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NUMERICAL AND EXPERIMENTAL STUDY ON PRODUCING ALUMINUM ALLOY 6061 SHAFTS BY CROSS WEDGE ROLLING USING A UNIVERSAL ROLLING MILL

TEORETYCZNO-DOŚWIADCZALNE BADANIA PROCESU WALCOWANIA POPRZECZNO-KLINOWEGO ODKUWKI ZE STOPU ALUMINIUM 6061 W UNIWERSALNEJ WALCARCE KUŹNICZEJ

The paper presents a selection of numerical and theoretical results of the cross wedge rolling process for producing stepped shafts made of aluminum alloy 6061. The numerical modeling was performed using the FEM-based Simufact Forming simulation software. In the simulations, we examined the kinematics of metal flow and determined the distribution patterns of effective strains, temperatures, axial stresses and the Cockcroft-Latham damage criterion. Variations in the rolling forces were determined, too. The numerical results were verified experimentally using a universal rolling mill designed and constructed by the present authors. This machine can be used to perform such processes as cross wedge rolling, longitudinal rolling and round bar cropping. During the experiments, we examined process stability and finished product geometry and recorded the torques. The experimental results confirm that axisymmetric aluminum alloy shafts can be produced by cross wedge rolling with two rolls. Last but not least, the experiments served to evaluate the technological potential of the rolling mill used.

Keywords: cross wedge rolling, aluminum alloys, FEM, experiment

W pracy przedstawiono wybrane wyniki badań teoretyczno – doświadczalnych procesu walcowania poprzeczno – klinowego odkuwki wałka stopniowanego ze stopu aluminium w gatunku 6061. Analizę teoretyczną przeprowadzono w programie Simufact Forming, bazującym na metodzie elementów skończonych. W trakcie symulacji analizowano kinematykę płynięcia materiału, wyznaczono rozkłady intensywności odkształcenia, temperatury, naprężeń w kierunku osiowym oraz kryterium zniszczenia wg Cockrofta Lathama. Ponadto określono parametry siłowe podczas walcowania. Weryfikacji doświadczalnej wyników modelowania numerycznego procesu walcowania dokonano w uniwersalnej walcierce kuźniczej, która stanowi własną konstrukcję. Zastosowana walcierka umożliwia realizację takich procesów jak: walcowanie poprzeczno-klinowe, walcowanie kuźnicze wzdłużne oraz dzielenie bezodpadowe. Podczas eksperymentu analizowano stabilność procesu, geometrie ukształtowanych odkuwek oraz rejestrowano wartość momentów obrotowych. Uzyskane wyniki prowadzonych badań potwierdziły możliwość kształtowania osiowosymetrycznych odkuwek ze stopów aluminium metodą WPK dwoma walcami. W trakcie eksperymentu określono również możliwości technologiczne walcarki.

1. Introduction

Cross wedge rolling (CWR) is one of the rotational metal forming techniques. It is most often performed using two rolls or two flat wedges. The advantages of CWR with two rolls include the possibility of both shaping parts directly out of bars and eliminating idle run of the tools. In contrast, the main shortcomings of this rolling technique are: the difficulty of constructing the tools and the necessity of using guiding blades. When rolling with flat wedges, on the other hand, the workpiece does not have to be guided in the course of the process and the tools are easy to construct. The major drawback of the CWR with two flat wedges is, however, the occurrence of idle run that amounts to 40% of the entire work cycle [1, 2].

Cross wedge rolling enables the forming of a wide range of products and it is most often used to produce stepped shafts

and axes. Cross wedge rolling is also widely used for forming billets for the die forging of elongated parts. In addition, the CWR technique can be employed to produce such parts as toothed shafts, screw spikes and balls [3-6]. In the past, some research was undertaken to investigate the application of CWR for producing twist drills [7]. Unfortunately, however, the complicated geometry of the tools and the difficulty of constructing them (owing to the lack of adequately accurate milling machines) led to abandoning the research on this technique. Recently, however, studies have been published on the application of CWR for the rolling of camshafts for combustion engines [8]. Given the considerable technological potential of cross wedge rolling, it is no wonder that this technique has gained wide recognition in the global industry and is still being developed.

Despite the fact that CWR processes are nowadays widely applied, the technique is mainly used to form steel alloys.

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Nonetheless, CWR is still rarely applied when it comes to the forming of non-ferrous alloys (aluminum, titanium and magnesium alloys). For this reason, we decided to investigate whether axisymmetric stepped shafts made of aluminum alloys can be produced by cross wedge rolling using a universal rolling mill equipped with rotating rolls.

This paper presents the numerical and experimental results of the cross wedge rolling process for producing stepped shafts made of aluminum alloy 6061 (Fig. 1). The numerical modeling was performed using the Simufact Forming simulation software, while the experiments were conducted using a rolling mill that is available at the State School of Higher Education in Chelm.

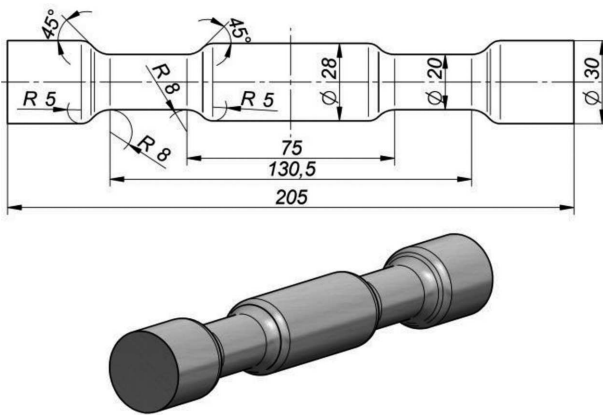


Fig. 1. Shape of an aluminum alloy 6061 stepped shaft

2. Numerical modeling

The numerical modeling of the CWR process for producing aluminum alloy stepped shafts was performed by the finite element method. The FEM-designed geometrical model of this process is shown in Fig. 2. The model consists of the following elements: 1 – billet (bar with a diameter of 30 mm and a length, L , of 150 mm), 2, 3 – working rolls with the circumferentially-wound wedges, and 4, 5 – guides for maintaining the workpiece in the machine workspace. The rolls were assumed to rotate in the same direction at a rotational speed, n , of 15 revolutions per minute. The workpiece (aluminum alloy 6061 bar) was modeled as a rigid-elastic object by eight node hexahedral elements. The material model of aluminum alloy 6061 was obtained from the materials database library of the software used [9]. The initial temperature of the workpiece was set to 460°C, while the temperature of the tools was maintained constant at 150°C. The material-tool contact surface was characterized by the constant friction model defined by a friction factor, m , set to 0.8. The material-tool heat transfer coefficient was 10 kW/m²K, while the heat transfer coefficient between the material and environment was 0.35 kW/m²K.

During the numerical simulations, we examined workpiece geometry and the kinematics of metal flow in consecutive stages of the rolling process as well as determined the distribution patterns of effective strains, temperatures, damage criterions, stresses and variations in forces.

The FEM-simulated changes in the shaft shape and the effective strains are illustrated in Fig. 3. At the beginning of

the process, the wedges mounted on the surface of the rotating rolls sink in the workpiece. In effect, the workpiece begins to rotate and a ring-shaped groove is formed on its circumference. In the consecutive stage, the groove becomes wider and wider until it reaches the length of the central step. Next, two necks are simultaneously formed on the workpiece. In this stage, the wedges acting on the material reduce the diameter of the steps to the minimum and then they make this cross sectional reduction applicable to the entire length of these steps. This stage of the process is connected with rapid elongation of the workpiece. To prevent both material cracking in the workpiece centre at early stages of the process and workpiece bending during the forming of the necks, the active surface of the central wedges is mounted lower. In effect, the tools have no contact with the already formed step.

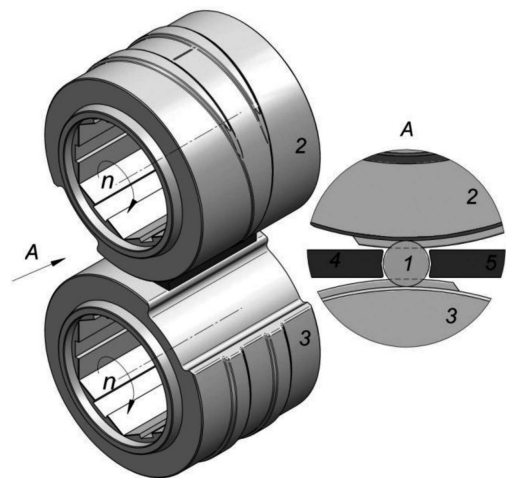


Fig. 2. Geometrical model of CWR for stepped shafts

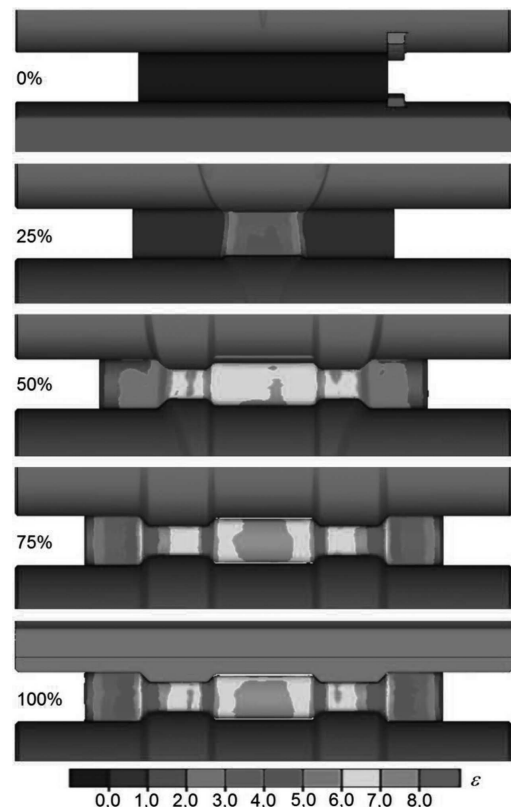


Fig. 3. FEM-simulated shape changes and effective strains

The final stage of the process when the shaft steps have the desired cross sectional reduction marks the beginning of sizing when the constant-width wedge tools remove all shape inaccuracies produced in the previous stages of the rolling process. It can be observed that the material is not evenly processed in the region where the steps were subjected to the same cross sectional reduction. The highest strains are present in the regions between the consecutive shaft steps of the shaft. Such distribution pattern of strains is typical of rotational metal forming processes and it results from considerable material-tool slipping. As a result, additional circumferential strains are generated by the friction forces, predominantly in the superficial layers of the workpiece.

Figure 4 compares the distribution patterns of the effective strains, temperatures and the Cockroft-Latham damage criterion of the stepped shaft as determined by FEM in the final stage of rolling. It can be observed that the distribution patterns are far from being uniform. The maximum effective strains (Fig. 4a) occur in the workpiece regions that underwent the highest cross sectional reduction. The maximum strains are local. They are mainly concentrated in the superficial layers of the deformed shaft steps. This strain pattern confirms that the material flow in the CWR process is superficial. In addition to this, more strains – as already mentioned – are generated in the circumferential direction by the friction forces. The temperatures of both the billet and formed product also have a significant effect on the rolling of aluminum alloys. The determined distribution pattern (Fig. 4b) is non-uniform and exhibits a considerably high drop in temperature of the formed part (up to approx. 350°C). This information is particularly important given a relatively long duration of the process (about 4 s) and low thermal capacity of the workpiece. The observed temperature drops are primarily caused by the transfer of heat to the tools and they are concentrated in the regions which are not subjected to cross sectional reduction. In contrast, the central steps of the shaft have higher temperatures. The temperature variations should be attributed to a varying degree of processing in individual regions of the shaft. In the central regions, heat losses are partly compensated for by both deformation and friction and they are mainly converted into heat, while the non-deformed shaft steps only give the heat away to the tools. It should be noted in this context that aluminum alloys exhibit high thermal conductivity, which means that the temperature in particular regions of the workpiece becomes partly uniform already during the sizing phase.

The simulations also involved predicting crack formation in the workpiece. To this end, we used the standard Cockroft-Latham criterion, which is defined by the formula [10]:

$$C = \int_0^{\epsilon} \frac{\sigma_1}{\sigma_i} d\epsilon, \quad (1)$$

where σ_1 is the maximum principal stress, σ_i is the effective stress, ϵ is the strain, while

C is the Cockroft – Latham criterion.

The Cockroft-Latham damage criterion calculated by (1) is compared to the boundary value obtained from the experiment. The results (Fig. 4c) demonstrate that the area near the workpiece centreline as well as the regions between the non-deformed and deformed shaft steps is most prone to crack-

ing. The Cockroft – Latham criterion is very high there (approx. 1.0) and can exceed the boundary values depending on the aluminum alloy [11], which can even lead to material cracking. Interestingly, the mechanism of crack formation will differ depending on the workpiece region. The crack formation in the central regions of the workpiece is caused by low-cycle material fatigue that is typical of rotary metal forming processes. In contrast, the regions between the non-deformed and deformed steps are characterized by the phenomenon of workpiece twisting, which results from variations in the circumferential velocities of forming the steps. This load pattern can lead to material cohesion loss, particularly if the material's plasticity becomes lower due to excessive workpiece cooling. It is to be noted in this context that although the numerical results point to very high values of the damage criterion, we did not observe any signs of material cohesion loss in the shafts produced in the experiments. Still, the risk of crack formation in the cross wedge rolling of aluminum alloy shaft is relatively high.

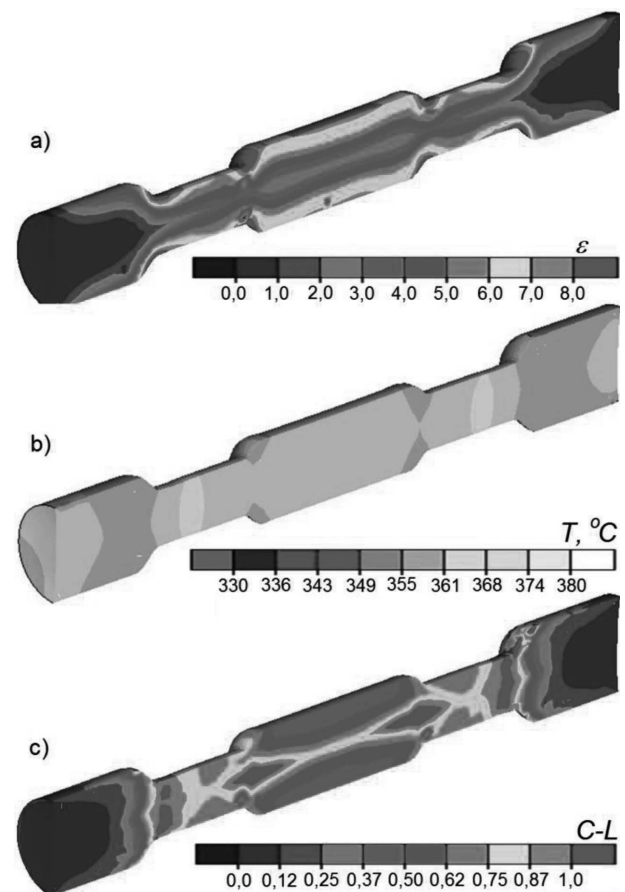


Fig. 4. FEM-simulated distribution patterns of: a) effective strain, b) temperature, c) Cockroft-Latham damage criterion

Another failure mode that can be observed in the cross wedge rolling of aluminum alloy stepped shafts is necking or workpiece rupture. The phenomenon is caused by the action of the tensile forces generated by the tools. As can be seen from Fig. 5, the distribution pattern of axial stresses (σ_z) is highly non-uniform. The highest stresses are concentrated in the central region of the workpiece (along its centerline), and the further it is from the centerline, the more rapidly these stresses drop. It can also be observed that the distribution of

the axial stresses depends to a great extent on a given stage of the process. When the workpiece is being rapidly elongated in the superficial layers, high axial compressive stresses occur and the core of the workpiece is elongated, too at the same time. The stresses are generated by the friction forces that act on the material-tool contact surface and thus prevent axial flow of the material, which generates different stresses in both the core and superficial regions of the workpiece. The highest tensile stresses occur in the final stage of the process when the pressures on the material surface drop rapidly and thus make the axial friction forces decrease. Consequently, the central part of the workpiece gets elongated by the action of the wedges, as there are no compressive stresses acting on the superficial layers of the workpiece. It should however be noted that the maximum axial stresses are relatively low (approx. 60 MPa), therefore they should not have any negative effect on the process.

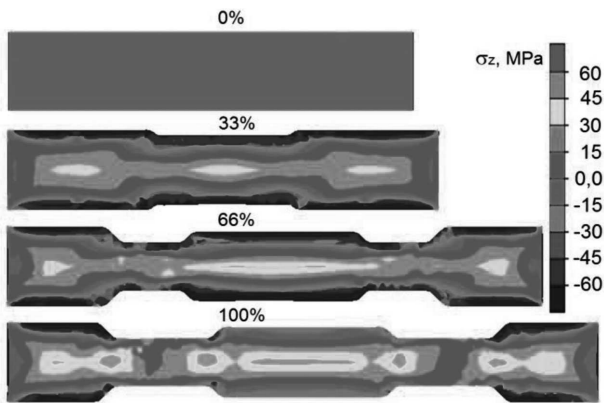


Fig. 5. FEM simulated distribution patterns of axial stresses depending on the stage of the CWR process

3. Experimental tests of the CWR for producing aluminum alloy shafts

The experimental tests of the cross wedge rolling of aluminum alloy shafts were performed using a universal rolling mill constructed by the present authors [13, 14]. The machine is available at the State School of Higher Education in Chełm. The rolling mill has a wide technological potential, as it enables running such process as cross rolling, cross wedge rolling, round bar cropping and longitudinal rolling. The machine is built of segments and has six fundamental elements (Fig. 6): a frame, a power unit, a set of rolls, a gear box, an electric power and control unit and a set of measuring instruments. The frame is a welded openwork structure made of channel bars with a square section. The frame has the power unit fastened to it on the one side and the rolls on to other. The power unit consists of a multi-phase gear box powered by a flywheel-driven electric motor. The torque is transmitted to the rolls via the power transmission system that consists of two articulated connectors. The mill stand consists of four steel plates that are joined such to form a rigid frame. The vertical plates of the machine frame serving as the mill stands have eccentric sleeves, where the main rolls of the rolling mill fastened by bearings. The axle base of the rolls changes due to

the revolution of the mechanically coupled eccentric sleeves. As a result of the simultaneous revolution of the four eccentric sleeves, the axes of the rolls either draw apart or get closer to one another. The forces and kinematic parameters of the rolling process were recorded by a measuring system consisting of two gauges: one for measuring torques and the other for measuring angular displacements. Signals received by the gauges were recorded digitally by a measuring card installed in a personal computer. The rolling mill is also equipped with an integrated electric power and control system. The system enables the supply of electric power to the electric power engine and to the additional equipment for inspection and measurement as well as control.

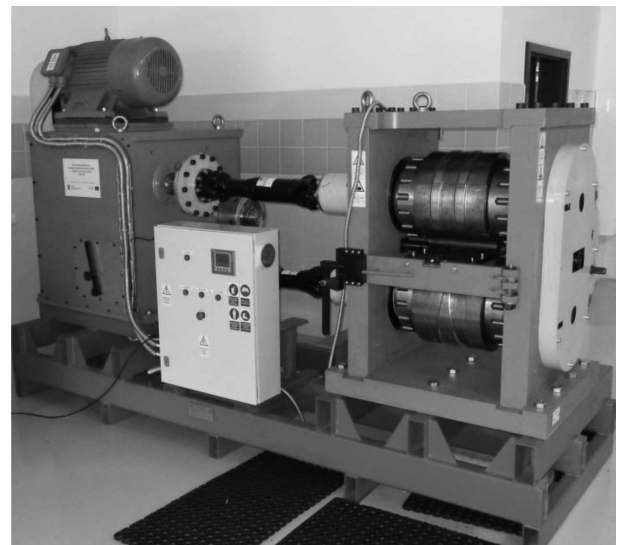


Fig. 6. Universal rolling mill for cross wedge rolling, round bar cropping and longitudinal rolling

Two sets of tools were mounted in the workspace of the rolling mill. The shape and overall dimensions of the tools are shown in Fig. 7. As already mentioned, the tools are made up of segments. The roll passes of the rolls are formed by six segments made of tool steel for hot working. The segments are mounted to the main rolls of the rolling mill by means of two front nuts, which enables easy retooling. The rolls have a wedge-like protrusions on their surface for forming shafts and they are defined by such parameters as a spreading angle, β , of 16° and a forming angle, α , of 45° . The end segments have special depressions to facilitate the removal of the produced shafts from the machine.

The billet were bars made of aluminum alloy 6061 (PA38 according to PN). They had an outside diameter of 30 mm and a length, L , of 150 mm (following the dimensions applied in the simulations). The billet was first heated in an electric chamber furnace to a forming temperature of approx. 480°C and then inserted by means of tongs into the rolling mill (made up of two rolls and two guides). The billet's axial position was set in the machine by a protruding stop mounted to the first tool.

Next, the tools were set in motion. Rotating in the same direction at a constant velocity, n , of 15 rev/min, the tools form consecutive shaft steps. Once they performed a full revolution, they were stopped and the shaft was removed from the rolling mill. During the rolling process, the workpiece position was

maintained in the machine by two guides mounted to the roll mill stands. The distance between the guides was slightly bigger than the diameter of the shafts being rolled, as a result of which the shafts did not get stuck in the machine in the course of the operation.

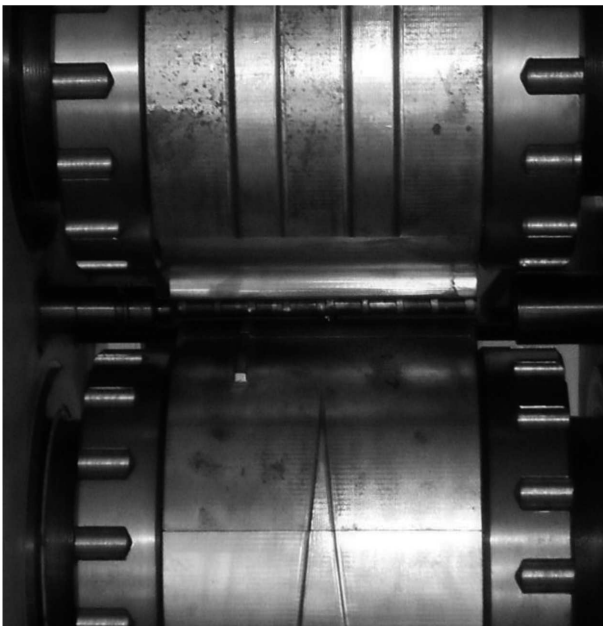
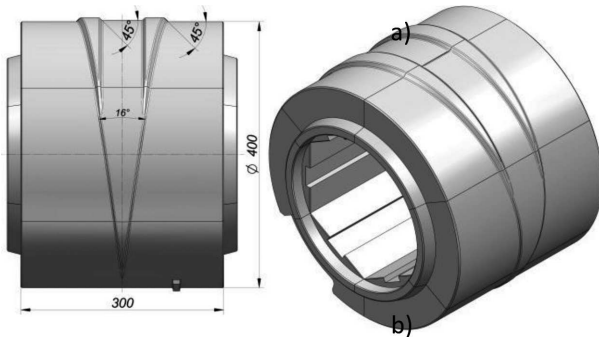


Fig. 7. Tools for rolling stepped shafts: a) CAD model, b) tools mounted on the main rolls of the rolling mill



Fig. 8. Aluminum alloy 6061 stepped shafts produced by cross wedge rolling

The rolling process was stable; we did not observe any phenomena that could have a negative effect on the quality of semi-finished products (slipping, necking, bending). The aluminum alloy 6061 stepped shafts produced in the experimental

tests are shown in Fig. 8. The products show high accuracy and shape repeatability. The only flaws observed upon inspection were spiral grooves on the surfaces of the formed shaft steps. Their occurrence was caused by the fact that the applied corner radius of the wedges was too small. It should however be mentioned that the depth of the grooves did not exceed 0.1 mm, which is still within the machining allowance.

The experimental results with regard to the shape and dimensions of the products show good agreement with the theoretical assumptions (shaft shape developed at the design stage) and numerical simulation results (Fig. 9). The surface of the formed shafts is predominantly smooth and free from defects. In order to detect potential internal defects in the formed shafts, we performed flaw detection tests using the ultrasonic flaw detector OmniScan UT. The results did not reveal internal cracks in the formed products. Neither did they reveal defects that are typical of CWR, including superficial cracks, overlap or centerline bending, despite the fact that the workpiece is considerably slender. Based on the above, it was concluded that aluminum alloy axisymmetric stepped shafts can be produced by the cross wedge rolling technique.

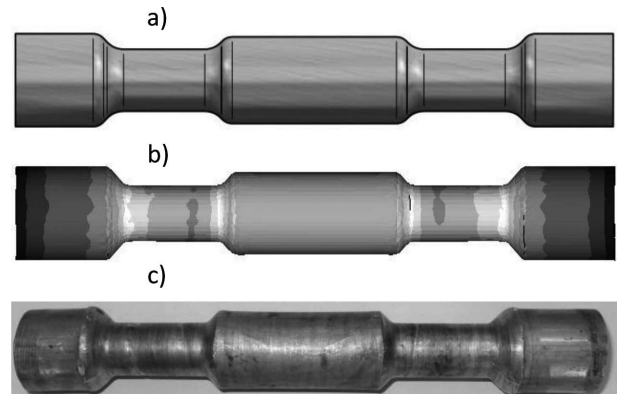


Fig. 9. Geometry of the shaft: a) CAD model, b) FEM, c) experimental

The numerical and experimental tests also involved the examination of torques, the variations in which are shown in Fig. 10. It is characteristic of these torque variations that the experimental and numerical results, both quantitative and qualitative, show good agreement. The observed difference in the extreme values of the torques obtained from the numerical modeling and experiments can be attributed to the discrepancies between the adopted material model of aluminum alloy 6061 and its actual properties. Also, the variations in the torques could result from the fact that it was difficult to maintain the same thermal conditions during both experiments and FEM modeling. It should however be stressed that the observed differences are relatively small (they amount to approx. 6.2%), which can be considered satisfactory as for this type of processes. Examining the torque variations, three fundamental stages can be distinguished. In the first stage, the wedges sink into the material to the desired depth, while the cross sectional reduction spreads from the centre towards the end faces over the required rolling length. This leads to a rapid increase in the torques. Following the rapid increase caused by the development of the deformation zone over the entire length of the workpiece, the torques become stable and remains rather unchanged, which marks the actual forming stage. The sizing

stage begins when the length of the forming zone does not increase. This stage is characterized by a rapid drop in the torques. During the experiment, it was impossible to determine the forces. Nonetheless, the high agreement between the numerical and experimental results of the torques allows us to suppose that a similar relationship between the numerical and experimental results would be observed for the forces, too.

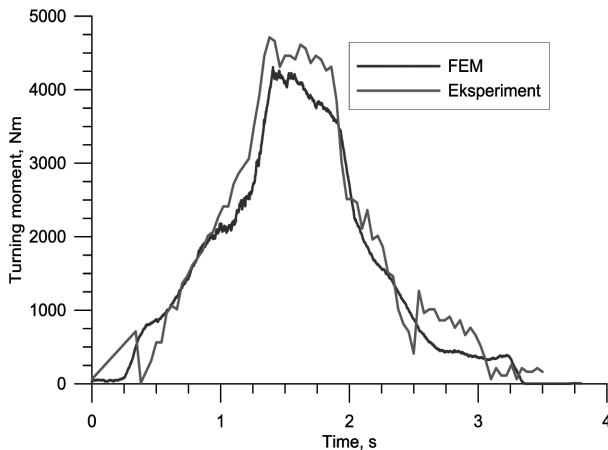


Fig. 10. Variations in the torque in the CWR of an aluminum alloy shaft

The tool force and its variations have a significant effect on the elastic strains of the rolling mill and hence on the accuracy of produced parts. Therefore, this parameter was also investigated in the tests. The variations in the tool force as simulated by the FEM are shown in Fig. 11.

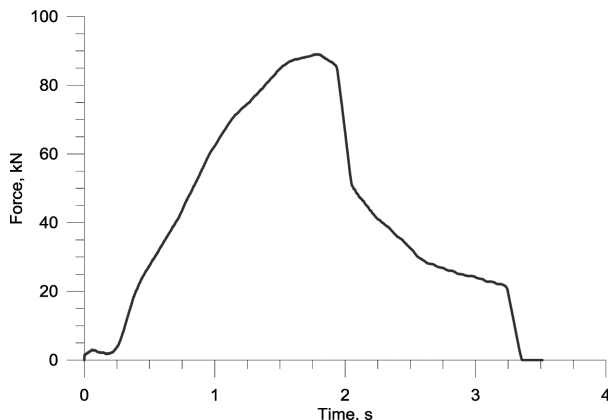


Fig. 11. FEM simulated variations in the tool force in the CWR of alloy 6061 shafts

As expected, it can be observed that the variations in the forces are similar to those in the torques. Also here three fundamental forming stages can be distinguished depending on the angular location of the tools relative to the workpiece. It is however worth noting that the maximum forces do not exceed 90 kN. Given the above, we concluded that the mill stand will not be considerably deformed during the rolling process and the produced shafts will have the desired accuracy.

4. Summary and conclusions

The conducted numerical and experimental tests confirm that both aluminum alloy forgings and finished axisymmetric

products can be produced by the cross wedge rolling method using rotating tools. Currently, CWR processes are widely applied to produce steel parts using both flat wedges and rolls. Unfortunately, however, the technique is seldom used for forming non-ferrous alloys. For this reason, it is fully justified that studies be undertaken to find new applications for CWR processes.

The study involved examining the CWR process in terms of its stability and failure modes. The forces occurring in the process were examined, too, since information about these parameters is vital from the technological standpoint.

The following conclusions have been drawn from the obtained results.

- Aluminum alloy parts produced by cross wedge rolling have the desired accuracy.
- In the course of rolling aluminum alloy shafts, the temperature drops significantly, this can have a negative effect on the process stability and properties of produced parts.
- Based on the FEM results, it was found that there is a risk of crack formation both in the central regions of the workpiece and in the regions located between the steps. This notwithstanding, the experimental results did not reveal any violation of material cohesion.
- No workpiece rupture or necking was observed during the rolling process.
- Shallow helical grooves were observed on the surface of the formed steps, which can result from the application of a too small corner radius of the tools.
- The produced parts exhibit considerable non-uniformity that will affect their mechanical properties. During the rolling process, the metal mainly flows on the surface.
- The numerical and experimental torque results show high quantitative and qualitative agreement.
- It is recommended that further research be conducted with the use of the universal rolling mill in order to determine the machine's capacity and to find new applications for cross wedge rolling.

Acknowledgements

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REFERENCES

- [1] Z. Pater, *Walcowanie poprzeczno-klinowe*. Wydawnictwo Politechniki Lubelskiej, Lublin 2009.
- [2] Z. Pater, A. Tofil, Experimental and theoretical analysis of the cross-wedge rolling process in cold forming conditions, *Arch. Metall. Mater.* **52**, 55-65 (2007).
- [3] Z. Pater, Cross-Wedge Rolling of Shafts With an Eccentric Step, *J. Iron. Steel Res. Int.* **18**, 26-30 (2011).
- [4] Z. Deng, M. Lovell, K. Tagavi, Influence of Material Properties and Forming Velocity on the Interfacial Slip Characteristics of Cross Wedge Rolling, *J. Manuf. Sci. Eng.* **123**, 647-653 (2001).
- [5] A. Tofil, Research of new splitting process of pipe billets from 2618A aluminium alloy basing on cross-wedge rolling. *Arch. Metall. Mater.* **58**, 725-729 (2013).

- [6] J. Bartnicki, Z. Pater, The aspects of stability in cross-wedge rolling processes of hollowed shafts, *J. Mater. Process. Technol.* **155-156**, 1867-1867 (2004).
- [7] T. Bulzak, J. Tomczak, Z. Pater, Przegląd metod kształtowania rowków wiórowych wiertel krętych ze stali narzędziowych, *Przegląd Mechaniczny* **6**, 15-21 (2013).
- [8] M.T. Wang, X.T. Li, F.S. Du, Current trends in cross wedge rolling for part forming, *ISIJ Int.* **45**, 1521-1525 (2005).
- [9] Simufact.material 2012. 0.0.14871, simufact engineering gmbh, Hamburg 2012.
- [10] A. Gontarz, J. Piesiak, Model pękania według kryterium Cockrofta-Lathama dla stopu magnezu MA2 w warunkach kształtowania na gorąco, *Obróbka Plastyczna Metali*. **4**, 217-227 (2010).
- [11] X. Duana, X. Velayb, T. Sheppard, Application of finite element method in the hot extrusion of aluminium alloys. *J. Mater. Sci. Eng.* **369**, 66-75 (2004).
- [12] H.N. Hana, K.H. Kim, A ductile fracture criterion in sheet metal forming process, *J. Mater. Process. Technol.* **142**, 231-238 (2003).
- [13] A. Tofil, Z. Pater, J. Tomczak, Dwuwalcowa klatka walcownicza, zwłaszcza do walcowania poprzecznego, wzdłużnego oraz dzielenia bezodpadowego. Polski patent PL 215512 (2013).
- [14] A. Tofil, J. Tomczak, Z. Pater, Przekładnia redukcyjna ze zmiennym kierunkiem obrotów wałów wyjściowych, z możliwością pomiaru momentu obrotowego. Polski patent, numer decyzji DP/P.395434/8/aper. (2011).

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