FEM analysis of manufacturing of a hollow product with an outer flange in a four-stage cold forming process

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Abstract. The paper presents the results of a FEM computer simulation of the cold forming process of a hollow sleeve forgings with an outer flange. Numerical simulations were carried out in DEFORM 2D / 3D. For the numerical calculations of the forming process the axisymmetric calculation module was used. As the test object, a tubular workpiece with an outer diameter of Ø50 mm and a wall thickness of 10 mm made of 42CrMo4 steel was used. The process of forming the rotary sleeve was conducted in four stages consisting of two technologies. The first stage of the research was the analysis and selection of parameters of the extrusion process, which was used for the first stage of forming. The processes of free extrusion and the use of a container were analysed. Furthermore different die angles and different wall thickness reductions were used. The products obtained in the extrusion process were upset in three conical blanks. The aim of the study was to analyse the numerical accuracy of the designed process of forming the hollow shaft with flange. The analysis of the results was based on the deformation intensity distribution maps, the Cockroft-Latham criterion distribution and the progress of the forming forces. On the basis of the conducted research, it was concluded that the presented process of forging a hollow product with a flange in four stages is possible to carry out correctly.

1. Introduction
In mechanical engineering, hollow sleeves are commonly used. Sleeves are hollow axisymmetric elements used, inter alia in the machinery, automotive, aviation and mining industries. The use of hollow elements is common due to one of the main advantages which is the reduction of the mass of the rotating elements in relation to the solid counterparts [1,2]. For example, the incorporation of the hollow shaft relative to the solid reduces the weight of the element by half while maintaining the same torsional strength.

Hollow flanged products can be manufactured in two methods. The first method is to make a hollow flange product as a monolithic element, made of one piece of billet material, while the second method is to make products with flanges as an element composed of two parts, a shaft and the flange [3-4]. Monolithic products are most often made by metal forming, machining and casting methods. Whereas axisymmetric elements with a flange made of two parts can be made, for example, by additive manufacturing, screwing and welding [5-7].

One of the most commonly used methods for making hollow axisymmetric elements is metal forming. The commonly used technologies are: forging, extrusion forging, rotary compression, cross wedge rolling, skew rolling and extrusion, performed under cold and hot forming conditions. Forming of hollow products is a frequently used manufacturing method due to its advantages such as material savings, improvement of mechanical properties and physical properties, low unit costs, the possibility
of forming complicated shapes. Simultaneously the product obtained as a result of metal forming maintains the continuity of the fibres in the product [8-11].

The selection of appropriate methods of producing axisymmetric hollow products depends on factors such as the shape of the final forging, the size of the series to be made, the type of material and the mechanical properties of the finished product. For the metal forming of hollow products such as a sleeve with a flange, the most commonly used methods are extrusion, extrusion with a movable sleeve and forging or a combination of these methods into one forming process. The workpiece used for plastic processing are tubes or rods [12,13].

The process of extruding is most often used to prepare a blank for the forging process. The extrusion method allows for forming products with an internal and external flange. The extrusion process is often combined with a forging process, which results in a forging process with a radial extrusion of the flange. However, in order to obtain a hole with the assumed geometry, a mandrel should be used to shape or calibrate the internal hole. On the other hand, for the forming of high-height flanges, the extrusion process with a movable sleeve can be used. The tools used in this process applied a sleeve which moves counter-rotating to the movement of the punch [14-18]. The variety of factors in the manufacturing process also necessitates a lot of experimental research on individual elements. An example of such research can be the fracture surface analysis, which gives supplementary reference about the damage process, but requires post-failure analysis, which was carried out by Macek et al. [19-20].

An analysis of the literature on the forming of hollow products with flanges allowed for the conclusion that it is possible to forming an axisymmetric product in a combined process consisting of the process of extrusion and forging into cones. Accordingly, the aim of the article was to conduct FEM computer tests, cold forming a hollow sleeve with an external flange in a four-stage process. After the FEM analysis, the obtained results were presented.

2. Research methodology

The results of numerical tests which are presented in the article, were carried out in the FEM computing environment. Numerical simulations were carried out in DEFORM 2D / 3D with the use of axisymmetric module. The applied calculation module uses a calculation technique consisting in simplifying the spatial model to a flat axisymmetric case.

The subject of the research was the four-stage process of producing an axisymmetric hollow sleeve with an external flange by means of metal forming methods. The analyzed type of sleeve can be used as an element of mining machines or in assemblies of automotive parts. The manufacturing process consisted of two main technologies. The first is the process of extrusion (free and with the use of a container) a tube workpiece with an outer diameter of Ø50 mm, a wall thickness of 10 mm and a length of 141.9 mm, made of 42CrMo4 steel. Second technology used is upsetting in conical die impression. Fig. 1 shows the dimensions of the tubular workpiece and a drawing of the finished sleeve forgings.

![Figure 1. Object of analysis: a) tubular billet, b) forging of a rotary sleeve with an external flange.](image-url)
The first part of the sleeve forming process research was analysis of the extrusion process, the diagram of which is shown in Fig. 2. In this case, the analysis of the process carried out with the use of three sets of tools with different variants of the die angles and different reductions in the thickness of the workpiece. The first set of tools had a die angle of 10° in which the wall thickness is reduced to a value of 8.35 mm. The second set of tools had dies with an angle of 7.5° and allowed the wall thickness to be reduced to a value of 8.35 mm. The last set of tools had a die angle of 10° and a wall thickness reduction to 9.2 mm.

![Figure 2. Schematic diagram of the pushing process.](image)

In the second part of the research, an analysis of the workpiece upsetting process in conical die was performed, the diagram of which is shown in Fig. 3. Blanks used to test the workpiece were obtained by extrusion in dies having 5°, 10° and 15° angle.

![Figure 3. Diagram of the upsetting process in a conical blank.](image)

The numerical study used a 42CrMo4 steel material in the annealed condition model. The material data used in the calculations were determined in own research on the basis of which the flow curve determined equation (1) used steel [21,22].

\[
\sigma = 1023 \cdot \varphi^{0.2}
\]  

where: \(\sigma\) - stress, MPa; \(\varphi\) - effective strain [-].

![Image](image)
For numerical tests of cold forming processes, the initial temperature of the workpiece and tools was assumed to be 20ºC. The value of the speed of the forming tools was assumed to be 1.66 mm / s. For the calculations, a model of constant friction was adopted with the value of the friction factor between the formed workpiece and the tools equal to $m = 0.3$. The present study is a continuation of previously published papers [21-27] regarding the project entitled: New metal forming technique for producing flanged hollow parts for the mining industry.

3. **Analysis of the results**

Collected data from the computer simulations allowed the analysis of the forming process of the rotary sleeve flange. In order to forge a rotary sleeve from a tubular workpiece Ø 50x10 mm, it is necessary to reduce the inner diameter and wall thickness of the workpiece. Therefore, for a main part of the forging has been proposed at the outset of the process of extrusion the mandrel with tubular workpiece to reduce the wall thickness.

Figure 4 shows the results of the pushing process. Pushing with the use of a die with an angle $\alpha = 10^\circ$ with a reduction in the thickness of the workpiece wall from 10 mm to 8.35 mm was unsuccessful. Prior to entering the die, the material buckled, which resulted in a very large gap between the workpiece and the mandrel. Further extrusion or upsetting in subsequent stages would result in folding of the material. In order to limit the material buckling phenomenon during extrusion through, a die with a reduced angle $\alpha = 7.5^\circ$ was used while maintaining the reduction of the workpiece wall thickness from 10 mm to 8.35 mm. Reducing the die angle had a measurable effect in reducing material buckling. However, in the section of the workpiece in front of the die, the pushed material still deviating from the wall of the calibrating mandrel. The next step to reduce the buckling of the material was to reduce the degree of reduction in the wall thickness of the tubular workpiece from 10 mm to 9.2 mm in a single pass. Lessen the degree of reduction in the wall thickness of the tubular workpiece had the best effect. The material did not undergo buckling, only dislodging from the mandrel wall. It is possible that in the second pushing stage, the defect would be aggravated and the material would folding. Therefore, this solution was also abandoned. Moreover, the pushing operation should be carried out in at least two passes, which would significantly increase the time of the technological process.

![Figure 4](image_url)

Subsequently, a process of extrusion tubular workpiece was proposed with the restriction of the outwards material flowing in front of the die. Thus, the pushing process was deflated to the process of extruding the tubular workpiece. In the proposed extrusion scheme, the buckling phenomenon of the workpiece in front of the die was eliminated. Subsequently, it was proposed that the material after extrusion would be expanded into transition cones. In order to select the appropriate angle (of the
analyzed: $\alpha = 5^\circ$, 10° and 15°) during pushing, in the aspect of the further forming stage, simulations of upsetting the forges obtained after pushing were carried out.

The results of upsetting for the transition cone of extruded blanks at different values of the angle $\alpha$ are shown in Fig. 5. By far the best results were obtained for the blank, which was extruded at the die angle $\alpha = 5^\circ$. In this variant, no material deviation from the wall of the inner hole calibrating mandrel of the forging was observed. By increasing the die angle $\alpha$, the material deviates more from the mandrel wall. In the case of a blank with the angle $\alpha = 10^\circ$, the distance between the material and the mandrel was $x = 0.42$ mm, and in the case of a blank with the angle $\alpha = 15^\circ$, the distance between the material and the mandrel was $x = 0.47$ mm. In addition to the distance from the mandrel, the height at which the material did not adhere to the mandrel increased.

![Figure 5. Upsetting cone dies after extrusion with different die angles: a) $\alpha = 5^\circ$ b) $\alpha = 10^\circ$ c) $\alpha = 15^\circ$.](image)

Figure 6 shows the force characteristics of the extrusion process at different $\alpha$ angles of the die. For the angle $\alpha = 5^\circ$, the highest pressing force was recorded, amounting to approximately 1750 kN. In other cases, the pressing force is much lower and amounting to approximately 1,200 kN. This is due to a longer conical area with a smaller die angle, which increases the frictional path between the extruded material and the die. Consequently, the frictional forces are greater than the material flow resistance at higher die angles $\alpha$. Despite the large force necessary to extrude the blank in the die with the angle $\alpha = 5^\circ$, the correct geometry of the product is crucial, which ensures the minimization of defects occurring in the later stages of the technological process. Therefore, in the following discussion, the semi-finished product extruded in the die with the angle $\alpha = 5$ was adopted for analysis.

Figure 7 shows a diagram of sleeve forging in four stages. In the first step, the material is being extruded in order to reduce the wall thickness of the workpiece material. In the next step, the flange part is swelled into transition cones during three stages. The four-stage forging process is feasible. The final product forged in the fourth step is free from defects such as folds or material deviating from the mandrel wall.
Figure 6. The course of force characteristics for extrusion at variable values of the angle $\alpha$.

Figure 7. The next stages of the forging process of the mining pick holder in four stages.

Analysing the progression of the shape during the forging for a cone in stage 3 (Fig. 7), a clear deviation of the material from the mandrel can be observed. The greatest gap between the material and the mandrel occurs in the middle of step 3. Subsequently, the material rests against the wall of the conical blank and the gap between the workpiece material and the mandrel becomes smaller as the upsetting continues. As a result, in the last stage of upsetting the material in stage 3, the gap between the processed material and the mandrel is leveled. The forging after stage 3 is without defects, such as folds, and the processed material adheres to the mandrel along the entire height of the cone. Fig. 8 shows the distribution of the strain intensity in the subsequent stages of the four-stage process. As a result of extrusion of the forging, an increase in deformation in this area of the product is visible.
As the process advances, the strain intensity increases. The greatest deformations occur in the flange part of the forging. The area of maximum deformation occurs in the lower part of the forging flange along its entire thickness from the cylindrical part of the flange to the inner wall in the hole. In the upper part of the flange, the deformations take the value 0, since this part of the material is not subjected to plastic deformation.

Fig. 9 shows the distributions of the Cockcroft-Latham criterion in the subsequent forging stages of the four-stage process. As the process advances, the Cockcroft-Latham criterion values increase. The highest values are found in the cylindrical part of the forging flange. This is where the greatest increase in diameter occurs in relation to the outer diameter of the workpiece. As a result, this area is subjected to tensile circumferential stresses, which can cause spread cracks. The area of increased values of the fracture criterion runs from the cylindrical surface of the flange, in which the highest values of this criterion occur, towards the inner hole of the forging. This area coincides with the area of increased values of plastic deformation.
The distribution of shear deformations in the forging in the four-stage process is shown in Fig. 10. The four-stage process forged piece has deformation area in, which is located in the lower part of the flange. On the other hand, from the forging wall, an area of form deformation of the opposite sign appeared in the opening. The distribution of maximum surface pressures for the analysed forging variants is presented in Fig. 11. In the four-stage forging process, the greatest pressures occur in stages 3 and 4. The maximum values of the pressures do not exceed 2500 MPa. The location of the greatest pressures includes the shank of the forging located in the die forging. It follows that the die and the inner hole calibrating mandrel will be subjected to the largest loads during forging. The pressures under the punch in the flange part are smaller and amount to a maximum of 2190 MPa. At stages 2 and 3, areas in which the forgings hole where the pressures are 0 MPa can be observed. This proves that in these places there is no contact between the forging material and the mandrel. In step 4, in which the finished forging is formed, the forging material is in contact with the mandrel over the entire area of the forging’s internal opening.
In the case of forging in the four-stage process, the maximum forging force in the last stage was 7008.5 Kn, see fig. 12. The course of forces for forging are typical for this type of operation, the force reaches its maximum over a short distance. For the first stage, which was extrusion, force after reaching the maximum value remained constant. The duration of the first stage is practically 2/3 of the time needed to process the forgings of the mining knife pick.

![Figure 12](image-url) Figure 12. Course of force characteristics for the four-stage forging process.

4. Conclusions
Based on the analysis of the results of numerical tests of the process of manufacturing a rotary sleeve with a flange, it was found that the best solution is to use one extrusion and three cone forging processes.

A preferred variant for the implementation of the first operation is the extrusion process with the use of a die with an angle $\alpha = 5^\circ$. The use of the smallest angle among the analysed forces, despite the very high values of forming forces, may improve the filling of the die blank in the further stages of upsetting. Moreover, the use of the extrusion process as the first operation makes it possible to reduce the outer diameter and wall thickness of the patch in one working movement of the tools.

For upsetting processes of conical blanks, the angle of the tapered die is a key parameter. With appropriately selected values, it is possible to eliminate the phenomenon of local buckling of the workpiece wall, thanks to which the correct forging is obtained.

Acknowledgements
The research was financed in the framework of the project: New metal forming technique for producing flanged hollow parts for the mining industry, No. LIDER/1/0003/L-9/17/NCBR/2018. Total cost of the Project: 1 197 000 PLN. The project is financed by the National Centre for Research and Development under the 9th edition of the LIDER Programme.

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