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TRANSFERSAL UPSETTING OF STEEL WIRE

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ABSTRACT

The results of stress and forming load analyses for transversal upsetting process of cylindrical specimens are presented. The analyses were performed for practical reasons in order to get adequate information for the balancing of progressive die for the forming of steel wire. Special attention has been paid to the process of transversal upsetting by flat dies for cylindrical specimens with the diameter between Ø3 mm and Ø6 mm. The results were obtained with the FEM simulations and experiment. The presented approximate equation for forming load and diagrams with the geometrical characteristics are used within the presented limits of diameters of cylindrical specimens.
Key words: *upsetting, FEM, wire*

1. INTRODUCTION

Transversal upsetting is one of the characteristic processes of cold forming of steel wire in progressive dies. Forming loads from this process are appreciably higher in comparison with the forming loads from other processes in progressive dies (for example punching or bending processes). In case when the upsetting process is one of the first steps in progressive dies, the eccentricity of the result - load can be expected, which makes it difficult to determine exact die position in the press.
The problem of transversal upsetting of cylindrical specimens has been only partially elaborated theoretically in technical literature and published papers. This problem was discussed by Vilotić et al. in [21]. Stress conditions and the forming load of upsetting of prismatic specimens were researched by the FEM analysis and experiment and obtained results have been compared.
Coaxial upsetting of different billet geometries and die configurations have been reported in a number of papers: [11, 13, 14, 15, 16, 17]. Analysis of stress state, forming load and forming limit were the main investigated topics in those works. Different die shapes were applied: flat,

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spherical, convex, concave die. Within the investigation of coaxial upsetting of cylindrical specimen effect of wire drawing on cold formability of a low-carbon steel was researched by Kivivuori [12]. In [19] Nastran and Kuzman analyzed the mechanical characteristics of cold drawing wire during the wire straightening process. In the sphere of plastic loads of steel wire, the loss of tensile strength of steel wire under the simultaneous action of contact loads was reported by Malinovski and Vankov[10].
The current paper deals with the transversal upsetting of cylindrical specimen. Geometrical characteristics of the process as well as forming load were obtained theoretically, by FEM analysis and experimentally. Comparative analysis was curried out. Transversal upsetting of steel wire with diameter between Ø3 mm and Ø6mm, with different tool geometries has been considered. The first part of the analysis shows the comparison between the results from the practical test and the FEM simulations (Abaqus). The comparison is followed by the presentation of results from the transversal upsetting of steel wire of different diameters and with different tool geometries. The analysis considers the material properties which were obtained from coaxial upsetting test.
The results from the presented research are intended for the planning of the upsetting process of steel wire in progressive dies and also on montage-automats.

2. MECHANICAL PROPERTIES OF THE SEARCHED STEEL WIRE

Manufacturer's data:
The data for mechanical properties and chemical specification were taken from the attest of the searched steel wire.
- tensile strength: σ_M=567N/mm^2
- diameter: 3.5mm
- chemical specification:

C (%)	S (%)	P (%)	Mn (%)	Si (%)	B (%)	N (%)
0.03	0.017	0.012	0.33	0.04	0.005	0.004

Results of the upsetting test:
The coaxial upsetting test was performed at the Faculty of Mechanical Engineering in Ljubljana, in the Laboratory for Forming. Dimensions of specimens were ϕ3.5x4.5mm. The strain-stress curve was calculated from the following equation [4]:

$$\sigma_f(\varphi) = \frac{4 \cdot F(\varphi)}{\pi \cdot \left(\frac{4 \cdot V_0}{\pi \cdot h(\varphi)}\right) \cdot \left(1 + \frac{\mu}{3 \cdot h(\varphi)} \cdot \sqrt{\frac{4 \cdot V_0}{\pi \cdot h(\varphi)}}\right)} \tag{1}$$

Obtained flow curve is given in Fig.1.

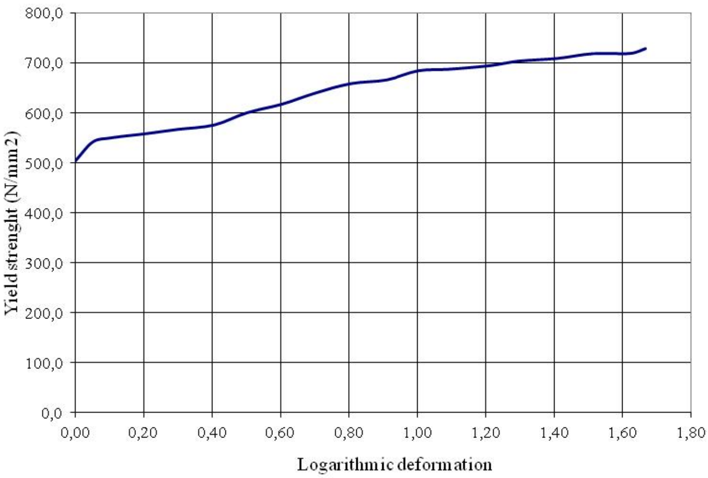


Fig.1 *- Strain-stress diagram (flow curve) for the searched steel wire*

3. INVESTIGATIONS OF THE UPSETTING PROCESSES OF STEEL WIRE

3.1 Upsetting of steel wire with a square cross-section

3.1.1 Theoretical solution

The most similar example of the upsetting which can be compared to the upsetting of cylindrical specimens, and is theoretically described in technical literature, is the upsetting of specimens with a square cross-section and length (Fig.2), which is in comparison with other two dimensions much longer ($l \rightarrow \infty$) [7]. Also in the case of the upsetting of cylindrical specimens the length is much bigger (~5x) in comparison with the diameter of the wire. In the case of the upsetting of the searched steel wire the same presumptions were used as in the case of the upsetting of specimens with the square cross-section (Fig.3).

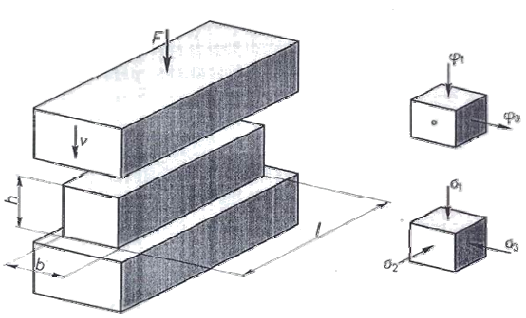


Fig.2 *- Upsetting of prismatic sample,* [7]

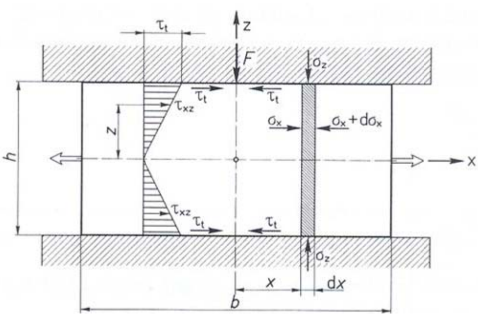


Fig.3 - *Stress conditions in the case of upsetting of prismatic specimens* [7]

Forming load

The first step in the analysis of the upsetting process for cylindrical steel wire was the comparison of theoretical results for forming load in the upsetting of prismatic specimens with the results from FEM simulations.

The equation for forming load by free upsetting of prismatic specimens has the following form [7]:

$$F = \iint |\sigma_n| \cdot dA = \int_{-b/2}^{b/2} |\sigma_z| \cdot l \cdot dx = 2 \cdot l \cdot \int_{0}^{b/2} |\sigma_z| \cdot dx \tag{2}$$

where $\sigma_n = \sigma_z$ is normal contact stress, $dA = l \cdot dx$ represents elementary contact surface and l represents the length of the specimen.

By the upsetting very high specimens with the ratio $2 \geq \mathrm{b/h} \geq 1$ the forming load is defined due to the following equation [2]:

$$F = 2l \int_{0}^{b/2} \beta \sigma_f \left[1 + \frac{2\mu}{bh} \left(\frac{b^2}{4} - x^2 \right) \right] dx \tag{4}$$

After the integration we get the following form:

$$F = l \beta \sigma_f \left[b + \frac{\mu \mathrm{b}^2}{3h} \right] \tag{5}$$

The forming resistance is defined as a division of the equation (5) with the contact surface:

$$\overline{\sigma_d} = \beta \sigma_f \left(1 + \frac{\mu b}{3h} \right) \tag{6}$$

3.1.2 Practical case

In the first part of the researches the comparison of the results of the upsetting process for prismatic specimens between the theoretical results (equation (5) and the results from the FEM simulation in Abaqus program was made. The results are represented in the diagram Fig. 4.

Information about the wire:
- square cross section: $\mathrm{h} = \mathrm{b} = 3.5$ mm
- length of the wire: $\mathrm{l} = 20$ mm

Information about the calculation:
- yield strength: the strain-stress curve (Fig. 1)
- factor: β=1.1
- stroke of the tool: $\Delta \mathrm{h}_0 = 1.75$ mm
- coefficient of friction: $\mu = 0.1$

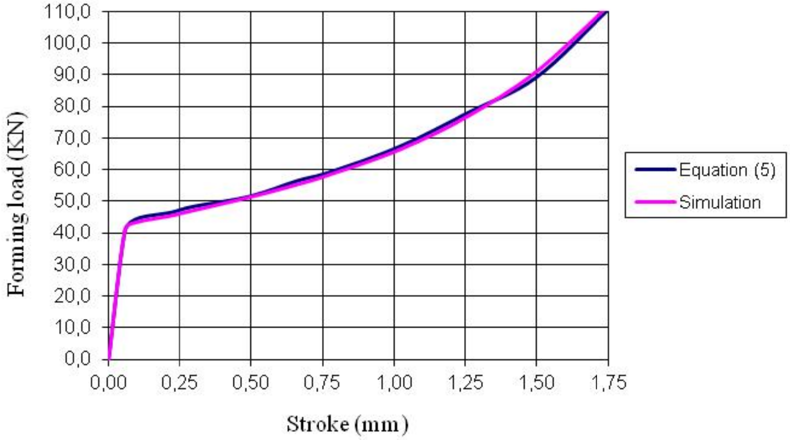


Fig.4 *- Forming load – stroke diagram*

3.2 Transversal upsetting of cylindrical specimen

3.2.1 Upsetting with flat dies

Geometry of the part after transversal upsetting of cylindrical billet with flat dies (Fig.5) is shown in Fig.6, as numerical values obtained by experiment and FEM analysis are given in table 1.

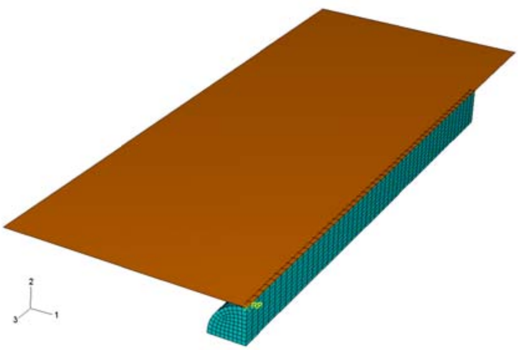


Fig.5 *- FEM model in Abaqus*

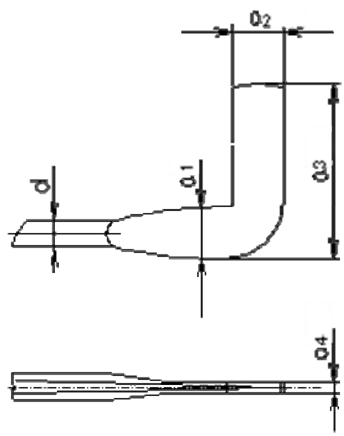
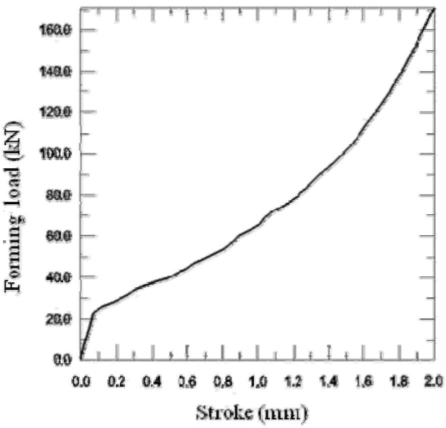


Fig.6 *- Specimen after upsetting in the experiment*

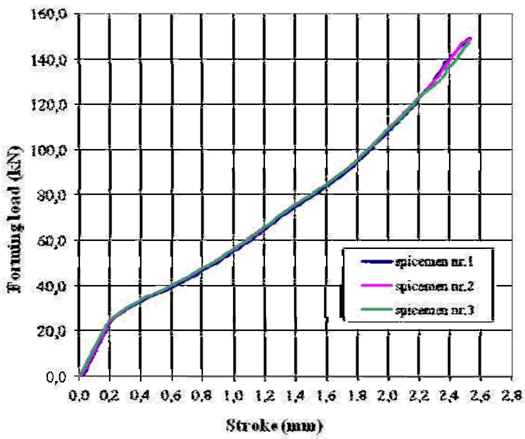
Distribution of forming load during the analyzed process is depicted in Fig.7a (FEM) and Fig.7b (experiment), respectively.

__Table 1__ - Characteristic values of the upsetting of specimens (Fig. 6) from experiment and the FEM simulation

	Spacemen nr.1	Spacemen nr.2	Spacemen nr.3	simulation
d	3.5	3.5	3.5	3.5
a_1 *[mm]*	6.07	6.00	6.09	6.36
a_2 *[mm]*	6.43	6.46	6.70	6.44
a_3 *[mm]*	24.60	24.20	24.80	24.42
a_4 *[mm]*	1.45	1.46	1.42	1.50
Stroke [mm]	2.54	2.54	2.53	2.0
Load [kN]	148.9	148.7	153.9	171.2



a)



b)

***Fig.** 7 – Load-stroke diagram in case of transversal upsetting of cylindrical billet with flat dies obtained by (a) FEM and (b) experiment*

Comment: The deviations on die stroke between the experiment and the simulation are due to irregular calibration of equipment for stroke measuring in the experiment. The deviations on stroke measuring have no influence on load measuring, which was performed indirectly by means of the increased oil pressure in the hydraulic cylinder.

Upsetting of steel wire with the diameter Ø3 mm and length l=40 mm

FEM diagram of load-stroke dependence (Fig.8) as well stress-state (Fig.9) in workpiece for case of transversal upsetting of cylinder *Ø3x40mm* are displayed below. In the Fig. 8 it can be seen that the breaking point happens between the stroke 0.05mm and 0.09 mm. This is the time when Von Mises' comparison stress exceeds the yield strength ($\sigma_f = 503 N/mm^2$) over the whole wire cross section (the plastic deformation of material happens over the whole wire cross section).

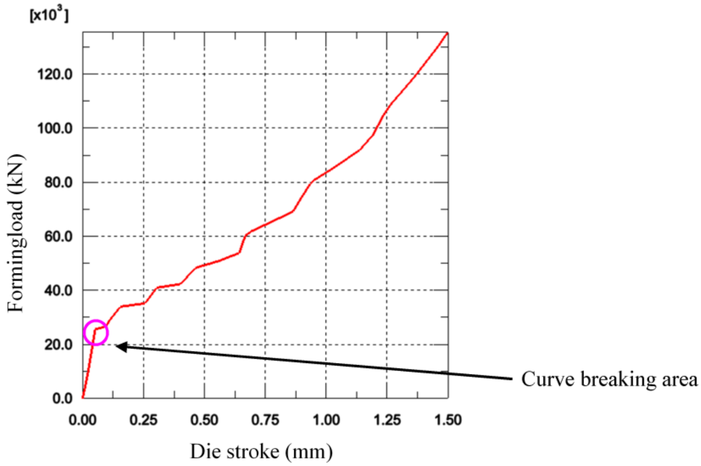
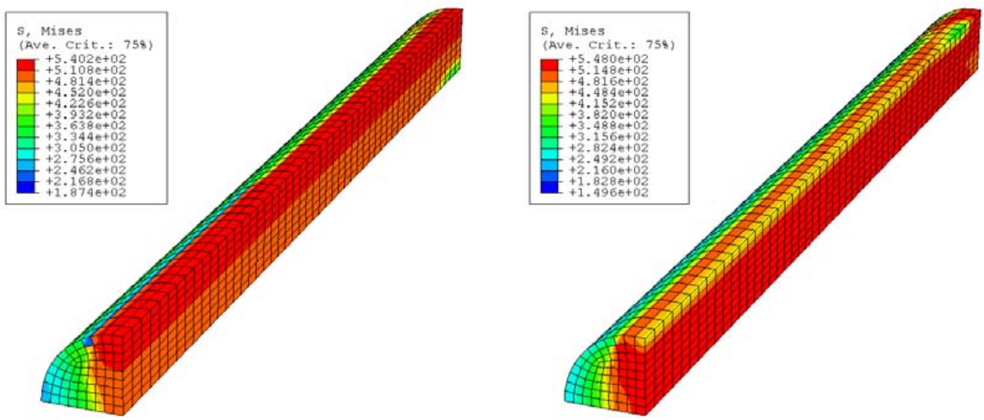


Fig.8 *- Upsetting load – stroke diagram (FEM) for specimen Ø3x40mm*



a) b)

Fig.9 *- Von Mises' comparison stresses: a) by die stroke 0.05 mm, b) by die stroke 0.09 mm*

Upsetting of steel wire with the diameter Ø5 mm and length l=40 mm

Load-stroke diagram and stress-state in workpiece for case of transversal upsetting of cylinder *Ø5x40mm* are given in Fig.10 and Fig.11. From both figures it can be seen that the breaking point happens between the strokes 0.13mm and 0.2 mm. That means in the time, when Von Mises' comparison stress exceeds the yield strength ($\sigma_f = 503\text{N/mm}^2$) over the whole wire cross section (the plastification of the material happens over the whole wire cross section).

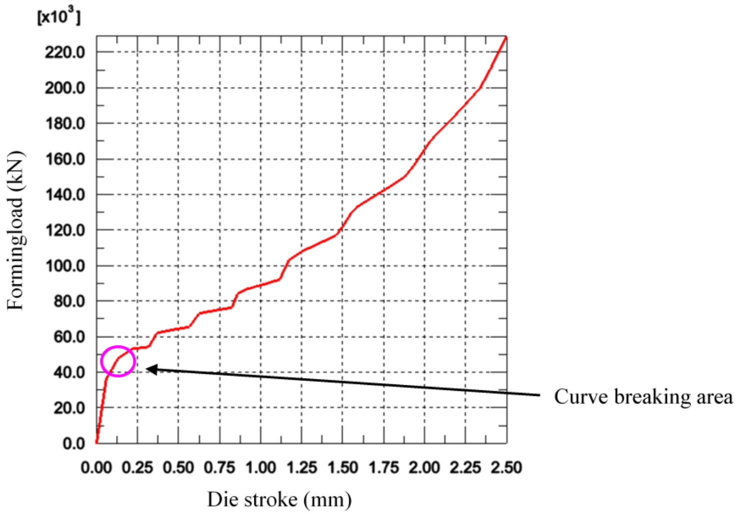


Fig.10 *- Upsetting load – stroke diagram (FEM) for specimen Ø5x40mm*

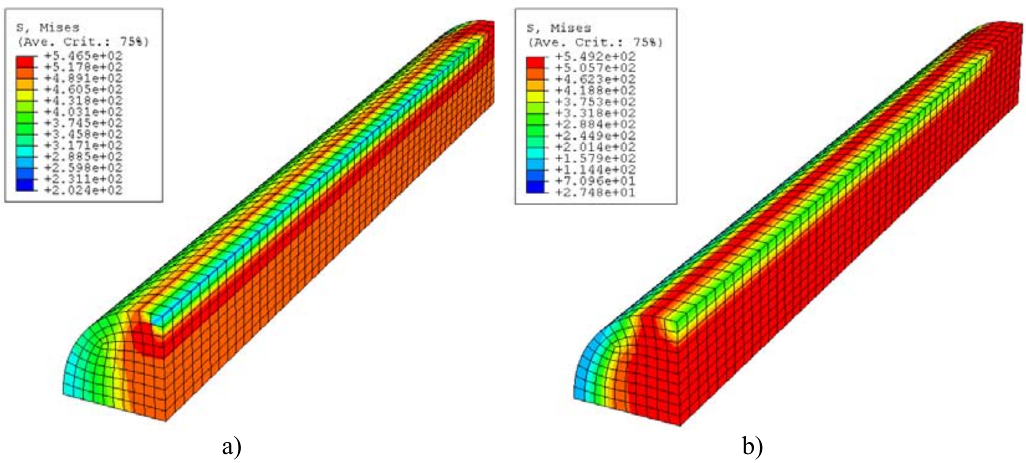


Fig.11 *- Von Mises' comparison stresses: a) by die stroke 0.13 mm, b) by die stroke 0.2 mm*

3.2.2 Influence of the die form

In this section the influence of die shape on forming load in case of case of transversal upsetting of cylinder *Ø4x40*mm is investigated by FEM. Three different die shapes are analyzed (Fig.12):

a) convex die (R_{die}=20mm),
b) concave die (R_{die}=20mm)
c) flat die

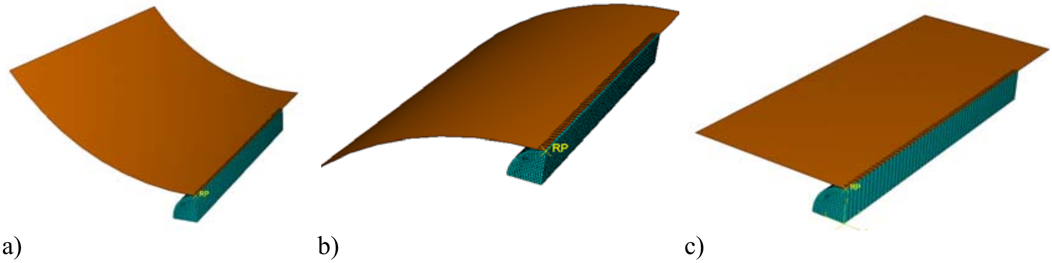


Fig. 12 *- Upsetting of the wire of diameter Ø4mm a) with convex die, b) with concave die, c) with flat die*

In the diagram Fig. 13 we can observe a similar load-stroke characteristic in the first part of the upsetting process for all three types of tool. In the further process the difference of load-stroke characteristic between all three types of tool appears. The forming load for concave tool differs significantly by larger stroke from other two types of tool, especially from forming load for convex die.

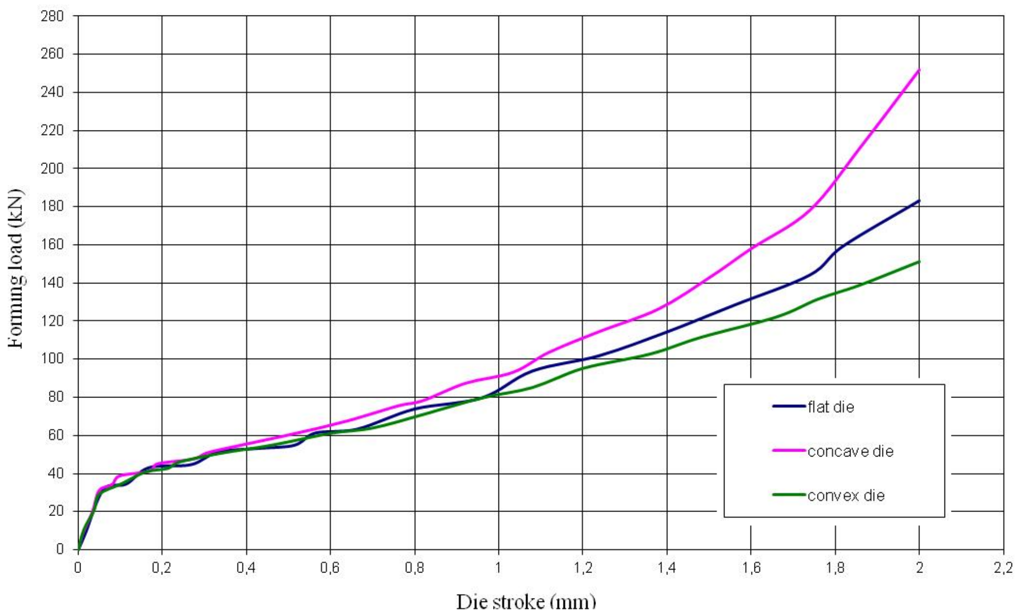


Fig. 13 *- Forming load – stroke diagram for the steel wire of diameter Ø4mm and different die forms (results from the FEM simulation in Abaqus)*

3.2.3 Influence of friction on forming load

In this part of the paper the influence of friction on the forming load is presented. The FEM analysis in Abaqus was performed for flat tool and three different diameters (3, 4 and 5mm) of steel wire. The coefficient of friction was chosen in the region of boundary and mixed friction (from μ=0.05 up to μ=0.3). In the analysis material properties from Fig. 1 were used.
The results suggest no influence of friction on the forming load up to the stroke about $1/4 \cdot d$. With further upsetting we get similar influence by different diameters of wire. The increase of the forming load at about $1/2 \cdot d$ is between 35% and 38%.

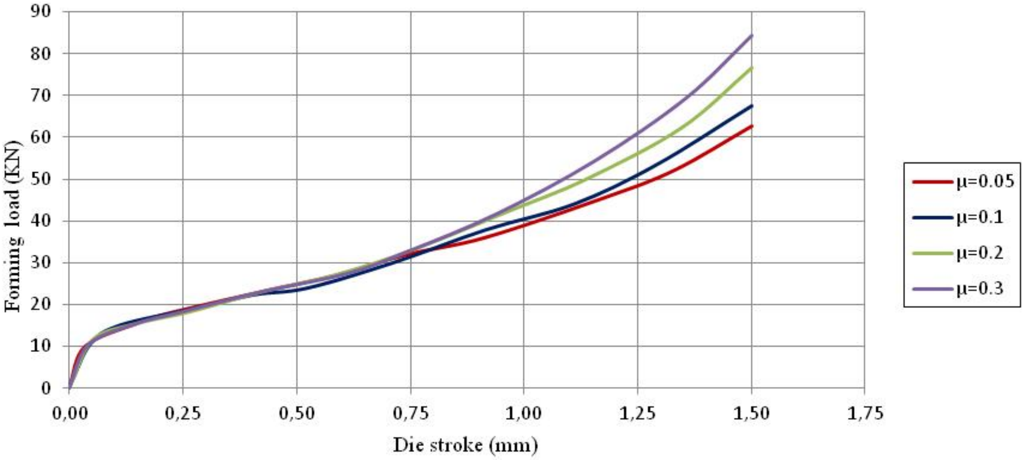


Fig.14 – Influence of friction on upsetting load (diameter of steel wire Ø3mm)

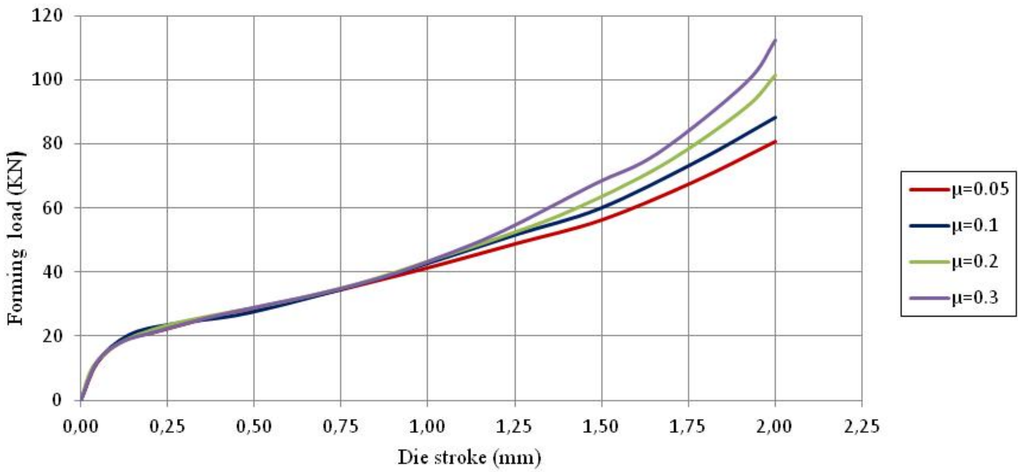


Fig.15 - Influence of friction on upsetting load (diameter of steel wire Ø4mm)

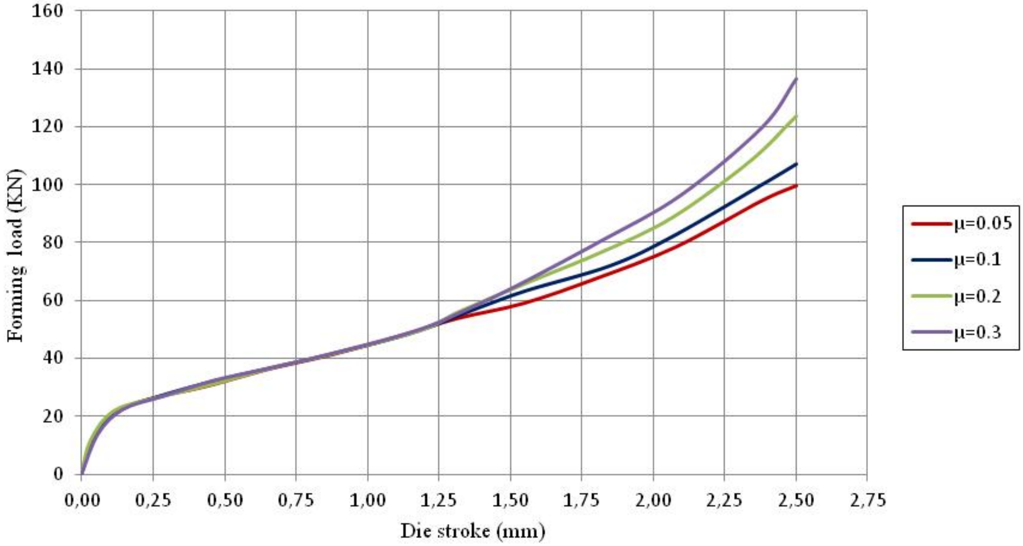


Fig.16 *- Forming Influence of friction on upsetting load (diameter of steel wire 53mm)*

3.2.4 Influence of friction on geometrical characteristics of contact surface

Diameter of wire d=Ø3mm

	μ=0.05	μ=0.1	μ=0.2	μ=0.3
Δz [mm]	1.5	1.5	1.5	1.5
l_0 [mm]	20.0	20.0	20.0	20.0
l_1 [mm]	21,84	21.21	20.7	20.58
b [mm]	3.95	4.03	4.05	4.2

Diameter of wire d=Ø4mm

	μ=0.05	μ=0.1	μ=0.2	μ=0.3
Δz [mm]	2	2	2	2
l_0 [mm]	20.0	20.0	20.0	20.0
l_1 [mm]	22.29	21.56	21.0	20.90
b [mm]	5.32	5.48	5.56	5.58

Diameter of wire d=Ø5mm

	μ=0.05	μ=0.1	μ=0.2	μ=0.3
Δz [mm]	2.5	2.5	2.5	2.5
l_0 [mm]	20.0	20.0	20.0	20.0
l_1 [mm]	22.56	21.92	21.17	20.94
b [mm]	6.48	6.76	6.86	6.91

Legend:

Δz stroke of flat tool
l_0 initial length of wire
l_1 length of contact surface after upsetting
b width of contact surface after upsetting
μ coefficient of friction

The results show that a higher coefficient of friction brings an increase on the width of the contact surface and reduces the length of the contact surface after upsetting. We can conclude that geometrical characteristics of the contact surface depend on the die stroke and also on the mechanism of friction, which depends from lubrication during the upsetting process.

3.2.5 Analysis of geometrical characteristics of contact surface by upsetting steel wire of different diameters

The results in Fig. 17 show the similarity of relative ratios *b/d* in dependence on *Δz/d*, where *b* is width of contact surface, *d* diameter of wire and *Δz* stroke of flat die. These results enable the assessment of width of the contact surface with regard to the die stroke. In the FEM simulation in Abaqus material properties from Fig. 1, flat die and coefficient of friction μ=0.1were considered.

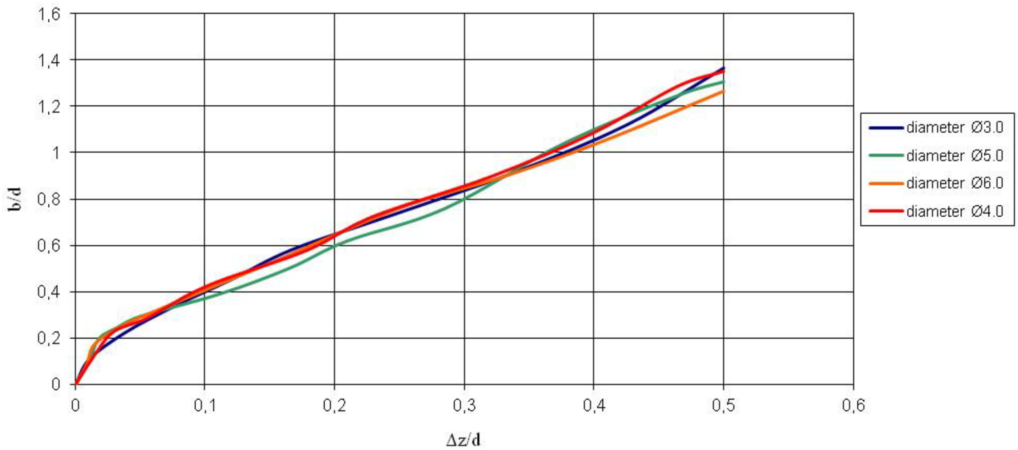


Fig.17 *- Ratio b/d - Δz/d by upsetting of steel wire*

3.3 Approximative calculation of the forming load for transversal upsetting of steel wire

On the basis of forming load for prismatic specimens (eq. 5) an approximate equation for the forming load for cylindrical specimens was established for practical reasons.

$$F = l\beta\sigma_f \left[\left(0.95 \cdot b + 0.18d\right) + \frac{\mu b^2}{3(h + 1.4d)} \right] \tag{7}$$

where are:

l length of formed steel wire

β coefficient of second main stress (considered the value $\beta = 1$)

σ_f	yield strength
b	width of formed steel wire
d	diameter of wire
h	height of formed steel wire
μ	coefficient of friction

3.3.1 Comparison of the results from the FEM simulation and theoretical calculation

Example 1: Data about wire:

- diameter: d=3.0mm
- length: l=20mm

Data about the calculation:

- yield strength: flow curve Fig. 1
- factor β=1
- die stroke: Δho=1.5mm
- coefficient of friction: μ=0.1

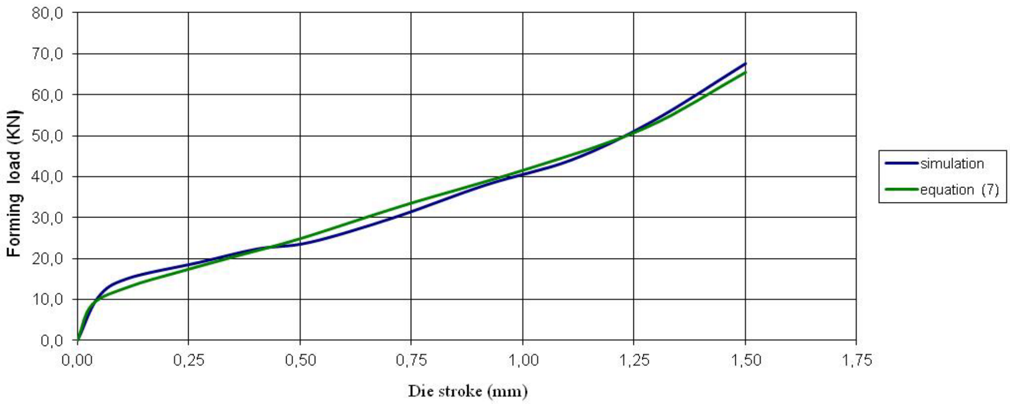


***Fig.18** - Forming load – stroke diagram for diameter of steel wire Ø3mm*

Example 2: Data about wire:

- diameter: d=4.0mm
- length: l=20mm

Data about the calculation:

- yield strength: flow curve Fig. 1
- factor β=1
- die stroke: Δho=2.0mm
- coefficient of friction: μ=0.1

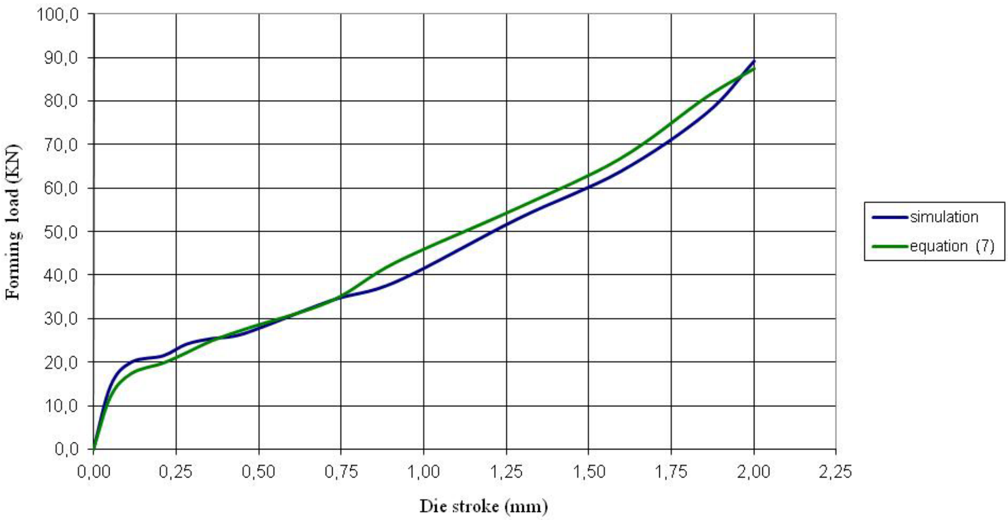


Fig.19 *- Forming load – stroke diagram for diameter of steel wire Ø4mm*

Example 3: Data about wire:

- diameter: d=5.0mm
- length: l=20mm

Data about the calculation:

- yield strength: flow curve Fig. 1
- factor $\beta=1$
- die stroke: $\Delta ho=2.5mm$
- coefficient of friction: $\mu=0.1$

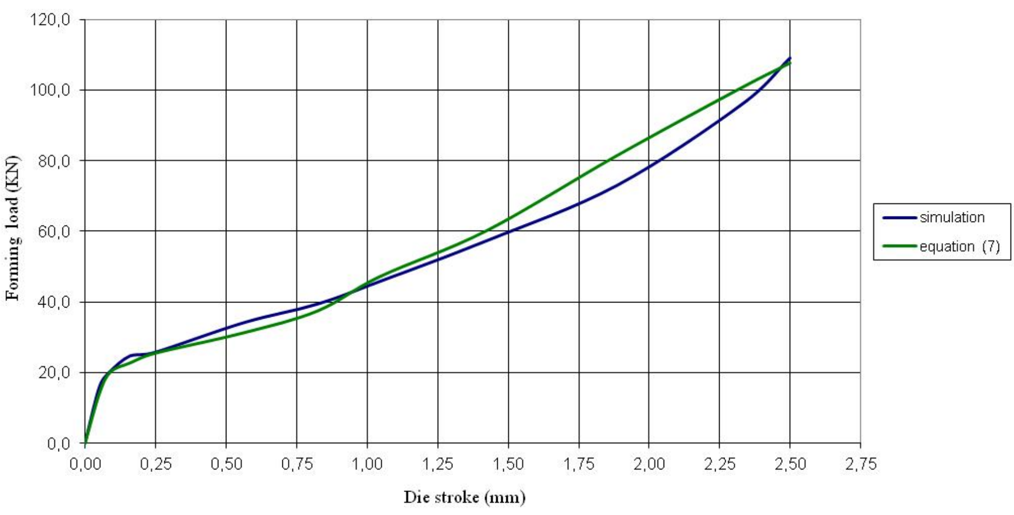


Fig.20 *- Forming load – stroke diagram for diameter of steel wire Ø5mm*

4. CONCLUSION

By observing the forming processes we can conclude that the transversal upsetting process generates the highest values of forming load both in progressive die as well as, for example, on montage-automat. The research of the upsetting process presented in this paper was carried out for the need of an exact analysis of the forming of steel wire in progressive die. This analysis was done for diameters of wire from Ø3mm up to Ø6mm. Within these limits we have found products made of steel wire, which were discussed in the master's paper. The influences of forming temperature and forming speed were not considered.

Fig.13 presents the forming load – stroke curves for different types of tool. As expected we get the highest value of forming load by upsetting with a concave formed tool and the lowest value by upsetting with a convex formed tool. This analysis was done for production reasons, where we can meet not only flat tools but also, for example, concave formed tools.

The analysis of friction shows a considerable influence of friction by larger strokes of tools on forming load and geometrical characteristics of formed wire. The increase of forming load at about $1/2 \cdot d$ by higher values of coefficient of friction (from μ=0.05 up to μ=0.3) is between 35% and 38%. These results show the importance of the lubrication mechanism.

The theoretical equation for forming load of transversal upsetting with flat tools for cylindrical specimens cannot be found in the published literature. The results, however, are interesting for practical use. For this reason the aproximative equation for the forming load for cylindrical specimens was established with the modification of equation 5. Comparing the results for the forming load between FEM simulation and aproximative equation it can be concluded that the approximative equation 7 in the range of diameters discussed above and by coefficients of friction between μ=0.1÷0.2 gives satisfying results for forming load. With higher coefficients of friction (μ>0.2) and larger strokes of flat tool we get some larger inaccuracies.

The results of the analysis of transversal uppsetting process presented in this paper are meant for practical use. The results enable the assessment of the forming load and geometrical characteristics of formed cylindrical specimens, for example steel wire.

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TRANSFERZALNO SABIJANJE ČELIČNE ŽICE

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REZIME

U ovom radu prikazana je analiza napona i sila prilikom transferzalnog sabijanja cilindričnih pripremaka. Uvodni deo rada navodi skorašnja relevantna istraživanja iz oblasti deformabilnosti i sabijanja cilindričnih uzoraka. Istraživanje u radu je vršeno iz praktičnih razloga kako bi se dobile adekvatne informacije vezane za sam proces deformisanja čelične žice. Poseban osvrt dat je na proces transferzalnog sabijanja žice pomoću ravnih alata. Takođe je vršeno i sabijanje pomoću konveksnih i konkavnih alata. Različite dimenzije žica su analizirane (između Ø3 mm i Ø6 mm). Izvršena je komparativna analiza numeričke simulacije i eksperimenta. Numeričke simulacije metodom konačnih elemenata vršene su u softverskom paketu Abaqus. Uticaj temperature i brzine deformisanja nije uziman u obzir. Kao što je i očekivano, najveće sile deformisanja dostignute su prilikom sabijanja sa konkavnim alatima, a najniže sa konveksnim. Tokom ispitivanja pokazano je da trenje ima veoma veliki uticaj na silu deformisanja, što navodi do zaključka da je neophodno dobro podmazivanje.
Ključne reči*: sabijanje, MKE. Žica*