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Research Article

Modelling of two well-known SPD methods (ECAP and MDF) and comparison with a numerical analysis method.

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Abstract – In this study, two Severe Plastic Deformation (SPD) methods, which significantly improve the mechanical properties of materials by causing significant improvements in the microstructure of materials, are comparatively analyzed. The study compares the most well-known and commonly used Equal Channel Angular Pressing (ECAP) and Multi-Directional Forging (MDF) methods. Both methods have significant advantages and disadvantages in terms of application and their effects on the material. In this study, which is a finite element analysis (FEA) study, both methods will be modelled and numerically analyzed, and the results will be examined comparatively. Therefore, the necessary application forces and changes in material strain values will be compared for both methods.

Keywords – ECAP, FEA, Mechanical properties, MDF, SPD

I. Introduction

Severe plastic deformation (SPD) methods have attracted the attention of researchers and materials scientists in recent years due to their effects on material microstructure and mechanical properties. SPD methods, especially those that refine the grain structures of metal materials to ultra-fine grain (UFG) and nanoscale levels, have become highly significant. Although the scientific study of SPD methods dates back to W. Bridgman's High Pressure Torsion (HPT) studies [1], [2] a century ago, SPD attracted attention with Segal's studies on Equal Channel Angular Pressing (ECAP) in the 1970s [3], [4]. Since the 1990s, studies on ECAP and HPT have accelerated [5], [6] and SPD methods have diversified and become widespread after the 2000s. Nowadays, numerous SPD methods have been introduced, and some researchers have modified known methods to make them more efficient [7]– [9]. Various SPD methods have been developed for different types of compact materials such as bulk, sheet, plate, [10] tube, [11] and disc, and the application of SPD on continuous materials is still a research topic. One of the SPD methods applied to bulk materials is Multi-Directional Forging (MDF), also referred to as Multi-Axial Pressing (MAP). [12], [13] MDF stands out for its ease of application and effectiveness compared to others. While methods like ECAP or HPT require high-pressure presses and complex molds or fixtures, and also most materials need to be heated above room temperature for these methods. In contrast, MDF can be performed between flat plates at room temperature using a simple compression testing machine or press machine.

However, there are some parameters affecting the application of SPD methods on materials, primarily the processing temperature and deformation rate. In SPD processes conducted at room temperature, the deformation rate is limited, as increasing it can lead to material damage. However, SPD applications conducted at low temperatures show greater improvement in the microstructure and mechanical properties of materials compared to those conducted at high temperatures.

Therefore, this study aims to comparatively examine two SPD methods: high deformation (ECAP) and low deformation (MDF). Numerical analysis studies will be conducted at room temperature, and the strain changes in an aluminum alloy subjected to 1 pass of ECAP versus 1 cycle of MDF will be investigated. Additionally, the force required for pressing versus the stroke changes will be graphically presented.

II. Materials and Method

In this study, a 5000 series aluminum alloy was chosen as the material. Aluminum alloys have been widely used and researched in recent years due to their high strength-to-weight ratio. The CAD modeling of experimental setups and numerical analyses were employed as the method. Two different SPD methods, namely ECAP and MDF, were modelled, and the same material was analyzed under the same conditions. The dimensions of the workpiece used in both methods were designed to have the same cross-sectional area (15mm x 15mm) in square sections. While the MDF workpiece was a cube with a side length of 15mm, the ECAP specimen was a rectangular prism with a length of 55mm. Both processes were conducted at room temperature, with a constant press advancement rate of 1mm/min, and a friction coefficient of 0.4, as typically assumed for aluminum, was used between the parts.

The CAD models of the experimental setups for ECAP and MDF processes are schematically illustrated below. The corner angle of the ECAP die was designed to be 90º, as commonly used, with a 10 mm radius provided to facilitate material flow. The pressing process in ECAP continued until reaching the region with a top die radius, which is considered as 1 pass in ECAP.

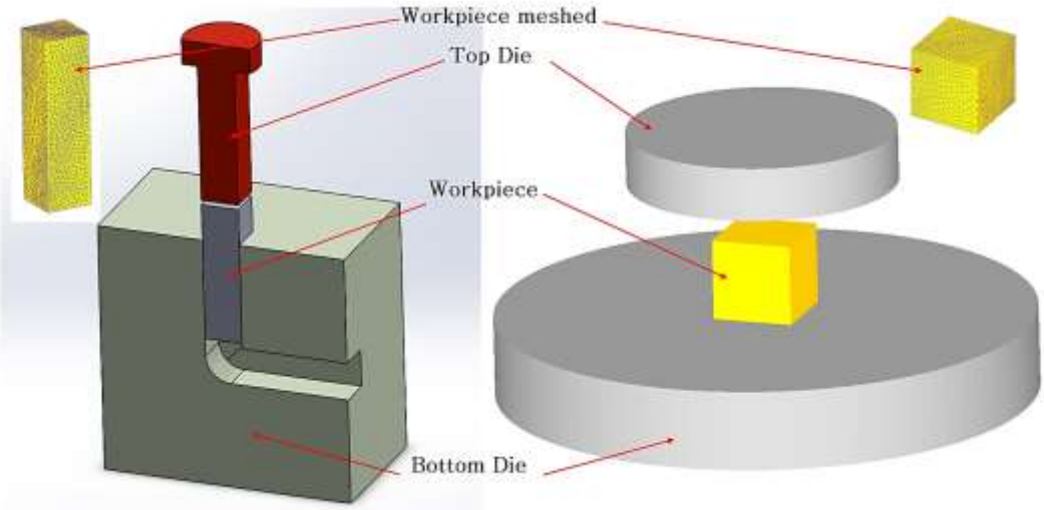

Fig. 1 Schematic shown of the ECAP system (left), and MDF system (right)

In MDF, pressing continued until a 10% deformation was achieved along the x, y, and z axes. The workpieces used in a study by Nalkıran and Şahbaz [14], the actual MDF experimental setup, and the schematic representation of the MDF system are provided in the figure below.

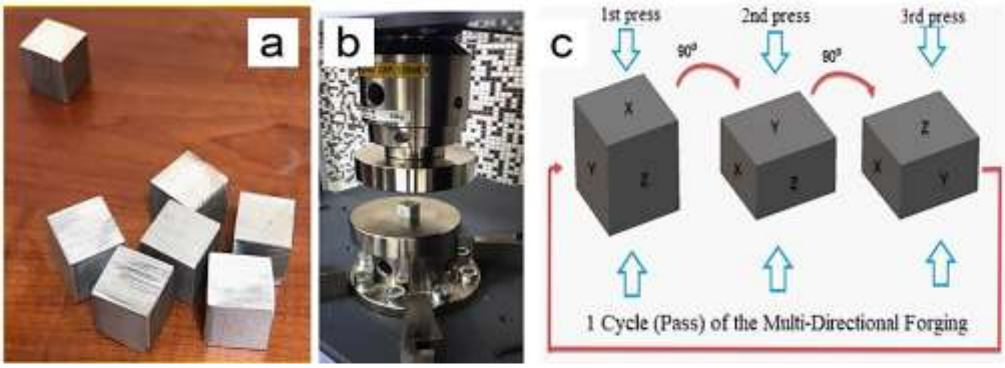

Fig. 2 MDF specimens: (a) before MDF process, (b) between the compression test plates, (c) schematic shown of MDF[14]

As seen in the diagram (Fig.2c), in the MDF process, after a certain ratio of pressing from each surface, the part is rotated by 90º, and the process is repeated. When pressing is completed from all three axes, it is considered as 1 cycle or 1 pass of MDF. In this study, according to the above-mentioned parameters, ECAP and MDF setups were prepared in a numerical analysis software and tests were carried out. ECAP was analyzed as one pass and MDF was analyzed as one pass with 10% pressing from all three surfaces.

III. Results

During numerical analysis, although partial shape changes occurred in the workpieces due to the applied pressing force, it can generally be said that they retained their cross-sectional areas and geometric shapes after 1 pass. This is one of the most important features of SPD methods, as it allows the process to be applied to the workpiece multiple times. The geometric shapes of the workpieces after 1 pass of ECAP and MDF are shown below in Figure 3.

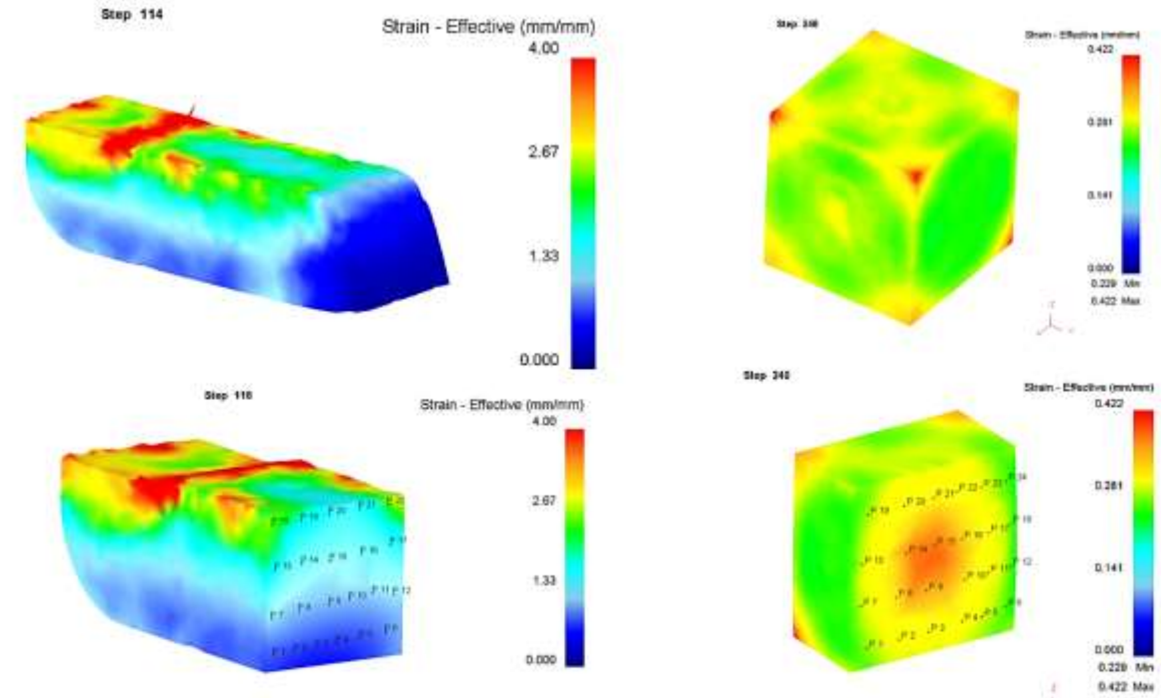

Fig. 3 The appearance of the workpieces and the strain distributions after 1 pass, the full view of the workpieces (top) and the cross-sectional view (bottom)

As seen in Figure 3, although there is some shape change due to the radius in the channel in the ECAP specimen, the cross-sectional area remains constant. In the MDF specimen, the shape is almost completely preserved, and the workpiece retains its cubic shape. Additionally, the strain distributions after 1 pass are also shown in Figure 3.

When examining the ECAP specimen, it is observed that there is a strain increase from bottom to top, starting from 0.83 and reaching 2.93 (Figure 4). Strain measurement was conducted by measuring the strain changes of 22 points on the workpiece's cross-sectional surface using the point-tracking method during ECAP process. The graph in Figure 4 presents the strain increase at these points obtained through the point-tracking method. It is observed that the strain values increase after passing through the radius and then remain constant. Additionally, it can be seen from the graph that the strain increase is softer at the points near the bottom of the specimen due to the radius, while it is sharper at the upper points. After numerical analysis, the strain increase in the material is interpreted as an increase in hardness and strength, and high strain values are desired. However, it is also important for the strain to be homogeneously distributed; for this reason, the ECAP method has been modified to develop the Exp-ECAP [7], [15] method. In our study, although the strain value reached 2.9, it was observed that the average strain in the central zones, which is homogeneous, was around 1.20.

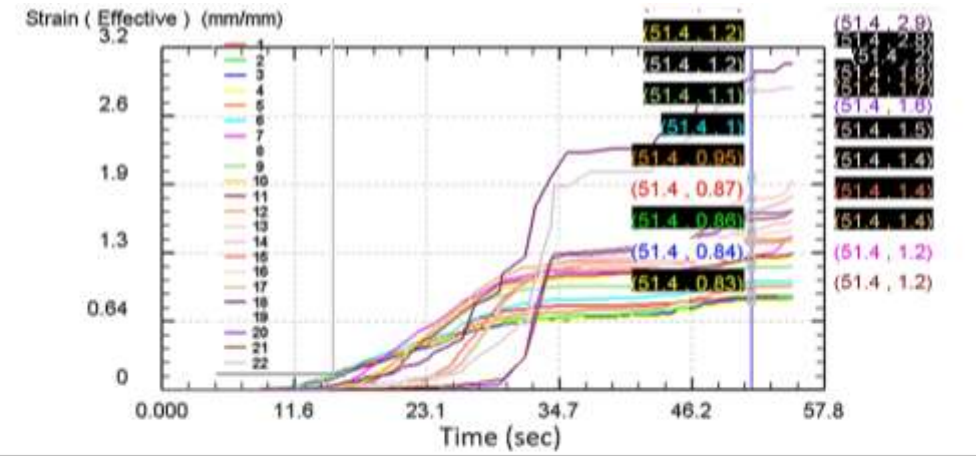

Fig. 4 Strain changes in the workpiece's cross-sectional area using the point-tracking method after 1 pass of ECAP.

Below, the strain changes in the material after 1 cycle of MDF are observed. From left to right, there is a proportional increase in strain on the workpiece after each of the three presses. Following the 1st press, a strain of 0.167 is reached, 0.306 after the 2nd press, and 0.422 after the 3rd press. This value corresponds to one-third of the strain obtained with 1 cycle of ECAP. Hence, a general approach would suggest that applying three cycles of MDF would achieve a strain value equivalent to one cycle of ECAP. Additionally, when comparing the strain distributions obtained after analysis, it can be said that the strain distribution after MDF is more homogeneous compared to ECAP.

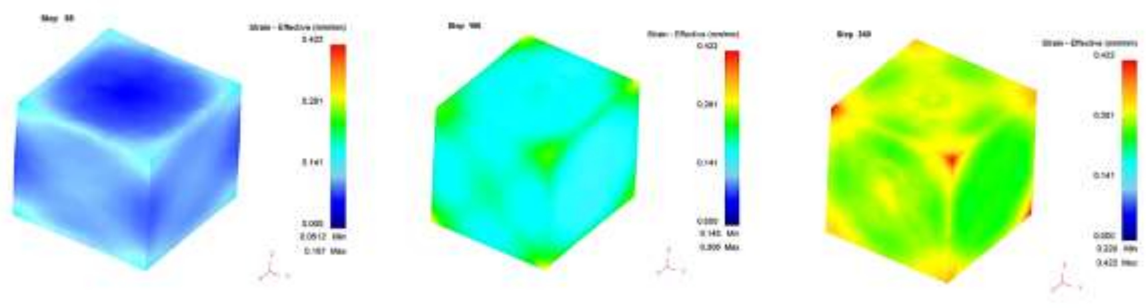

Fig. 5 Strain changes occurring on the workpiece during the application of one pass of MDF, x-axis after the 1st press (left), y-axis after the 2nd press (middle), z-axis after the 3rd press (right)

Another aspect to compare is the forces applied to the material during ECAP and MDF. While a maximum force of 34 tons is required for one cycle of ECAP, only 9 tons maximum is sufficient for the MDF process. This situation is illustrated in the following graphs (Fig.6).

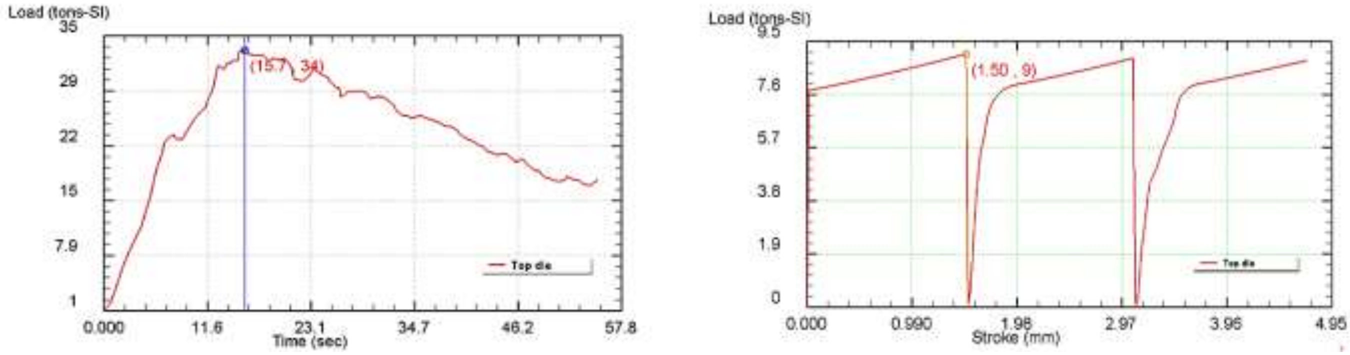

Fig. 6 The graph on the left shows the force applied during one cycle of ECAP, while the graph on the right shows the force applied during one cycle of MDF (3 presses).

IV. DISCUSSION AND CONCLUSION

In this study, two different SPD methods were numerically analyzed and the results were compared. ECAP and MDF processes applied to bulk materials were analyzed on the same material under the same conditions, with the same cross-sectional area.

The results were examined and compared in terms of applied forces and strain distributions:

- The required force for one pass of ECAP is 34 tons.
- The required force for one pass of MDF is 9 tons.
- The strain gain obtained with ECAP is 1.20.
- The strain gain obtained with MDF is 0.422. (Approximately one-third of ECAP)
- While the strain distribution in ECAP is not homogeneous,
- The strain distribution after MDF is close to homogeneous.
- In addition to the homogeneous strain distribution, another advantage of MDF is ease of application. While high forces are required for ECAP application, well-designed mold manufacturing is necessary, MDF can be performed between two compression plates of a simple compression testing machine even at room temperature.
- Moreover, since high deformations occur with ECAP, it is not possible to apply this process experimentally at room temperature on aluminum materials. It has been reported by researchers that fractures occur in the material if applied. Therefore, lower strains are obtained in heated ECAP systems. Since MDF can be applied at low deformation rates, it can be applied at room temperature. This is another important feature that highlights MDF.
- It can be suggested as a future study for researchers to prepare and apply experimental setups of this study.

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