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Numerical analysis of three-stage the forming process hollow forgings with an outer flange

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Abstract

This article presents the results of computer simulations used to investigate the forming of a hollow cold-worked forging with an outer flange. Numerical simulations were performed in Deform 2D/3D using a calculation module for axial-symmetric cases. A $\phi 57\times 12.5$ mm tube-shaped billet from 42CrMo4 grade steel was used. The forming process involved two and three stages, consisting of extrusion the shaft portion and forging the flange. The objective of this research was to determine the accuracy of the forming process used to produce the hollow part. This technology was analyzed using the effective strain distributions, the Cockcroft-Latham fracture criterion values, and the forming force progression. The results showed that it was possible to use this three-stage process to forge elements from a tube-shaped billet.

Introduction

Hollow elements are frequently used in machine construction, automotive, aviation, chemical, and energy industries. They are most often used as transmission shafts, since the moment of inertia can be minimized due to the limited mass of the rotating elements. For example, a hollow shaft is 50% lighter than the whole shaft when its outer diameter is 20% bigger than the whole shaft (Bartnicki & Pater, 2005; Pater, 2009).

Moreover, various structural materials are used to manufacture machine parts and components for transportation, maritime, or mining industries (Winiarski et al., 2019; Szala et al., 2019; Tomków, Czupryński & Fydrych, 2020). The most suitable materials for fabrication are structural steels (Sun et al., 2018; Szala et al., 2020; Winiarski et al., 2020), aluminum (Winiarski, Gontarz & Dziubińska, 2017; Ayer, Bingöl & Karakaya, 2019), or magnesium (Ayer, 2017; Gontarz et al., 2018) alloys. However, from the range of components, hollow elements are usually manufactured using machining or metal forming. Machining allows the production of elements with high dimensional and shape accuracy, at the expense of chips and filings. During metal forming, the shape and dimensions of the workpiece are changed, along with the mechanical and physical properties, due to preserving the continuity of the metal microstructure and strengthening the material (Pater & Samołyk, 2013).

The choice of the proper method to manufacture hollow elements depends on the geometry and application (Amborn et al. 1995). Hollow elements are usually produced by specific metal forming methods, such as forging, extruding, cross-wedge rolling, and rotational compression, but forging is the most common (Colla et al., 1995; Hu & Wang, 2004; Aliiev et al., 2011). Products with complicated geometries are usually produced in a few operations, whereas only a single operation is necessary for simple elements (Gontarz, Pater & Tofil, 2011).

Multi-stage metal forming processes are usually applied in forging screws, which require three-to-five operations (MacCormack & Monaghan, 2002; Kılıçaslan & İnce, 2016; Chen et al., 2017; Chen et al., 2018). In his works, Pang presented a multi-operational process to forge the preform of a shaft. In one study, he presented a method for forming a conical part in three forging operations (Pang, Lowrite & Ngaile, 2017). In the first operation, a tube-shaped billet was heated only in the part subjected to forming. Then, the heated part of the billet was upset in a closed die in such a manner that the material only flowed to the material axis until the inner hole of the tube was filled. In the next operation, the upset end of the billet was forged into a conical impression; and in the final stage, the flange of the shaft was formed. In a second publication, Pang (Pang & Ngaile, 2019) forged the same shaft using only two operations, which did not require cone forging.

Oftentimes, the process of forging hollow elements is combined with extrusion processes (Park, Lim & Hwang, 1998; Wang et al., 2002; Winiarski, Gontarz & Samołyk, 2019). Among the extrusion processes of hollow elements, there are free forging and forging with a central mandrel. During the free forging of hollow elements, only the outer surface is formed, whereas the shape of the hole depends on the character of the material flow. Using the mandrel in the extrusion process as an additional tool allows a hole to be formed in such a shape that the finished product has the smallest possible allowance for machining. Another extrusion process is extrusion with a movable sleeve. In this process, the sleeve moves in the direction opposite the punch, making it possible to manufacture hollow elements with flanges where the height of the flange is several times greater than the billet wall thickness in one operation (Winiarski & Gontarz, 2017).

Hollow elements can also be produced using the cross-wedge rolling method, which uses mandrels of a certain shape inside the workpiece. Two methods of cross-wedge rolling are employed: in the first, a mandrel of a fixed diameter is used, which remains in place during rolling; in the second, special mandrels mounted in handles are used and moved along the axis of the rolled object. The cross-wedge rolling process can be also used to manufacture preforms (Neugebuer et al., 2002; Ji et al., 2017; Shen et al., 2019).

In the three-roll rotational compression, the cross-section of the semi-finished tubular product is reduced using three identical rolls that rotate in the same direction and simultaneously move radially toward the element axis. The tool shape is determined by the geometry of the compressed element, whereas the billet is a tube or a sleeve. In the first stage of the process, the billet is placed between the tools; then, during compression, it is rotated by the rolls, which reduces the inner diameter of the produced during subsequent steps. This is accompanied by an increase in the thickness of the billet wall, as well as the length of the end pins (Pater et al., 2015).

The literature on forming hollow elements suggests that it is possible to manufacture hollow elements using several processes and operations. Thus, this article presents the results of numerical simulations of two- and three-stage processes for forging hollow elements with an outer flange. The obtained forging can be used as a semi-finished product to produce rotational mining knife sleeves or elements of drive transmissions in mechanical gearboxes.

Research methodology

Computer simulations of the forging process were conducted in DEFORM 2D/3D. In this program, the finite element method was used, in which the real model was substituted by the discrete model built from a finite number of elements and nodes.

The geometry and selected dimensions of the analyzed forging are shown in Figure 1b. For the tests, a billet with a 57 mm outer diameter and a 12.5 mm thick wall (Figure 1a) was selected. It was assumed that the product will be manufactured in two and three stages. In the first variant, the shaft portion of the forging was extruded, and the flange was made in a one-stage forging in a conical finishing impression.

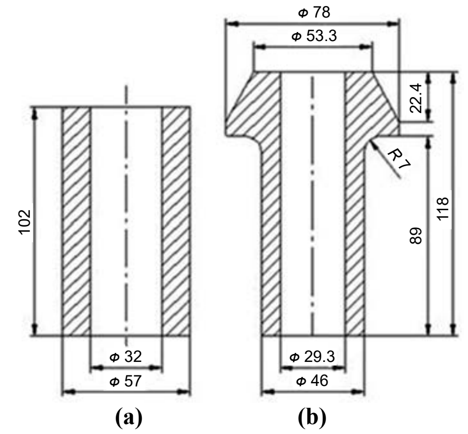

Figure 1. Shape and geometrical dimensions of: (a) a tube-shaped billet, (b) forging with an outer flange

In the second variant, it was assumed that the flange will be forged in two conical impressions – initial and finishing.

In the first stage of research, a numerical analysis was conducted on the extrusion process of the shaft part of the formed forging. Two dies were used during testing, in which the angles α of the die were set to 7.5° and 15° (Figure 2a). In the second stage, tests were conducted to investigate the forging process of a flange in one and two conical impressions (Figure 2b and c) from extruded preforms.

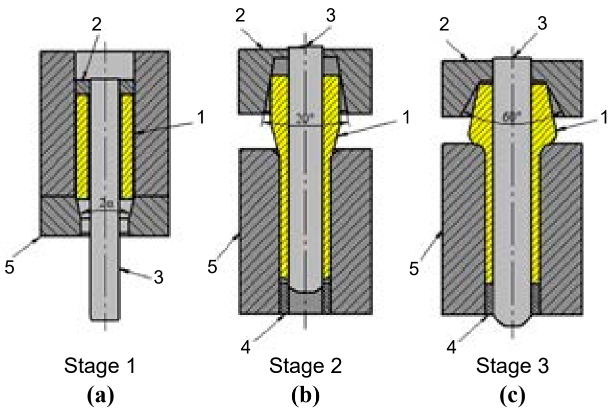

Figure 2. Tools for forging hollow elements with a flange: (a) die for extruding the shaft portion and dies for forging the flange with an initial (b) and (c) finished impression; 1 – billet, 2 – punch, 3 – mandrel, 4 – ejector, 5 – die

It was assumed that the billet was made of 42CrMo4 grade steel, the chemical composition of which is presented in Table 1. The flow curve of the material for spheroidized steel (spheroidizing was performed at 720°C for 9 h) was described by equation (1), determined in previous research (Szala et al., 2020).

$$\sigma_p = 1023 \cdot \varphi^{0.2} \tag{1}$$

where σ_p is the flow stress, MPa; and φ is the strain.

Table 1. Chemical composition of 42CrMo4 grade steel

C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Cu
0.38 – 0.45	0.4 – 0.7	0.17 – 0.37	0.035	0.035	0.9 – 1.2	0.3	0.15 – 0.25	0.2	0.05	0.025

During computer simulations, the initial temperature of the billet and tools were assumed to be 20°C, and the speed of the forming tool was 100 mm/min. In the shear friction model, the friction factor between the billet and the tools was assumed to be $m = 0.3$. The heat transfer coefficient was assumed to be 10 kW/m^2 K.

Results

The analysis of the results of the first stage indicated that using a die with an angle $\alpha = 7.5°$ caused the extruding force to be higher than $\alpha = 15°$; therefore, the larger angle seems to be more beneficial. Moreover, the second stage of the research demonstrated that the angle of the matrix was important to the forging of conical impressions. A larger die angle had a smaller influence on local buckling of the billet wall, which makes it even more favorable. Analysis of the flange forging process using only the finished impression showed that during this operation, the billet wall buckling was so great that folding began to occur. Therefore, a defective forging was obtained in the two-stage process. To eliminate this phenomenon, a two-stage flange forging was applied using the initial impression. The shape progression of the forging at each stage of the process is presented in Figure 3. The first stage, extrusion with a die of $\alpha = 15°$, progressed correctly. During the forging of a conical initial impression, local buckling of the billet wall was still observed at the initial stage of the process; however, it was insignificant and decreased as the process progressed, causing the material to fill the entire impression and comes into contact with the mandrel along its entire length. During forging of the finished impression, billet wall buckling was not observed because, in the second forging operation, the ratio of the length of the deformed end of the tubal billet to the wall thickness was significantly smaller than in the first operation. Thus, the process was uninterrupted, and the forging was defect-free.

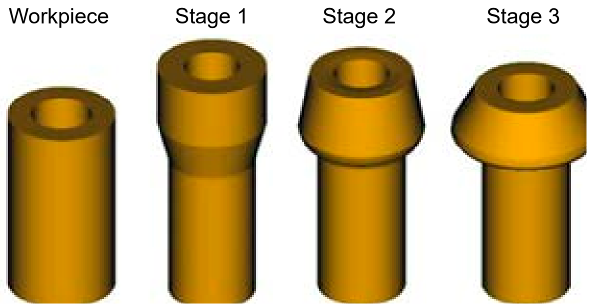

Figure 3. Progression of the shape of forgings at each stage of the process

Figure 4 presents the effective strain distribution in a forging formed in three stages. In the first stage, the maximum strain (1.25) was located in the forging's shaft. In the second and third stages, the maximum strain was located in the bottom part of the flange and radially progressed throughout the entire thickness. The maximum strain in the second stage was 1.56, whereas it was 2.5 in the third stage.

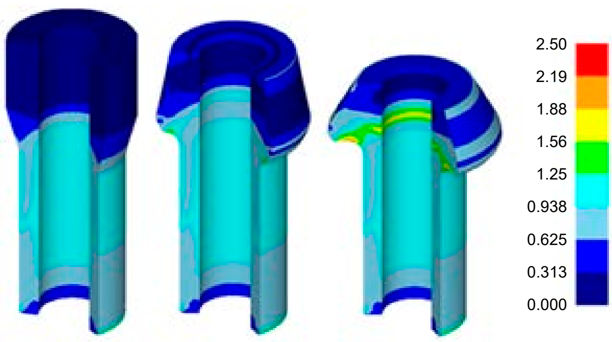

Figure 4. Effective strain distribution in the final phase of each forming stage

Figure 5 presents the distributions of the value of Cockcroft-Latham integral, which indicates the areas in which the loss of material cohesion was most likely to occur. The greatest value of 0.25 was located in the roll part of the flange. Such localization of the maximum values was caused by tensile tangential stress due to a significant increase in the billet diameter. Nevertheless, the established values of the integral were deemed safe for the analyzed material grade, which has limit values of 0.5–0.6.

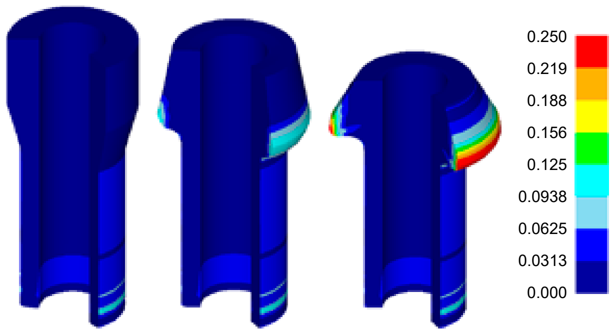

Figure 5. Distribution of the Cockcroft-Latham criterion in the final phase of each forming stage

The distribution of surface pressure distribution is shown in Figure 6. The most significant pressure during extrusion was located in the middle of the frontal surface and the bottom part of the flange. In the final stage, however, the maximum pressure was located throughout the entire length of the inner and outer shaft surface of the forging. All of the stages were characterized by surface pressures less than 2500 MPa, which indicates that the selected tools should be subjected to initial compression to ensure proper mechanical durability.

The progression of force characteristics during each stage is shown in Figure 7. The maximum force was 4000 kN, 4240 kN, and 6818 kN for the first,

Figure 6. Surface pressure (MPa) distribution in the final phase of each forming stage

second, and third stages, respectively. The forming force in the first stage appears to be important for ensuring tool durability. In this case, the tool with the greatest load was the tubal punch, with inner and outer diameters of 29.3 mm and 57 mm, respectively, which resulted in the forces transferred by it to generate compressive stress equal to c.a. 2100 MPa. This value is transferable by the materials currently used in cold working, allowing this process to be performed in a laboratory setting.

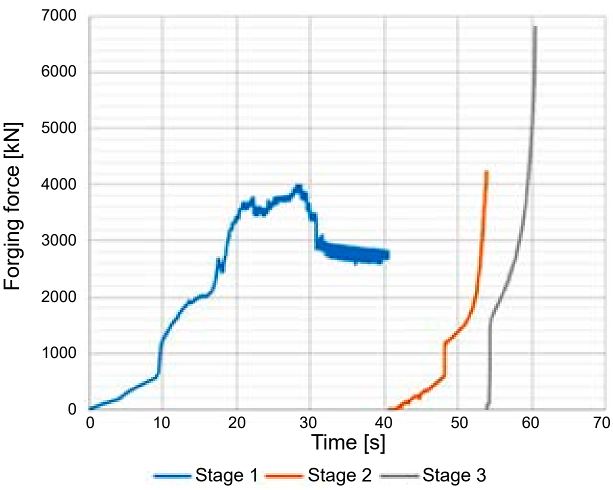

Figure 7. Progression of force characteristics

Conclusions

The results of the numerical tests showed that the shape of the extruded preform significantly influenced the correct progression of the forging of conical impressions. This process was limited by the occurrence of local buckling of the billet wall, which resulted in folding. To prevent this phenomenon, it is advised to increase the number of impressions.

The results also showed that cold forging requires the tools to apply relatively high unit pressures to deform the material. The numerical test results showed that a three-stage process is necessary to forge hollow elements with an outer flange from a tubal billet with the dimensions ϕ57×12.5 mm. This could not be accomplished using a two-stage process due to local buckling of the billet wall, which caused folding during subsequent stages of conical impression forging.

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