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FINITE ELEMENT ANALYSIS OF EQUAL CHANNEL ANGULAR PRESSING OF Al-Mg 5083 ALLOY

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ABSTRACT

Bulk nanostructured materials represent the application of nanotechnology in the engineering material area. Severe Plastic Deformation (SPD) and in particular Equal Channel Angular Pressing (ECAP) are efficient and low cost top-down methods for producing ultrafine or nanostructured bulk materials. Alluminum alloys are very popular materials used for production of ultrafine-grained and nanomaterials by SPD. Understanding both the contact phenomenon at the interface between die and the workpiece in terms of material flow and phenomena associated with strain and forming load in ECAP process becomes important. In this paper, a tridimensional Finite Element Analysis of ECAP was performed for Al-Mg 5083 alloy.

KEYWORDS: severe plastic deformation, equal channel angular pressing, alluminum

1. Introduction

Materials with ultrafine – grains (UFG) or nanometric structures (NS) offer significant advantages in terms of large strength, hardness and ductility or high strain rate superplasticity [1]. They have great impact in biomedical, electronics, military, aerospace, and automotive. Industries and academics have shown great interest in fabrication of NS materials with high performance to weight ratio such as Al, Mg, Al-Mg etc.

Wrought non heat-treatable Al-Mg alloys are attractive for different components due to their good weldability, moderate strength, but excellent corrosion resistance. Increasing strength by SPD without any supplementary alloying is a convenient way to raise up the potential of the material while maintaining all other mechanical properties. At the same time, developing superplasticity, the material reaches ultrafine structure with reasonable thermal stability, without the presence of secondary phase due to special alloying elements. In these conditions, there is considerable interest in using Al-Mg alloys for structural applications.

Among various techniques developed to obtain UFG materials [2], the Equal Channel Angular Pressing (ECAP) is one of the most effective processes. Fig. 1 shows a schematic principle that outlines the important geometric factors of the ECAP process [3].

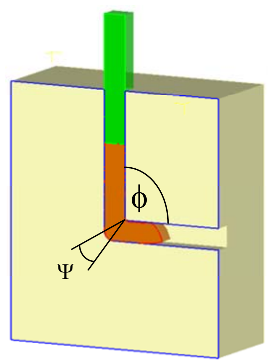

Fig. 1. *Principle of ECAP and die geometry components.*

In ECAP, a billet is pressed through a die that contains two equal cross-sectional channels. In the vertical channel, the billet moves as a rigid body while all deformation is localized in the small area around the channel’s meeting line (the bisecting plane). The metal is subjected to a simple shear strain under relative low pressure compared to the traditional extrusion process [3]. Because the cross-section of the billet remains the same during extrusion, the process can be repeated until the accumulated deformation reaches the imposed level.

The billet removal involves a new development of ECAP procedure. The introduction of a new sample returns the ECAP process to the initial configuration which permits the next pressing cycle to follow. The new sample is inserted and pressed from the top and the previous sample moves to the right trough the horizontal channel of die.

As the microstructures and the mechanical properties of the plastic-deformed materials are directly related to the degree of plastic deformation, the understanding of the strain and stress development is very important in a successful ECAP process design. The theoretical effective strain according to the die geometry is given in Eq. (1), as formulated by Iwahashi et al. [4]:

$$\bar{\varepsilon} = \frac{1}{\sqrt{3}}\left[2\mathrm{ctg}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi\,\mathrm{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] \quad (1)$$

where the significance of terms are revealed in Fig.1. For $\phi = 90°$ and $\psi = 0$, an equivalent strain of 1.15 is achieved. Note that Eq. (1) was derived for ideal perfect-plastic behavior and frictionless conditions.

From the technological point of view, a successful SPD process requires to surpass two obstacles. First the load level (which directly affects the tool design) and second an adequate formability of the material so that it can withstand high degrees of repeated deformation. Unfortunately there are no criteria which ensure a guaranteed successful SPD of the material. Only a favorable stress distribution can decide the success of SPD.

Designing both processing and tools needs to take into account the deformation behavior of the billet in combination with effects of strain hardening, friction and die geometry. In this paper, a tridimensional FEA is performed to analyze the ECAP process of Al-Mg 5083 alloy. The purpose of FEA is to evaluate load level, strain and stress distribution during severe plastic deformation in order to successfully pursue the future ECAP processes.

2. Experimental approach and procedures

2.1. Finite Element Analysis

To carry out the simulation, commercial finite element code DEFORM was used. The workpiece (10x10x60mm) consisting a plastic body in whole deformation process was discretized in 8000 tetrahedral elements (this is equivalent to at least 36 elements across the width of the billet). The tolerance, positioning of the workpiece and top/bottom die, convergence criteria, re-meshing conditions, and boundary conditions were specified before the execution of the simulation process.

Adaptive meshing was used in the simulation. Poisson's ratio 0.33 and Young's modulus 69GPa were assumed.

The hardening behavior is considered isotropic and independent of strain rate at room temperature. The simulation was performed at room temperature for a stroke of about 50 mm under a constant speed of 8.75 mm/s.

The friction force along contact surfaces was modeled by constant shear friction law $F_r = m \cdot \tau_o$ where τ_o is the yield stress in shear and m = 0.12 is the friction coefficient [5].

The die considered for analysis corresponds to high strength hardened steel with the channel angle $\phi = 90°$ and outer corner radius of 2 mm which means $\psi \approx 12°$.

2.2. Processing Al-Mg 5083

A commercial available AA 5083 with a composition in wt.% of 4.5%Mg, 0.7%Mn and aluminum balance was used in this study. Specimens with dimensions of 10x10x60mm were machined from as-received alloys. A subsequent annealing at 723K for 1h was performed before ECAP. The ECAP process was conducted at room temperature (Fig. 2) with a constant speed of 8.75 mm/s, using a die with $\phi = 90°$ and $\psi = 12°$. All samples and inner walls of the dies channels were lubricated using zinc stearate.

Fig.2. *Experimental device for ECAP.*

3. Results and discussions

3.1. Working load and model validation

Matching of simulates with experimental load data is important to validate the modeling we have used. Fig.3 shows the load – displacement curve during the ECAP of AA 5083. Four stages can be distinguished on the curve (Fig.3) [5].

In Stage I, the load increases rapidly with the ram displacement, reaching a maximum. This stage begins when the head of the billet first touches the bottom wall of the die channel at the outer corner and ends when the workpiece head bends over the corner. In Stage II the load decreases until the upper surface of the billet begins to touch the upper wall of the outlet channel.

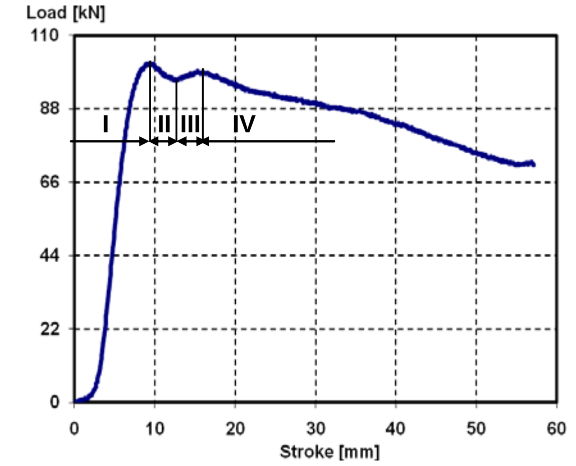

Fig.3. *Experimental load – displacement curve for one pass ECAP of AA 5083.*

In the next stage (Stage III), a slow increase in load marks the period from the moment the billet head touches the upper wall (end of Stage II) to the moment when sufficient contact is established between the upper surface of the billet head and the upper wall of the outlet channel. The load increases because of the deformation in the billet head.

The load decreases gradually with the displacement in Stage IV.

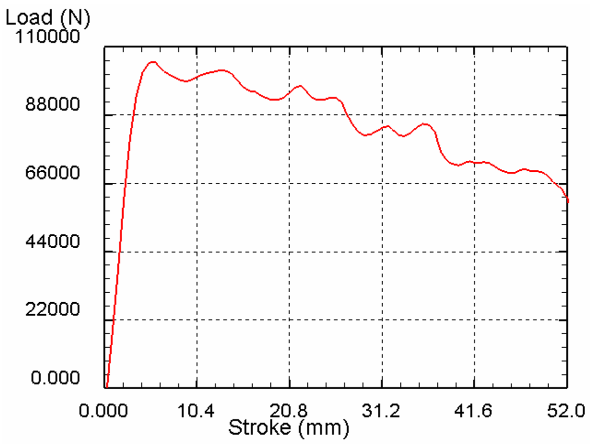

Fig.4. *Predicted load evolution for the first pass ECAP of AA 5083 (simulation).*

When the billet is pressed from the inlet channel to the outlet channel through the die corner, the contact area in the inlet channel decreases and in the meantime the length of the gap in the outlet channel grows until the head of the billet comes out of the outlet channel. As a result, the total contacting area between the billet and the die wall always decreases with the ram displacement, and so when we have real friction, the response is visible in the load versus displacement curve.

Fig 4 shows the predicted load evolution for the first pass ECAP of the investigated alloy. The maximum level of working-load and the general evolution are in good agreement with experimental results, confirming the validity of the ECAP modeling.

3.2. Strain and stress distribution

Theoretically, uniform strain in the entire sample can be achieved if the deformation follows simple shear perfectly.

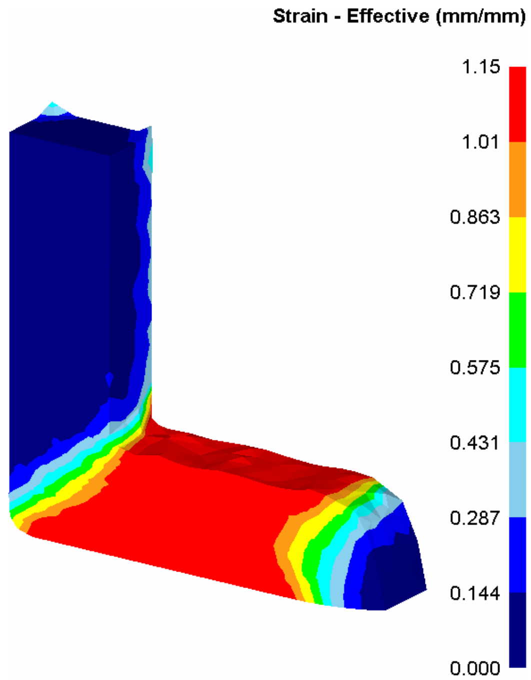

Fig.5. *Strain distribution - ECAP of AA 5083 (longitudinal section).*

As the workpiece exits from the plastic deformation zone, the strain distribution starts to stabilize and there are no further variations in the strain. It is shown that at the middle of the total deformation step, a steady state deformation behavior is found. The deformation histories are different for the head part and the tail part. It is obvious that transient regions of the head and tail ends receive smaller amounts of strain. Figure 5 shows strain distribution as a color map for the first ECAP pass of the investigated alloy. The non-uniform strain achieved in plastic deformation zone (PDZ) and the origin of inhomogeneous behavior are well-known [6]. A few equidistant tracking points (P_1…P4) are defined in longitudinal section of the workpiece across the PDZ in order to estimate strain distribution after the material leaves the main deformation area corresponding to the bisecting plane of the die channels (fig.6).

Naturally and according to Eq. (1), the outer corner radius determines a decrease of the effective strain. Final average strains from the steady-state region are in good agreement with those given by Eq. (1).

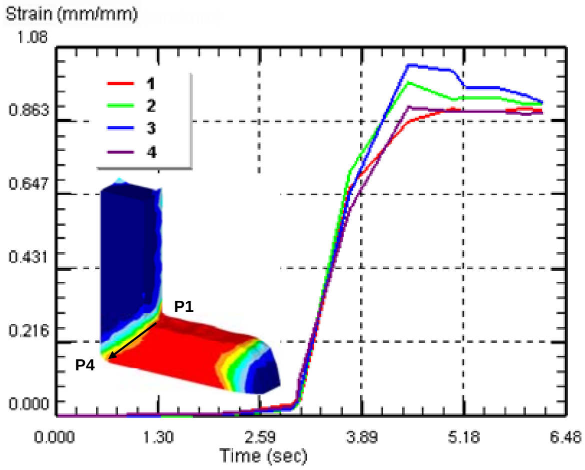

Fig.6. *Strain distribution in longitudinal section for the tracking point P_1-P_4 of PDZ.*

The effective stress distribution (Fig. 7) shows high effective stresses in PDZ and in the region prior to PDZ. This is due to the intense compressive action within the inlet channel of the die.

Note that effective stresses are always positive no matter the stress type (compression or tensile stress).

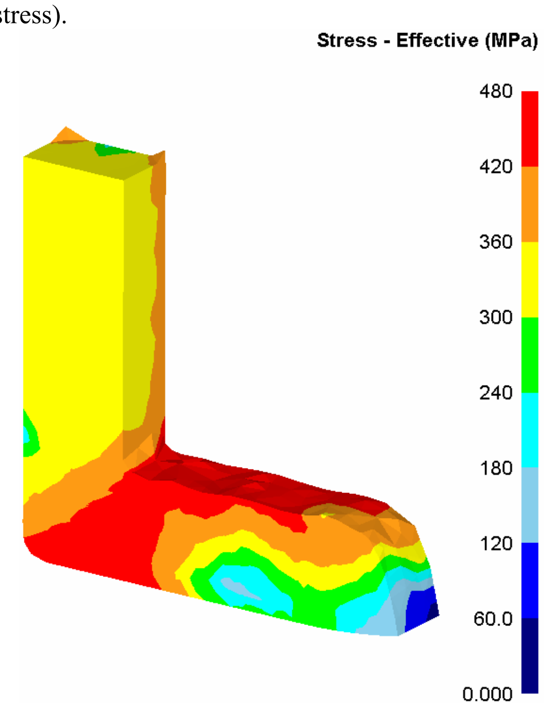

Fig.7*. Effective stress distribution - ECAP of AA 5083 (longitudinal section).*

But, if principal stresses are revealed as maximum positive stresses in the same area as in the effective stress distribution, it means that the region is dominated by tensile tensions which can cause cracks in the workpiece, fig.8. So, the maximum principal stress distribution becomes relevant.

Fig.8. *Cracking during ECAP process. Cracks start from upper surface of the billet.*

The nature of cracking on upper surfaces of the billet can be depicted from the principal stress distribution (Fig.9). High positive maximum principal stresses occur along the top surface of the billet in the exit channel immediately after the plane of channels intersection. This fact is confirmed by other authors [7].

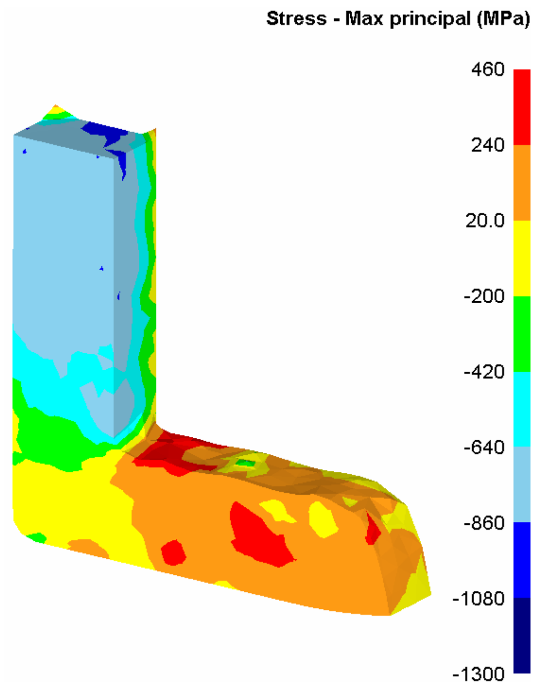

Fig.9*. Principal stress distribution - ECAP of AA 5083 (longitudinal section).*

4. Summary and conclusions

Finite Element Analysis was performed to evaluate ECAP process of AA 5083. The analysis shows the maximum estimated load level which is found in very good agreement with experiments on severe plastic deformations of AA 5083.

At the same time, simulations suggest that the accumulation of high positive maximum stresses on the upper surface of the billets is the main cause of appearance of the cracks on the mentioned area. If the stresses surpass the strength of the material, a technological solution including die geometry and/or processing temperature must be considered for a successful pursue of equal channel angular pressing.

Using the obtained results, tool and process design will become more accurate with all the benefits for research implementation.

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