FEM analysis of the manufacturing of hollow forgings from a tube billet

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Abstract. The study presents an analysis of the manufacturing process of a hollow forging. The process was proposed to consist of three stages. In the first stage (extrusion) wall thickness was reduced and the flange was formed. In the two subsequent stages the flange was formed. The material flow was examined using FEM. The issue of defect occurrence in the area of a hole caused by the material moving away from the mandrel was especially researched. Moreover, the strain state was analysed in the following forging operations. The distribution of the fracture criterion was presented. Moreover, a prediction of the forces necessary for the process to be performed in real conditions was carried out. The conclusion is that the proposed scheme of forming hollow forgings may be implemented in industrial conditions.

1. Introduction
Hollow elements are widely used in machine construction. Hollow shafts and axles are used in machine construction for two reasons, mainly due to the fact that it is necessary to decrease the mass of the structure e.g. in aviation, motorization and wind energy [1]. The other reason is the structure characteristics, e.g. hollow shafts in dual-clutch transmissions or mining knives [2].

Hollow elements are manufactured by machining, casting and very popular 3D printing. In the case of machining, it is possible to drill holes in full semi-finished products as well as to produce finished products from tube semi-finished billet [3]. In order to manufacture the product by casting, cores are used [4]. In the case of 3D printing, support structures are used in order to avoid the hole collapsing [5]. The above presented traits allow mostly unproblematic manufacturing of hollow elements. Despite numerous advantages, certain disadvantages to each method ought to be mentioned. In the case of machining, the manufacturing efficiency is low, whereas material usage is significant. Casting may pose problems in terms of the low parameters of the cast material. Moreover, not all materials can be cast. 3D printing technology is very universal, but its efficiency is not high. Currently the cost of 3D printing (metal printing) is very high, which hinders serial implementation of this method in technology. In the case of plastic forming the occurrence of a hole in the element poses certain difficulties. In the case of this method it is necessary to punch a hole in the billet, which requires a significant amount of energy. Using a tube requires the usage of mandrels in order to prevent the hole from buckling and folding. For this reason, new methods of metal forming of hollow elements are sought.

One of the newest metal forming technologies is rotary compression [6]. In this method a section of a tube is formed using three rotating rolls which additionally move in the radial direction and compress
the formed material. The tools employed in this technology have a generatrix similar to the outline of the formed hollow element. Rotary compression allows one to form hollow elements freely or use a calibrating mandrel to create the inner hole [7]. Rotary compression allows one to manufacture the following hollow elements: rails, axles, stepped shafts and worm gear shafts [8]. The characteristics of this technology are high quality and low cost of the tools.

CNC skew rolling is another new technology allowing one to manufacture hollow elements [9]. Three rotating rolls are used, with their radial direction controlled numerically. Controlling the radial movement of the rolls in the real time allows one to form any outline of a hollow shaft with one set of rolls. The main trait of this technology is its high versatility [10]. Additional benefits of this technology are high efficiency and low tool cost. New technological solutions must be verified by a series of tests and modelling. Examples include the fractographic inquiry is the basal course of operation after the failure of construction material pieces [11,12].

The forming technologies presented above are highly innovative and offer numerous benefits. Nevertheless, it is necessary to purchase specialist forging machines in order to apply these technologies. In many cases the producers of hollow elements are not willing to invest in new machines. For this reason, alternative technologies using typical forging machines such as presses are researched. This study presents results of an analysis of the process of forging a hollow element in a press. The analysed technology consisted of extrusion and multi-operation forging.

2. Materials and methods

This article presents the results of an analysis of the forging process in which a mining knife holder was produced from a commercial tube with the wall thickness \( t_0 = 10 \text{ mm} \) and outer diameter \( D = 55 \text{ mm} \). Figure 1 presents both the billet and the final forging after the cold forming process.

![Figure 1](image)

**Figure 1.** Object of analysis: a) tube billet, b) forging of a mining knife holder.

Due to the wall thickness being \( t_0 = 10 \text{ mm} \) and wall thickness of the front part of the forging equal \( t = 8.35 \text{ mm} \) it is necessary to reduce wall thickness of the billet. For this reason, it was proposed to firstly perform extrusion of the billet in order to reduce wall thickness (front part) and simultaneously increase wall thickness in the container for the flange part. The following operations consisted of forging on a forcing cone and final forging. Verification of the developed process of producing a rotary sleeve was performed using Deform 2D ver 11.0 software. The material was modelled as elasto-plastic object. The tools were modelled as rigid objects. Material model of annealed 42CrMo4 grade steel was obtained as a result of an upsetting test [13]. Its rheology is expressed by the following equation:
\[ \sigma_f = 1023.67 \cdot \varepsilon^{0.21}, \]  

where: \( \sigma_f \) - flow stress, \( \varepsilon \) - effective strain.

Friction conditions were also determined in an upsetting test performed for an angular sample. On the basis of the performed tests, it was assumed that the friction factor equals \( \mu = 0.15 \) [14] provided that the surface is lubricated with mineral oil with an addition of Molybdenum Disulphide. The forging process was performed in cold working conditions with the temperature of the environment 25°C. Extrusion and forging simulations were carried out in axially-symmetric 2D conditions. It was assumed that the process will be realised in a hydraulic press with the press slider moving at the speed of 1.6 mm/s. Discretization of the workpiece was performed using 5000 plane 4-node elements. Geometrical models of the extrusion and forging processes are presented in Figure 2. The present study is a continuation of previously published results [13,14,16-20] regarding the project entitled: New metal forming technique for producing flanged hollow parts for the mining industry.

![Figure 2. Geometrical models of the analysed processes: a) extrusion, b) forging.](image)

### 3. Results

The following forging operations were presented in Figure 3. No concerning phenomena such as underfilling of the impression or forging lap were observed. In order to better illustrate the progression of each operation, the progression of the shape in each operation was analysed separately.

Figure 4 presents a more detailed progression of the extrusion process. Firstly, the material is inserted into the hole of the matrix, where it is blocked. The material is being upset in the container as a result of the punch moving. The material fills the container from the punch towards the die. The container fills in one direction (towards the mandrel), which decreases the risk of buckling, which may occur with the material flowing in two directions (towards the mandrel and the container). In this case of extrusion the material flows through the matrix hole only after the container is full, which decreases the risk of forging lap occurrence.

The final stage of container filling was presented in Figure 5. On the basis of the presented scheme it can be stated that at this stage no alarming phenomena occur. The gap between the mandrel and the formed material decreases gradually. The manner in which the container fills does not increase the risk of forging lap.
Figure 3. The stages of forging a mining knife handle from a tube billet: a) initial state, b) the first operation – extrusion, c) the second operation – forging on a forcing cone, d) the third operation – final forging.

Figure 4. Stages of the extrusion process.

Figure 5. A precise presentation of the changes to the shape at 50% and 75% progression of the operation.

Figure 6 presents a scheme of material flow during forging on a forcing cone. In the initial stages the conical impression reduces the outer diameter of the material. After the bottom of the punch reaches the front of the semi-finished product, material upsetting occurs. At the moment of upsetting it can be observed that the material moves away from the mandrel calibrating the inner hole. The created gap is not big and therefore it disappears in the final stage of upsetting. The hole was observed to reach its maximum dimensions in the middle of the process. At 50% progression of the process, the width of the gap was 0.79 mm, whereas the height equalled 26.57 mm. At 75% the dimensions of the gap decreased to 0.54 mm and 17.15 mm, respectively. At such dimensions of the gap, with the height several dozen times greater than the width, the risk of overlap occurrence is not high. The possibility of the tool impression not filling completely is higher.

Figure 7 presents the progression of the shape of the flange impression during the final forging. The presented data suggest that during the final forging operation the material also moves away from the mandrel wall. The material begins to move away at 25% progression of the process. The biggest gap
may be observed at 50% progression, whereas at 75% the gap is no longer visible. It can therefore be stated that despite an insignificant movement of the material away from the mandrel at the initial stage of the process, forging in the final impression progresses correctly. The maximum size of the gap at 50% progression of the process was as follows: 0.67 mm width and 15.9 mm height. At 70% progression the dimensions of the gap decreased to, respectively, 0.26 mm and 9.02 mm. The dimensions of the gap at the last forging stage are smaller than the dimensions of the gap that appeared during the previous forging operation. In this case the risk of overlap also does not occur.

![Figure 6. Progression of the shape after the second operation of forging on a forcing cone.](image)

Figure 7. Shape progression during the final forging.

Figure 8 presents a distribution of effective strain in subsequent operations of forging a mining knife handle. Effective strain in the flange part of the forging increases along with the advancement of the process. In the upper part of the flange the value of strain equals 0, since this part of the element is not subjected to plastic strain. The greatest values of effective strain can be observed in the flange part of the forging. The area of maximum strain (marked with the letter A) is located in the bottom part of the flange throughout its entire thickness from the roll part of the flange to the inner wall of the hole. Such a location of the strain may weaken the material along the area in which the greatest plastic strain occurs. As a result, a shear fracture may occur in this area.

The distribution of the Cockcroft-Latham criterion in the subsequent operations is presented in Figure 9. In the case of this manufacturing technology, increased values of the Cockcroft-Latham integral occur in the roll area of the flange as well as in the bottom front part on the hole surface. The maximum values of damage criterion in the flange area do not exceed 0.2. The increased value of the
criterion in the area of the flange is caused by the occurrence of significant tensile tangential stress. In the front part of the forging the values of the Cockcroft-Latham criterion are significantly smaller and do not exceed 0.125. The obtained values of fracture criterion are relatively low and material fracture is not likely to occur.

Figure 8. Effective strain distribution at each stage: a) extrusion, b) forging on a forcing cone, c) final forging.

Figure 9. Distribution of Cockcroft-Latham damage criterion in the subsequent stages: a) extrusion, b) forging on a forcing cone, c) final forging.

Figure 10. Distribution of surface load in the final phase of the subsequent stages: a) extrusion, b) forging on a forcing cone, c) final forging.
Distribution of surface pressure in the final stages of each operation is shown in Figure 10. In the second operation of the technological process the load on the surface of the hole equals 0 MPa. This indicates that in these areas the impression of the tools is not entirely filled. Maximum surface pressure occurs in the second and third forging operations. The maximum surface pressure was observed to be equal c.a. 2300 MPa. In the case of the extrusion process the areas with the maximum surface pressure were located on the cone surface, more precisely in the area of transition radiuses between the roll parts and the cone. In this case, the values of surface pressure may be decreased by using rounding to a greater radius. The obtained values of surface pressure do not exceed values typical for cold forming processes [15]. For this reason, materials used for cold forming tools may be used for manufacturing tools for forging and extrusion.

The possibility of realising the technical process and the dimension of the forging machine depend, to a great extent, on the values of forming forces. The progression of the forming forces in the subsequent technological operations was presented in a scheme in Figure 11. The extrusion process is performed with the constant value of forming force equal c.a. 2000 kN. In the case of forging operations the forces reach much more significant values. During forging on a forcing cone the maximum force equaled 4585 kN. In the case of final forging the maximum force reached 7917 kN.

Figure 11. Force characteristics for the subsequent stages of forging a mining knife handle from a tube billet.

4. Conclusion
The obtained results of numerical calculations indicate that the process of forging a mining knife handle from a commercial billet Ø55 x 10 mm may be performed in three operations. An additional benefit to this process is the possibility of utilizing typical forging machines, e.g. presses. The phenomenon of the material moving away from the calibrating mandrel in each operation is insignificant and does not cause defects, such as lap forging or folding. The obtained values of fracture criterion allow one to safely perform the process without the risk of material cracking. Maximum surface load does not exceed the values typical for cold working. In order to perform the process a press with a compression force equal to 10 MN is required. The obtained results of numerical calculations indicate that the presented process may be implemented in industry conditions.

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