

*metal forming, innovative processes,
cross wedge rolling, helical wedge rolling,
rotary compression, rolling extrusion*

Jarosław BARTNICKI¹
Zbigniew PATER¹
Andrzej GONTARZ¹
Janusz TOMCZAK¹

INNOVATIVE METAL FORMING TECHNOLOGIES

In this paper the new metal forming technologies developed at Lublin University of Technology are presented. The team of Metal Forming and Numerical Modeling Department focus on finding new solutions for different parts manufacturing. Among them, the researchers were interested in rotational forming processes for full and hollow parts: cross wedge rolling, helical wedge rolling, rotary compression and rolling extrusion. Short descriptions of the chosen processes and realized research of them are shown.

1. CROSS WEDGE ROLLING (CWR)

Cross wedge rolling is a technological method which has been used for over 50 years to produce parts such as stepped axles and shafts [1]. Owing to extensive research works done in recent years, the technological scope of the production method has been expanded to include: forming of hollow parts [2],[3], rolling shafts with eccentric steps [4] and with toothed steps [5], forming of parts with a non-circular cross section [6], and wasteless splitting of round bars [7].

In order to decrease the length of wedge tools and, thus, to increase production efficiency, a new variant of the cross wedge rolling process, called multi-wedge cross rolling, has been introduced in China [8]. In this process variant, a part of a considerable length (e.g. an automobile semi-axis) is formed simultaneously by several pairs of wedges, which form its particular steps.

Multi-wedge cross rolling can also be successfully employed in the production of short parts, with several of them being formed at the same time. Such parts include steel balls, which are used in vast quantities in ball mills or rolling bearings. The present study will show the multi-wedge cross rolling process for steel balls, which can become an alternative for industrially used methods based on helical rolling or die forging.

¹ Lublin University of Technology, Department of Computer Modelling and Metal Forming Technologies, Lublin,
E-mail: j.bartnicki@pollub.pl

A geometrical model (Fig. 1) of the multi-wedge cross rolling process has been designed using DEFORM-3D, assuming that the billet (with dimensions of $\varnothing 34\text{mm}$ by 240mm) is made from AISI 1078 steel, which material model has been taken from the material model database of the applied software. The billet diameter was smaller than the ball diameter, due to which, the risk of internal cracking in the products being formed was smaller [9]. It was also assumed that prior to rolling the billet material is heated all over its volume to the temperature of 1180°C , the wedge tools have the constant temperature of 150°C and they move in the opposite directions at the same velocity of 0.2m/s , the value of friction occurring on the material-tool contact surface is determined by friction coefficient $\mu=0.5$, and the value of material-tool heat exchange factor is of $10\text{kW/m}^2\text{K}$. Figure 2 shows the course of the multi-wedge cross rolling process. At the initial process stage, all the wedges simultaneously sink into the billet positioned by means of the guiding paths and, consequently, form necking's which separate individual balls. The serrations made on the guiding paths both increase the value of forces responsible for the billet rotation and prevent uncontrolled slipping. At this stage of the process, the ball shape undergoes sizing. Next, the balls are separated, which is done by driving special knives which height is gradually increased into the material. In the output zone, the diameter of the impression created by two working tools gradually increases. Due to this fact, it is to smoothly remove the balls from between the tools and to decrease the cross section ovalisation of the semi-finished products.

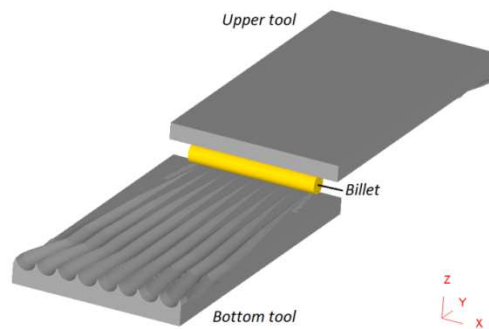


Fig. 1. Geometrical model of the multi-wedge cross rolling process for 8 balls designed with DEFORM-3D

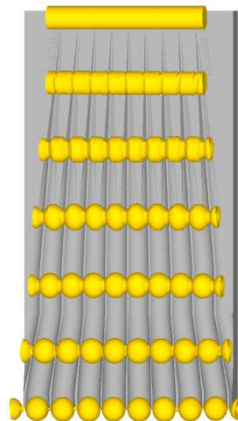


Fig. 2. Shape progression of semi-finished balls in the multi-wedge rolling process

Laboratory tests of rolling balls have been carried out with the use of the rolling mill LUW-2 (Fig. 3), available at Lublin University of Technology. The unit consists of a rolling stand, a bottom slide, an upper slide, a power unit, and a frame. The slides move due to two hydraulic operators, which maximum stroke is of 630mm. The operators are powered by a hydraulic feeder, which has an electric motor with a power of 11kW. The maximum working pressure in the hydraulic unit reaches 20MPa.

Considering the dimensions and power of the rolling mill, 4 balls with the diameter of 22mm could be simultaneously formed in the conducted laboratory tests. The wedge tools used in the experimental tests are shown in Fig. 4. Ball rolling with the parallel method has been carried out with the wedge tools which are shown in Fig. 4. The tools were made from AISI H11 tool steel. They were equipped with special guiding paths, which force the rotational movement of the billet at the initial process stage. Additionally, the bottom tool has a special recess in which the billet is placed (see Fig. 4). The billet with the diameter of 20mm and the length of 110mm, is made from AISI 52100 steel (the choice of the material stems from the fact that this steel grade is used in the production of balls for rolling bearings).

As a result of the rolling process, the balls with a desired shape are obtained and their production accuracy is of $\pm 0.3\text{mm}$. They are shown in Fig. 5. It is worth mentioning that the shape of the obtained balls is equally accurate in the cutting zone, where small burrs may sometimes occur. The indentations visible on the surface of the balls are within the machining allowance and their size may be decreased with the application of induction heating, which reduces the amount of scale.



Fig. 3. Flat wedge rolling mill LUW-2 used at Lublin University of Technology



Fig. 4. Billet and the wedge tools used in the tests of multi-wedge rolling of the balls with a diameter of 22mm

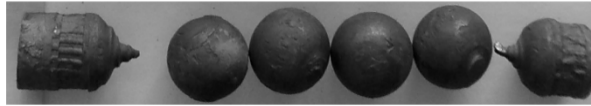


Fig. 5. Balls with diameter of 22mm, made from AISI 52100 steel, obtained in the multi-wedge rolling method at Lublin University of Technology

2. HELICAL-WEDGE ROLLING (HWR)

A scheme of the HWR process for producing balls is shown in Fig. 6. It is assumed that the balls are formed between two rolls with the roll passes, which axes are turned relative to the billet axis by the angle γ . In the course of rolling, the semi-finished product is held in the correct position thanks to the use of guiding blades, which shape is identical as the shape of the guiding blades currently used in the process of helical rolling of balls [12].

The rolls (with the nominal diameter D), which are used in the HWR process, comprise two basic parts: the input (conical) part and the forming (cylindrical) part where the wedge is wound up on a barrel of the roll and it is used to roll semi-finished balls, either connected to one another by connectors (the situation shown in Fig. 6) or separated (the rolls need to be equipped with an additional cutting coil). The role of the input part is to size the billet diameter, which is significant if billets of low production accuracy are used.

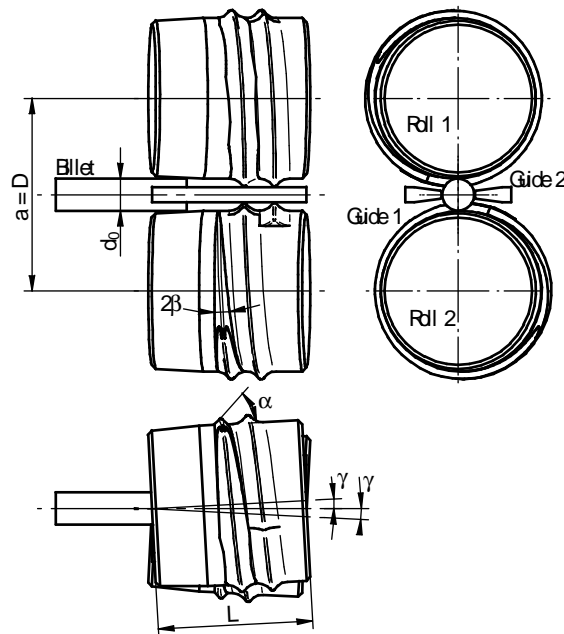


Fig. 6. Scheme of the analyzed HWR process of balls

Experimental tests of the HWR process of balls were conducted using a two-roll skew rolling mill available at AGH University of Science and Technology in Cracow, Poland. Owing to the overall dimensions of the rolling mill, it was decided that balls with

a diameter of 33mm should be formed. As it is shown in Fig. 7, the rolls used in the experimental tests had the following parameters (in accordance with Fig. 6): the spreading angle β equal 2° , the forming angle α equal 45° , the nominal roll diameter D equal 215mm, the roll length L equal 205mm, the feed angle γ equal 3° . To ensure the process stability, two guiding devices, also shown in Fig. 7, were additionally made. The guiding devices were attached to the body of the rolling mill by means of a connector in the form of a dovetail. The way in which the tools were placed in the rolling mill is illustrated in Fig. 8. This Figure shows a view of the side where semi-finished balls exit the rolling mill.



Fig. 7. Rolls with helical wedges (left) and guiding blades (right) used in experimental tests of HWR of balls with diameter of 33mm



Fig. 8. Way of placing tools in HWR of balls formed at AGH UST in Cracow

3. ROLLING EXTRUSION

A rolling extrusion method has been proposed as a new method of metal forming processes. The schema of this method is shown in Fig. 9. The rolling extrusion process is based on forming of billet material of circular section (full or hollow) by means of rotating tools, and on its moving by the pusher's plane motion [10],[11]. During the contact of the

material and tools, material rotates around its own axis and its external surface undergoes rotary compression.

It is possible to adjust the product's diameter by means of the forming rolls spacing. The implementation of the rolling extrusion technology is not connected, in the assumption, with limiting of the product length and allows for any setting of the forming cycle, within the scope of matching of rolls rotational movement and the linear movement of the pusher displacing the formed material. Research works on rotary metal forming processes were conducted in laboratory conditions. They show that for forming of products with holes, the usage of at least three working tools is especially favourable. The advantage of such a solution is a unified distribution of stresses and strains in the product, due to which lower measurement deviations of manufactured elements are obtained. Economical profits, apart from material savings, are also gained mainly by limiting of machining in the whole working cycle.

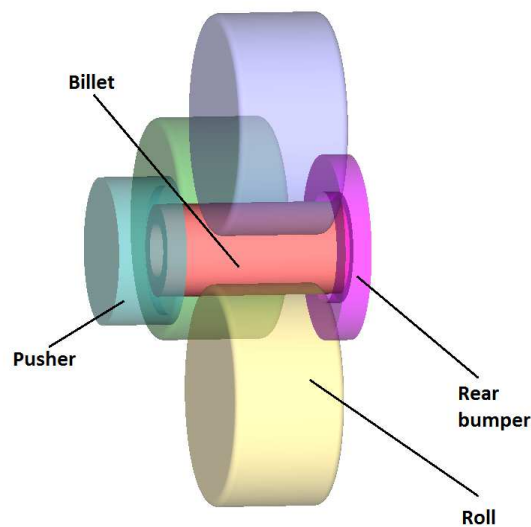


Fig. 9. Scheme of rolling-extrusion method with rear bumper

An alternative possibility of widening of the scope of metal forming technology application on shorter series of stepped axi-symmetrical products of joints, shafts and axles type can be the rolling - extrusion method. Additional possibilities are provided by a rear bumper or mandrel, positioning the billet into the workspace and limiting axial material flow or forming circular or shaped holes inside formed materials. In experimental research works on rolling extrusion process, a prototype aggregate PO-2 (Fig. 10), being the equipment of laboratories at Lublin University of Technology, was used.

This machine is a developed version of the former aggregate PO-1 and allows for realization of the forming processes at programmed sequences of particular tools movement. This solution allows for realization of a wide scope of research, limited mainly by rolling moment on rolls equal 700Nm on each tool. The force squeezing the pusher reaches 100kN maximally. Servo-motors controlling rolls spacing and the bumper placement allow for obtaining forces of 60kN.



Fig. 10. Rolling extrusion aggregate PO-2 used at Lublin University of Technology

The rolls mounted on the machine and the results of rolling extrusion process with two different feed rates are shown in Fig. 11. The application of a constant value of feed rate results in this case from slipping phenomenon appearance and a characteristic triangulation of the part shape.

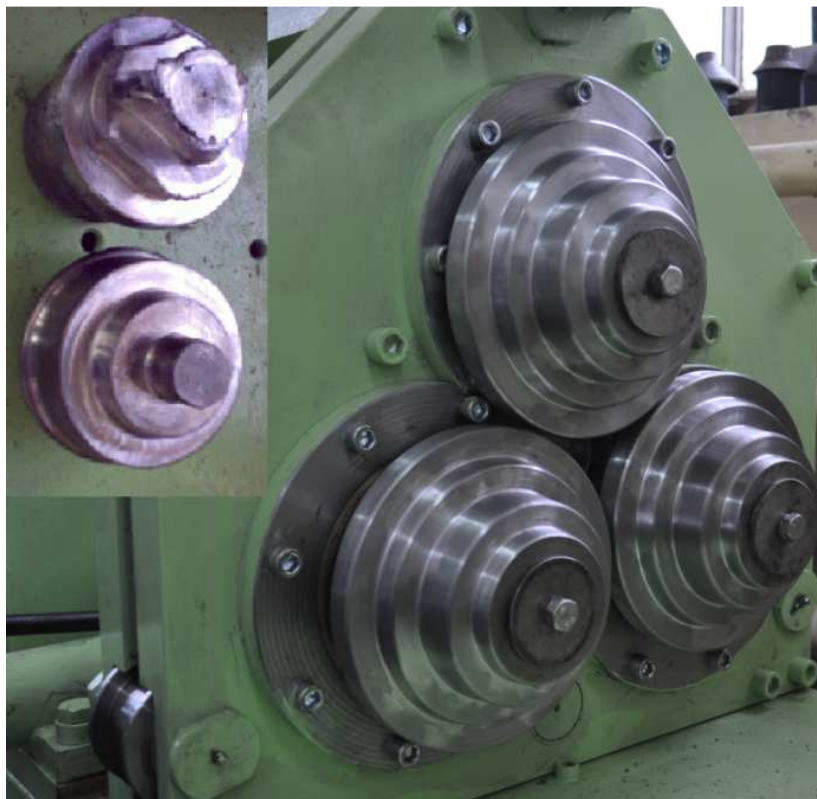


Fig. 11. Rolls in working position and obtained parts: upper-with triangulation due to slipping phenomena ($p = 5\text{mm/rot}$ during all process), lower-with correct shape (feed rate decreases from $p = 5$ to $p = 1\text{mm/rot}$ at the end)

4. ROTARY COMPRESSION

Model of the process designed for the analyzed case of a stepped hollow shaft forming is shown in Fig. 12. This model consists of three equal tools-shaped rolls (1) and billet (2). Tools rotate with constant velocity $n_1 = 65 \text{rot/min}$ in the same direction and move radially with constant velocity $v = 0,002 \text{m/s}$ in the direction of the product axis. At the end of rolling the rolls translational motion is switched off, yet, tools rotary movement is left, which finally sizes the forging shape [13].

Basing on the results of numerical calculations the design of a prototype aggregate for rotary compression process was made and, finally the machine was built – Fig. 13.

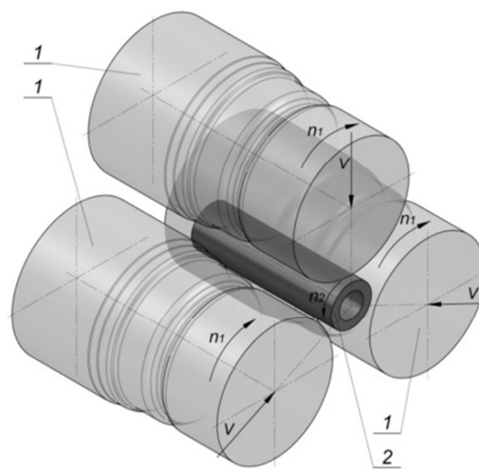


Fig. 12. Geometrical model of rotary compression of hollowed shaft forging



Fig. 13. Prototype aggregate for rotary compression process

The results of the first experimental test of this new metal forming process show good convergence between laboratory research and numerical assumptions during simulations. The workspace of rotary compression aggregate and obtained final part is shown in Fig. 14.

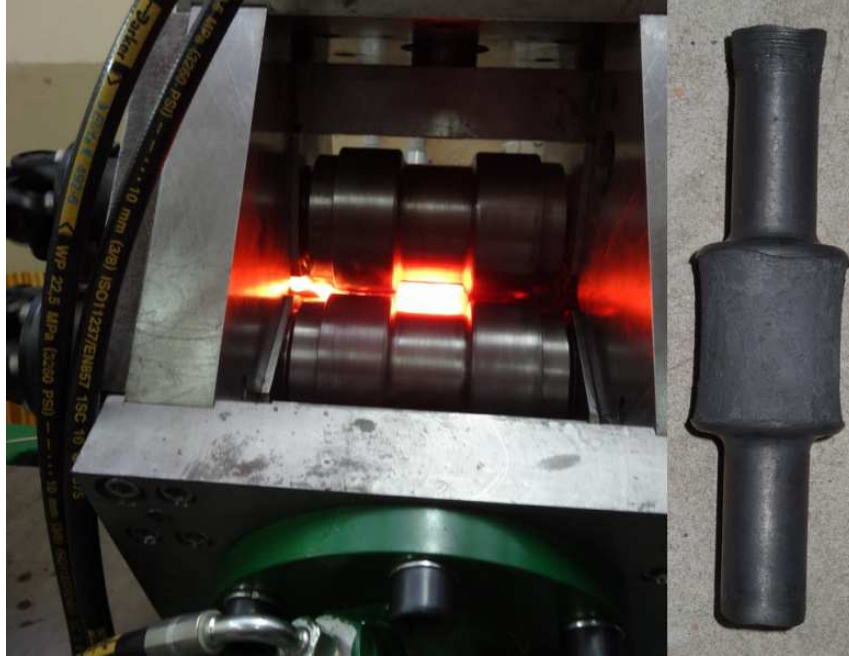


Fig. 14. Rotary compression of stepped shaft and final result of forming

5. THREE SLIDE FORGING PRESS APPLICATIONS

Connecting rods constitute the components of the machine and play a crucial role in current industrial economy. They transmit the drive from the engine to the driven machine. As the connecting rods work character results mainly in fatigue loads transmission, it should have good mechanical properties that require the use of die forging manufacturing method. For example, 90% of all connecting rods in China are made from billets forged in hot conditions [15]. Powder forging and casting technology [14],[15],[16] is used in the rest 10% parts. Connecting rod manufacturing processes utilizing forging with flash [15],[17],[18] and forging without flash [19÷23] have been analyzed in the specialized literature. Recently, more and more papers dealing with the issue of connecting rods manufacturing by means of powders pressing have been observed [24],[25]. A large interest in technologies of connecting rods forging results from the fact that they are manufactured in large series. Even small decrease of manufacturing costs for a single part or increase of mechanical properties would result in enormous effects on a global scale. Considering the above, the authors of this paper did research on the technology of connecting rod forming without flash. This process should guarantee lower material consumption in comparison with forging with flash and better mechanical characteristics, due to the preservation of fiber continuity in forging (operation of flash trimming is not present here). It was assumed that

forging without flash can be realized in three slide forging press, for which a prototype model was designed and manufactured at Lublin University of Technology in Poland (Fig. 15). This press has three movable slides which considerably increase its technological properties. The description of the machine design and various forming technologies are discussed in details in work [26÷28].



Fig. 15. Three slide forging press

Considering technological possibilities of three slide forging press, tools were designed and made. The set consists of two side tools and two vertical ones (Fig. 16).

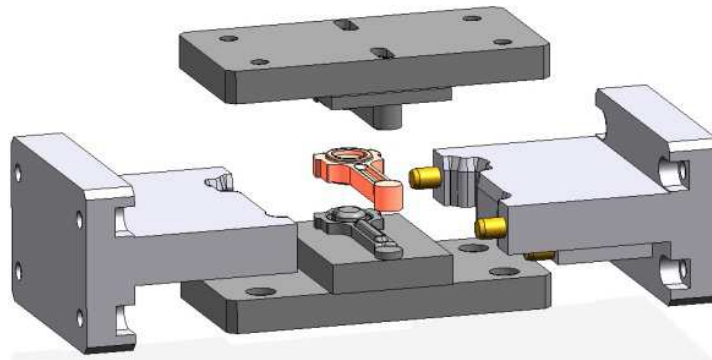


Fig. 16. Graphical model of tools for forging of connecting rod without flash

The most important stage of the process designing was working out preform shape, which would guarantee proper filling of the impression. In order to do this, following preforms were designed, and next, on the basis of the results of numerical simulations and experimental research on lead, their shape and dimensions were verified. The following preforms are presented in Fig. 17.

The software Deform 3D, based on finite element method, was used in simulations. In calculations concerning lead, material model based on own research was used [16]. Friction

conditions between tools and formed material were described by model of constant friction, assuming friction factor $m=0.4$ for the pair lead - tool steel. As the lead forging process was realized at room temperature, thermal calculations were not considered in simulation. For preform guaranteeing proper filling of the impression, numerical simulations and experimental research of forging of the analyzed part from 6101A aluminum alloy were made. In calculations, material model from the software library and friction factor $m=0.3$, corresponding with friction conditions for the friction pair aluminum alloy - tool steel with lubrication, were applied. Aluminum alloy was formed in hot conditions by heating of preform to temperature 470°C and tools to temperature 250°C .

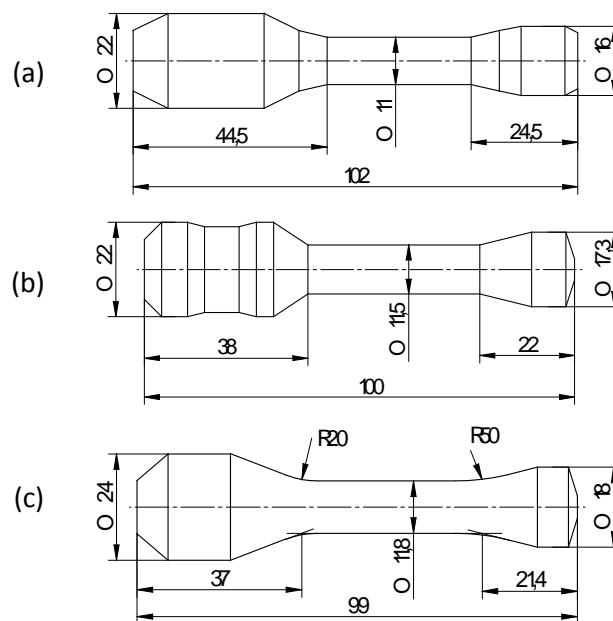


Fig. 17. Shapes and main dimensions of preforms: (a) No. 1, (b) No. 2 and (c) No. 3

The main aim of model research on lead was working out of preform shape and dimensions, which guarantee obtaining a product of the assumed quality. The first shape of the preform (Fig. 17a) was worked out on the basis of forging cross sections diagram, changing concave surfaces into convex ones and retaining constant volume. It should be noticed that dimensions of the preform small head are larger than the dimensions of the impression in this place. Because of that the first stage of the process is based on flattening of preform small head by side tools movement. Only at the second stage of the process upper tool movement and forming of final part take place. The comparison of theoretical and experimental shape at the following stages of the process is shown in Fig. 18. As it can be seen, good conformity of shape is present, which informs about proper formulating of numerical model of the process. On the basis of the conducted research, it was stated that the application of preform No. 1 led to the lack of filling of the impression in the shank and small head. This fault removal is relatively simple and it is based on the appropriate increase of material volume in places of its lack.

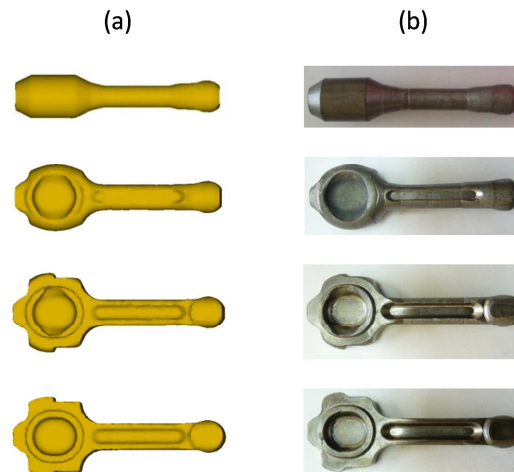


Fig. 18. Comparison of shape of forging forged from preform No 1: (a) results of numerical simulation, (b) experimental results

6. SUMMARY

Presented in this paper technologies would be applied in industry. Moreover, all the presented solutions are patented and protected. Some technologies, especially concerning CWR, are implemented in Polish factories. Future research works in this field are focused on aviation applications of the proposed manufacturing methods, especially for hollow parts (rotational technologies) and elements with ribs (three slide forging press). At the same time, the staff of Metal Forming and Numerical Modeling Department do research works in another fields not mentioned in this paper. This activities concerns orbital forming, flanges flow forming and extrusion of part with helical outline. Results of these numerical calculations and laboratory experiments are presented in other publications.

ACKNOWLEDGEMENTS

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund – Project Modern material technologies in aerospace industry, No POIG.0101.02-00-015/08 is gratefully acknowledged.

REFERENCES

- [1] FU X.P., DEAN T.A., 1993, *Past developments, current applications and trends in the cross wedge rolling process*, International Journal of Machinery Tools Manufacture Design, Research and Application, 33/3 367-400.
- [2] URANKAR S., LOVELL M., MORROW C., LI Q., KAWADA K., 2006, *Establishment of failure conditions for the cross-wedge rolling of hollow shafts*, Journal of Materials Processing Technology, 177, 545-549.
- [3] PATER Z., BARTNICKI J., 2006, *Finished cross-wedge rolling of hollowed cutters*, Archives of Metallurgy and Materials, 51/2, 205-211.

- [4] PATER Z., 2011, *Cross-wedge rolling of shafts with an eccentric step*, Journal of Iron and Steel Research, International, 18/6, 26-30.
- [5] PATER Z., GONTARZ A., TOFIL A., 2011, *Analysis of the cross-wedge rolling process of toothed shafts made from 2618 aluminium alloy*, Journal of Shanghai Jiaotong University (Science), 16/2, 62-166.
- [6] PATER Z., GONTARZ A., WEROŃSKI W., 2008, *Cross rolling of parts with non-circular cross section*, Archives of Civil and Mechanical Engineering, 8/2, 139-147.
- [7] TOMCZAK J., PATER Z., BULZAK T., 2013, *Effect of technological parameters on the rotary compression process*, Eksploatacja i Niezawodność – Maintenance and Reliability, 15, 279–283.
- [8] ZHAO J., SHU X., HU Z., 2007, *Computer aided design for cross wedge rolling tools of automobile semi-axes*, Journal of Materials Processing Technology, 187-188, 41-45.
- [9] CELIKOV A. I. et al., 1971, *Special rolling machines*, Metallurgija, Moscow.
- [10] BARTNICKI J., 2009, *The theoretical and experimental research of rolling – extrusion process*, Ed. Politechnika Lubelska, Lublin, 1-118.
- [11] NEUGEBAUER R., GLASS R., KOLBE M., HOFFMANN M., 2002, *Optimisation of processing routes for cross rolling and spin extrusion*, Journal Material Processing Technology, 125-126, 856-862.
- [12] PATER Z., TOMCZAK J., BARTNICKI J., LOVELL M.R. AND MENEZES P.L., 2013, *Experimental and numerical analysis of helical-wedge rolling process for producing steel balls*, International Journal of Machine Tools & Manufacture, 67, 1–7.
- [13] TOMCZAK J., PATER Z., 2012, *Analysis of metal forming process of a hollowed gear shaft*, Metalurgija, 51/4, 497-500.
- [14] KAZANECKI J., 2003, *Production of seamless pipes*, Ed. AGH, Krakow, (in Polish).
- [15] WANG Q., HE F., 2004, *A review of developments in the forging of connecting rods in China*, Journal of Materials Processing Technology, 151, 192-195.
- [16] YIN F., WANG G.X., HONG S.Z., ZENG Z.P., 2003, *Technological study of liquid die forging for the aluminum alloy connecting rod of an air compressor*, Journal of Materials Processing Technology, 139, 462-464.
- [17] GRASS H., KREMPASZKY C., WERNER E., 2006, *3-D FEM-simulation of hot forming processes for the production of a connecting rod*, Computational Materials Science, 36, 480-489.
- [18] HATZENBICHLER T., BUCHMAYR B., 2008, *Vorformoptimierung für das Gesenkschmieden mittels numerischer Simulation*, Berg- und hüttenmännische Monatshefte, BHM, 153, 413-417.
- [19] TAKEMASU T., VAZQUEZ V., PAINTER B., ALTAN T., 1996, *Investigation of metal flow and preform optimization in flashless forging of a connecting rod*, Journal of Materials Processing Technology, 59, 95-105.
- [20] VAZQUEZ V., ALTAN T., 2000, *Die design for flashless forging of complex parts*, Journal of Materials Processing Technology, 98, 81-89.
- [21] VAZQUEZ V., ALTAN T., 2000, *New concepts in die design - physical and computer modeling applications*, Journal of Materials Processing Technology, 98, 212-223.
- [22] DOEGE E., BOHNSACK R., 2000, *Closed die technologies for hot forging*, Journal of Materials Processing Technology, 98, 165-170.
- [23] BEHRENS B. A., DOEGE E., REINSCH S., TELKAMP K., DAEHNDEL H., SPECKER A., 2007, *Precision forging processes for high-duty automotive components*, Journal of Materials Processing Technology, 185, 139-146.
- [24] BELLET M., 1999, *Finite Element Analysis of compressible viscoplasticity using a three-field formulation. Application to metal powder hot compaction*, Computer Methods in Applied Mechanics and Engineering, 175, 19-40.
- [25] DALE J.R., 2005, *Powder forged or C-70 steel? Now the MPIF strikes back*, Metal Powder Report, 60, 14-17.
- [26] GONTARZ A., 2005, *Effective forming processes on three slide forging press*, Edited by Lublin University of Technology, Lublin, (in Polish).
- [27] WEROŃSKI W., GONTARZ A., PATER Z., 2006, *The research of forging process of eccentric part on three slide forging press*, Journal of Materials Processing Technology, 177, 214-217.
- [28] GONTARZ A., 2006, *Forming process of valve drop forging with three cavities*, Journal of Materials Processing Technology, 177, 228-232.