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New Formulas of Shear Strain during Equal-channel Angular Pressing Process with Consideration of Influences of Velocity and Motion Trajectory

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Abstract: The influences of die parameters on shear strain were investigated by using two-dimensional finite element simulation. New formulas of shear strain were proposed. According to the results of formulas, the shear strain showed a linear dependence on the difference between internal and external fillet radius and the slope was determined by the intersection angle. The simulation results indicated that the velocities of the points from different zones were different in the specimen and the motion trajectories of different points did not follow geometrical laws. The influences of the average velocity and the motion trajectory on shear strain were incorporated in the formula to calculate the shear strain produced during equal-channel angular pressing process. The reliability of simulation results has been partially validated by experiments.

Key words: equal-channel angular pressing; finite element method; shear strain; velocity; motion trajectory

The process of equal-channel angular pressing (ECAP) is such a procedure in which a material is subjected to an intense plastic strain by simple shear[1-5]. As the specimen passes through the intersection between both channels with identical section, the material is severely deformed by shear deformation. Submicrometric or even nanometric grain size can be obtained by using ECAP, which favors the improvement of mechanical properties, such as yield stress and ultimate stress[6-9]. Generally, as the important influencing factors of shear strain, the die geometrical parameters mainly include intersection angle Φ, internal fillet radius R_{int}, external fillet radius R_{ext}, and width of channel D[9-11].

In order to describe the plastic strain produced during ECAP, Segal et al.[1] first calculated the shear strain in the die with a sharp corner. Iwahashi et al.[12] proposed a die configuration which had a fillet radius in the outer part of the ECAP die and analyzed the shear strain. Luri et al.[9] further considered both internal and external fillet radius of the ECAP die and predicted the shear strain. However, the above formulas could not explain why the ECAPed specimen was inhomogeneous.

Finite element method (FEM)[13,14] has been widely used to analyze the ECAP procedure since it shows some advantages over slip line theory[15], analytical modeling of material flow[16], upper-bound method[17-19], as well as artificial neural network method[20], including powerful analysis function, high reliability and more details during ECAP process. Until now, FEM has been widely used to investigate the deformation homogeneity[21], the role of friction[22], back pressure[23] and die geometry[9,10,24] during ECAP process. Furthermore, strain hardening[25], strain-hardening rate[26] and plastic instability[27] during ECAP process have also been simulated using FEM.

In this paper, the influence of die geometrical parameters on shear strain during ECAP process was analyzed. Two-dimensional finite element analysis was carried out by using general purpose finite element software DEFORM-2D. The emphasis was placed on the velocities, the distance and the motion

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trajectories for the different locations of points during ECAP process. Considering the effect of the velocities and the motion trajectories, new formulas of shear strain were proposed. In addition, the influence of die structure on homogeneity was studied by using the new formulas. The simulation results were partially verified using XRD test, optical micrographs and distribution of the microhardness.

1 Finite Element Simulation

According to the previously reported literatures[9,10], there were four main geometrical parameters, including Φ, R_{int}, R_{ext}, and D as shown in Fig. 1. A die with Φ of 120° and D of 10 mm was used in the simulation. R_{int} and R_{ext} were changed from 0 to 10 mm with an increment of 1 mm. The die and punch were modeled as rigid bodies. A constant punch speed of 2 mm/s was imposed on the rigid plunger. An perfect plastic material was employed as the processed specimen because die corner gap would be formed as the material strain-hardening rate increased[28]. The yield stress σ_s of the specimen was 300 MPa. To make the specimen fully fill the die, a constant back pressure P (300 MPa), was applied under boundary condition. The friction between the die channel and specimen was assumed to be zero during the simulation.

According to study by Suo et al.[29], the plastic strain in the middle region was much more uniform and larger than those of the tail and head regions. Nine points in the middle region were used to analyze the strain homogeneity and the points positions were defined as shown in Fig. 1. Points 1—9 in the plane were equidistant from one to another and the distance was 1 mm in X axis direction. The distance from the points 1—9 to the head of the specimen was 15 mm in Y axis direction.

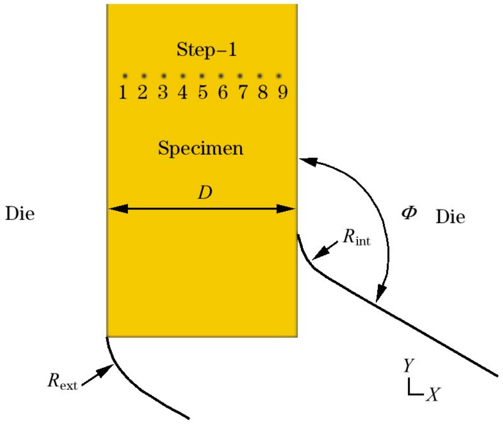

Fig. 1 Die structure and target points for FEM simulation

2 Experimental

The material used in this investigation was hot-rolled 304L stainless steel with composition in mass% of C 0.01, Cr 18.56, Ni 8.82, Si 1.58, S 0.008, P 0.015, Mn 0.5, and Fe balance. Before processing, the specimens were annealed at 1150 ℃ for 2 h followed by air quenching. Circular specimens with dimensions of ϕ10 mm×6 mm were pressed via ECAP process at room temperature with the ram speed of 2 mm/s. A die with $\Phi=120°$, $D=10$ mm, $R_{\text{int}}=0$ and $R_{\text{ext}}=10$ was used.

The phase constitution was determined by X-ray diffraction (XRD) on a Panalytical X-pert′PRO diffractometer at room temperature using CuKα radiation. Microstructure observations were carried out on an Olypus-Pmg311u optical microscope. The Vickers microhardness test was performed using an HX-1000TM digital hardness tester. The schematic diagram of measured plane is shown in Fig. 2. The microhardness value was measured using a regular grid pattern with spacing of 1 mm in X direction and 0.5 mm in Y direction. The central zone was the center of the measured plane and the external zone was about 1.0—1.5 mm from the bottom edge.

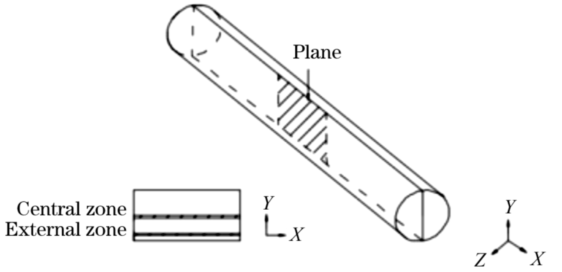

Fig. 2 Measured plane of ECAPed specimens

3 Results and Discussion

3.1 Theoretical analyses

According to the studies performed by Luri et al.[9], the shear strain γ is given by Eq. (1):

$$\gamma=\begin{cases}2\cot\left(\dfrac{\Phi}{2}-\dfrac{x}{2}\right)-(\pi-\Phi)\left[1-\cot\left(\dfrac{\Phi}{2}-\dfrac{x}{2}\right)\cdot\tan\left(\dfrac{\Phi}{2}\right)\right] & R_{\text{int}}>R_{\text{ext}}\\ 2\cot\left(\dfrac{\Phi}{2}\right) & R_{\text{int}}=R_{\text{ext}}\\ 2\cot\left(\dfrac{\Phi}{2}+\dfrac{x}{2}\right)-(\pi-\Phi)\left[1-\cot\left(\dfrac{\Phi}{2}+\dfrac{x}{2}\right)\cdot\tan\left(\dfrac{\Phi}{2}\right)\right] & R_{\text{int}}<R_{\text{ext}}\end{cases}\qquad(1)$$