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THE IMPACT OF DIE ANGLE ON TOOL LOADING IN THE PROCESS OF COLD EXTRUDING STEEL

VPLIV KOTA MATRICE NA OBREMENITEV ORODJA PRI HLADNI EKSTRUZIJI JEKLA

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This paper presents an analysis of tool loading in the technology of the cold forward extrusion of steel. In the process of plastic deformation it is necessary to know the contact stress as a prerequisite for a more accurate analysis of the stress and strain on the internal structure of the continuum. In this way, accurate boundary conditions at the contact surfaces are obtained for the achieved conditions of deformation, which represent the starting values for generating numerical approximations of the plasticity parameter changes within the deformable volume. In the process of the forward extrusion of steel the workpiece material is exposed to all-round pressure during the entire process. Due to the high surface pressure at the head of the punch and the solid walls of the die, the material flows in the direction of the opening of the exchangeable conical surfaces of the die. During the extrusion process, the greatest resistance occurs in the direction of the axis displacement, i.e., the head punch, while the walls of the tools suffer considerably smaller loads. However, this has crucial importance for the accuracy and the quality of the finished part.

Keywords: cold extrusion, angle die, contact stress, FEM

V članku je opisana analiza obremenitve orodja pri hladni ekstruziji jekla v smeri naprej. Pri procesu plastične deformacije je treba poznati kontaktno napetost, ki je prvi pogoj za bolj natančno analizo napetosti in deformacije na notranjo strukturo kontinuuma. Tako je mogoče doseči natančne mejne razmere na kontaktnih površinah pri določenih pogojih deformacije, ki so začetne vrednosti za generiranje numeričnih približkov spremembe parametrov plastičnosti v deformabilnem volumnu. Pri ekstruziji materiala v smeri naprej je prešanec med celotnim procesom izpostavljen okolišnjemu pritisku. Zaradi visokega površinskega pritiska na čela trna in trdne stene valjastega orodja material teče v smeri premika osi, torej čela trna, medtem ko je obremenitev stene orodja mnogo manjša, vendar je zelo pomembna za natančnost in kakovost iztiskanca.

Ključne besede: hladna ekstruzija, kot matrice, kotaktna napetost, FEM

1 INTRODUCTION

Analyses of the uni-directional extrusion process have been made by many authors. First of all, this is a process of volume deforming in which the workpiece material is subjected to overall pressure throughout the entire process. Due to the high surface pressure on the extruder head and on the rigid matrix walls, the material flows towards the opening on the conical matrix surfaces. During the extrusion process the greatest forces occur in the extrusion axis direction, i.e., on the punch head and on the matrix walls.

Many examples from industry show, in a clear manner, that realistic lifetime calculations for cold-forging tools should be focused on the accurate prediction of the number of load cycles until the appreciable continual damage or the initiation of fatigue cracks.

In addition, the results gained from previous investigations show that lifetime predictions only based on finite-element analyses are characterised by intolerable inaccuracies[1].

2 EXPERIMENTAL SET-UP

The satisfying experimental matrix rigidity and annulling of high pressure in the radial direction can be achieved in two ways. One of them is to increase the matrix-wall thickness up to a certain limit, thus obtaining the required matrix rigidity. The other solution is installing the clamping-ring application, thus bringing the matrix body into a pre-stress state of the opposite sign with respect to the stresses occurring during the extrusion process itself.

If, in the first case, we regard the receiver as a fairly thick pipe of outer diameter D_1, under high inner pressure loading, then its walls are subjected to a radial stress of pressure R_r and tangential extension stress R_t whose greatest value is on inner receiver diameter D_0.

$$R_r = -p,\ R_t = \frac{a^2+1}{a^2-1} \cdot p = C \cdot p \quad (1)$$

where $a = D_1/D_0$.

By superposition these two stresses, according to the plastic yield hypothesis, the following overall stress is obtained:

$$R_u = \sqrt{R_r^2 + R_t^2 - R_r R_t} = p \cdot \sqrt{1 + C + C^2} \qquad (2)$$

Assuming that, for instance, the outer receiver diameter is four times larger than the inner diameter, i.e., $a = 4$, we find that $R_u = 1.85 \cdot p$.

Along with the further increase of the outer diameter, the overall stress reduction in the receiver walls is not adequate. In the case when $a = 10$, which is not quite justified in real exploitation conditions, $C = 1.02$ and $R_u = 1,75p$ is obtained, i.e., the overall stress reduction is 9.5 % along with an outer receiver dimension increase of 2.5 times. Since the receiver must remain in the elasticity range, i.e., since there must be no plastic deformation ($R_u < R_e$) throughout the process, we can approximately determine the greatest value of the working pressure in the receiver made of alloyed tool steel submitted to heat treatment:

$$R_e \approx 2\ 000 \text{ MPa}, \ p_{max} = 1\ 100 \text{ MPa}$$

The above-presented analysis has been used as the basis for experimental tool design for the forward-extrusion procedure. Unlike the exploitation tools, these tools, **Figure 1**, enable an extrusion force measurement on the punch as well as that of the radial forces in the lower part of the tool on the receiver wall.

The extrusion force on the punch can be measured in many ways. In this investigation, the choice of measurement procedure is made by means of the universal force transducer (2 000 kN), which can be placed either in the upper or the lower part of the tool, as is our case, through which the overall loading is transmitted along the extrusion axis. For the measurement of the radial forces, the measuring pin load-cell method (**Figure 2**), ascribed Plancak et al.[2], is the most suitable for this kind of plastic metal-deforming process.

Figure 1: Experimental tool, receiver
Slika 1: Eksperimentalno orodje: prejemnik

Figure 2: Measuring pin load-cell for radial forces
Slika 2: Merilna celica s trni za radialne sile

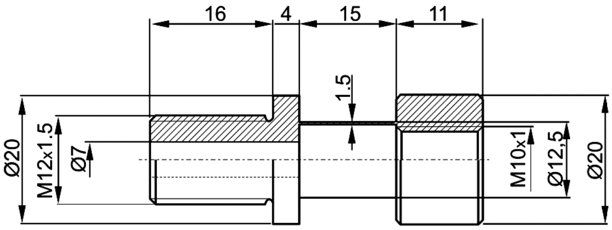

Figure 3: Measuring capsule
Slika 3: Merilni valj

The loading due to the contact between the workpiece and three measuring pins is transmitted to the measuring capsule (**Figure 3**) placed on the outer matrix wall.

The extension of the measuring wall of the capsule which is 1.5 mm thick, due to the radial forces in the receiver tool, actually yields the loading magnitude on the matrix walls. On each capsule wall there are two measuring bands HBM (measurement and compensation ones) glued and joined into a semi-bridge (Wheatstone) necessary to carry out their calibration with a known loading and thus set up a relation between the capsule wall elongation and the force being transmitted.

In order to obtain complete information about the magnitude and the kind of stress throughout the extrusion process, the measuring pins distribution is defined by the matrix geometry as well as the workpiece size. For these reasons, there are three measuring pins

Figure 4: Experimental tool, receiver with three measuring pin load-cells
Slika 4: Eksperimentano orodje: prejemnik s tremi merilnimi trni

placed in radial way in the extrusion matrix body at an angle of 120° to the measuring pin that is in direct contact with the workpiece during the extrusion process. In order to obtain complete information about the loading magnitude during the process, the measuring pins are placed at various heights in the material receiver (**Figure 4**).

In order to provide for variants of the presented tool solution, the very deformation focus (conical matrix part) and calibration zone are made in special dies introduced into the matrix body. The characteristic conical tool surface, on the given matrices, has three values of the angle, i.e., 60°, 90° and 120° (**Figure 5**), which will directly affect both the extrusion forces and the radial forces in the tool.

The material of the workpiece was low-carbon steel Ck 10 (DIN) for cold forging[3]. The flow stress at room temperature was modeled by the strain hardening function $K = 285 + 539.7 \cdot \varphi^{0.304}$ MPa, obtained from the Rastegaev compression test according reference[3]. The Young's modulus and the Poisson's ratio were 210 GPa and 0.3, respectively. FEM analysis was performed on a constant friction model, with the friction factor $m = 0.5$ K.[4]

3 SIMULATION RESULTS AND FEM ANALYSES

The coordinate system for presenting the results comprises a time x-axis with the number of readings equal to 800 with a step, the time interval between two signals of 0.003 s as well as the *y*-axis with the force in kN on the x-axis one part is singled where the workpiece extrusion process and the extruded-part ejection process are marked.

The measurement results show a certain regularity (**Figures 6, 7** and **8**) and similar effects can be noticed in all the extrusion processes. The force upon the punch shows, before the very extrusion process, a marked instability as well as a very high increase, after which it drops to its minimal value throughout the overall deforming process. The force instability, as well as its increase, can be explained by considering the most favorable initial position of the workpiece in the tool and by the needed – relatively high – force for the very beginning of the material flow on the matrix insert walls. A marked force drop shows that the first phase is completed, that the material filled up the input part of the cone; after that the force starts to increase rapidly to a maximum, after which the material flow on the conical tool parts begins. The maximum value has a marked increase along with the matrix-angle increase.

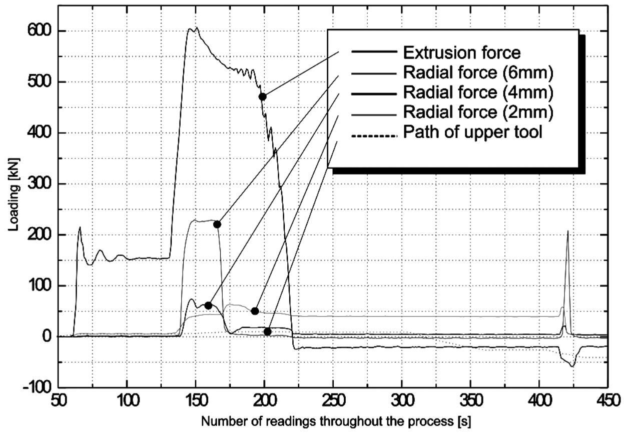

Figure 6: Force distribution at a die angle of 60°
Slika 6: Sile pri kotu matrice 60°

In all diagrams the radial forces are denoted by the relative height at which they were measured. Namely, as there is a difference regarding the height of the place at which the pin contact to the workpiece; at every 2 mm from the upper edge of the matrix insert, at mutual matrix angles of 120°, there is a different increase in the given forces recorded. In the beginning of the process, the maximum radial force is achieved at the highest pin with respect to the matrix insert at the moment when the extrusion force achieves its maximum value, i.e., when the initial unstable phase is completed and the material

Figure 5: Extrusion matrices with various cone angles
Slika 5: Ekstruzijske matrice z različnimi koti

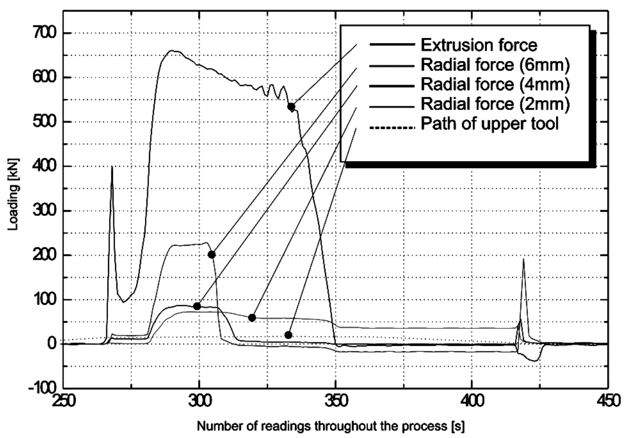

Figure 7: Force distribution at a die angle of 90°
Slika 7: Sile pri kotu matrice 90°

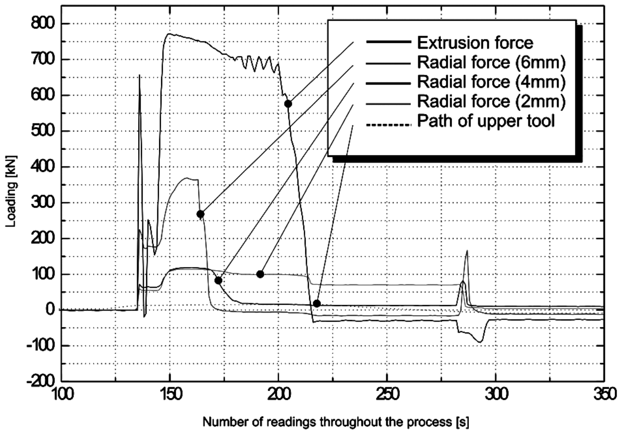

Figure 8: Force distribution at a die angle of 120°
Slika 8: Sile pri kotu matrice 120°

flowness has already started. This is explained by the very workpiece itself at this particular moment (barrel-like form in the receiver) and immediately after it, when the workpiece material filled up the whole material receiver volume and when its "maximum diameter slides" along the matrix walls. After reaching its maximum value as well as its retention, this force drops to almost a zero value. A less distinct maximum is reached by the radial force on the second pin, at the height of 4 mm from the die insert, but in an almost identical period of time when the first radial force reaches its maximum. The lowest pin with respect to the matrix pickup records almost the same magnitude of radial force as that on the second pickup, but it can clearly be seen that it preserves this value, with some slight decline, until the end of the extrusion process, since the non-extruded volume of the material from the receiver also remains at its height.

The extrusion force on the extruder has values ranging from 560 kN to 600 kN in the matrix with the smallest cone angle of 60°, i.e., 660 kN to 690 kN for the matrix with a cone angle of 90°, or to 720–790 kN in the

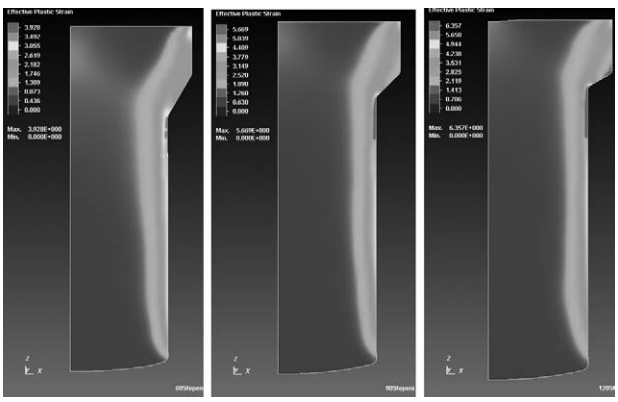

Figure 9: Field of efective plastic strain at three die angles: 60°, 90° and 120°
Slika 9: Polje efektivnih plastičnih deformacij pri treh kotih matrice 60°, 90° in 120°

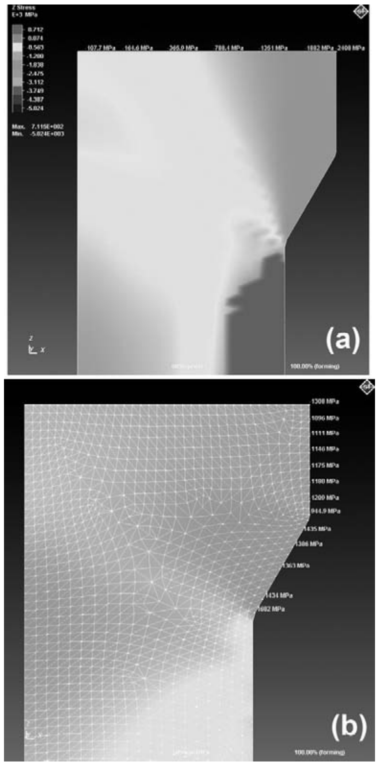

Figure 10: Contact stress at a die angle of 60°: a) on the punch and b) on the receiver wall in the radial direction
Slika 10: Kontaktne napetosti pri kotu 60°: a) na batu in b) na steni prejemnika v radialni smeri

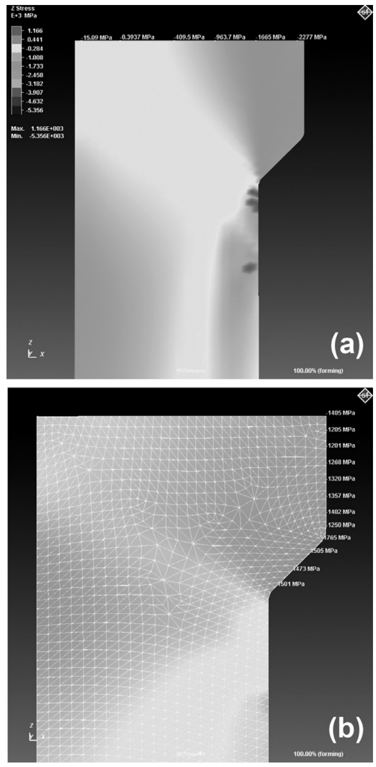

Figure 11: Contact stress at a die angle of 90°: a) on the punch and b) on the receiver wall in the radial direction
Slika 11: Kontaktne napetosti pri kotu 90°: a) na batu in b) na steni prejemnika v radialni smeri

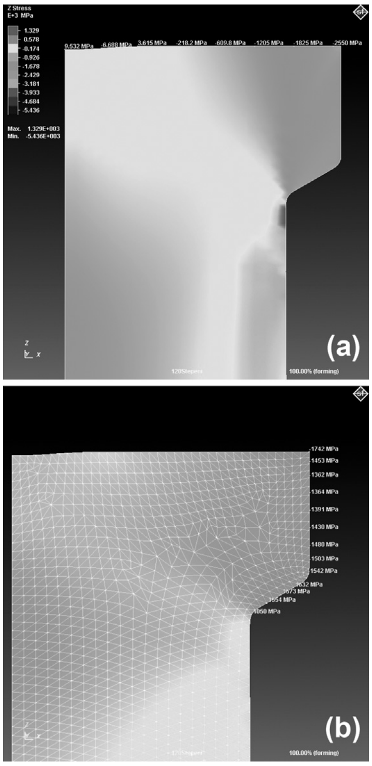

Figure 12: Contact stress at a die angle of 120°: a) on the punch and b) on the receiver wall in the radial direction
Slika 12: Kontaktne napetosti pri kotu 120°: a) na batu in b) na steni prejemnika v radialni smeri

matrix with a cone angle of 120°. Reduced to the cross-sectional area of the workpiece, over which this force is transmitted, working pressures of 1900–2500 N/mm^2 occur in the extrusion process. The radial force on the matrix wall, depending on the cone angle, moves in the interval from 50 kN to 230 kN for 60°, i.e., from 70 kN to 230 kN for 90° and 100 kN to 350 kN for 120°. The force increase follows the height of the measurement place on the receiver wall. In the radial direction there are considerably smaller pressures and they move within the limits from 945 N/mm^2 to 1742 N/mm^2.

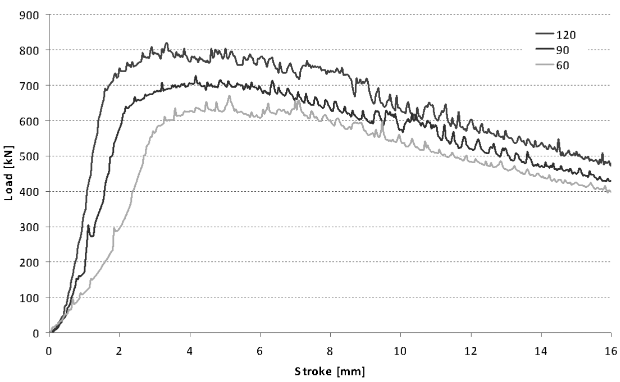

Figure 13: Loading distribution during the working stroke
Slika 13: Razporeditev obremenitev med delovnim ciklom

On the right-hand side of all the diagrams, there is a marked instability of all the forces associated with the ejection phase of the extruded piece from the die and the matrix itself.

A numerical 2D Finite-Element Method (FEM) analysis of the investigated models of forward extrusion was performed using Simufact. Forming 10.0 software package[5]. The commercial FEM package enabled the entire forming process to be simulated, while simultaneously predicting a large number of parameters at both the workpiece and the tool[6]. In this paper the FEM is employed to predict stress-strain state, the forming load and the geometry of the workpiece. To simulate the process, a model of elastic-plastic material for the workpiece was chosen, as the die and punch are considered to be rigid bodies. Due to the axial-symmetry of the deformation process, only one-half of the workpiece was modeled. The displacement of the punch is defined to be 16 mm and the punch velocity as 0.1 mm/s.

The workpiece model was initially meshed with advancing front quad elements with a size of 0.3 mm, the total number of which was 2 220. In the simulation, the remeshing of the starting elements was executed in the most highly deformed zones of the workpiece. The remeshing procedure was performed at every five increments in order to minimize the effect of the tool penetration through the elements due to large workpiece deformations.

Stress-strain components within the workpiece volume obtained by the FE analysis are shown in **Figures 9, 10, 11** and **12**. It is significant that the stress-strain state is very heterogeneous[7].

The FEA-simulation-predicted load-stroke diagram closely resembles the ones obtained experimentally (**Figure 13**). Initially, the load increases quickly up to 1.8 mm (120°), 2.2 mm (90°) and 3.4 mm (60°) of the punch stroke. As the punch stroke progresses further, the load continues to increase gradually. The final phase is marked by a noticeable load decrease.

4 CONCLUSIONS

The analysis of the tool loading points to the order of the loading magnitude as well as the force effect distribution over time during the process. The tool loading is of a variable character and the order of magnitude directly depends on the workpiece diameter, the finished part diameter and the extrusion angle in the deformation focus. The measurement itself aims at pointing to the loading magnitude at the contact surfaces, while, in further work, this could serve as input data for solving the stress-distribution equations with respect to the volume of the extruded part.

A special set of interchangeable tools, with three different angle dies, condition different values and levels of change in the radial force, as well as the degree of damage to the tools, which directly affect its service life, is used. The change of radial force in time points to the changeable shape of the workpiece during the process and to the surface of contact within the receiver tool.

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5 REFERENCES

[1] B. Falk, U. Engel, M. Geiger, Fundamental aspects for the evolution of the fatigue behaviour of cold forging tools, Journal of Materials Processing Technology, (**2001**), 158–164

[2] M. Plancak, A. N. Bramley, F. H. Osman, Some observations on contact stress measurement by pin load cell in bulk metal forming, Journal of Materials Processing Technology, (**1996**), 339–342

[3] Steels for cold forging – their behaviour and selection, ICFG document No.11/01, ISBN 3-87525-148-2, 2001

[4] K. H. Jung, H. C. Lee, J. S. Ajiboye and Y. T. Im, Characterization of Frictional Behavior in Cold Forging, Tribology Letters, 37 (**2010**), 353–359

[5] Simufact.Forming. 10.0. Documentation

[6] J. Kusiak, M. Pietrzyk, J. L. Chenot, Die Shape Design and Evaluation of Microstructure Control in the Closed die Axisymetric Forging by Using FORGE2 Program, ISIJ International, 34 (**1994**) 9, 755–760

[7] Z. Peng, T. Sheppard, A study on material flow in isothermal extrusion by FEM simulation, Modelling and simulation in materials science and engineering, 12 (**2004**), 745–763