COMPARISON OF NUMERICAL AND EXPERIMENTAL CHANGES IN AXIAL FORCES FOR PUSHING THROUGH A CONICAL DIE PROCESS OF ROUND BARS MADE FROM S355 STEEL

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Abstract

The paper presents computer modelling and experimental results of investigations on pushing through a conical die process of round bars. The calculations were carried out using the commercial code QFORM-2D, based on the Finite Element Method (FEM). The investigations involved the use of circular sectioned S355 (1.0577) steel segments of rods with diameter of 9 mm. Result of calculations of pushing through a conical die process were validated against experimental data in terms of changes in forces for different elongation factors (λ_1 = 1.24, λ_2 = 1.37, λ_3 = 1.57). The aim of the paper is to compare the experimental and computer modelling changes in forces for different degree of deformations. The results of investigations into pushing through a conical die process might be used as guidelines to develop a technological process for industrial practice.

Keywords: FEM, conical die, S355 steel

1. INTRODUCTION

Different conventional methods of metal forming are employed while manufacturing stepped parts or reducing the cross section of the shafts and round bars. Drawing, forging with the use of swaging machines and cross rolling are used in industrial practice [1-3]. In the 1970s, Marciniak Z. and Kopacz Z. developed a cold rolling method which allowed forming of cylindrical gears, involute splines and other circular profiles [4]. The most essential features of the WPM method, distinguishing it from other known methods, involve the use of two circular segments as the tools and the adoption of a kinematics that allows one-directional rolling with a symmetrical system of forces relative to the axis of the rolled material. In the case when the jaws with internal smooth rolling surfaces are used as the tools, it is possible to reduce the cross section of the shafts and tubes. The maximum initial diameter of shaft from medium steel to be reduced is 30 mm [4]. Relative new manufacturing technologies of stepped parts are cross-wedge rolling and rolling-extrusion forming process [5]. In the process of rotary forcing, material is formed by means of three rotational tools. The charge is provided by means of a pusher pushing the billet in a working space between the profiled rolls [5].

A place of applying force causing deformation is the main difference between pushing of material through a die process and drawing process. The force is acting in the entry zone of material in pushing process. Principal stresses depend on yield point (mechanical properties) and degree of deformation of material [1,6]. The deformation ratios of material for drawing process and pushing of material through a die process in industrial practice is determined by elongation factor λ. It is given by formula [1,2,4,6]:

$$\lambda = \frac{A_0}{A_1} = \frac{d_0^2}{d_1^2} \qquad (1)$$

where:

A_0 - cross sectional area of the billet (mm^2)

A_1 - cross sectional area of the material after deformation (mm^2)

d_0 - the diameter of the billet (mm)

d_1 - the diameter of segment of rods after deformation (mm)

The process of pushing of material through a die has been reported in some studies [2,3,5]. Those covered experimental investigations.

The paper presents computer modelling and experimental results of investigations on pushing through a conical die process of round bars made from S355 steel. The aim of the paper is to compare the experimental and computer modelling changes in forces for different degree of deformations. The deformation ratios of material were defined as elongation factor λ and relative strain ε_l. Relative strain was given by formula [6]:

$$\varepsilon_l = \frac{\Delta l}{l_0} \tag{2}$$

where:

Δl - displacement of the punch (mm)

l_0 - length of the material before deformation (mm)

2. METHODOLOGY

Calculations of metal flow and study changes in loading were carried out with commercial code QFORM2D based on Finite Element Method (FEM). The deformed material is considered to be incompressible rigid-plastic continuum and elastic deformations are neglected. The system of governing equations includes the following [7]:

- equilibrium equation

$$\sigma_{ij,j} = 0 \tag{3}$$

- compatibility conditions

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \tag{4}$$

- constitutive equation

$$\sigma'_{ij} = \frac{2\bar{\sigma}}{3\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij} \tag{5}$$

- incompressibility equation

$$v_{i,i} = 0 \tag{6}$$

- expression for flow stress

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \tag{7}$$

where:

σ_{ij} - components of stress tensors (MPa)

$\dot{\varepsilon}_{ij}$ - components of strain-rate tensors (-)

v_i - velocity components (m/s)

σ'_{ij} - deviatoric stress tensor (MPa)

$\bar{\sigma}$ - effective stress (MPa)

$\bar{\varepsilon}$ - strain (-)

$\dot{\bar{\varepsilon}}$ - strain rate (1/s)

T - temperature (°C).

In equations 3 - 7, summation convention is used. The prime denotes a derivative with respect to the axis following it. The indexes *i* and *j* for two-dimensional problems vary from 1 to 2, and repeated subscript represents summation. The friction model proposed by Levanov et. al [7] is used for the contact region of workpiece surface. Equation (8) can be considered as a combination of the constant friction model and the Coulomb friction model. The formula combines the advantages of both models [7]:

$$F_t = m\frac{\bar{\sigma}}{3}(1-\exp(-1{,}25\frac{\sigma_n}{\bar{\sigma}}) \quad (8)$$

where:

m - the friction factor

σ_n - the normal contact pressure (MPa).

The flow stress characteristics were given as a function of the strain rate. On the basis of literature data [8] function was adopted for numerical modelling of pushing through a conical die process of round bars made from S355 steel. Chemical composition of material [9] is shown in **Table 1**.

Table 1 Chemical composition of S355 steel [9]

C (%)	Mn (%)	P (%)	S (%)	Si (%)
0.23 max.	1.60 max.	0.05 max.	0.05 max.	0.05 max.

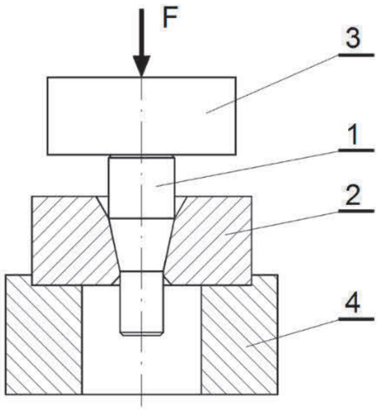

Figure 1 Tool for pushing through a conical die process, where: 1 - workpiece, 2 - conical die, 3 - punch, 4 - holder of the die

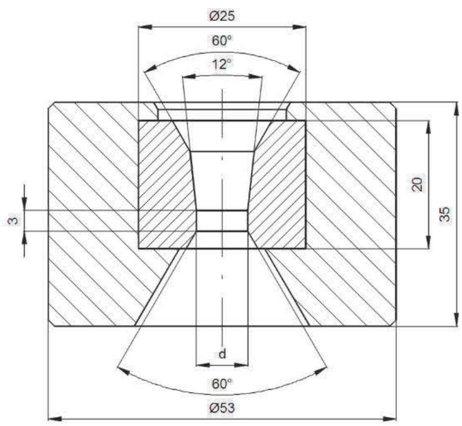

Figure 2 The shape and main dimensions of conical die

The investigations into pushing through a conical die process involved the use of circular sectioned S355 steel segments of rods with diameter d_0 = 9 mm and length l_0 = 23 mm. The experimental part of the research was conducted at a special stand which included the following:

- a tool for pushing through a die process of round bars equipped with replaceable conical dies,

- ZD100 testing machine modified by LABORTECH, 1 MN force (the machine is compliant with metrological requirements for Class 1 and was calibrated as per PN-EN ISO 7500-1:2005),
- a computer stand with Test&Motion software (LABORTECH) to measure forces and displacements.

Figure 1 shows the diagram of the press tools for pushing through a die process of round bars used in the experiment. Conical dies with different diameter of sizing portion of a die (d = 7.1 mm; 7.6 mm and 8.0 mm) were made from sintered carbides in steel die cases. The shape and main dimensions of conical dies used in this investigation are presented in **Figure 2**.

3. RESULTS AND ANALYSIS

The numerical and experimental investigations produced round bars with different nominal diameter: d_1 = 8 mm, 7.6 mm and 7.1 mm; which corresponded to different elongation factors: λ_1 = 1.24, λ_2 = 1.37, λ_3 = 1.57, respectively. Results of the simulation process showed that the model of boundary conditions, presented in previous chapter, proved adequate. To analyze metal flow in the computer program, the flow lines were imposed. They formed a grid that made it possible to view the displacement and distortion of the metal selected volumes in deformations. In the simulation, ten inner flow lines along the 0X and 0Y axes were assumed. Numerically calculated last stages of pushing through a conical die process of round bars made from S355 steel for different elongation factors at the same displacement of the punch Δl = 8 mm are presented in the **Figure 3.** At this displacement it was possible to receive the cylindrical part of initial material without any changes for elongation factors λ_1 = 1.24 and λ_2 = 1.37 but it started in the formation of a barrel in this part for factor λ_3 = 1.57. That was confirmed by the tests carried out at stand with ZD100 testing machine.

The patterns of changes in loads obtained from computer modeling and experimental investigations of pushing through a conical die process of round bars made from S355 steel for different elongation factors are presented in **Figure 4**. In the graphs, Δl denotes the displacement of punch. Both in experimental and modeling investigations, the axial force increased together with an increase in the displacement of the punch Δl and relative strain ε_l. ε_l

The analysis of changes in numerically calculated (**Figure 4 a**) and experimental (**Figure 4 b**) loads in pushing through a conical die process indicates that as the forming process advances in time, which is represented by an increase in the displacement Δl (or relative strain ε_l), the force increases at different elongation factors.

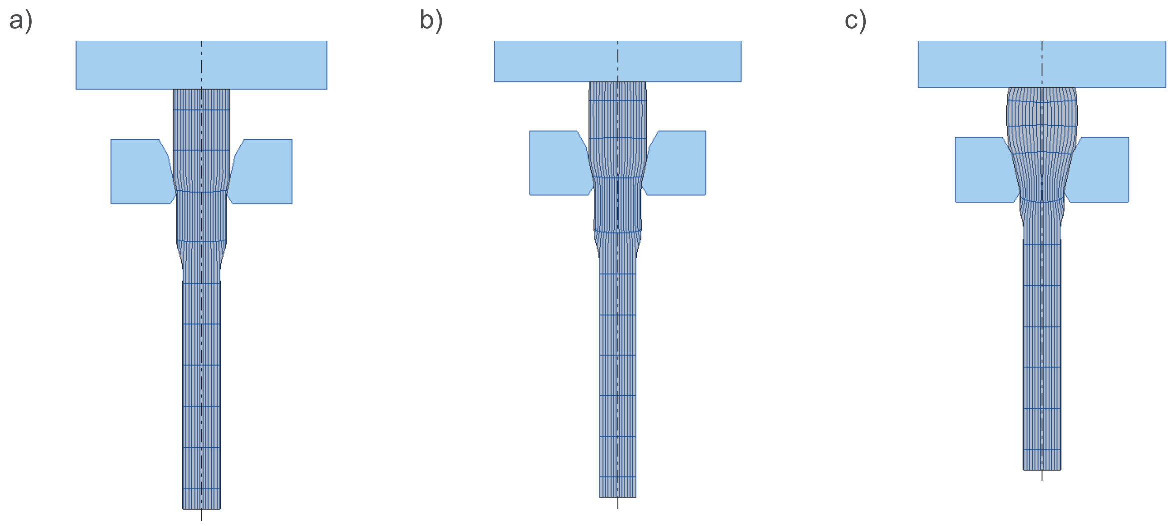

Figure 3 Numerically calculated last stages of pushing through a conical die process of round bars made from S355 steel for different elongation factors: a) λ_1 = 1.24, b) λ_2 = 1.37, c) λ_3 = 1.57).

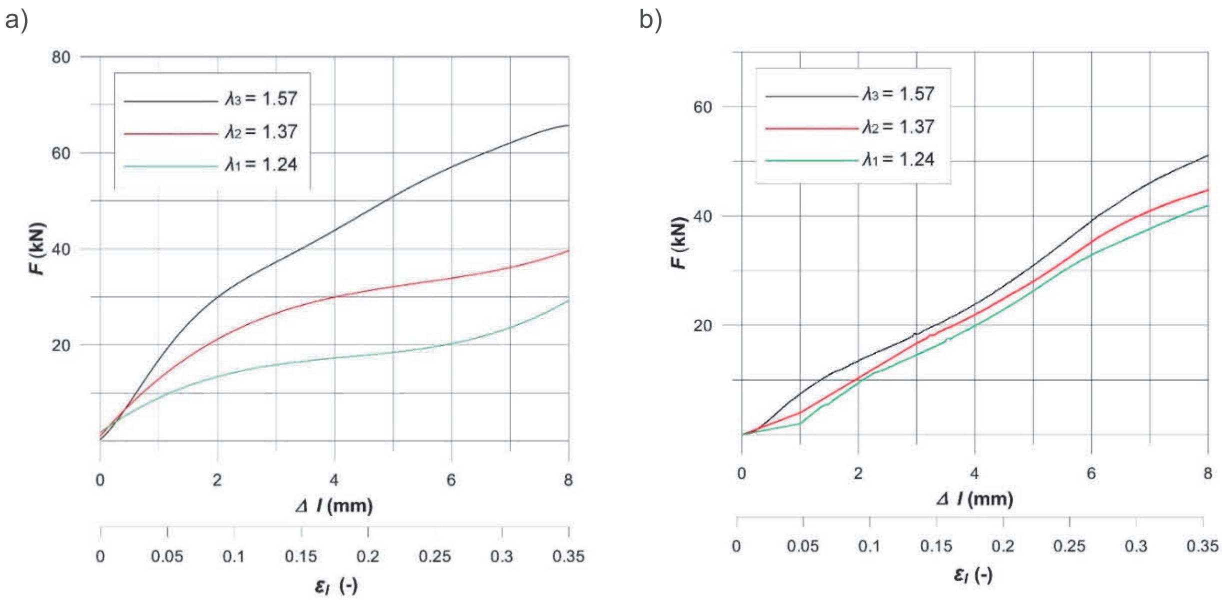

Figure 4 Comparison between computer calculated (a) and experimental (b) changes in forces for different elongation factors

The maximum values of loads obtained in pushing through a conical die process of round bars made from S355 steel were analyzed. The values were received at displacement Δl = 8 mm and relative strain ε_l = 0.35 for different elongation factors λ. On the basis of the comparative analysis of forces, it was possible to state that the maximum experimental values of forces were greater that those obtained numerically for elongation factors λ_1 = 1.24 and λ_2 = 1.37. The differences ranged from 10 % to 30 % at relative strain ε_l = 0.35. For elongation factor λ = 1.57, the maximum of numerically calculated value of force was greater than those obtained experimentally (the difference between the maximum values of forces did not exceed 22 %) at the same relative strain ε_l.

The greatest force values were recorded in investigations at the maximum elongation factor λ_3 = 1.57 (calculated load F = 65.7 kN and experimental value F = 51.06 kN) whereas the lowest for λ_1 = 1.24 (calculated load F = 29.3 kN and experimental value F = 41.92 kN). The relative difference between those values was approx. 55 % for computer modelling and approx. 18 % for experiment, respectively.

4. CONCLUSION

On the basis of investigations carried out into pushing through a conical die process of round bars made from S355 steel for different elongation factors, it can be stated as follows:

1) It was possible to conduct pushing through a conical die process of round bars made from S355 steel for elongation factors: λ_1 = 1.24 and λ_2 = 1.37 at relative strain ε_l = 0.35. For assumed maximum value of factor (λ_3 = 1.57) the round bar was upsetting. The 2D FE model successfully described the pushing through a conical die process of round bars.
2) The pattern of changes in loads obtained from computer modeling of pushing through a conical die process of round bars at different elongation factors was very similar to experimental force profiles. The differences between the maximum values of experimental and numerical forces did not exceed 30 %.
3) Both in experimental and modeling investigations, the axial force increased together with an increase in the relative strain ε_l (displacement of the punch Δl) and elongation factors λ. The minimum experimental force value obtained for elongation factor λ_1 = 1.24 is lower by approx. 18 % than the force value obtained for λ_3 = 1.57 (at the same relative strain ε_l = 0.35). The relative difference for numerical calculated force values was approx. 55 % (between minimum and maximum elongation factors).

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