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Finite Element Analysis of the Bending Behavior of a Workpiece in Equal Channel Angular Pressing

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For the first time, a detailed and systematic finite element study was carried to identify the parameters which cause the bending of the workpiece in equal channel angular pressing. These simulations were carried out by using commercial finite element code Abaqus with different materials behavior, processing parameters, and die geometries. The results showed that the optimal ways to reduce the bending of strain rate sensitive materials in ECAP without varying the strain homogeneity are the usage of lower processing speed and the increase in length of the die exit-channel.

Keywords: equal channel angular pressing, corner angle, finite element analysis, bending, strain hardening, strain rate sensitivity, friction

1. INTRODUCTION

Equal channel angular pressing (ECAP) is one of the most promising severe plastic deformation (SPD) techniques, moving towards industrialization to fabricate bulk ultrafine grain materials [1-6] and compaction of powders [7,8] for different applications. To fabricate the bulk ultrafine grain materials, variety of die designs with different tool angles, and different processing routes have been used [1]. The strain distribution and deformation behavior during the ECAP, which was influenced by tool angles, friction, and material behavior, was studied through finite element analysis (FEA) [9-20].

However, very little emphasis has been given to the bending behavior of workpiece in ECAP. Indeed, there are several examples showing workpieces bent during ECAP in Ti and polymeric materials [21,22]. The bending of workpieces that were straight before ECAP produces many serious problems in the next processing, e.g. input of the workpiece for the next ECAP. The bent workpiece needs additional straightening or surface polishing [23-27] even if the amount of bending is small, and, hence, needs to be controlled during ECAP. However, there is no previous detailed study on the bending behavior in ECAP. Thus, in the current study the bending behavior of the workpiece in ECAP is analyzed through FEA by considering the effects of material, geometric, and processing parameters individually. Suggestions were made for alternate routes to reduce the bending of the workpiece in ECAP.

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2. FINITE ELEMENT ANALYSIS

In order to investigate the bending behavior in ECAP, detailed finite element simulations were carried out by using the commercial finite element code Abaqus [28]. Elastic-plastic material behavior is considered for all simulations. 2D plane strain simulations were carried out by using a workpiece width of 10 mm. Table 1 shows the details of simulation parameters used in the current studies. A friction coefficient of 0.1 is considered for all simulations. Figure 1 shows the finite element model of ECAP along with an indication of workpiece, ram, and die parts.

3. RESULTS AND DISCUSSION

Workpiece bending in ECAP is basically due to the asymmetric geometry of ECAP dies, which generates compressive

Table 1. Finite element simulation variables used to study the bending of workpiece in ECAP

Material $\sigma=k\varepsilon^n\dot{\varepsilon}^m$ Coefficient K		100 MPa
	Strain hardening exponent n	0, 0.2
	Strain rate sensitivity m	0, 0.1, 0.2, 0.3
Geometry	Outer corner angle ψ	0, 20°
	Exit channel length*	2 W, 5 W
Processing	Punch speed V	1, 0.1, 0.001 mm/s

*W = width of the work-piece

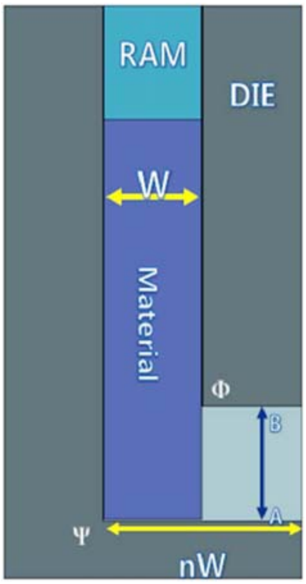

Fig. 1. Finite element model of ECAP where 'ϕ' is the channel angle, 'ψ' is the outer corner angle, 'W' is the width of the workpiece, 'nW' (n times the width of the workpiece) is the length of the exit-channel, and 'A-B' is the steady state region for analyzing the effective strain variation across the width of the workpiece.

and tensile states in the inner and outer regions, respectively, in the main deforming corner region. The influences of material behavior, processing parameters, and die geometry on the bending of the workpiece in ECAP are described in the following paragraphs.

Figure 2 shows the deformed geometries of the workpieces for different material behaviors. In case of perfectly plastic material (n = 0, m = 0), slight bending near the front end of the workpiece and the generation of severe strains along the bottom region are observable. The higher shear deformation in the bottom region locally elongates bottom region compared to the other upper region within the die channel; hence, the workpiece bends after getting out of the exit-channel. The generation of severe strains along the bottom region is due to the effect of friction. In the case of strain hardening material with n = 0.2, no bending is observable at the front end of the workpiece and the strain is uniform along the width direction due to the compensating effect of friction and strain hardening. The shear strain in the bottom

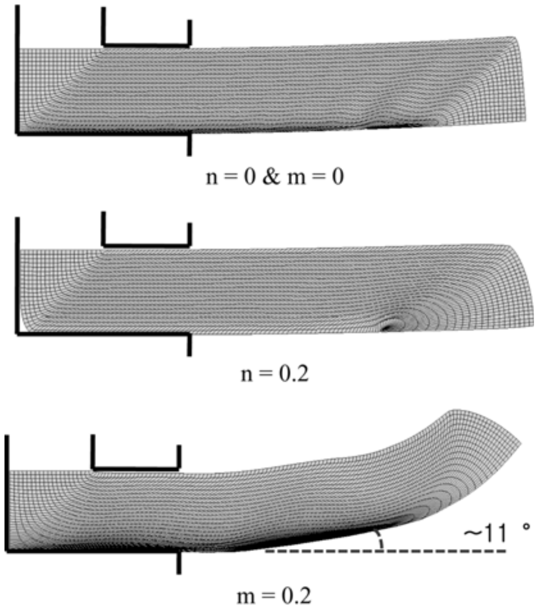

Fig. 2. Deformed workpiece with perfectly plastic (n = 0 & m = 0), strain hardening (n), and strain rate sensitivity (m) materials.

region is increased due to the friction effect and is reduced due to strain hardening effect. Strain hardening also generates a corner gap between the workpiece and die, which has been widely discussed in earlier studies [3,9,13,14]. This uniform deformation along the width direction is the main reason for the lack of bending. The strain rate sensitive material with m = 0.2 showed very large deformation in the bottom region (i.e. locally sheared and elongated); hence, the workpiece bends 11°, which is predominantly large.

From the deformed geometries of Fig. 2 with different materials behavior, it can be concluded that strain hardening is not an important factor for workpiece bending in ECAP. The main factor for bending among the investigated factors is the strain rate sensitivity of the workpiece.

Figure 3 shows the effect of strain rate sensitivity 'm' on the bending behavior in ECAP with different outer corner angle dies of ψ=0° and 20°. With increasing strain rate sensitivity, the strain in the bottom region becomes higher, and bending is higher with ψ=0°. The trend of bending behavior in the round corner die of ψ=20° is also similar to that of the sharp corner die with an increase in strain rate sensitivity. However, the strain in the bottom region is bit lower due to the smooth flow of the workpiece along the round corner. Bending is higher with a round corner die for high strain rate sensitive materials (m = 0.2 and 0.3) than those of a sharp corner die. It should be noted that the distinct bent workpiece in references are all strain rate sensitive materials, i.e. Ti-6Al-4V at 900 °C [22] and polycarbonate [21].

To analyze the influence of bending, the equivalent plastic strain variation across the width of the workpiece from bottom to top, A-B located in Fig. 1, in the central steady region

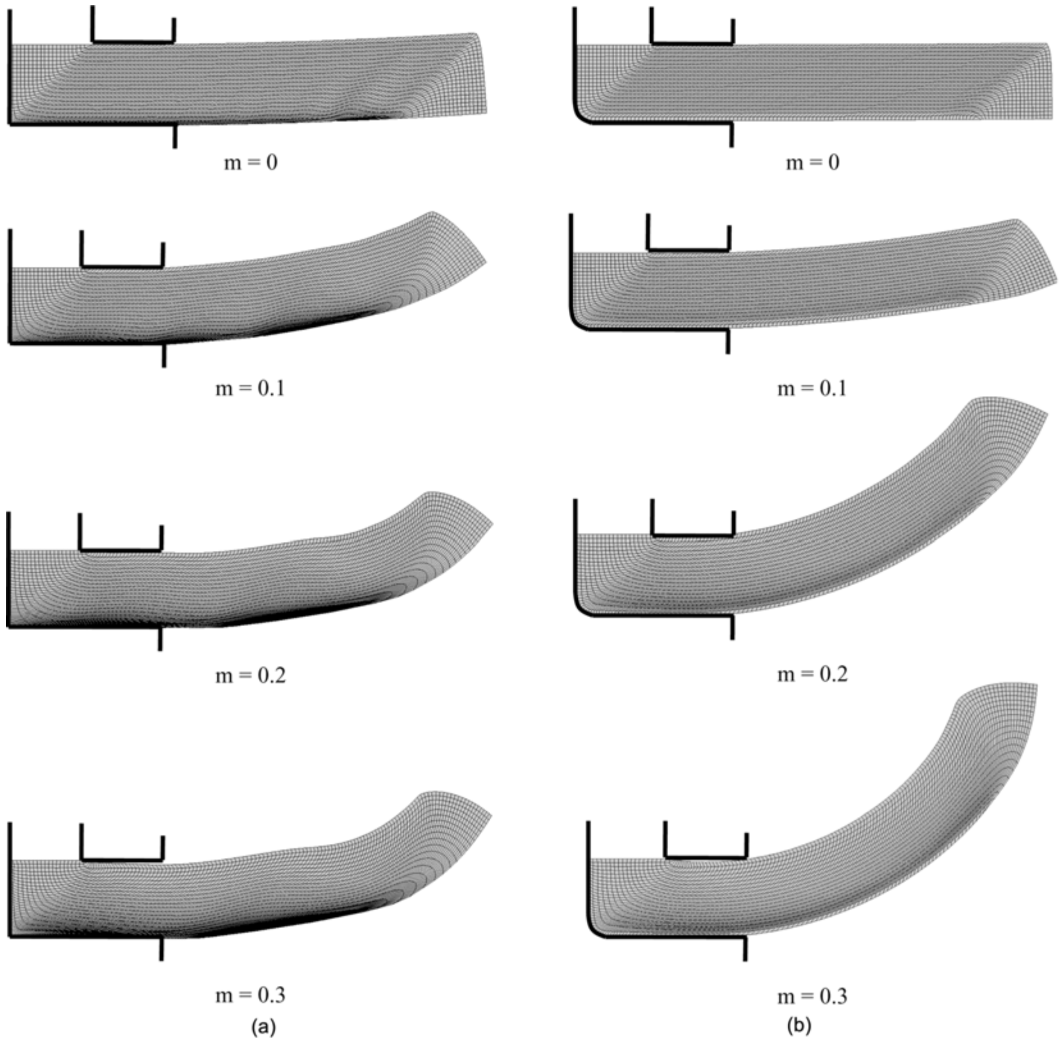

Fig. 3. Deformed workpiece processed through different outer corner angle dies (a) $\psi = 0^{\circ}$ and (b) $\psi = 20^{\circ}$ with different strain rate sensitivities.

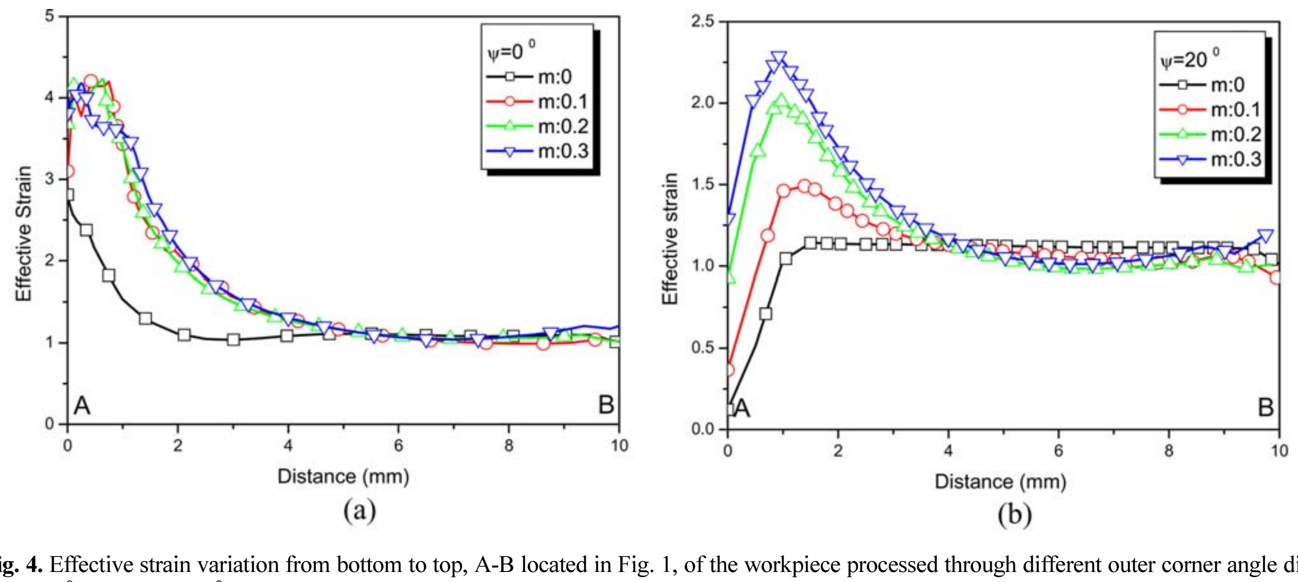

Fig. 4. Effective strain variation from bottom to top, A-B located in Fig. 1, of the workpiece processed through different outer corner angle dies (a) $\psi = 0^{\circ}$ and (b) $\psi = 20^{\circ}$ with different strain rate sensitivities.

is plotted in Fig. 4 for different strain rate sensitive materials with $\psi = 0^\circ$ and 20°. In the case of a sharp corner die, $\psi = 0^\circ$, the strain variation showed a similar trend with an increase in strain rate sensitivity, except with $m = 0$. However, the strain in the bottom 30 % of the width is very high compared to that above 70 % of the width. With the round corner die, $\psi = 20^\circ$, the strain is uniform above 70 % of the width for all strain rate sensitivities. However, the bottom 30 % of the width showed a gradual increase in strain with an increase in strain rate sensitivity. This clearly shows that the strain across the width of the workpiece becomes heterogeneous with an increase in strain rate sensitivity in a round corner die.

From the above two paragraphs, one can understand that the bending and strain heterogeneity become more pronounced with a round corner die. Hence, it is necessary to find ways to reduce the bending and strain heterogeneity in rate sensitive materials. Strain rate sensitivity is a material's intrinsic property at a fixed temperature and microstructure, but the controllable variables are die geometry and processing conditions. Thus, the simulations were carried with different processing speeds and different die exit-channel lengths to find the optimal routes to reduce the bending of the workpiece in rate sensitive materials. However, it should be stressed that the heterogeneity in the strain can be related to the bending response in a fixed geometry. If the geometry of the die is different, e.g. round corner and sharp corner dies, absolute strain values are different and it is meaningless to compare strain values between them in terms of bending.

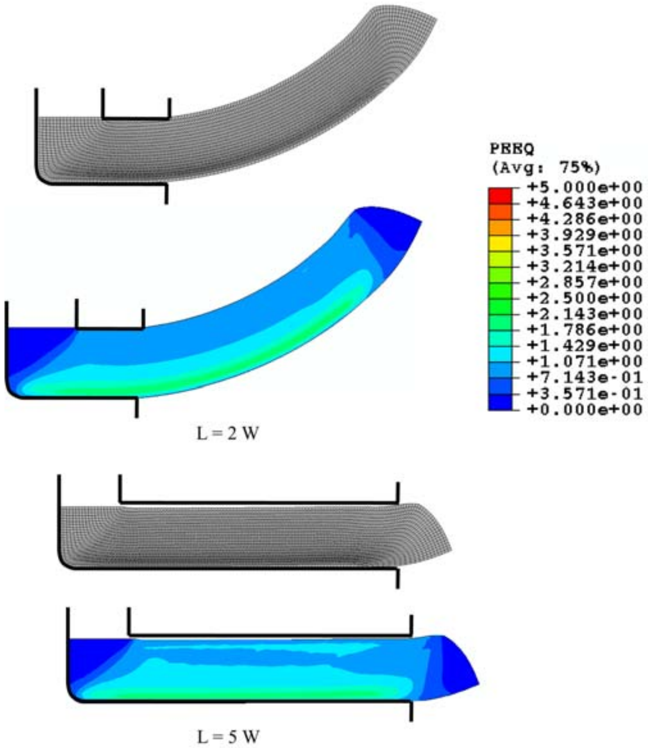

Fig. 6. Deformed workpiece and effective strain distribution with different die exit channel lengths for a strain rate sensitivity of 0.2, an outer corner angle of 20°, and a processing speed of 1 mm/s.

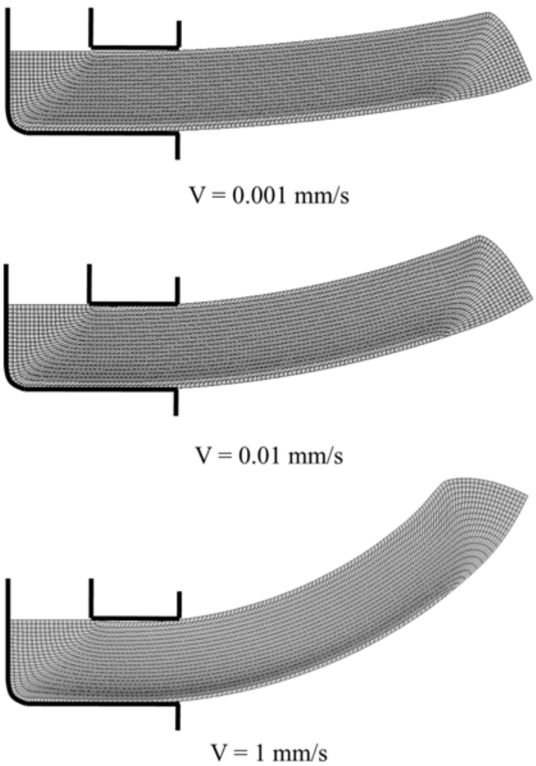

Fig. 5. Deformed workpiece with different processing speeds for a strain rate sensitivity of 0.2, and an outer corner angle of 20°.

Figure 5 shows the influence of the processing speed on the bending behavior of the workpiece. These simulations were carried out at different processing speeds for particular strain rate sensitivities with round corner dies. A lower processing speed of $v = 0.001$ mm/s showed lower bending of the workpiece. Thus, it clearly shows that strain inhomogeneity and workpiece bending can be reduced by decreasing the processing speed in rate sensitive materials.

The influence of exit-channel length on the bending behavior of the workpiece is shown in Fig. 6 in terms of deformed geometry and effective strain distribution. These simulations were carried out with different exit-channel lengths (two times the width of the workpiece and five times the width of the workpiece) for particular strain rate sensitivity and particular processing speed with round corner dies. Long exit-channel length showed lower bending compared to short exit-channel length; however, the strain distribution is almost uniform in both cases. Thus, this shows that there is a possibility to reduce the bending of the workpiece in rate sensitive materials by processing the workpiece with a large exit-channel length die, i.e. five times that of the workpiece width without varying the strain distribution.

The strain rate sensitivity cannot be reduced at elevated temperature. Hence, in those cases, the workpiece bending can be reduced by reducing the pressing speed and by extending exit-channel length of the die. The former method can enhance the strain homogeneity, but productivity becomes reduced. Therefore, increasing the exit-channel length is the optimal way to reduce workpiece bending in ECAP. These solutions are especially useful for ECAP processing at high temperature and high strain rate sensitive materials.

4. CONCLUSIONS

For the first time, detailed finite element simulations were carried out to analyze the bending of the workpiece in equal channel angular pressing by using commercial finite element code Abaqus. Simulations were carried with different materials behavior, processing parameters, and die geometries. The results showed that the bending of the workpiece in ECAP is mainly influenced by the strain rate sensitivity. With an increase in strain rate sensitivity, the workpiece processed through the round corner die showed increased bending and strain heterogeneity in comparison to the sharp corner die. The optimal ways to reduce the bending of strain rate sensitive materials in round corner dies are reducing the processing speed and increasing the length of the die exit-channel.

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