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Producing hollow drive shafts by rotary compression

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ABSTRACT

The paper presents the numerical and experimental results of producing hollow parts by a new method of rotary compression. First, the most popular methods for producing axisymmetric hollow parts are described. Next, the paper examines the forming of such parts by rotary compression. With the method, a hollow billet is shaped by tools that both rotate and translate relative to the axis of the billet. In order to estimate the technological viability of rotary compression, we numerically model the rotary compression process for a drive shaft by the finite element method. The 3D FEM simulations are performed using the Simufact Forming software suit. Thermal phenomena are investigated. The numerical results are then verified under laboratory conditions. The experimental results show a good agreement with the FEM results, which confirms that hollow parts such as stepped axes and shafts can be produced by rotary compression.

1. Introduction

One way of reducing production and maintenance costs of vehicles is to decrease their mass. A lower mass of vehicles to be produced means that material consumption can already be reduced at the production stage; while the use of lower mass vehicles results in reduced fuel consumption and emissions as well as in higher load capacity and better technical performance of such vehicles. Their mass can be reduced, among others, by the application of modern low-density constructional materials, such as light metal alloys, composite materials and plastics. It is to be noted however that components of suspension and power transmission systems are still predominantly made of steel, which is the material with a relatively high specific gravity. Nonetheless, the mass of these components can still be reduced by replacing solid parts with their hollow counterparts. One group of machine parts that could be manufactured hollow comprises axes and shafts, including toothed ones [1–4]. Due to the type of load they carry (mainly, bending and torsional moments), hollow axes and shafts exhibit strength properties comparable to those of solid parts; at the same time, however, they are more lightweight than their standard solid counterparts.

Nevertheless, it should be stressed that the above benefits offered by hollow parts can only be taken full advantage of provided that these parts are made from hollow billets with some finishing allowance. This solution requires, however,

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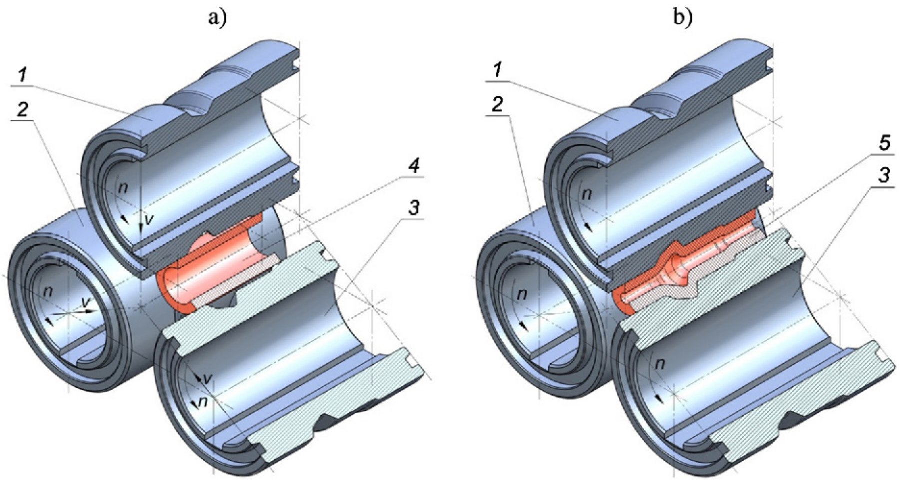

Fig. 1 – Schematic design of the rotary compression process for a hollow stepped shaft: (a) start of the process and (b) end of the process.

that advanced forming technologies be developed to enable the production of parts made of both solid billets and hollow ones (commercial tubes).

Stepped shafts and hollow axes currently applied in the automotive industry are mainly produced from die forgings by machining techniques. Despite the use of semi-finished products, the production of these parts still involves relatively high material and labour consumption, which results, among others, from the necessity of removing substantial technological allowance and making holes. Their production could be modernized by the application of forming processes for hollow shafts. To do so, we could employ the rotary compression technique developed at the Lublin University of Technology [5,6]. Rotary compression is a process wherein hollow billets (tubes) are shaped into axisymmetric hollow forgings by three identical cylindrical rolls. The rolls rotate in the same direction and, at the same time, travel radially to the axis of the workpiece (Fig. 1). The billet (tube) is put between the tools. During the process, the tools make the billet rotate, reducing the steps of a shaft.

Compared to current manufacturing techniques for hollow products, rotary compression offers a number of benefits, the most important being better strength properties of products formed thereby, higher production efficiency, as well as lower implementation and production costs. In addition, the process is relatively easy to run and can easily be automated.

This study presents the results of theoretical and experimental investigations of a hot rotary compression process for producing a hollow multi-stepped shaft (Fig. 2) used in the power transmission system of a vehicle.

In the study, it is proposed that the forgings of shafts be produced from tubes in one operation. This solution seems optimal for economic and technological reasons, as it allows reducing both the number of operations to be performed and the amount of material used (Fig. 2). As a result, the production time is shorter, fewer machines and technological devices need to be used, and the production costs are reduced.

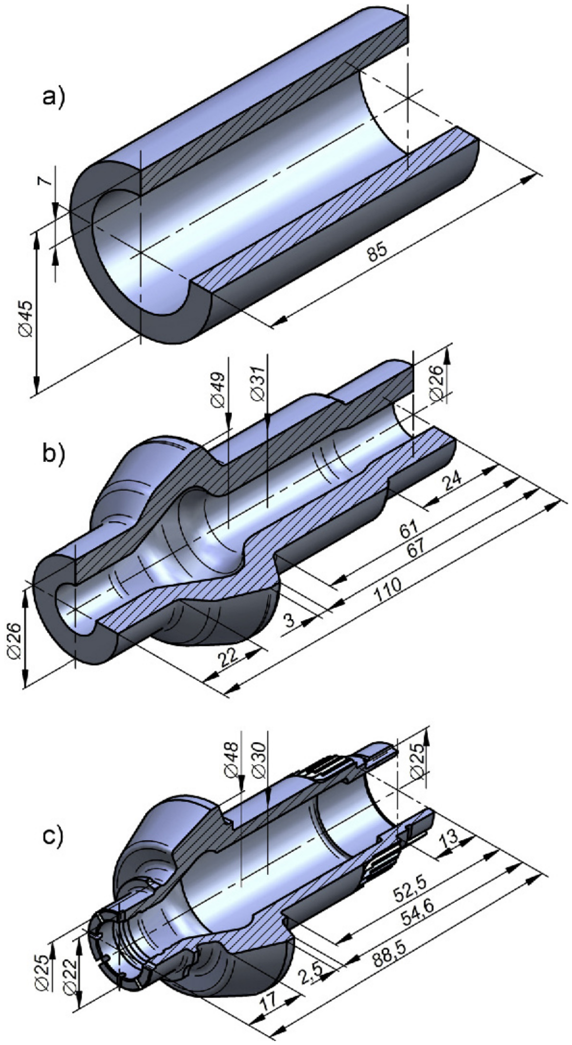

Fig. 2 – Shape and dimensions of: (a) hollow billet, (b) hollow drive shaft forging, and (c) finished drive shaft.

2. Numerical modelling of the rotary compression process for producing a hollow stepped shaft

Using numerical methods, we evaluated the technological viability of producing hollow stepped shafts by rotary compression. Also, we determined the range of technological parameters that enable process stability. Numerical simulations were performed by the finite element method using the commercial Simufact Forming software suite version 12.0, since this software is frequently employed in the analysis of metal forming processes and the numerical results show a good agreement with the experimental data [7–10]. The main objective of the investigation was to determine the kinematics of metal flow, thermal parameters and phenomena disturbing the stability of the rotary compression process for hollow stepped shafts.

The geometrical model of the rotary compression process for a shaft used in the numerical modelling is shown in Fig. 1. The model consists of three identical tools and a billet. The profile of the working space of the tool corresponds to the outside shape of a shaft to be produced. In the process, the tools rotate in the same direction at a constant velocity, *n*, set to 36 rpm and, at the same time, they travel towards the axis of the billet at a constant velocity, *v*, set to 3.5 mm/s. The tube used as the billet has an outside diameter of 45 mm and a thickness wall, *g*, of 7 mm, and a length, *l*, of 85 mm. The billet was modelled by eight-node hexagonal elements and was assigned the properties of C45 steel, as this material is widely used to produce a variety of gears, shafts, axes, toothed shafts, connecting rods, etc. The elastic–plastic model C45 steel applied in the numerical modelling was obtained from the material database library of the database of Simufact Forming; it was defined by the following dependence [11]:

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

where T is the temperature (ranging from 700 °C to 1250 °C), ε is the strain, $\dot{\varepsilon}$ is the strain rate.

In the simulations, the billet was heated to a temperature of 1150 °C, while the temperature of the tools was maintained constant at 80 °C. The constant friction model on the metal–tool contact surface was applied, with the friction factor set to the boundary value $m = 1$ [12,13], the heat transfer coefficient between the material and the tool was set to 20 kW/m^2 K, while that between the material and environment was 0.3 kW/m^2 K.

The shape of a hollow stepped shaft obtained in the FEM analysis as well as the distribution of the effective strain on both the surface and in the cross sections of the shaft are shown in Fig. 3. As can be observed, the shape of the produced shaft is as required. Moreover, the profiles of cross sections of the successive shaft steps (both of the inside and outside walls) are free from excessive ovalization. The satisfactory geometry of the product confirms the suitability of the adopted forming technique for producing hollow shafts. The kinematics of both the tools and workpiece motion has a significant effect on the process and the final shape of the product. In rotary compression, the tools rotate in the same direction and set the billet into a rotational motion. Due to the rotational motion of the workpiece, the material reduction is gradual and occurs simultaneously in three areas spaced every 120° on the circumference of the workpiece. This nature of deformation ensures better process stability and lower forming forces, when compared to other forming techniques. First, the rotating and radially moving tools shape the end steps of a shaft, which is accompanied by a rapid radial and axial flow of the metal. This leads to a non-uniform increase in both thickness of the workpiece wall and length of the shaft's end steps. All steps of the shaft are then being reduced until the workpiece diameter is reduced as required. In the final stage of the process, the tools only rotate to remove any product shape inaccuracies generated in the previous stages of the rotary compression process. Examining the material flow kinematics, it can be observed that the end steps of the shaft are shaped during the radial and axial flow of the metal. The central step of the shaft is shaped when the material flows mainly radially towards the axis of the workpiece, which is accompanied by a rapid increase in thickness of the workpiece wall.

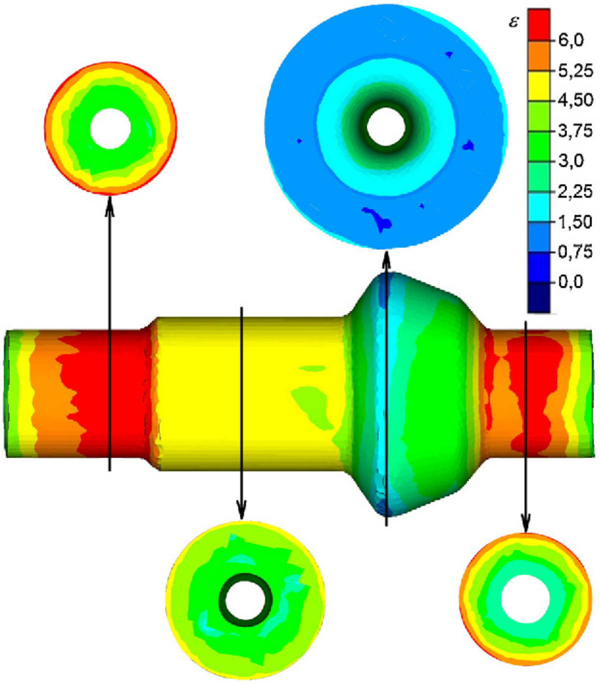

Fig. 3 – FEM-obtained effective strain in a hollow shaft.

In the region of the conical step (one with the highest diameter), the material undergoes upsetting, which leads to a higher diameter of the produced shaft compared to the original diameter of the billet (the hollow workpiece had an outside diameter of 45 mm, while the maximum diameter of the finished shaft increased to about 49 mm). This significant increase (by approx. 9%) in the diameter of the central step is possible only if we use very short workpiece lengths (in the present case – approx. 4 mm) that will not contact the tools until the final stage of the process. With longer lengths, this phenomenon of diameter increase is local and it occurs in the regions near end faces of shafts that are not to be deformed or near steps that are to be sized. Examining the strains (Fig. 3), it can be noted that the material is not uniformly deformed. The strains in the cross sections are ring-shaped. The highest strains are observed in the close-to-surface layers of the end steps of the shaft; then, the strains decrease the closer it is to the inside wall of the workpiece. This type of deformation is characteristic of rotary metal forming processes and it results from the kinematics of tool and workpiece motion. In addition, what can be observed here are significant differences in circumferential velocities of the steps being compressed, due to a variable radius of the tools. In effect, the material slips between the tools and, consequently, substantial strains are produced on the circumference by friction forces, which does not, however, alter the workpiece geometry.

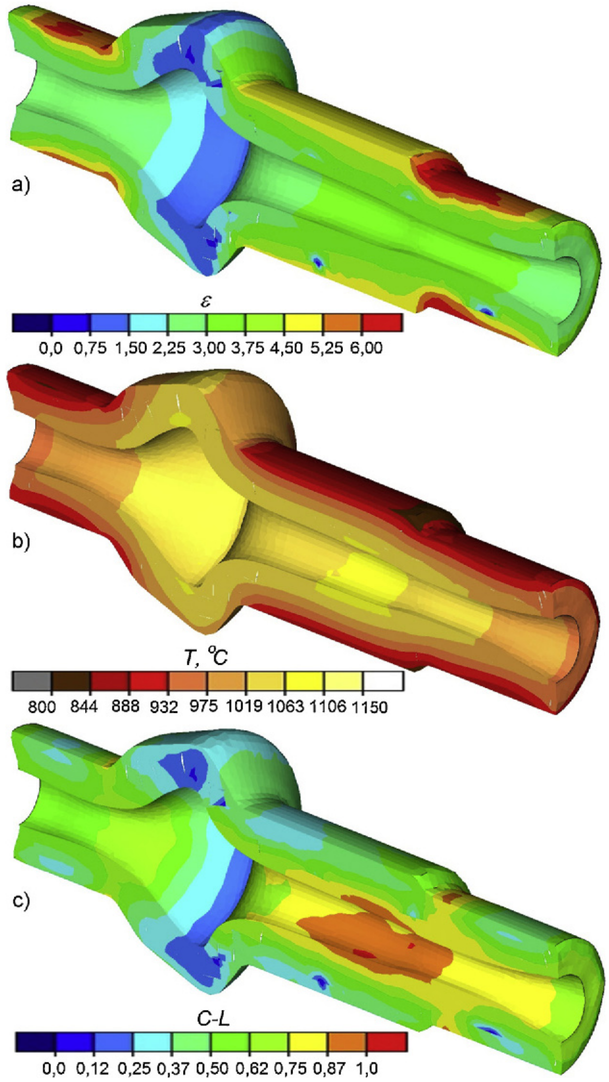

Fig. 4 – FEM-obtained distributions of: (a) effective strain, (b) temperature, and (c) Cockcroft–Latham damage criterion.

The FEM-obtained distributions of the effective strain, temperature and Cockcroft–Latham damage criterion are compared in Fig. 4. It can be observed that these distributions are not uniform. The maximum strains are located in these workpiece regions that were subjected to the highest cross-sectional reduction (Fig. 4a). As observed earlier, the close-to-surface regions are deformed to a much greater extent than the ones in the centre. Furthermore, the temperatures of the billet and of the finished product have a significant effect on the process. One characteristic of the obtained distribution (Fig. 4b) is a non-uniform and relatively high drop in temperature of the workpiece (up to approx. 800 °C). This information is particularly important due to a relatively long time of the process (approx. 11 s) and a low thermal capacity of the workpiece. The observed drops in the temperature predominantly result from the fact that heat is transferred to the tools; these drops occur on the outside surface of the workpiece, where the material remains in a cyclic contact with the much colder rolls for the entire duration of the process. The excessive cooling of the material can lead to a lower plasticity of the material as well as to higher deformation resistances, which can consequently disturb the rotary compression process. This observation was confirmed by the numerical modelling and experimental tests of forming parts at lower temperatures. We found that reducing the workpiece temperature to below 800 °C hinders radial flow of the material, which can lead to the loss of stability of shaft walls and thus to substantial ovalization of the cross section of shaft steps. To avoid this, it is recommended that workpieces with high diameter reduction ratios (as is the case in the process described in the present paper) should be formed at high heating temperatures. Also, in the series production of shafts, the temperature of the tools will be higher (approx. 200 °C) than we assumed in the numerical analysis. Consequently, the temperature drops of finished parts will not be as sharp as those observed in the simulations, which will undoubtedly improve stability of the process. In the simulations, we also investigated crack formation in the workpiece. To this end, we employed the standard Cockcroft–Latham criterion described by [13]:

$$C = \int_0^{\varepsilon} \frac{\sigma_1}{\sigma_i} d\varepsilon, \quad (2)$$

where σ_1 is the maximum principal stress, σ_i is the effective stress, ε is the strain, and C is the Cockcroft–Latham damage criterion.

The Cockcroft–Latham criterion determined by (2) is juxtaposed with the experimentally calculated boundary value. The calculation results (Fig. 4c) demonstrate that the regions located on the surface are most prone to cracking in rotary compression. The value of the Cockcroft–Latham criterion in these regions equals approx. 1, which is close to the boundary values when material cracking can occur. It can however be observed that the range with the maximum values of the Cockcroft–Latham criterion is narrow. They are concentrated in the surface layers of the hole, in the vicinity of the central step of the shaft, or the region where thickness of shaft walls increases to the greatest extent. As a result, this region is most prone to cohesion loss on the material's surface. It should however be noted that the surface layers where potential cracking will occur are, at the same time, the allowance to be removed in finish machining. It can also be observed that values of the damage criterion are quite high between the end and central steps of the shaft. This region is characterized not only by a considerable diameter reduction but also by a rapid twist of the end step, which is caused by different circumferential velocities of the steps being rotary compressed. This load patter can thus lead to tearing off the end step of the shaft, particularly if the workpiece is overcooled, so plasticity of the material it is made of is lower. Nonetheless, the experimental results do not reveal any signs of material cohesion loss in the above-mentioned region.

3. Experimental tests of the rotary compression process for producing a hollow stepped shaft

The satisfactory numerical results preliminarily confirmed the possibility of producing hollow shafts by rotary compression. Therefore, we found it justified to perform experimental tests of producing hollow shafts by the proposed technique. The main objective of the tests was to verify the numerical models and to ultimately determine the technological potential of rotary compression. To perform the tests, we used a forging machine designed and constructed at the Department of Computer Modelling and Metal Forming Process at the Lublin University of Technology (Fig. 5) [14]. With the use of the machine, the rotary compression process can be run in compliance with the design adopted in the numerical simulations. The machine for rotary compression consists of a frame, a power unit, a gear box, a system of rolls, a hydraulic power unit for the rolls and a set of measuring instruments. The rotary compression process is performed in the rolls system by three radially moving slides with working rolls mounted to them. The forces and kinematic parameters of the rotary compression process were measured using a measuring system consisting of a torque converter, a displacement sensor and pressure measuring sensors. Signals emitted by the sensors were recorded digitally with a measuring card.

Fig. 5 – Machine for rotary compression used in the experiments.

As billet, we used C45 steel tubes which had an outside diameter of 45 mm, a wall thickness, g_o, of 7 mm and a length, L, of 85 mm (in accordance with the dimensions set in the numerical modelling). The tubes were first heated in an electric chamber furnace to a forming temperature of approx. 1150 °C, and then fed with the pliers into a feed mechanism for maintaining the billet position in the machine's working space (formed by the three rotating rolls). Next, the rotating and radially moving rolls made the billet rotate, thus shaping the successive shaft steps (Fig. 6a). Once the slide travelled the length corresponding to the required diameter reduction, the translational motion was stopped only to start the sizing of workpiece shape during a further revolution of the rolls. In the final stage of the process, the tools opened in a radial manner and the produced forging was ejected from the working space of the machine in the special feed container (Fig. 6b). In the process, the rolls were rotated in the same direction at a constant velocity, n, of 36 rpm and, at the same time, they travelled radially at a constant velocity, v, set to 3.5 mm/s.

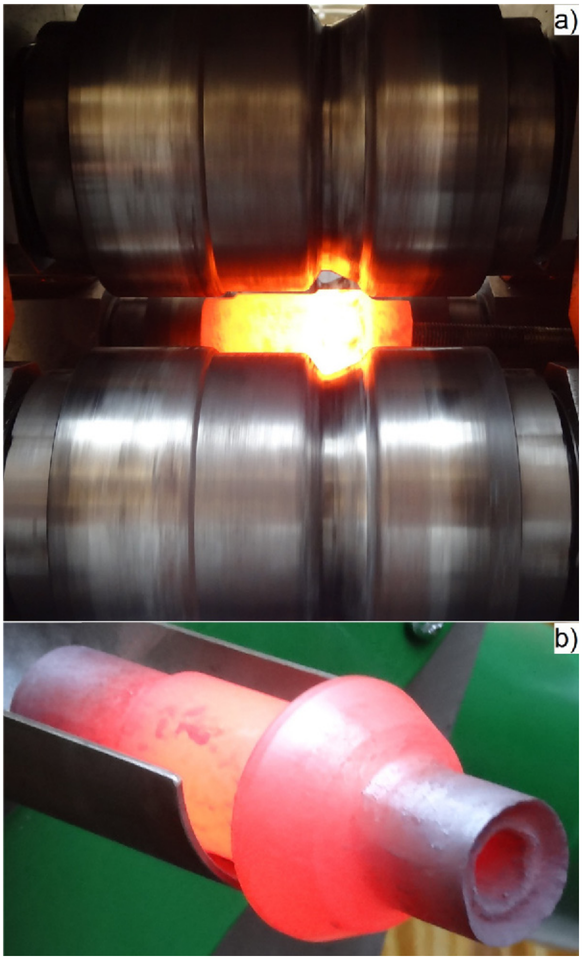

Fig. 6 – Experimental tests of the rotary compression process for a hollow drive shaft: (a) start of the process and (b) finished forging.

The experimental results (with regard to shape and dimensions of the products) show a good agreement with both the theoretical assumptions (required shape of the shaft) and numerical results. The surface of the shafts is smooth and free from any defects. No internal cracking was observed, either. Based on these findings, it was concluded that the rotary compression technology can be employed to shape tubes into hollow stepped shafts. The forging of a hollow stepped shaft obtained in the numerical modelling and experiments as well as a finished shaft produced from this forging are shown in Fig. 7. The produced forging exhibits high dimensional and geometrical accuracy. The machining allowance (approx. 1 mm on the outside diameters) is sufficient, so after its removal the product shape will correspond with that in the production drawing (Fig. 7c).

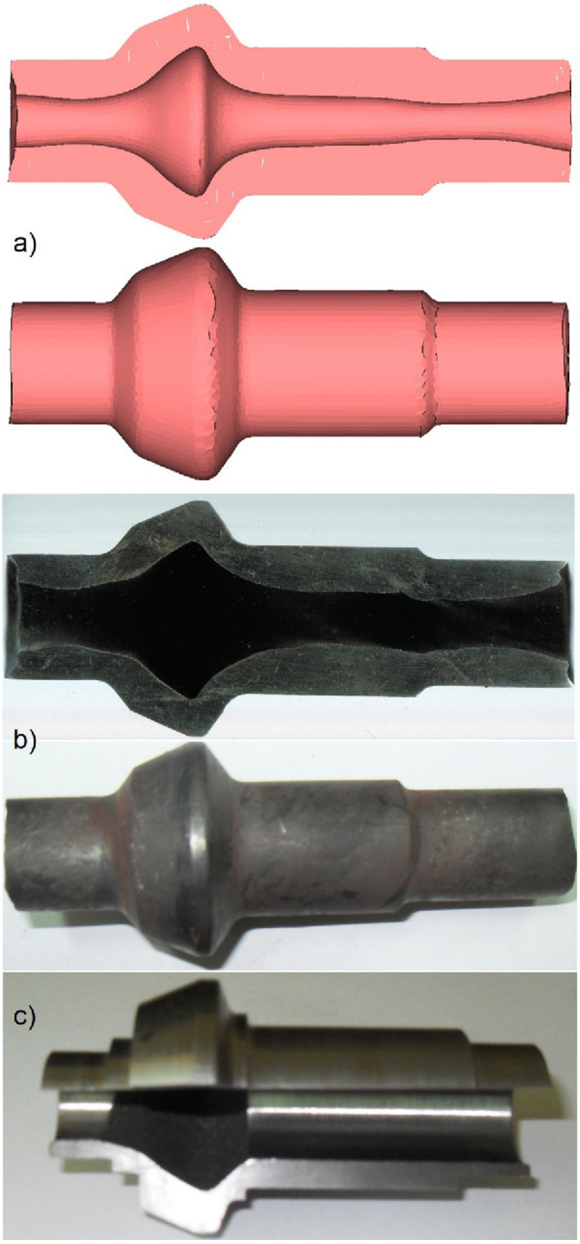

Fig. 7 – Shape of a hollow stepped shaft forging: (a) FEM, (b) experiment, and (c) stepped shaft made from the forging.

The ends of the workpiece rapidly elongate during the forming process. As a result, the workpiece length increases compared to the original length of the billet, which means a higher machining allowance, too. The elongation of the end steps of the shaft can be reduced by equipping the rolls with flanges to constrain the material in the tools and thereby prevent its axial flow.

Fig. 8 compares the shaft wall thickness obtained in the experiments with that modelled by FEM. As can be seen in the figure, the workpiece wall thickness changes during the process, which is caused by the radial and axial flow of the material. Importantly, the dominant trend is that the workpiece wall increases, which ensures higher strength properties of the product. The observed increase in wall thickness is not however uniform over the entire length of the shaft steps being formed. The highest wall thickness increase can be observed in the central steps of the shaft, as they are constrained by the ring-shaped surfaces of the tools. As a result, the material predominantly flows in a radial direction towards the axis of the workpiece. A somewhat different trend can be observed with regard to wall thickness of the end steps of the shaft – here, the wall thickness gradually decreases the closer it is to the end face, which is caused by the axial flow of the material in this area.

Examining the nature of variations in the wall thickness of the shaft, one can observe a high agreement between the experimental and FEM results (Fig. 8). In both cases, wall thickness changes in the same areas of the workpiece. The principal difference between the experimental and numerical results concerns the magnitude of the wall thickness increase. The wall thickness increase of the numerically modelled workpiece is higher by approximately 15% compared to that obtained in the experiments. The observed differences can be due to the fact that the material cools faster in the experiments than is the case in the numerical modelling. The excessive

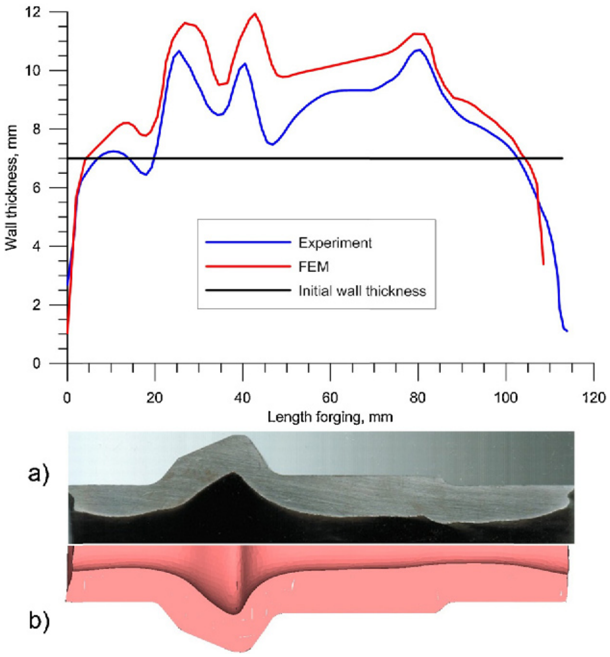

Fig. 8 – Variations in the workpiece wall thickness: (a) experiment and (b) FEM.

cooling of the workpiece leads to an increase in deformation resistances to radial flow of the metal and, as a result, to a lower increase in thickness of the workpiece wall.

The numerically and experimentally determined variations in the forces and torques in the rotary compression process are shown in Fig. 9. The experimental and numerical results show a high agreement, both in terms of quality and quantity.

The variations in the forces and torques in rotary compression depend on a given stage of the process. In the initial stage, the forces and torques gently increase due to the reduction in the workpiece diameter in the region of end steps. Next, when all steps of the shaft are being shaped simultaneously, the forces and torques rapidly increase. This rapid increase in the forces parameters is caused by both an increase in thickness of the workpiece wall and a rapid cooling of the material, which leads to higher plastic resistances to the material flow. The highest forces and torques occur at the final stage of the process, when the position of the tools corresponds with the required reduction in outer diameter of the workpiece. The translational motion of the rolls is then stopped and the rolls are only left to rotate. This makes the sizing of the workpiece shape begin, which is the final stage of the rotary compression process when the forces and torques rapidly decrease. Despite a high agreement between the FEM and experimental variations in the force parameters, the forces and torques are higher in the experiments (in the final stage of forming and during sizing). This confirms the above observations that the material cools faster in the experiments compared to the numerical model.

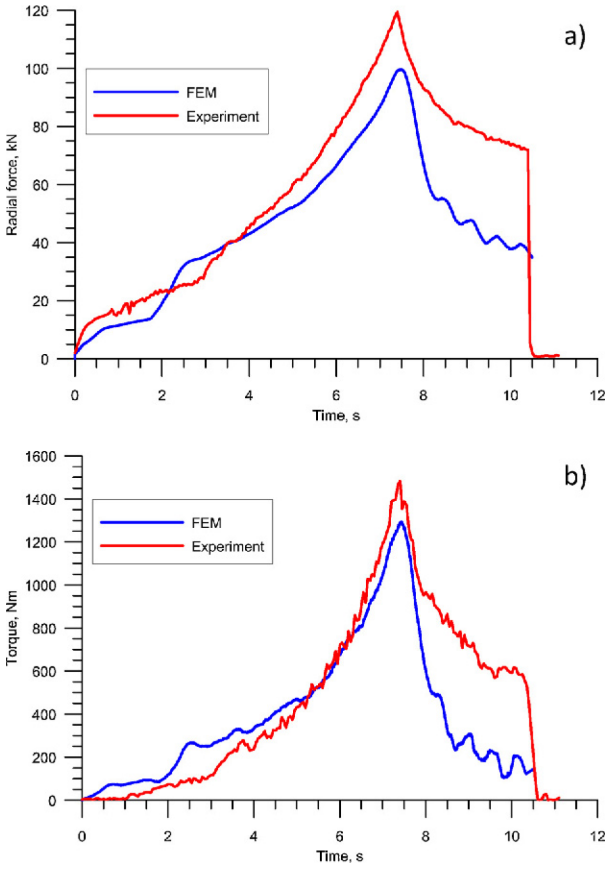

Fig. 9 – Variations in: (a) tool force and (b) torque.

4. Summary and conclusions

The rotary compression process for hollow parts is an innovative alternative to conventional methods for producing hollow axes and shafts. The main advantages of this process include high efficiency, simple tool design, the use of hollow billets, enhanced strength properties of parts produced thereby and the ease of process automation. The simple design of the tools allows to effectively form parts in both small batches and on a mass scale. Owing to the possibility of using hollow billets, rotary compression is characterized by a much lower material consumption compared to other manufacturing techniques, such as machining or conventional metal forming processes. All these render the rotary compression technique very attractive for industrial applications, hence it is believed that the process will be developed further.

The conducted theoretical and experimental analyses of the rotary compression process have confirmed that hollow billets (tubes) can be shaped into hollow forgings of stepped shafts. In addition, based on the results, the following conclusions have been drawn:

- rotary compression processes can be modelled numerically;
- the numerical and experimental results show a high agreement;
- in rotary compression, both wall thickness of the workpiece and length of the workpiece ends are increased;
- the rotary compression process for hollow parts exhibits a significant non-uniformity of strains;
- in rotary compression, the workpiece diameter locally increases, which enables the use of billets that will have a lower diameter than that of the finished product;
- temperature has a significant effect on the rotary compression process;
- excessive cooling of the material leads to an increase in the forming forces, which can disturb the process;
- further investigations should be conducted in order to determine the relationships between technological parameters of the rotary compression process and the quality of produced parts.

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