Numerical analysis of a two-stage forming process for a hollow part with external flange

G Winiarski¹, T Bulzak¹ and M Szala²

¹Lublin University of Technology, Faculty of Mechanical Engineering, Department of Computer Modelling and Metal Forming Technologies, 36 Nadbystrzycka Street, 20-618 Lublin, Poland
²Lublin University of Technology, Faculty of Mechanical Engineering, Department of Materials Engineering, 36 Nadbystrzycka Street, 20-618 Lublin, Poland

g.winiarski@pollub.pl

Abstract. This paper presents the results of a numerical analysis of a two-stage forging process for producing a hollow part with an external flange. The numerical analysis was performed via the finite element method using Deform-2D/3D. The analysed case included a cold forming process. The billet was a tube made of a low alloy steel grade 42CrMo4 with its flow curve described by a constitutive equation. The forming process involved the use of two operations: extrusion and forging in a tapered die cavity. The objective of the study was to determine whether the proposed forming technique could be used for production of hollow flanged parts. The kinematics of material flow, distributions of effective strains and the Cockcroft–Latham ductile fracture criterion, as well as force parameters were examined. The conducted research confirmed the correctness of the proposed method.

1. Introduction

Manufacturing processes for hollow parts with flanges generally fall under three types of manufacturing techniques, i.e., machining, forming and casting. The application of these technologies depends on many factors, including product geometry, production volume, material yield, and manufacturing costs. Therefore, different metal alloys manufactured with usage of forming technology are systematically investigated. Especially low alloy steels [1,2], stainless steel [3,4], titanium [5], magnesium [6–8] and aluminium based [9,10] machine parts and components are fabricated with the metal forming techniques. Steel metal forming processes have been employed for more than century [11,12] and its production processes are still being developed. However, usually before the implementation of the forming technique into the manufacturing, the computational simulations are conducted [13–18].

The use of forming techniques usually ensures high productivity and material yield. Despite these advantages, the forming of hollow parts with flanges is associated with many limitations, which means that not all forming technologies can be used to this end. For this reason, the problem of forming hollow products has often been a subject of many scientific studies [19–22]. Forming methods for hollow parts may be divided into two groups: methods in which the flange is secured to the shank of the shaft and methods in which monolithic hollow shafts are formed. Regarding the methods in which the flange is secured to the shank, the most frequently employed techniques are those in which the first step of the shaft is formed by wall buckling or upsetting. Next, after mounting the flange, the shaft end is re-flanged or upset in order to secure the flange [23–25]. Monolithic shafts can be manufactured
using a variety of techniques. One of widely used techniques is extrusion. Extrusion of hollow parts from tubular billets is performed using tools provided with a central forming mandrel. This technique makes it possible to form parts with both external and internal flanges [26–28]. Another widely used technique is upsetting. Depending on the type of tools, closed- or semi-open and open-die upsetting can be distinguished. The key technological parameter in upsetting is the ratio between the height of a freely protruding part of the hollow billet to its wall thickness and diameter. If this ratio is incorrect, overlap will occur in the flange area [29,30]. Another method for producing hollow flanged parts is flanging. There are many variations of this method, e.g. free flanging or flanging with the use of a die or a ball-shaped tool [31–34]. A slightly different method is orbital forging. A characteristic of this incremental deformation technique is that the forming tool performs rotating motion, which means that the momentary contact surface during the shaping of the workpiece is small, and thus the forming force is low too. The most common failure modes in the orbital forging of hollow parts include cracking of the formed flange and buckling of the tube wall [16,17,35]. Hollow parts are also often formed by hydroforming. The use of high internal hydraulic pressure and additional axial feed of tools makes it possible to adjust the tubular billet to the shape of the die cavity, while minimising the phenomenon of workpiece wall thickness reduction [14,36,37].

The literature review shows that forming techniques for hollow flanged products are used to produce specific types of parts. In order to increase the range of products that can be manufactured with these techniques, several methods can be combined in one manufacturing process. This paper presents an example of a process combining methods of extrusion and forging to produce a hollow part with a relatively large in diameter flange; such parts are difficult to produce by means of only one forming technique. The billet used in the study is a tube section with its outside and inside diameters bigger than the diameter of the shank. The objective of the study is to determine whether the proposed forming technique is a viable method for producing the analysed part that can be used as a semi-finished product for mining rotary knives sleeves or hollow shafts with bevel gears.

This paper is a continuation of the research group studies regarding the numerical simulations and experimental research connected with developing new cold metal forming methods for producing hollow parts with flanges.

2. Research methodology

The hollow part with an external flange (Figure 1b) was formed from a tube with dimensions Ø60 x 10 x 114 mm (Figure 1a). The forging process was performed via two operations: extrusion and forging in a tapered die cavity. In the extrusion operation (Figure 2a), the shank with an outside diameter of 46 mm was formed. This process was performed using a die with a reduction angle of 2α = 50° and a rounding radius of R = 5 mm. The die chamber diameter D and the calibrating tool part diameter d were 61 mm and 46 mm, respectively. Following extrusion, the workpiece was subjected to forging in a tapered die cavity (Figure 2b) which dimensions were the same as those of the flange.

The proposed forming method was verified by a numerical analysis performed using the finite element method-based Deform-2D/3D software. The process was simulated as a cold forming process, assuming the deformation was axisymmetric. The billet was assigned to the properties of 42CrMo4 steel with its flow curve described by a constitutive equation (1). The strain hardening coefficients were estimated by the previous experimental study described in [15]:

$$\sigma_p = 1023 \cdot \varphi^{0.2}$$  \hspace{1cm} (1)

The initial temperature of tools and the billet was set for 20°C. The contact between tools and the workpiece was described by a shear friction model with a friction factor μ=0.3; in addition, the heat transfer coefficient was set on 10 kW/m²K. The linear velocity of the punch and the top die was maintained constant at 100 mm/min. In the extrusion operation, the mandrel was either driven by the punch or moved automatically due to the action of forces generated by the workpiece, as shown in Figure 2a. In the forging operation, the mandrel was fixed and only the top die was moving, Figure 2b.
3. Results and discussion
First of all, the kinematics of material flow was examined in individual operations of the analysed two-stage forging process. Successive stages of the extrusion operation are shown in Figure 3. Due to
the large reduction of the internal hole diameter (from 40 mm to 29.3 mm), there is a risk of overlap formation. At the beginning of filling the die chamber, the material is blocked in the die insert. Next, the outside diameter of the workpiece is increased until the material comes into contact with the die wall. The thickness of the workpiece wall increases as the workpiece is upset by the punch. The increase in the wall thickness is uneven, and it first occurs from the punch side. As the process advances, the wall thickness of the lower regions of the workpiece increases. The results show that no alarming phenomena occur toward the end of filling the die chamber. The gap between the mandrel and the workpiece is gradually reduced, and the pattern of filling the gap with the material does not indicate the risk of overlap formation. The thickness of the workpiece wall increases from the punch towards the die. This is a desired effect because it minimises the risk of overlap formation. As the upsetting of the material progresses, the gap height and width proportionally decrease. After the die chamber is completely filled, the material is squeezed through the die insert, which makes it possible to reduce the thickness of the workpiece wall.

Figure 3. Changes in the shape of the workpiece during extrusion.

Changes in a shape of the workpiece during the final forging operation are shown in Figure 4. At the beginning of the forging operation, the outside diameter of the workpiece is reduced in the tapered cavity of the top die. In this stage, the material is upset to some extent; simultaneously it flows in the opposite direction to that of the die, filling the die cavity. This pattern of material flow in the first operation of the analysed process results from the fact that the diameter of the workpiece after extrusion is equal to 61 mm, which means that it is bigger than the end-face diameter of the forged part (53.3 mm). When the process is about 50% to complete, it may be observed that the material does not adhere completely to the mandrel calibrating the internal hole. When the process is about 75% to complete, the gap between the mandrel and the workpiece is invisible, and no overlap is formed in this area. The complete filling of the top die cavity occurs toward the end of the process. Summing up, the final forging operation proceeds correctly over the entire range of the tool path.
Figure 4. Changes in the shape of the workpiece during final forging.

Figure 5 shows the distribution of effective strains in the successive operations of the analysed forging process. In the extrusion operation, the effective strains in the shank are about 1.5. In the lower region of the shank, the strains are lower, which results from the fact that the tube initially goes through the die insert with lower wall thickness reduction. In this region of the shank, the thickness of the workpiece wall is hence reduced from almost the initial thickness of 10 mm. The strains in the flange are higher than those in the shank. This results from upsetting the tube in the die chamber and performing the final forging operation in the tapered cavity of the top die. The highest strains of up to about 2.3 (marked with the letter A) are located at the bottom of the flange over its entire thickness.

The distribution of the Cockcroft-Latham ductile fracture criterion in individual operations of the analysed process are shown in Figure 6. The highest value of this criterion amounting to approx. 0.25 can be observed in the cylindrical region of the flange. In contrast, the ductile fracture criterion does not increase in the shank. This means that the flange region is the most prone to cracking. Nevertheless, the ductile fracture criterion value amounting to 0.25 seems to be a safe value for the analysed steel grade, because the limit values for this material range between 0.5 and 0.6.

Distributions of the surface pressures toward the end of individual operations of the analysed process are plotted in Figure 7. The highest pressures amounting up to approx. 2300 MPa can be observed in the final forging operation. In the extrusion operation, the pressures close to 2300 MPa can only be observed in some regions of the workpiece. During the forming process the workpiece is invariably in contact with tools, i.e., there are no regions where the pressures are equal to 0 MPa. This means that the die cavities are filled correctly in both operations.

Variations in the forming force during successive operations are plotted in Figure 8. In the extrusion operation, the force gradually increases as the die is being filled with the material. In the steady-state extrusion, after the die has been filled, the force remains stable at about 3500 kN. The highest increase in the force can be observed toward the end of the final forging operation, with the force amounting to approx. 8500 kN.

Figure 5. Distribution of the effective strains toward the end of: a) extrusion, b) final forging.
4. Conclusion

The paper presents the numerical analysis of a two-stage forming process for a hollow part with external flange. The aim of the work was to examine if the analysed forging could be made in two stages. Simulations were conducted for the billet material made of 42CrMo4 steel. The theoretical results have demonstrated that the forging process for producing the analysed hollow part with an external flange can be performed by two operations: extrusion and forging in a tapered die cavity. The shank part of the forging is formed in the extrusion operation, whereas the flange part is formed in the forging operation. In the extrusion process, thickness of the tube wall is increased one and a half times. As a result, the extent of the material from which the flange is to be formed is reduced 1.37 times, what is very favourable. Owing to this, the final forging can be performed in one impression. The kinematics of material flow during the formation of a flange is desired because, first, the material flows in the opposite direction to that of the die, filling the die cavity, and then, it undergoes upsetting. Thereby, the risk of workpiece wall buckling and overlap formation is reduced. The study has shown that conducting of the process requires relatively high forces (in the range of 3500-8500 kN), which means that in experimental validation tests tools should have to be prestressed in order to ensure that they have sufficient mechanical strength. Calculations connected with mechanical strength of tools will be done by the authors in future studies.
Acknowledgement
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 Program.

References
[1] Hashmi S 2017 Comprehensive Materials Finishing (Kidlington, Oxford, United Kingdom: Elsevier)
[2] Rakhit A K 2000 Heat Treatment of Gears: A Practical Guide for Engineers (Materials Park, OH: ASM International)
[3] Zhan M, Guo K and Yang H 2016 Advances and trends in plastic forming technologies for welded tubes Chin. J. Aeronaut. 29 305–15
[4] Szala M and Łukasik D 2018 Pitting Corrosion of the Resistance Welding Joints of Stainless Steel Ventilation Grille Operated in Swimming Pool Environment Int. J. Corros. 2018 1–7
[5] Yang H, Fan X, Sun Z, Guo L and Zhan M 2011 Recent developments in plastic forming technology of titanium alloys Sci. China Technol. Sci. 54 490–501
[6] Ayer Ö 2019 A forming load analysis for extrusion process of AZ31 magnesium Trans. Nonferrous Met. Soc. China 29 741–53
[7] Gontarz A, Drozdowski K, Dziubinska A and Winiarski G 2018 A study of a new screw press forging process for producing aircraft drop forgings made of magnesium alloy AZ61A Aircr. Eng. Aerosp. Technol. 90 559–65
[8] Ayer Ö 2017 Simulation of helical gear forming of az31 magnesium material Adv. Sci. Technol. Res. J. 11 187–91
[9] Zheng K, Politis D J, Wang L and Lin J 2018 A review on forming techniques for manufacturing lightweight complex—shaped aluminium panel components Int. J. Lightweight Mater. Manuf. 1 55–80
[10] Shi C and Shen K 2018 Twin-roll casting 8011 aluminium alloy strips under ultrasonic energy field Int. J. Lightweight Mater. Manuf. 1 108–14
[11] International A S M 1985 ASM Handbook: Formerly Ninth Edition, Metals Handbook. Metallography and microstructures (ASM International)
[12] Kowal M and Szala M 2020 Diagnosis of the microstructural and mechanical properties of over century-old steel railway bridge components Eng. Fail. Anal. 110 104447
[13] Ayer Ö 2017 A numerical study for prediction of forming load and experimental verification of bimetallic disc upsetting Teh. Vjesn. 24 1679–88
[14] Yuan S J, Liu G, Huang X R, Wang X S, Xie W C and Wang Z R 2004 Hydroforming of typical hollow components J. Mater. Process. Technol. 151 203–7
[15] Szala M, Winiarski G, Wójcik Ł and Bulzak T 2020 Effect of Annealing Time and Temperature Parameters on the Microstructure, Hardness, and Strain-Hardening Coefficients of 42CrMo4 Steel Materials 13 2022
[16] Grosman F, Madej Ł, Ziolkiewicz S and Nowak J 2012 Experimental and numerical investigation on development of new incremental forming process J. Mater. Process. Technol. 212 2200–9
[17] Samolyk G 2013 Investigation of the cold orbital forging process of an AlMgSi alloy bevel gear J. Mater. Process. Technol. 213 1692–702
[18] Altinbalik T and Ayer Ö 2008 A theoretical and experimental study for forward extrusion of clover sections Mater. Des. 29 1182–9
[19] Jia Z, Ye T, Han Z, Xiao Y and Ji S 2019 Study on die-less spinning of cone–cylinder combined hollow parts J. Mater. Process. Technol. 271 488–98
[20] Shen J, Wang B, Zhou J, Huang X and Li J 2019 Numerical and experimental research on cross wedge rolling hollow shafts with a variable inner diameter Arch. Civ. Mech. Eng. 19 1497–510
[21] Pang H and Ngaile G 2019 Development of a non-isothermal forging process for hollow power transmission shafts J. Manuf. Process. 47 22–31
[22] Winiarski G, Bulzak T A, Wójcik Ł and Szala M 2020 Numerical Analysis of a Six Stage Forging Process for Producing Hollow Flanged Parts from Tubular Blanks Adv. Sci. Technol. Res. J. 14 201–8
[23] Alves L M, Afonso R M and Martins P A F 2019 Joining sheets to rods by boss forming CIRP Ann. 68 265–8
[24] Alves L M, Afonso R M, Silva C M A and Martins P A F 2018 Joining tubes to sheets by boss forming and upsetting J. Mater. Process. Technol. 252 773–81
[25] Sviridov A, Rusch M, Almohallami A, Bonk C, Bouguecha A, Bambach M and Behrens B-A 2017 Creating load-adapted mechanical joints between tubes and sheets by controlling the material flow under plastically unstable tube upsetting Procedia Eng. 207 968–73
[26] Gontarz A and Winiarski G 2017 Numerical and Experimental Study of Producing Two-Step Flanges by Extrusion with a Movable Sleeve Arch. Metall. Mater. 62
[27] Winiarski G, Gontarz A and Dziubińska A 2017 The influence of tool geometry on the course of flanges radial extrusion in hollow parts Arch. Civ. Mech. Eng. Vol. 17 986–96
[28] Winiarski G, Gontarz A and Samolyk G 2019 Flange formation in aluminium alloy EN AW 6060 tubes by radial extrusion with the use of a limit ring Arch. Civ. Mech. Eng. 19 1020–8
[29] Hu X L and Wang Z R 2004 Numerical simulation and experimental study on the multi-step upsetting of a thick and wide flange on the end of a pipe J. Mater. Process. Technol. 151 321–7
[30] Wang Z, Lu J and Wang Z R 2001 Numerical and experimental research of the cold upsetting–extruding of tube flanges J. Mater. Process. Technol. 110 28–35
[31] Rosa P A, Rodrigues J M C and Martins P A F 2004 Internal inversion of thin-walled tubes using a die: experimental and theoretical investigation Int. J. Mach. Tools Manuf. 44 775–84
[32] Rosa P A R, Rodrigues J M C and Martins P A F 2003 External inversion of thin-walled tubes using a die: experimental and theoretical investigation Int. J. Mach. Tools Manuf. 43 787–96
[33] Mohamed F A, El-Abden S Z and Abdel-Rahman M 2005 A rotary flange forming process on the lathe using a ball-shaped tool J. Mater. Process. Technol. 170 501–8
[34] Qiu X M, He I. H, Gu J and Yu X H 2014 An improved theoretical model of a metal tube under free external inversion Thin-Walled Struct. 80 32–7
[35] Groche P, Fritsche D, Tekkaya E A, Allwood J M, Hirt G and Neugebauer R 2007 Incremental Bulk Metal Forming CIRP Ann. 56 635–56
[36] Pandey A K, Walunj B S and Date P P 2018 Simulation based approach for light weighting of transmission components using tube hydroforming Procedia Manuf. 15 915–22
[37] Xu Y, Ma Y, Zhang S, Chen D, Zhang X, Li J and Zhao C 2016 Numerical and experimental study on large deformation of thin-walled tube through hydroforging process Int. J. Adv. Manuf. Technol. 87 1885–90