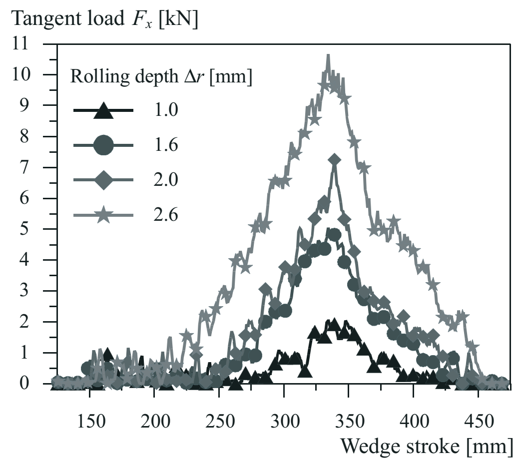

Fig. 15. Distributions of tangent force F_x measured in CWR with compression at: α = 40°, γ = 1°, d_0 = 17.8 mm

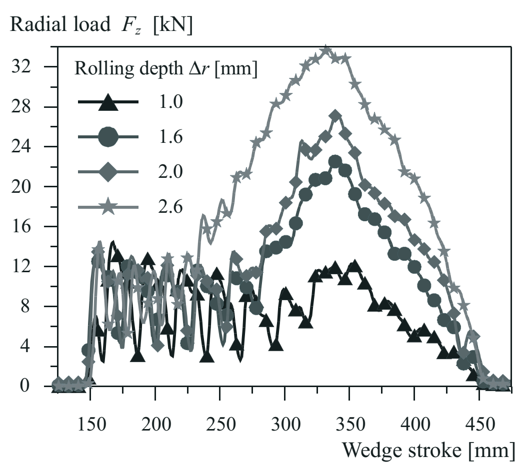

Fig. 16. Distributions of radial force F_z measured in CWR with compression at: α = 40°, γ = 1°, d_0 = 17.8 mm

The stability of the CWR process in cold forming conditions may be disturbed in the result of the presence of uncontrolled slipping or breaking of the rolled part. The uncontrolled slipping is present when the sum of moments of forces favorable to the formed workpiece rotation is smaller than the sum of moment of forces inverse to that rotation. In this case the workpiece loses the ability to rotary movement and the wedges moving in plane motion form two separate flat grooves. The main parameter deciding about the possibility of slipping presence is friction factor m on the metal – tool surface of contact. In order to determine the minimal (limiting) value, at which this process could run in a stable way, a lot of numerical simulations were made. In calculations the geometric dimension of the wedge tool were changed (forming angle α within the scope of 20° ÷ 60°, lift angle γ within the scope of 0.5° ÷ 5°). For each pair of angles α and γ, calculations were repeated many times changing the friction factor m on the metal – tool contact surface. In the result of calculations, the rotary speed ω of workpiece and the shape of its cross-section surface were determined. It was stated that the decrease of factor m was connected with the decrease of the workpiece rotary speed. Because of that, difficulties in the ovalization removal appeared. In extreme conditions the workpiece loses its possibility to rotary movement, the wedge slides on its surface and the wedge groove is formed only on the part of bar circumference. The limiting value of friction factor m_{gr}, at which the uncontrolled slipping was not present was determined in arbitral way (with the precision of up to 0.01) in further iterations. The numerical analysis was made for the two chosen CWR schemata, that is free and with compression.

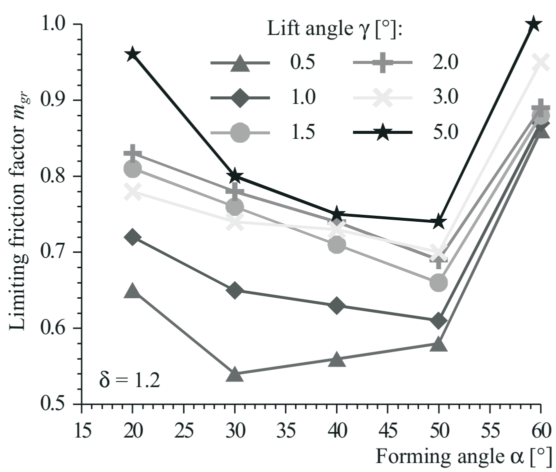

Fig. 17. Calculated by FEM dependency of limiting values m_{gr} of friction factor on wedge angles (α and γ) in the free CWR process at δ = 1.2

In Fig. 17 are presented limiting values of friction factor m_{gr} calculated numerically depending on wedges angular parameters α and γ. The given comparison concerns the CWR free process. On the basis of data shown in this figure, it can be stated that the decrease of lift angle γ favors more stable (due to the uncontrolled slipping) course of the CWR process, which is however connected with the wedge elongating. Moreover, it is noticed that the application of forming angles α within the range of 30° – 50° also results in the decrease of probability of the discussed disturbance presence. It should be noted that the tool angular parameter (α and γ) should be chosen in such a way that the friction factor m for the friction pair metal – tool is bigger than the value m_{gr} relevant to this pair of angles.

More stable, in case of the uncontrolled slipping presence, is the CWR process with compression. It is because of favorable influence of additional friction forces present on the workpiece external surface (outside the zone of the formed groove) and helping in its rotation. This is confirmed by diagrams of limiting values of friction factor (calculated at the same forming parameters as in the discussed earlier free CWR) shown in Fig. 18. On the basis of data present in these diagrams it is stated that the change of the CWR schema caused that the limiting values of friction factor needed for the process realization were lower than the values present in the typical friction pairs. This is confirmed by the fact that during rolling tests of grooves on bars from steel C45 (running at m = 0.45) there was no single case of disturbances in the form of uncontrolled slipping.

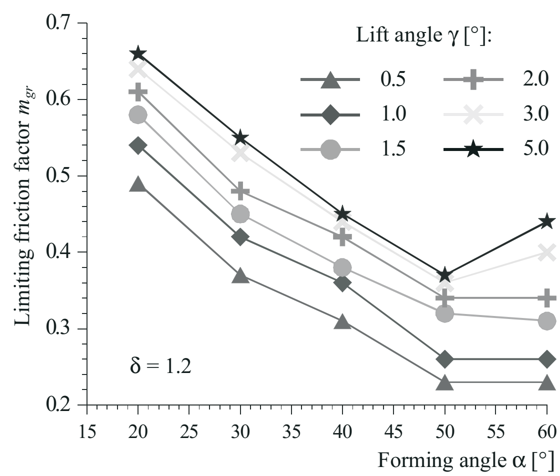

Fig. 18. Calculated by FEM dependency of limiting values m_{gr} of friction factor on wedge angles (α and γ) in the CWR process with compression at δ = 1.2

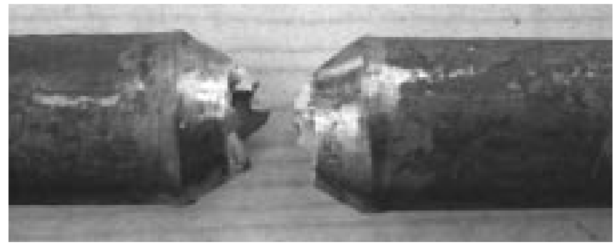

Fig. 19. Breaking of the rolled part at: α = 40°, γ = 1°, Δr = 3,5 mm, d_0 = 17,8 mm

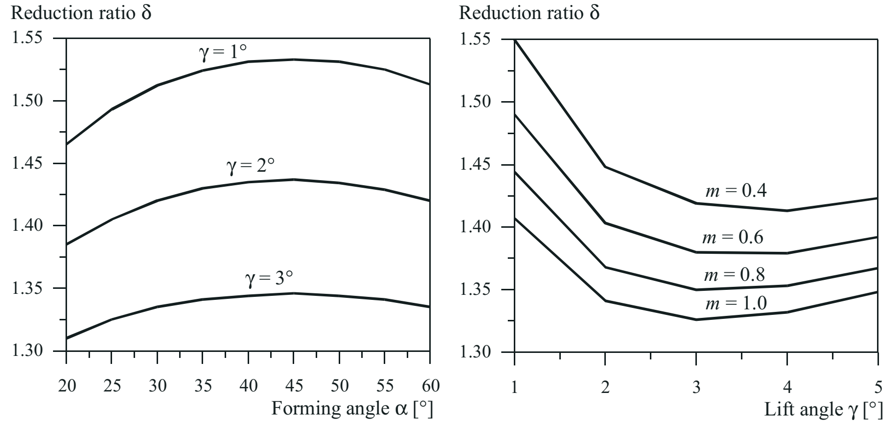

Fig. 20. Maximal values of reduction ratio δ, calculated from the breaking condition equation of bar from steel C45

Break of rolled workpiece is present when the tensile stresses in the direction of the workpiece axis (caused by the axial rolling force component) have the limiting value equal the cohesion strength [4]. The example of a workpiece broken in the CWR process with compression is shown in Fig. 19.

Considering the conditions in which axial stresses did not exceed the cohesion strength, the limiting values of reductions were calculated, in the CWR process of bars from steel C45 shown in Fig. 20. From this figure results the increase of the lift angle γ and friction factor m causes a considerable increase of tensile axial stresses. However, the influence of the forming angle α on the workpiece breaking is not so important, yet, the best forming conditions are obtained for α = 45°.

5. Summary

On the basis of calculations and experimental research it was stated as follow:

1. using the CWR method in cold forming conditions, a V-groove on the bar circumference can be formed;
2. the rolling process can be made in two ways: by means of the free CWR (contact between tools and metal is only in the area of the formed groove) and using the CWR method with compression (contact between tool and metal is on the workpiece whole length);
3. strains in the groove zone are of laminar character (in the form of rings) and reach maximal values in the external layers;
4. during free CWR, the metal is partially accumulated before the wedge leading to the increase of the rolled part diameter – the increase diameter depends on the applied forming angle α;
5. forming forces value depends on the CWR process parameters, forces undergo decreasing together with the application of larger angles α and smaller reduction ratio δ;
6. stability of the CWR process can be limited in the result of presence of uncontrolled slipping or breaking of the rolled part – the best forming conditions, due to the avoiding the mentioned above disturbances, are present when applying tools with forming angle α = 45°.

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