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A MICRO-MACRO ANALYSIS OF THE TOOL DAMAGE IN PRECISION FORMING

MIKRO-MAKROANALIZA POŠKODB ORODJA ZA NATANČNO KOVANJE

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A micro-macro finite-element model for predicting the cyclic stress-strain response and damage evolution in tool-steel materials is presented. The elasto-plastic constitutive model at the macro-scale combines isotropic and kinematic hardening with continuum damage. This permits relatively precise modelling of the critical regions in the tooling systems over a large number of loading cycles. The macroscopic stress-strain fields are coupled with representative volume elements at the micro-level, where interactions between the primary carbides (M_6C, MC, V_8C_7) and the martensitic matrix are evaluated. This provides a detailed insight into the stress-strain fields at the micro-level and reveals the damage mechanisms at the micro-scale. The performance of the model is demonstrated on an industrial example of a tool for the cold precision forming of metals.

Key words: damage, micro-macro, finite element method, tool steels, precision forming of metals

Predstavljen je numerični model za analizo cikličnih napetostno-deformacijskih odzivov in razvoja poškodb orodnih jekel na različnih dimenzijskih skalah po metodi končnih elementov. Makroskopski elasto-plastični konstitutivni model povezuje izotropno in kinematično utrjevanje s poškodbami kontinuuma. To omogoča razmeroma natančno modeliranje kritičnih območij v sistemu orodij za veliko število obremenitvenih ciklov. Makroskopska napetostno-deformacijska polja so povezana z reprezentativnimi volumenskimi elementi na mikroravni, kjer analiziramo medsebojne vplive med primarnimi karbidi (M_6C, MC, V_8C_7) in martenzitno osnovo. S tem dobimo podroben vpogled v napetostno-deformacijska polja in poškodbene mehanizme na mikroravni. Uporabnost mikro-makromodela je prikazana na industrijskem primeru orodja za natančno preoblikovanje kovin v hladnem.

Ključne besede: poškodbe, mikro-makro, metoda končnih elementov, orodna jekla, natančno preoblikovanje kovin

1 INTRODUCTION

The tooling systems applied in production of cold forged components are repetitively subjected to very high loads. Despite of the high strength materials and prestressing applied to die inserts, these loads often cause local plastic deformation of the dies. Even though the plastic deformations caused by each forming cycle are relatively small they accumulate during the production and can eventually lead to the initiation of fatigue cracks. Once a fatigue crack is initiated it can grow and lead to the failure of tooling system. Statistical investigations show that more than eighty percent of cold forging tools fail in this way.

The designers are therefore interested in identifying and optimising those design parameters that have strong impact on the fatigue response of tooling systems. In this work the response is modeled by an elasto-plastic constitutive model, which combines isotropic and kinematic hardening with continuum damage. This permits relatively precise modelling of stress/strain response of tool steels over large number of loading cycles and estimation of accumulated damage. A method for evaluating the sensitivity [1] of damage to material parameters and optimisation [2] can be combined with this approach.

2 CONSTITUTIVE MODEL

The elasto-plastic material model developed by Pedersen [3] is considered. This model takes into account simultaneous evolution of isotropic and kinematic hardening and damage. Since the strains in the tool are expected to be small (<1) an additive decomposition of the strain tensor ε_{ij} into elastic and plastic parts is assumed;

$$\varepsilon_{ij} = \varepsilon^{e}_{ij} + \varepsilon^{p}_{ij} \tag{1}$$

The elastic stress strain relationship is given by

$$\sigma_{ij} = L_{ijkl} \cdot \varepsilon^{e}_{kl} \tag{2}$$

where L_{ijkl} is the tensor of elastic moduli. The summation convention is adopted for repeated indices. It is noted that experimental investigations of tool steel materials do not reveal significant effect of damage on their elastic response. The rate of plastic strain is derived from the normality rule

$$\dot{\varepsilon}^{p} = \dot{\lambda} \frac{\partial f}{\partial \sigma_{ij}} \tag{3}$$

where f is the yield surface and $\dot{\lambda}$ is the plastic multiplier derived from the consistency condition, $\dot{f} = 0$. The flow rule implicitly comprises damage D as follows:

$$f = \tilde{\sigma}_e - (R + k) = 0 \tag{4}$$

where

$$\tilde{\sigma}_e = \sqrt{\frac{3}{2}\tilde{s}_{ij}\tilde{s}_{ij}} \tag{5}$$

$$\tilde{s}_{ij} = \tilde{\sigma}_{ij} - \frac{1}{3}\delta_{ij}\tilde{\sigma}_{kk} \tag{6}$$

$$\tilde{\sigma}_{ij} = \frac{\sigma_{ij}}{1-D} - X_{ij} \tag{7}$$

$$\dot{f} = \frac{\partial f}{\partial \sigma_{ij}}\dot{\sigma}_{ij} + \frac{\partial f}{\partial X_{ij}}\dot{X}_{ij} + \frac{\partial f}{\partial R}\dot{R} + \frac{\partial f}{\partial D}\dot{D} \tag{8}$$

In the above equations X_{ij} is represents kinematic hardening while the scalars R and k describe isotropic hardening.

2.1 Kinematic hardening

The back stress tensor X_{ij} is the centre of the yield surface in stress space, it is defined by the following evolution equations

$$X_{ij} = \sum_{n=1}^{3} X_{ij}^{(n)} \tag{9}$$

$$\dot{X}_{ij}^{(n)} = \frac{2}{3}\gamma^{(n)} X_{mn}^{(n)}(1-D)\dot{\varepsilon}_{ij}^{pl,c} - \left(\frac{X_e^{(n)}}{X_\infty^{(n)}}\right)^{m_n} X_{ij}^{(n)}\gamma^{(n)}\dot{\lambda} \quad \text{and} \tag{10}$$

$$X_e^{(n)} = \sqrt{\frac{2}{3}X_{pq}^{(n)}X_{pq}^{(n)}} \tag{11}$$

2.2 Nonlinear isotropic hardening

The scalar k is assumed to be constant while evolution equation for R is defined by

$$\dot{R} = b(R_\infty(\Lambda, q) - R)\dot{\lambda} \tag{12}$$

where b is a material parameter and $R8(?,q)$ represents the limit of isotropic hardening or softening.

2.3 Continuum damage

Many different evolution equations have been proposed in the literature to describe irreversible damage development. For the industrial example described in this paper the following equation has been applied

$$\dot{D} = \frac{\sigma_e^2\left(\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_{kk}}{3\sigma_e}\right)^2\right)}{2\cdot S\cdot E(1-D)^2}\dot{p}\cdot\alpha(p) \tag{13}$$

where

$$\alpha(p) = \begin{cases} 1, \text{za } p \geq p_d \\ 0, \text{za } p < p_d \end{cases} \tag{14}$$

$$\dot{p} = \frac{\dot{\lambda}}{1-D} \tag{15}$$

$$p_D = \mathrm{Max}(p_{(D=0)}) \tag{16}$$

$$D_C = \mathrm{Max}(D_{(p)}) \tag{17}$$

3 COMPUTER IMPLEMENTATION

The material model has been implemented into a specialised commercial finite element system [4] by using the code development concept [4-6] shown in **Figure 1**.

The symbolic system [5,6] for automatic code generation is based on the *Mathematica* package and allows constitutive models, element formulations and response functionals to be described on a highly abstract level. The formulations are automatically processed by computer, to derive consistently linearised element stiffness matrices, loading vectors and sensitivity terms for either direct differentiation method or adjoint method. From these expressions the computer code is automatically generated for different languages including C and FORTRAN; this code can then be integrated into a finite element environment which performs both direct and sensitivity analyses on a global structural level. An optimisation shell is also build around the finite element software to allow automatic optimisation of design parameters. The interactions between the symbolic system, the finite element environment and the optimisation shell are indicated in **Figure 1**.

4 INDUSTRIAL APPLICATION

The computational model has been applied to multi-scale damage analysis an industrial tool (**Figure 2a**) for production of an automotive precision part [7]. In the first step the macro-mechanical tool loads have been

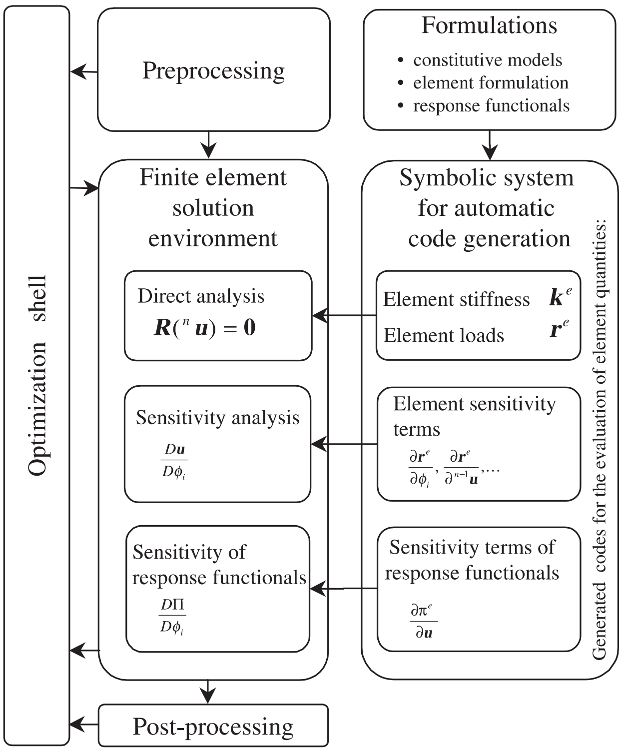

Figure 1: Code development concept
Slika 1: Koncept za razvoj programske kode

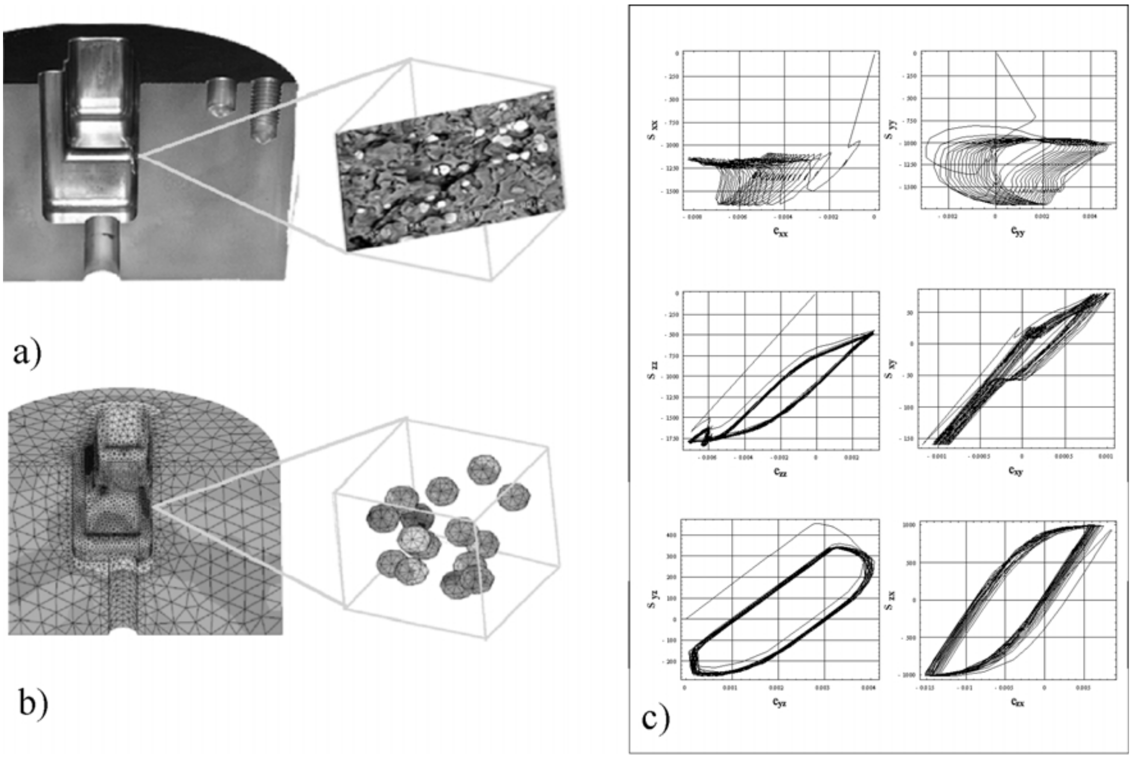

Figure 2: Micro-macro analysis of an industrial tool for cold precision forming of metals: (a) real macro-micro problem; (b) stress fields in virtual FE model at macro and micro levels; (c) cyclic stress-strain response of RVE of tool steel.

Slika 2: Mikro-makroanaliza industrijskega orodja za natančno preoblikovanje kovin v hladnem: (a) relni makro-mikroproblem; (b) napetostno polje v virtualnem MKE-modelu na makro- in mikroravni; (c) ciklični napetostno-deformacijski odziv RVE orodnega jekla

evaluated by the finite element simulation of the forming process. These loads were then repetitively applied to the working surface of the prestressed die insert. In **Figure 2c** the macroscopic stress-strain response of the tool at the most critical location is shown for the first fifty forming cycles. These loading cycles were then mapped to the to the representative volume element (RVE) of a high strength powder metalurgical tool steel in order to evaluate stress-strain fields at the micro level where interactions between spherical primary carbides (M_6C, MC, V_8C_7) and martensitic matrix occur. In **Figure 2b** the stress levels in carbides are shown. The model [8] can be extended to tribological problems where damage and wear of tool surfaces can be evaluated by taking into account stress concentrations due to surface roughness, temperature changes due to dissipation of plastic work and friction, internal stresses at the microstructure due to different thermal expansion of the carbides and the martensitic matrix as well as cooling effects due to the presence of lubricants.

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