3D finite element study of temperature variations during equal channel angular pressing

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ABSTRACT

Equal channel angular pressing is the most promising method of severe plastic deformation with the capability of producing ultrafine-grained materials. The temperature variation in the sample during ECA-pressing is a key factor in determining the final microstructure and mechanical properties of the processed material. Therefore, in the present study, temperature rise and temperature distribution in the sample were studied with the aid of finite element simulation. In this regard, the effect of friction, ram speed and material type on the amount of temperature rise as well as the temperature profile in the sample was investigated. Results of FEM simulations showed good consistency with the temperature data obtained in the experimental work. In addition, it was shown that the sample temperature increases with the increase of friction, ram speed and work hardening coefficient of the material.

1. Introduction

Nanostructured metallic materials have unique mechanical, chemical and physical properties. These materials have many engineering applications. One method for processing of these materials is severe plastic deformation [1-3]. Among different methods of severe plastic deformation, ECAP is the most common technique. This method was used for the first time by Segal et al. in 1977 [4]. Schematic representation of this method is shown in Fig1. ECAP die has two intersecting channels of square or circular cross-section. The intersection angle of the two channels and the outer curvature angle are marked with Φ and Ψ, respectively. In this approach, a sample with circular or square cross-section is crossed through the die channel. Shear strain is exerted on the sample when passing through the intersection of the two channels. The amount of the strain applied to the samples, in one pass through the die channel, is calculated by the following equation [5]:

$$\bar{\varepsilon} = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right] + \psi\,\mathrm{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right) \qquad [1]$$

Since the microstructure and grain size of ECAPed materials are very dependent on deformation conditions, deformation process should be studied carefully. Most studies in this field were conducted using finite element simulation. In these reports the deformation process is considered as an isothermal process [6-11]. Under such a condition, the results of finite element simulation are true only in the

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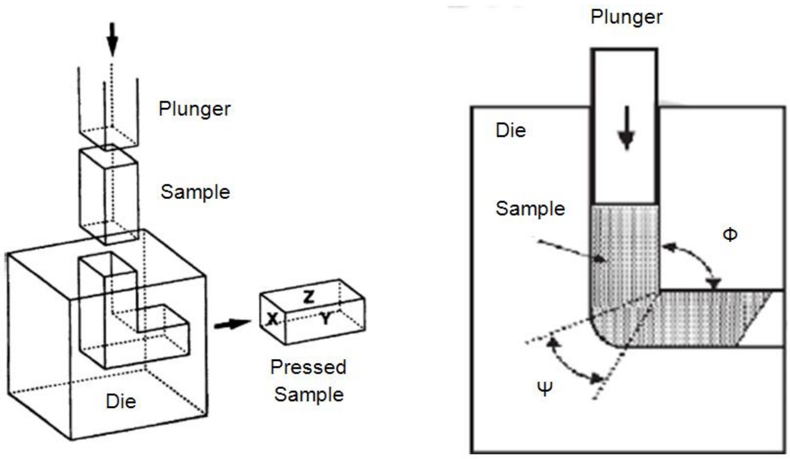

Fig. 1. Schematic representation of the ECAP process [5]

Table 1. Coefficients of the flow characteristics of the investigated materials [13]

Alloy	m	n	C	B (MPa)	A (MPa)
Al-1%Mg	0.78	0.266	0.0234	116.32	53.68
Al-3%Mg	0.65	0.236	0.0421	177.46	82.56

case of low pressing speed processes [14]. At high rates of the deformation process, the value of temperature rise during deformation is very high. During the ECAP process, an increase in temperature has a strong effect on the resultant microstructure and flow behavior of the material. The two-dimensional simulation of temperature changes during ECAP exists [13] but heat transformation is a three-dimensional problem. In addition, the effect of tensile strength on temperature rise during equal channel angular pressing has been studied by Kim et al. [14] but there is not any systematic study on the prediction of the effect of processing parameters and material properties on the three-dimensional temperature distribution in the sample. Therefore, in this research, the effect of various deformation parameters including pressing speed, friction coefficient and material type on the temperature changes during deformation is investigated using three-dimensional finite element simulation.

2. Experimental

In this study, three-dimensional finite element analysis of temperature-displacement was conducted by the use of ABAQUS 6.7 software. To investigate the effect of deformation parameters on the temperature and flow behavior of the metal, Al-1%Mg and Al-3%Mg were used as reference alloys due to their thermal and mechanical properties as reported in the literature [13]. For high accuracy of the simulation results, a model can be used that involves the effect of temperature and strain rate on the flow stress of the material. In the present study, Johnson-Cook model was used. In this model, the flow stress of the material is calculated using the following equation [12]:

$$\sigma = (A + B\varepsilon^n).\left[1 + C\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})\right].\left[1 - (\frac{T - T_r}{T_m - T_r})\right] \quad [2]$$

where ε, $\dot{\varepsilon}$, T, T_m, T_r, and $\dot{\varepsilon}_0$ are strain, strain rate, temperature, melting temperature, reference temperature, and reference strain rate, respectively. Also, A, B, C, n and m are material parameters.

The material parameters of the two investigated aluminum alloys are presented in Table 1. In addition, thermal properties and the effect of normal pressure on heat transfer from work piece to the die are shown in Table 2. In the finite element simulation the sample dimensions are selected as 10*10*60 mm^3. The sample is meshed with 6000 thermal-displacement elements. Besides, it was assumed that 90% of the work is converted to heat.

Table 2. Heat transfer coefficients for the investigated alloys [13]

conductivity(W/m K)	density(kg/m^3)	specific heat(J/kg K)	alloy
200	2700	890	Al-1%Mg
130	2670	890	Al-3%Mg

Conductivity as a function of radial pressure

Interface Pressure (MPa)	0	0.03	0.085	14	85
Heat Transfer Coefficient (Kw/m^{3}K)	0.5	0.9	4	6.5	7.5

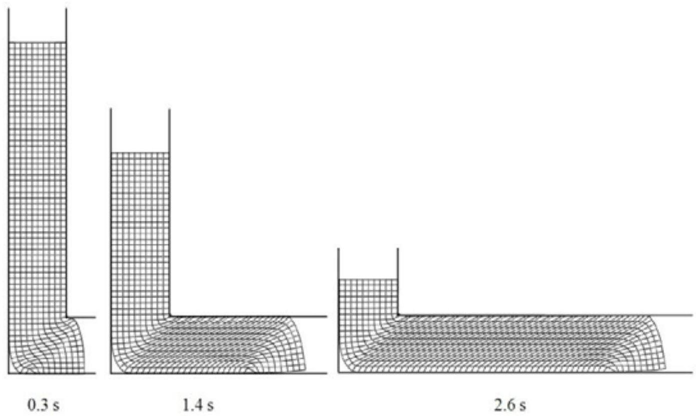

Fig. 2. Element distortion during ECAP

3. Results and Discussion

3. 1. Deformation of the sample during ECAP

Starting with the moving down of the punch and its contact with the sample, very strong shear stress is applied to the sample. Under shear stress, the material flows toward output channel. Fig 2 shows the element distortion during deformation of Al-3Mg alloy at different time steps. As can be seen, rectangular elements cross the intersection of the two channels and distorted into a parallelogram shape. Fig 3 represents strain, strain rate and temperature distribution in the sample (Al-3%Mg) in frictionless condition and the pressing speed of 18 mm/s. The processed sample is divided into four regions based on the distribution of the strain inside it. At the beginning of the deformation process, no shear stress acts on the head of the sample. Accordingly, this part of the sample does not bear any shear deformation. This part of the sample is called the area without deformation (region I in Fig 3). In the next zone, deformation is uniform throughout the area of the applied constant shear strain (Region II in Fig 3). In this region, the elements are regularly stretched through the shear direction. The third part of the sample is deformation zone. The imposed strain in this part of the sample increases with movement along the longitudinal axis of the sample and the flow direction. This area is clearly distinguished considering the applied strain rate (Fig 3 (b)). It is obvious that maximum temperature is located in region (III) of the sample. The fourth region is the free end of the sample (Fig 3).

3. 2. Comparison of the simulation results with real data

Fig 4 shows the central temperature of the sample as a function of time. The solid curve corresponds to the results of the simulation and the dashed line is relevant to the real changes in temperature at the center of the sample which was obtained by inserting a thermocouple through the center of the specimen [15]. These curves are divided into two regions. Regions I and II show the variations of temperature and the temperature at the center of the specimen during the deformation and cooling in the die, respectively. The maximum temperature is related to the central area when passing through

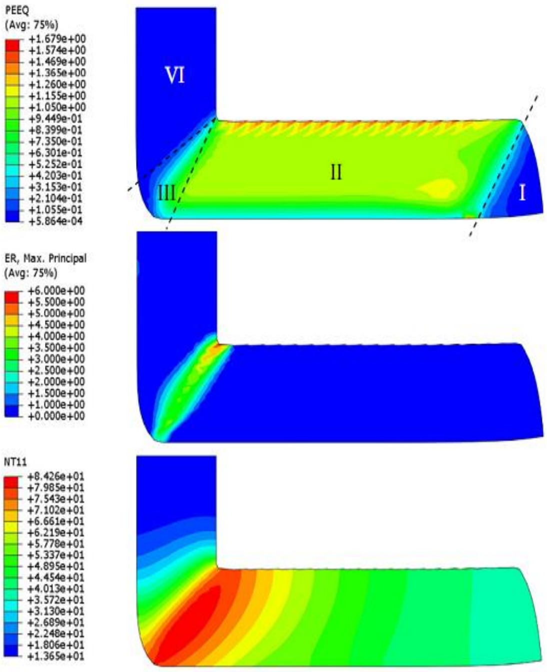

Fig. 3. Distribution of the strain (a), strain rate (b) and temperature (c) inside the sample during ECAP

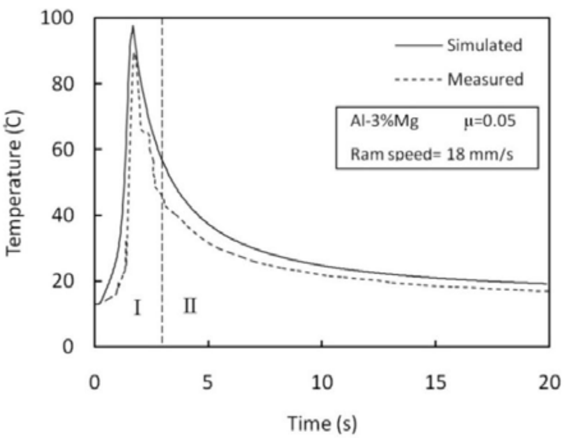

Fig. 4. Comparison between real temperature variations at work-piece centerline and the simulation results [13, 14]

the intersection of the two channels. As can be observed, there is a good consistency between the simulated and the actual temperature variations. However, the actual temperature is slightly lower than the simulated temperature. The slight difference between the actual and the simulated temperature is due to the different way of punch moving [13]. In the simulation, the punch velocity is considered to be constant (18 mm/s) during the deformation process, while in operation, the punch velocity is not constant. In practice, the sample velocity is zero at the beginning of the deformation process [13], while in the beginning of the simulation the punch velocity is constant and equal to 18mm/s. The rapid increase of temperature in the simulation mode to the real mode is not unexpected. The rapid decrease in the deformation temperature at real mode is due to the gradual decline of the punch velocity at the end of the deformation process [13].Given the foregoing, it can be concluded that the finite element analysis results are of high accuracy.

3. 3. The effect of friction on temperature variations

Fig 5 shows the temperature distribution of Al-3%Mg alloy after applying deformation with the rate of 18 mm/s and different friction coefficients. As can be seen, the temperature distribution in the sample is not uniform. The maximum temperature is in the region of intersection of the two channels. Also, the temperature decreases with an increase of distance from the deformation zone. The comparison exhibits that the temperature distribution in the sample is not changing with altering friction between the samples and the die channel. Only the temperature of the sample is affected by the friction coefficient. By increasing the friction coefficient, the temperature of different regions of the sample is raised. Temperature variations in the center of the sample during deformation with ram speed of 18mm/s are shown in Fig 6. Friction has no effect on the pattern of temperature changes in the center of the sample. Thus, with movement of the central part of the sample within the die toward the deformation zone, the temperature increases gradually and reaches the maximum temperature in the deformation zone. After the deformation, the sample temperature gradually decreases due to heat transfer from the sample to the die. As can be seen, with increasing the friction, the center temperature of the sample increases. Fig 7 shows the influence of friction on the maximum temperature rise in the center of the sample. As can be seen, the amount of temperature rise in the sample increases with increasing friction between the specimen and the die channel wall. It is clear that the temperature of the center of

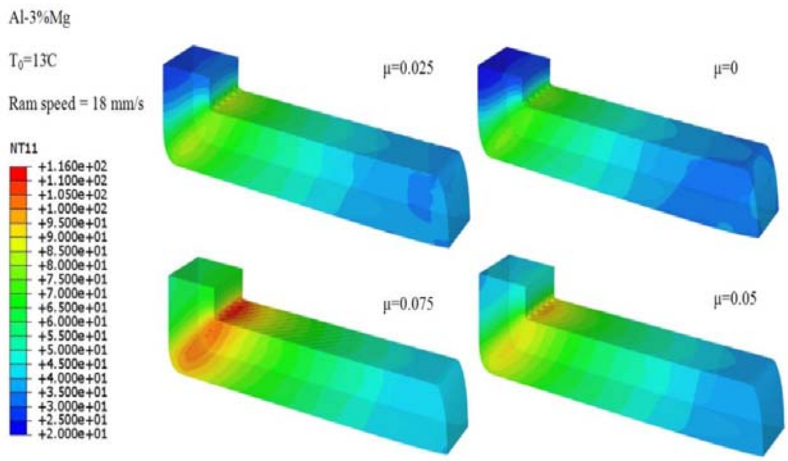

Fig. 5. Temperature distribution in the deformed sample with punch velocity of 18 mm/s at different friction coefficients

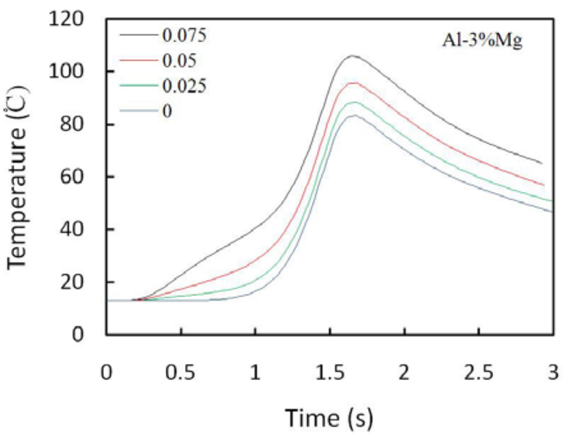

Fig. 6. The effect of friction coefficient on temperature variation at the sample centerline with the ram speed of 18mm/s.

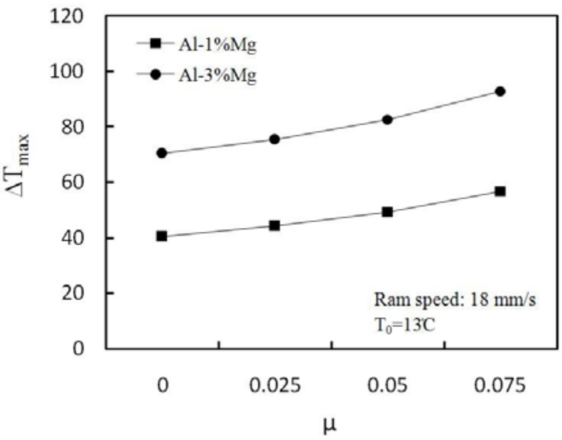

Fig. 7. The effect of friction coefficient on maximum temperature rise at the specimen

the Al-3%Mg samples is higher than that of the Al-1%Mg specimens. This is due to the high specific heat capacity of the Al-1%Mg alloy and higher flow stress of the Al-3%Mg alloy. With increase of the flow stress, the deformation temperature increases. The temperature of the material at a constant deformation heat increases with decreasing the value of specific heat capacity.

3. 4. The effect of punch velocity on the temperature variations inside the sample

Temperature distribution in the sample after deformation at different punch speeds is shown in Fig 8. In all parts of the sample the temperature increases with increasing the punch speed and therefore imposes strain rate. The increase in temperature is due to an increase in deformation heat generation during the ECAP process. It is observed that the velocity of the punch did not have any impact on the temperature distribution pattern of the sample. Fig 9 represents the effect of the punch speed on the temperature variation through the sample center line. As can be seen, at high punch speeds the temperature at the centerline of the sample increases suddenly and decreases after the deformation. At low punch speeds, the temperature increase and decrease occur gradually. Fig 10 shows the maximum increase of temperature at the sample centerlines for the Al-1%Mg and Al-3%Mg alloys. With increase of the pressing speeds, the maximum temperature rise in the center of the sample

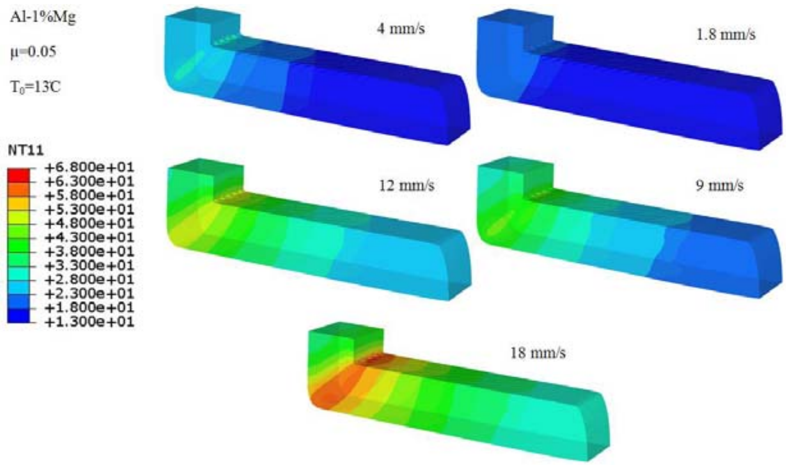

Fig. 8. The effect of the ram speed on temperature distribution inside work-piece

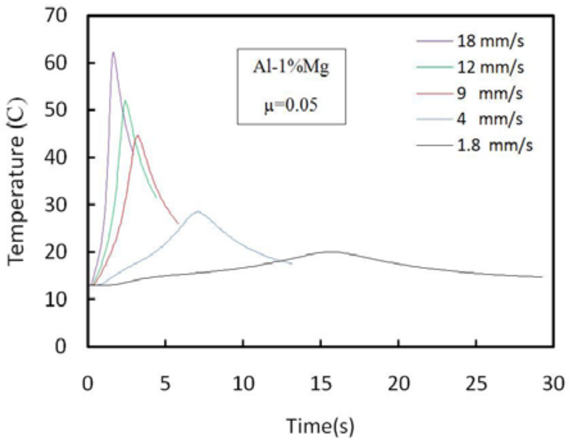

Fig. 9. The effect of the pressing speed on temperature variation at the centerline of the sample

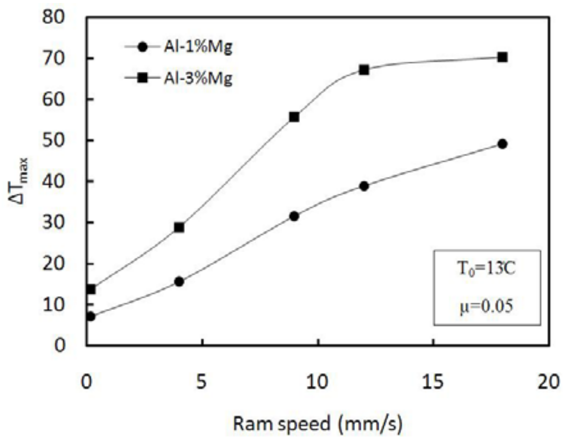

Fig. 10. The effect of pressing speed on maximum temperature rise at centerline of the sample

increases. However, in the case of Al-1%Mg alloy, the temperature is higher than Al-3%Mg due to the low heat transfer coefficient and specific heat capacity.

4. Conclusions

In the present study, the effect of deformation parameters and material type on the flow behavior and temperature variations during equal channel angular pressing was investigated. The results are summarized as follows:

1. 3D finite element simulation was used to calculate the temperature rise during severe plastic deformation. A good consistency between the simulation and experimental results was observed.

2. It was found that the amount of temperature rise increased with increasing the strength and strain hardening coefficient of the material.

3. From the simulation results it was concluded that friction coefficient and pressing speed have a strong effect on temperature rise during equal channel angular pressing.

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