Numerical analysis of back pressure equal channel angular pressing of an Al-Mg alloy

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Abstract. Ultrafine grain size provides enhanced mechanical and/or physical properties such as strength and high ductility, superplasticity at relatively low temperatures and high strain rate and better corrosion resistance. Well-known as one of the most promising and effective structure refining method among other severe plastic deformation (SPD) techniques, equal channel angular pressing (ECAP) has been intensively investigated due to spectacular improvements in structure and therefore properties of bulk ultrafine grained/nanostructured materials. A successful ECAP requires surpassing two obstacles: the necessary load level which directly affects tools and a favourable stress distribution so the material withstanding the accumulated strain of repeated deformation. Materials could withstand more passes if a back pressure (BP) is applied. In traditional ECAP, tensile stress along the contact surface between the work piece and the upper wall of the outlet channel leads to crack initiation, while in the presence of BP, a negative (compressive) stress appears during the process balancing the tensile stress. In this study a comparative tridimensional finite element analysis (FEA) is performed to evaluate the flow of an Al-Mg alloy depending on different BP levels and process parameters. The results in terms of load level and strain distribution show the influence of BP on the material behaviour, opening opportunities for industrial applications.

1. Introduction

Bulk metallic materials such as wrought non age-hardenable Al-Mg alloys became interesting alternatives for various structural applications in spite of generally moderate strength, but good corrosion resistance. Increasing overall strength without any supplementary alloying that oppositely alters other features of the materials such as weldability, becomes an objective worthy of investigation. A convenient way to improve the potential of Al-Mg alloys is rising up the strength by structural refinement. In recent years, severe plastic deformation (SPD) has proved as a suitable top-down method for grain refinement in bulk metals and alloys, down to submicron or even nanometric size.

Ultrafine grain (UFG) size provides enhanced properties - mechanical and/or physical - such as strength and high ductility [1,2], superplasticity at relatively low temperatures and high strain rate [3,4] better corrosion resistance [5,6] and superelasticity [7,8]. Well-known as the most promising and efficient structure refining way among SPD methods, equal channel angular pressing (ECAP) has been intensively investigated due to spectacular achievements in structure and properties of bulk ultrafine grained/nanostructured materials.

Based on repetitive extrusion through a simple die having two equal cross-sectional rectangular channels that make between them a certain angle \( \phi \) usually in the range of 90 - 150º, ECAP can be easily resumed by reinserting the billet previously ECAPed and having obviously an identical cross-
sectional geometry and dimensions. Until the material reaches the critical zone nearby the intersection plane of the die’s channel, the billet moves in the inlet (usually vertical) channel similar to a rigid body without any plastic deformation. While crossing the surrounding area of the bisecting plane of the two equal cross section channels, which defines the plastic deformation zone (PDZ), the work piece is subjected to simple shear. To resume the process, a new billet is inserted into the vertical channel pushing out from the horizontal channel the remaining sample previously deformed.

Friction plays a key role during ECAP, influencing the load and overall material flow and therefore the strain distribution. The effects of friction on strain are still undecided since the reported results are quite contradictory. In evaluating the friction effects two causes act both individually and synergistically: real friction coefficient and model used to estimate friction (Coulomb or shear friction model). Obviously, the trend is to decrease friction as long as it stands up as a tangible technological factor [9-11], being a limitation of ECAP: the larger the length of sample, the larger the load and the risk of punch buckling. On the other hand, the reduction in friction does not assure the expected strain homogeneity [12].

One of the main milestones to be overcome in ECAP remains the successful plastic deformation without damaging the work piece. In traditional ECAP, tensile stress along the contact surface between the work piece and the upper wall of the outlet channel leads to crack initiation. A favorable stress distribution such that the material withstanding the accumulated strain of repeated deformation without cracking could be achieved if a back pressure (BP) is applied by using a counter punch. A negative (compressive) stress appears during the process balancing the tensile stress. So the material could withstand more passes if BP is applied.

Therefore, combining ECAP and BP in so called back pressure-equal channel angular pressing (BP-ECAP) it becomes a suitable approach to improve strain homogeneity and prevent damaging especially for hard-to-deform materials such as Al-Mg-Si [13, 14] or Mg alloys that have a precarious formability at room temperature (RT). Gu et al. [15] have successfully conducted BP-ECAP at RT on the as-cast AZ31 alloy using high BP of 400 MPa. Jäger et al. [16] and Kocich et al. [17] managed to process Ti at RT by using BP-ECAP.

The aim of this study is to evaluate advantages/disadvantages of the using of BP-ECAP. The paper focuses on checking the engineering feasibility of BP-ECAP for different BP levels using normal punches in order to get better strain homogeneity and an overall behavior of Al-Mg alloys during BP-ECAP.

Figure 1. Schematic principle of ECAP: a) simple ECAP; b) BP-ECAP.
2. Experimental materials and tools
The BP-ECAP process was conducted according to schematic principle shown in Fig. 2a. A commercial available Al-Mg alloy (AA5052) with composition of 2.8%Mg – 0.2%Cr (% weight) was experimented in this work.
Specimens with initial shape of rectangular prism having dimensions of 10 × 10 × 60 mm were machined from the above designated alloy. The samples shaped as square prisms were inserted in vertical position, as it is schematically suggested in Fig. 1. Subsequently, to achieve a better formability of the material by removing inherent strain hardening from previous metal-working processes, an annealing at 623 K for 1h has been conducted before ECAP. This it results in an initial grain size of ≈ 100μm.
The BP-ECAP process was performed at RT with a constant crosshead speed of 1 mm/s, using a die with φ = 90° with sharp corners i.e. no outer or inner radius transition between channels. A horizontal dedicated hydraulic cylinder assures the necessary BP (Fig. 2b). The punch and counter punch interrelated movements are controlled by a special speed drive. The BP is progressively applied to the material backward in the horizontal (outlet) channel by using a controlled hydraulic unit, so the nominal level (20; 30; 40 and 50 MPa) is achieved after 5 s [18]. The maximum stroke is set as 50 mm, since the vertical punch has to stop at the precise position corresponding to the upper wall of the outlet channel. Both the specimens and inner walls of the die channels have been lubricated using zinc stearate which is a sufficiently powerful mold release agent and also a good lubricant.

3. Finite element simulation
The simulation was conducted by using the commercial code DEFORM 3D™. The constitutive stress-strain relationship of the nominated alloy (AA5052) was experimentally obtained. Tensile tests have been performed according to tensile testing standard (ISO 6892-1: 2009), by using an Instron 3382 universal testing machine. It was obtained [19] that flow stress - strain relation is governed by equation: σ(MPa) = 402.29·e^{0.30} and that was designated in DEFORM 3D™ software as constitutive equation of the nominated material.
All simulations were performed in isothermal conditions of 20ºC with a punch speed of 1 mm/s, using specimens with same dimensions and shapes as in experiments. BP-ECAP is undoubtedly a friction sensitive process, so the shear model was designated [9]. Simulations were conducted taking into account a friction factor of 0.12 [20]. The tolerance, contact positioning of the work-piece and die,
convergence criteria, remeshing parameters together with boundary conditions has to be indicated before starting the execution of the simulation process.

Because simulations have been carried out at RT, the hardening behaviour of the material is considered independent of strain rate. To avoid the inevitable volume loss, a value of $10^6$ was indicated as volume penalty constant. The billet was discretized in 8000 elements (tetrahedral) ensuring a sufficiently fine mesh to describe all effects according to Figueiredo et al. [21]. Taking 12000 tetrahedral elements does not refine results as it was expected, but increases twice the computing time. Poisson’s ratio 0.33 and Young’s modulus 69 GPa were assigned. Four different BP levels have been simulated in ECAP: 20, 30, 40 and 50 MPa.

4. Results and discussions

4.1. Working-load under back pressure conditions

The working-load is the most asked common parameter for any plastic deformation process. The nominal load is especially used in tool designing, and its evolution in time depicts the process itself. Fitting the experimental and simulated loads became a common practice to validate a modelling performed with FEA. The working-load evolution is depicted in terms of simulated (Fig. 3) and experimental results (Fig. 4). During BP-ECAP the working-load was recorded by using a dedicated National Instruments data acquisition system with LabVIEW interface.

As it was expected, the overall load increases as the BP increases, too. As one can see, for ECAP without BP (i.e. 0 MPa) when the counter punch is subjected only to ordinary friction or no counter punch is present, the maximum load is about 48 kN (Fig. 4a). Naturally, increasing the BP leads to the peak load increasing too (up to 60 kN for BP = 50 MPa) but not equally i.e. there is a difference between the corresponding BP-load and the exceeding load recorded during BP-ECAP.

Figure 4 shows the simulated and experimental working-load evolution for simple ECAP [15] and BP-ECAP with 40 MPa respectively, where the main stages can be identified.

At the beginning (I) the load suddenly increases due to higher compression: the load reaches its peak and the billet continues to bend along the corner to the upper wall of the horizontal channel, meeting the counter punch. The material starts to flow without a drastic constrain and the load slowly decreases (II) till the counter punch oppositely acts against flow material. Then the billet tends to completely fill the outlet channel flowing over the counter punch in a steady-state process (III). Because of decreasing in friction due to reduction in contact area between the work piece and the channels, load decreases. Obviously, the material undergoes conventional load from the front pressure (FP) and the corresponding BP load.
4.2. Strain distribution under back pressure conditions

Idealistically, for a theoretical simple shear along to the bisector plane of the two channels of the die - depicted by a perfect shearing thin plane - a uniform strain distribution could be normally to be achieved. But in practice, because of the material imperfections, friction, tools geometry and work hardening, an inhomogeneous strain distribution across the width and length of the work piece is always found (Fig. 5).

At the beginning of the extrusion when the billet is strongly compressed, being practically upset in the inlet channel, the material sticks to the inner walls of the channel due to intense friction and after that, when the punch overcomes the yield strength of the material, it starts flowing over that. As the work piece leaves PDZ, the strain becomes more and more stabilized and no further significant variation in the strain takes place. It is known that at the middle of the sample a steady state deformation behaviour occurs. Undoubtedly, both ends of the sample receive different (lower) strain. Moreover, the head and tail are strongly distorted, so to resume the simple ECAP process, they have to be removed, especially when the sample is rotated same sense 90º (route B_C) or alternating sense ± 90º (route B_A) around its longitudinal axis before reinserting. The main advantage of BP-ECAP is that the deformed sample has identical shape and dimensions being ready to be reinserted in the die. Figure 5 shows that for BP = 20 and 30 MPa, a relatively uniform strain distribution can be achieved at the
middle of the sample, in comparison with classical ECAP (i.e. 0 MPa) showing larger strain especially at the bottom of the sample. Larger compression (40-50 MPa) it results in higher strain that even in this situation is not much higher than the effective strain of 2.

The relatively larger strain from the bottom region of the sample (BP = 50 MPa) can be balanced during the subsequent ECAP pass if a 180° rotation of the sample around its longitudinal axis is performed (i.e. route C).

5. Conclusions
A comparative 3D FEA was conducted to evaluate the behavior of a non age-hardenable Al-Mg alloy during ECAP and BP-ECAP, respectively. The study aims to check the engineering feasibility of BP-ECAP for different BP levels (20÷50 MPa) using a modified ECAP die. The results depicted in terms of load and strain distribution, showing the influence of BP, are the following:

Under BP condition the loading evolution changes. In traditional ECAP - when no counter punch is presented or the counter punch is subjected only to simple friction - the maximum load corresponding to the nominated material (AA5052) does not exceed 48 kN. Obviously, the overall and peak load increases, as it was expected: increasing BP leads to an increasing of the peak load but not equally i.e. there is a difference between the corresponding BP-load and the exceeding load recorded during BP-ECAP. That because of the increased friction due to the larger compression of the material subjected to FP and BP simultaneously.

It is shown that the overall strain does not increase dramatically, as could be expected. The relatively larger strain from the bottom region corresponding to traditional ECAP is balanced by BP even for higher BP levels. The back end of the sample receives a balanced strain, more closely to the average strain of the steady state region. A generally fair strain with reasonable homogeneity can be obtained using BPs between 20 and 30 MPa. To avoid damaging of the work piece, higher levels of BP (up to 50 MPa) has to be applied.

6. References
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