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The Design of a Die for the Processing of Aluminum through Equal Channel Angular Pressing

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***Abstract*—**The processing of metals through Equal Channel Angular Pressing (ECAP) leads to their remarkable strengthening. The ECAP dies control the amount of strain imposed on the material through its geometry, especially through the angle between the die channels, and thus the microstructural and mechanical properties evolution of the material. The present study describes the design of an ECAP die whose utilization and maintenance are facilitated, and that also controls the eventual undesired flow of the material during processing. The proposed design was validated through numerical simulations procedures using commercial software. The die was manufactured according to the present design and tested. Tests using aluminum alloys also indicated to be suitable for the processing of higher strength alloys.

***Keywords*—**ECAP, mechanical design, numerical methods, SPD.

I. Introduction

The Severe Plastic Deformation (SPD) processes are increasingly used in industries. Various researches analyze the grain refinement caused by SPD [1]-[3]. The most important SPD techniques are the ECAP [4], Multi-directional Forging (MDF) [5], also denominated Multiaxial Compression (MAC) [6], [7] and High Pressure Torsion (HPT) [8]. ECAP is a very common SPD method and remarkably strengthens metals through grain refinement and dislocation density increase [8]. ECAP involves the deformation of the material through two channels with equal cross-sections and with a fixed angle between them [9]; the workpiece dimensions are not altered by processing. ECAP also allows the processing of workpieces with large dimensions and any desirable number of passages through the channels, thus leading to high rates of production of deformed material [10].

The geometry and the angle between the channels control the imposed deformation by the ECAP dies [11]. Single body ECAP dies, where the channels are machined directly in a single tool steel block, lead to an adequate rigidity of the dies, but do not allow eventual cleaning and maintenance of the die channels, which are commonly damaged by the wear associated with the intense material/die friction during processing. Single block dies thus involve either an increase in their channel cross-section dimensions or are completely discarded, in case the channel damage becomes intolerable and must be re-machined.

A possible solution to this ECAP die design problem has been the construction of dies with three adjacent plates; the central plate contains the processing channels, while the two other adjacent plates confine laterally the channel in the central plate [12]. Another possibility is the use of a two piece die, where one of the die parts contains the processing channels and the other part is flat and constrains the flow of the material in the ECAP channels [13]. These two solutions greatly facilitate the die maintenance, which is necessary in order to keep the die channels under acceptable working conditions. A special difficulty in the two above mentioned designs is that the die parts are usually joined through sets of screws, that are submitted to high tensile stresses during the material processing; these screws often display inadequate rigidity, that may lead to the elastic opening of the die parts and to an undesirable flow of the material between the die parts. Such flow commonly raises intolerably the necessary processing loads, causes local damages to the die channels and thus makes the processing impossible.

Reference [14] developed an ECAP die with a sliding lower channel, eliminating most of the friction between the material and the lower ECAP channel and thus lowering the processing load. This is an interesting design solution, but it does not preclude the flow of the material between the die parts, especially between the moving part and the fixed ones, causing the problems already described in the previous paragraph.

This paper presents a new design for an ECAP die, involving two parts, similarly to the situation employed by [13]. However, instead of using screws for the joining of these two parts, their external shape is conical and inserted into an internally conical envelope. As processing loads are raised, the conical external envelope imposes an increasing compressive load on the two internal ECAP die parts. The new design was analyzed through numerical simulations and then successfully implemented for the processing of aluminum.

II. Materials and Methods

The processed material was commercial purity aluminum (99.7% purity), with a yield strength of 40 MPa. The die was manufactured with an AISI H13 tool steel, quenched and tempered to 52 HRC and displaying a yield strength of 1400 MPa; this material exhibits high strengths both at ambient and at high temperatures. Small workpiece cross-sections lead to low processing loads and thus allow the use of smaller dies. AISI H13 tool steel has also been previously used for ECAP dies for processing of IF steels [15]; on the other hand, the processed material displays small dimensions, making it difficult to evaluate the obtained mechanical properties. A

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balance of these two opposing factors led to the choice of a square, 16 x 16 mm cross-section for the die channels. To generate a high level of strain for each ECAP pass, the angle between the ECAP channels was taken as 90°, imposing a strain of approximately 1.15 for each ECAP pass [11].

The die was designed taking into consideration the size of the workpieces to be processed, its weight, its mechanical strength, the ease in its utilization and the possibility of use at elevated temperatures. Such temperatures are reached through the insertion of electrical heating elements in holes at the upper part of the dies. A numerical analysis of the situation as employed in order to evaluate the effect of the imposed loads on the die strength.

Numerical simulations utilized the software DEFORM 3D V11.1 (SFTC Corp, Ohio, USA). The flow curve of the material corresponded to a rigid, perfectly plastic behavior with an yield strength of 100 MPa, thus associated with a safety factor of 2.5 in the design of the die. The processing speed was the same adopted for the experimental testing of the die: 20 mm/min [4]; the shear friction factor between the material and the die was taken as 0.2.

III. Results and Discussion

Figs. 1 and 2 display an illustration of the die parts and of the fully mounted die, as well as a photograph of the manufactured die, shown in Fig. 3. One of the parts of the die exhibits the channels, whereas the other part displays a flat surface that closes the channels. These two parts have an outside conical shape fitting into an envelope with an internal conical shape.

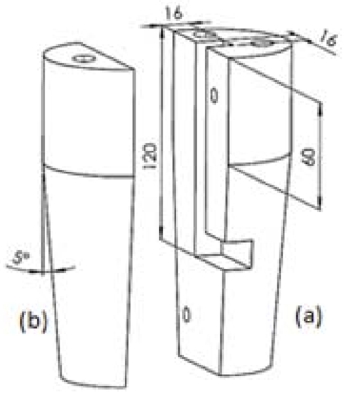

Fig. 1 ECAP die: (a) Die part containing the channels and (b) flat die part

The numerical simulation of the processing indicated the necessity of an applied load of 85.7 kN, which was approximately the experimentally measured value. Such an applied extrusion load corresponds to an opening load between the two die halves of 358.7 kN. The simulation indicated that even under such a high separation force, the two die halves did not open, either geometrically or elastically.

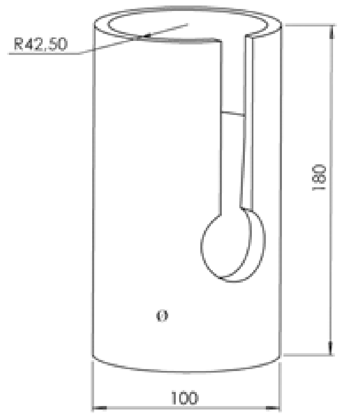

Fig. 2 ECAP die: Internally conical die envelope

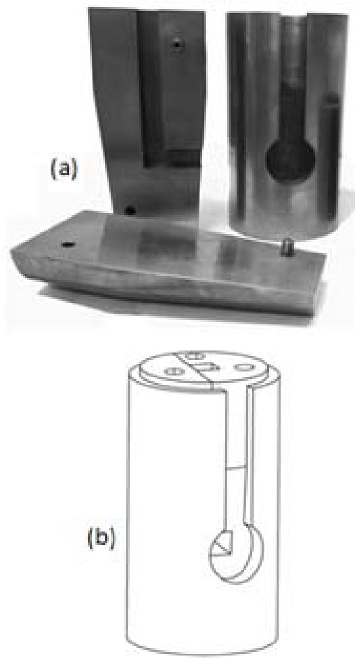

Fig. 3 ECAP die: (a) The photograph of the manufactured die and (b) the mounted parts

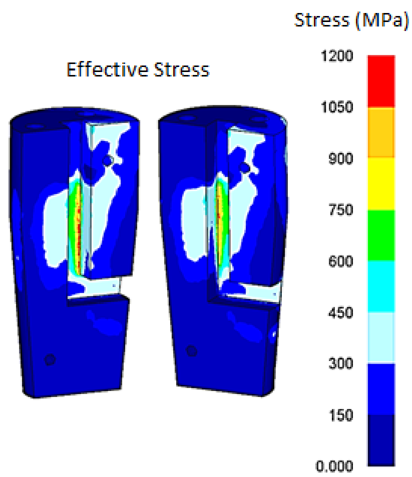

Fig. 4 Distribution of the effective in the die part containing the channels, at the moment when the maximum extrusion load is applied

Figs. 4 and 5 illustrate the distribution of the effective stress and of the maximum principal stress for the die part containing the channels, at the moment when the maximum extrusion load is applied. The highest levels of stress occur at the corners of the channels, due to the stress concentrations. The maximum effective stress was 1100 MPa, which is below the material yield strength.

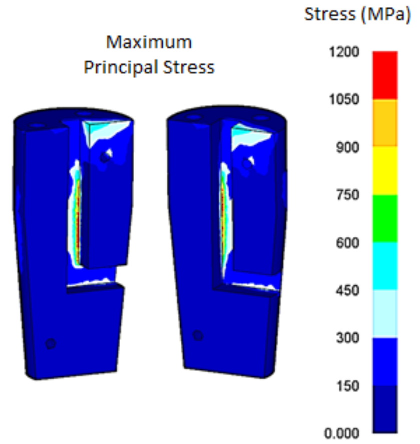

Fig. 5 Distribution of the maximum principal stress in the die part containing the channels, at the moment when the maximum extrusion load is applied

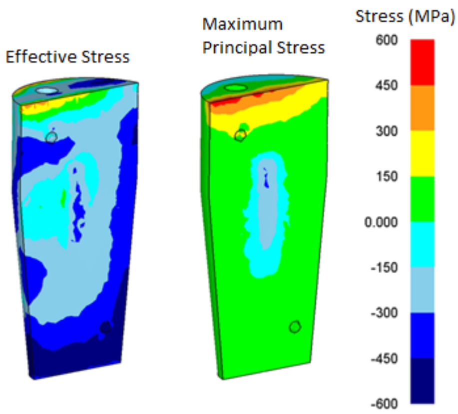

Fig. 6 Distribution of the effective stresses and of the maximum principal stress in the constraining, flat die part the moment when the maximum extrusion load is applied

The data in Figs. 7 and 8 correspond to the distribution of the effective stress and maximum principal stress in the internally conical die envelope, again at the moment when the extrusion load is at its maximum. The maximum applied effective stress in this part was 650 MPa, again appreciably below the material yield stress. The highest stress is observed in the circular base of the vertical die opening, since the die parts apply a rising force on the external envelope as the processing load increases.

Following the numerical analysis of the die behavior, the die was manufactured according to the present design and has been under normal operation without any special difficulties. Since the safety factor adopted is quite high, the die has also been utilized successfully for materials which are stronger than commercial purity aluminum, such as various aluminum alloys [16].

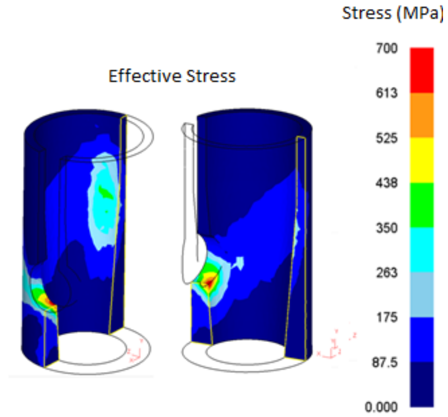

Fig. 7 Distribution of the effective stresses in the internally conical die envelope, at the moment when the maximum extrusion load is applied

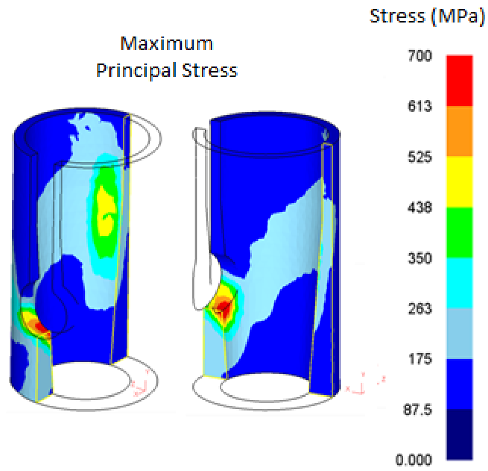

Fig. 8 Distribution of the maximum principal stress in the internally conical die envelope, at the moment when the maximum extrusion load is applied

IV. Conclusions

SPD processing through ECAP leads to high deformation in the material but rely on high applied loads. The design of the ECAP dies should thus take into consideration all the necessary requirements for its adequate behavior, including the operator safety and costs as low as possible. This situation makes a numerical simulation of the situation crucial in order to obtain the desired results and possibly regarding future changes in the dies.

According to the numerical simulation of the processing of commercially purity aluminum in the presently designed ECAP die, the highest effective stress in the die (1100 MPa) occurred near the corners of the part of the die containing the extrusion dies and at the moment when the extrusion load reached its maximum. This value was still below the die material yield strength (1400 MPa); in addition, the region where this maximum stress occurs does not correspond to a situation where fatigue considerations should be covered.

The die manufactured according to the present design performed adequately during its experimental use, and even allowed the processing of aluminum alloys displaying yield strengths above that for commercial purity aluminum.

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