INFLUENCE OF DIE DESIGN AND PROCESS PARAMETERS ON WORKING LOAD AND DAMAGE DURING EQUAL CHANNEL ANGULAR PRESSING

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Abstract

Equal Channel Angular Pressing (ECAP) is one of the most effective Severe Plastic Deformation (SPD) techniques for grain refinement in metallic materials. One of the technological problems of ECAP is processing the material by large strain without cracking of the workpiece. The aim of paper is to investigate the damaging and load evolution during ECAP of aluminum alloys. A Finite Element Analysis (FEA) was performed for different die designs and process parameters to depict the influence of die geometry and friction condition on deformation behavior and material damaging. Experimental tests were performed for testing the numerical prediction. The results provide a useful tool for optimizing ECAP process avoiding tool and billet damaging.

Keywords: aluminium, severe plastic deformation, finite element analysis, damage

1. INTRODUCTION

According to Hall-Petch relationship, it is well known that refining the grain size (d) increases the yield strength ($\sigma_y$) and the hardness (HV) of the materials:

$$\sigma_y = \sigma_{yo} + \frac{K}{\sqrt{d}}$$

(1)

where $\sigma_{yo}$ is the intrinsic yield stress and $K$ is a constant for the given material.

Severe plastic deformation (SPD) is a well-established method in the recent years for grain refinement in metals and alloys [1]. Among various SPD techniques - such as Multiaxial Forging [2], High Pressure Torsion [3], Cyclic Extrusion Compression [4], Accumulative Roll Bonding [5] and Equal Channel Angular Pressing (ECAP) [6] - the latter is the most promising and interesting due to its capability of producing large fully dense samples with the ultrafine (or nanometer scale) grain size by repeating the process while maintaining the original cross-section of the workpiece.

In ECAP, a billet is pressed through a die that contains two equal cross-sectional channels intersecting at a predetermined angle $\phi$ (see fig.1) - commonly 90 or 120°. The metal is subjected to a simple shear strain along the bisect plane of the channels [6]. 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 theoretical effective strain according to the die geometry is given by Eq. (2), as formulated by Iwahashi et al. [7]:

$$\varepsilon = \frac{1}{\sqrt{3}} \left[ 2 \cotg \left( \frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \cos \left( \frac{\phi}{2} + \frac{\psi}{2} \right) \right]$$

(2)

where the significance of terms are revealed in fig.1. For $\phi = 90^\circ$, an equivalent strain of approximately 1 is achieved. Note that Eq. (2) was derived for ideal perfect-plastic behavior and frictionless conditions.
From the technological point of view, a successful SPD process requires surpassing of two obstacles. First the load level (which directly affects the tool design, especially in large dimensions of the billet) and second an adequate formability of the material so that it can withstand high degrees of repeated deformation. Inherent failures of ECAP if not made a correct process design were reported. Among them, especially billets damages due to the cracking on their upper surfaces were found [8]. Related to these, it is important to understand the influence of die geometry and friction conditions on billet damage and ECAP load.

In this paper a tridimensional FEA is performed to investigate the damaging and working load level during ECAP. Experimental tests were performed in order to test the numerical prediction. The direct effect of the knowledge of load and damaging during ECAP is to prevent both tool damage and cracking of billets.

2. EXPERIMENTAL MATERIALS AND PROCEDURES

2.1. Processing Al-Mg alloy by ECAP

There is considerable interest in using Al-Mg alloys for structural applications due to their good weldability, moderate strength, but excellent corrosion resistance. Increasing strength by SPD without any supplementary alloying it’s a convenient way to rise up the potential of the material with maintaining all other mechanical properties. A commercial available aluminum AA 5052 alloy with a composition in wt.% of 2.8%Mg – 0.2%Cr and aluminum balance was used in this study. Specimens with dimensions of 10x10x60mm were machined from as-received alloy. A subsequently annealing at 723K for 1h was performed before ECAP. The ECAP process was conducted at room temperature with a constant speed of 8.75mm/s, using dies with $\phi = 90^\circ$. All samples and inner walls of the dies channels were lubricated using zinc stearate. To confirm the modeling results of FEA, the evolution of working load vs. punch displacement in first ECAP pass was registered by data acquisition using National Instruments equipment.

2.2. Finite element analysis

Commercial finite element code DEFORM 3D was used to carried out the simulations. The workpiece (10x10x60mm) considered a plastic body in whole deformation process was discretized in 8000 tetrahedral elements. According to Figueiredo et al. [9] a mesh of 8000 elements is sufficiently fine to reveal localized effects (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. 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 friction force along contact surfaces was modeled by constant shear friction law $F_r = \mu \cdot \tau_y$, where $\tau_y$ is the yield stress in shear and $\mu$ the shear friction coefficient which usually varies between 0.08 (carbide dies) and 0.12 (steel dies). To depict the influence of friction conditions, three different values for friction coefficient were considered: 0.08, 0.10, and 0.12.

Three design scenarios (symbolized 90_R_r) are analyzed by FEA to reveal the deformation behavior and its relationship with the design configuration:

A - there is no arc transition, the channels are intersected at a sharp corner: $R, r = 0 \text{ mm (90}_0_0)$
2.3. Damage in ECAP

Damage generally relates to the likelihood of fracture in a part. The Cockcroft-Latham damage model has shown to be a good indicator of certain types of tensile ductile fracture [10]. According to this model, a damage factor \( D_f \) (which is a constant corresponding to a critical condition associated with fracture) is defined by the following relationship [9]:

\[
D_f = \int_0^{e_r} \sigma_T d\bar{e}
\]

where \( \sigma_T \) is the maximum principal tensile stress within the billet, \( d\bar{e} \) is the effective strain increment and the integral is evaluated from zero strain to the final effective strain, \( e_r \).

The criterion was later normalized by incorporating the effective stress \([11]\), to give normalized damage factor \( D_{fN} \):

\[
D_{fN} = \int_0^{e_r} \frac{\sigma_T}{\bar{\sigma}} d\bar{e}
\]

Using Eq. (4), fracture occurs when \( D_{fN} \) reaches a critical value which depends upon the material and its processing history and which must be determined. This form of the Cockcroft-Latham relationship where the maximum principal tensile stress is normalized by the equivalent stress is generally considered to provide a reasonable prediction of the fracture of metals during ECAP processing [24] and therefore Eq. (4) will be used in the following study.

To determine the critical damage factor the alloy was tested in compression to failure to determine the maximum possible damage (accumulated damage). Then, the compression test was simulated by considering specimen having the same geometry as in real compression test and by characterizing the material behavior from the stress-strain curve recorded in compression test. To provide a direct correlation with the experiments, the simulation was stopped at the step where the reduction was similar to the maximum reduction in the experimental specimen at failure [11]. The stress and strain conditions for the compression test were then followed in the simulation thereby providing the critical damage factor which is in fact the accumulated damage at failure. The simulation performed in the mentioned conditions reveals that the critical damage factor for AA5052 was \( D_f = 0.310 \).

3. RESULTS AND DISCUSSION


For this research the deformation load is not so critical because of quite small billet dimensions. However, matching of simulates with experimental load results is important to validate the modeling. Fig. 2 shows load-displacement curve during the ECAP process of AA5052 using a die with channel angle of \( \phi = 90^\circ \) and no outer/inner arc of curvature between channels. The maximum level of working-load and the general evolution are in good agreement with experimental results, confirming the validity of ECAP modeling.

For die with sharp inner and outer corner, four distinguished stages can be identified. The dashed line highlights the evolution of load and helps identify the four stages. Different simulated steps of ECAP corresponding to the four stages were superimposed over graph (fig.2b).
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. In the next stage (Stage III), a slowly increase in load marks the period from the moment the billet head touches the upper wall (end of Stage II) to the moment that sufficient contact is established between the upper surface of the billet head and the upper wall of the outlet channel. Load increases because of deformation in the billet head. The load decreases gradually with the displacement in Stage IV because the contact area in the inlet channel and plastic deformation in the billet head decrease [12].

The magnitude of the maximum load is most interesting from the viewpoint of die designs. The present results show that the peak load is reached prior to achieving the steady state and it is higher than the steady state load. This is a normal feature for a strain hardenable material [12]. For AA5052 alloy, the maximum ECAP working-load for the first pass is around 50kN. For 90_0_0 load is bigger due to high constraint of the sharp die corners. Obviously, the friction coefficient has an important influence on working-load level, as we can see in figs. 3 - 5.
Furthermore, for dies with round corners of the channels, three stages in load evolution can be distinguished. That might be explained by the lack of constraint on the billet head.

It was demonstrated that the lesser shear zone in the outer part of the workpiece occurs because of shorter travel path of the outer part compared to the inner part within deformation zone when the inner corner angle of die is non-zero [13]. As we can see from the comparison of figs. 3 - 5, the decrease of load in the steady-state stage is associated with friction coefficient. Obviously, in all cases, working load for every scenario tends to a certain value at the end of the process and that is a normal thing indicating the level of real friction during the process.

3.2. Damaging prediction during ECAP

Using damage factor as defined in Eq. (4), fig.6 shows damage distribution for the three scenarios, for a friction coefficient of \( m = 0.12 \). The highest level of damage (0.850) corresponds to 90_0_0 die. Outer fillet corner of the die channels (90_2_0 die) determines only a small decreasing of maximum damage (0.775). A significant change takes place for inner fillet corner of the die channels (90_0_2 die) when the level of damage down to the value of 0.230, due to increasing compressive deformation component.

In accord with failure condition \((D_{fN} > D_{f})\), the damage should clearly appears for the two cases A and B. Indeed, experimental data confirm this hypothesis. Fig.6 shows billets cracking on upper surfaces of the billets for 90_0_0 and 90_2_0 scenario.

Friction conditions have different influences on damaging, fig.7. For 90_0_0 and 90_2_0 scenario, no relevant changes determined by friction conditions were found. Instead, for 90_0_2, it is obviously that maximum considered friction corresponding to \( m = 0.12 \) gave the minimum damage factor (0.230). Furthermore, for all friction conditions, a non-zero inner corner radius significant decreases the damaging during ECAP, and this is the main conclusion of this work.
4. SUMMARY AND CONCLUSIONS

Finite Element Analysis was performed to predict damaging and working-load level for an aluminum-based alloy during Equal Channel Angular Pressing. To estimate the damage, the Cockcroft-Latham model was used, and experimental test were conducted to validate the numerical prediction.

The analysis shows that the die influences the damage during ECAP. Three design scenarios which included outer and/or inner corner radius of the die channels were analyzed. The die design with sharp outer corner and inner corner radius provides the minimum damage during ECAP.

FEM simulations suggest there will be no spectacular changes of damage factor determined by friction conditions while the main influence on damaging during ECAP belongs to the die design.

REFERENCES