

Geometrijska natančnost pri vlečenju okroglih palic Geometrical Accuracy in Drawing Round Rods

ZLATO KAMPUŠ - KARL KUZMAN - ALOJZ GAJŠEK

V prispevku je opisana analiza vplivnih elementov na natančnost vlečenih palic z dvema modeloma. Prvi, narejen z enačbami elastoplastomehanike, je preprost in primeren za vgradnjo v eksperimentne sisteme. Z drugim modelom, narejenim z metodo končnih elementov (MKE), smo predvsem potrdili pravilnost prvega. Pravilnost izračunov je preverjena z industrijskimi preskusi.

Ključne besede: vlečenje palic, natančnost geometrijska, metode končnih elementov, eksperimentni sistemi

The paper gives an analysis of factors influencing the accuracy of drawn rods using two models. The first one, made with the elasto-plasticity equations, is simple and suitable for integration into expert systems. The second one, made using the finite element method (FEM), was above all used to verify the accuracy of the first. The correctness of the calculations was verified through industrial experiments.

Keywords: rod drawing, geometrical accuracy, finite element methods, expert systems

0 UVOD

V zadnjih nekaj letih prevladuje tudi v tehniki preoblikovanja želja za izboljšanje natančnosti izdelkov do te mere, da jih lahko uporabimo z minimalno obdelavo ali celo brez dodatne mehanske obdelave [1] do [4].

Seveda pa moramo za izdelavo stalno kakovostnih, to je v ožjem tolerančnem razredu narejenih izdelkov, poznati vse dejavnike, ki vplivajo na dimenzijsko natančnost.

V Laboratoriju za preoblikovanje na Fakulteti za strojništvo v Ljubljani se že nekaj let ukvarjam z analizo vplivnih dejavnikov na natančnost, ki je potrebna za izboljšanje natančnosti procesa, predvsem pri iztiskovanju [5] in stanjevalnem vleku [6].

Vlečenje je postopek, pri katerem je sorazmerno natančen izdelek dosežen z majhnimi stroški, saj je premer vlečene palice odvisen samo od nekaterih preoblikovalnih razmer in preproste matrice. Premer vstopne odprtine matrice se navadno določi na podlagi izkušenj. V primeru, ko še nimamo poprejšnjih podatkov o kakovosti ali deformaciji, je za določitev premora matrice potrebno poglobljeno poznavanje parametrov procesa, ki vplivajo na izhodni premer palice.

Z računalniško podprtimi numeričnimi metodami, kakršna je npr. metoda končnih elementov (MKE) [7] in [8], lahko dobro popišemo razmere, ki vladajo med vlečenjem, in dobimo sorazmerno natančne rezultate. Ena od pomanjkljivosti metode končnih elementov je dolga doba računanja, saj je treba uporabiti elastoplastični model za palico in votlico. Zato smo si za cilj zadali izdelati analitični model, ki bo zaradi preprostega in hitrega izračuna primeren za vgradnjo v eksperimentni sistem za določanje natančnosti pri vlečenju. Za ugotavljanje pravilnost modela se navadno naredijo preskusi, pri katerih pa

0 INTRODUCTION

In recent years, the trend of metal forming technology has been to improve the accuracy of products to the extent that they can be used with minimum, or even without any additional machining [1] to [4].

Naturally, to ensure the constant quality of products, i.e. products made within a narrow tolerance class, all factors which influence dimensional accuracy must be known.

In the Laboratory for Metal Forming, Department of Mechanical Engineering in Ljubljana, we have dealt for several years with the analysis of factors influencing accuracy, above all in extrusion [5] and in ironing [6].

Drawing is a process in which the relative accuracy of products can be achieved with low costs, since the diameter of the drawn rods depends only on certain forming conditions and on a simple die. The diameter of the die is usually determined on the basis of experience. In cases when previous data on quality and deformation are not available, in-depth knowledge of the process parameters which influence the output diameter of rods is necessary to determine the diameter of the die.

With computer-aided numerical methods, such as e.g. FEM [7] and [8], the circumstances during drawing can be well described and relatively accurate results can be obtained. One of the disadvantages of FEM is the involvement of long calculation times, since the elasto-plastic model needs to be used for the rod and the perforated die. The objective of this research was therefore to build an analytical model which would be suitable for integration into an expert system for the determination of accuracy in drawing based on simple and quick calculation. In order to verify the accuracy of the model, experiments are usually performed, but they are limited by economic and technical

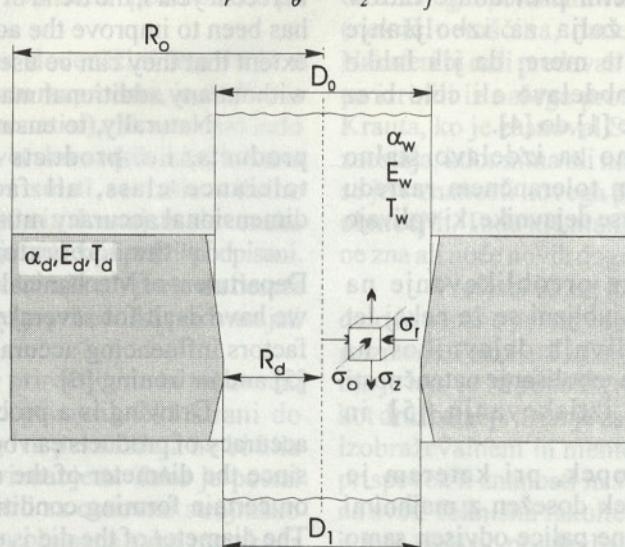
smo omejeni s finančnimi in tehničnimi težavami. Zato smo za overitev modela uporabili kar enega od komercialnih programov za končne elemente ABAQUS. Seveda pa smo naredili tudi nekaj preizkusov in preverili oba teoretična modela.

1 ANALIZA NA TEMELJU ELASTOPLASTO MEHANSKIH ENAČB

Pri tej analizi smo izhajali iz dejstva, da so napetosti v preoblikovalni coni, ki jih lahko izračunamo s teorijo plastičnosti, tudi glavne elastične napetosti v matrici. Vzdolžno napetost lahko izračunamo po enačbi [9] (sl. 1):

$$\sigma_z = \sigma_{fm} \cdot \varphi_e \left(1 + \frac{\mu}{\hat{\alpha}_{an}} + \frac{2}{3} \cdot \frac{\hat{\alpha}_{an}}{\varphi_e} \right) \quad (1).$$

Radialna in obročna napetost sta enaki in ju lahko izračunamo iz pogoja plastičnosti po Tresci:



Sl. 1. Model vlečenja
Fig. 1. Model of drawing

Matrici se med vlečenjem poveča premer vstopne odprtine D_d za ΔD_d , ki pa se ga po analitični poti zaradi geometrijske in obremenitvene nelinearnosti ne da izračunati. Premer palice je v valjnjem delu matrice enak premeru elastično deformirane matrice. V modelu izračun pomika vstopne odprtine temelji na izračunu pomika idealizirane oblike in radialne idealizirane obremenitve, popravljene s korekcijskim faktorjem K. Njegova vrednost je $K < 1$, in ga je treba vstaviti na podlagi numeričnega izračuna (npr. MKE).

Ko pride palica iz matrice, je obremenjena samo še z vzdolžno napetostjo σ_z , zato se premer palice nekoliko poveča za ΔD_p . Po končanem vleku se zaradi razbremenitve vzdolžne napetosti premer zopet poveča za ΔD_f . Ko se segreta palica ohladi na

constraints. For this reason, one of the commercial programs for FEM - ABAQUS - was used to verify this model. Naturally, several experiments were also performed, and both theoretical models were checked.

1 ANALYSIS ON THE BASIS OF ELASTO-PLASTICITY EQUATIONS

In this analysis, we based our work on the fact that stresses in the forming zone which can be calculated using the theory of plasticity are the principal elastic stresses in the die. Longitudinal stresses can be calculated using equation [9] (Fig. 1):

Radial and circumferential stresses are equal. They can be calculated using the Tresca yield criterion:

$$\sigma_r = \sigma_\theta = \sigma_z - \sigma_f \quad (2).$$

During drawing, the die diameter D_d increases by ΔD_d , but it can not be calculated analytically due to geometrical and load nonlinearity. Rod diameter in the oval zone of the die is equal to the diameter of the elastically deformed die. In the model, the calculation of the displacement of the die inlet opening is based on the calculation of the displacement of idealised shape and radial idealised stress, corrected by a correction factor K. The value is $K < 1$ and this needs to be taken into account in numerical calculation (e.g. by FEM).

When a rod comes out of a die it is loaded only by longitudinal stress σ_z , hence the diameter of the rod increases slightly, i.e. by ΔD_p . After the end of drawing, the rod diameter increases slightly by ΔD_f due to the unloading of longitudinal stress. When the heated rod is cooled to the temperature of the

temperaturo okolice, se njen premer zmanjša za ΔD_r . Končni premer ohlajene palice odstopa od premera vstopne odprtine matrice za:

$$\Delta D_{tot} = \Delta D_d + \Delta D_p + \Delta D_l - \Delta D_r$$

Z uporabo Hookovega zakona lahko posamezne člene izračunamo. Premer palice po vlečenju je:

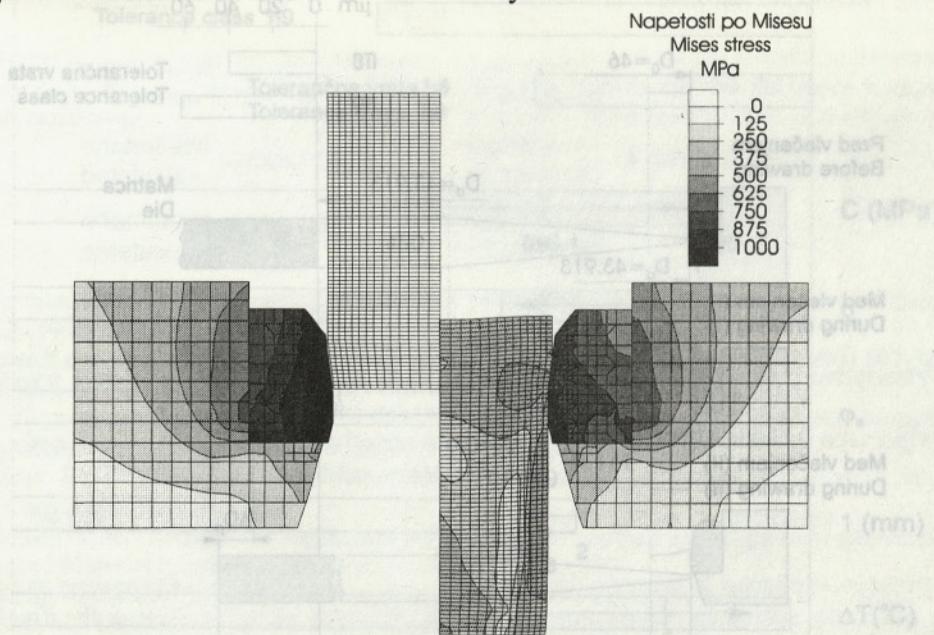
$$D_1 = 2R_d + \Delta D_{tot}$$

$$D_1 = 2\left\{ R_d + K \frac{R_d}{E_d} \frac{\sigma_{rm} R_d^2}{R_o^2 - R_d^2} \left[\nu - 1 - (1+\nu) \frac{R_o^2}{R_d^2} \right] + R_d \alpha_d \Delta T_d - \frac{R_d}{E_w} (\sigma_r - \nu(\sigma_r + \sigma_z)) - R_d \alpha_w \Delta T_w \right\} \quad (3)$$

The individual terms of the equation can be calculated using Hooke's law. The rod diameter after drawing is:

2 ANALIZA Z METODO KONČNIH ELEMENTOV (MKE)

Simulirali smo s programom za končne elemente ABAQUS. Ker nas je zanimala elastična deformacija matrice zaradi mehanske in topotne obremenitve, smo tudi za orodje uporabili trdne elemente (sl. 2). Uporabili smo 4-vozliščne bilinearne vrteninske elemente s povezano termično deformabilnostjo.



Sl. 2. Razporeditev Misesove ekvivalentne napetosti v modelu MKE
Fig. 2. Distribution of Mises equivalent stress in an FEM model

Na sliki 3 je prikazana razporeditev temperature v palici in matrici kot posledica nastale topote zaradi preoblikovalnega dela in trenja v matrici. Dejansko je temperatura palice, predvsem pa matrice višja, saj smo simulirali začetek vleka. Med vlečenjem se matrici po eni strani povisuje temperatura zaradi prestopa topote in s tem tudi vpliva povratno na temperaturo vlečenca, po drugi strani pa se z okrepljenim mazanjem in hlajenjem topota tudi odvaja.

environment, its diameter decreases by ΔD_r . The final diameter of a cooled rod deviates from the die diameter for:

The individual terms of the equation can be calculated using Hooke's law. The rod diameter after drawing is:

2 ANALYSIS USING FEM

A simulation was performed using a program for the finite element method, ABAQUS. Since we were interested in the elastic deformation of the die as a result of mechanical and thermal loading, other elements were also used for the die (Fig. 2): 4-node bilinear coupled temperature-displacement axisymmetric elements were used for rod and die.

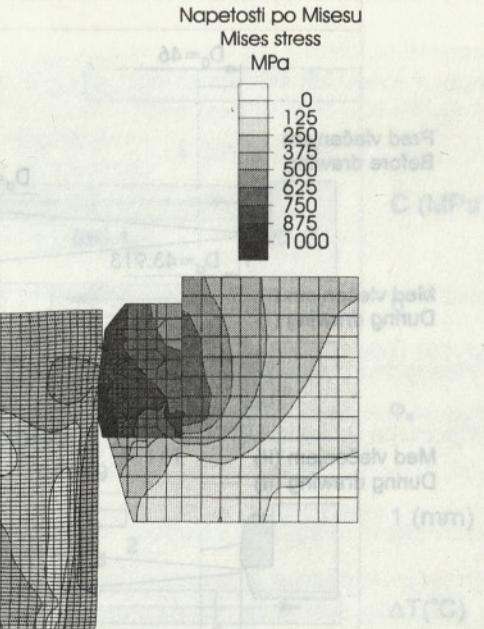
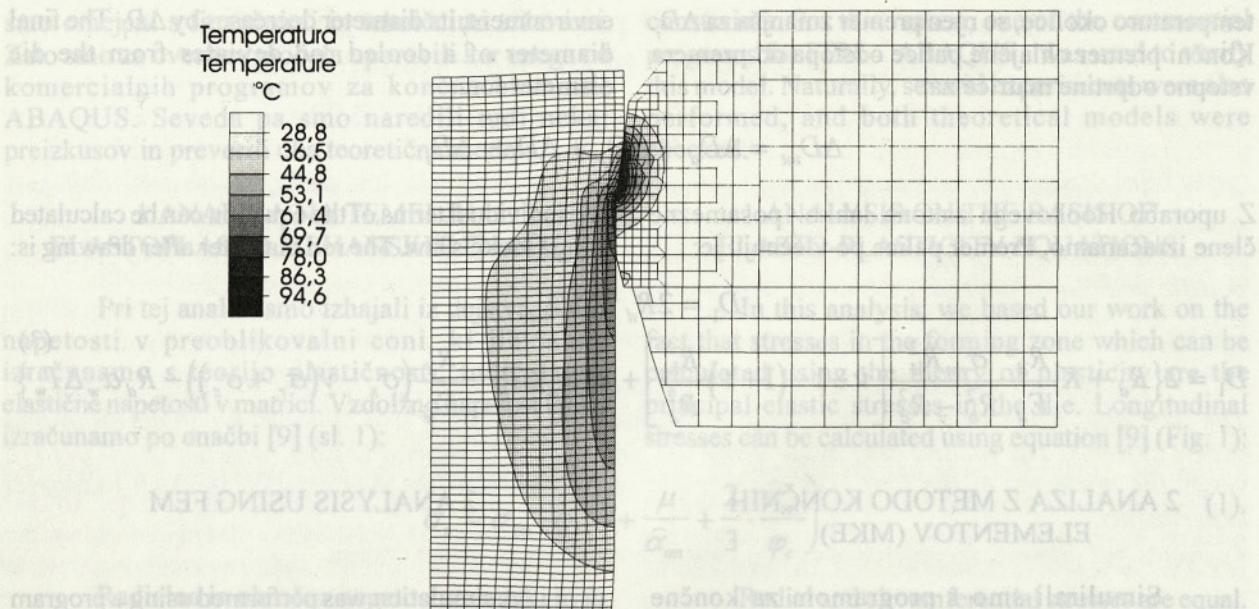
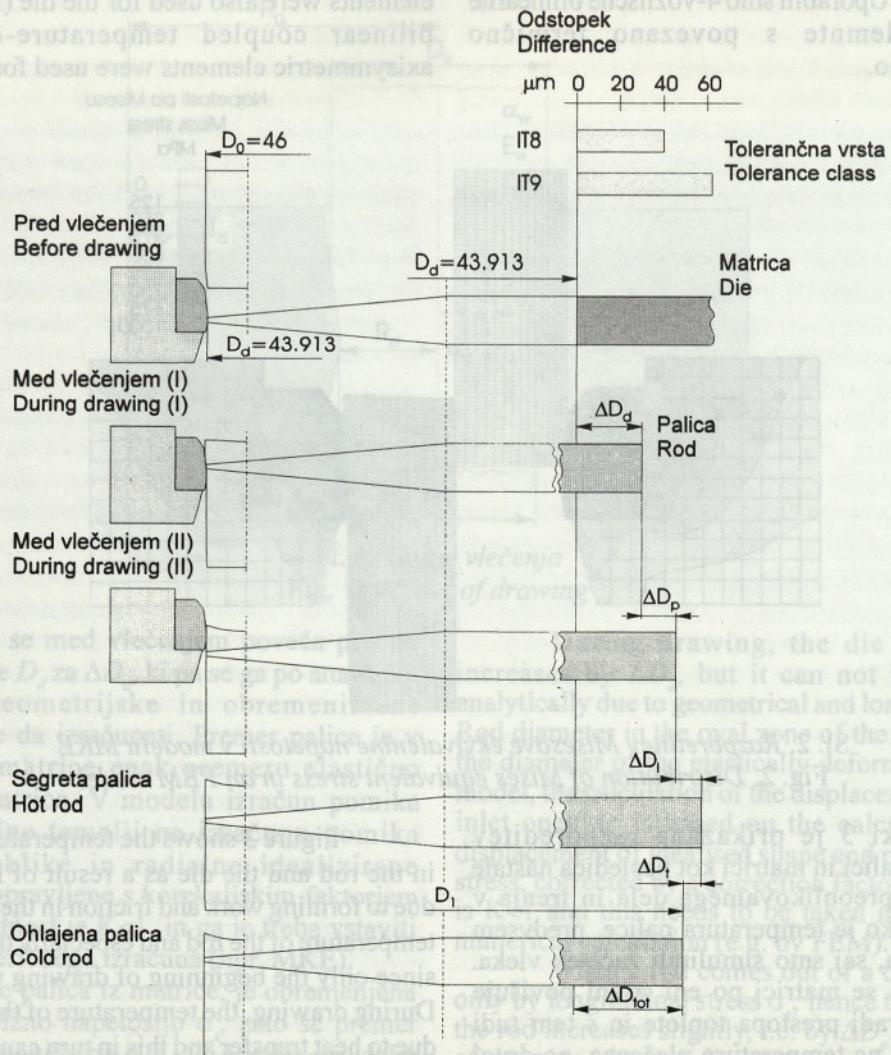


Figure 3 shows the temperature distribution in the rod and the die as a result of heat generated due to forming work and friction in the die. The actual temperature of the rod and especially the die is higher, since only the beginning of drawing was simulated. During drawing, the temperature of the die increases due to heat transfer and this in turn causes an increase in rod temperature, but, on the other hand, heat is also diffused due to intensive lubrication and cooling.



Sl. 3. Razporeditev temperature na začetku vlečenja

Fig. 3. Distribution of temperature at the beginning of drawing



Sl. 4. Spreminjanje premera palice med vlečenjem

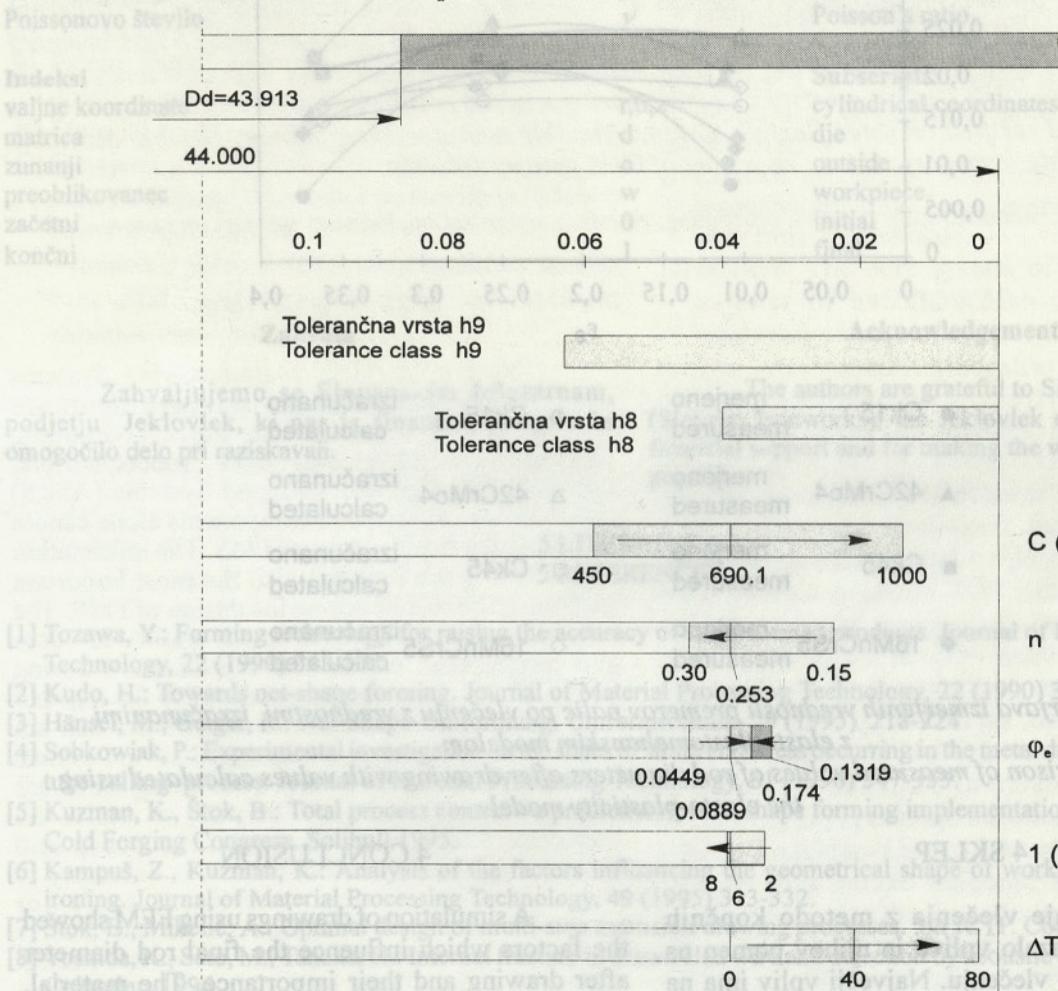
Fig. 4. Change of rod diameter during drawing

Na sliki 4 je prikazano, kako se spreminja premer palice med vlekom. Vhodni premer palice je bil $D_o = 46$ mm, notranji premer vstopne odprtine matrice po krčnem nasedu pa je bil $D_d = 43,913$ mm. Na sliki sta tudi vrisani tolerančni polji IT8 in IT9, tako da imamo primerjavo za oceno velikosti deformacije palice v posamezni faziji vleka.

V numerični model smo vstavljeni podatke za različne preoblikovalne lastnosti materiala C in n , stopnjo deformacije φ , dolžino kalibrirne cone l in temperaturo matrice T_d (sl. 5). Vidi se, da imajo na premer palice največji vpliv preoblikovalne lastnosti materiala (večji premer C povečuje, n pa zmanjšuje) in temperatura matrice T_d .

Figure 4 presents changes in rod diameter during drawing. The input rod diameter was $D_o = 46$ mm, while the inner die diameter after prestressing the die with a shrink ring was $D_d = 43.913$ mm. The figure also shows tolerance intervals IT8 and IT9 for comparison with rod deformations in individual phases of drawing.

Data on different forming properties of material, C and n , degree of deformation φ , length of cylindrical zone l , and die temperature T_d were entered into the numerical model (Figure 5). It can be seen that the forming properties of the material and the die temperature T_d have the greatest influence on rod diameter (an increase in C causes an increase in rod diameter, while n decreases it).



Sl. 5. Vplivni dejavniki na velikost premera vlečene palice

Fig. 5. Factors influencing rod diameter

3 VERIFIKACIJA ELASTOPLASTIČNEGA MODELA S PRESKUSI

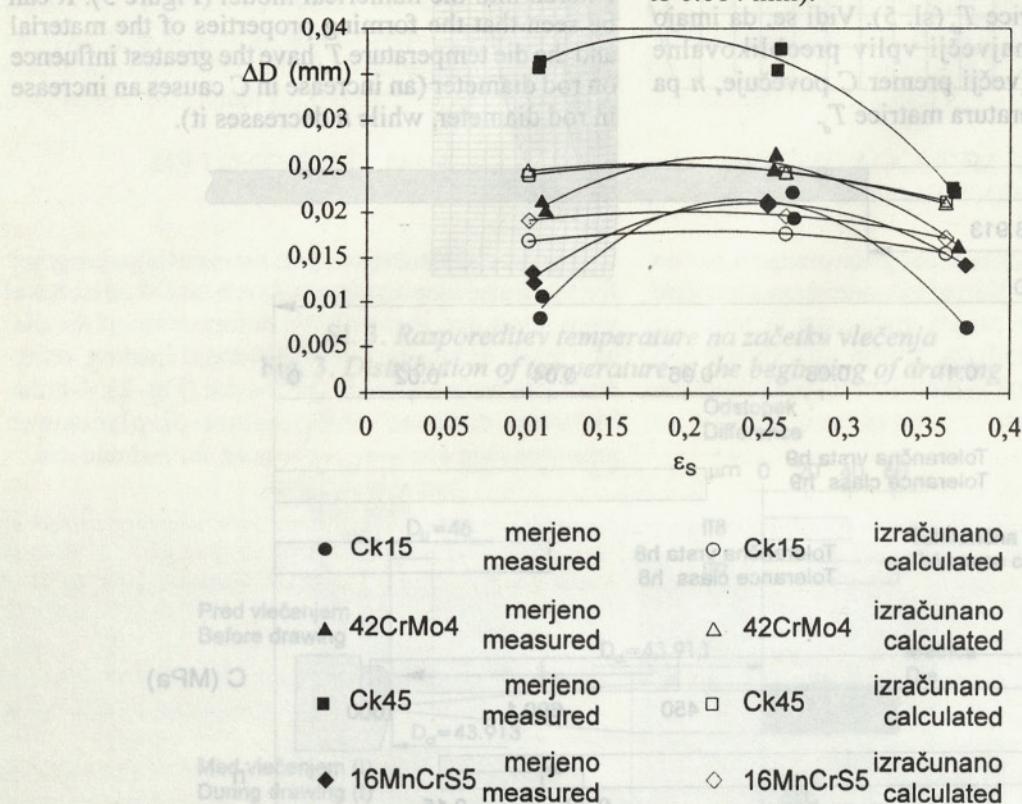
Algoritem, izpeljan iz enačb elasto-plastomehanike, ki je zaradi preprostosti in hitrosti izračuna zelo primeren za hitro določitev potrebnega premera matrice, smo preverili s preskusi. Z matrico

3 VERIFICATION OF THE MODEL OF ELASTO-PLASTICITY BY EXPERIMENTS

An algorithm derived from elasto-plasticity equations - which due to its simplicity and rapid calculation, is very suitable for a quick determination of the necessary die diameter - was verified by

premera $D_d = 19,875$ mm smo potegnili palice štirih različnih kakovosti premerov 21, 23 in 25 mm. Zmerili smo odstopke od premera matrice $\Delta D = D_i - D_d$ in jih vrisali v diagram (sl. 6). Teoretični model smo poprej "umerili" z ustreznimi korekturnimi faktorji. Slike se vidi, da za prve tri materiale teoretični model dokaj dobro popisuje dejansko stanje, za material 42CrMo4 pa so odstopki nekoliko večji (ΔD do 0,014 mm).

experiments. Using a die with a diameter of $D_d = 19.875$ mm, we drew rods of four different qualities with diameters of 21, 23 and 25 mm. The deviations from die diameter $\Delta D = D_i - D_d$ were measured and entered into a diagram (Figure 6). The theoretical model was first calibrated with corresponding correction factors. It can be seen from Figure 6 that, for the first three materials, the theoretical model describes the real state quite well, while for material 42CrMo4 the deviations are slightly greater (ΔD up to 0.014 mm).



Sl. 6. Primerjava izmerjenih vrednosti premerov palic po vlečenju z vrednostmi, izračunanimi z elastoplastomehanskim modelom

Fig. 6. Comparison of measured values of rod diameters after drawing with values calculated using the elasto-plasticity model

(mm) 14 SKLEP

Simuliranje vlečenja z metodo končnih elementov je pokazalo vplive in njihov pomen na končni premer pri vlečenju. Največji vpliv ima na spremembo premera palice material s svojimi preoblikovalnimi lastnostmi, temperatura matrice in stopnja deformacije.

Algoritem, ki uporablja enačbe elasto-plastomehanike, je preprost in primeren za hitri izračun. Dopolniti ga je treba z eksperimentalno ali s kako drugače dobljenimi korekturnimi vrednostmi (elastična deformacija vstopne odprtine matrice, temperatura matrice). Algoritem smo preverili z industrijsko dobljenimi vrednostmi in dobili zadovoljujoče odstopke (v tolerančnem razredu IT 7).

4 CONCLUSION

A simulation of drawings using FEM showed the factors which influence the final rod diameter after drawing and their importance. The material, with its forming properties, die temperature and degree of deformation, exerts the greatest influence on changes in rod diameter.

An algorithm which includes the elasto-plasticity equations is simple and suitable for quick calculation. It needs, however, to be supplemented by correction values obtained experimentally or through other methods (elastic deformation of inlet die opening, die temperature). The algorithm was checked using industrially obtained values, and satisfactory deviations were obtained (in the IT 7 tolerance class).

Geometrijska natančnost pri vlečenju okroglih palic - Geometrical Accuracy in Drawing Round Rods

2) Velikost in sestava stroja: 1. Sestava: izdelki

5 OZNAČBE 5 SYMBOLS

materialne konstante	C, n	material constants
premer	D	diameter
modul elastičnosti	E	modulus of elasticity
polmer	R	radius
temperatura	T	temperature
koeficient raztezanja	α	coefficient of linear thermal expansion
vstopni kot odprtine matrice	α_{an}	die inlet opening angle
prirastek	Δ	increment
napetost	σ	stress
srednja napetost tečenja	σ_{fm}	mean flow stress
srednja radialna napetost	σ_{rm}	mean radial stress
logaritemska deformacija	φ_e	natural strain
koeficient trenja	μ	coefficient of friction
Poissonovo število	ν	Poisson's ratio

Indeksi

valjne koordinate	r, θ, z
matrica	d
zunanji	o
preoblikovanec	w
začetni	0
končni	1

Zahvala

Zahvaljujemo se Slovenskim železarnam, podjetju Jeklovlek, ki nas je finančno podprlo in omogočilo delo pri raziskavah.

5 LITERATURA 5 REFERENCES

- [1] Tozawa, Y.: Forming technology for raising the accuracy of sheet-formed products. Journal of Material Processing Technology, 22 (1990) 343-351.
- [2] Kudo, H.: Towards net-shape forming. Journal of Material Processing Technology, 22 (1990) 307-342.
- [3] Hänsel, M., Geiger, R.: Net-Shape-Umformung. Umformtechnik, 29 (1995) 218-224
- [4] Sobkowiak, P.: Experimental investigation on the states of strain and stress occurring in the metal during the continuous tube-rolling process. Journal of Material Processing Technology, 61 (1996) 347-353.
- [5] Kuzman, K., Štok, B.: Total process control - a prediction for net shape forming implementation. 9th International Cold Forging Congress. Solihull 1995.
- [6] Kampuš, Z., Kuzman, K.: Analysis of the factors influencing the geometrical shape of workpieces produced by ironing. Journal of Material Processing Technology, 49 (1995) 313-332.
- [7] Štok, B., Mihelič, A.: Optimal design of multi-step extrusion/drawing processes. 5th ICTP. Columbus 1996.
- [8] Yoshida, K., Sato, M., Tanaka, H.: Internal fracture in drawn clad wire and detection by acoustic emission. 5th ICTP. Columbus 1996.
- [9] Geleji, A.: Bildsame Formung der Metalle in Rechnung und Versuch. Berlin 1960.

Naslov avtorjev: dr. Zlato Kampuš, dipl. inž.
prof. dr. Karl Kuzman, dipl. inž.
Alojz Gajšek, dipl. inž.
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6
1000 Ljubljana

Prejeto: 28.8.1997
Received: 28.8.1997

Authors' Address: Dr. Zlato Kampuš, Dipl. Ing.
Prof. Dr. Karl Kuzman, Dipl. Ing.
Alojz Gajšek, Dipl. Ing.
Faculty of Mechanical Engineering
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia

Structure and subsystems

801

Acknowledgement

The authors are grateful to Slovenske železarne (Slovene Ironworks), the Jeklovlek company, for their financial support and for making the work on this project possible.