A comparative analysis of a four-stage and five-stage cold forging of a hollow element

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Abstract. The paper presents the results of a computer simulation of the process of cold forging of a hollow element with an outer flange. Computer testing was conducted in DEFORM 2D/3D using the calculation module 2D. A tube-shaped billet, made of 42CrMo4 grade steel and the inner diameter of Ø45mm, wall thickness 8 mm and length 193.5 mm was used. The analysed process was conducted in two variants. The first one was conducted in four stages, with the first two stages consisting of upsetting the flange part and the next two stages forging on cones. In the second variant, an additional stage of forging on cones was performed, aiming at elimination of the folding on the inner wall of the forging. An analysis of the technology was conducted on the basis of distributions of effective strain, values of the Cockcroft-Latham fracture criterion and progresses of the forming force. On the basis of the research conducted, it was claimed that the five-stage forging process is more favourable.

1. Introduction

Hollow elements are frequently used in various aspects of the everyday life. Axially symmetric hollow elements are used, among others, in automotive and machine construction, usually in the form of hollow shafts, sleeves and housing. Especially, due to the fact that may contribute to reduction in mass of rotating assemblies [1,2]. Hollow elements can be manufactured by the following principle methods machining, centrifugal casting and metal forming, as well as with usage of modern additive manufacturing methods [3-7]. However, during machining the billet is formed to a desired shape by manually removing the excess material in the form of chips and fillings. In the manufacturing process of hollow elements using machining forgings, casts additive fabricated components are required [4,8].

The most frequently used method for manufacturing hollow elements with flanges is pressure centrifugal casting. In this method, liquid metal is poured into a rotating mould. The liquid is pressed into the surface of the mould by the centrifugal force. The casts manufactured by centrifugal casting are characterised by better quality, homogenous structure, better mechanic properties, higher resistance to corrosion and wear, insignificant allowances for finishing and the possibility of manufacturing multilayer product, with each layer made of different metal. This process allows to manufacture thin-walled products. Among main defects of centrifugal casting are the high cost of the devices and low profitability of the process for small batches of casts.

Metal forming allows to obtain hollow parts using methods where the shape of the finished product, finished with machining is acquired. An advantage of metal forming are increased mechanical and physical properties of the finished product, resulting from metallic structure
uniformity and strengthening of the material. Despite the literature of the subject denotes that non-ferrous metal alloys undergo fabrication by metal forming, steel is the most frequently plastic-treated material [4, 9-13]. Therefore, metal formed – structural steels presents higher mechanical properties than the cast iron parts [14, 15]. Moreover, even the primary manufacturing technology of the metallic materials plays the crucial role, the methods for improvement in the material durability and toughness are systematically studied. Therefore, Macek et al [16] studied the effect of shot peening of the fatigue strength of S235, S355 and P460 structural steels. Soyama [17] summarises the methods for surface durability improvement via cavitation peening, Wang et al [18] investigated effect of 35CrMo plain roll steel laser cladding with V and Cr rich coatings on the operational properties. Budzyński et al [19] studied the influence of nitrogen ion implantation on the tribological properties of low-alloy high strength Hardox and Raex steels. Szala et al reported on the stainless steel (grade X5CrNi18-10) wear prevention by AlTiN hard films deposition [20] or low alloyed 40Cr4 steel wear resistance improvement with usage of atmospheric plasma deposited MMC (metal matrix composite) [21], similarly Maslarevic et al. [22] proposed the MMCs for wear prevention application. Additionally, in the paper of Bounezour et al [23] the effects of work hardening on mechanical metal properties of steel and aluminium alloys were studied.

Summing up, the low alloy structural steel properties can be shaped in various ways, however the most promising technology for steel-components manufacturing is metal forming. Among the methods of metal forming used for manufacturing hollow elements, there are: forging with radial extrusion, extrusion, upsetting, orbital forging, rotational compression, cross rolling. The choice of the forming method depends on the shape and the number of elements to be manufactured. The forgings with complex shapes are manufactured using several operations or metal forming processes [24-27]. Oftentimes, forging methods are applied to manufacture hollow stepped elements. The most frequently used method is forging with extrusion. This process is based on two metal forming methods, forging and extrusion [28, 29]. In the process of forging with extrusion the tube-shaped material is being pressed by the punch, as a result of which upsetting of the billet occurs. Next, the material is extruded in the radial and axial direction in accordance with the shape of the tool. In order to obtain the desired shape of the element forming mandrels are used [30].

Another process frequently used for forming hollow elements is extrusion [31-34]. In order to extrude hollow elements from tube-shaped billet, tools with a central forming mandrel are used. This technology allows to form elements with inner and outer flanges. Another form of extruding hollow stepped elements is extruding with a movable sleeve. In this process a movable sleeve moves in the opposite direction to the punch. Due to such tool kinematics, it is possible to form hollow forgings with flanges in one operation and with the height of the flange several times higher than the thickness of the billet wall [35].

On the basis of the analysis of the specialist literature on forming hollow elements it was stated that it is possible to manufacture those elements using several processes and operations. Due to this fact, the paper presents the results of numerical testing of a hollow preform in four and five stages. The analysed forging may be used as a semi-finished product in the production of sleeves for mining rotating knives or the elements of driveline.

2. Research methodology

For computer testing of the forming process of a stepped forging with a flange DEFORM 2D/3D was used. Calculation technique in the applied program is based on the finite element method. Numerical calculations were conducted in a 2D calculation module. The object of the research was a hollow forging with a flange, shown in Figure 1. For the simulation, a tube-shaped billet with the following dimensions was assumed: outer diameter 45 mm, wall thickness 8 mm and length 193.5 mm.

In the case of a Ø 45 x 8 mm tube the upsetting ratio (fragment of the billet that will be transformed into the flange) \( m = h/g \) equals 14. At such a high value of the upsetting ratio \( m \), the process ought to be performed in stages. There are two options of upsetting the tubal material. In the first one, the tube is upset on the conical impressions. With such a high value of \( m \), however, this process is not
economical due to a remarkably high number of the forging stages. In the second case, tube upsetting is conducted in a closed die. Applying such a system is possible to increase the wall thickness by 30% in one stage at \( m \geq 5 \). For the purpose of forging of the analysed element from a \( \Phi 45 \times 8 \text{ mm} \) forging, a mixed variant was selected. In this variant, the first stages of forging consisted of upsetting in a closed die, and then forging on conical impressions.

The investigated process consists of 4 and 5 operations. In the first variant, forging was based on two operations of flange upsetting and two operations of forging on conical impressions. In the second variant, a third operation of forging on conical impressions was added (Figure 2).

The material used for numerical testing was annealed 42CrMo4 grade steel. Material data used in the calculations were determined via own research [36]. On their basis, an equation of the flow curve (1) of the used steel was determined.

\[
\sigma_p = 1023 \cdot \phi^{0.2}
\]

where: \( \sigma_p \) – true stress, MPa; \( \phi \) – true strain.

For the computer testing the initial temperature of the billet and the tools was assumed to be 20ºC, whereas the speed of the forming tools 1.66 mm/s. For the simulation, the model of shear friction was applied, for which the friction factor between the billet and tools \( m=0.3 \).

3. Analysis of the results
An analysis of the results obtained from the 4-stage variant 1 allowed to state that the first two stages of the forging process are correct. In stage 3, however, it was observed that the material moved away from the mandrel (Figure 3). In the last stage of the first variant, the phenomenon from stage 3 intensified, as a result of which material folding occurred.

For this reason, a simulation of variant 2 with an additional stage of forging in a conical impression and final forging in the fifth stage was performed. After such a correction, the entire folding was located in the allowance for finishing (Figure 4).
Figure 2. The tools used for the process of forming a hollow forging with a flange: a) die for upsetting the flange part, b) dies for forging on conical impressions; 1 – punch, 2 – billet, 3 – ejector, 4 – mandrel, 5 – die.

Figure 3. Progression of the shape for the forging in each stage of the process.
Figure 4. Defects such as folding and the material moving away from the mandrel.

Figure 5 shows a distribution of effective strain. In the case of 4-stage forging, the strain values in the finished element are higher than in the case of 5-stage forging. The maximum strain was located in the flange part of the forging. Another type of material flow in the 4-stage increased the values of effective strain in the area of material folding. Material flow in this area occurred in two directions, which causes the strain to increase.

Figure 5. Distribution of effective strain in subsequent stages of forging.
The area of maximum strain is located from the spot of material folding (stage 4) to the base of the flange. In the case of the element forged in the 5-stage process, the area of the highest strain is also located along the base of the flange. The beginning of the area of the highest strain is located in the spot where the material began to move away from the mandrel. In the shank part of the forging the strain is ridiculously small, since the initial 8 mm wall thick is upset to as little as 8.5 mm. Increasing the number of stages does not cause the strain to increase exceedingly. For this reason, a higher number of forging stages should not cause excessive material strengthening.

The obtained distributions of the Cockcroft-Latham criterion were presented in Figure 6. The greatest values of this criterion were observed in the final stage of forging. In both cases, the greatest values of the Cockcroft-Latham criterion were localised in the roll part of the flange. In the case of four-stage forming, the greatest values occurred in the range 0.156÷0.188, whereas in the case of five-stage forging, the range was 0.188÷0.219. Therefore, the risk of material cracking is higher for the five-stage process. In the finished forgings an additional zone of higher values of the Cockcroft-Latham criterion occurred. This area was similar to the area of the highest plastic strain. In the case of 4-stage forging this area was significantly longer than in the case of 5-stage forging process.

Material cracking can also be a result of shear stresses causing shear fracture. The occurrence of shear stress will cause strains total which may result in interruption of material cohesion. Figure 7 presents the distribution of strain total in finished forgings. In the case of the four-stage process, a visible localisation of strain total in the ‘A’ area can be observed. This area is located along the entire thickness of the flange. It is highly possible that during this process cracking of the flange may occur. As far as the five-stage process is concerned, the area of the maximum strain total ‘A’ is significantly smaller and does not include the entire thickness of the flange. By increasing the number of the forging stages, it was possible to minimise the concentration of strain total.
Figure 7. Distribution of strain total γxy for the elements forged in the process consisting of a) four stages, b) five stages.

The possibility of performing the technological process of forging in cold working conditions depends on the surface pressure in the area of material-tool contact. Significant surface pressure are less favourable as far as the tool life is concerned. Figure 8 shows the maximum surface pressure in the final phases of each forging stage. Along with the increase in process advancement, an increase in the surface pressure may be observed.

In the first forging stage, the maximum surface pressure occurs under the front of the punch and reaches up to 2190 MPa. In the second stage, the pressure under the front of the punch reaches up to 2500 MPa. Additionally, an increase in the pressure in the shaft portion of the forging up to c.a. 1880 MPa occurs. In the third stage, more significant pressure occurs in the shank part of the forging (2190 MPa), whereas under the front of the punch 1880 MPa. The distributions of surface pressure in stages 3 and 4 of the second variant are remarkably similar. In the final stages the highest values of pressure occur in the shank part of the forging, up to 2500 MPa. In the flange part of forging produced in four stages, the area of the maximum values of pressure (colour red) is bigger than in the case of the forging produced in five stages. In the 1, 2, 3 and 4 stage of the second variant in the inner part of the forging in the flange area it can be observed that the surface pressure equals 0 MPa. This phenomenon indicates the fact that the material moves away from the calibrating mandrel. In the case of stage 5, the area in which surface pressure equals 0 MPa is very insignificant.

Figure 9a presents force characteristics of the four-stage forging process. The presented force values concern the forces registered in punches. The scheme indicates that, along with the advancement of the process, the maximum value of forging force increases. The highest value of force determining dimensions of the technological machine occurs in the fourth stage and equals 6916.5 kN. The progress of the force characteristics is typical for the forging processes. In the first stage of the process, the force increases slowly, whereas in the last stage it increases rapidly, reaching the maximum in a noticeably short time. The increase of the force for each forging stage is a result of occurring phenomena. The first phenomenon concerns strain hardening of the material, whereas the second one – the increase of the contact area between the material and the tool.

Figure 9b presents the progress of the force characteristics for the five-stage forging process. The character of the progress of the force parameters is similar to the four-stage process. Adding another stage allowed to decrease the maximum value of the forging force in the final stage. The maximum value of the forging force in the fifth stage equalled 6624.3 kN and was lower approx. 300 kN than the maximum force in the four-stage process. In both cases, the most significant increase of force compared to the previous stage occurs in the final stage. This is, of course, connected to the greatest increase of the material-tool contact surface.
Figure 8. Distribution of the surface pressure for the highest forging force in each stage (scale in MPa).

Figure 9. Progress of the force characteristics for the a) four-stage, b) five-stage forging process).
4. Conclusions
On the basis of the analysis of the results obtained from numerical calculations of the process of forming a forging with a flange, it was stated that in the case of using a Ø 45 x 8 mm tube-shaped billet the five-stage process is more favourable. Performing the process in five stages allows to eliminate material folding on the inner wall of the forging. The phenomenon of the material moving away from the calibrating mandrel in the inner hole is less significant for the five-stage process than for the four-stage one. Moreover, in the five-stage process smaller forming forces, as well as surface pressure occur. In the four-stage forging process, the greatest force was obtained in the last step. This force is greater by 4.2% from the maximum force obtained by a five-step process. Although it is a small percentage it translates into a difference of about 300 kN force.

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