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Simulation of a Material Undergoing Equal Channel Angular Process Using Finite Element Anallysis with MARC©

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Abstract – MARC; a very useful finite element analysis software is used in an ECAE (Equal channel angular extrusion) process applied to a material. The *MARC* was used to simulate the ECAE process and also for calculating the strain conditions. Channel angle, friction between die and pressed material, and also the fillet radius of the channels were investigated to look at their effects on the transversal strain distribution in the deformed body of the material for a single ECAE pass. In addition, the material of interest had similar simulation performed after two passes. Simulation of second passes in ECAE process has rarely been reported.

Index Terms: Two passes, Equal channel angular extrusion, finite element simulation, MARC.

1 INTRODUCTION

qual channel angular extrusion (ECAE) is a process where a metal work piece is subjected to high strain by extrusion between two channels that meet at an angle without or with curvature, but otherwise of uniform cross-sectional areas, as depicted in Fig. 1. Along with elevated temperatures, the subject material accumulates large strain from each pass through the two channels, which enables simultaneous microstructure transformation. The subject material can thus undergo repeated processes of ECAE to obtain a fine-grained microstructure. Vital factors that determine the success of ECAE include magnitude of strain, distribution of strain, and temperature. Affecting the former two factors, there are influential variables such as number of extrusion passes, angle between inlet and outlet channel (ϕ), curvature(s) at the channel intersection, entry orientation rotation between passes, and amount of friction, etc. While the original developers of ECAE, Segal, 1995 has provided a simple analytical formula, Iwahashi et al., 1996 gave a more involved one

$$\varepsilon = \frac{2\cot(\phi/2 + \phi'/2) \quad + \quad \phi' \operatorname{cosec}(\phi/2 + \phi'/2)}{\sqrt{3}} \qquad (1)$$

(definition of ϕ and ϕ′ are described in Fig. 1) for estimating strain obtainable for given process parameters, it is an average value. So, finite element computation is meaningful in order to offer detailed information such as strain distribution and friction effect. There have been some finite element analyses available for ECAE using widely known software packages such as ABACUS [Suh et al., 2001] and DEFORM [Kim et al., 2001; Zuyan et al., 2000; Kim, 2001; Semiatin et al., 2000 and Bowen et al., 2000] or specific one as ANTARES. In this paper, another commonly used code, MARC, will be employed to calculate the strain conditions after one single ECAE pass under various processing parameter as well as two passes which had been less performed before.

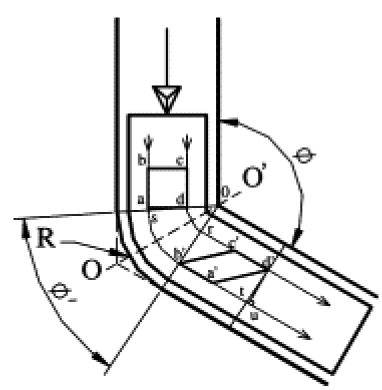

Fig. 1: Schematic showing the working principle of ECAE.

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2 PROCEDURES

In this finite element analysis, 2D plane strain modeling is adequate since material flow in the *z*-direction is restricted. Stress–strain behavior is assumed to be perfectly elastic–plastic. A computer simulation of the ECAE with a 20mm×20mm cross-sectional area and 70 mm long was run. A plane representing the workpiece was divided into a mesh of 500 equal rectangular elements with 11 transverse nodes (*x*-direction) and 51 longitudinal nodes (*y*-direction). After the workpiece is driven through the angular shear zone, a representative line along the 23rd row of the body mesh is considered for showing strain distribution. The calculated strain at each node (from nos. 245 to 255) on this line has been plotted (Fig. 2). In order to compute cases for which a workpiece would receive ECAE passes twice, the simulation with the continuous channel included two bends in forward or opposite directions as depicted in Fig. 3. This simulation is understood to have an equal effect on the workpiece as if it was in the real process.

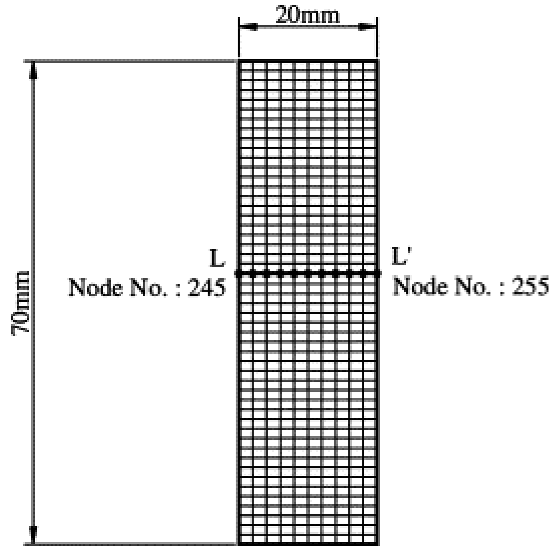

Fig. 2: Finite element meshing frame and the representative cross-sectional line on which strain distribution will be displayed.

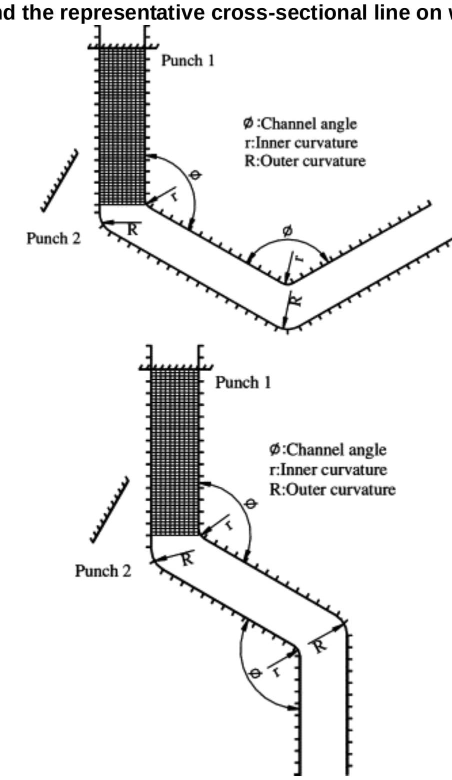

Fig. 3: Two re-entry cases with bends in the same and opposite directions, which simulates two passes of ECAE without entry rotation (top), and with 180° entry rotation (bottom).

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3 RESULTS AND DISCUSSION

3.1 Validation of the FEA

To verify that the results by finite element calculation are meaningful, analytical solution can be compared for simple or ideal cases. Three channel angles 120°, 105° and 90° with varied angular curvatures are considered. It needs to be pointed out that the listed strain value derived from analytical formula gives a single value. On the other hand, FEA can yield strain distribution across the extruded specimen as demonstrated in the following figures showing strain results. The values calculated by MARC and listed in Table 1 for a comparison are from the plateau part of the distribution curve.

Table 1. Comparison of strain by analytical formula and FEA under frictionless condition

Channel angle, ϕ (°)	Outer angular curvature, R (mm)	Corresponding angle to $R\phi'$ (°)	Equivalent strain (Eq. (1))	Equivalent strain (MARC)
120	20	60	0.605	0.639
	15	44.54	0.609	0.655
	10	28.82	0.623	0.643
	5	13.76	0.643	0.656
	0	0	0.667	0.652
105	20	75	0.756	0.801
	15	55.24	0.766	0.823
	10	35.01	0.796	0.824
	5	16.25	0.839	0.839
	0	0	0.886	0.838
90	20	90	0.907	0.920
	15	65.48	0.927	0.998
	10	40.25	0.983	1.017
	5	18	1.063	1.010

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3.2 Single ECAE pass under various processing conditions

3.2.1 Effect of the angle between extrusion channels

Strain distribution along the marked line L–L′ within the deformation zone for different angular conditions (ϕ=90°, 105° and 120°) are compared (Fig. 4). The effect is distinctive the sharper the angle, the higher the resulted strain.

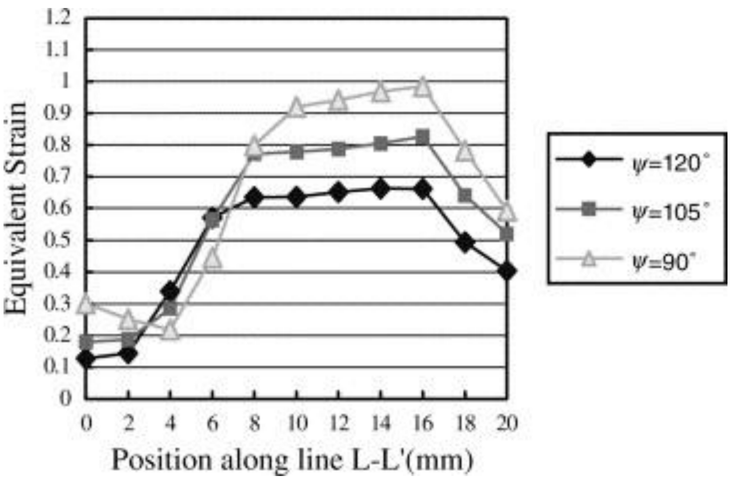

Fig. 4: Effect of the angle between channels on extrusion strain (μ=0.1, r=0, R=20 mm).

3.2.2 Effect of angular curvature

The point of angular intersection can be slightly rounded to present a smoother transition between channels for the subject material and facilitate billet passing. The effect of the curvature on strain conditions was investigated. Analysis showed that the inner curvature has a modest affect on strain distribution. However, it creates bigger unfilled gap for not or less rounded intersection (Fig. 5). When the outer curvature becomes larger, the strain distribution in the subject material shifts towards the right, and the bandwidth for uniform strain region is narrowed (Fig. 6).

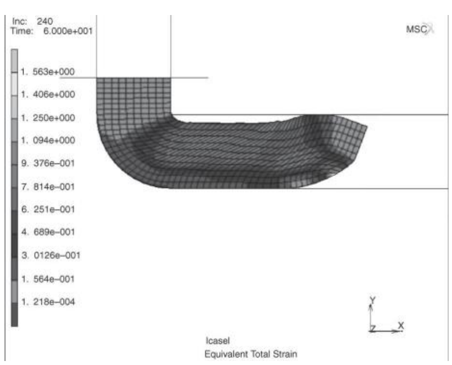

Fig. 5: The depleted region is the largest at sharpest inner curvature, r=0 (φ=90°, R=20 mm, μ=0.1).

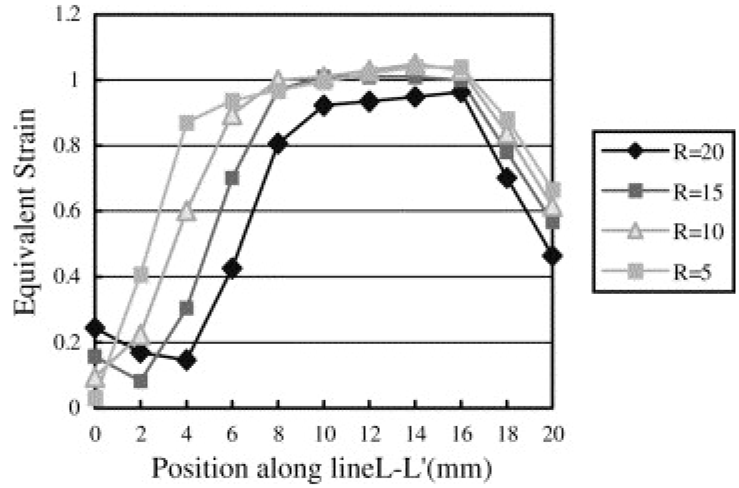

Fig. 6: Strain distribution corresponding to different outer angular curvature R (φ=90°, r=5 mm, μ=0.1).

3.2.3 Effect of friction between channel wall and work piece

The friction coefficients μ=0.1, 0.3, and 0.5 were used for calculation of each of the three channel angles and various angular curvatures. As displayed in a representative case (Fig. 7) , fiction condition does not affect the resulting strain distribution. It should be noted however, that the extrusion force may not be independent of friction, even though the strain clearly is.

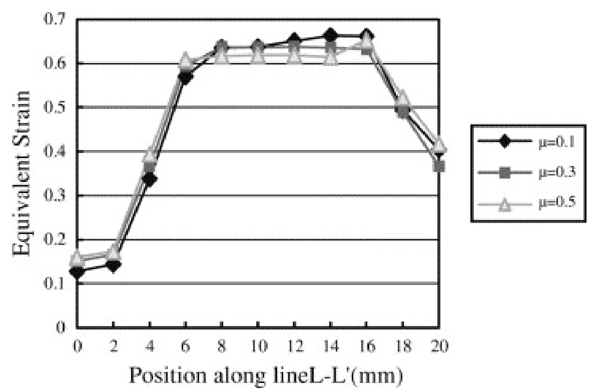

Fig. 7: Strain distribution corresponding to various frictional coefficients (φ=120°, r=0, R=20 mm).

3.3 Double passes

To simulate no entry rotation, a billet is passed through two sequential angular channel bent forward of 120°. The resulting strain distribution is shown in Fig. 8. Strain for the most part excluding the outer region after two passes is raised to a level toward but less than two times. In addition to confirming the general recognition of strain accumulation, this also predicts that the skin region of the subject material behaves differently. It would be interesting to verify this prediction by experiment. The other case, with the same extrusion channel angle but with 180° entry rotation, is presented in Fig. 9. When compared to the previous case, this figure indicates a dramatic outcome where the two-pass extruded material receives negligible strain. This can be explained that the positive strain installed after first pass is offset by the negative strain from the following second pass. However, real effect on structural change of material should not be concluded none because of this arithmetically nominal nil strain. The meaning of this calculation will be to remind that this route could yield some interesting phenomenon. Two more similar cases with channel angle of 105° were evaluated, and the results shown in Fig. 10 and Fig. 11 were similar to their counterpart with little dissimilarity.

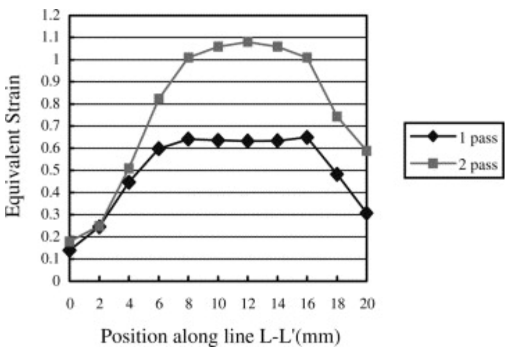

Fig. 8: Strain distribution after two passes of ECAE at φ=120° without entry orientation rotation (R=10 mm, r=5 mm, μ=0.1).

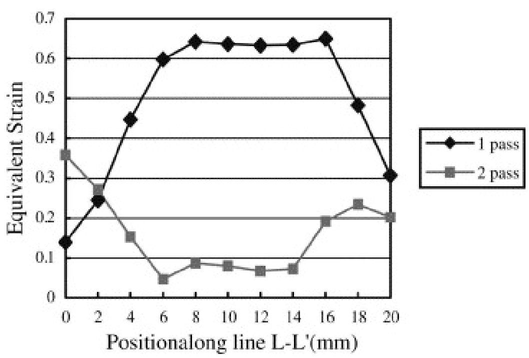

Fig. 9: Strain distribution after two passes of ECAE at φ=120° with 180° entry orientation rotation (R=10 mm, r=5 mm, μ=0.1).

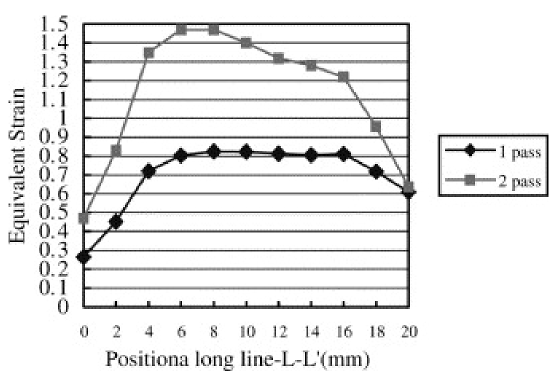

Fig. 10: Strain distribution after two passes of ECAE at φ=105° without entry orientation rotation (R=10 mm, r=5 mm, μ=0.1).

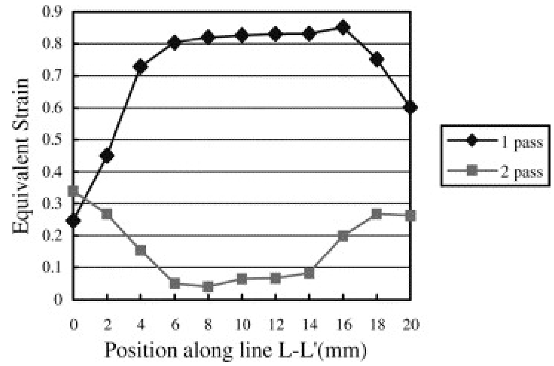

Fig. 11: Strain distribution after two passes of ECAE at φ=105° with 180° entry orientation rotation (R=10 mm, r=5 mm, μ=0.1).

4 SUMMARY

This work has presented the simulation of an equal channel angular extrusion process using a finite element analysis and the distribution of strain during the process to create some derivations with some parameters (die angle, friction between material and channels, etc). Factors of interest for the one-pass simulation were found to be die angles and fillet radii. For the multiple passes, however, the orientation of the sample for subsequent passes is of much interest. A two-dimensional simulation was presented in this work, but a third dimension should have been added for multiple; this would be considered in future works.

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