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Analiza geometrijske natančnosti pri stanjševalnem vleku

Analysis of Geometrical Accuracy In Ironing

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V članku je prikazana analiza geometrijske natančnosti procesa stanjševalnega vleka, pri katerem je bil surovec lonček, izdelan z globokim vlekom brez držala pločevine. Postavljeni sta dva teoretična modela, s katerima lahko ugotavljamo večino vplivnih dejavnikov na geometrijsko obliko vlečencev. Prvi temelji na elementarni teoriji elasto-plastomehanike. Podane so enačbe za izračun notranjega in zunanjega premera vlečenca. Za drugi model je uporabljen program za reševanje z metodo končnih elementov ABAQUS. Prikazana je skladnost obeh teoretičnih modelov s preizkusi. V sklepnu so podane ugotovitve in kritična analiza obeh modelov.

Accuracy analysis of ironing cups, which had been previously made by deep drawing without a blankholder, is shown in the paper. Two theoretical models were built, enabling the study of most of the influences on geometrical accuracy. The first was based on the elementary theory of elasto-plasticity. Equations for the calculation of inner and outer diameters of the workpiece are given. An FEM program is used for the other model. The models were verified experimentally. The findings and a critical analysis of both models are given in the conclusion.

0 INTRODUCTION

One of the principal aims of forming technology today is to obtain precise products (Net shape) [1], [2], which can be built into the existing assembly, or require only slight finish-machining. The reasons for the introduction of net-shape forming are technical, economic [3] and human [1].

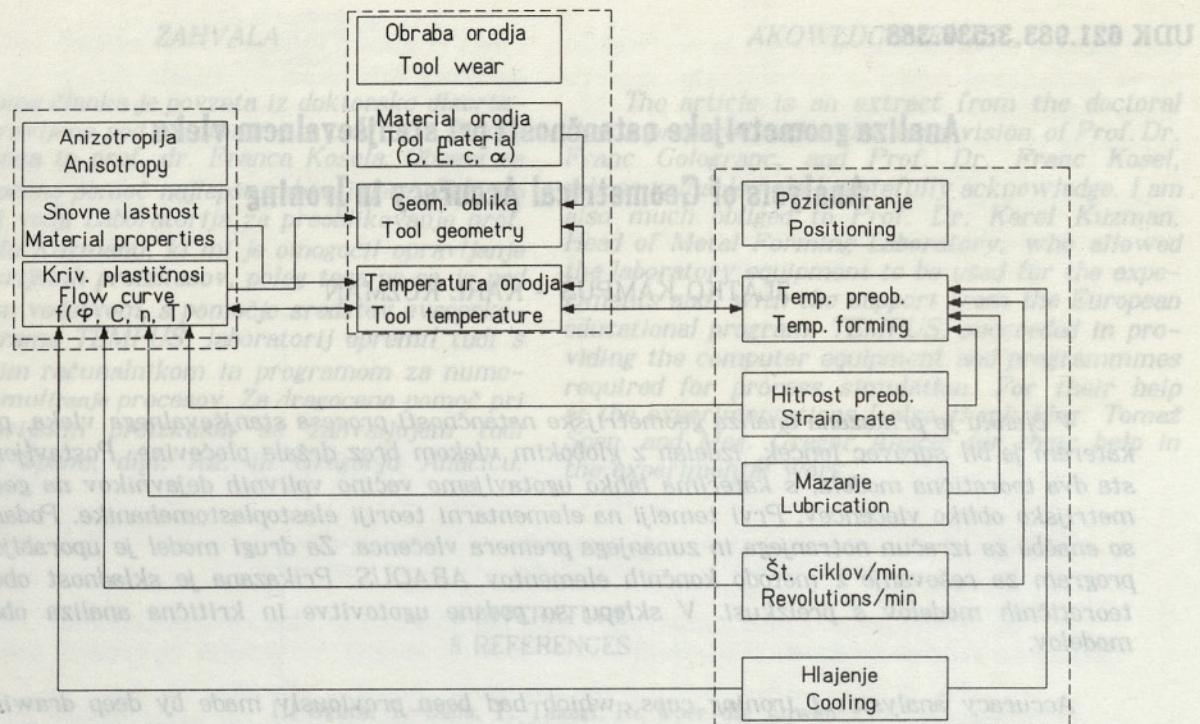
To achieve a high accuracy of formed products, we must know and control the process. To manufacture products of high quality, that is within the range of tolerance, we must know all the factors which influence dimension accuracy (Fig. 1). The condition is constant high quality of the forming materials.

The factors which influence the dimension of products were analysed from the process control point of view. A computer aided model, based on the theory of elasto-plasticity was derived, enabling the study of most of the influences on accuracy. The second model, based on the finite element method (FEM), includes a full elasto-plastic stress analysis. The models were verified experimentally.

Danes je eden glavnih ciljev preoblikovalne tehnologije obvladovanje natančnih izdelkov (Net-Shape) [1], [2], ki jih lahko neposredno vgradimo v obstoječi sklop, ali pa je potrebna le manjša mehanska obdelava. Razlogi za uvajanje te vrhunske tehnologije so poleg ekonomskih in tehničnih [3] tudi želja, da naredimo preoblikovalni proces bolj human [1].

Da lahko izdelamo natančen izdelek, moramo poznati in obvladovati proces. Za izdelavo stalno kakovostnih, to je v ožjem tolerančnem razredu narejenih izdelkov, moramo poznati vse dejavnike, ki vplivajo na dimenzijsko natančnost (sl. 1). Pri tem je seveda pogoj stalna (vrhunska) kakovost preoblikovanega materiala.

Z vidika obvladovanja procesa stanjševalnega vleka smo analizirali dejavnike, ki vplivajo na dimenzijsko natančnost izdelka. Izpeljali smo dva računalniško podprtta modela. Prvi model temelji na teoriji elasto-plastomehanike, s katerim lahko spremljamo večino vplivov na natančnost, drugi pa na metodi končnih elementov (FEM), v katerega je vključena popolna elasto-plastična napetostna analiza. Modela sta preverjena s preizkusi.



Sl. 1. Povezava med glavnimi spremenljivkami preoblikovalnega procesa (stanjševalnega vleka)
Fig. 1. Interactions between major process variables in metal forming (ironing)

1 SIMBOLI IN OZNAČBE

1 SYMBOLS AND DEFINITIONS

| | | | |
|--------------------|---|--------------------|--|
| A | – ploščina | A | – area |
| c | – specifična toplota | c | – specific heat |
| C | – konstanta materiala | C | – constant |
| d, D | – premer | d, D | – diameter |
| E | – modul elastičnosti | E | – modulus of elasticity |
| G | – strižni modul | G | – shear modulus |
| h | – preoblikovalna pot | h | – forming travel |
| n | – eksponent utrjevanja | n | – strain-hardening exponent |
| r, R | – polmer | r, R | – radius |
| R_m | – natezna trdnost | R_m | – ultimate tensile strength |
| s | – debelina | s | – thickness |
| t | – čas | t | – time |
| T | – temperatura | T | – temperature |
| u | – pomik | u | – displacement |
| w | – specifično preoblikovalno delo | w | – specific work |
| α | – kot vstopne odprtine matrice, linearni razteznostni temperaturni koeficient | α | – die inlet opening angle, coefficient of linear thermal expansion |
| B_0 | – izhodiščno vlečno razmerje | B_0 | – deep-drawing ratio |
| Δ | – razlika | Δ | – increment |
| δ_{ij} | – enotski tenzor | δ_{ij} | – unit tensor |
| ε_{ij} | – deformacijski tenzor | ε_{ij} | – strain tensor |
| η | – preoblikovalni izkoristek | η | – forming efficiency |
| μ | – koeficient trenja | μ | – coefficient of friction |
| v | – Poissonovo število | v | – Poisson ratio |
| ρ | – gostota | ρ | – density |
| φ | – logaritemsko deformacija | φ | – natural strain |
| σ | – normalna napetost | σ | – normal stress |
| σ_f | – napetost tečenja | σ_f | – flow stress |
| σ_{ij} | – napetostni tenzor | σ_{ij} | – stress tensor |

INDEKS

| | |
|-----------|-----------------------------|
| r, t, z – | valjne koordinate |
| o | stanje pred preoblikovanjem |
| 1, 2 | stanje po preoblikovanju |
| fm | srednja |
| m | matrica |
| p | peščič |
| s | superponiran |
| z | zunanji |

Preostale uporabljeni označbe in kratice so pojasnjene med besedilom.

2 ANALIZA GEOMETRIJSKE OBLIKE VLEČENCA Z ELEMENTARNO TEORIJO ELASTOPLASTOMEHANIKE (EM)

Pri pripravi modela za izračun elastičnih deformacij po preoblikovanju izhajamo iz napetosti v valjastem območju matrice, ki se lahko izračuna. Za osnovo smo vzeli enačbe, ki so bile eksperimentalno preverjene na FS in vključujejo tudi vpliv superponirane sile [4], [5]. Izpeljave so bile narejene na nekaterih predpostavkah in poenostavitevah, kakor je npr. homogeno napetostno-deformacijsko stanje, ravninsko deformacijsko stanje, Coulombovo trenje s konstantnim tornim koeficientom μ in drugo.

V valjastem območju matrice, ki ga lahko imenujemo tudi območje glajenja (v njem ni več preoblikovanja), so napetosti po prerezu skoraj nespremenljive:

$$\sigma_{zk} = 1,15 \sigma_f - (1,15 \sigma_f - \sigma_{z0}) e^{(-2\pi R_2 \mu_m h)/A_2} \quad (1),$$

$$\sigma_{rk} = - (1,15 \sigma_f - \sigma_{z0}) e^{(-2\pi R_2 \mu_m h)/A_2} \quad (2),$$

$$\sigma_{tk} = \frac{\sigma_{zk} + \sigma_{rk}}{2} \quad (3),$$

in so:

$$\sigma_{z0} = \frac{1}{b-1} \left\{ \left(\frac{A}{A_0} \right)^{b-1} [\sigma_s(b-1) - 1,15 \sigma_{fm}] + 1,15 b \sigma_{fm} \right\},$$

$$b = \frac{\mu_m}{\sin \alpha} + \frac{1}{\cos \alpha} - \frac{\mu_p}{m \tan \alpha},$$

$$m = \frac{r_1 + \frac{s_0 + s_1}{2}}{r_1}.$$

SUBSCRIPTS

| | |
|-----------|-------------------------|
| r, t, z – | cylindrical coordinates |
| o | prior to forming |
| 1, 2 | subsequent to forming |
| fm | mean |
| m | die |
| p | punch |
| s | superposed |
| z | outside |

Other symbols and abbreviations used are explained in the text.

2 ANALYSIS OF GEOMETRICAL SHAPE OF WORKPIECES WITH THE ELEMENTARY THEORY OF ELASTO-PLASTICITY (EM)

The stress in the cylindrical zone, which can be calculated, is used to build a model for the calculation of elastic strain after forming. Equations, which were verified experimentally and include the influence of superposed force [4], [5], were derived. The derivation was made considering the homogeneous stress-strain state, plane-strain state, Coulomb friction μ etc.

In the cylindrical zone of the die, which we can call the smooth zone, the stresses are nearly constant in a section:

$$\sigma_{zk} = 1,15 \sigma_f - (1,15 \sigma_f - \sigma_{z0}) e^{(-2\pi R_2 \mu_m h)/A_2} \quad (1),$$

$$\sigma_{rk} = - (1,15 \sigma_f - \sigma_{z0}) e^{(-2\pi R_2 \mu_m h)/A_2} \quad (2),$$

$$\sigma_{tk} = \frac{\sigma_{zk} + \sigma_{rk}}{2} \quad (3),$$

whereby:

Izhajamo iz spoznanja, da v območju glajenja ni več plastične deformacije in so te napetosti tudi največje elastične napetosti.

Deformacija matrice je odvisna od radialne σ_{rk} in vzdolžne σ_{zk} napetosti, ki se po višini vstopne odprtine spremenjata. Natančno se te deformacije s teorijo elastomehanike ne da izračunati in je potreben numerični način. Ena od možnosti je tudi idealiziran izračun z uporabo Lamejevih enačb, korigiranih z eksperimentalno ali teoretično dobljenimi vrednostmi.

Po izstopu iz matrice se zunanji in notranji premer nekoliko povečata, ker vlečenec z zunanje strani ni več stiskan. Ko je vlečenje končano, se geometrijska oblika zopet nekoliko spremeni, ker v steni vlečenca v vzdolžni smeri ni več natezne napetosti σ_{zk} , v pestiču pa ni več tlačne napetosti zaradi pritiska dna vlečenca na pestič. Ko vlečenec snamemo s pestiča, se mu zunanji in notranji premer nekoliko zmanjšata, saj ni več obremenjen z radialno napetostjo zaradi medsebojne elastične deformacije pestiča in vlečenca. Deformacije so računane z uporabo Hookovega zakona:

$$\sigma_{ij} = 2 G \epsilon_{ij} + \frac{\nu}{1 - 2\nu} \epsilon_{kk} \delta_{ij}.$$

Vpliv nastale topote na geometrijsko obliko je znaten. Zaradi zvišanja temperature se povečata premere matrice in pestiča, to pa vpliva na končno dimenzijo vlečenca. Po ohladitvi se vlečenec ohladi na temperaturo okolice, zato se mu zunanji in notranji premer zmanjšata.

Temperaturi preoblikovanca in orodja se bolj ali manj ves čas spreminja. Ko položimo surovec – lonček na pestič, prehaja topota (razen pri prvem – začetnem vleku) z orodja na preoblikovanec. Ko se začne preoblikovalna operacija, nastaja v preoblikovalnem območju in na stični ploskvi med premikajočim se pestičem in orodjem topota. Del te topote prehaja v dno vlečenca, del v še nepreoblikovano steno, del pa prehaja s prestopom na orodje in okolico. Razmere se med preoblikovanjem neprestano spreminja. Vlečenec se ves čas segreva, višja je tudi temperatura orodja.

Zaradi vseh teh vplivnih dejavnikov, ki se med preoblikovanjem spreminja, natančna matematična rešitev toplotnega prehoda takega preoblikovalnega sistema ni mogoča. Lahko se izračunajo posamezni deli takega toplotnega procesa, kakor je npr.: nastala topota pri preoblikovanju, toda že pri izračunu nastale topote zaradi trenja med vlečencem in orodjem se pojavljajo velike matematične težave, rešljive le z idealiziranjem problema [6].

This is based on the fact that plastic deformation ceases in the smooth zone and that these stresses are the largest.

The deformation of the die depends on the radial σ_{rk} and axial σ_{zk} stresses, which change along the height of the die. We cannot accurately calculate this strain using the theory of elasticity, so a numerical method is needed. One possibility is to calculate it by means of Lame equations, corrected by experimental or theoretical values.

After leaving the die, the inside and outside diameter increase slightly, because the workpiece is not under pressure from outside. When the drawing is finished, the geometrical shape changes again, because the wall, in the longitudinal direction, is not under tensile stress σ_{zk} , and the punch is not under compressive stress resulting from the workpiece bottom pressing the punch. When the workpiece is taken down from the punch, the inside and outside diameter become slightly smaller, because the workpiece is not loaded by radial stress resulting from reciprocal elastic strain of the punch and workpiece. The deformations are calculated by Hooke's law:

$$\sigma_{ij} = 2 G \epsilon_{ij} + \frac{\nu}{1 - 2\nu} \epsilon_{kk} \delta_{ij}.$$

The influence of generated heat on the geometrical shape is considerable. The punch and die diameters increase because of a rise in temperature and this influences the end dimensions of the workpiece. After cooling, the temperature of the workpiece decreases to that of the surroundings, so the inside and outside diameters become smaller.

The temperatures of the tool and workpiece change continuously. When we put a cup on the punch, heat is transferred (except in the first draw) from the tool onto the workpiece. When the forming operation begins, heat is generated in the forming zone and in the area of contact between the moving punch and the workpiece. A part of it is transferred to the bottom of the workpiece, a part onto the unformed wall and a part is transferred onto the tool and into the surroundings. The conditions during forming change. The workpiece is warming up all the time, and the temperature of tools gets also higher.

Because of all the influences which change during forming, an exact mathematical solution of heat transfer in such a forming system is not possible. Parts of this thermal process, such as heat generated in forming can be calculated, but great difficulties already appear in the calculation of the heat generated by friction between the workpiece and tools, so a solution is possible only by idealizing [6].

V izdelanem modelu, ki temelji na teoriji elastoplastomehanike, je izračunano zvišanje temperature zaradi preoblikovanja po enačbi:

$$\Delta T = \frac{w}{\rho c} \frac{1}{\eta} \eta_0 \quad (4).$$

Pri tem je izkoristek odvoda toplote:

- $\eta_0 = 0$ za izotermno preoblikovanje
- $\eta_0 = 1$ za adiabatno preoblikovanje.

Znižanje in zvišanje temperature vlečenca in orodja zaradi, npr. vpliva hladnega ali toplega orodja, pa določimo s korekcijskimi koeficienti. Pravilne vrednosti teh koeficientov, ki imajo vrednost od 0 do 1, lahko dobimo le s preizkusi.

Če se stejemo ustrezne pomike, lahko izračunamo celoten pomik oziroma premer hladnega vlečenca. Upoštevati moramo, da se je tudi premer pestiča in matrice povečal zaradi raztezanja.

Notranji polmer vlečenca je:

$$r_{ik} = r_p + r_p \alpha \Delta T (\eta_{php} - 1) + \frac{r_p}{E} \left[\frac{\sigma_{rk} + \sigma_{zk} (2\nu - 3\nu)}{2} + \sigma_{zk} \frac{R_m^2}{r_p^2} \right] \quad (5).$$

η_{php} — izkoristek ohranjanja temperature pestiča. Če bi bila temperatura pestiča enaka temperaturi preoblikovanca, bi bil $\eta_{php} = 1$.

Za izračun zunanjega premera hladnega vlečenca bi morali poznati pomik vstopne odprtine matrice u_m .

Če bi bila matrica popoln obroč zunanjega premera R_z in bi vlečenec enakomerno pritiskal po vsej vstopni odprtini matrice, bi bil pomik notranjega robu:

$$u_{mon} = \frac{R_m}{E} \frac{\sigma_{rk} R_m^2}{R_z^2 - R_m^2} \left[\nu - 1 - (1 + \nu) \frac{R_z^2}{R_m^2} \right] \quad (6).$$

Matrice za stanjševalni vlek niso obremenjene po vsej vstopni odprtini. Da bi se približali dejanski deformaciji, lahko uvedemo korekcijski faktor K. Natančnejši izračun pomika notranjega polmera matrice je:

$$u_{mo} = u_{mon} K ; K < 1 \quad (7).$$

Korekcijski faktor K je odvisen od obremenitve in geometrijske oblike matrice. Pomik vstopne odprtine matrice pa je:

$$u_m = K \frac{R_m}{E} \frac{\sigma_{rk} R_m^2}{R_z^2 - R_m^2} \left[\nu - 1 - (1 + \nu) \frac{R_z^2}{R_m^2} \right] + R_m \alpha \Delta T \eta_{phm} \quad (8),$$

In the model based on the theory of elastoplastic mechanics, a rise in temperature due to forming is calculated by the equation:

Here the efficiency of heat transfer is:

- $\eta_0 = 0$ for isothermal forming,
- $\eta_0 = 1$ for adiabatic forming.

The rise and fall in the temperature of the workpiece and tools due to the influence of cold or hot tool are taken into account by using correction factors. The correct values for these correction factors, which have a value from 0 to 1, can only be obtained by experiments.

If we sum up the corresponding displacements, we can calculate the total displacement or the diameter of the cold workpiece. We also have to consider the increase in the diameters of punch and die due to thermal dilatation.

The inside diameter of the punch is:

η_{php} — efficiency of temperature conservation of the punch. If the temperature of the punch was equal to the temperature of the workpiece, then $\eta_{php} = 1$.

To be able to calculate the outside diameter of the cold workpiece, we have to know the displacement of the die inlet opening u_m .

If the die were a perfect ring with an outside diameter R_z , with the workpiece pressing uniformly on all inlet opening, the displacement of the inside edge would be:

$$u_{mon} = \frac{R_m}{E} \frac{\sigma_{rk} R_m^2}{R_z^2 - R_m^2} \left[\nu - 1 - (1 + \nu) \frac{R_z^2}{R_m^2} \right] \quad (6).$$

Ironing dies are not loaded on all inlet openings. To approach the actual displacement, we can introduce a correction factor K. A more accurate calculation of the displacement of the inside die radius is:

The correction factor K depends on the load and the geometrical shape of the die. The displacement of the inlet die opening is:

pri tem η_{phm} upošteva nižjo temperaturo matrice.

S predpostavko, da se tudi matrica elastično deformira, je zunanj polmer hladnega vlečenca:

$$R_{ik} = R_m + R_m \alpha \Delta T (\eta_{phm} - 1) + K \frac{R_m}{E} \frac{\sigma_{rk} R_m^2}{R_z^2 - R_m^2} \left[\nu - 1 - (1 + \nu) \frac{R_z^2}{R_m^2} \right] - \frac{R_m (\sigma_{rk} + \sigma_{zk})}{2E} (1 - 2\nu) \quad (9).$$

3 ANALIZA

GEOMETRIJSKE OBLIKE VLEČENCEV Z METODO KONČNIH ELEMENTOV

Ker je surovec za stanjševalni vlek lonček, izdelan z globokim vlekom, smo najprej simulirali ta postopek. Za model rondele smo izbrali kvadratne osnosimetrične elemente s štirimi integracijskimi točkami in linearno interpolacijo. Geometrijska oblika pestiča in matice je enaka geometrijski obliki orodja pri laboratorijskih preizkusih: premer pestiča je bil $d_p = 40$ mm, vstopna krivulja matrice pa v obliki traktrise.

Preden pa so se rezultati analize uporabili za model stanjševalnega vleka, je bilo treba pravilnost rezultatov globokega vleka preveriti s preizkusi.

Na sliki 2 je narejena primerjava med geometrijsko obliko lončka, dobljenega s simuliranjem in preizkusom. Pri dejanski debelini sta narisani dve krivulji debelin zaradi ravinske anizotropije. Največji zunanj premer lončka je pri simuliranju skoraj enak izmerjenemu, debelina pa na nekaterih mestih odstopa od povprečne debeline za nekaj desetink milimetra [7].

V model stanjševalnega vleka je vključena geometrijska oblika lončka globokega vleka prek vhodne datoteke z vozlišči. Ta začetna napaka geometrijske oblike (debelina stene, dobljena s simuliranjem je večja od dejanske) nekoliko vpliva na geometrijsko obliko vlečenca in potek preoblikovalne sile. Mreža lončka je zaradi majhnih deformacij pri globokem vleku ostala enaka in je ni bilo treba spremenjati. Uporabljeni so kvadratni osnosimetrični elementi s štirimi integracijskimi točkami. V elementih je bila upoštevana tudi linearna interpolacija temperature.

Preoblikovalne lastnosti elementov lončka so podane z neutrjeno krivuljo plastičnosti, saj so bili lončki po globokem vleku žarjeni.

where η_{phm} takes lower matrix temperature into account.

With the assumption of elastic die deformation, the outside radius of a cold workpiece is:

3 ANALYSIS OF GEOMETRICAL SHAPE OF WORKPIECES BY FINITE ELEMENT METHOD

Since a workpiece for ironing is a cup made by deep drawing, we first simulated this process. For the blank models, we choose quadratic axi-symmetric elements with four integration points and linear interpolation. The geometrical shape of the punch and die is the same as the geometrical shape of the tool in the experiments. The diameter of the punch was $d_p = 40$ mm, the drawing die had a tractrix inlet shape.

Before the results of the analysis were used for model of ironing, the results of deep drawing had to be verified by experiments.

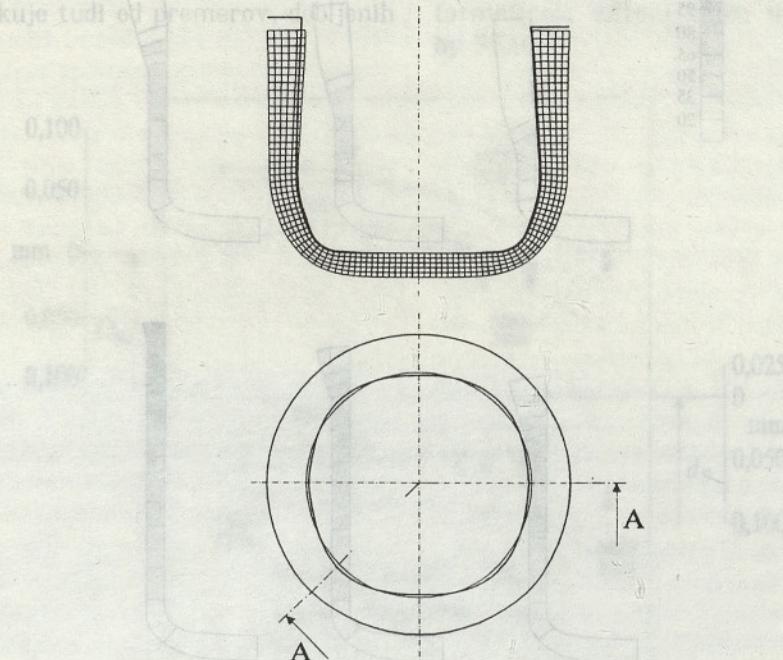
In figure 2, a comparison is made between geometrical shapes of the cup from simulation and from experiment. At actual thickness two curves are drawn due to planar anisotropy. The largest outside cup diameter from simulation nearly equals the measured one, while the thickness in some locations deviates from the average by a few tenths of a millimetre [7].

In the model of ironing, the geometrical shape of a deep-drawn cup is included by an input data file with nodes. This initial error in the geometrical shape (the wall thickness in the simulation is larger than the experimental) influences the geometrical shape of the workpiece and the forming force. The mesh of the cup, due to a small deformation in deep-drawing, was equal and it did not need to be changed. In the analysis, axi-symmetric quadratic elements with four integration points were used. If a full stress-thermal analysis were to be made, it should also include linear temperature interpolation in the elements.

The forming properties of the cup elements are given with a non-hardening flow curve, since the cups were annealed after drawing.

PREREZ A-A
SECTION A-A

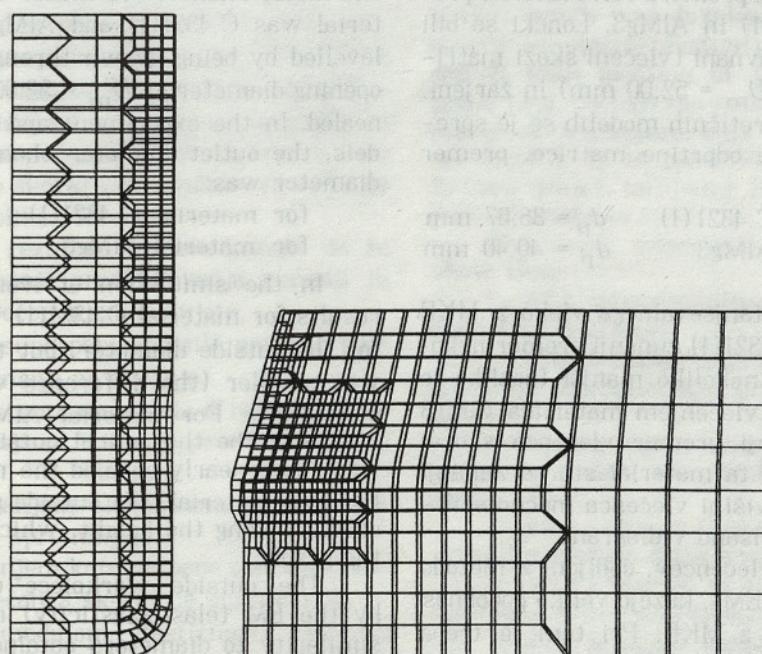
enek izmerjenemu, medtem ko je pri nekaj modelih zelo razlikuje tudi od premerov z MKE.



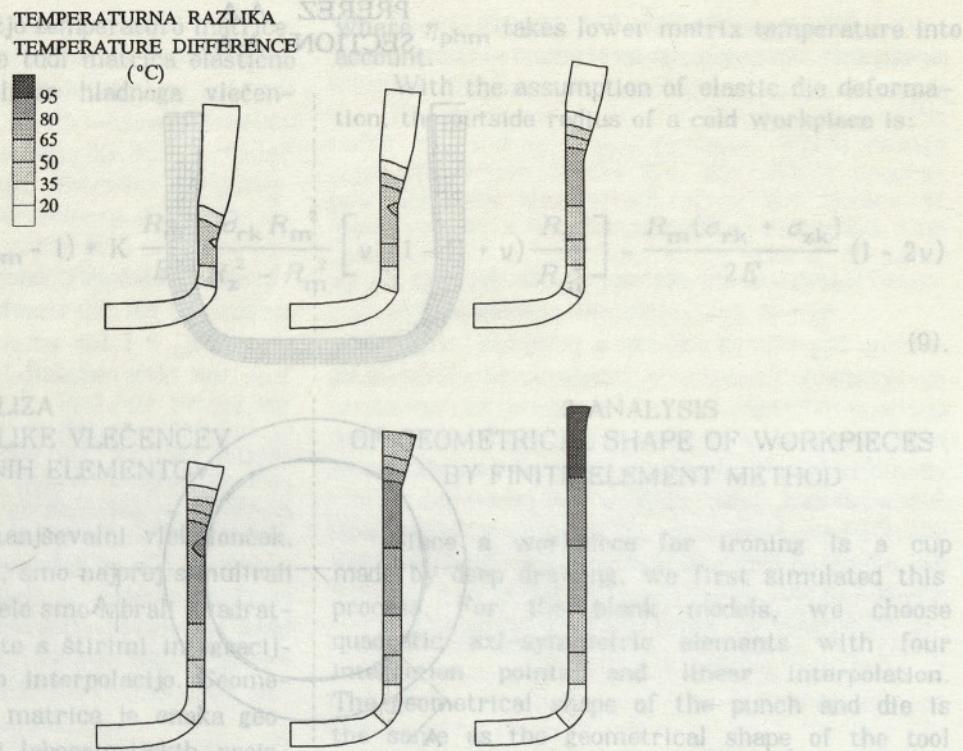
Sl. 2. Primerjava simulirnega prereza lončka z dejanskim
Fig. 2. Comparison of simulated cup cross section with the experimental

Pri tem modelu sta tudi pestič in matrica razdeljena na štirirobne aksialnosimetrične elemente. Na sliki 3 je prikazana povečana elastična deformacija pestiča in matrice med vlekom, na sliki 4 pa je prikazan porast temperature vlečenca v različnih stopnjah vlečenja.

In this model, the punch and die are also divided into four quadriangular axially symmetric elements. In figure 3, enlarged elastic deformations of the punch and die during the draw are presented. In figure 4, the temperature of a part at different stages of the ironing process is presented.



Sl. 3. Povečana elastična deformacija pestiča in matrice med vlekom
Fig. 3. Enlarged elastic deformations of the punch and die during drawing



Sl. 4. Porast temperature vlečenca v različnih stopnjah vlečenja

Fig. 4. Temperature distribution in different drawing stages

4 SKLADNOST ANALITIČNIH REZULTATOV Z EKSPERIMENTALNIMI

V diagramu na sliki 5 je narejena primerjalna analiza vpliva velikosti deformacije na spremembo zunanjega in notranjega premera [8]. Material preoblikovanca je Č.4321(1) in AlMg3. Lončki so bili po globokem vleku poravnani (vlečeni skozi matrico z vstopno odprtino $D_m = 52,00$ mm) in žarjeni. Pri preizkusih in v teoretičnih modelih se je spremenjal premer vstopne odprtine matrice, premer pestiča pa je bil:

$$\begin{array}{ll} \text{za material Č.4321(1)} & d_p = 38,67 \text{ mm} \\ \text{za material AlMg3} & d_p = 40,40 \text{ mm} \end{array}$$

S simuliranjem stanjševalnega vleka z MKE dobimo za material Č.4321(1) zunanji premer nekoliko večji, notranji pa nekoliko manjši (razlika je 0,025 do 0,030 mm). Z vlečenjem materiala AlMg3 pa je teoretični zunanji premer vlečenca skoraj enak izmerjenemu. Za ta material sta se zunanji in notranji premer po višini vlečenca močno spremenjala, kar je tudi vrisano v diagram.

Zunanji premeri vlečencev, dobljeni z metodo elastoplastomehanike (EM), kažejo veliko podobnost s premeri, dobljenimi z MKE. Pri tem je treba opozoriti, da so v model vstavljeni podatki za deformacijo matrice, dobljeni z MKE. Velikost notranjega premera za material Č.4321(1) je skoraj

4 AGREEMENT OF ANALYTICAL RESULTS WITH THE EXPERIMENTAL

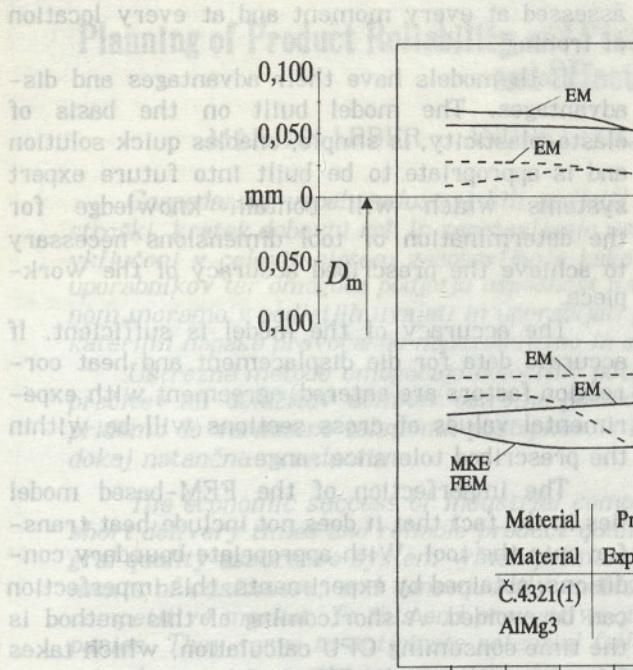
In figure 5, a comparative analysis of the influence of deformation on a change in the outside and inside diameter is made. The workpiece material was Č.4321(1) and AlMg3. The cups were levelled by being drawn through a die with inlet opening diameter of $D_m = 52.00$ mm and then annealed. In the experiment and in theoretical models, the outlet diameter changed and the punch diameter was:

$$\begin{array}{ll} \text{for material Č.4321(1)} & d_p = 38.67 \text{ mm} \\ \text{for material AlMg3} & d_p = 40.40 \text{ mm} \end{array}$$

In the simulation of ironing by FEM, the results for material Č.4321(1) were a little larger for the outside diameter, but the inside diameter was smaller (the difference was from 0.025 to 0.030 mm). For material AlMg3 after drawing, however, the theoretical outside diameter of the workpiece nearly equaled the measured diameter. For this material, the outside and inside diameter changed along the height, which is also shown in the graph.

The outside workpiece diameters obtained by the EM (elastoplasticity) method show great similarity to diameters obtained by FEM. It has to be stressed that data used for die deformation were obtained by FEM. The magnitude of the inside diameter for material Č.4321(1) is very

enak izmerjenemu, medtem ko je pri aluminiju ta nekoliko manjši in se posebno pri velikih deformacijah, močno razlikuje tudi od premerov, dobljenih z MKE.



Sl. 5. Primerjava teoretičnih odstopkov premerov od izmerjenih pri različnih deformacijah

Fig. 5. Comparison of part diameters obtained by experiments and theoretically

5 SKLEP

Z modelom, ki smo ga razvili z uporabo elementarne teorije elastoplastomehanike, je analizirana vsaka faza stanjevalnega vleka. V vsakem trenutku in mestu stanjevalnega vleka (na pestiču, obremenjen, ohlajen) sta poznana notranji in zunanji pomik roba vlečenca in pomik orodja, zato se lahko simulirajo skoraj vse veličine, ki vplivajo na geometrijsko obliko vlečenca.

- Pomembnejši rezultati modela kažejo, da se
- z večjo stopnjo preoblikovanja zunanji in notranji premer vlečenca zmanjšujeta,
 - z večanjem superponirane sile notranji polmer zmanjšuje, zunanji pa zvečuje,
 - z večjo konstanto materiala C notranji premer vlečenca zmanjšuje, zunanji pa ostane skoraj nespremenjen,
 - s spremenjanjem eksponenta n dimenzije vlečenca skoraj ne spremenijo,
 - s spremenjanjem kota vstopne odprtine matrice dimenzije vlečenca skoraj ne spremenijo,
 - z večjim modulom elastičnosti vlečenca premera zmanjšujeta,
 - z večjim vlečnim razmerjem B_0 pri globokem vleku premera pri vrhu lončka povečujeta.

close to the measured values, while for aluminum, it is smaller and, especially at large deformations, differs from the diameters obtained by FEM.

5 CONCLUSION

Every phase of ironing was analysed with the model, which was developed on the basis of the theory of elasto-plasticity. In each moment and at each location of ironing (on the punch, under load, cooled) the inside and outside displacements of workpiece edge and tool displacement are known. It is possible to analyse nearly all factors which influence the geometric shape of formed products.

The most important results of the model show that:

- with larger strains, the inside and outside diameters decrease,
- with a higher superposed force, the inside diameter decreases and the outside diameter increases,
- with a higher constant C , the inside diameter decreases, the outside remains nearly the same,
- with a change in strain-hardening exponent n , the dimensions of the workpiece remain the same,
- with a change in the angle of die, the dimensions of the workpiece remain the same,
- with a higher modulus of elasticity of the workpiece, both diameters decrease,
- with a higher drawing ratio B_0 , both diameters at the top of the cup increases.

Z uporabo programa za reševanje z metodo končnih elementov ABAQUS smo izdelali model, ki vključuje elastično deformacijo orodja in prevod toplotne. Lahko se vključujejo skoraj vse vplivne veličine in ugotavlja njihove vplive v vsakem trenutku in mestu stanjševalnega vlečenja.

Tako prvi kakor drugi teoretični model imata svoje prednosti in pomanjkljivosti. Model, zgrajen na temelju elastoplastomehanike (EM), omogoča z uporabo računalnika preprosto in hitro rešitev in je primeren za vgradnjo v prihodnje ekspertne sisteme, ki bodo imeli nekoč vgrajeno tudi znanje za določitev potrebnih dimenzij orodja za doseg natančnega, v načrtovanem razredu izdelanega vlečenca.

Natančnost modela EM je razmeroma dobra. Če vstavimo vanj ustrezne natančne podatke za deformacijo matrice in toplotne korekcijske faktorje, je pokrivanje z eksperimentalnimi vrednostmi prečnega prereza v tolerančnem razredu IT8.

Nepopolnost modela, ki temelji na metodi končnih elementov je v tem, da v njem ni vključen prestop toplotne na orodje. Z ustreznimi robnimi pogoji, dobljenimi s preizkusi, to pomanjkljivost odpravimo. Slaba stran te metode je v trajanju računanja CPU, ki znaša na delovni postaji Apollo 720 pri popolni analizi okoli 8 ur.

The ironing procedure was simulated by the ABAQUS program, a model was built which includes elastic deformation of tool and heat transfer. Nearly all factors and their influence can be assessed at every moment and at every location of ironing.

Both models have their advantages and disadvantages. The model built on the basis of elasto-plasticity, is simple, enables quick solution and is appropriate to be built into future expert systems which will contain knowledge for the determination of tool dimensions necessary to achieve the prescribed accuracy of the work-piece.

The accuracy of the model is sufficient. If accurate data for die displacement and heat correction factors are entered, agreement with experimental values of cross sections will be within the prescribed tolerance range.

The imperfection of the FEM-based model lies in the fact that it does not include heat transfer onto the tool. With appropriate boundary conditions, obtained by experiments, this imperfection can be avoided. A shortcoming of this method is the time consuming CPU calculation, which takes 8 hours on the Apollo 720 workstation.

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