Osnovni koncept numerične simulacije radialnega kovanja

Basic Concepts of Numerical Simulation of a Radial Forging Process

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UDK: 621.73.045:519.6
ASM/SLA: F22, Q24, 1—66, U4g, U4k

1. UVOD

S spoznanji splošnih principov fizikalne metalurgije[1] postajajo preoblikovalni procesi v vročem pomembnejši. Preoblikovanje v vročem že dolgo ni več samo spreminjanje oblike preoblikovanca, temveč termomehanska obdelava materiala, ki naj privede do ugodnih strukturnih sprememb. Pri upoštevanju medsebojnih odvisnosti med strukturo, lastnostmi in obnašanjem materiala med plastičnim preoblikovanjem so deformacija, hitrost deformacije in temperatura tiste fizikalne večine, ki imajo odločilni vpliv. Nadzorovana porazdelitev teh termomehanskih parametrov med preoblikovanjem je potrebna pri optimiranju preoblikovalne operacije. Preoblikovalni procesi v vročem so zahtevni za eksperimentalna opazovanja zaradi visokih temperatur in preoblikovalnih hitrosti. Od tod tudi potreba po matematičnih in numeričnih modelih, ki pripomorejo k boljšemu razumevanju eksperimentalnih rezultatov ali celo delno nadomeščajo draga preizkušanja. Tri klasične metode za analizo preoblikovalnih procesov so bile pogosto uporabljane v preteklosti[2]:

- metoda elementarne plastomehanike
- metoda drsnih linij
- metoda zgornje in spodnje meje.

Analiza preoblikovalnih procesov je zahtevna in mnogo poenostavitvenih predpostavk je bilo vpeljanih v klasičnih metodah, da bi se izognili matematičnim težavam, kar je seveda zmanjševalo njihovo uporabnost. Napredek numeričnih metod v zadnjem času, posebej metode končnih elementov[3] (MKE) in vzporedno zmanjševanje cen računalniških obdelav, ponuja možnost za realnejše simulacije preoblikovalnih procesov.

2. MATEMATIČNI MODEL

Za analizo porazdelitev napetosti, deformacij in temperature, ki se spreminjajo znotraj deformacijske cone med preoblikovanjem, je nujna uporaba numeričnih metod. Razvoj MKE na področju plastomehanike[4] in prenosa toplote ponuja zadovoljivo orodje za računalniško simulacijo preoblikovalnih procesov v vročem.

Simulacijo preoblikovalnega procesa v vročem lahko idealiziramo[5], kot je to prikazano na **sliki 1**.

1. INTRODUCTION

Since the general principles of physical metallurgy were recognised[1], the hot working processes are no longer only concerned with shape changes but also consider the thermomechanical treatment which contributes to beneficial structural changes within the material. In considering the interaction between the structure, properties and performance of the material under plastic deformation, the strain, strain rate and temperature are quantities which have a fundamental influence and a controlled variation of these thermomechanical parameters is essential for optimising the forming operation. The nature of hot working processes makes experimental observations difficult, due to the high temperatures and speeds involved. Therefore mathematical and numerical models have a role to play in either improving the interpretation of experimental results or even replacing, in part, an expensive testing programme. Three classical methods for analysing metal forming problems have been widely used in the past[2]:

- elementary plasticity
- the slip line method
- the upper and lower bound method.

Metal forming processes are complex and many simplifying assumptions have been introduced to these classical methods in order to avoid mathematical difficulties. This, however, limits their applicability. Recent developments of numerical methods, in particular the Finite Element Method[3] (FEM), and a parallel reduction in unit computing costs offer an opportunity for a more realistic simulation of working processes.

2. MATHEMATICAL MODEL

The complex stress-strain and temperature distributions which vary across the deformed region during the deformation process require the use of numerical methods. Developments in the FEM in the field of plastomechanics[4] and heat transfer offer a satisfactory tool for computer simulation of hot working processes.

The numerical simulation of the hot working process can be idealised[5] as shown in **Fig. 1**.

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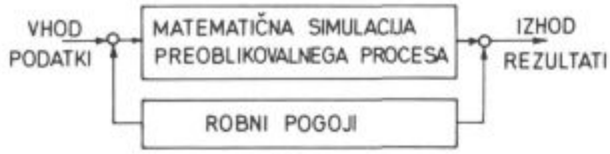


Slika 1:
Simulacija preoblikovalnega procesa.

Vhodni podatki predstavljajo lastnosti in začetno stanje preoblikovanca, kot so: oblika, porazdelitev temperature, sestava in mikrostruktura materiala.

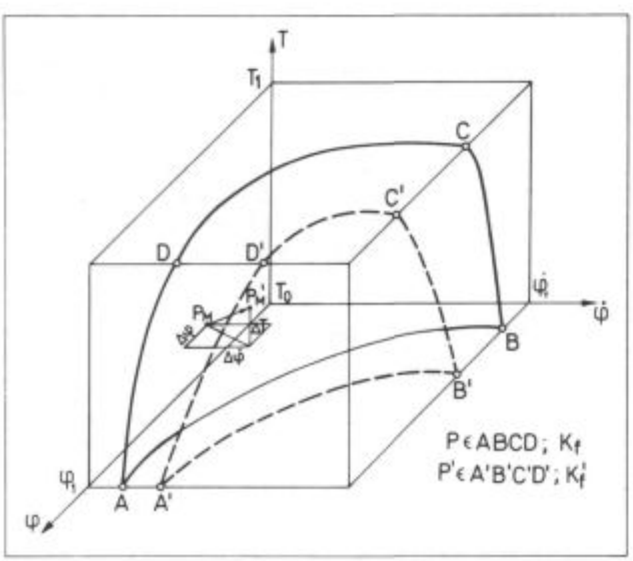
Matematična simulacija preoblikovalnega procesa: Pri MKE razdelimo preoblikovanec na manjša območja, imenovana elementi. Togost vsakega elementa je določena z njegovo geometrijo in lastnostmi materiala, ki jih elementu pripišemo. Oba vpliva obravnavamo ločeno in zato relativno enostavno vgrajujemo različne *materialne modele.* Model preoblikovanca dobimo s sestavljanjem togostnih matrik elementov. Takšen pristop omogoča analizo različnih geometrijsko zahtevnih preoblikovalnih procesov.

Z robnimi pogoji simuliramo različne pogoje, v katerih poteka proces.

Izhodni rezultati. Po obdelavi rezultatov numerične analize določimo optimalne tehnološke pogoje. Nazoren grafični prikaz rezultatov je pomemben sestavni del analize z MKE.

3. MATERIALNI MODEL

Pri modeliranju obnašanja materiala med plastično deformacijo je potrebno poznavanje ustrezne napetosti tečenja. V splošnem je ta odvisna od sestave in mikrostrukture materiala in od hitrosti deformacije, temperature ter deformacijskega stanja, povzročenega s plastično deformacijo. Napetost tečenja določimo z nateznim, tlačnim ali torzijskim preizkusom[6]. Pogosto napetosti tečenja niso dosegljive za specifične kombinacije termome-



Slika 2:
Ploskve napetosti tečenja v prostoru termomehanskih parametrov.

Fig. 2:
Flow stress surfaces in the space of the thermomechanical parameters.

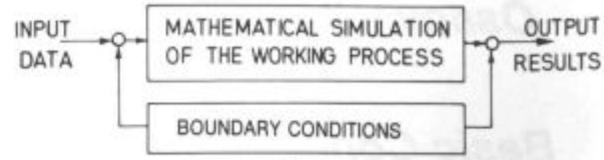


Fig. 1:
Simulation of the working process.

Input data represent the material properties and initial state of the workpiece; such as shape, temperature distribution, composition and microstructure of the material.

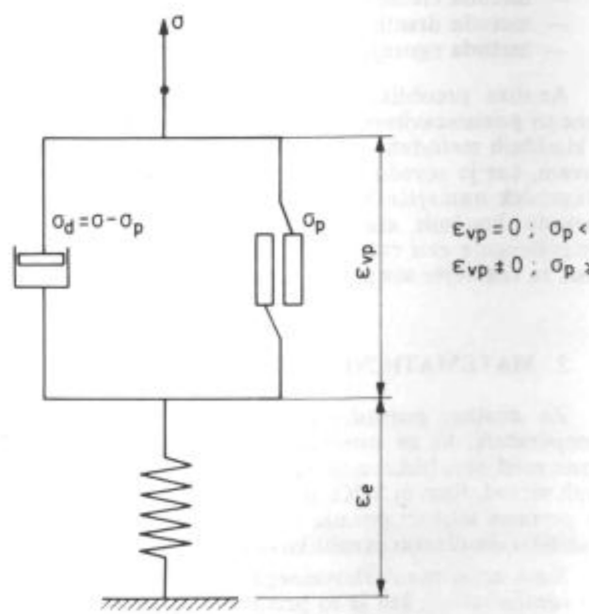
Mathematical simulation of the working process: In FEM the workpiece is divided into small regions termed elements. The stiffness of each element is determined by its geometry and material properties. Both effects are considered separately and therefore it is relatively simple to incorporate different *material models.* The workpiece model is obtained by combining the stiffness contribution of each element. Thus any complex shape of the workpiece model can be analysed using the FEM.

Boundary conditions are applied to simulate different conditions under which the process is to operate.

Output results: A decision on the most suitable set of operating conditions can be made by postprocessing the numerical results. Graphical representations play an integral part in the interpretation of the numerical results of a FEM analysis.

3. MATERIAL MODELS

In the modelling of material behaviour during metalworking processes a knowledge of the appropriate flow stress for the material is essental. In general this will depend on the composition and microstructure of the material and on the strain rate, temperature and deformation modes imposed by the working process. The flow



Slika 3:
Osnovni enodimenzionalni elasto-viskoplastični reološki model.

Fig.3:
Basic one-dimensional elasto-viscoplastic rheological model.

hanskih parametrov in jih ocenimo s pomočjo poznanih podatkov. Znane so različne interpolacijske enačbe, kot na primer Hajdukova[7] ali Sellars-Tegartova enačba[8]. Na podlagi teh enačb lahko določimo potencial napetosti tečenja v prostoru deformacije, hitrosti deformacije in temperature[5] **(Sl. 2)**. Ploskev A-B-C-D je določena z φ, $\dot{\varphi}$, T, ki povzročajo enako napetost tečenja K_f pri določenem stanju mikrostrukture materiala. V splošnem se v delcu materiala med preoblikovanim procesom termomehanski parametri spreminjajo iz φ, $\dot{\varphi}$, T v φ', $\dot{\varphi}'$, T' in temu ustrezno se spremeni napetost tečenja iz K_f v K'_f, ki je določena s ploskvijo A'-B'-C'-D'. Za napovedovanje sprememb termomehanskih parametrov med preoblikovalnim procesom v vročem uporabljamo elasto-viskoplastični materialni model, združen s prenosom toplote.

4. OSNOVNE ENAČBE ELASTO-VISKOPLASTIČNOSTI

Osnovni enodimenzionalni elasto-viskoplastični reološki model, ki je predstavljen na **sliki 3**, lahko razširimo za primer splošnega kontinuuma. Postopek je podrobno opisan v literaturi [4]. Na tem mestu bodo predstavljene le najosnovnejše enačbe **(Sl. 4)**.

Hitrost deformacije je razdeljena na elastično $\dot{\varepsilon}_e$ in visokoplastično $\dot{\varepsilon}_{vp}$ komponento **(En. 1)**. Elastična hitrost deformacije je določena s Hookeovim zakonom, medtem ko $\dot{\varepsilon}_{vp}$ izrazimo z ustreznim zakonom tečenja. S tem dobimo enačbo **(En. 2)**, kjer je γ parameter tečenja in Φ je funkcija, ki je različna od nič samo za pozitivne vrednosti funkcije F. Začetek visokoplastičnega obnašanja določa pogoj, izražen s skalarno enačbo **(En. 3)**, kjer je K_f napetost tečenja pri enoosnem preizkusu in χ parameter utrjevanja. Enačbi **(En. 1)** in **(En. 2)** lahko zapišemo v inkrementalni obliki in tako dobimo izraz **(En. 4)**, ki določa spremembo napetosti v časovnem koraku $\Delta t_n = t_{n+1} - t_n$. Z uporabo implicitne časovno integracijske sheme **(En. 6)**, kjer je hitrost viskopolastične deformacije na koncu časovnega intervala izražena s pomočjo prvih dveh členov Taylorjeve vrste **(En. 7)**, dobimo končni izraz za inkrement napetosti. **(En. 8, 9)**. Plastično delo se med preoblikovanjem spreminja v toploto, kar povzroča prirastek temperature. Povprečno hitrost generacije toplote v časovnem koraku izračunamo s pomočjo izrazov **(En. 10, 11)**, kjer je f frakcija plastičnega dela, ki jo akumulira material.

Analiza nestacionarnega prenosa toplote z MKE je opisana v literaturi [9].

5. ROBNI POGOJI

Z robnimi pogoji simuliramo pogoje, v katerih poteka preoblikovalni proces. V splošnem ločimo mehanske in termalne robne pogoje.

5.1. Mehanski robni pogoji

Mehanski robni pogoji so odvisni od oblike in gibanja orodja ter od trenjskih razmer med orodjem in preoblikovancem.

Med preoblikovanjem se preoblikovalni stroj elastično deformira. Problem poenostavimo, če privzamemo, da je stroj tog. Tako je gibanje orodja popolnoma popisano z gibanjem ene točke, ki ga izračunamo iz kinematike stroja[10]. Ti podatki so del vhodnih podatkov in so lahko časovno odvisni.

stress is determined from true stress — true strain data obtained from tension, compression or torsion tests[6]. Frequently stress — strain data are not available for specific combinations of the required conditions and they must be estimated from data that are available. Various expressions have been suggested for the interpolation of high temperature data, for example Hajduk's[7] relation or the Sellars — Tegart expression[8]. On the basis of these expressions the material flow stress surface in the strain, strain rate and temperature space can be represented[5] **(Fig. 2)**. Surface A-B-C-D is defined by the φ, $\dot{\varphi}$, T required to give the same flow stress K_f for a particular state of the microstructure of the material. In a part of the deformed material the thermomechanical parameters φ, $\dot{\varphi}$, T will change to φ', $\dot{\varphi}'$, T' during the forming process and the flow stress will be changed from K_f to K_f' defined by surface A'-B'-C'-D'. To predict the change of the thermomechanical parameters during the hot working operation an elasto-viscoplastic material model coupled with heat transfer is used.

4. BASIC CONCEPTS OF ELASTO-VISCOPLASTICITY

The basic one dimensional elasto-viscoplastic rheological model shown in **Fig. 3** can be extended to the case of general continua. Details of this approach are provided in Ref. 4 and only essential expressions are reproduced in **Fig. 4**.

The total strain rate is separated into elastic $\dot{\varepsilon}_e$ and viscoplastic $\dot{\varepsilon}_{vp}$ components **(Eq. 1)**. The elastic strain rate obeys Hooke's law and $\dot{\varepsilon}_{vp}$ is expressed by the appropriate viscoplastic flow rule. This gives the governing equation **(Eq. 2)** where γ is fluidity parameter and Φ is taken as non-zero for positive values of the yield function, F, only. The onset of viscoplastic behaviour is governed by a scalar yield condition **(Eq. 3)** where the uniaxial yield stress is denoted by K_f and χ is a hardening parameter. The rate equations **(Eq. 1, 2)** can be written in an incremental form to give the stress increment occuring in time step $\Delta t_n = t_{n+1} - t_n$ **(Eq. 4)**. Use of the implicit time integration sheme **(Eq. 6)** where the viscoplastic strain rate at the end of the time step is predicted by a limited Taylor series expansion **(Eq. 7)** resultes in **(Eq. 8, 9)** for the stress increment. Most of the plastic work done during the time step is converted into heat and gives an increase of temperature. The average rate of heat generation within the time step which enters the thermal analysis is calculated according to **(Eq. 10, 11)** where, f, is a fraction of the plastic work stored in material.

Thermal transient finite element analysis is described in Ref. 9.

5. BOUNDARY CONDITIONS

The boundary conditions represent the conditions under which the process is to operate. Generally we distinguish between mechanical and thermal boundary conditions.

5.1. Mechanical boundary conditions

The mechanical boundary conditions depend on the shape and movement of the die and the friction at the die — workpiece interface.

During the course of the forming process the forming machine undergoes elastic deformation. To simplify the problem the forming machine is assumed to be rigid. Therefore the motion of the die can be completely described by specifying a velocity at one point which can be calculated from the kinematics of the forging ma-

OSNOVNE ENAČBE ELASTO-VISCOPLASTIČNOSTI
BASIC EQUATIONS OF ELASTO-VISCOPLASTICITY

$$\{ \dot{\epsilon} \} = \{ \dot{\epsilon}_e \} + \{ \dot{\epsilon}_{vp} \} \quad \ldots (1)$$

$$\{ \dot{\epsilon} \} = [E]^{-1} \{ \dot{\sigma} \} + \gamma <\Phi(F)> \frac{\partial F}{\partial(\sigma)} \quad \ldots (2)$$

$$F((\sigma),\chi) = f((\sigma)) - K_f(\chi) = 0 \quad \ldots (3)$$

Inkrementalna oblika osnovnih enačb:
Incremental form of the basic equations:

$$\{ \Delta\sigma^n \} = [E] \{ \Delta\epsilon_e^n \} = [E] \left[\{ \Delta\epsilon^n \} - \{ \Delta\epsilon_{vp}^n \} \right] \quad \ldots (4)$$

$$\{ \Delta\epsilon^n \} = [B^n] \{ \Delta U^n \} \quad \ldots (5)$$

$$\{ \Delta\epsilon_{vp}^n \} = \Delta t_n \left[(1-\Theta) \dot{\epsilon}_{vp}^n + \Theta \dot{\epsilon}_{vp}^{n+1} \right] \; ; \; 0 \leq \Theta \leq 1 \quad \ldots (6)$$

$$\{ \dot{\epsilon}_{vp}^{n+1} \} = \{ \dot{\epsilon}_{vp}^n \} + \frac{\partial(\dot{\epsilon}_{vp})}{\partial(\sigma^n)} \Delta\sigma^n \quad \ldots (7)$$

$$\{ \Delta\sigma^n \} = [\hat{D}^n] \left[[B^n] \{ \Delta U^n \} - \{ \dot{\epsilon}_{vp}^n \} \Delta t_n \right] \quad \ldots (8)$$

$$[\hat{D}^n] = \left[[E]^{-1} - \Theta \Delta t_n \left[\frac{\partial(\dot{\epsilon}_{vp})}{\partial(\sigma^n)} \right] \right]^{-1} \quad \ldots (9)$$

Povprečna hitrost generacije toplote v časovnem koraku
Average rate of heat generation within the time step:

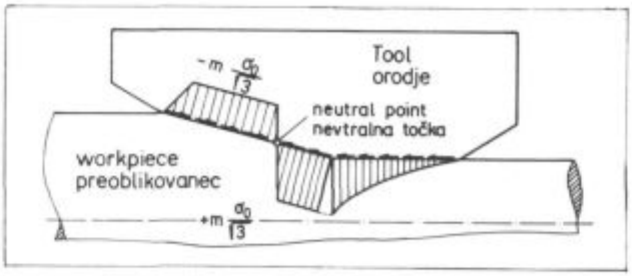
$$\dot{Q}^n = (1-f) \{ \sigma^{n+\alpha} \}^T \frac{1}{\Delta t_n} \left[\{ \epsilon_{vp}^{n+1} \} - \{ \epsilon_{vp}^n \} \right] \quad \ldots (10)$$

$$\{ \sigma^{n+\alpha} \} = \{ \sigma^n \} + \alpha \{ \Delta\sigma^n \} \; ; \; 0 \leq \alpha \leq 1 \quad \ldots (11)$$

Slika 4:
Pregled osnovnih enačb.

Fig. 4:
Owerview of basic equations.

Proces radialnega kovanja v vročem poteka brez maziv pri visokih temperaturah, zato so trenjske razmere v stiku med orodjem in preoblikovancem zahtevne za numerično obravnavo. Porazdelitev strižnih napetosti v kontaktu lahko ustreza Coulombovemu zakonu, pravilu o konstantni strižni napetosti ali lepljenju. Smer strižnih napetosti je odvisna od relativnega gibanja med orodjem in preoblikovancem. Ker je relativno gibanje materiala odvisno od trenjskih razmer, je problem očitno nelinearen. Mesto nevtralne točke, kjer ni relativnega gibanja, najdemo z iteracijskim procesom. Ko najdemo pozicijo nevtralne točke, lahko trenjske razmere predpišemo, kot je to prikazano na **sliki 5**.



Slika 5:
Predpostavljene trenjske razmere.

Fig. 5:
Assumed friction conditions.

5.2. **Termalni robni pogoji**

Med preoblikovanjem preoblikovanec izgublja toploto zaradi stika s hladnejšim orodjem in s sevanjem. Za opisovanje teh pogojev uporabljamo standardne matematične robne pogoje.

— predpisano temperaturo na stični površini
— predpisan toplotni tok skozi stično površino
— Newtonov zakon o prenosu toplote

6. ILUSTRATIVNI PRIMER

Z MKE smo analizirali proces radialnega kovanja na kovaškem stroju z zaokroženimi kladivi, ki je shematično prikazano na **sliki 6**. Napetostno-deformacijsko stanje pri takšnem kovanju je kvaziaksisimetrično. Geometrijo delovnih površin kovaškega kladiva razdelimo na tri dele:[11, 12]

I — vhodno cono
II — kalibrirno cono in
III — izhodno cono.

Skoraj vsa plastična deformacija nastopi v vhodni coni. Glavna parametra vhodne cone sta kot α na kladivu ter povprečna vhodna hitrost V_{inp} materiala. Za kovanje z redukcijo *∅ 120/∅ 80 mm*, ki smo ga analizirali, je bil kot $\alpha = 10°$ in $V_{inp} = 45$ *mm/s*. Iz teh podatkov in iz poznane kinematike stroja lahko izračunamo:

L_d projekcijo vhodne dotikalne površine na os simetrije (113.4 mm)
U_{inp} pomik vhodnega materiala v smeri simetrijske osi po vsakem udarcu (10 mm)
W_{rad} delovni hod kladiva v radialni smeri (1.76 mm)
t_{ud} čas trajanja udarca (0.018 s)

Uporabljeni podatki o materialu[13]:

Material: X5CrNi18.8
Začetna temperatura 1000°C

chine.[10] These velocity data are part of the input and can be varied with time.

Since the radial forging operation is carried out at high temperatures without lubrication the friction conditions at the tool-workpiece interface face are complex. The distribution of the shear stress at the interface may obey either Columb's law, the constant shear rule or sticking friction conditions. However, the direction of the shear stress is unknown due to relative movement of the material at the interface. Since the relative movement is friction dependent the problem clearly becomes nonlinear. The position of the neutral point, where relative sliding is zero must be found by an iterative procedure. After the position of neutral point is established the friction conditions can be prescribed as presented in **Fig. 5**.

5.2. **Thermal boundary conditions**

During the forming process the workpiece loses heat due to contact with the colder die and also by radiation. To model these effects, standard mathematical boundary conditions are used:

— prescribed temperature at the contact surface
— prescribed flux across the contact surface
— Newton's law of heat transfer

6. ILLUSTRATIVE EXAMPLE

A roundfaced die radial forming proces which is schematically presented in **Fig. 6**, has been analysed using FEM. The stress-strain field is assumed to be quasi-axisymmetric in this case. The geometry of the working surfaces of the radial forging die is divided into three parts:[11, 12]

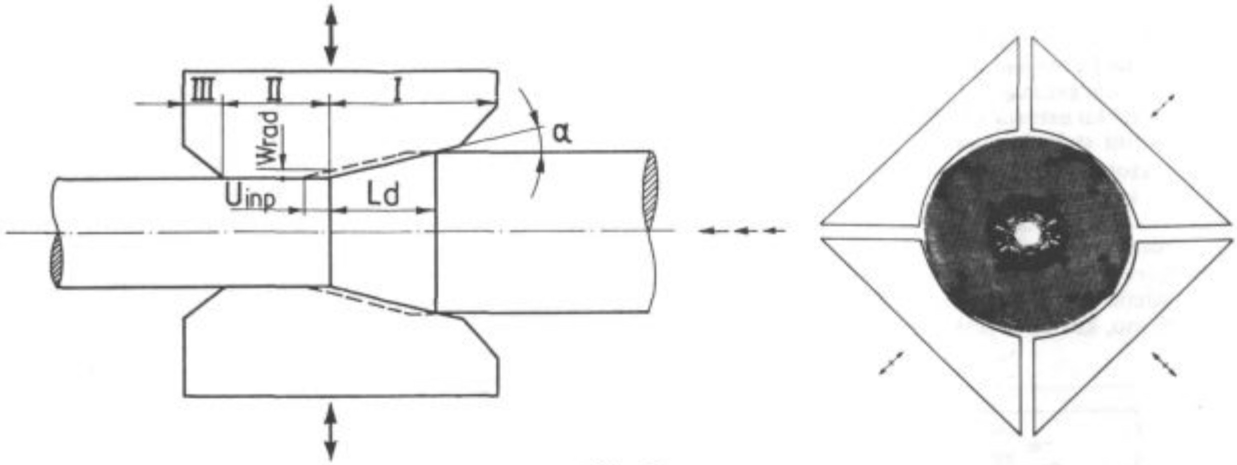
I — the inlet cone
II — the sizing cone
III — the outlet cone

Nearly all the plastic deformation occurs in the inlet cone. The main parameters of the inlet cone are the angle α of the die and the average speed V_{inp} of the input material. In the present example the reduction was *∅ 120/∅ 80 mm* and the inlet cone angle α and speed V_{inp} were 10° and 45 mm/s respectively. From this data and kinematics of the machine the following boundary conditions are evaluated:

L_d projection of the inlet cone contact area on to the centreline axis (113.4 mm)
U_{inp} displacement of the input material along the centraline axis after each punch (10 mm)
W_{rad} displacement of the die in the radial direction while in contact with the workpiece (1.76 mm)
t_{ud} duration of the punch (0.018 s)

The material properties used in this example are given below:

Material: X5CrNi18.9
Initial temperature 1000°C



Slika 6:
Shematični prikaz procesa radialnega kovanja.
Fig. 6:
Schematical view of the radial forging process.

Lastnosti materiala pri začetni temperaturi kovanja:[13]

- modul elastičnosti 120 kN/mm²
- Poissonov količnik 0.34
- gostota 7430 kg/m³
- specifična toplotna kapaciteta 650 J/kg K

Interpolacijska funkcija za napetost tečenja:

$$K_f = K_{fo} \cdot A_1 \cdot e^{-m_1 T} \cdot A_2 \cdot \varphi^{m_2} \cdot A_3 \cdot \dot{\varphi}^{m_3}$$

kjer je

$K_{fo} = 189.5$ N/mm²
$A_1 = 12.997$ $m_1 = 0.00258$
$A_2 = 1.570$ $m_2 = 0.196$
$A_3 = 0.740$ $m_3 = 0.128$

Uporabljeni so bili 8-vozliščni Serendipity aksialno simetrični končni elementi z reducirano (2×2) numerično integracijsko shemo[14] ter von Misesovim kriterijem tečenja z izotropnim modelom utrjevanja materiala.[4] Nelinearni elasto-viskoplastični problem smo reševali z metodo tangencialne togosti. Pri tem smo uporabili implicitno časovno integracijsko shemo s korekcijo napetosti na koncu vsakega časovnega koraka[15]. Sistem linearnih enačb smo reševali s frontalno metodo[16].

REZULTATI

Na **slikah 7, 8 in 9** so prikazane posamezne faze razvoja prirastka plastičnih deformacij v preoblikovalni coni med udarcem kladiva. S pomočjo rezultatov MKE lahko na enak način predstavimo prostorsko in časovno porazdelitev ostalih termomehanskih parametrov med preoblikovanjem. To so temperatura ter vse komponente in primerjalne vrednosti tenzorjev napetosti, deformacij in hitrosti deformacij. Določevanje sil, momentov in energije, potrebne za preoblikovanje, je z MKE natančnejše kot pri klasičnih metodah. V mnogih primerih nas zanima tok materiala. Pri kovaško-valjavski liniji, na primer, je glavna naloga kovaškega stroja zapiranje notranjih napak v materialu. Simulacija zapiranja notranjih poroznosti v materialu z MKE je grafično prikazana na **sliki 10**.

Material properties at the initial temperature:[13]

- Young's modulus 120 kN/mm²
- Poisson's ratio 0.34
- density 7430 kg/m³
- specific heat capacity 650 J/kg K

Interpolation function for high temperature data:[7]

$$K_f = K_{fo} \cdot A_1 \cdot e^{-m_1 T} \cdot A_2 \cdot \varphi^{m_2} \cdot A_3 \cdot \dot{\varphi}^{m_3}$$

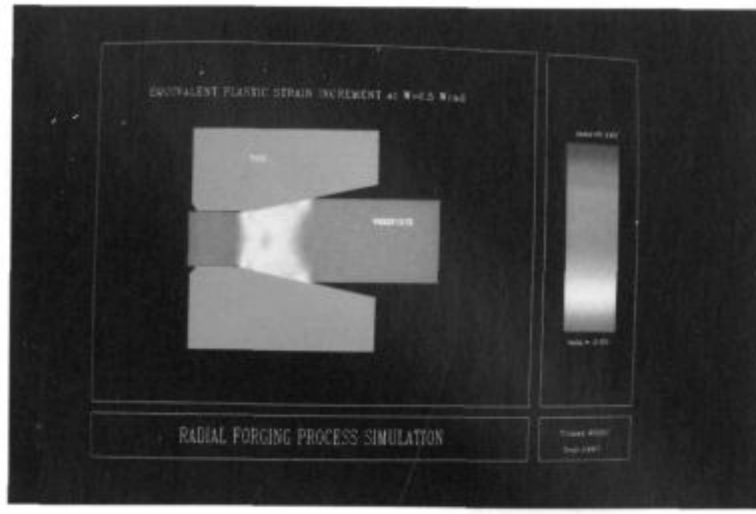
with:

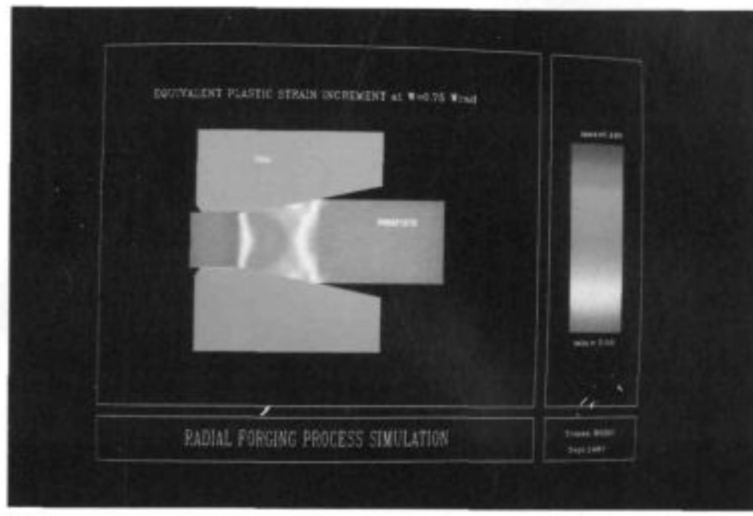
$K_{fo} = 189.5$ N/mm²
$A_1 = 12.997$ $m_1 = 0.00258$
$A_2 = 1.570$ $m_2 = 0.196$
$A_3 = 0.740$ $m_3 = 0.128$

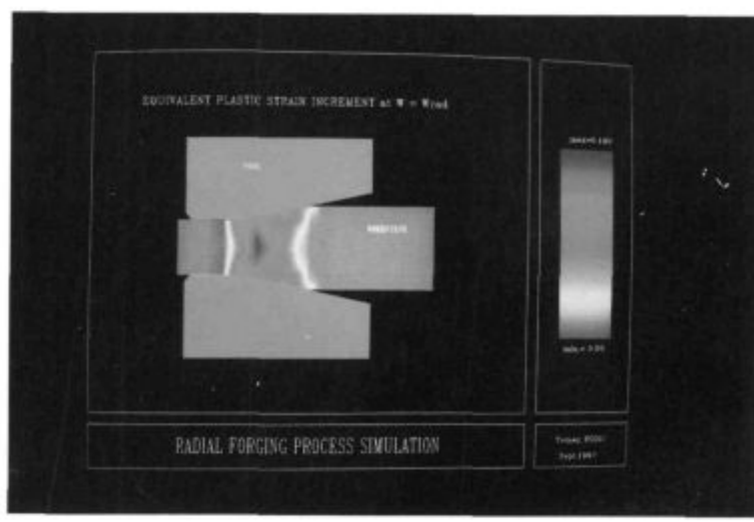
The 8-noded Serendipity axisymmetric elements with reduced (2×2) numerical integration scheme[14] were used. A von Mises yield function with isotropic strain hardening was employed.[4] The nonlinear viscoplastic problem was solved by tangential stiffness solution algorithm. An implicit time integration scheme with the stress correction at the end of each time step was performed.[15] The resulting set of linear equations were solved by the frontal technique.[16]

RESULTS

Figures 7, 8 and 9 show the distribution of the increment of the equivalent plastic strain developed at three positions of the die during one stroke of the forging machine. The distribution and history of the other thermomechanical parameters can be similarly represented. These parameters are temperature and all components and equivalent values of the stress, strain and strain rate tensors. Calculation of forces and energy consumption during the forming process by FEM is more accurate than by classical methods. In many cases the material flow is of great interest. In the forging-rolling production line, for example, the main purpose of the forging machine is to close the internal rupture. Modelling of the closure of an internal rupture in a continuous cast billet by the radial-forging process is illustrated in **Fig. 10**.

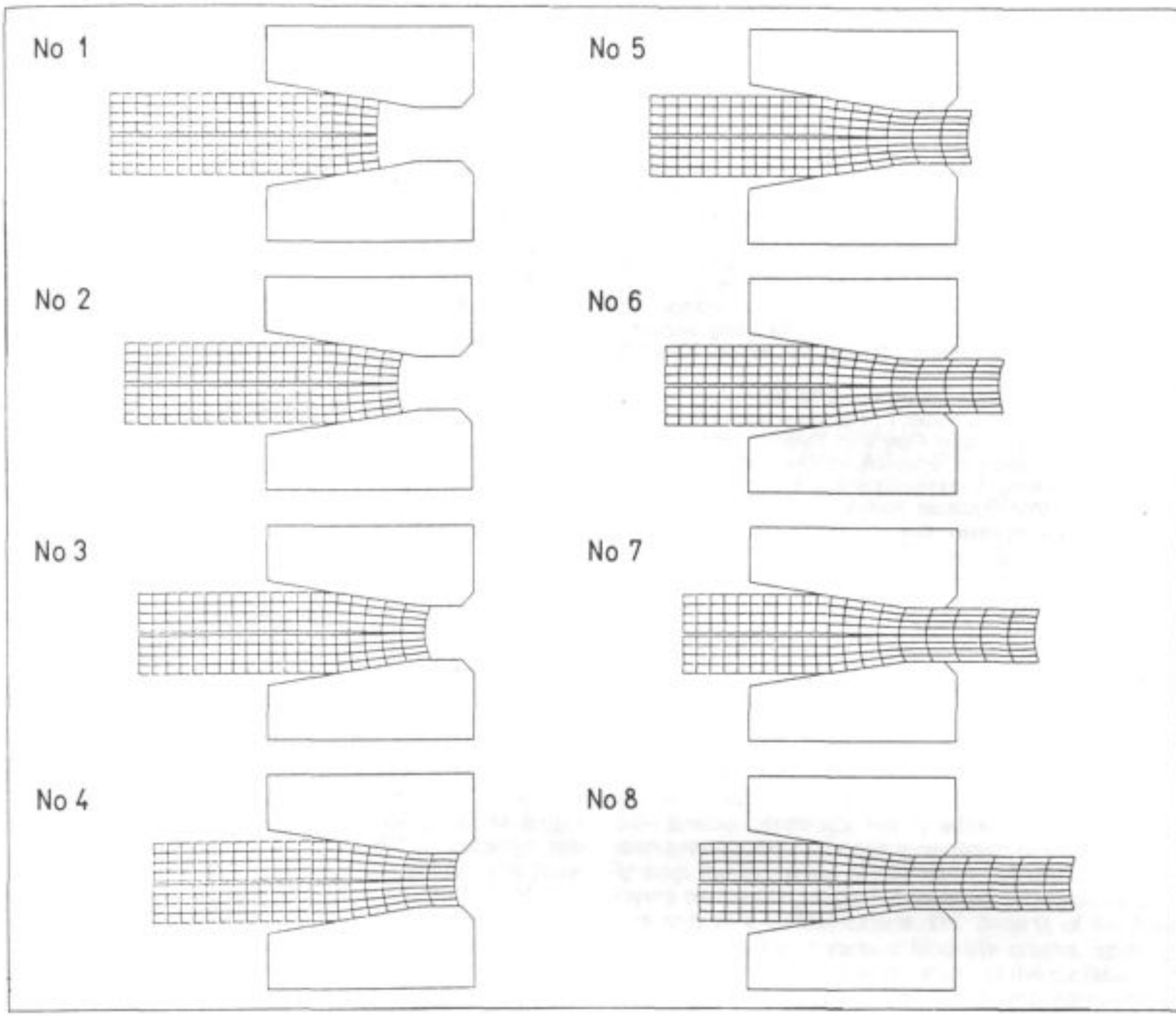






Slike 7, 8 in 9:
Prirastek plastičnih deformacij v preoblikovalni coni med udarcem kladiva.

Fig. 7, 8 and 9:
Increment of the equivalent plastic strain developed at three positions of the die during one stroke of the forging machine.



Slika 10:
Modeliranje zapiranja notranjih odprtin v konti-liti gredici z radialnim kovanjem.

Fig. 10:
Modelling the closure of an internal rupture in a continuous cast billet by the radial-forging process.

7. ZAKLJUČEK

MKE je pogosto uporabljena metoda za analizo preoblikovalnih procesov. V primerjavi s klasičnimi metodami ima naslednje prednosti: z MKE lahko rešujemo primere z zahtevno geometrijo preoblikovanca; problem lahko rešujemo z različnimi materialnimi modeli; možno je obravnavanje nestacionarnih napetostno-deformacijskih in temperaturnih polj. V prihodnje pričakujemo vgrajevanje novih spoznanj s področja fizikalne metalurgije v numerične modele. Prvi koraki v tej smeri so bili že storjeni.[17, 18]

6. CONCLUSIONS

The FEM is now widely used for the analysis of metal forming processes. In comparison with classical methods the FEM has certain advantages: various complex shapes can be considered, it enables implementation of diferent material models and treatment of transient stress-strain and temperature fields. In the future the inclusion of the metalurgical development in the numerical modelling of hot working processes is expected. The first steps toward this goal have already been made.[17, 18]

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