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ANALYSIS OF COLD FORGING PROCESS BY ADAPTIVE FEM METHOD

Saša Ranđelović[1], Friedrich Krumphals[2], Miloš Jovanović[1], Dejan Tanikić[3], Dalibor Đenadić [3]

[1]University of Nis, Faculty of Mechanical Engineering, Nis, Serbia
[2]Graz University of Technology, Austria
[3]University of Belgrade, Technical Faculty in Bor, Serbia

ABSTRACT

In this paper is presented implementation of adaptive finite element method in real conditions of plastic deformation during cold forging process simulation, with observing of the characteristic areas in stress-strain field in tool cavity, as well as material displacement. The researches and development of this methods and their application in non-linear solid mechanics in last decade are focused on creating the most suitable algorithm model for analyze for concrete forming process. These efforts resulted in flexible and adaptable numerical methods which allow following deformation process through observing of material flow, stress-strain state and many other process parameters for very complex predefined conditions. The analyses and results of this numerical model that approximate real-state forming process with a high level of accuracy is a great advantage of this methods, especially in case of solving problems with large boundary motion in non-linear solid mechanics, for instance, in bulk forging technology.
Key words*: Forging technology, ALE formulation, mesh distortion,*

1. INTRODUCTION

An early attempt on creating realistic numerical model of liquid fuel motion in nuclear reactor, with a simultaneous progress of computer method, led to research and development of many different numerical descriptions and FEM methods for solving problems in field of non-linear solid mechanics. Finally, some of these methods, due their similarity, founded application in simulations of metal forming processes.

The classical methods, the pure Lagrangian and the pure Eulerian methods, are usually employed in continuum mechanics. Because of the shortcomings of these methods, such as element entanglement during material distortion in application of Lagrangian method, and convective effects accompanied with requiring a sophisticate mathematical mappings that follows application of Eulerian method, the new approach, which tries to combine the good characteristics of both methods, and in the same time excludes their disadvantages, were developed [1,4].
The arbitrary Lagrangian-Eulerian (ALE) method is based on the arbitrary movement of reference frame, which is continuously rezoned in order to allow a precise description of the moving interface and to maintain the element shape. This method unites a precise definition of the moving boundaries and interfaces without appearing of convective effects from Lagrangian method, with advantage of strong element distortion possibilities from Eulerian method [1,2,3,4].
The ALE method and other approaches used to treat non-linear path - dependent materials need an implicit interpolation technique, which implies a numerical burden which may lead to uneconomically process, especially in fast-transient dynamic analysis. In comparation to classical Lagrangian method, the ALE method is much more competitive if adequate stress updating technique is implemented. In opposition to the classical methods, where distorted and locally coarse mesh may occur, ALE method shows greater level of adaptivity and adequate meshes with regular shaped elements.
The main challenge for the non-linear FEM methods applied on solid mechanics problems is precise numerical description of boundary conditions in both cases – the free boundary and contact boundary conditions. In the same time, one of the goals is tendention to minimize time costs by avoiding too frequent remeshing during simulation.
The methods used to treat non-linear path-dependent materials usually need an implicit interpolation technique, implies a numerical burden which may be uneconomical, particularly in fast-transient dynamic analysis of solids, where explicit algorithms are usually employed.

2. GOVERNING EQUATIONS IN THE ALE METHOD

The configuration of a continuous medium under motion can be presented by the same material points, and this configuration may change with time. The motion is described by one-to-one mapping relating the material point, X, in its initial position with its actual position, x, at the moment of time, t:

$$d = x(X,t) - X \tag{1}$$

The mapping conditions require that Jacobian $J = \det\left[\frac{\partial x_i}{\partial X_j}\right]$ is non-vanishing.

The computational frame in the ALE description is a reference independent of the particle motion and it may be moving with an arbitrary velocity [2,3,4].
Material velocity, v_i is defined by:

$$v_i = \frac{\partial x_i}{\partial t}\Big|_x \tag{2}$$

and mesh velocity :

$$\hat{v}_i = \frac{\partial x_i}{\partial t}\Big|_{\chi} \tag{3}$$

If the physical property is the spatial coordinate x yield:

$$v_i = \hat{v} + w_j \frac{\partial x_i}{\partial \chi_j} \tag{4}$$

or :

$$c_i = v_i - \hat{v}_i \tag{5}$$

where is:

$c_i = w_j \dfrac{\partial x_i}{\partial \chi_j}$ - convective velocity

w - material velocity in the reference system,

c - relative velocity of the mesh according reference model.

The relationship between the material time derivative, the referential time derivative and the spatial derivative:

$$\frac{\partial f}{\partial t}\Big|_{x} = \frac{\partial f}{\partial t}\Big|_{\chi} + c_i \frac{\partial f}{\partial x_i} \tag{6}$$

The conservation laws that govern the motion of the continuum in ALE description are written as:
Continuity equation:

$$\frac{\partial \rho}{\partial t}\Bigg|_{\chi} + c_j \frac{\partial \rho}{\partial x_j} = -\rho \frac{\partial v_j}{\partial x_j} \tag{7}$$

Momentum balance equation :

$$\rho \frac{\partial v_i}{\partial t}\Big|_{\chi} + \rho c_j \frac{\partial v_i}{\partial x_j} = \frac{\partial \sigma_{ij}}{\partial x_j} + b_i \tag{8}$$

Energy conservation:

$$\rho \frac{\partial e}{\partial t}\Big|_{\chi} + \rho c_j \frac{\partial e}{\partial x_j} = \sigma_{ij} \frac{\partial v_i}{\partial x_j} + \rho a - \frac{\partial}{\partial x_i}\left(k_{ij} \frac{\partial \theta}{\partial x_j} \right) \tag{9}$$

where is : ρ - density ; σ - Cauchy stress tensor; θ- thermodynamic temperature; b- body force per unit of volume; e - specific internal energy, a – work of internal force; k - thermal conductivity tensor [1].

The right hand side of ALE conservation laws equations is written in classical Eulerian form, and the arbitrary motion of the mesh is presented on the left hand side.
The purpose of using material time derivatives, referential time derivatives and spatial derivatives in the same equation is to relate Cauchy stresses and thermal conductivity with conservation laws.

2.1. Boundary conditions

One of the main applications of the adaptive FEM methods, as well as ALE method, is large boundary motion problems which are directly related with a momentum equation. It is usually assumed that values of velocities and heat flux or temperature are given. The velocities vary with time and extra equation is needed to determine (the unknown position of the free surface).
In the ALE formulation are employed the same boundary conditions used in Eulerian and Lagrangian descriptions because boundary conditions depend on concrete problem configuration and not the applied method. Along the domain boundaries must be defined kinematic and dynamic conditions. Usually this is presented as:

$$v_i = g_i \ in \partial R_x^g \tag{10}$$

$$\sigma_{ij} n_{xj} = h_i \ in \partial R_x^h \tag{11}$$

where g and h are given boundary velocity and pressure, respectively, n_x is the outward unit normal to ∂R_x and ∂R_x the piecewise smooth boundaries of spatial domain R_x ([4], [5]).

Cauchy stress tensor is defined as a function of temperature, density and velocity fields:

$$\sigma = s(\theta, \rho, v) \tag{12}$$

While its material time derivative by means of stress field and knowledge :

$$\frac{\partial \sigma}{\partial t}\Big|_{x} = r(\theta, \rho, v, \sigma) \tag{13}$$

Any of the commonly used constitutive equations can be written in the previous manner. Therefore, the application of such models is moving in a wide range of problems of deformation of solids, from small deformation linear elasticity in the area, to large deformations in viscoplasticity. For example, any plastic material can be defined as to behave as follows:

$$\frac{\partial \sigma_{ij}}{\partial t}\Big|_x = \Delta\sigma_{ij}^c + W_{ik}\sigma_{kj} + \sigma_{ik}W_{kj} \tag{14}$$

where is: $\Delta\sigma_{ij}^c$ the objective or real increase of stress and represent part of the actual stress σ due to the deformation of material - "pure strain", eg.:

$$\Delta\sigma_{ij}^c = C_{ijkl}v_{(k,l)} \tag{15}$$

where C is reaction of material which depend from stress σ, $v_{(k,l)}$ is velocity components of extension tensor $v_{(i,j)} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$.

Generalization of viscoplastic materials commonly used by defining a yield surface and assuming that the strain rate can be linearly divided into elastic and plastic components. It is important to note that hardening rule explicitly defines the evolution of yielding surface is usually written in incremental form.

The remeshing techniques are concerning with the definition of mesh velocity $\hat{v}$, for example, if $\hat{v}$ = 0 using Euelerian method and but if $\hat{v} = v$ using Lagrangian method. Evidently that trying to find the best choice for applied description of material and mash velocity, and a low cost algorithm for updating the mesh constitute represent main task of ALE method.

There are two cases of boundary conditions. The first assumes that all domain boundaries have a known position at every instant which include Euler's internal and external boundaries of the flow, with prescribed movement of material surfaces and solid-wall boundaries. The second refers to the unknown free surface at the boundary of the domain (or generally the material surface) and will be reduced to the previous position when the free surface is known. These equations is used for surface identified as Lagrange, $c = w = 0$ is useful for solving problems of structural mechanics problems.

3. COLD FORGING SIMULATION OF VALVE HOUSING

Analysis of metal plastic deformation by finite element method and its results largely depend on the choice of software package in which it is performed, and the choice of mathematical models that describe the specific problem. The results of such a complex analysis depend on the scope and accuracy of entering a large number of parameters of real processes.

One of the more complex examples of successive volume of cold forging technology, in four phases, is shown in the figure below. Steel cylindrical phosphate workpiece, AISI 1010, weighing 29 g, you get the valve body (Fig. 1).

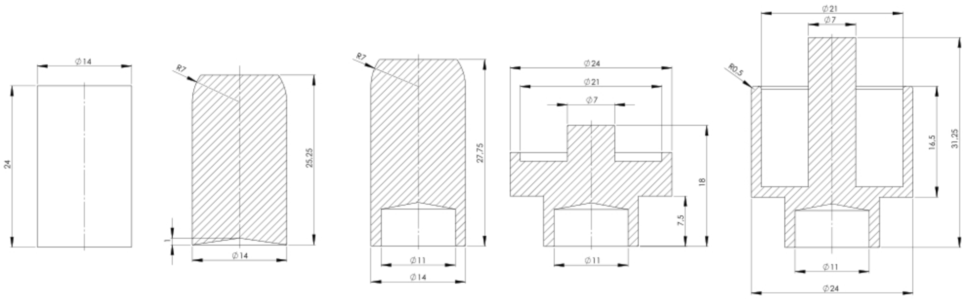


Fig. 1 - Forging workpiece and final part after four operations

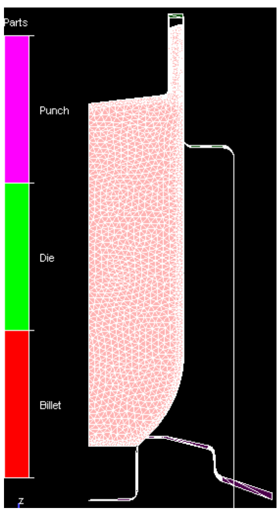


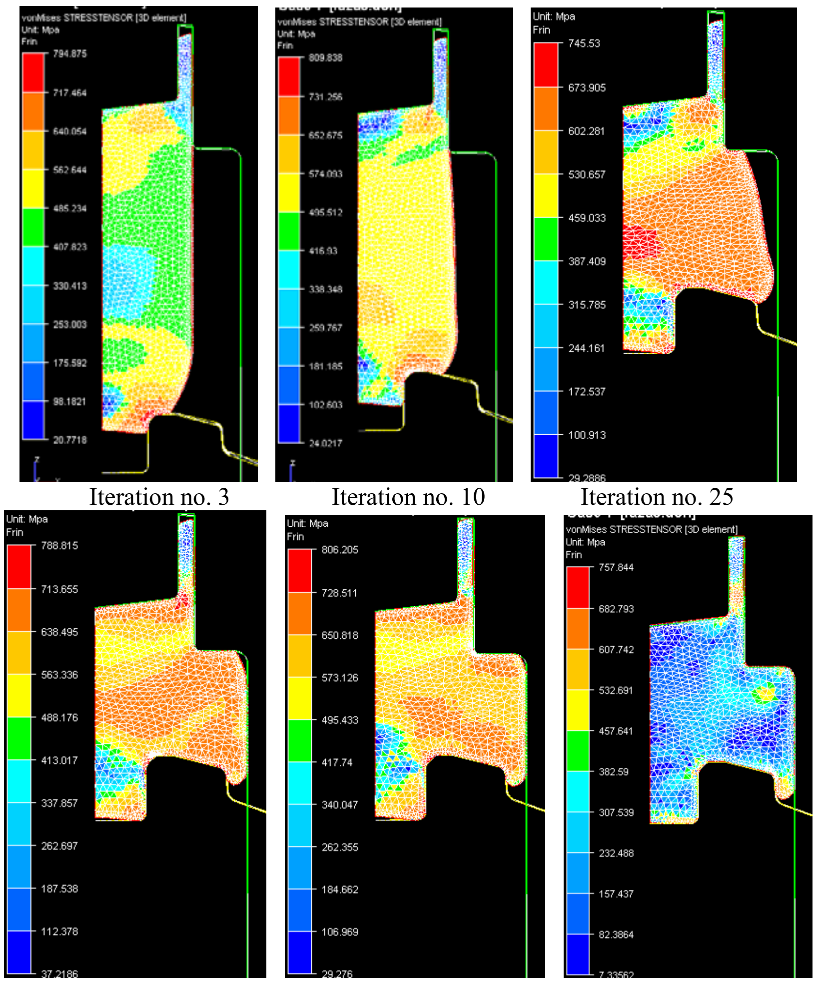
Fig. 2 - Model of workpiece at start forging process on third stage with grid of tetrahedral finite elements

The first phase include the initial forming of workpiece where it does not get any final geometry of the finished work but it gets the final contours of technology for the next stage of forging. After entering the tool geometry and model of workpiece for the third phase, and their mutual positioning gives the initial configuration for the third phase forging (Fig. 2).

Especially in the third stage of forging will come to the fore the accuracy of the spherical surface to enable better contact with the tool to the material flowed in the right direction [5,6] (Fig. 2).

When analyzing the current state of the field displacement in x direction shows the extreme values in the radial direction while the field displacement along z direction shows a maximum at the contact surfaces of the bottom tools. At this point exist parts of volume continuum who have suffered the largest plastic deformation that is where the greatest stresses on the criterion of von Mises-a. This field clearly indicates the the parts of volume through which only transfers the deformation force and the parts of volume which intensively deforms in the radial direction.

Immediately after 25 iterations followed by a moment of termination of the free radial flow within the mold cavity continuum and the more intensive material flow in the direction of relative movement of the upper tool. This will get the most remote parts of the volume of its contours and geometry of the finished part in the third phase forging. If the observed trends mentioned it is the forward or the backward extrusion continuum within tools at very high degrees of deformation (iteration 40). A more detailed analysis of the process and outlines the tools suggests that it is actually a backward extrusion process where there is a small tool cavities accomplish due to very high pressure on the frontal surface of the tool (fig. 3). While the highest volume of parts already obtained in the second phase of forging, it would now only got slightly more of their height, the point at the bottom of the tools is just beginning the formation of thin parts by volume (iteration 40). Adaptive finite element mesh adaptation coming to the fore in order to accurately simulate flow through narrow channels (iteration 80) without significant change of the outer contour. Only iteration almost 120 shows the end state when it is a very small part of the remote volume remained unfilled.



Iteration no. 3 Iteration no. 10 Iteration no. 25

Iteration no. 40 Iteration no. 80 Iteration no. 120

Fig.3 - Continuum flow in the third phase and the von Mises stress field

The case of unknown free surface is reduced to one where all the domain boundaries are fixed or given prescribed motion. The continuous generation of new mesh - remeshing is fully defined when the mesh velocity $\hat{v}$ is given within the domain.

This can be done by simple ad-hoc formula, solving equations of potential that maintain element regularity or any other mesh generation algorithm to conserve the element connectivity. Most of these remeshings method are based on defining the new position of nodes (Fig.4), and then calculate mesh velocity by finite difference aproximation [7,8,9,10,11].

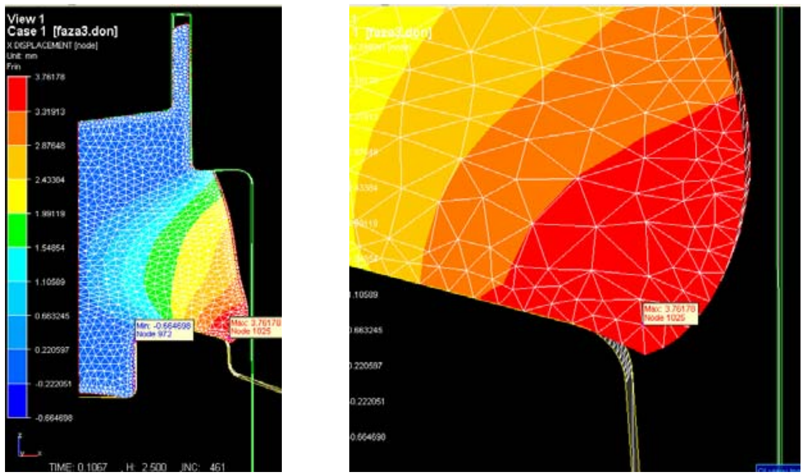


Fig.4 - Meridian cross section of workpiece and a die during deformation process with locally refined mesh presented on x direction

4. CONCLUSION

The overall impression of the ALE method, which was presented here show the applicability and effectiveness of this method to solve the problem of continuum mechanics. This method increases the main advantages of the finite element method for modeling complex geometries and boundary conditions of surfaces. It allows a smooth and easy processing and closing of borders and boundaries with a moving free surfaces, and excellent flexibility in the movement generated mesh model. The result is a very flexible modeling method that allows adjustment of high distortions of the continuum and moving boundary surface, computational efficiency (in terms of computational cost of data processing simulation), and numerical modeling of precision especially in the functions of copying material surfaces, and interpolation along the enrichment of specific areas.

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ANALIZA PROCESA HLADNOG KOVANJA POMOĆU ADAPTIVNOG POSTUPKA METODE KONAČNIH ELEMENATA

Saša Ranđelovic[1], Friedrich Krumphals[2], Miloš Jovanović[1], Dejan Tanikić[3], Dalibor Đenadić [3]

[1]Univerzitet u Nišu, Mašinski fakultet, Niš, Srbija
[2]Tehnološki univerzitet Grac, Austria
[3]Univerzitet u Beogradu,Tehnički fakultet u Boru, Srbija

REZIME

U ovom radu je predstavljena implementacija adaptivnog postupka metode konačnih elemenata u realnim uslovima plastične deformacije tokom simulacije procesa hladnog kovanja, sa praćenjem karakterističnog područja naponsko-deformacionog stanja u šupljini alata, kao i toka materijala. Istraživanja i razvoja ovog metoda i njihova primena na nelinearne probleme mehanike čvrstog tela, u poslednjoj deceniji su fokusirani na formiranje najpogodnijih algoritama za analizu konkretnih procesa oblikovanja. Ovi napori su rezultirali razvojem fleksibilnih i adaptivnih numeričkih metoda koje omogućavaju praćenje procesa deformisanja kroz posmatranje toka materijala, naponsko-deformacionog stanja i mnogih drugih parametara procesa sa veoma kompleksnim predefinisanim uslovima. Analize i rezultati ovog numeričkog modela koji aproksimira realne uslove procesa deformisanja sa visokim stepenom tačnosti veoma su bitni, posebno u slučaju rešavanja nelinearnih problema sa velikim graničnim pomeranjim u mehanici čvrstog tel, kao što je npr. slučaj pri zapreminskoj obradi deformisanjem.

Ključne reči: *Tehnologija kovanja, ALE formulacije, mesh distorzija*