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# ANALYSIS OF HOT EXTRUSION OF ALUMINIUM ALLOY BY NONLINEAR FEM CODE

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## ABSTRACT

*The process parameters and size of characteristic plastic values in aluminium hot extrusion technology are key points that influence product properties. The values in the temperature filed, the strain rate, elements of stress tensor of aluminium alloy AA6005 is investigated according to different process conditions. The software simulation was accomplished in the commercial FEM package FORGE2008 to calculate both the scalar values evolution as well as the tensor values during the forward extrusion process.*
***Key words:*** *Hot extrusion, FEM, Stress strain analysis, Strain rate*

## 1. INTRODUCTION

It is known that the product properties of hot extrusion technology are closely correlated to the extrusion parameters like the extrusion ratio, the extrusion speed, the initial temperature of the billet, container and die, the microstructure and purity of aluminium alloy, geometry and quality of tool surfaces and the die configuration and etc.[1].
In this paper investigation which aim is to obtain optimal parameters in hot extrusion is described.
In current investigation the billet is aluminium alloy, AA6005 or chemical compound AlMgSi0.6Cr on the working temperature 450°C.
The friction coefficient was defined according Coulomb law with strong heat exchange on the contact surface with tool wall (Fig. 1). The billet model was represented by finite element mesh with basic cell size 2.25 on the majority part of volume without plastic deformation and finest mesh, 1.2, of the finite elements in the area of strong plastic deformation where expect and formed dead metal zone of flowing material is expected.

The logarithmic degree of deformation is φ = 2.64, from begin full cross section, with diameter 45 mm to finish full cross section, with diameter 12 mm. This process represents axe-symmetrical deformation state with analysis on the part of deformable volume with normal vectors on the meridian boundary plane (Fig. 2). The moving part of toll is the upper tool or pusher with constant velocity 7 mm/s.

Hence it is important to consider the influence of the process conditions on the evolution of structure, such as the homogenization treatment both to dissolve particles that are detrimental to the materials formability and to spheroidize plate like particles, respectively [2,3]. Moreover, the initial microstructure of the billet and extrusion parameters like the extrusion speed, the initial temperature of the billet, container and die, the extrusion ratio, quality of tool surfaces and the die configuration control the materials hardening and softening as well as the substructure evolution during extrusion, which has a great effect on the final grain structure [4,5].

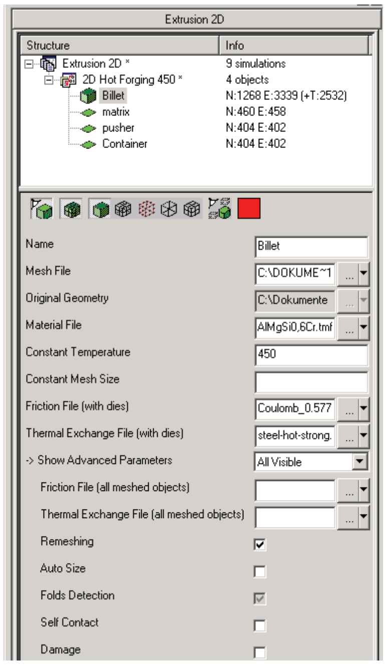


*Fig. 1- Input parameters*

In general the finished parts should have uniform mechanical properties through the thickness and along the length with no surface flaws such as tearing, die lines and coarse grains. These surface imperfections would affect processes like anodising, possibly leading to product rejection. The traditional way to control these properties is the application of empirical knowledge of their complex relationship with forming parameters and metallurgical response. However, there are commercial finite element model (FEM) codes, which can be coupled with sound microstructure models [4,5]. Controlling the substructure evolution during processing and hence the recrystallization kinetics is a challenging and demanding task for the aluminium extrusion industry.

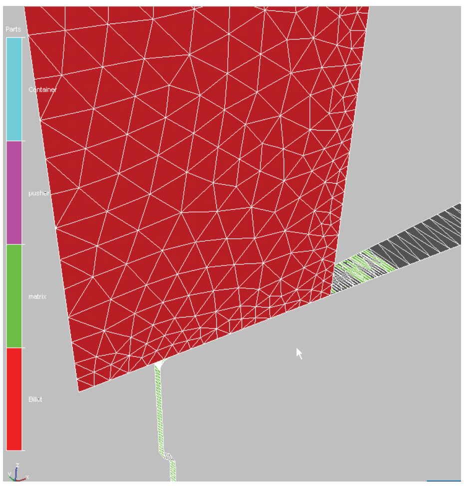

*Fig. 2 - Axe symmetric part of the billet and the die*

## 2. MODELLING AND SIMULATION

A software FEM package FORGE2008®TRANSVALOR was used to simulate the forward extrusion of hot aluminium alloy with solid sections. As a reason of the high extrusion ratio, a high deformation degree occurs with variable friction coefficients, temperature changes and variable stress and strain rate values (Figs. 2, 3). The data structure of the program includes the governing equations, the mesh of the billet, the rheology of the material, the tool description, the frictional interface and the numerical parameters [6].

In the part $\Omega$, when inertia and body forces are neglected, the equilibrium equations is written [6]. On the boundary, a zero stress vector is imposed on the free surface $\partial\Omega_s$ and on the interface $\partial\Omega_c$ between the part and the tool, the non penetration constraint is imposed, in addition to the friction law, when the normal stress is compressive:

$$v_s \cdot n = 0 \quad \text{if} \quad (\sigma \cdot n) \cdot n < 0 \tag{1}$$

For any virtual velocity field $v^*$ and the associated virtual strain rate tensor $\dot{\varepsilon}^*$, the rate form of the virtual work principle is written:

$$\int_{\Omega} \sigma : \varepsilon^* dV - \int_{\partial\Omega_c} \tau \cdot v^* dV = 0 \tag{2}$$

which must be associated with the incompressibility condition:

$$div(v) = 0 \tag{3}$$

and non penetration condition (1). An accurate way to impose all these conditions is to use the mixed velocity-pressure formulation, which is given for any virtual (*) velocity field $v^*$ and any pressure $p$:

$$\int_{\Omega} s : \dot{\varepsilon}^* dV - \int_{\partial\Omega_c} \tau \cdot v^* dS - \int_{\Omega} p\, div(v^*)\, dV = 0, \tag{4}$$

where $s$ is the deviatoric part of stress tensor, $\dot{\varepsilon}^*$ the local strain rate tensor, $dV$ the element of volume deformation, $dS$ the element of contact surface between tool and billet and $\tau$ denotes the tangential stress on the contact zone. The weak form of the incompressibility constraint results in:

$$\int_{\Omega} p^* div(v) dV = 0, \tag{5}$$

where $p^*$ is the virtual pressure. The program uses implicit FEM to calculate the hot working parameters: load, strain rate, temperature field and deformation. A Lagrangian method is adopted for the program, which can thus accurately define the material properties, state variables and boundary conditions.

The remeshing values are controlled by the average target size of an element and the sharing is specified by mesh-boxes, i.e. boxes that define regions of the mesh on which a mesh size is imposed during the computation.

The simulation approach is based on a viscoplastic constitutive model, which neglects the elastic behaviour of the metal in working process.

The meshing is based on two concepts: the quality of the elements and the shape geometry. During the simulation of forward extrusion, large deformations are predominant which require a Lagrangian mesh to be defined. Thus, complete remeshing is mandatory in areas of excessive deformation of volume.

In this section the results of nonlinear FEM analysis with characteristic values of forward extrusion process on higher temperature for aluminium alloy is described.

The temperature field in the meridian cross section of the billet, from 314.349°C to 450.591°C on contact surface with tool die and container indicates their interaction and the heat transfer from billet to tool parts (Fig. 3). In the area near transfer radius on matrix, the temperature field, in the plane of deformable volume, was represented with three characteristic point on the input of deformation zone, at node 582 (388.22 °C), in the deformation zone, at node 604 (407.061 °C) and the outlet zone, at node 606 (424.371 °C) with central temperature of billet on the level of begin temperature and colder volume of billet near contact surface.

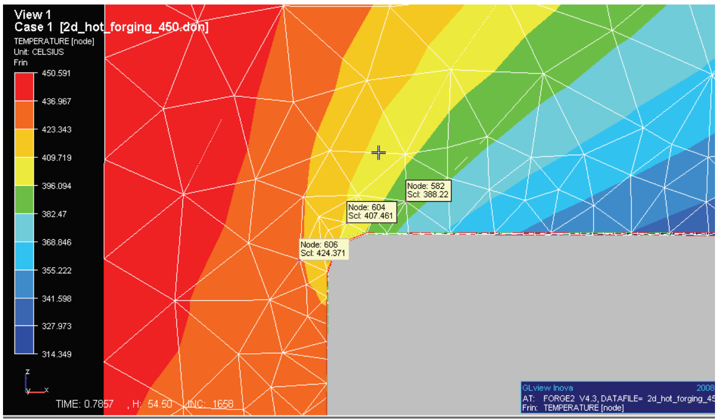


*Fig. 3 - The temperature field represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The strain rate is one of the most important parameters, which illustrates the continual plastic deformation and the quality of the finished part (Fig. 4). In this investigation the transfer radius of tool has a value of 1 mm, which decisively influences the field of strain rate [7], with values from 6.407$s^{-1}$ (node 582) on input of deformation zone, in the deformation zone, at node 604 (24.095 s-1), and the outlet zone, at node 606 (14.21 s-1).

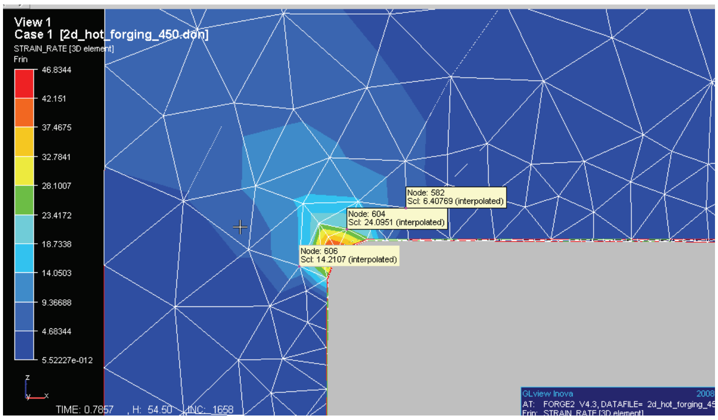


*Fig. 4 - The strain rate field represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The field of xx stress tensor components (Fig. 5), in the same points of the plane of deformable volume, near transfer radius on lower tool or matrix, indicate on total compress with small extension at the outlet cross section, the input of deformation zone, at node 582 (-141.618 MPa), in the deformation zone, at node 604 (- 97.895 MPa) and the outlet zone, at node 606 (-54.111 MPa).

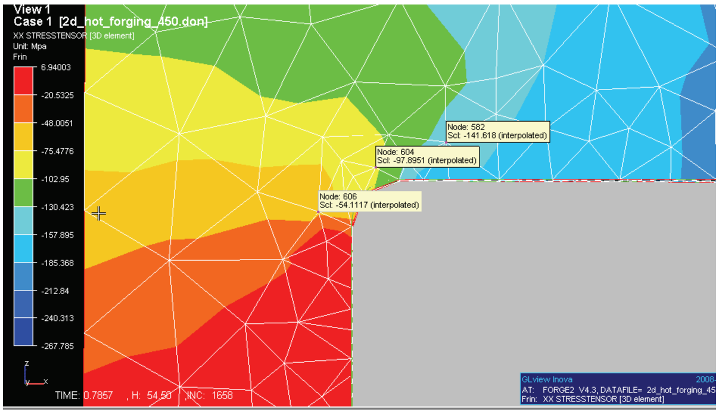


*Fig. 5 - The field of xx stress tensor represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The field of yy stress tensor components (Fig. 6), in the same points of the plane of deformable volume, near transfer radius on lower tool or matrix, indicate on similar distribution, at the input of deformation zone, at node 582 (-194.558 MPa), in the deformation zone, at node 604 (- 122.439 MPa) and the outlet zone, at node 606 (-29.624 MPa).

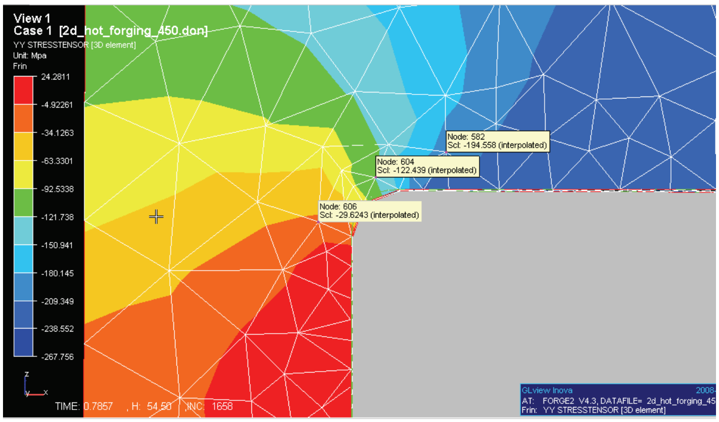


*Fig. 6 - The field of yy stress tensor represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The field of zz stress tensor components (Fig. 7), in the same points of the plane of deformable volume, near transfer radius on lower tool or matrix, indicate on biggest stress of compress and very small field stress of extension, on the input of deformation zone, at node 582 (-217.966 MPa), in the deformation zone, at node 604 (- 123.59 MPa) and the outlet zone, at node 606 (16.067 MPa). The high change of the zz stress tensor component in the meridian cross section indicates the noncontinual stress distributions near transfer die radius.

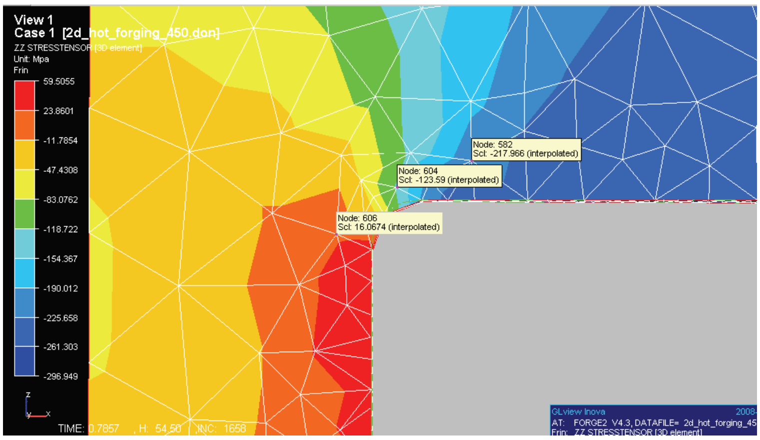


*Fig. 7 - The field of zz stress tensor represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The field of von Mises stress tensor components (Fig. 8), in the same points of the plane of deformable volume, near transfer radius on lower tool or matrix, specify distributions of plastic stress on the input of deformation zone, at node 582 (75.016 MPa), in the deformation zone, at node 604 (87.976 MPa) and the outlet zone, at node 606 (70.307 MPa) [12].

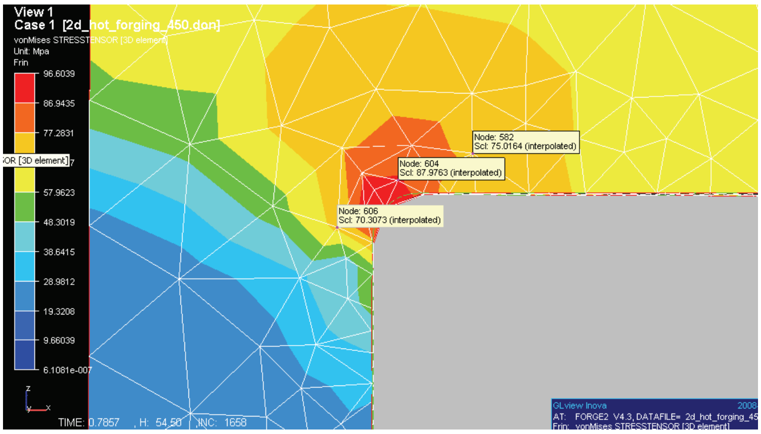


*Fig. 8 - The field of von Mises stress tensor represented by mesh of tetrahedral finite elements in the area of plastic deformation*

The extrusion simulation was performed to achieve the local process conditions temperature and strain rate, which are input parameters for the physically based microstructure evolution model. This model, based on contemporary understanding of microstructure evolution and the interaction

of dislocations with microstructure essentials, gives a reasonable description of the hardening behavior and accounts adequately for changes of material chemistry, in particular for age-hardened alloys.
The used three-internal-variables model (3IVM) consists of a kinetic equation of state and a set of equations for the substructure evolution (mobile dislocations, immobile dislocations in the cell interiors and immobile dislocations in the cell walls) [8,11]. To predict recrystallization, the 3IVM is coupled with a model describing static recrystallization [9,10]. If the stored deformation energy increases by generating dislocations and if the dislocation density gradient exceeds a critical value at preferential locations like grain boundaries, triple junctions or particles (>1µm), the material starts to recrystallize.

## 3. CONCLUSION

A nonlinear FEM simulation of an aluminium alloy extrusion process was performed to obtain process parameters, which influence on quality of finished part. Furthermore a mechanical based model was introduced, in order to change characteristic of the real parts of tool and process parameters. Namely, the combination of all theoretical approaches, results of nonlinear simulation and experience from real process enables a sound prediction and solutions for new technology tasks.

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# TEHNOLOGIJA TOPLOG ISTISKIVANJA LEGURE ALUMINIJUMA NA OSNOVU NELINEARNE FEM ANALIZE

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## *REZIME*

Parametri procesa i vrednosti karakteristika plastičnosti po zapremini pripremka kod tehnologija istiskivanja aluminijuma su ključni faktori koji utiču na karakteristike proizvoda. Predmet istraživanja su vrednosti u temperaturnom polju, brzina deformacije, vrednosti tenzora napona legure aluminijuma AA6005 za različite uslove procesa. Softverska simulacija je realizovana pomoću FEM paketa FORGE2008 kako za proračun promene skalarnih veličina tako i tenzorskih veličina u toku procesa istosmernog istiskivanja.
***Ključne reči:*** *Toplo istiskivanje, FEM, Naponsko deformaciona analiza, Brzina deformacije*