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A METHOD FOR PRODUCING HOLLOW SHAFTS BY ROTARY COMPRESSION USING A SPECIALLY DESIGNED FORGING MACHINE

OBCISKANIE OBROTOWE ODKUWEK DRAŻONYCH W SPECJALNYM AGREGACIE KUŹNICZYM

The paper presents a new method for manufacturing hollow shafts, where tubes are used as billet. First, the design of a specially designed forging machine for rotary compression is described. The machine is then numerically tested with regard to its strength, and the effect of elastic strains of the roll system on the quality of produced parts is determined. The machine's strength is calculated by the finite element method using the NX Nastran program. Technological capabilities of the machine are determined, too. Next, the results of the modeling of the rotary compression process for a hollow stepped shafts by the finite element method are given. The process for manufacturing hollow shafts was modeled using the Simufact.Forming simulation program. The FEM results are then verified experimentally in the designed forging machine for rotary compression. The experimental results confirm that axisymmetric hollow shafts can be produced by the rotary compression method. It is also confirmed that numerical methods are suitable for investigating both machine design and metal forming processes.

Keywords: rotary compression, forging machine, hollow shafts, experiment, FEM

W artykule zaprezentowano nowatorską technologię kształtowania drażonych odkuwek z wykorzystaniem wsadu rurowego. Następnie opisano konstrukcję opracowanego i wykonanego agregatu kuźniczego do realizacji procesu obciskania obrotowego. Przedstawiono wyniki numerycznej analizy wytrzymałościowej urządzenia oraz wpływ odkształceń sprężystych klatki roboczej na jakość kształtowanych odkuwek. Obliczenia wytrzymałościowe urządzenia wykonano metodą elementów skończonych w środowisku NX Nastran. Określono również możliwości technologiczne agregatu. Następnie przedstawiono wyniki modelowania metodą elementów skończonych procesu obciskania obrotowego drażonej odkuwki elementarnego wałka stopniowanego. Do przeprowadzenia symulacji numerycznych kształtowania odkuwek drażonych wykorzystano pakiet oprogramowania Simufact Forming. Wyniki symulacji MES zweryfikowano doświadczalnie w kuźniczym agregacie do obciskania obrotowego. W rezultacie przeprowadzonych badań potwierdzono możliwość kształtowania drażonych odkuwek osiowo-symetrycznych metodą obciskania obrotowego. Potwierdzono również zasadność stosowania metod numerycznych w analizie konstrukcji oraz procesów kształtowania plastycznego metali.

1. Introduction

Rotary compression is one of the innovative methods for manufacturing hollow machine parts [1, 2]. It allows to manufacture axisymmetric hollow parts, stepped axes and shafts. In this process, the cross section of a tube is reduced by three identical rolls; the rolls are rotated in the same direction and, simultaneously, they are displaced radial to the axis of the workpiece (Fig. 1). The shape of the rolls (1, 2, 3) corresponds to an outline of the workpiece being compressed (4); sections of tubes or tube blanks are used as billet. At the beginning of the process, the workpiece is positioned between the rolls; during the compression process, it is rotated by these tools about its own axis. Due to the action of the tools, the outer diameter of subsequent steps of the part

is reduced, which leads to an increase both in wall thickness of the workpiece and in length of the end necks of the shaft.

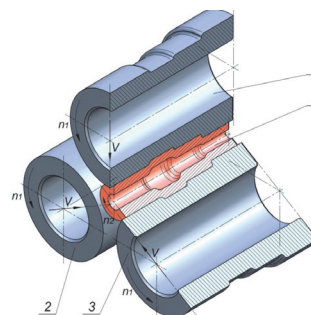


Fig. 1. Design of the rotary compression process for a hollow stepped shaft: 1, 2, 3 – tools (rolls), 4 – workpiece

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Compared to the presently used techniques for manufacturing hollow parts, rotary compression offers numerous benefits, such as enhanced strength properties of parts formed thereby, higher production output of the process, lower implementation and production costs. In addition to this, the process is relatively easy to run and can easily be mechanized and automated. Therefore, it seems justified to develop this forming method as a process that is complementary to widely used machining techniques for producing hollow parts [3 - 5].

In order to determine technological capabilities of rotary compression, the process was numerically simulated by the finite element method [6, 7]. The numerical results confirmed the technological assumptions to be correct, demonstrating at the same time that the relations between individual parameters of the process, process stages, and geometry of final products can be exhaustively determined only by means of experimental tests. Due to the specific nature of tool kinematics in rotary compression, the process requires the use of specialist machines. For this reason, a forging machine for manufacturing hollow stepped axes and shafts by rotary compression was designed at the Lublin University of Technology [8]. The machine was then constructed and used in experimental tests.

The present study describes the design of the forging machine for manufacturing axisymmetric hollow parts; technological capabilities of this machine are determined, too. Also, the numerical results of testing the strength of the machine's roll system are given. In addition to this, the study presents the results of the modeling of the rotary compression process for a hollow stepped shaft by the finite element method. The results are then experimentally verified using the designed forging machine for rotary compression.

2. Design of the forging machine for rotary compression

The forging machine for rotary compression was designed at the Lublin University of technology as part of the research on rotary forming processes for axisymmetric parts, including hollow parts. The developed forging machine allows to run the process such that the tools are rotated in the same direction and simultaneously displaced relative to the axis of the workpiece. The forging machine for rotary compression consists of seven basic units (Fig. 2): a frame – 1, a power unit – 2, a gear box – 3, a system of rolls – 4, a hydraulic power unit for the rolls – 5, an electric power and control unit – 6, and a set of measuring instruments – 7. The frame is a welded openwork structure made of thin-walled elements with a square section. To the frame, a power unit is fastened; the power unit comprises a gear-motor made of an electric three-phase motor and a bevel-cylindrical two-stage gear.

Torque is transmitted from the gear-motor by a crown-pin flexible coupling and a torque converter to the gear box, where it is then distributed to three working shafts of the machine (Fig. 3). The dividing gear box consists of four toothed shafts – 17, which are in mesh with one another; the shafts are fastened by means of bearings to vertical plates – 9, mounted in the main plate – 8, and, additionally, clamped with one another by means of an upper plate. The actual rotary forging process takes place in the roll system, where three slides – 12 move

radially along with the working rolls – 13 that are fixed to the said sliders by means of bearings. The body of the roll system consists of two segments stands – 10, connected to each other by three plates – 11, to which hydraulic cylinders – 20 are fastened. The working shafts and the tools mounted on them, i.e. the forming rolls – 14 are rotated during the process in the same direction and at the same velocity. To facilitate retooling, the tools per each slide were constructed as two divided segments and they are fastened to the working rolls by means of front nuts – 15. The three slides and the tools are radially displaced by means of a hydraulic power system which consists of three hydraulic cylinders, a hydraulic feeder as well as a set of valves and hydraulic distributors. The slides are driven in sliding linear guides, placed in the roll stand housing and distributed radially by every 120° relative to the axis of the workpiece. The displacement of the three slides is synchronized hydraulically (via a three-way, gear flow divider) and mechanically (via a gear mechanism – 18). Owing to the change in the axis distance between the working shafts during compression, the torque is transmitted from the gear box to the roll system by means of Cardan shafts – 21.

The billet is fed into the work space of the machine by means of a specially designed guide – 19 which also maintains the workpiece in the desired position at the initial stage of the process.

To examine force and kinematic parameters of the rotary compression process, a special measuring system was constructed. The system consisted of a torque converter for the digital recording of torque during the forming process, a displacement sensor for registering actual velocity and position of the tools, and pressure measuring sensors (based on pressure measurement, the radial force on workpiece can be determined). The electrical system, which powered and protected particular units of the machine, was placed in an electrical box inside the frame. Basic technical specification of the designed and constructed forging machine is given in Table 1.

TABLE 1
 Technical specification of the forging machine for rotary compression

Technical specification	
Engine power [kW]	22
Shaft torque [Nm]	2200
Shaft rotational velocity [rots/min]	36
Minimum tool linear velocity v_{min} [mm/s]	0,1
Maximum tool linear velocity v_{max} [mm/s]	15
Maximum radial force [kN]	120
Maximum workpiece length [mm]	160
Maximum billet diameter [mm]	60
Minimum workpiece diameter [mm]	19
Minimum tool diameter d_{min} [mm]	100
Maximum tool diameters d_{max} [mm]	130
Overall dimensions L x B x H [m]	2,3x1x2,15
Weight [kg]	2700

On its design, the machine was also subjected to comprehensive tests with regard to the strength of its main units. To this aim, at the initial stage of the design process,

the engineering methods based on the fundamental laws of material strength were applied to determine the smallest sections possible of the machine's main components [9]. After that, numerical methods were used to verify the machine design with regard to its strength and rigidity. The numerical computations were made by the finite element method using the NX Nastran program for determining the linear characteristics of material strength. The preliminary results demonstrate that the roll system, the rigidity and strength of which are critical for the operational reliability of the machine and product quality, is subject to the highest load. For this reason, the present study focuses on the presentation of strength analysis results for this particular unit. In the computations, all elements of the roll

system had a Poisson's ratio ν of 0.3 and an elastic modulus (Young's modulus) E of $2.1 \cdot 10^5$ MPa. The boundary conditions between individual segments, the clamping plates, the hydraulic cylinders and slide components were described by a default function for screw joints, which corresponds to actual joints between these elements. The other joints were set to no penetration and zero distance linear contact. The discretization of the roll system model made for the purposes of the FEM simulations was performed by means of 8 mm big four-node tetragonal elements. The size of these elements depended on the overall dimensions of the digitized components. The numerical computations were made for maximum loads via applying 120 kN point forces to three work rolls of the

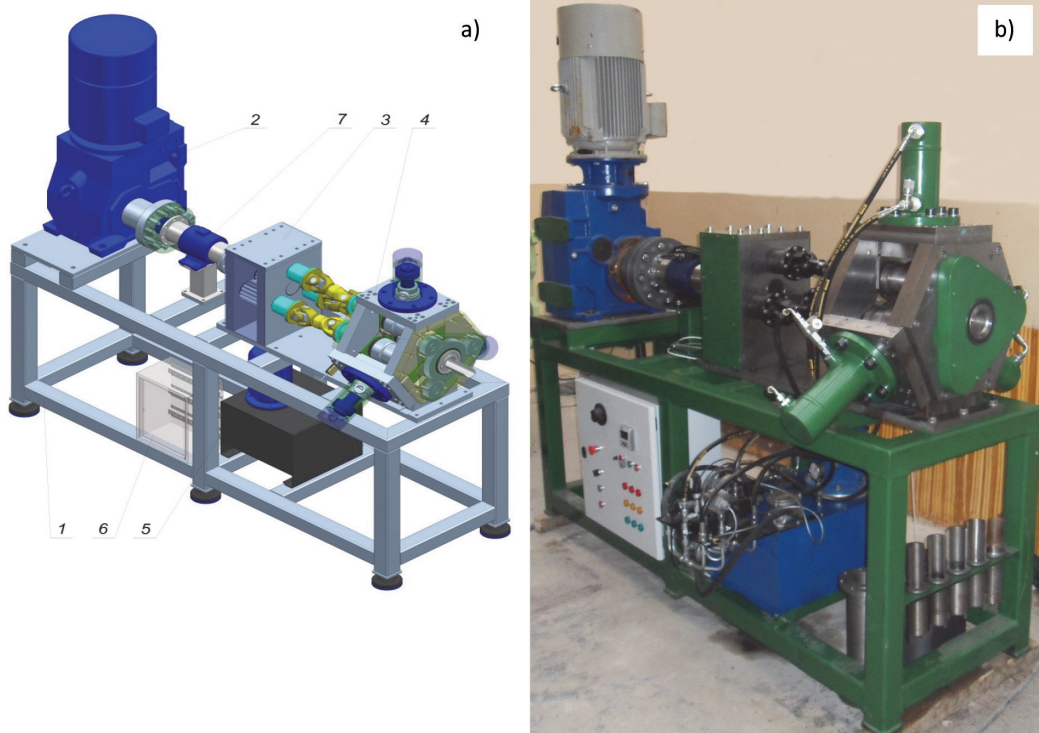


Fig. 2. Forging machine for manufacturing hollow shafts by rotary compression: a) CAD model, b) photograph of the machine (description in the body of the manuscript)

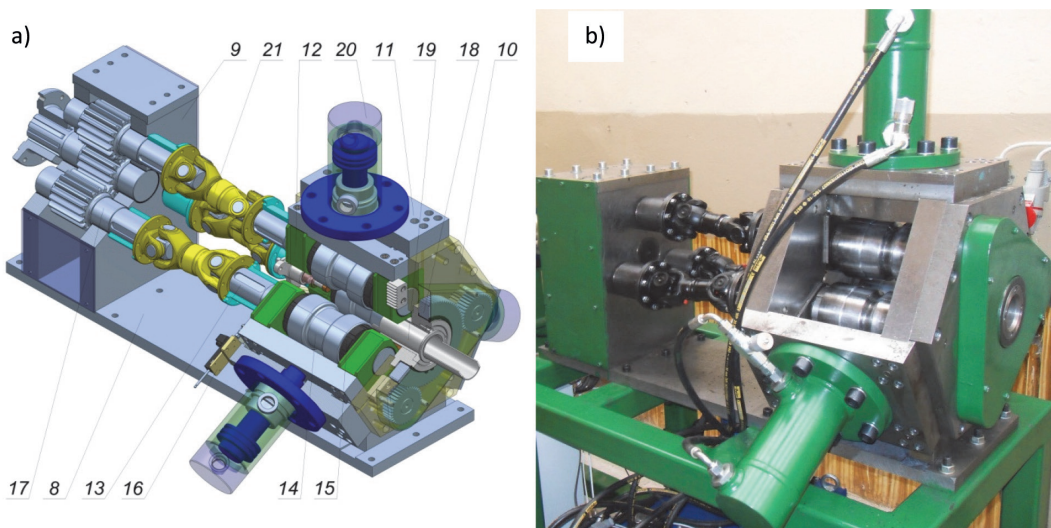


Fig. 3. Gear box and the roll system for rotary compression: a) CAD model, b) photograph of the machine (description in the body of the manuscript)

machine, following the direction of motion of the slides. These forces were applied at the mid-length of the shafts (between the bearings), their sense corresponded to the resistance of the metal during the process. The FEM simulation results helped determine the distributions of reduced stresses according to the Huber-Mises hypotheses and the distribution of displacements of the roll system components under the external load applied. The results are compared in Fig. 4 as maps showing the distributions of stresses and displacements. The results with regard to reduced stresses were used to determine the degree of material effort for the key components of the machine. Most importantly, however, the risk of exceeding yield point for the most loaded elements of the roll system could be determined. The roll system displacement results were used to evaluate the system's rigidity, as this factor affects the accuracy of final parts. Analyzing the results, it can be observed that the slide beams are under the highest load – the reduced stresses amount up to 200 MPa in the area where the hydraulic cylinders are mounted. These values are however acceptable (the yield point for 42CrMo4 is about $R_e = 900$ MPa), as they will not cause any permanent strains in these elements. The remaining

components of the machine, including the main shafts, are subject to much lower load. Considerably high elastic strains can be observed analyzing the displacement results. It can be noted that the main shafts of the machine are displaced by about 0.6 mm; this figure being the total displacement value resulting from elastic strains of the stands, slides, clamping plates and main shafts. It should however be noted that when parts are hot-worked, the FEM – determined deflection is within the production tolerance and will not affect the accuracy of products to any significant extent (the only change will involve higher machine finish allowances). The effect of the roll system's elastic strains on the accuracy of parts will not be significant either, given the presence of the sizing stage in the rotary compression process.

At this stage, the tools are not displaced toward the axis of the workpiece; they only perform a rotational motion, thereby removing shape inaccuracies caused, among others, by elastic strains of the machine components. In effect, the radial force during sizing is by several times lower, which leads to a considerable reduction in the elastic strains of the machine at the final stage of the compression process.

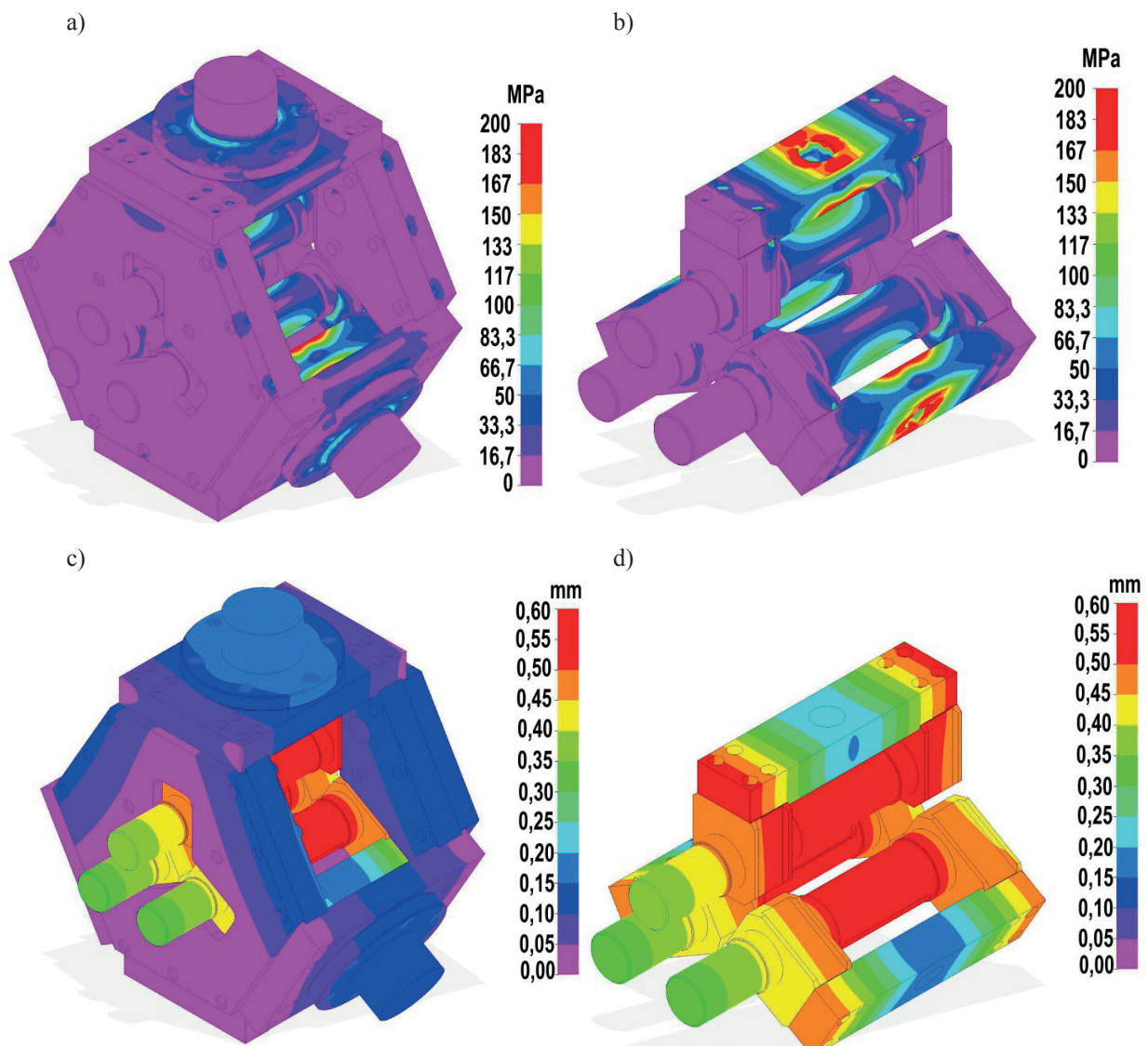


Fig. 4. FEM-determined distributions of: a) reduced stresses of the roll system b) reduced stresses of the slides, c) roll displacements, d) slide displacements

3. Producing a hollow shaft in the rotary compression machine

Constructed in compliance with the developed design, the machine will be used for the production of hollow axes and shafts, including ones with toothed steps and worms. Parts of this type are widely applied in automotive, aircraft and machine-building industries. For this reason, it is fully justified that a new efficient and cost-effective method for manufacturing these parts out of commercial tubes be developed.

The technological capabilities both of the method and of the designed machine were examined in the compression process. To this aim, a series of numerical and experimental tests were performed to produce hollow shafts with end steps, hollow shafts with necking in their centre, as well as multi-stepped shafts. This study presents the numerical and experimental results of producing a hollow shaft with necking in its central part (Fig. 5).

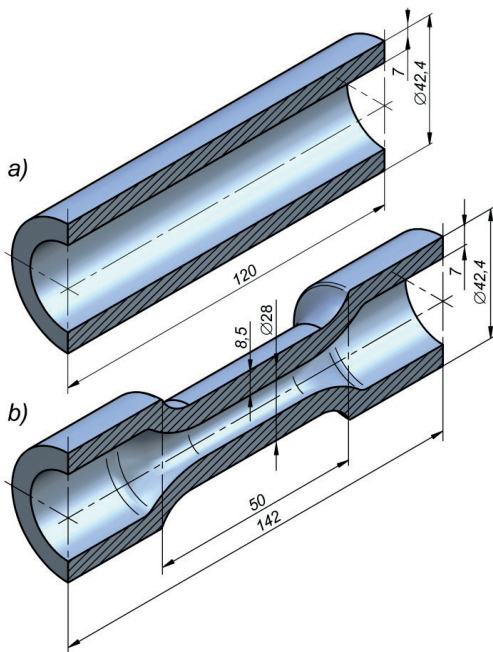


Fig. 5. Shape and dimensions of: a) billet, b) hollow shaft

First, the rotary compression process for a hollow shaft was modeled numerically. The computations were made by the finite element method (using Simufact Forming version 11.0), which had been widely used to investigate different mechanical problems [10 - 16]. Fig. 6 shows the geometrical model of the process designed for the purpose of the study. The model consisted of three identical tools (rolls) and billet (C45 steel tube section with outer diameter $D = 38$ mm, wall thickness $g = 7$ mm and length $L = 120$ mm), modeled by 8-node cubic elements. The rigid-plastic model was assigned the properties of C45 steel, the properties of which were taken from the database library of the software used. It is described by the following equation (1) [17]:

$$\sigma_p = 2859.85 \cdot e^{(-0.00312548 \cdot T)} \cdot \varepsilon^{(0.000044662 \cdot T - 0.101268)} \cdot e^{\left(\frac{-0.000027256 \cdot T + 0.000818308}{\varepsilon}\right)} \cdot \dot{\varepsilon}^{(0.000151151 \cdot T - 0.00274856)}, \quad (1)$$

where: T is the temperature (between 700°C and 1250°C), ε is the strain, $\dot{\varepsilon}$ is the strain rate.

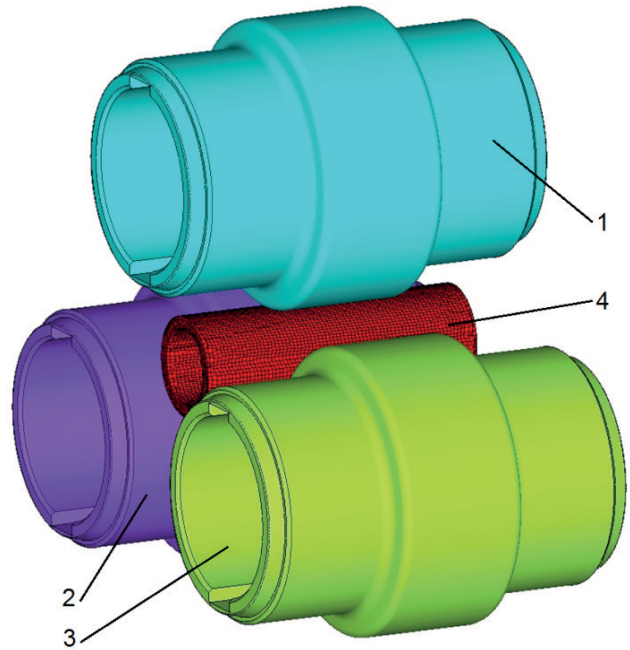


Fig. 6. Geometrical model of the rotary compression process for a hollow shaft with necking: 1, 2, 3 – tools, 4 - billet

In addition, the billet was heated all over its volume to a temperature of 1150°C , while the temperature of the tool was maintained constant at 80°C . The rolls were rotated in the same direction at the same velocity n set to 36 rotations per minute; simultaneously, they were displaced relative to the axis of the workpiece at a constant velocity v of 1.5 mm/s. The boundary value of the friction factor on the material-tool contact was set to $m = 1$ [18], the material-tool heat exchange coefficient was set to $30 \text{ kW/m}^2\text{K}$, while the material-environment heat exchange coefficient was set to $0.35 \text{ kW/m}^2\text{K}$.

The FEM-produced shape of the hollow shaft is shown in Fig. 7. During the compression process, the moving tools deform the central section of the billet; this is accompanied by rapid metal flow radial to the axis of the workpiece, which leads in this region to an increase in wall thickness.

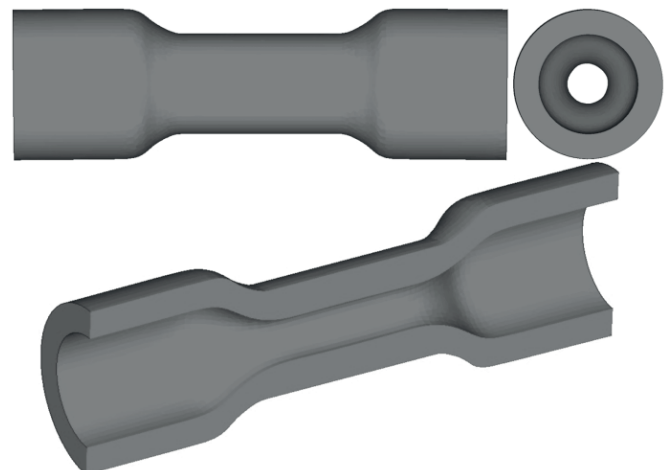


Fig. 7. FEM-simulated shape of a hollow shaft

Due to lack of constraints on the end face of the workpiece, the material is also displaced axially, which results in an increased workpiece length compared to the initial value.

The FEM-determined distributions of effective strain, temperature and the Cockcroft-Latham damage criterion at the final stage of compression are shown in Fig. 8. As expected, only the central region of the shaft is deformed; it is there where the billet diameter is reduced. In contrast, the ends of the shaft are not deformed. In connection to this it is to be observed that the effective strain distribution (Fig. 8a) is not uniform in the central region, which is where the diameter is reduced. The highest strains are concentrated in the surface layers; the closer it is to the internal wall of the workpiece, the lower the strain. Such distribution of strains is typical of rotary metal forming processes in which considerable slipping between material and tools takes place. As a result, additional, circumferential strains are generated by the friction forces in the surface layers of the workpiece. The FEM-determined temperature distribution is not uniform, either (Fig. 8b). The surface regions of the formed necking are much cooler compared to other regions of the workpiece. This results from rapid heat transfer to the much cooler tools that contact the material in these areas throughout the process. Such a high drop in temperature may have undesired effects on the process (e.g. higher resistance to deformation, reduced material deformability), leading to workpiece shape distortions. It is to be noted that tool temperature in the series production of shafts will be set much higher compared to the temperature set in the numerical calculations. In effect, a drop in workpiece temperature will be much lower. The numerical computations also attempted to predict the occurrence of cracking. To this aim, the standardized Cockcroft-Latham criterion was applied (Fig. 8c). The results demonstrate that the internal wall of the final shaft is the most crack prone region. In this region the Cockcroft-Latham criterion has the boundary values (about 1.0), which is enough for cracks to occur. It should be observed, however, that the extreme values of this criterion are located at the surface, therefore even if cracking takes place, potential cracks will occur in the surface layers which are part of the technological allowance that is removed in the subsequent machining.

The numerical results were validated under laboratory conditions, using the designed and constructed machine. The technological parameters set in the experiment were identical to those set in the simulations. For the purpose of the experiments, two tools for the forming of central necking were mounted on three working shafts of the machine, in accordance with the process design used in the simulations.

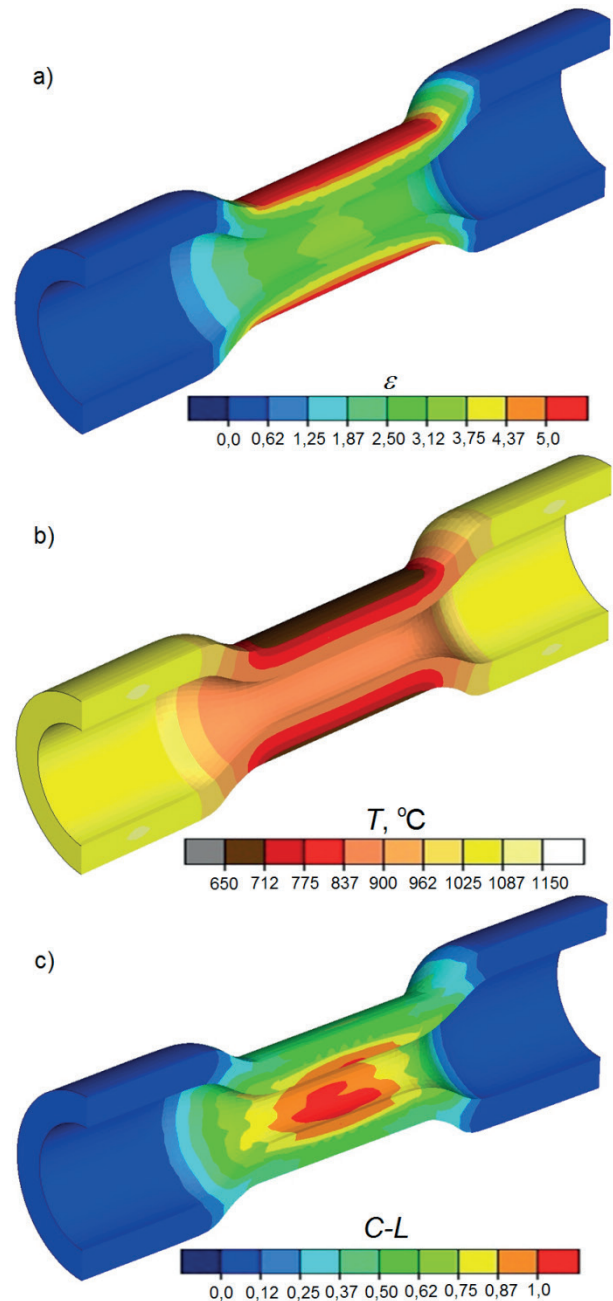


Fig. 8. FEM-simulated distributions of: a) effective strain, b) temperature, c) Cockcroft Latham damage criterion

The billet used in rotary compression was made of C45 steel tubes with an outer diameter of 42.4 mm, wall thickness $g = 7$ mm and length $L = 120$ mm. The tubes were first heated in an electric chamber furnace to the forming temperature of about 1150°C ; after that, they were fed by means of tongs into the working space of the machine (formed by three rotating rolls) (Fig. 9a). Next the tools, which were rotating in the same direction at constant velocity $n = 36$ rots/min and, simultaneously, moving radially at constant velocity $v = 1.5$ mm/s, made the billet rotate, reducing its diameter in the centre. Following the slide travel equal to the required diameter reduction, the linear motion was stopped. The workpiece shape underwent sizing during the subsequent rotations of the rolls. At the last stage of the process, the tools were opened radially and the part formed left the working space of the machine via

the feed mechanism located in the housing of the roll mill (Fig. 9b).

The main aim of the experiments was to confirm whether the rotary compression process could be employed to produce hollow stepped shafts by the proposed forming method. In the experiments, the following were examined: process stability, geometrical parameters of produced shafts, and forces of the process.

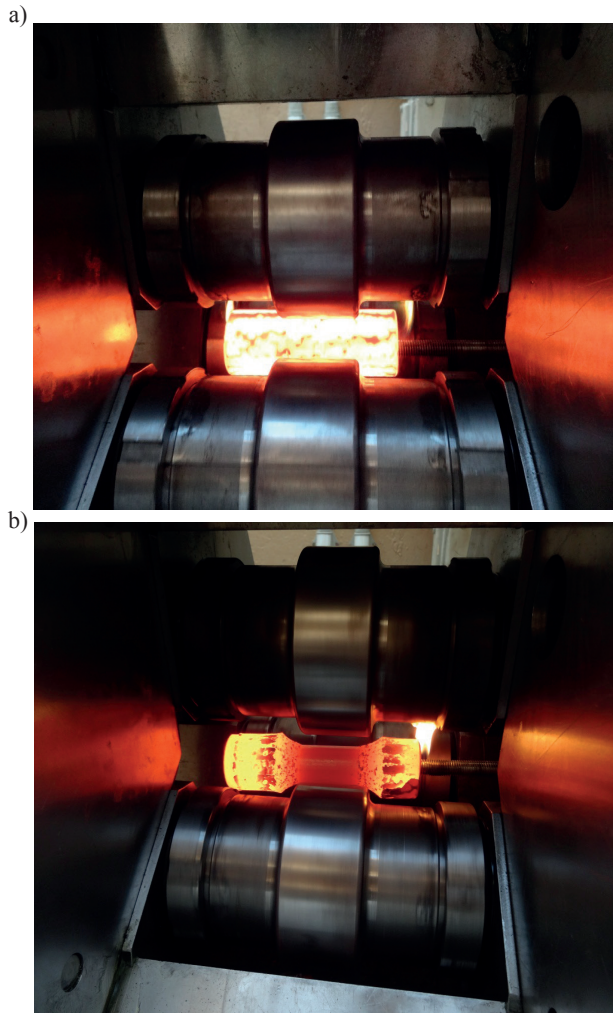


Fig. 9. Rotary compression of a hollow shaft in a specially designed forging machine: a) billet in the working space of the machine, b) final part

The experimental results demonstrated that tubes can be formed into hollow stepped axes and shafts via the rotary compression method using the designed forging machine. The experimental results (regarding the shape and dimensions of compressed parts) are in good agreement with both theoretical assumptions (desired workpiece shape) and numerical simulation results. The shape of a hollow shaft produced in the experiments is shown in Fig. 10. The figure shows that wall thickness increases during the compression process, which results from radial material flow. In addition, the material is axially displaced during the process, which leads both to an increase in the workpiece length and to a local decrease in workpiece thickness. The observed wall thickness increase is not uniform over the entire length of the necking formed. The highest thickness of walls was observed in the central

area of the final shaft (wall thickness increased to approx. 8.5 mm). Then, the closer it is to the non-deformed surfaces of the shaft necks, a gradual decrease in the wall thickness can be observed. This results from axial material flow in the area of temporary radii of the tools. It also there where the highest decrease in the wall thickens (up to about 6.2 mm) was observed. The wall thickness decrease can be considerably reduced or even eliminated via limiting the possibility of workpiece elongation during the process. Apart from the local wall thickness decrease, a slight deformation of the workpiece axis was observed, too. This shape defect is caused by lack of support for the workpiece in the zone of the end necks of the shaft - these shaft necks did not contact the tools during the compression process. This undesired phenomenon can be easily prevented if the tool design is adjusted such that all steps of the workpiece contact the working surfaces of the rolls at the last stage of the process.

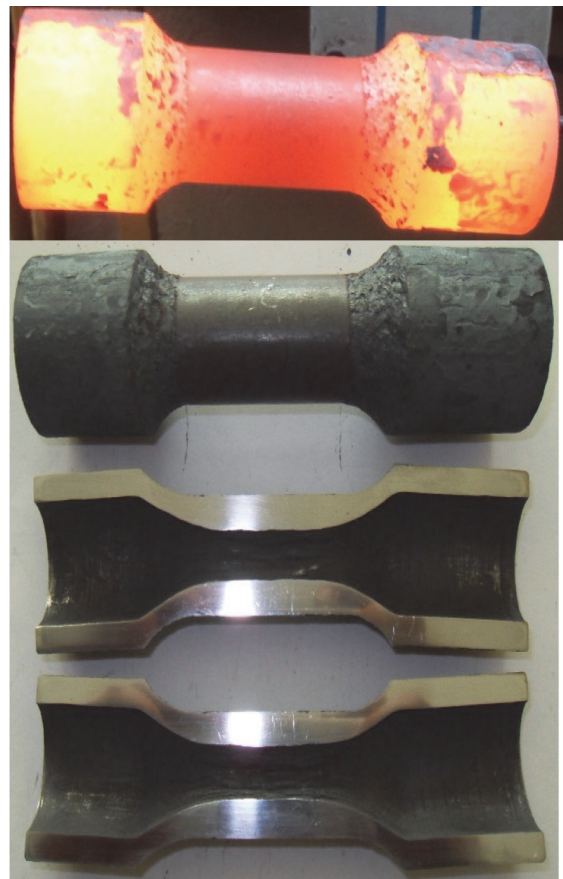


Fig. 10. Hollow shafts produced by rotary compression in a specially designed forging machine

Comparing the numerical results of producing hollow shafts with the data obtained in the experiment, it can be observed that the numerical and experimental results show a high agreement, both in terms of quality and of quantity. In both cases, the variations in the wall thickness are distributed in a similar manner (Fig. 11). The increase in wall thickness is similar, too. Interestingly, the internal wall of the necking also reveals the presence of shallow cracks (at a depth of about 0.3 mm, the measurement was performed on the microscope workbench), the location of which corresponds to the distribution of maximum values of the Cockcroft-Latham

criterion. The high agreement of the results confirms that the application of numerical methods in the analysis of complex metal forming processes is justified.

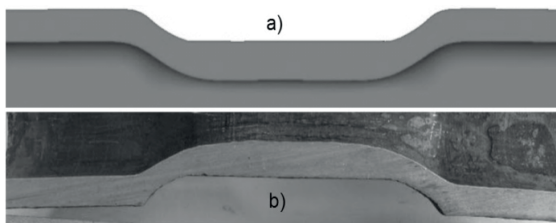


Fig. 11. Axial section of hollow shafts: a) FEM, b) experimental

The research on rotary compression also involved examining the force parameters of the process (radial force and torque); the variations in which (FEM and experimentally determined) are compared in Fig. 12. Characteristically, both the experimental and numerical results show a high agreement. The simple geometry of the shaft is also reflected in the way in which the force parameters change during the process. Once the tools are close to the surface of the workpiece (which takes place after about 2 s), a relatively sudden increase in the forces and torques can be observed, which results from material plasticization and material-tools contact. In the subsequent stage of the process, the increase in the forces and torques is less rapid. This is a steady-state stage of the process, when the workpiece diameter is gradually reduced in the central region. It must be stressed that any increase in the forces and torques at this stage results from an increase in wall thickness and rapid cooling of the material, which leads to higher resistance to deformation. The last stage of the process, which involves the sizing of workpiece shape, is accompanied by rapidly decreasing force parameters.

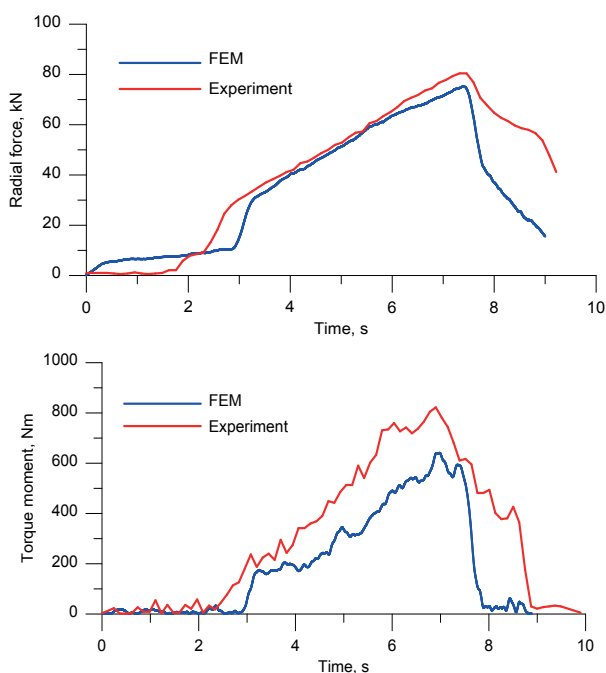


Fig. 12. Force parameters determined by FEM and experimental analysis of rotary compression: a) radial force, b) torque

4. Summary and conclusions

Numerical techniques are nowadays more and more often applied to investigate metal and metal alloy forming processes. When designing new technologies, tools and machines, it is possible to optimize process parameters and even design solutions already at the initial stage of the design process, thereby reducing the number of implementation tests to be conducted. This is particularly important with regard to new and relatively expensive technologies, where the final result is difficult to predict and every error made entails grave financial consequences. For this reason, it is therefore justified that in such cases pre-implementation virtual analysis be conducted in order to determine optimum process parameters to ensure the production of parts with high geometric and mechanical properties.

The innovative rotary compression method described in the paper allows for forming tubes into hollow stepped axes and shafts. In effect, the material consumption and labor costs are reduced, which is of economic importance from the point of view of both series and mass production. The application of this process requires, however, the use of non-conventional machines and devices with complex kinematics of tools. To illustrate this, the present study describes the design of a forging machine for rotary compression used in the experimental tests on producing hollow shafts by the proposed method.

Based on the analysis results, the following conclusions have been drawn:

- the rotary compression method can be applied to produce stepped axes and shafts from tubes;
- shafts produced by rotary compression are characterized by higher wall thickness of formed steps;
- shafts produced by rotary compression processes exhibit a high non-uniformity of strains;
- during the rotary compression process for hollow shafts, the internal wall of the workpiece may crack;
- the developed design of the forging machine allows that the rotary compression process for hollow shafts be run in accordance with the design;
- the results of the tests performed with regard to machine strength demonstrate that subjecting the machine to the required load does not damage the machine structure or deforms the critical components of this machine; during the operation of the forging machine, high elastic strains of the roll system can occur; these strains should not, however, exert negative effect on accuracy of produced parts as the machine load is successively decreased during the sizing stage;
- it is justified that further research be conducted to determine both process limiting and the combined effect of technological parameters of rotary compression and geometry of both billet and produced parts.

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