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A Theoretical and Experimental Analysis of Rotary Compression of Hollow Forgings Formed Over a Mandrel

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The paper presents selected results of studies of the process of forming hollow stepped shaft forgings by rotary compression with rotary tools. The aim of the study was to determine whether rotary compression could be performed using an additional tool – a mandrel, which, when positioned in the cavity of the workpiece, could be used to shape the surface of the cavity. A theoretical analysis was based on finite element modeling using Simufact Forming software. During the simulations, distributions of deformation intensity, temperature, and the Cockroft–Latham fracture criterion were determined. Predictions were also made regarding phenomena such as slippage and deformation of forging pieces and material cracking, as potential impediments to the investigated process. Additionally, force parameters were determined during the forming of forgings. Numerical results were verified experimentally. Rotary compression tests for hollow forgings were carried out in a special forging machine designed by the present authors. The results were validated on the basis of the geometric parameters of formed forgings and the force parameters of the process. The results confirm that hollow stepped shaft forgings can be formed in the process of rotary compression using a mandrel. Forgings formed over a mandrel are characterized by greater precision and quality compared to freely formed blanks (without a mandrel).

Keywords: rotary compression, hollow forgings, stepped shaft, finite element method (FEM), experiment.

Introduction. The widespread tendency to reduce the costs of maintenance of machines and equipment leads to an increasing use of hollow elements for their construction. Hollow parts, among other things, substantially reduce the weight of a structure while allowing to maintain its required strength parameters [1–4]. In many cases, the use of hollow elements also leads to material and energy savings at the stage of manufacturing. Hollow machine parts are produced using metalworking methods, in which the workpiece is formed hollow along its full length (with some stock allowed for finishing). In addition to the economic benefits, this approach also has practical merits. The use of metalworking methods improves the strength properties of elements (continuity of grain in the stock material is preserved and, in the case of cold working, the material is strengthened) [5]. It should be noted, however, that the currently used metalworking methods for forming hollow elements, in most cases, are characterized by a high degree of complexity, which requires the use of expensive machines and equipment [6]. As a result, the efficient use of such processes is only possible in high-volume and mass production settings [7, 8]. Unfortunately, the forging industry in Poland characteristically produces a large variety of products formed in small batches, which often limits the possibility of applying metalworking techniques in the manufacturing of hollow products. In view of this, it seems worth seeking new technological solutions that would make metalworking of hollow elements profitable even in small production runs. Developing an efficient and cheap metal forming technology for manufacturing hollow elements will undoubtedly boost the competitiveness of companies and improve the efficiency of manufacturing processes.

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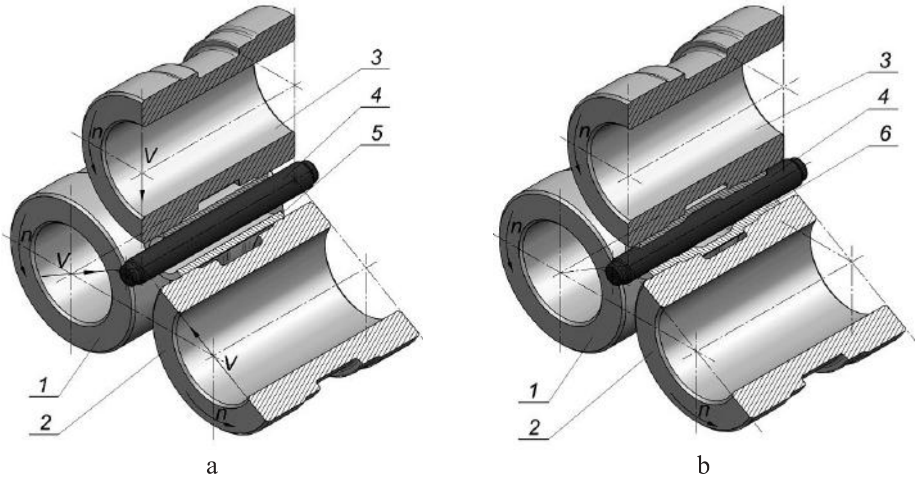
One method that corresponds well with systems of flexible manufacturing of hollow machine parts is rotary compression.

It is a relatively new method of producing hollow stepped shaft and axle forgings from tubular blanks [9, 10]. In the process, a tube-like or a bush-like blank is rotary compressed with three tools (rollers), which rotate and simultaneously translate in the direction of the axis of the blank. The tools used in the process are stepped rolls in which the contour of the work surface is the inverse of the desired shape of the shaft forging. As an effect of the rotational impact of the tools on the material, the outer diameter of the successive steps of the product is reduced. This is accompanied by an increase in billet wall thickness, which in many cases can be regarded as a benefit for strength and often also structural reasons. A characteristic feature of products formed using rotary compression is their axially symmetrical shape. Compared with other currently used hollow-product manufacturing methods, rotary compression has several advantages, the most important of which are reduced forming forces, improved product strength, increased productivity, simple tool and machine design, reduced material and labor consumption and a relatively simple process scheme, which can be easily mechanized and automated [11]. Studies conducted so far fully confirm the possibility of using rotary compression to form hollow forgings from tubular workpieces, but their main focus has been the forming of the outer surface of hollow forgings, with the inner surface (the bore) being deformed freely as an effect of radial flow of the material [12, 13]. Such material flow kinematics lead to heterogeneous changes in wall thickness and poorer quality of the bore surface, increasing stock allowance that has to be removed during finishing. The above defects can be partially eliminated by supporting the surface of the opening on a mandrel. The use of a mandrel allows simultaneous forming of the steps of the forging and the surface of the bore in a controlled manner. A schematic diagram of rotary compression of forgings over a mandrel is shown in Fig. 1. During the compression process, the mandrel can rotate freely along with the forging. It acts as an additional tool that shapes the inner surface of the forging.



a b

Fig. 1. Process scheme of rotary compression of hollow forgings over a mandrel: beginning (a) and end (b) of the process: (*1–3*) stepped rollers, (*4*) mandrel, (*5*) billet, and (*6*) forged part.

In order to establish whether hollow stepped shaft forgings could be manufactured by rotary compression over a mandrel, a series of numerical calculations were performed. The results obtained were then verified in laboratory experiments. The theoretical and experimental investigations were carried out for the process of forming a hollow stepped shaft forging from a tubular blank (Fig. 2).

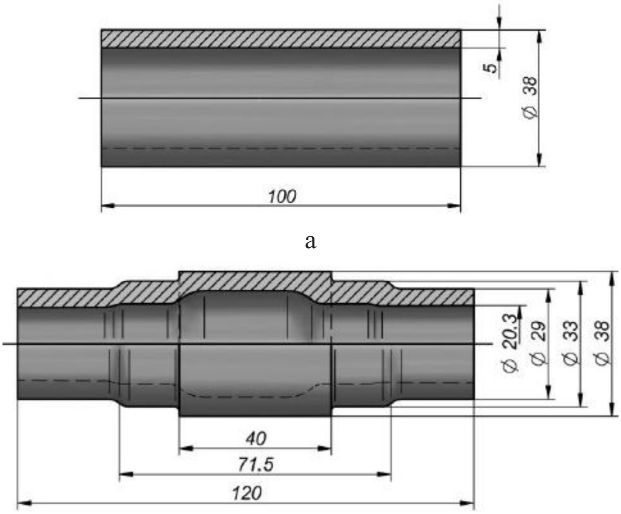


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Fig. 2. Shape and dimensions of the blank (a) and forging (b).

FEM Numerical Analysis of Rotary Compression of Hollow Forgings over a Mandrel. Numerical analysis of the process of forming the forgings was performed using the finite element method. The calculations were done under three-dimensional strain using Simufact Forming software version 14.0. A geometric computational model was developed which corresponded with the process scheme shown in Fig. 1.

The stepped roller tools (*1–3*) and the mandrel (*4*) were modeled as rigid bodies. On the other hand, the billet (a C45-type tube segment with an outer diameter $D = 38$ mm, wall thickness $g_0 = 5$ mm, and length $l_0 = 100$ mm) was modeled as a rigid-plastic body using eight-node first-order elements. The material model for C45 steel used in the computations was gleaned from the Simufact Forming 14 library [16] and was given by

$$\sigma_p = 2859.85\exp(-0.00312548T)\varepsilon^{0.0000044662T-0.101268}\times$$

$$\times\exp\left(\frac{-0.000027256T+0.000818308}{\varepsilon}\right)\dot{\varepsilon}^{0.0001511151T-0.00274856}, \qquad (1)$$

where T is the temperature (in the range of 700 to 1250°C), ε is the strain, and $\dot{\varepsilon}$ is the strain rate.

In addition, it was assumed in the calculations that at the initial stage of the process the entire volume of the billet was heated to a temperature of 1180°C, while the tools had a constant temperature throughout the forming process which was 100°C for the rollers and 400°C for the mandrel. In the process, the rollers rotated in the same direction at an identical speed $n = 36$ rpm, simultaneously moving in the direction of the billet axis at a constant speed $V = 1$ mm/s. The mandrel placed inside the billet was free to rotate around its own axis. The contact surface between the material and the tools was described by the constant friction model. Since rotary compression was performed as a hot forming process, calculations were done under the assumption that the limit value of the friction coefficient $m = 1$. In addition, it was assumed that the heat exchange factor between the material being formed and the tool was 20 kW/($\mathrm{m}^2 \cdot$K), and that between the material and the surroundings was 0.35 kW/($\mathrm{m}^2 \cdot$K).

The results of the calculations allowed us to analyze the kinematics of material flow in the hollow forgings rotary-compressed over a mandrel. Figure 3 shows how the shape of the product changes during the successive stages of the process. It can be seen that in the first stage of the process, material flows freely in the area of the forging bore (which is associated with the fact that the diameter of the mandrel is smaller than the diameter of the hole in the blank).

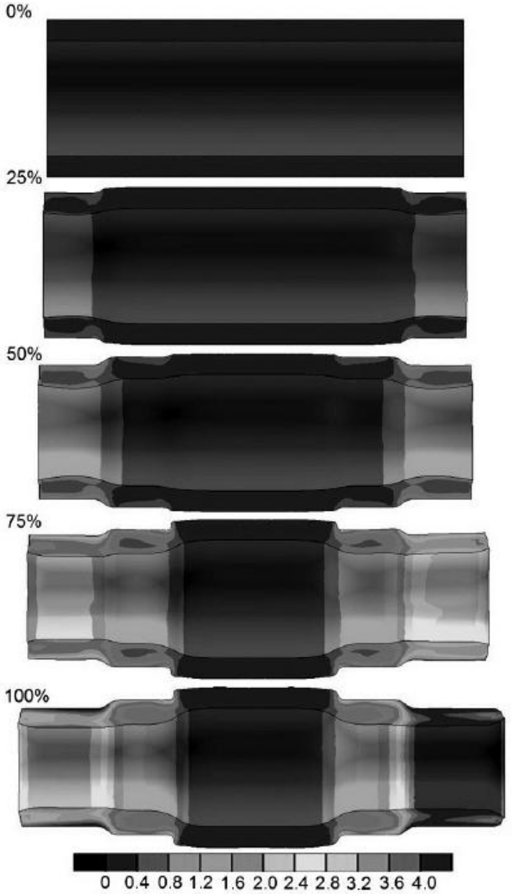


Fig. 3. Changes in the shape of a hollow stepped shaft forging during rotary compression over a mandrel as determined by FEM. The distribution of deformation intensity is shown.

As the outer diameter of the billet at the end journals of the workpiece is reduced, the material moves in the direction of the billet axis, which causes an uneven increase in wall thickness. Small displacements of material along the axis of the forging can also be observed, particularly in the area close to the surface. In the second stage of the process, as the outer diameter of the blank becomes smaller and smaller, the material at the surface of the hole comes into contact with the mandrel. As an effect of the mandrel restricting radial material flow, the forging wall in the area of the end journals is squeezed down and pushed out. This leads to a strong distortion of the cross section of these steps and a significant increase in their length. At the same time, the bore in the area of the central (transition) steps deforms in a free manner. In the final stage of rotary compression, after the tools have traveled the required path for the blank to achieve the assumed degree of deformation, the rolls continue to rotate but the translational motion is stopped. By rotating, the tools calibrate the shape of the forging, removing the surface irregularities generated in the previous phases of the process. Figure 3 also shows deformation intensity distributions in axial sections of the blanks. The distributions point to a large heterogeneity of deformation. In the areas close to the surface, the material undergoes more processing compared to the central zones. This is a characteristic feature of rotational metalworking processes. This phenomenon is related to the kinematics of the process, in which there is slippage between the material being formed and the tools as well as large deformations in the circumferential direction (caused by friction forces). Importantly, deformations in the circumferential direction do not change the geometry of the product but result in a considerable increase in deformation intensity (especially in the surface layers), which is reflected in the ring-like character of the obtained distributions (Fig. 4). There is also a large difference in deformation values at the end journals of the forging. The difference observed is related to the shape of the mandrel over which the billet is being formed. To simplify loosening the mandrel out of the hole of the forging, the mandrel was slightly tapered (1:150). As a result, the diameter of the bore of one of the end journals of the forging was nearly 1 mm larger than the diameter of the bore of the step on the opposite side of the head, which resulted in a greater reduction in wall thickness in this area and increased deformation intensity.

The shape of the hollow shaft forging determined using FEM (Fig. 4) is highly consistent with the designed contour. No deformation of the cross sections of the formed ring-shaped steps was observed. Only the faces of the extreme journals of the forgings had a slight deformation caused by the uneven flow of material in the axial direction. The deformations of the end faces of the product should not affect its final quality as they are found in the stock allowance that will be removed during the finishing.

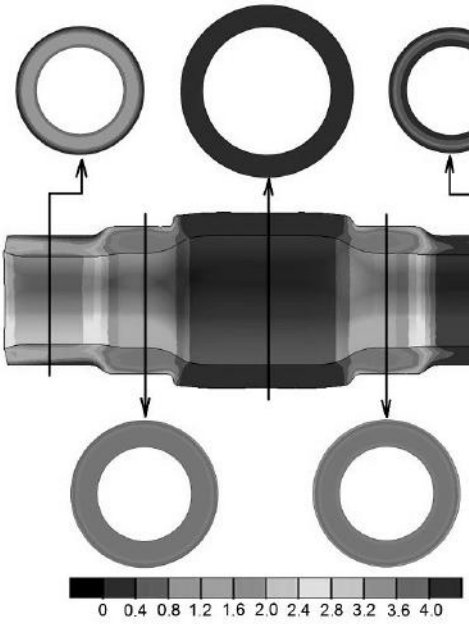


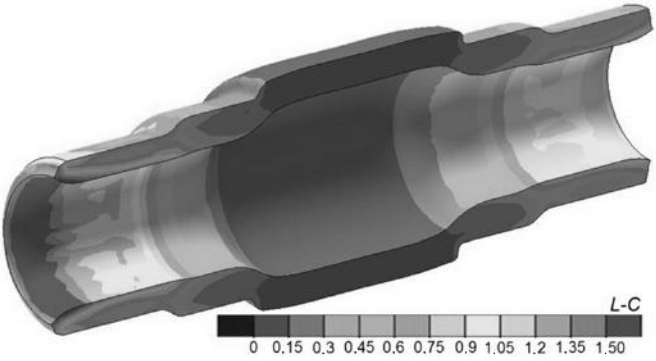
Fig. 4. Distribution of deformation intensity in a longitudinal section and transverse sections of a hollow stepped shaft forging formed by rotary compression over a mandrel.

During the calculations, the possibility of fracture of compressed forgings was also predicted. To this end, the Cockroft–Latham normalized (ductile fracture) criterion was used as given by [14]:

$$C=\int_0^{\varphi}\frac{\sigma_1}{\sigma_i}\,d\varphi, \tag{2}$$

where σ_1 is the maximum principal stress, σ_i is the stress intensity, φ is the strain, and C is the Cockroft–Latham integral.

The Cockroft–Latham integral determined from (2) is compared to the (empirically determined) limit value. The results of the calculations (Fig. 5a) show that in hollow forgings formed by rotary compression over a mandrel, fractures are most likely to occur in areas close to the surface of the cavity. The values of the Cockroft–Latham integral for these areas are relatively high, and – for simple deformation patterns – exceed the fracture limit. For rotational processes, the values of the Cockroft–Latham constant are several times higher than for simple load patterns [11, 15]. This means that the material should not fracture during rotary compression. Furthermore, it can be seen that the maximum values of the criterion characterize a small portion of the forgings. They are mainly concentrated in areas near the surface of the hole, i.e., the stock allowed for finishing. The rolling process is considerably affected by the temperature of the billet and the formed product. A characteristic feature of the distribution in Fig. 5b is the irregular and fairly large drop in temperature in the formed workpiece (to about 800°C). This observation is particularly important in view of the relatively long duration of the process (about 6 s) and the small heat capacity of the workpiece (the initial wall thickness was 5 mm). The observed decreases in temperature are primarily related to the transfer of heat to the tools and occur in those areas of the forging in which the material cyclically comes into contact with much cooler tools throughout the process. Such large temperature drops undoubtedly have a negative impact on the course of the compression process, hindering a plastic flow of material. As a result, excessive cooling of the material may contribute to the deformation of the cross section of the steps being formed and even fracture of the forging's walls.



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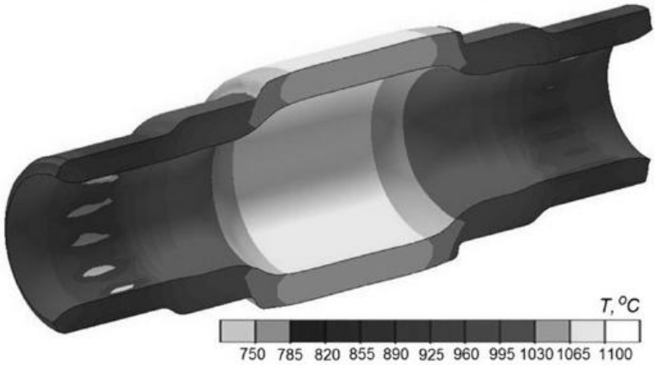

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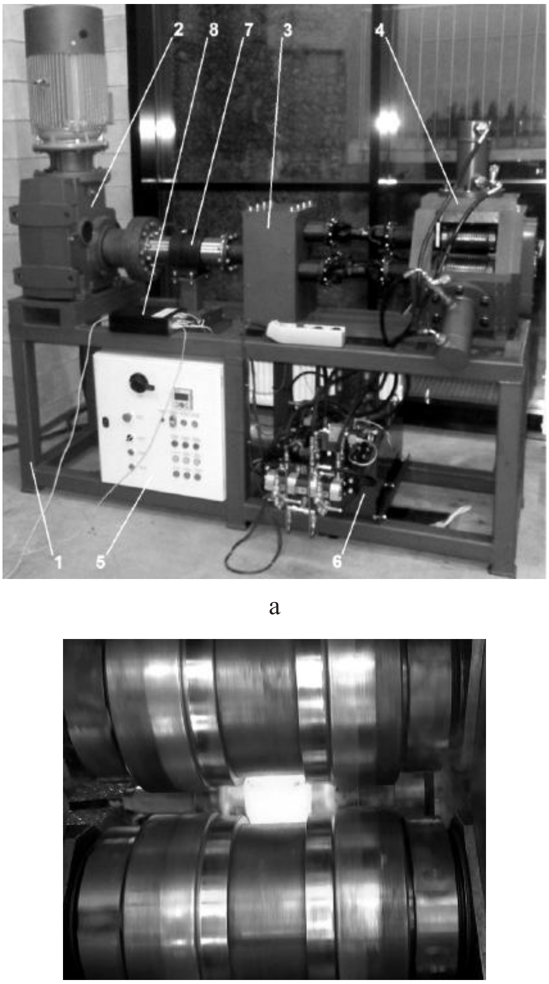
Fig. 5. Distribution of the Cockroft–Latham ductile damage criterion (a) and temperature (b), as determined by FEM.

Experimental Tests of Rotary Compression of Hollow Forgings Over a Mandrel. To verify the numerical models developed and to ultimately confirm the feasibility of the technology, experimental tests of the process were carried out in laboratory conditions. The tests were performed using a forging machine designed and built at the Department of Computer Modelling and Metal Forming Technologies of the Lublin University of Technology (Fig. 6) [11]. The device makes it possible to form parts in accordance with the scheme used for numerical simulations.



a

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Fig. 6. Test stand: (a) rotary compression machine; (b) an image of a forging being rotary-compressed over a mandrel.

The rotary compression machine has a segmental structure and consists of a support frame (*1*), a drive unit (*2*), a pinion stand (*3*), a rolling stand (*4*), power supply and control systems (*5*), a hydraulic drive system for driving the work rollers (*6*), and a measuring system (*8*). Workpieces are rotary-compressed in the rolling stand, in which three slides (movable chocks) move radially guiding the work rolls journaled in them. A measurement system consisting of a torque converter (*7*), a displacement transducer and a pressure transducer was used to record the force and kinematic parameters of the rotary compression process. Signals from all sensors were recorded digitally by the measuring system.

For experimental purposes, three sets of tool segments (in the shape of stepped rolls, Fig. 6b) were mounted over the work rolls of the rotary compression machine. The billets were sections of commercial C45 steel pipes with the following dimensions (identical to those adopted for FEM calculations): an outer diameter of $\varnothing 38$ mm, wall thickness $g_0 = 5$ mm, and length $l_0 = 100$ mm. Semi-finished products were heated in an electric chamber furnace to a forming temperature of about 1150°C, and then introduced by means of tongs into the feed which positioned the billet in the working space of the machine (formed by the three rotating rollers). As a next step, the tools, which simultaneously rotated and moved radially, set the billet in rotary motion and reduced the diameter of the end steps of the forging (Fig. 6b). When the movable chocks have traveled a path needed to reduce billet diameter to the required size ($\delta = D/d = 1.31$), the translational movement was stopped but the rollers continued to rotate in order to calibrate the shape of the forgings. In the last phase, the tools slid apart radially, and the formed forging was removed along with the mandrel from the machine's working space. The formed forgings were free-cooled in the air and visually inspected to detect possible defects. During the tests, the successive phases of the process were analyzed in detail to detect phenomena that could interfere with the process (slippage, distortion of cross section, wall squeezing, flaking). However, no such problems were found. Preliminary visual inspection of the forgings did not show defects that would disqualify those parts from being used in the further manufacturing process (surface finishing). The surface of the forgings was relatively smooth and free of scale, which was automatically removed during the process by the tools and fell to the lower plate of the machine. The measurements showed that the geometric parameters (shape and dimensions) of the forgings were in line with the design assumptions. The hollow stepped shaft forgings formed during the experimental tests are shown in Fig. 7.

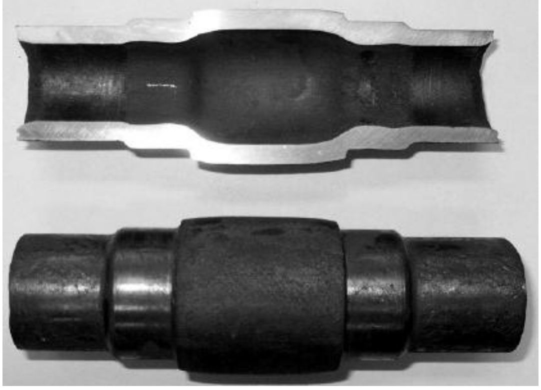

Fig. 7. Hollow stepped shaft forgings formed over a mandrel in the process of rotary compression.

In the course of the analysis, the shape of the forgings determined by FEM was also compared with that of the forgings obtained in the experimental tests (Fig. 8). There was a good agreement, both in terms of quality and quantity, between the computational and experimental results, which fully confirmed the adequacy of the assumptions made during FEM modeling. According to these assumptions, in both cases, the surface of the hole is formed by the mandrel only in the area of the end journals, while the opening in the area of the central steps of the forging deforms in a free manner. This results in an increase in wall thickness of the forging in these areas. In both cases, the faces of the forging are also deformed due to the uneven flow of material in the axial direction. As the action of the mandrel restricts the radial flow of the material, the wall of the blank is squeezed down and pushed out, which leads to an intense elongation of the end journals. As a result, the forging becomes much longer compared with the initial length of the billet, which means more stock is left for later removal on the end steps of the shaft It is also important that no cracks were observed on the surface of the bore (despite the high value of the fracture criterion obtained in the FEM analysis). On the basis of these observations, it was unequivocally established that hollow stepped shaft forgings of required quality can be formed from tubular billets by rotary compression using a mandrel.

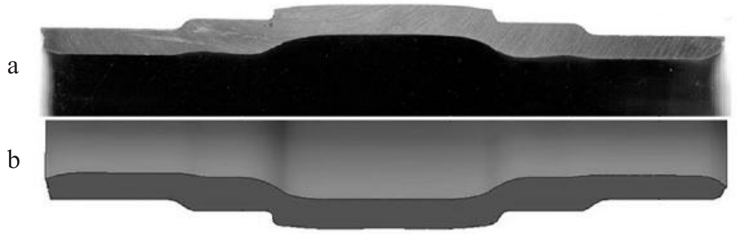

Fig. 8. Axial cross sections of hollow stepped shaft forgings: (a) formed during experimental tests; (b) determined numerically using FEM.

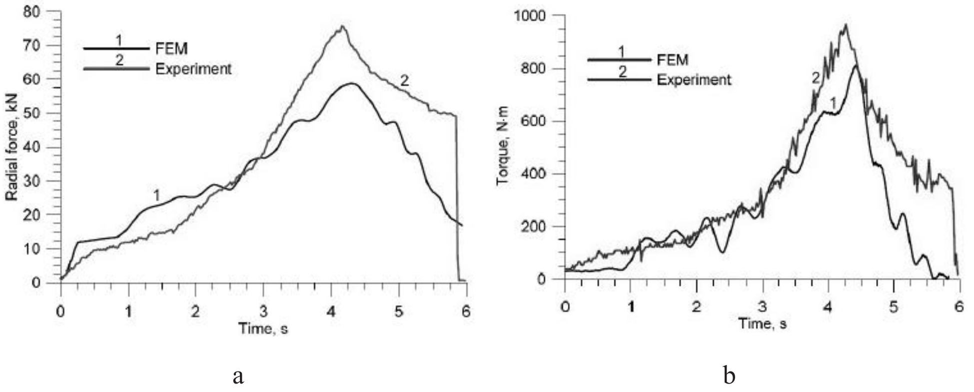

Fig. 9. Experimental force parameter curves: (a) tool contact force; (b) torque.

Other important parameters that were analyzed during the study were the radial-force and torque curves for the forming process. Accurate estimation of the maximum values of these parameters facilitates proper development of the technology and then enables verification of the structural and technological assumptions. Moreover, knowing the force characteristics, one can easily monitor the process for interfering phenomena. The distributions of the radial (tool contact) force and torque are shown in Fig. 9. A characteristic feature of the curves is the good agreement between experimental and numerical results, both qualitative and quantitative. It is evident that the curves and the values of tool contact forces and torque for rotary compression depend on the stage of the process. At the initial stage of forming, there is a slight increase in contact force and torque, which is associated with the reduction in the diameter of the blank in the area of the end journals. The next stage, during which all steps of the forging are formed simultaneously, there is a sudden increase in contact force and torque. The rapid increase in the value of the force parameters is due to the increasing wall thickness in the area of the central steps of the forging and the squeezing (crushing) of the walls of the end journals. The rapid increase in the force parameters at this stage of the process is also related to the intense quenching of the material resulting in an increase in its flow resistance. The highest values of forces and torques were recorded in the final phase of the forming process when the tools occupied a position that corresponded to the required reduction of the outer diameter of the blank. In the final phase of rotary compression (calibration), a rapid decrease in tool thrust force and torque is observed. At this stage of the process, the tools no longer move in the radial direction but only perform a rotational motion to tune-off the irregularities in the shape of the forging. Despite the high qualitative convergence between the FEM and the experimental force parameters, the values of contact force and torque obtained in the experiments were higher (mainly in the final stage of forming and during calibration). The discrepancies are due to the faster cooling of the material during the experimental tests than assumed in the numerical model.

Conclusions. The results of the tests confirmed that hollow stepped shaft forgings can be formed in the process of rotary compression using a mandrel.

However, because the mandrel restricts the flow of material in the area of the bore, this type of forming process is much more difficult to execute than rotary compression without a mandrel, in which material flows freely in the radial direction. When the surface of the hole rests on the mandrel, the wall of the blank is crushed (squeezed down and pushed out) during compression, which is accompanied by intense elongation of the material. The results of the tests also demonstrate that the deformation limits for the outer surfaces of a blank formed over a mandrel are much lower than those obtained during the forming of forgings without a mandrel. There is also a need to precisely determine the initial thickness of the wall and the degree of deformation in relation to the shape and dimensions of the mandrel. Improper selection of geometric and kinematic parameters may result in the incomplete reproduction of the contour of the mandrel or thinning out the wall of the forging, which results in the distortion of its cross section or even the longitudinal cracking of the wall.

In spite of the fact that rotary compression using a mandrel is more difficult to perform, the benefits that can be achieved by restricting the free flow of material within the cavity area fully justify further research. It should be noted that rotary compression of hollow products is still an innovative process and represents an interesting alternative to traditional methods of manufacturing hollow shafts and axles. Another advantage of the process is that it can be used in both small-batch as well as mass production settings. The use of tubular billets in rotary compression leads to considerable material savings compared to other manufacturing techniques such as machining or conventional metal forming. Therefore, industrial application of the rotary compression technology is expected to improve the competitiveness of companies manufacturing hollow parts and improve the efficiency of the manufacturing processes.

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