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FEM ANALYSIS OF EFFECT OF DIE ANGLE ON STRAIN AND STRESS STATE IN PROCESS OF DRAWING OF STEEL FOR PRESTRESSED CONCRETE

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In the paper the results of a computer simulation of the drawing process of steel wires for a prestressed concrete have been presented with FEM software (Forge 2). Dies with a different die angle $2a$ = 8°, 12°and 18° were used in the drawing process of a DB92 steel wire rod with 5,5 mm in diameter (according to Polish Standards) in five passes for final wires with 2,5 mm in diameter. After every pass mechanical properties and draw stresses were determined.

Key words: *FEM Analysis, process of drawing, die*

FEM-analiza utjecaja kuta matrice na deformiranje i naprezanje u procesu izvlačenja čelika za prenapregnuti beton. U radu su prikazani rezultati kompjuterske simulacije procesa izvlačenja čeličnih žica za prenapregnuti beton. Simulacija je provedena sofverom FEM (Forge 2). Uz matricu sa različitim kutom $2a$ = 8°, 12° i 18° za izvlačenje žice rabljena je čelična šipka DB92 s promjerom od 5,5 mm (prema poljskim standardima). Da bi se dobila žica promjera 2,5 mm, šipka se morala provući 5 puta kroz matricu. Poslije svake provlake određivana su mehanička svojstva i naprezanje vučenja.

Ključne riječi: *FEM-analiza, proces izvlačenja, matrica*

INTRODUCTION

A die angle is one of the most important parameters for a drawing process. It should be chosen in that way that a draw stress is low, a wire surface quality is satisfactory and die durability is high [1]. The temperature of a wire in deformation zone depends on amounts of heat generated during a drawing.

This heat consists of two components; one is the work piece deformation and another is friction between the wire and the die. Especially, the amount of the heat from the friction work strongly depends on a die angle [2].

The main aim of this work is a computer simulation of the drawing process of high carbon steel wires for prestressed concrete a calculation of the temperature distribution in the deformation zone for different die angles, as well as an estimation of the effect of those angles on the distribution of stress and strain in a die. It should enable estimation of a possibility of occurring of the strain aging in drawn wires and explanation of dependence of mechanical properties of wires on a die angle.

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EXPERIMENTAL PROCEDURES

Finite element method

Finite element method simulation of a drawing process has been performed by Forge 2 software elaborated in Ecole des Mines, Paris. An elastoplastic approach has been used [3].

A hardening curve of the material has been determined from the equation

$$K = K_0\left(1 + ae^n\right)e^{\frac{b}{T}} \qquad (1)$$

where:

K_0, a, n - constants for a given angle $2a$,
e - strain,
b - temperature constant,
T - temperature.

The values of constants assumed in the simulation were as follows:

$m = 0{,}07$; $E = 2\times10^{11}$ MPa; $b = 0$;

$K_0 = 834{,}025$ MPa, $a = 0{,}980$, $n = 0{,}600$, $(2a = 8°)$;

$K_0 = 843{,}323$ MPa, $a = 0{,}751$, $n = 0{,}910$, $(2a = 12°)$;

$K_0 = 842{,}190$ MPa, $a = 0{,}807$, $n = 0{,}849$, $(2a = 18°)$.

Drawing tests

A bull block-drawing machine was used in a drawing process. A wire rod before a drawing was protected in a lead bath. The chemical composition of the steel DB92 (according to Polish standards) for prestressed concrete was as follows: C - 0,90 %, Mn - 0,68 %, Si - 0,14 %, S - 0,025 %, P - 0,018 %, Cr - 0,05 %, Ni - 0,069 %.

After protecting and descaling in a water solutions of a sulphuric acid and liming a wire rod 5,64 mm in diameter was drawn into a final wire 2,49 mm, with a draw speed of 0,85 m/s in the following schedule: 5,64 ® 4,70 ® 3,99 ® 3,39 ® 2,92 ® 2,49 mm. Dies made of sintered carbides with different angles $2a = 8°$, 12 and 18° were used in the research. A natrium soap has been used as a lubricant. A drawn force was measured with a strain gauge.

After every draw tensile strength R_m, yield strength $R_{0.2}$, uniform elongation A_r and contraction Z were determined. Average values of 6 specimens were used for figures.

RESULTS OF COMPUTER SIMULATION

Temperatures in deformation zones

In the Table 1. are also presented temperatures in wire axis and at the wire surfaces in deformation zones of dies with angles $2a = 8°$, 12°, 18°. In brackets in this Table there are also average temperatures of those zones.

From this Table it is clear that maximal temperature in the 1st poss (5,64/4,70) occurs on the wire surface at die angle $2a = 8°$ and is equal to 328,9 °C, and is more than 60 °C higher than for other two die angles.

In the final pass (2,92 / 2,49) the maximal temperature also occurs for die angle $2a = 8°$ and is equal 453,2 °C and similarly as in the 1st pass it is about 60 °C higher than for $2a = 12°$ and 18°.

From the Table 1. it results that the higher differences between temperatures in the wire axis and on the wire surface in deformation zone at the first pass are dies with the smallest angle $2a = 8°$.

At the die exit wire surface temperature (for $2a = 8°$) is equal to 320 °C and is as much as 145 °C higher than the temperature in the wire axis. For $2a = 12°$ this difference is 92 °C and for $2a = 18°$ only 68 °C.

At the 5th (final) pass 2,92 / 2,49 those temperatures are much higher as well as differences between surface and axis of wires.

At the exit ($2a = 8°$) the wire temperature is equal to 425 °C and is higher 160 °C than the temperature in the axis. For $2a = 12°$ it is 382°C on the surface and 260 °C on the axis (difference 122 °C).

For $2a = 18°$ the surface temperature is 370 °C and 275 °C on the axis (difference 95 °C). The mean temperature of the wire is also highest for the drawing in dies with angle $2a = 8°$. For example at the die exit it is equal to 203,9 °C; for $2a = 12°$ and 18° respectively 181,7 °C and 187 °C (see Table 1.).

Hydrostatic stresses in deformation zones

For DB92steel all considered angles $2a = 8°$, 12°, and 18° in the approach zone are observed two peaks of hydro-

Table 1. **Temperatures in a deformation zone during drawing of wires from steel DB92 in dies with different cone angle. In numerators is placed temperature at the cone and bearing surfaces and in denominators temperature in wire axis. In brackets mean temperatures**

Tablica 1. **Temperatura u zoni deformacije pri izvlačenju žice iz čelika DB92 u matricama s različitim kutom konusa. U brojnicima su smještene temperature u konusu i nosivim površinama, a u nazivnicima temperature u osi žice. U zagradama su srednje temperature**

Place of calculation	1st draw (5,64/4,70)			5th draw (2,92/2,49)		
	$2\alpha = 8°$	$2\alpha = 12°$	$2\alpha = 18°$	$2\alpha = 8°$	$2\alpha = 12°$	$2\alpha = 18°$
Die entrance	$\frac{33}{25}$ (28,48)	$\frac{38}{25}$ (29,75)	$\frac{40}{30}$ (33,02)	$\frac{45}{29}$ (33,57)	$\frac{50}{32}$ (39,36)	$\frac{58}{40}$ (50,09)
At 25 % of cone generetrix	$\frac{88}{50}$ (57,77)	$\frac{82}{42}$ (54,67)	$\frac{75}{45}$ (57,29)	$\frac{130}{60}$ (80,71)	$\frac{108}{58}$ (74,99)	$\frac{105}{75}$ (89,96)
At 50 % of cone generetrix	$\frac{154}{90}$ (99,75)	$\frac{148}{87}$ (90,99)	$\frac{113}{95}$ (94,22)	$\frac{220}{130}$ (146,83)	$\frac{170}{120}$ (131,27)	$\frac{160}{140}$ (142,89)
At 75 % of cone generetrix	$\frac{230}{135}$ (147,04)	$\frac{170}{130}$ (131,89)	$\frac{154}{142}$ (134,02)	$\frac{315}{200}$ (216,76)	$\frac{238}{190}$ (193,66)	$\frac{220}{200}$ (200,95)
At 100 % of cone generetrix	$\frac{300}{175}$ (196,28)	$\frac{230}{155}$ (166,72)	$\frac{200}{165}$ (166,87)	$\frac{413}{250}$ (279,83)	$\frac{308}{240}$ (250,95)	$\frac{285}{240}$ (251,51)
At half of bearing part	$\frac{330}{175}$ (205,54)	$\frac{263}{158}$ (179,11)	$\frac{254}{165}$ (186,52)	$\frac{454}{260}$ (307,03)	$\frac{382}{265}$ (296,03)	$\frac{354}{254}$ (284,63)
Die exit	$\frac{320}{175}$ (203,87)	$\frac{254}{162}$ (181,75)	$\frac{238}{170}$ (187,08)	$\frac{425}{265}$ (300,73)	$\frac{382}{260}$ (293,51)	$\frac{370}{275}$ (299,91)

static stresses. For $2a$ = 12° and 18°, values of those two peaks are similar in the range 500 to 600MPa. For $2a$ = 8°

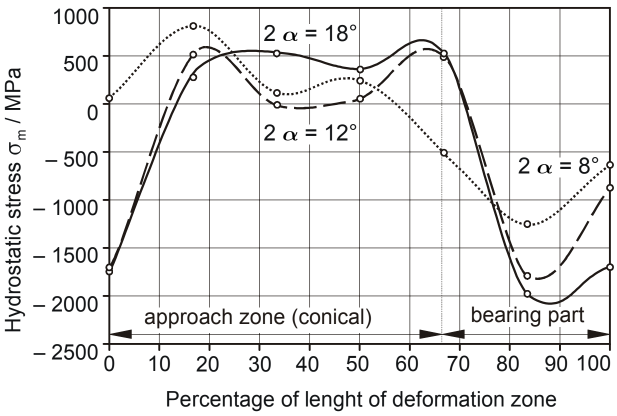

Figure 1. **Distributions of hydrostatic stresses σ_m along the wire axis in a deformation zone during drawing of wires in a pass 2,90 / 2,50 mm in dies with different angles 2α = 8°, 12°, 18°; steel DB92**

Slika 1. **Raspored hidrostatičkeg naprezanja σ_m duž osi žice u zoni deformiranja pri izvlačenju žice u provlaci 2,90 / 2,5 mm kroz matricu s različitim kutovima 2α = 8°, 12°, 18°; čelik DB92**

the highest value of s_m occurs at the beginning of this zone and equals 812 MPa (see Figure 1.).

Distributions of longitudinal stresses s_z on the cross sections of wires

In Figure 2. are shown distributions of longitudinal stresses on the cross sections of wires during drawing in dies with different angles and in the first draw.

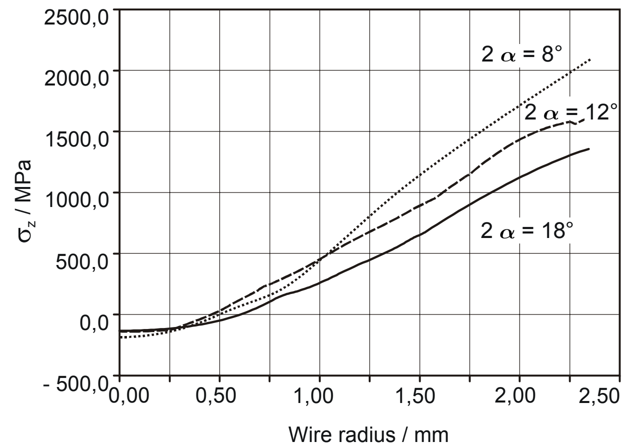

Figure 2. **Distributions of longitudinal stress σ_z on the wire cross-section in pass 5,64 / 4,70 mm for different die angles**

Slika 2. **Raspored uzdužnog naprezanja σ_z na presjeku žice u provlaci 5,64 / 4,70 mm za različite kutove matrice**

In draws 5,64 / 4,70 and 3,99 / 3,39 the highest stress was observed at the wire surface at drawing in dies with $2a$ = 8° but in final pass the highest stress at the surface is for the drawing in the die with $2a$ = 18°.

In the final draw (2,92 / 2,49) the differences between values of s_z in the wire axis and on the surface were much smaller for $2a$ = 8° and 12° as compared to $2a$ = 18°.

Mechanical properties of drawn wires

In Figure 3. are shown relationships of tensile strength R_m and yield strength $R_{0.2}$ versus true strain *e*.

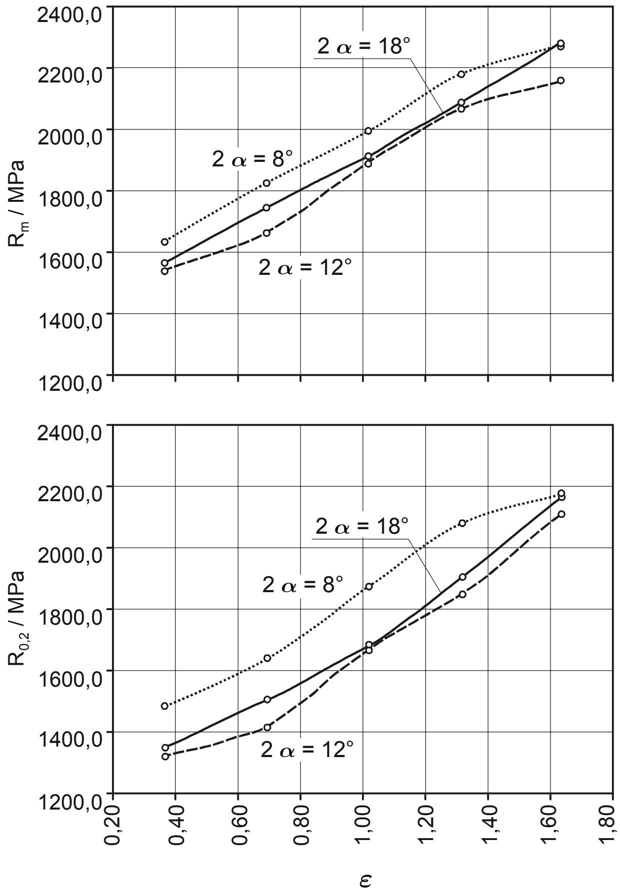

Figure 3. **Dependence of tensile strength R_m and yield strength $R_{0.2}$ versus true strain ε for drawing in dies with different angles**

Slika 3. **Ovisnost vlačne čvrstoće R_m i granice razvlačenja $R_{0.2}$ o stvarnom naprezanju ε za izvlačenje i matricama s različitim kutovima**

For a whole range of an investigated strain the lowest values of R_m and $R_{0.2}$ are for the angle $2a$ = 12° and the highest for $2a$ = 8°. For final wires 2,49 mm in diameter tensile strength R_m after drawing in dies with $2a$ = 8° equals 2273 MPa, with $2a$ = 12° - 2160 MPa and for $2a$ = 18° - 2280 MPa.

ANALYSIS

A common defect in wire drawing is a central bursting. Avitzur [2] has proved that when the combination of reduction, cone angle and friction obey the criterion which he elaborated central burst (CB) might be expected.

According to Avitzur [2]central burst might be expected if CB £ 0. Shear factor m can be assumed as average for carbon steels as 0.09073 [Table 9.1 p. 239] for reductions from 20 to 35 %. For investigated angles we obtained:

CB (4°) = 0,01492 > 0,

CB (6°) = 0,01304 > 0,

CB (9°) = 0,00869 > 0.

It means that for all tested angles a = 4°, 6°, 9° according to Avitzur criterion there are no risks of central bursting in the first draw. Values of Avitzur criterions for central bursting CB during drawing of wires from DB92 steel for different die angles and subsequent draws were calculated. All values are positive what means that in no pass for all investigated die angles there were any risks of central burst formation.

CONCLUSIONS

1. It has been found that drawing of high carbon steel wires as wires for prestressed concrete in the die $2a$ = 8° has resulted in the highest increase of the wires temperatures (as compared with the drawing for two others die angles) what in turn increased the strength properties of those wires (R_m, $R_{0.2}$) due to aging phenomena.
2. A distribution of hydrostatic stresses in deformation zone in the wire axis and in the central part of the wire is most advantageous (most compressive) for a drawing in a die with the angle $2a$ = 18°.
3. According to Avitzur criterion of central bursting there are no risk of appearance of this defect for all draws, reductions and angles analyzed in this paper.

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