Prediction of Temperature Rise in Equal Channel Angular Pressing

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In order to investigate the temperature rise of the workpiece during equal channel angular pressing (ECAP), a lumped heat transfer analysis was made. The main deforming zone was taken as the analysis domain. The temperature rise due to the work of plastic deformation and the frictional heat was considered. An equation for the temperature rise during the ECAP process was derived. The temperature increment increases with the strength of the material, the ram speed and the channel angle, and decreases as the density, the heat capacity and the die corner angle increase. The model was applied to Al and Al alloys with different ultimate tensile strengths. The calculated temperature rise is in good agreement with published experimental results.

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1. Introduction

Equal channel angular pressing (ECAP) is conducted not only at a room temperature but also at elevated temperatures. Although the former is more common, as the grain refinement effect and the associated strengthening of the material can be fully retained, hot or warm working may be required for difficult-to-work alloys that may develop shear cracking during ECAP.¹⁾ The temperature change, due to plastic work release, die chill and frictional heat between the die and the specimen, is important under both cold and hot working conditions, because a temperature rise may induce phase transformations or changes in the microstructure, notably in the grain boundary structure.²⁾ These effects, in turn, can modify the flow stress of the workpiece material as well as other mechanical properties. Since the grain refinement by severe plastic deformation is supposed to be related to the short-range diffusion, the warm working or the recovery process play an important role. Hence, estimating the temperature rise during ECAP is of significant interest for process design.

Numerous studies on ECAP²⁾ were performed and significant progress was made on the process and the understanding of fundamental properties of the pressed materials. On the other hand, few studies of heat transfer during ECAP were conducted. Yamaguchi *et al.*³⁾ measured the temperature change of the Al and the Al alloy specimens at various ram speeds. DeLo and Semiatin¹⁾ investigated the non isothermal behaviour of metals during ECAP using finite element analysis. Segal⁴⁾ found recrystallized grains inside localized shear zones demonstrating significant adiabatic heating. However, to the author's knowledge, no theoretical investigation of the thermal problem associated with ECAP has ever been reported in the literature. Although the finite element method with thermomechanical coupling produces a lot of information, an approximate analytical solution is still necessary for a fast parametric study. It is therefore meaningful to develop a simplified quantitative formulation to predict the temperature rise within the workpiece during ECAP in order to understand the material properties and to optimize the process design.

cess design.

In the present study, a lumped heat transfer analysis was performed to investigate the temperature rise of the workpiece during ECAP. Various factors affecting the temperature change will be discussed.

2. Heat Transfer Analysis

Figure 1 shows the schematic diagram of ECAP, where two channels of equal cross-section intersect at an oblique angle Φ . The die corner angle Ψ lies between $\Psi = 0$ and $\Psi = \pi - \Phi$. The dashed area that indicates the main deforming zone is a heat generating zone due to plastic work and frictional heat. For the heat transfer analysis, the main deforming zone is taken as the calculation domain. If the die corner angle Ψ is zero, deformation occurs an immediate vicinity of the plane, *i.e.* the shear plane, lying at the intersection of the two channels. In ECAP, the length of a workpiece is much longer than its width or thickness. ECAP can be regarded as a steady state process, like continuous casting or hot rolling, except for the two end parts of the workpiece where the steady state assumption does not hold. Since the convection term ($\rho Cu(dT/dt)$) is much larger than the conduction

Fig. 1 Schematic diagram of ECAP. The main deforming zone (dashed area) is a deformation induced heat generating zone.

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term ($k(d^2T/dx^2)$) owing to the high speed of motion of the workpiece in the ECAP process, the conduction heat transfer along the length of the workpiece is negligible. Here ρ , C , k , u , T , t and x denote density, heat capacity, thermal conductivity, velocity, temperature, time and coordinate in the length direction, respectively. The above assumption is generally used in steady state motion process.^{5,6)}

The internal heat generation due to the plastic work within the main deforming zone of the specimen is transferred to the ECAP die and the remaining energy is stored. The internal heat generation due to the plastic work is usually around 90% of the work of plastic deformation.⁷⁾ The plastic deformation work W per unit volume can be represented as

$$W = \int \bar{\sigma} d\bar{\epsilon}, \quad (1)$$

where $\bar{\epsilon}$ and $\bar{\sigma}$ are the equivalent von Mises strain and stress, respectively. Since the strain is high and stress is almost saturated during ECAP, the plastic work (the area in the stress-strain curve) can be approximated as the product of the final strain, ϵ , and the final (or saturation) stress, σ . That is, $W = \sigma\epsilon$.

The heat generation rate per unit area due to the friction between the ECAP die and the workpiece,⁷⁾ q_f , is calculated as

$$q_f = f_s u = m(\sigma/\sqrt{3})u, \quad (2)$$

where f_s is the friction stress, u is the relative velocity between the die and the workpiece, and m is the friction factor. The frictional heat, q_f , may be assumed to be evenly distributed between the die and the deforming material, thus, half of the frictional heat is taken to be transferred to the workpiece.^{5,6)}

Ignoring the temperature distribution within the main deforming zone of the specimen, the problem reduces to a lumped analysis, in which details of temperature distribution within the specimen are neglected and average temperature increment is considered. The energy balance can then be written as the following energy conservation equation,

$$\rho CV \Delta T = 0.9\sigma\epsilon V - Ah\Delta T \Delta t + 0.5m(\sigma/\sqrt{3})uA\Delta t, \quad (3)$$

where ρ , C , V , ΔT , A , Δt and h denote the density of the material, its heat capacity, the volume of the calculation domain (*i.e.* of the main deforming zone), the temperature increment in the domain, the outer surface area of the domain contacting the die, the dwell time of the domain within the deforming zone and the heat transfer coefficient between the workpiece and the die, respectively. By taking the passing time of the volumetric center point through the main deforming zone, the average dwell time Δt can be written as

$$\Delta t = \frac{d}{u} \frac{\Psi}{\sqrt{2\pi}}, \quad (4)$$

where d is the diameter of the cylindrical workpiece. The average dwell time, Δt , is high if the ram speed, u , is low. Another important factor determining Δt is the die corner angle Ψ , in that the average dwell time Δt increases with the die corner angle Ψ .

In eq. (3), the left hand side term is the energy stored within the domain and the first term on the right hand side is the

energy generated. The second and the third terms on the right hand side are the estimated heat transferred to the outer part of the deforming zone and the heat generated through friction, respectively. The temperature rise ΔT of the workpiece can be rewritten as follows:

$$\Delta T = \frac{0.9\sigma\epsilon + 0.5m(\sigma/\sqrt{3})u \frac{A}{V}\Delta t}{\rho C + \frac{A}{V}h\Delta t}. \quad (5)$$

From the geometrical consideration, the volume and the surface area of the main deformation zone are $V = (\pi^2/4)d^3(\Phi/2\pi)$ and $A = \pi^2 d^2(\Phi/2\pi)$, respectively.

For the strain ϵ developed during ECAP that enters eq. (5), the equation proposed by Iwahashi *et al.*⁹⁾ can be used.

3. Results and Discussion

In order to assess the model proposed, the calculated temperature rise is compared with the experimental data for Al and Al alloys available in the literature.³⁾ The channel angle Φ and the die corner angle Ψ were 90° and 45° , respectively, which corresponds to an effective strain of 0.969. The diameter d of the cylindrical workpiece was 10 mm. The parameter values for pure Al and the alloys (Al-1Mg, Al-3Mg and Al 1100) used are set to be the same: $\rho = 2700 \text{ Kg}\cdot\text{m}^{-3}$, $C = 900 \text{ J}\cdot\text{Kg}^{-1}\cdot\text{K}^{-1}$.⁸⁾ The friction factor $m = 0.2$ between the workpiece and the die, which is a typical value^{5,6)} in the cold forming of metals with conventional lubricants, was used. The heat transfer coefficient $h = 2000 \text{ N/m}\cdot\text{s}\cdot\text{K}^{10)}$ was used.

Figure 2 shows a comparison of the calculated (using eq. (5)) and the experimental temperature increments for various materials with the ultimate tensile strength at various ram speeds, with $\Phi = 90^\circ$ and $\Psi = 45^\circ$. The temperature increment increases with the strength of the material according to eq. (5), all other conditions being the same. The calculated line matches the experimental temperature increment of the Al and Al alloys well for both fast ($18 \text{ mm}\cdot\text{s}^{-1}$) and slow

Fig. 2 Comparison of the calculated and experimental temperature increase for various materials with the ultimate tensile strength at very fast ram speed, $\Phi = 90^\circ$ and $\Psi = 45^\circ$.

Table 1 The factors affecting temperature rise of a workpiece during ECAP.

Material factors	Increasing the temperature rise	Flow stress
	Decreasing the temperature rise	Density, heat capacity
Process factors	Increasing the temperature rise	Ram speed, Strain, Die intersect angle, Die friction, Die temperature
	Decreasing the temperature rise	Die corner angle, Die chill

($0.18 \text{ mm} \cdot \text{s}^{-1}$) conditions: the temperature rise increases linearly with the ultimate tensile strength, although the calculated temperature line lies slightly lower than the experimental ones. Although the average temperature increment in Al alloys is smaller than 100 K, it may exceed 150 K for copper that has a flow stress in excess of 400 MPa. The local temperature rise can be even higher than 200 K. This temperature rise can result in the recovery of the defect structure of grain boundaries and in a pronounced decrease of the internal stresses in Cu.²⁾ The temperature rise during ECAP can be even more serious for high strength materials. For example, the ultimate tensile strength of Ti is above 1500 MPa and, in this case, the increased temperature of the Ti workpiece can easily be higher than the starting temperature for grain growth, *i.e.* 350 K.²⁾

The possible factors which can affect the temperature rise of the workpiece during ECAP are listed in Table 1. Most of the factors can be elucidated by eq. (5). The factors in Table 1 can be utilised as indicative for a heat transfer analysis of ECAP, at least qualitatively. By adjusting both the material and the process factors shown in Table 1, it would be possible to control the mechanical properties related to temperature.

4. Conclusions

A lumped heat transfer analysis that ignores the temperature inhomogeneity of the workpiece was made in order to investigate the temperature rise of the workpiece during ECAP. The deforming zone was taken as the analysis domain. The temperature rise due to the work of plastic deformation and the frictional heat was considered. The temperature rise equation for ECAP was derived. The temperature rise increases with the strength of the material, the ram speed and the channel angle, and decreases as the density, the heat capacity and

the die corner angle increase. The model was applied to Al and Al alloys with different ultimate tensile strengths. The calculated temperature rise is in good agreement with published experimental results. Due to the deformation induced heat release, the temperature rise during ECAP with high ram speed, especially for high strength materials, can be as large as to raise the workpiece temperature above the recovery temperature or the grain growth temperature. The heat transfer analysis presented in this study can be used as an informative method to control the ECAP process parameters.

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