Cold forging of a hollow flanged part by an unconventional extrusion method

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Abstract. This paper presents a numerical analysis of a new cold forming process for a hollow part with an external flange. The following techniques were used: forward extrusion, an unconventional method of extrusion with a moving sleeve, and upsetting in a tapered die cavity. The billet (42CrMo4 steel tube) was formed at ambient temperature. The study aimed to investigate the proposed method in terms of forged part accuracy. The following are examined and discussed: material flow, process force parameters in relation to tool strength, energy consumption of individual operations, as well as the distributions of strains, stresses, temperature and Cockcroft-Latham integrals in the produced part. The study has confirmed that hollow forged parts with external flanges of relatively large diameters and heights can be cold formed in several operations using different techniques.

1. Introduction

Hollow parts are used in different branches of industry. Their applications include drive shafts, sleeves, fasteners, etc. Manufacturing methods for such parts differ and depend on many factors, the most important being part function, required properties, production rate, and material grade. The methods can be grouped under three manufacturing processes, i.e. casting, machining, and forming. Each of the processes has its specified and justified share in the production of hollow parts. Nevertheless, special focus should be put on forming techniques as they are most widely used in the big-lot production of parts with high strength properties. The selection of individual forming methods for producing hollow parts strictly depends on the product and billet geometry and forming temperature. Radial extrusion is a frequently used method for producing parts with side protrusions [1-3]. Unfortunately, however, the flange may crack or its height may decrease during a radial flow of the material. This phenomenon can be minimized e.g. by using rings that constrain the free radial flow of the material [4,5]. Billets can come in the form of bars or tubes, and they are deformed in closed or open die cavities [6,7]. In the case of hollow parts, the formation of a hole can be supported by the use of a mandrel or a medium e.g. fluid or elastomer [8-10]. Fluids are also used in hydroforming [11-13]. This method is used for forming hollow parts with complex shapes that are difficult to obtain using other methods [14].

Upsetting is another process for producing hollow parts [15-18]. A significant limitation of this process is the risk of local buckling of a tube wall leading to overlap, which makes it considerably difficult to form high flanges with large diameters. To increase the applicability of upsetting, the process can be performed in several stages in order to gradually increase the flange dimensions [19].
Extrusion is another technique for forming hollow parts. This process comes in many variations, the most widely used being forward and backward extrusion. Apart from conventional extrusion methods, one can distinguish unconventional extrusion methods, including extrusion with a moving sleeve. The sleeve moves in an opposite direction to that of the punch, which makes it possible to form flanges of great height in one tool pass [20,21].

Another group of forming processes for hollow products includes processes in which the tools and/or workpiece perform the rotary motion. Rotary forming methods include: cross wedge rolling [22-24], rotary compression [25], rotary swaging [26, 27], rolling extrusion [28, 29]. These processes are characterized by high efficiency and are predominantly used for producing axisymmetric parts. Taking these varieties of factors, such as the way of loading or types of manufacturing, also generate the need for many tests and prediction models, such as fatigue or surface metrology [30,31].

Based on the review of methods for manufacturing hollow parts, it can be concluded that the selection of an appropriate technique depends on the product geometry. Individual techniques are dedicated to the production of strictly defined types of forgings, which limits the scope of their applicability. Therefore, this paper presents a new method for forming hollow products. The forged part is produced in several stages using the following techniques: forward extrusion, a new extrusion method with the use of a moving sleeve, and upsetting. The combination of several techniques makes it possible to produce forged parts with flanges of relatively large diameters and heights compared to the wall thickness of the billet (tube). The study aimed to examine the robustness of the proposed concept and to analyse individual stages of the forming process.

2. Research methods

The forming process under analysis was conducted for a forged part shown in Fig.1. Forged parts of this type can be used as semi-finished products for sleeves of rotary cutters in the mining industry. The billet was in the form of a tube with an outside diameter of 55 mm, wall thickness of 10 mm, and two lengths: 130 and 140 mm. Due to the fact that the outside diameter of the billet is bigger than the internal diameter of the shank, it was necessary to reduce the cross-section of the billet over a specified length. To that end, forward extrusion with the use of a mandrel was applied, as schematically shown in Fig. 2. In this process, the outside diameter and wall thickness of the billet are reduced at the same time. Another stage of the forging process involves flanging. Due to its relatively large volume, the flange cannot be formed in one operation. For this reason, two operations were performed: first, a novel method of extrusion with a moving sleeve in a semi-open die cavity was applied, followed by upsetting in a tapered die cavity. Schematic designs of the two processes are shown in Figs. 3 and 4, respectively. In extrusion with a moving sleeve, the part of the billet from which a flange is formed is put in a moving sleeve; in its lower zone, the sleeve has a cavity whose diameter is equal to that of the formed flange. The punch load causes the material to fill the die cavity. After that, the sleeve begins to move in an opposite direction to that of the punch. As a result, the flange height increases. Following the extrusion process with a moving sleeve, flanging is continued by upsetting in a tapered die cavity.

![Figure 1. Hollow forged part with an external flange.](image-url)
Figure 2. Schematic design of forward extrusion: a) start of the process, b) end of the process; 1- punch, 2- mandrel, 3- billet, 4- die.

Figure 3. Schematic design of extrusion with a moving sleeve in a semi-open die cavity: a) start of the process, b) end of the process; 1- punch, 2- moving sleeve, 3- preform, 4- mandrel, 5- lower die, 6- ejector.

Figure 4. Schematic design of upsetting in a tapered die cavity: a) start of the process, b) end of the process; 1- punch, 2- upper die, 3- billet, 4- lower die, 5- mandrel, 6- ejector.
The forming process from billets of two different lengths was conducted with the technological parameters listed in Table 1. The forging process for a 130 mm long billet was performed in three operations, whereas that for a 140 mm long billet was performed in four operations.

The proposed forming method was verified via numerical calculations by the finite element method, using Deform-2D/3D. The forming process was performed under cold working conditions at 20°C. The billet was made of 42CrMo4 steel in an annealed state. The flow curve of the tested steel grade was described by constitutive equation (1) [32]. The contact between the workpiece and the tools was described using a constant friction model with the friction factor set at \( m = 0.3 \). The coefficient of heat exchange between the workpiece and the tools was made equal to 10 kW/m²K. The velocity of the punch in individual operations was maintained constant at 100 mm/min.

The present study is a continuation of previously published results [32-39] regarding the project entitled: New metal forming technique for producing flanged hollow parts for the mining industry. In current study, two variants of mandrel kinematics were analysed. In the first variant, the mandrel moved with the same velocity as the punch (denoted by TR), while the other variant assumed that the mandrel was stationary (denoted by TS).

\[
\sigma_p = 1023 \cdot \varphi^{0.2},
\]  

where:

- \( \sigma_p \) is the flow stress,
- \( \varphi \) is the strain.

### Table 1. Parameters of individual operations in the analysed forming process.

| Operation no. | Name of operation                          | Billet dimensions [mm] |
|---------------|--------------------------------------------|------------------------|
|               |                                            | Ø55 x 10 x 130         | Ø55 x 10 x 140         |
| I             | Forward extrusion                          | \( \alpha_{in}=30^\circ \), R = 5 mm, |
| II            | Extrusion with moving sleeve               | \( D_k = 62 \text{ mm}, h_o = 24 \text{ mm}, \alpha_{t}=20^\circ \), R = 5 mm |
| III           | Upsetting in tapered die cavity I          | \( \alpha_s=54^\circ \) |
| IV            | Upsetting in tapered die cavity II         | \( \alpha_s=30^\circ \) | \( \alpha_s=54^\circ \) |

### 3. Results and discussion

The results demonstrate that the forming process for the 130 mm long billet is correct (Fig. 5). Nevertheless, the press load in the final stage of the forming process (upsetting in a tapered die cavity) is relatively high and amounts to approx. 7961 kN. For the case of the billet with a length of 140 mm, the volume of the flange increases while the forming force decreases by approx. 7.5% compared to the process conducted using the 130 mm long billet. This is desired in terms of tool load.

Apart from reducing the press load in the final forging stage, the use of the 140 mm long billet also causes that, during upsetting in a tapered die cavity with an apex angle \( \alpha_s \) of 54°, the wall of a perform produced by extrusion with a moving sleeve undergoes local buckling (Fig. 6). The buckling is so extensive that the material is unable to fill the die cavity in this region (no contact with the mandrel during the final forging stage). To avoid this negative phenomenon, the upsetting operation was conducted in two tapered die cavities with their apex angles \( \alpha_s \) of 30° and 54°. Individual stages of the forming process are shown in Fig. 7.
Figure 5. Changes in the shape of the workpiece during individual stages of the forming process conducted with a billet with the dimensions of Ø55 x 10 x 130 mm: a) forward extrusion, b) extrusion with moving sleeve in the semi-open die cavity, c) upsetting in the tapered die cavity.

Figure 6. Local buckling of the wall of a preform produced by extrusion with a moving sleeve during upsetting in a tapered die cavity with the apex angle $\alpha_s = 54^\circ$; billet: Ø55 x 10 x 140 mm.

Figure 7. Changes in the shape of the workpiece shape during individual stages of the forming process conducted with a billet with the dimensions of Ø55 x 10 x 140 mm: a) billet, b) forward extrusion, c) extrusion with a moving sleeve in a semi-open die cavity, d), e) upsetting in a tapered die cavity.

Further analysis of the four-stage forging process consisted of performing calculations in which the movement of the mandrel was modelled in two different ways. In the first variant, the mandrel was driven and moved with the same velocity as the punch. In the other variant, the mandrel was made
stationary. The study aimed to determine optimal conditions of the process in terms of minimizing the force transmitted by the tools that were most prone to damage, i.e. punches and ejectors. Figs. 8÷11 show the maximum values of the loads applied to the tools during individual stages of the forming process. It was found that the process performed with a moving mandrel led to reduced punch load and increased ejector load. On the other hand, the use of a stationary mandrel led to the opposite situation, i.e. the punch load was increased while the ejector load was reduced. Considering the above, it was assumed that forward extrusion and extrusion with a moving sleeve should be conducted using a moving mandrel, whereas upsetting in a tapered die cavity should be performed with the use of a stationary mandrel. In this process, the punch and ejector can carry compressive stresses of up to approx. 1900 MPa. These values should be considered safe for tool materials (steel and sintered carbides) dedicated for cold working conditions.

![Graph](image1.png)

Figure 8. Punch load in Stage I.

![Graph](image2.png)

Figure 9. Punch and ejector loads in Stage II.
Figure 10. Punch and ejector loads in Stage III.

Figure 11. Punch and ejector loads in Stage IV.

Figure 12 shows the distributions of effective strain and stress, temperature, and the normalized Cockcroft–Latham ductile fracture criterion in a part forged from a billet with the dimensions of Ø55 x 10 x 140 mm.

It can be observed that the effective strain values in the flange increase with increasing the flange diameter, from the end face towards the shank. The highest values of approx. 2.5 are located in the largest diameter region of the part. In the shank the highest strain of approx. 0.8 is located at the outer surface of the part.

The maximum effective stresses of 1090 MPa are located in the largest diameter region of the flange. The effective stresses are considerably lower in the shank and at the end face of the flange. This results from the fact that, in this region, the material is in a closed die cavity. In effect, the stress state is similar to the tri-axial state of stress, which means that the principal stresses are similar and, consequently, the effective stress value is low.
An analysis of the temperature in the forged part reveals that the highest values of approx. 160ºC are located in the region where the stresses and strains are the highest, i.e. in the largest diameter region of the flange. In other regions of the product, the temperatures increase slightly above the initial temperature value of 20ºC, which is due to the low values of strain and large material-tool contact surface.

An analysis of the normalised Cockcroft–Latham ductile fracture criterion is of quite significant importance in cold forming processes. The material undergoes hardening during forming, while a lack of thermally activated processes (e.g. recrystallization) may lead to crack formation. In the analysed forged part, the maximum values of the criterion are located on the flange rim and equal to approx. 0.27. This value seems safe for the tested steel grade 42CrMo4, for which the limit values range approx. 0.5-0.6.

![Figure 12](image)

**Figure 12.** Distributions of: a) effective strain, b) effective stress (MPa), c) temperature (ºC), d) normalized Cockcroft–Latham ductile fracture criterion in a part forged from a billet with the dimensions of Ø55 x 10 x 140 mm.

Table 2 lists the value of work performed by the tools in individual forming operations. The first operation (forward extrusion) is the most energy-consuming as it requires the supply of approx. 63% of total energy required for forging a part. This results from the fact that in this operation, the displacement of the tools is the highest and thus the force is relatively high within almost the entire range of movement. In other operations, the work of the tools is several fold lower, which primarily results from lower values of their displacement. Additionally, high forces are only reached toward the end of the forming operations.
Table 2. Energy consumption of the forging process for a hollow part forged from a billet with the dimensions of Ø55 x 10 x 140 mm.

| Operation no. | Tool                     | Work, kJ |
|--------------|--------------------------|----------|
| I            | Punch (TR)               | 149.8    |
|              | Mandrel (TR)             | 14.1     |
|              | Total                    | 163.9    |
| II           | Punch (TR)               | 29.3     |
|              | Mandrel (TR)             | 5.7      |
|              | Moving sleeve (TR)       | 6.2      |
|              | Total                    | 41.2     |
| III          | Punch (TS)               | 14.2     |
|              | Upper die (TS)           | 8.9      |
|              | Total                    | 23.1     |
| IV           | Punch (TS)               | 16.5     |
|              | Upper die (TS)           | 12.7     |
|              | Total                    | 29.2     |
|              | Total                    | 257.4    |

4. Conclusions
The results of the study investigating a cold forging process for producing a hollow part with an external flange lead to the following conclusions:

- The application of a sequence of three different techniques makes it possible to produce a correct forged part with a flange having a relatively large diameter and height;
- An increase in the volume of the flange causes a decrease in the maximum forming force by about 7.5%;
- The kinematics of the mandrel has a significant impact on the tool load; the use of a moving mandrel causes a reduction in the punch load and an increase in the ejector load; an opposite situation is observed when the process is performed with a fixed mandrel;
- Forward extrusion is the most energy-consuming operation, which results from the fact that the displacement of both the punch and the mandrel in this operation is the greatest relative to other all tools used in individual operations of the analysed forging process.

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