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THE ANALYSIS OF THE STATE OF STRAIN IN PARTS FORMED BY MEANS OF THE WEDGE-ROLLS ROLLING (WRR)

ANALIZA STANU ODKSZTAŁCENIA W WYROBACH KSZTAŁTOWANYCH METODĄ WALCOWANIA KLINOWO-ROLKOWEGO (WKR)

In this paper a new method of cross — wedge rolling (CWR) was characterized. This method was named wedge — rolls rolling (WRR). Comparing with other CWR method, in WRR process only one forming wedge and two rolls supporting the workpiece during rolling are used. Depending on the applied tools geometry six schemata of WRR were distinguished. These schemata were compared with each other on the basis of the analysis of forming of shaft with a single necking. The theoretical calculations show that the best results are obtained when the profiled rolls and wedge permitting the contact with the formed part on whole length are used. In the further part of this paper the influence of wedge angles (forming angle α and spreading angle β) and rolling depth Δr on rolling, especially on strains distributions in formed parts is presented. In this paper the possibility of final forming with the WRR method of a part of ball pin type, rolled in double system, was also analyzed.

W opracowaniu scharakteryzowano nową metodę walcowania poprzeczno-klinowego (WPK), którą nazwano walcowaniem klinowo-rolkowym (WKR). W procesie tym w odróżnieniu od dotychczas znanych metod WPK wykorzystuje się tylko jeden klin kształtujący oraz dwie rolki podtrzymujące wyrób w trakcie walcowania. W zależności od geometrii stosowanych narzędzi wyróżniono sześć schematów WKR, których porównania dokonano analizując przykład kształtowania wałka z pojedynczym przewężeniem. Na podstawie obliczeń teoretycznych stwierdzono, że najlepsze rezultaty uzyskuje się stosując rolki profilowe oraz klin zabezpieczający kontakt z kształtowanym wyrobem na całej jego długości. W dalszej części opracowania przedstawiono wpływ kątów klina tj. kształtującego α i rozwarcia β oraz gniotu bezwzględnego Δr na przebieg walcowania, a w szczególności na rozkład odkształceń uzyskiwanych w wyrobach walcowanych. W artykule przeanalizowano również możliwość kształtowania na gotowo, metodą WKR, odkuwki typu sworzeń kulisty walcowanej w układzie podwójnym.

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1. Introduction

Cross wedge rolling (CWR) is a modern forming process used mainly in manufacturing axi – symmetrical products of stepped axes and shafts type. Main advantages of this forming method, comparing with other forming technologies, include: high productivity, better making use of material, higher mechanical characteristics, simplicity of automatization, lower consumption of energy. This forming method is also environment friendly.

Although, the CWR method has many advantages it is not widely applied in manufacturing realities, mainly because of the difficulties connected with wedge tools designing. These tools should guarantee stability of the rolling of products with assumed quality. The users of rolling mills for CWR processes recommended mill manufacturer designing of tools necessary for activating the production of new product. Such a solution increases the costs of implementation and it makes difficult widening of this interesting technology on new fields of application. In order to improve this situation, numerical simulations are taken into consideration. Thanks to the complex calculations (made by means of the finite element method — FEM) it is possible to check the correctness of the designed CWR variant. Moreover, numerical modelling can be also used for searching of new CWR method e.g. such methods which application would be economically justified in small serie manufacturing conditions.

At present, in industrial conditions five schemata of CWR (Fig. 1) are used [1-2]. In these schemata two or three wedges mounted on rolls or flat or concave rolling mill plates are used. Because of the tools dimensions (which length sometimes exceed 2 m) the cost of their manufacturing is decisive when the size of minimal series guaranteeing profitable production is taken into consideration.

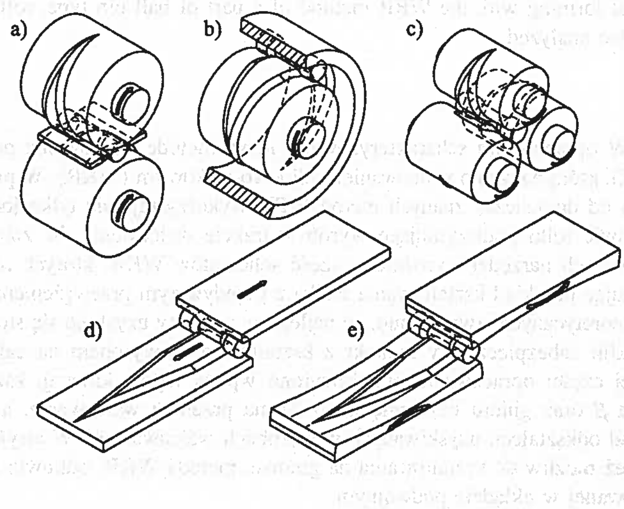

Fig. 1. Used in the industry cross — wedge rolling in systems: a) two rolls, b) roll — concave wedge segment, c) three rolls, d) two flat wedges, e) two concave wedges

The lowest costs of implementation are present in the CWR process with two flat wedges, where tolls manufacturing is made easier and where the production is profitable at medium series. Further lowering of costs is probable to obtain applying the rolling method in which only one tool wedge is used. Such a forming method, worked out by the author, was called wedge — rolls rolling (WRR) method.

In the current paper, the description of the WRR technology, probable to use schemata of this process and problems of state strain in the rolled parts are discussed.

2. Short characteristic of Wedge — Rolls Rolling (WRR)

The wedge — rolls rolling is based on forming of axi — symmetrical shafts by means of only one wedge (Fig. 2). In this process the charge is placed on the two

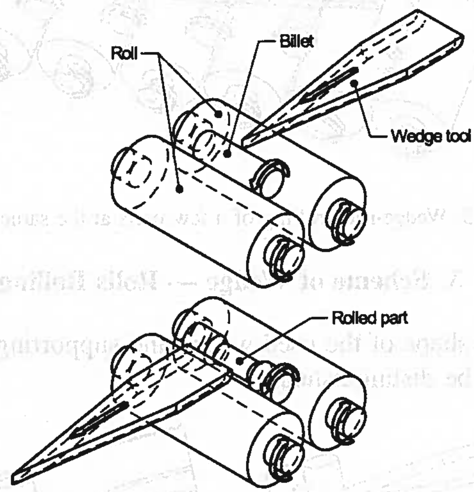

Fig. 2. Schema of the wedge-rolls rolling (WRR)

driving rolls moving in the opposite direction to the advancing wedge. During forming the wedge knifing the material gives it the desire shape. Comparing with the applied until now CWR method, wedge — rolls rolling has many advantages, these include:

- L o w e r   c o s t s   o f   i m p l e m e n t a t i o n. This process requires the application of only one flat wedge, the costs of implementation of this technology are considerably lower than in the most effective CWR method and it becomes economically justified even in low series manufacturing conditions.
- L o w e r   t e n d e n c y   t o   t h e   a p p e a r a n c e   o f   i n t e r n a l   c r a c k s   i n   t h e   r o l l e d   p a r t s. It is assumed that material cracking often present in the CWR processes in the axial zone of the workpiece is the effect of cyclically changing sign of stresses (from negative stresses to positive, from positive to negative, etc.) which leads to the presence of fatigue cracks. The application of three forming

tools (one wedge and two rolls) results in changing the stress distribution, which is close to that appearing in the forming process with three wedge-rolls, where axial cracks are almost absent.

- **Easier elimination of scale.** During the WRR process in hot condition, the scale falls (gravitationally) between rolls and is not present on the lower wedge surface, as it is in the flat CWR processes.
- **Higher productivity.** Extending the wedge stroke and adding other rolls (according to the Fig. 3) by means of WRR method it will be possible to form a few or even more products at the same time.

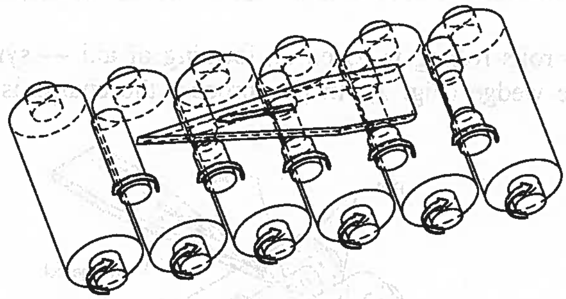

Fig. 3. Wedge-rolls rolling of a few parts at the same time

3. Scheme of Wedge — Rolls Rolling

Depending on the shape of the used wedge and supporting rolls such schemata of the WRR process can be distinguished.

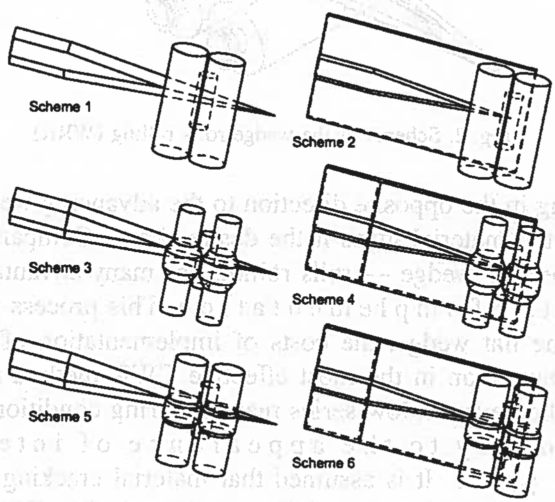

Fig. 4. Considered due to the applied tools shape scheme of the WRR

- Scheme 1 — Fig. 4a. Wedge — rolls rolling on smooth rolls with the wedge, which design allows for the contact between tool and material only at the length of the formed necking. Rolls contact the rolled workpiece only on the external surface (which is the same as the charge diameter) outside the necking zone.
- Scheme 2 — Fig. 4b. In this process the wedge allowing for the contact with the formed part on its whole length is used. Driving rolls, identically as in the schema 1, contact material only outside the forming zone.
- Scheme 3 — Fig. 4c. In this case of WRR the wedge and profiled rolls allowing for contact with the material only on the length of the formed necking. The other steps of workpiece have free surfaces without contact with tools surfaces.
- Scheme 4 — Fig. 4d. In the WRR process realized accordingly to that scheme profiled rolls (of identical shape in the scheme 3) and the wedge contacting the workpiece on its whole length are used.
- Scheme 5 — Fig. 4e. In this case of the WRR process the wedge identical as in the scheme 3 is used. This wedge contacts the material only in the zone of the formed necking. However, the rolls design allows (after the whole squeezing of material filling the rolls profile) for influencing the formed workpiece on its whole length.
- Scheme 6 — Fig. 4f. This case of WRR is realized using the wedge from the scheme 4 and the rolls from the scheme 5. Assuming such tools allows for favorable influence on the formed workpiece (from 3 sides) on its whole length.

In order to calculate the possibilities of practical application of the chosen WRR scheme numerical simulations of the wedge rolling process, with the geometry shown in Fig. 5 were made. In the calculations made by means of the FEM method it was assumed

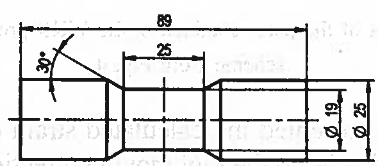

Fig. 5. The shaft used in the contrastive analysis of the six scheme of the WRR process

that wedges move with the velocity of 0.12 m/s and rolls move with such an angular velocity that their linear velocity is the same as the wedge one. It was also assumed that all wedges have the same angles that is spreading angle β=5° and forming angle α=30°. Moreover, it was assumed that the formed shaft is made of commercially pure lead, for which the flow curve is described by the equation [3]:

$$\sigma_p = 25,35\varepsilon^{0,249}\dot{\varepsilon}^{0,065}, \tag{1}$$

where: σ_p — yield stress, ε — strain $\dot{\varepsilon}$ — strain rate.

In the calculation friction model depending on slipping velocity and the limiting value of the friction coefficient m = 1 were assumed. It should be noticed that such a choice of the WRR process parameters was connected with the planned (in near future) to realize laboratory tests of rolling.

Thanks to the application of FEM it was possible to compare the shape of parts formed in the WRR processes realized according to the given schemata. In Fig. 6 the obtained parts in three projections are shown: with the same direction as the wedge moving direction (upper Figure), direction perpendicular to the plane coming through rolls longitudinal axes (bottom Figure) and direction parallel to rolls axes (side Figure).

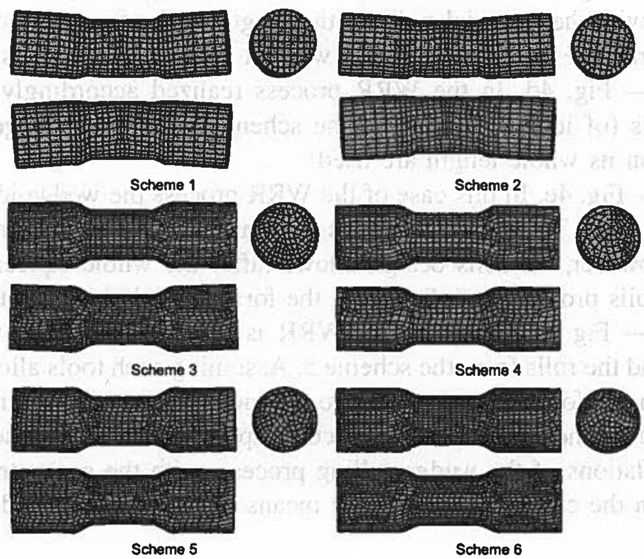

Fig. 6. The expected FEM shapes of the parts obtained in the WRR processes, obtained according to the scheme from Fig. 4

However in Fig. 7 are presented the calculated strain distributions in the parts in longitudinal plane (perpendicular to the tool moving direction and spreading symmetrically rolls) and cross plane (covering with the wedge symmetry plane) correspondingly.

On the basis of data from calculations it is stated that in the WRR processes on smooth rolls (schemata 1 and 2) the workpiece undergoes the undesired bending. It is the result of the displacement of opposite forces influencing the material (the wedge presses in the zone of medium necking while rolls press the extreme parts of the workpiece). This leads to the appearance of bending moment resulting in the undesired deformity of the part. Moreover, it was observed that the medium, necked part of the workpiece undergoes the displacement in the tangent direction. In consequence, apart from bending there appears eccentric displacement of the formed necking in relation to the obtaining of the necking diameter much bigger than it was planned.

As it was expected, the use of the profiled rolls in a considerable way increases the quality of products. This happens because the rolls protrusion prevent the tangent displacement of the necked zone of workpiece, limiting the possibility of the eccentric

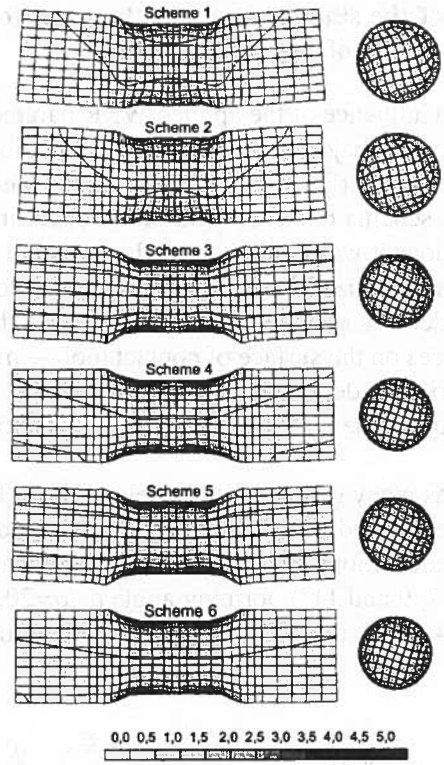

Fig. 7. Distribution of strains in the rolled parts obtained at analyzed scheme of the WRR process

distribution of the separated steps of parts. However, in the cases where the wedge contacted with the shaft only on the length of the formed necking (used scheme 3 and 5), the axial bending of the workpiece was still present. The shape of the part cross — cut was far from the desired circular shape with the diameter of 19 mm. Satisfactory results are obtained only when schemata 4 and 6 are used (in which the profiled rolls and the wedge guaranteeing the contact with the material on the whole length of the part are applied).

From Fig. 7, in which the distributions of strain in the formed parts are shown, it results that strains are distributed in a linear way, which is characteristic for the CWR processes [4-5]. The greatest strains are localized in the external zones of the formed necking while the smallest strains appear in the axial zones. Moreover, on the basis of calculations it is stated that in the forming processes with smooth rolls strains have lover values in comparison with rolling with the profiled rolls. It is assumed that the lower material flow in the tangent direction (circumferential), characteristic for the cross — wedge rolling process, is appearance of lower strains during rolling on smooth rolls.

4. The analysis of the state of strain in the parts formed by means of the WRR method

In order to define the influence of the applied WRR parameters on the distributions of strains in the formed parts, majority of numerical calculations were made, using the commercial software MSC.SuperForm 2004. Calculations were made for the forming process according to the schema 6, which guarantees obtaining final parts of the best precision. In the calculations it was assumed that the parts are rolled from steel of C45 type and that the process is realized in the isothermal conditions with the temperature T=1100°C. Material model was assumed from the library of the used software. Due to the change of friction forces on the surface of contact tool — material, in the simulation the model of constant friction depending on velocity of the metal slip in relation to the toll. It was at the same time stated that the friction factor has the limiting value m=1.0 [6].

For the analysis needs many geometrical models of the WRR process (one of them is shown in Fig. 8) were worked out. In the Fig. 8 basic geometrical parameters are also given. During the calculations such parameters were changed: spreading angle β (assumed values β=3, 5, 7, 9 and 11°), forming angle α (α=20, 25, 30, 35 and 40°) and rolling depth Δr = 2, 3, 4 and 5 mm. Taking into consideration, 100 cases of forming were analyzed.

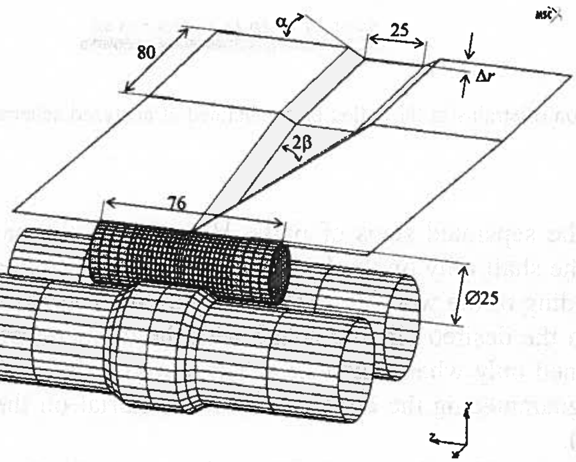

Fig. 8. Geometrical model of the WRR process used in the FEM calculations at estimating the influence of the process parameters on the strain distributions obtained in the products

During the analysis of the influence of the angle α (Fig. 9) on strain distributions obtained in the parts, formed by means of WRR method, it was stated that lowering the value of forming angle α increases in a considerable way the strain zone in the rolled workpiece. This fact results from the increasing influence of tools on material. The comparison of strains in the cylindrical zone of the formed necking does not show significant differences. In all cases maximal strains are present near the tools corners and their maximal values are similar. The biggest strain was noted for the WRR case when α=20° and the lowest was for α=25°. However, the differences in values of those strains is lower than 6%. Interesting conclusions can be drawn from the comparison of strains distributions obtained for the cross cuts of the formed necking. These distributions have the form of rings which course is more regular (concentric) when the applied angle α has low value. Hence, lowering tools forming angles α in the WRR processes allows for the stability of the rolling process.

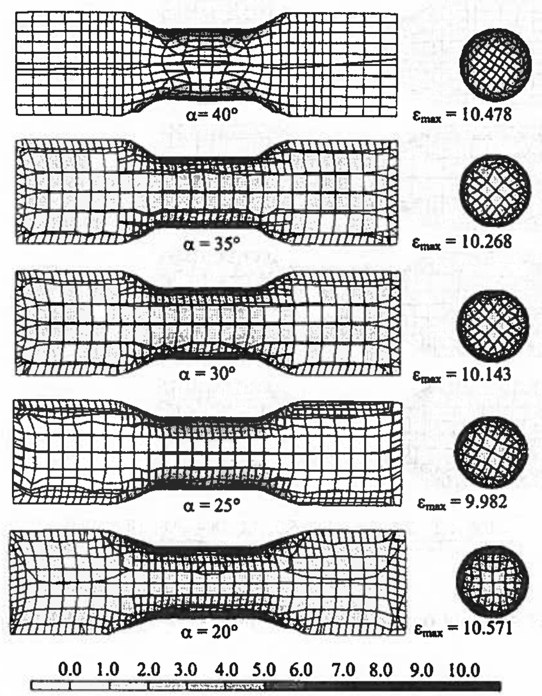

Fig. 9. Calculated strains distributions in the parts rolled with use of WRR when β = 7°, Δr = 4 mm

In Fig. 10 strain distributions for the WRR processes realized at α=30°, Δr = 4 mm and β with the range of (3÷11)° are presented. The comparison of the obtained results shows strong dependency between β angle and the obtained values of strains. It was stated that lowering the angle β from the value 11° to the value 3° resulted in increasing of strains at about 75%. This increase was caused by making greater the length of forming wedge which led to the bigger material flow in the tangent direction. In consequences the redundant strains were increasing and the consumption of energy was also bigger. As it results for the Fig. 10 the change of the angle β value (in the analyzed scope) did not cause significant differences of the obtained shapes of the necking. Hence, while designing the WRR processes maximal values of angle β guaranteeing the stability of the rolling process should be assumed. Such an attitude will allow to minimize the wedge dimensions, to shorter the time of forming and minimize the energy consumption.

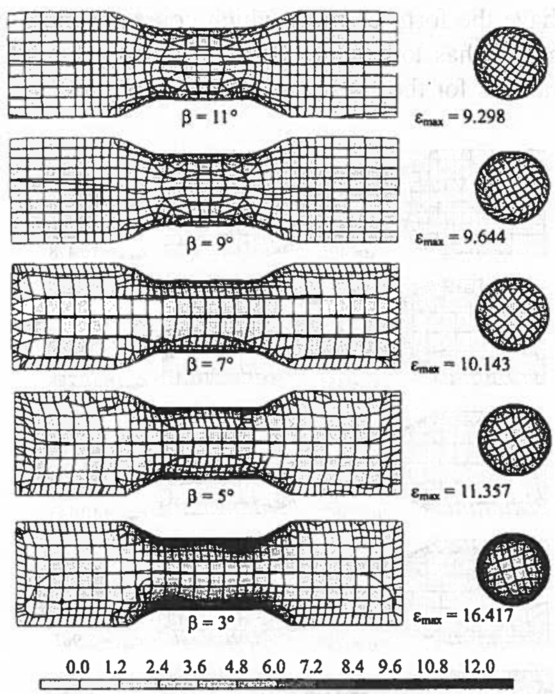

Fig. 10. Calculated strains distributions in the parts rolled with use of WRR when α = 30°, Δr = 4 mm

In Fig. 11 are presented the distribution of strains calculated for the workpieces rolled when: $\alpha = 30°$ $\beta = 7°$ and changing Δr from 2 to 5 mm. As it was expected, increasing the rolling reduction ratio resulted in bigger values of strains in the rolled parts. Fig. 11 shows that a sample rolled when Δr = 5 mm was formed not only on a length of necking but also out of necking. This was caused by rapid cutting of the wedge into material and pressing this wedge to the rolls which formed the workpiece on its whole length. Because of this disturbance the desired circular shape of necking was not obtained for this case of rolling.

Properly formed necking with the assumed parameters ($\alpha = 30°$, Δr = 5 mm) requires application of the wedge which will cut into material in a less rapid way. It can be obtained by lowering the spreading angle β. This way of thinking can be confirmed by strains distributions obtained for the WRR cases when α=30°, Δr = 5 mm, β=5° and β=3° (shown in Fig. 12).

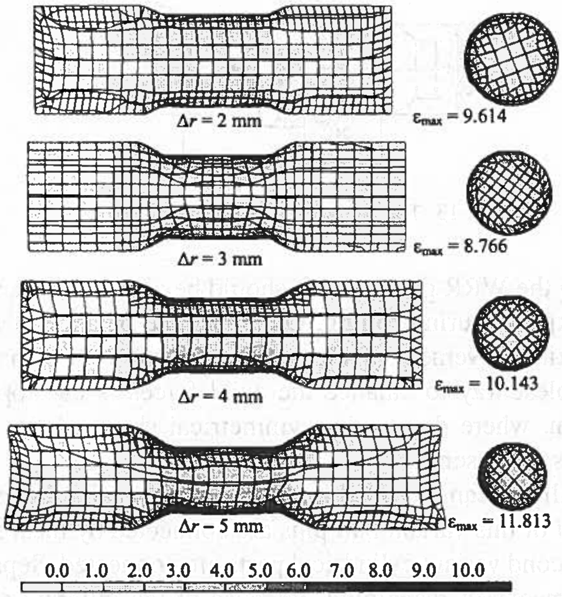

Fig. 11. Calculated strains distributions in the parts rolled with use of WRR when $\alpha = 30°$, $\beta = 7°$

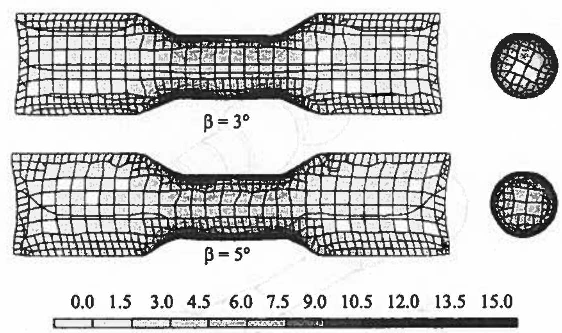

Fig. 12. Calculated strains distributions in the parts rolled with use of WRR when $\alpha = 30°$, $\Delta r = 5$ mm

5. The analysis of the WRR process of the part of ball-pin type

The presented above results of the analysis concerned the simple forming cases in which shafts with the single necking were rolled. Applying the WRR processes for manufacturing parts with such a simple shape would limit the area of application of this interesting technology only to the preforms forming. In order to prove that this method may be also used in rolling of parts of more complex shapes, the analysis of forming process by means of the WRR method of ball-pin (shown in Fig. 13) was made.

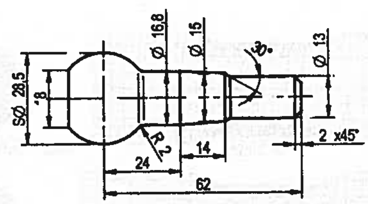

Fig. 13. The analyzed part of ball pin type

While designing the WRR processes, it should be aimed to balance the axial forces influencing the workpiece during rolling. Obtaining the balance of the forces protects against undesired axial movement of the workpiece and it also increase the stability of rolling. The simplest way to balance the axial forces is the application of rolling in the double system, where due to the symmetrical shape of the final products the equilibrium of forces is present.

The analyzed ball-pin can be rolled in double system using the two variants shown in Fig. 14. In the first of this variant ball pins are connected by means of ball — shaped parts, while in the second variant cylindrical parts are connected. Separating of ball pins will be realized by means of machining. Because of the different shapes of ball pins parts obtained in the particular variants for their forming tools of different geometry are needed.

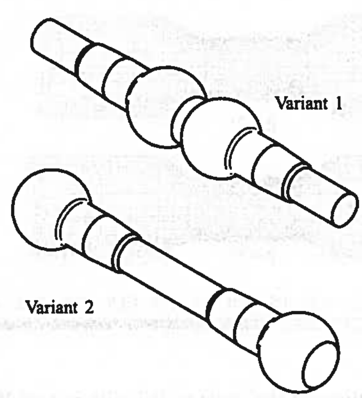

Fig. 14. Possible to apply variants of WRR of ball-pins formed in double system

Yet, the shape of rolls depends on the part geometry. More complex shape have forming wedges shown in Fig. 15. These wedges consists of four zones: knifing, forming, sizing and output. A characteristic feature for the WRR processes is the gradual lowering of the wedge working surfaces at the length of the first two zones. It is connected with the compensation for the change of position (vertical) of the workpiece during forming which results from the gradual squeezing of material into the rolls protrusions. In the second variant the wedge has stopping battens which limit the longitudinal flow (axial) of material. This in consequence leads to forming of ball parts.

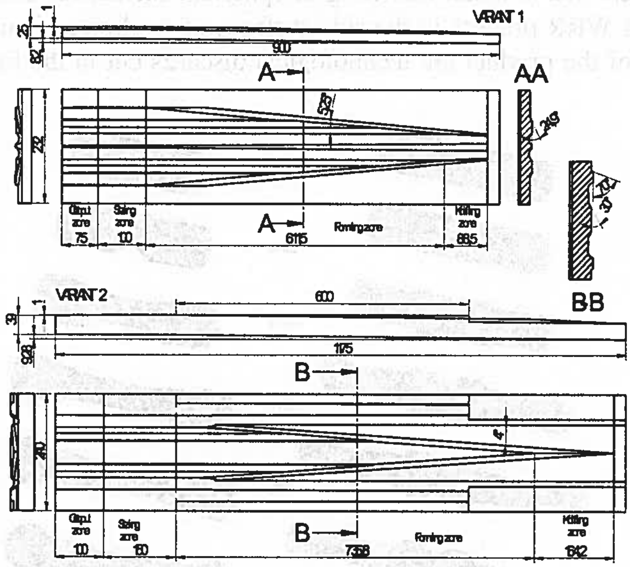

Fig. 15. Geometry of forming wedges designed for realization of the WRR processes of ball pins rolled in double system

In order to check the possibility of ball-pins forming numerical simulations for both proposed variants of rolling were made. It was assumed that the wedge moves with the velocity of 0.4 m/s. It was assumed that cylindrical bars with dimensions ⌀24×100 and ⌀26×80 mm were used as charge for the first and the second variants of forming considerably. In the calculations it was assumed that material used for forming parts is steel C45. Material model for this steel was taken from the library of the software MSC.SuperForm 2004. It was assumed that the charge before rolling is heated to 1100°C and that all tools have the same temperature 150°C. The rest of the parameters include: coefficient of heat transfer between workpiece and tools — 10000 W/m^{2}K, coefficient of heat transfer between workpiece and environment — 350 W/m^{2}K and the temperature of the environment 30°C. In the calculation constant friction model was used. This model depends on slip velocity of metal in relation to tool, the assumed limiting value of friction factor — m=1. Thanks to the conducted calculations with the use of FEM method, it is possible to analyze precisely the changes of the workpiece shape during the WRR process. In Fig. 16a the progression of shape of workpiece rolled according to the first variant is shown, and in Fig. 16b the progression of shape of workpiece rolled according to the second variant is present. The analysis of the data in this figure shows that in case of rolling according to the first variant in the first two phases of the process (that is knifing and forming) the wedge forms the material in three places at the same time. The advantage of such rolling is shortening of the wedge length. In this variant of WRR ball parts are formed in the last phases of the process. However, it is stated that the shape of the formed balls is slightly different from the expected one. A small flattening of spherical surfaces is obtained. Moreover, in this variant of WRR process in the side surfaces of workpiece funnels were formed and these parts of the product are technological discards cut in the further machining.

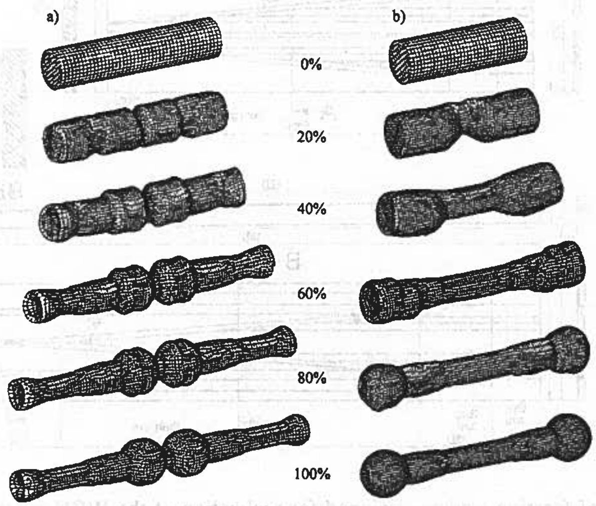

Fig. 16. Calculated progression of shape of parts rolled according to: a) variant 1, b) variant 2

During the WRR process according to the second variant the wedge cuts into the charge only in one place, gradually reducing its diameter. Next, on the length of forming zone this reduction is spirally developed to the required width. At the beginning the free flow of material in the axial direction is limited when the side surfaces of the workpiece contact the wedge side stopping battens. In the result of the battens influence ball parts of the pins are formed. It should be noticed that the obtained in this variant shape of the ball parts is approved without any doubts.

Using the FEM method it is also possible to analyze precisely the changes of the state of strain taking place in the WRR process. The analysis of the data in Fig. 17 and Fig. 18 shows that strains have laminar distribution. Yet, the biggest value of strains represent in the external layers and decrease in towards the central zone of rolled part. In the case of localization of the maximal strains it is stated that they appear in the conical part of the workpiece. However, the material is the least deformed in its ball part. The above remarks are correct for both analyzed variants of the WRR process.

Comparing the numerical values form both analyzed WRR processes it is stated that bigger value of strains (at about 30%) appear at the second rolling variant. This results from the application in this process a longer wedge (at about 30%) than the first case. Although the strains are bigger in the second variant of the WRR process of ball-pins, this variant is more profitable from the practical point of view. This case

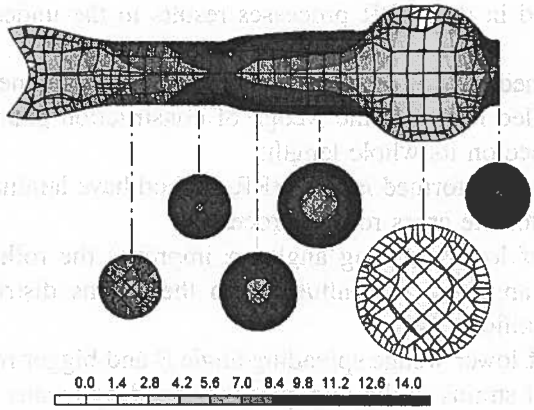

Fig. 17. Calculated strains distributions in the part rolled according to variant 1

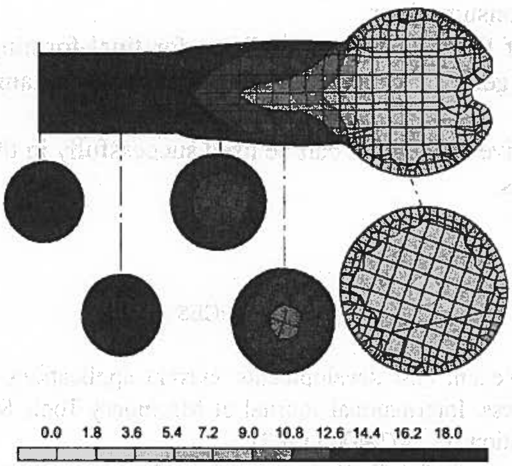

Fig. 18. Calculated strains distributions in the part rolled according to variant 2

consumes less material because of the lack of technological discards which are present in the first variant and which are connected with removing of the workpieces ends with the formed funnels.

6. Conclusions

On the basis of the analyses and numerical calculations it is justified to form such conclusions:

- because of the wedge and supporting rolls geometry six schemata of the wedge rolls rolling process can be mentioned;

- smooth rolls used in the WRR processes results in the undesired bending of the formed part;
- the properly formed part of the assumed shape can be obtained using in the WRR process the profiled rolls and the wedge of construction guaranteeing the contact with the workpiece on its whole length;
- the strains in the parts formed in the WRR method have laminar distribution which is characteristic for the cross rolling processes;
- the application of lower forming angles α improves the rolling stability, and the changes of this angle do not influence on the strains distributions in the final products in a significant way;
- the application of lower wedge spreading angle β and bigger rolling depth Δr leads to the increase of strains in the workpieces formed by means the WRR method;
- for practical application it is advisable to assume maximal values of wedge spreading angle β which allows for the stability of the WRR process, such a solution allows to lower the size of the wedge, shortens the time of forming and lower the process energy consumption;
- the application of the WRR method allows for final forming axi — symmetrical parts of complex geometry, which was presented in the example of part of ball pin type;
- FEM is the effective tool which can be used successfully in the analysis of complex forming processes.

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