J. TOMCZAK

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ROTARY COMPRESSION PROCESS FOR PRODUCING TOOTHED HOLLOW SHAFTS

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The paper presents the results of numerical analyses of the rotary compression process for hollow stepped shafts with herringbone teeth. The numerical simulations were performed by Finite Element Method (FEM), using commercial software package DEFORM-3D. The results of numerical modelling aimed at determining the effect of billet wall thickness on product shape and the rotary compression process are presented. The distributions of strains, temperatures, damage criterion and force parameters of the process determined in the simulations are given, too. The numerical results obtained confirm the possibility of producing hollow toothed shafts from tube billet by rotary compression methods.

Key words: rotary compression, forming, hollow shafts, gears, FEM

INTRODUCTION

Hollow products are more and more often used as parts of vehicles and aircraft, which results from the need to reduce both weight of machines and their production as well as operation costs. Lower machine weight means lower material consumption at the manufacturing stage as well as lower fuel consumption and emission, yet higher load capacity of the machine during its operational use. Axles and shafts, including toothed shafts [1, 2], belong to the group of machine parts that can be replaced by hollow elements; given the character of carried loads (bending and twisting moments, in particular), hollow substitutes of shafts and axles exhibit strength properties similar to those of solid products. Nonetheless, it should be observed that the potential of hollow elements can be fully exploited if semi-finished products used as billet are also produced as hollow parts and, additionally, provided with small machining allowances. This however, requires that advanced metal forming technologies be developed to enable the production of parts from hollow billet in the form of commercial tubes.

This study presents the results of a numerical analysis of hot rotary compression for producing multi-stepped hollow shafts with herringbone teeth (Figure 1). It is proposed that toothed shafts be produced in one operation, using tubes as the billet.

Such solution seems optimal in both economic and technological respects, as it would lead to reducing the number of operations applied [3]. In effect, the production time could be shortened, while the production process itself could be run using fewer machines and devices, which means lower production costs.

J. Tomczak, Lublin University of Technology, Lublin, Poland

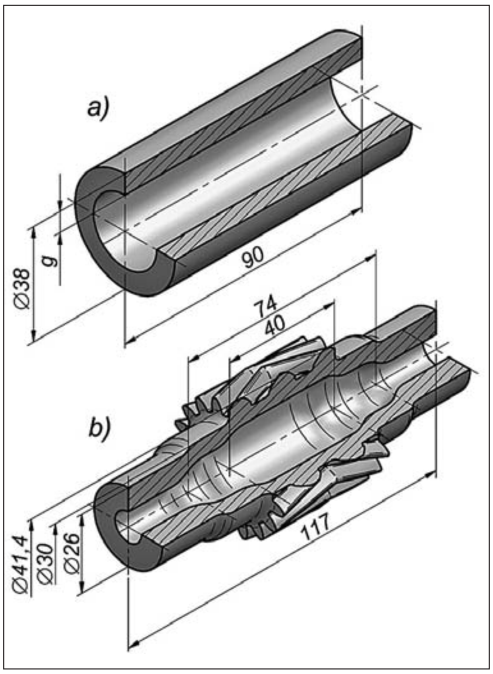

Figure 1 Shape of investigated semi-finished products: a) billet, b) hollow shaft with herringbone teeth

GEOMETRICAL MODEL OF THE ROTARY COMPRESSION PROCESS FOR PRODUCING TOOTHED HOLLOW SHAFTS

In order to confirm the feasibility of forming axisymmetric hollow products with teeth by rotary compression, a series of numerical simulations were performed to model the forming process for a shaft that is illustrated in Figure 1. The number of teeth being formed was $z = 18$, the normal modulus was set to $m_n = 2$, the angle of tooth profile was $\alpha = 20^o$, while the angle of tooth line inclination was set equal to $\beta = 15^o$. The simulations were performed by finite element method, using DEFORM-3D v. 10.2, the software which had been previously used to model numerically rotary processes for forming metals and their alloys [4 - 6], and the results obtained had been positively verified in experimental tests.

The geometrical model of the rotary compression process for shafts used in the simulations corresponds to the forming process shown in Figure 2. The model consists of three identical tools: stepped rolls (1, 2, 3) and a billet. The rolls are equipped in their central region with herringbone teeth. In the course of the process, the tools rotate in the same direction at a constant velocity of n_1 = 60 rpm, simultaneously moving towards the axis of the billet at a constant velocity of v = 5 mm/s. The billet is a tube with an outer diameter of 38 mm, wall thicknesses of g = 6,5 mm and g = 9 mm, respectively, and with a length of l = 90 mm. The billet was modelled using four-noded tetragonal elements. The numerical analysis was based on the assumption that hollow shafts would be produced from 16MnCr5 steel as this material is widely used to produce various gears, shafts, axles, toothed shafts, connecting rods etc. In the numerical simulations, the model was assigned the properties of 16MnCr5 steel, obtained from the database library of DEFORM-3D [7].

It was assumed that the billet was heated to a temperature of 1 100 °C, while the temperature of the tools was set to 150 °C and maintained constant in the course of the process. The constant friction model was adopted in the simulations; the friction factor had a boundary value of m = 1, the material-tool heat exchange coefficient was set to 15 kW/m^{2}K, and between material and environment - 0,35 kW/m^{2}K

NUMERICAL SIMULATION RESULTS OF THE ROTARY COMPRESSION PROCESS FOR HOLLOW PARTS

The simulations were performed to evaluate the suitability of the developed method for forming stepped hollow shafts with gears. The below figures show the numerically-determined shapes of hollow shafts and the distributions of effective strains: for a shaft formed from the billet with a wall thickness of g = 6,5 mm (Figure 3) and for a shaft formed from the billet with an initial wall thickness of g = 9 mm (Figure 4). It can be observed that in both analyzed variants, the shape of products is correct and corresponds to the one assumed at the design stage. During the compression process, end shaft necks are the first to be formed; at the same time, the metal flows radially to the axis of the billet causing an increase in wall thickness in these regions. In the subsequent stages of the process, all shaft steps are formed simultaneously; teeth on the central step of the shaft are formed here, as well. The teeth are formed from pitch diameter. In this region, the material is deformed only at a small depth, so it mainly flows radially in a direction opposite to that of the tools, filling in the spaces between the teeth in the rotating rolls. Near the end shaft necks, where the material is not restrained by the side collars of the tools, axial displacement of the material can be observed, which leads to elongation of forgings.

This phenomenon is particularly intensive at the surface regions for shafts formed from the billet with a higher wall thickness (g = 9,0 mm), where much more significant elongation of end necks could be observed. In the final stage of the process, i.e. sizing, the tools perform only a rotary motion to remove inaccuracies generated in the previous stages. Initial thickness of the billet wall has a significant effect on the geometry of finished products and the course of the compression process. What can be observed is that strains in both examined cases are not homogenous, and their cross-sectional distributions have a ring structure. The highest

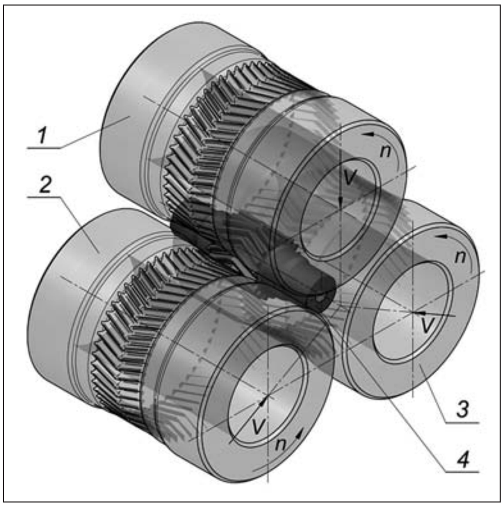

Figure 2 Design of the rotary compression process for producing multi-stepped hollow shafts with gears

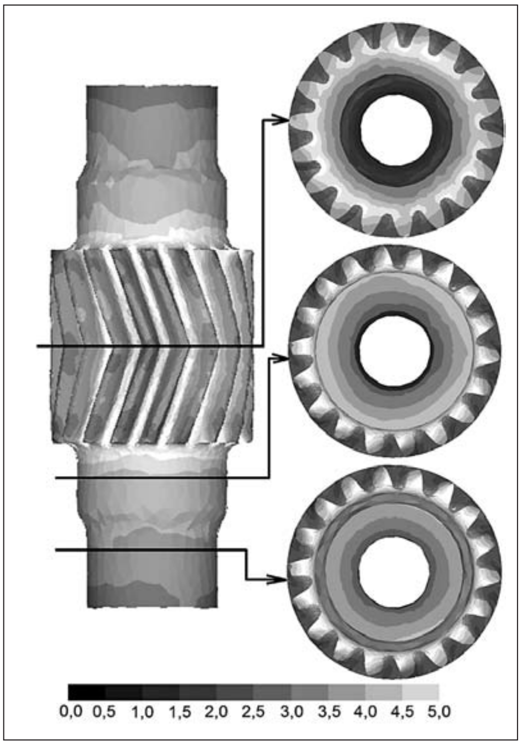

Figure 3 Shape of the hollow toothed shaft with the distribution of effective strain for billet with initial thickness of g = 6,5 mm

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values are observed at surface layers, which is typical of rotary metal forming processes and results from the kinematics of tool and workpiece motion. Considerable differences in circumferential velocities of the steps being compressed can be observed here, which results from a variable radius of the tools. Consequently, slipping between the material and tools occurs, and substantial circumferential strains are generated by friction forces. It is also characteristic of this process that for the billet with a higher wall thickness strains reach much higher values (Figure 3) compared to the process run using the billet with a lower wall thickness (Figure 4).

This can be explained by higher radial metal flow resistances (caused by higher rigidity of the billet) that generate much higher circumferential strains. The high values of strains also result from the displacement of a much greater amount of material towards the axis of the billet. It can also be observed that in both examined cases the material is not deformed on the inner wall of the teeth. This means that the teeth are formed when the material flows on the surface in a direction opposite to that of the motion of the tools.

Figures 5 and 6 show the distributions of effective strains, temperatures and damages according to the Cockcroft-Latham criterion in toothed hollow shafts, as determined in the final stages of the compression process for billets with different wall thicknesses.

As can be seen from the figures, increasing wall thickness of the billet generally leads to an increase in effective strain in the surface regions of cylindrical shaft necks. By contrast, in the case of gears, higher values of strain (located near the root of the teeth) were observed for forgings made from the billet with lower wall thickness.

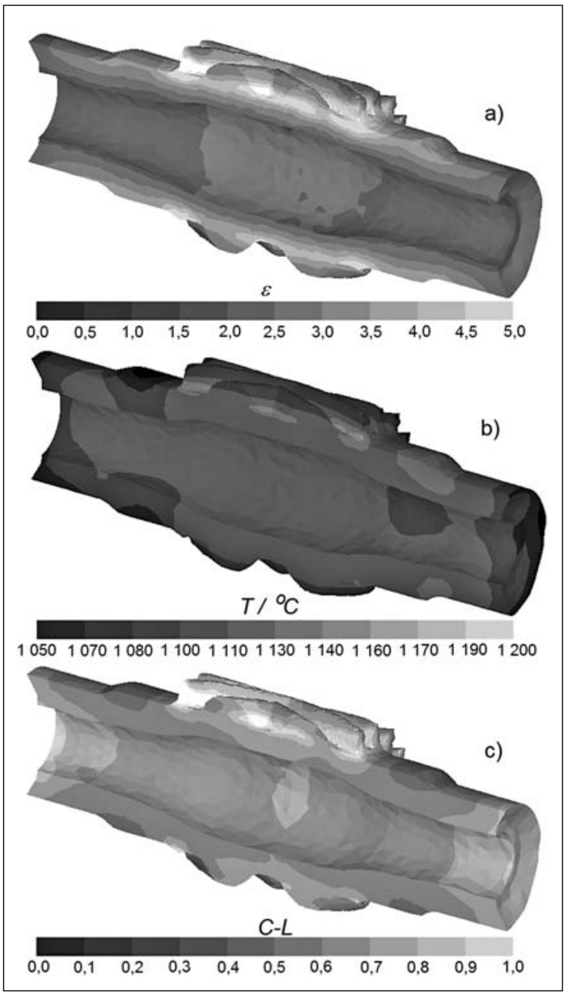

Figure 5 FEM-calculated distributions of: a) effective strain, b) temperature, c) Cockcroft-Latham criterion for a shaft produced from billet with initial wall thickness of $g = 6{,}5$ mm

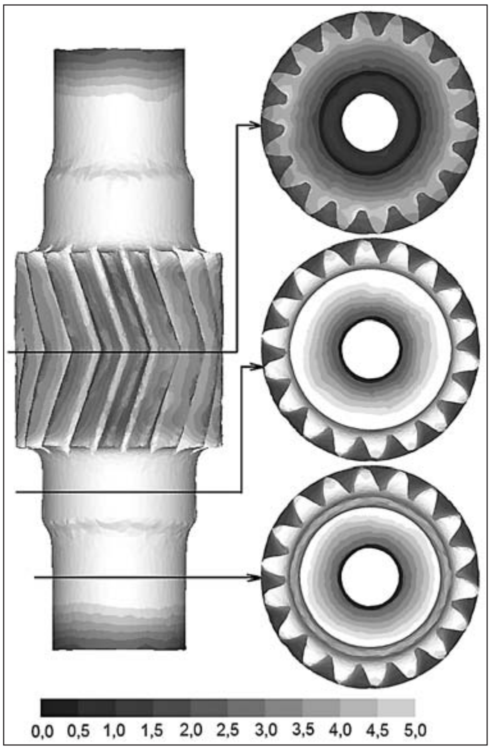

Figure 4 Shape of a toothed hollow shaft and the distribution of effective strain for billet with initial wall thickness of $g = 9{,}0$ mm

The temperature distributions (Figure 5b) and (Figure 6b) are also inextricably linked to the initial wall thickness of billets. For billets with lower wall thickness, higher temperature drops can be observed due to intensive cooling of the material (lower heat capacity of the billet). Nonetheless, despite a relatively long forming time, the temperature drops in both examined cases are insignificant; what is more, there are some regions where increases in the temperature can be observed. This is caused by the heat generated while the metal is being formed.

The numerical simulations were also aimed at predicting crack occurrence according to the Cockcroft-Latham criterion (Figure 5c and Figure 6c). The results obtained demonstrate that metal cracking is more likely to occur when shafts are produced from the billet with lower wall thickness. The most crack-prone region is a tooth in the vicinity of the root. The value of the Cockcroft-Latham integral in this region is similar to boundary values (approx. 1,0 for constructional steel) at which cracking can occur. Figure 7 shows the force parameters determined in the simulations. Observable that an increase in billet wall thickness leads to an increase in both the radial force of the tools and torque. As can be seen

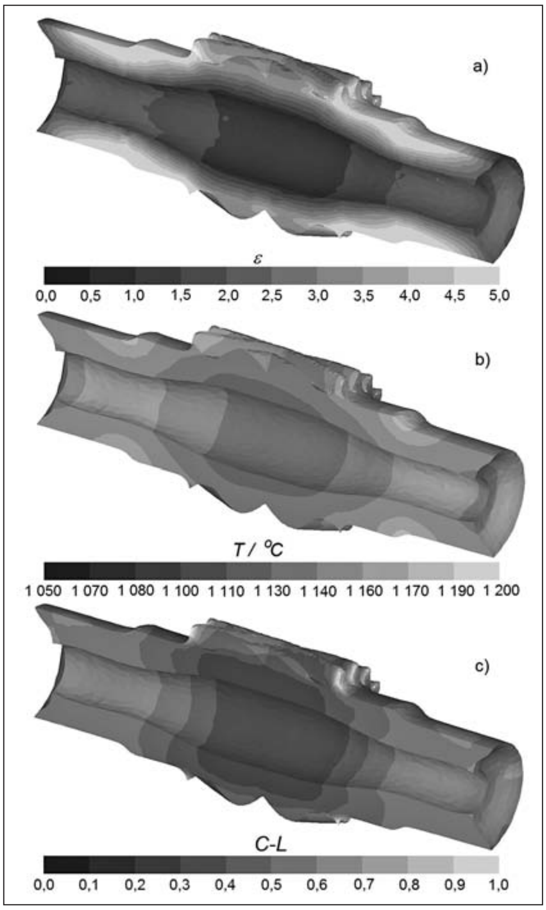

Figure 6 FEM-calculated distributions of: a) effective strain, b) temperature, c) Cockcroft-Latham criterion for a shaft produced from billet with initial wall thickness of g = 9,0 mm

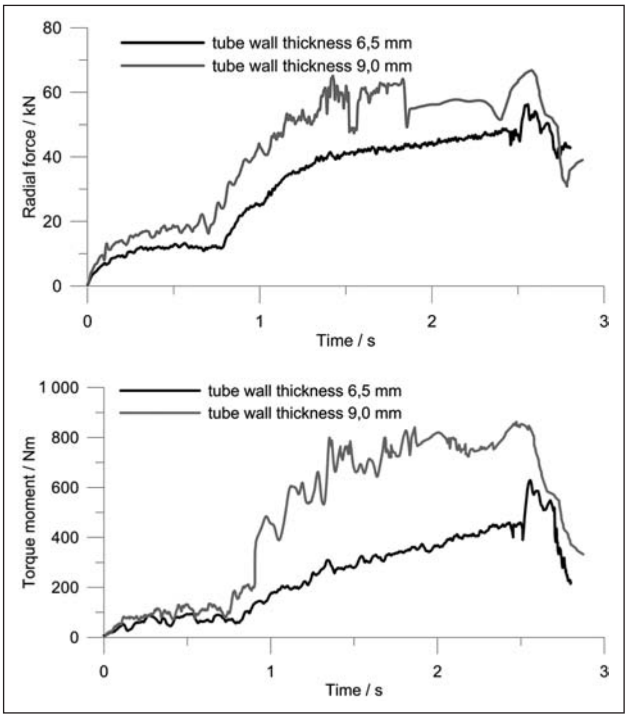

Figure 7 FEM-determined force parameters in rotary compression: a) radial force, b) torque

from the charts, the compression process for shafts consists of four stages. In the first stage, only end steps of the semi-finished product undergo compression, this process being accompanied by a relatively subtle increase in the force (Figure 7a) and torque (Figure 7b). In the second stage of the process, central steps are formed, which is combined with further compression of the end steps.

This causes a sudden increase in the forces. In the subsequent stage of the process, teeth are formed and the cross sections of the steps are compressed at the same time. It is also in this stage that the forces and torques increase in a relatively gentle manner to reach their maximum values. The final stage of the process consists in the sizing of forging shape, which takes place at a rapid decrease in the force parameters.

CONCLUSIONS

The FEM-based numerical analysis of rotary compression has confirmed that this process can be used to form multi-stepped hollow shafts with gears. The discussed method for forming hollow products is innovative and has not been yet industrially applied anywhere in the world. At present, such products are mainly produced by machining methods, which involves however substantial amounts of materials, energy and labour. By forming shafts from tube billet by rotary compression, it is possible to reduce material consumption and, what is more important, product weight, increasing its strength properties at the same time. As a result, operational costs of machines and devices can be significantly reduced, too. In addition to this, the production of multi-stepped shaft with teeth in one operation can lead to considerable reduction in production costs as well.

The results obtained in the investigation of the rotary compression process for toothed hollow shafts are promising. It is therefore fully justified that further research on determining relations between particular process parameters and product accuracy and quality be conducted.

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Note: The professional translator for English language is M. Jung, Lublin, Poland