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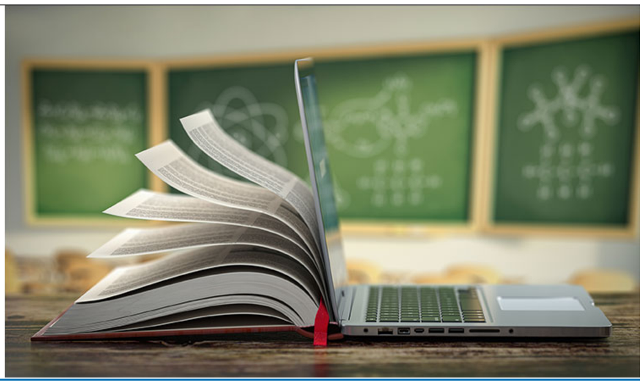

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Theoretical estimation, simulation and experimental evaluation of deformation-induced heating of magnesium during lateral extrusion

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Abstract. Theoretical estimation, computer simulation and experiment were performed to evaluate temperature of the deformation heating of magnesium during severe plastic deformation by lateral extrusion method. The simulation of the deformation process was carried out by DEFORM-3D. Experimental temperature measurement of magnesium deformation-induced heating at the deformation zone was made. According to the simulation, temperature of the magnesium billet has reached 114°C during deformation. Experimental results showed that the maximum temperature of deformation heating of the material is ~ 140°C.

1. Introduction

It is known that severe plastic deformation (SPD) methods, such as equal channel angular pressing (ECAP) or high pressure torsion (HPT), are used to obtain materials with ultrafine-grained structure and improved mechanical properties [1, 2]. SPD could be performed at different temperatures, either at higher or lower than the recrystallization temperature of material. However, to produce fine-grained structure material, it is recommended to deform metal at low temperature to prevent active recrystallization process. Nevertheless, even at low-temperature deformation, the heating could be possibly induced by large compressive stresses and by friction between the billet and the inner container wall [3]. In this case, the highest temperature would be in the deformation localization zone. On the one hand, the deformation heating has positive aspects, e.g., the plasticity of the deformable materials is increased and the load on the experimental tool is reduced. On the other hand, a rise of temperature during deformation can lead to the surface oxidation, the increase in the size of the new forming crystallites, and the development of the texture unfavorable for further deformation.

Earlier, in [4, 5], we revealed a new SPD-method called the lateral extrusion (LE). LE-method has allowed us to deform such low-plasticity metal as magnesium at room temperature without any pre-heating. As a result, we have obtained magnesium with fine-grained structure after one-pass deformation. Nonetheless, there is still an open question of the magnesium billet temperature in the deformation localization zone during the LE-process.

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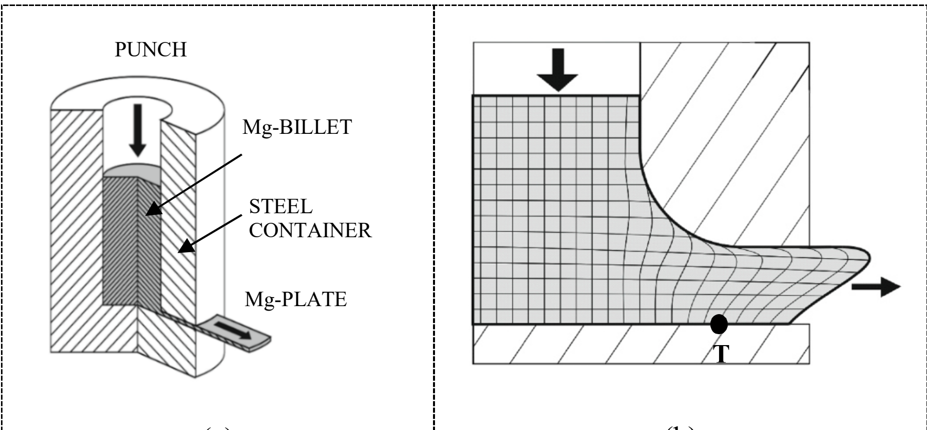
The aim of the study is to evaluate deformation-induced heating of magnesium at low-temperature SPD by theoretical estimation as well as computer simulation and experimental measurements.

2. Material and methods

2.1. Lateral extrusion method

To perform LE-deformation, a cylindrical billet of commercially pure magnesium MG90 was used as the initial material. The billet has a diameter of 42 mm and a height of 40 mm. The Mg-billet was placed in a steel container (figure 1a). At the base bottom of the container, there is a rectangular channel perpendicular to the container. The size of the channel is 42 mm in width and 1 mm in height. The billet is coated with wax and molybdenum disulfide lubricant to reduce friction [6]. The deformation process was performed at room temperature in one pass without pre-heating of the Mg-billet. Under load, the material has started to flow through the channel. Depending on the texture of the initial material, loading stress has reached 0.7 – 1.2 GPa [4]. Obviously, the deformation localization zone is in the intersection of the container and the channel (figure 1b). Magnesium flowed out in the form of a 1 mm thick plate. True strain after LE-deformation is ε ~ 3.9.



(a) (b)

Figure 1. Lateral extrusion scheme (a) and deformation zone with indication of the location of the thermocouple T (b).

2.2. Theoretical estimation and 3D-simulation

To evaluate the distribution of temperature fields in magnesium at LE-process, computer simulation was performed by DEFORM-3D software. A finite element model of LE-equipment and the billet was created in DEFORM-3D pre-processor. The size of the model Mg-billet corresponds to the physical experiment. The boundary condition of the third kind was used for non-isothermal simulation. In this case, heat exchange between the billet and the steel container is characterized by a constant value of the thermal output. At the billet-container contact boundary, the Siebel friction law was used with the coefficient 0.2.

2.3. Experimental method

To measure magnesium temperature during LE, a hole was made in the bottom of the steel container, and a thermocouple was set in the intersection of the container and rectangular channel (figure 1b). The thermocouple was placed to be in direct contact with flowing magnesium plate. In our experiment, we used the type K thermocouple (the Chromel/Alumel thermocouple) with high linearity in the temperature range from 0 to 250°C. The analog signal from the thermocouple was digitized by a Metakon-613-T-TP-1 device and recorded by a computer with a frequency of one measurement per second.

3. Results and discussion

For theoretical estimation of deformation-induced heating of magnesium in the deformation-localization zone, the sizes of the zone, the friction forces and load stresses were taken into account.

Stress F of lateral extrusion is

$$F = S_0 \times q, \quad (1)$$

where S_0 is cross-sectional area of the billet, q is load on the punch.

Friction force F_{fr} at the moving billet is

$$F_{fr} = \pi \times D \times h \times f, \quad (2)$$

where D is diameter of the billet, h is the height of the billet, f is the friction coefficient of 0.5. In this case, the value of the force (F_{pd}) induced on plastic deformation in the steady-state process of LE is

$$F_{pd} = F - F_{fr}. \quad (3)$$

To estimate the work of plastic deformation, it is necessary to find the value of billet displacement (l) required to fill the deformation zone with metal in the steady-state LE-process:

$$l = \frac{V}{S_0}, \quad (4)$$

$$A = F_{pd} \times l, \quad (5)$$

where V is the volume of deformation zone (7.144×10^{-6} m^3).

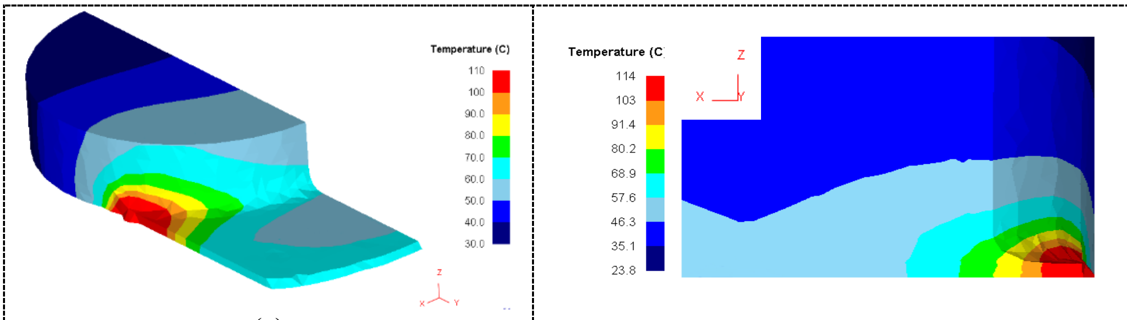
The temperature of deformation-induced heating (ΔT) of magnesium in the deformation zone during LE is

$$\Delta T = \eta_h \times \frac{A}{V \times \rho \times c}, \quad [7]\ (6)$$

where η_h is a heat output coefficient ($\eta_h = 0.9$), A is the work in the deformation localization zone, V is the volume in the deformation localization zone, ρ is Mg density, c is heat capacity of Mg. According to the results of mathematical estimation, the temperature (ΔT) of deformation-induced heating is about 52°C.

Therefore, magnesium temperature in the intersection zone of channels is ~ 75°C at LE (assuming that the temperature of Mg before deformation is the ambient temperature of 23°C).

3D-simulation has made it possible to evaluate the temperature field not only in the deformation zone but over the entire volume of the billet as well (figure 2). Generally, it is seen that the temperature distribution at SPD is non-uniform. It varies from 24°C to 114°C (figure 2a, b). Moreover, the edges of the plate have been found to be heated more than the central part (figure 2a). During LE, in the deformation zone (figure 1b), the microvolumes of the metal move along different paths. Thereby, accumulated shear deformations of different intensities arise in different areas. When magnesium flows in a rectangular channel, it is affected by the frictional forces of the channel surfaces which are directed against of the flow direction. This leads to the difference in rates of metal layers movement along the rectangular channel [6]. In the central part of the forming plate, only the upper and lower surfaces of the forming plate contact with the channel surface, due to what the middle layer of the forming plate flows faster. At the same time, the edges of the forming Mg-plate overcome the additional friction forces of the side surfaces of the channel. It probably causes an increase in both internal shear stresses in microvolumes of the metal at the edges of the forming plate and in internal energy. As a consequence, stronger heating of magnesium during deformation occurs.



(a) (b)

Figure 2. Temperature distribution of Mg in the deformation localization zone: XYZ-plane, at the begging of LE-process (a) and XY-plane, during LE-process (b).

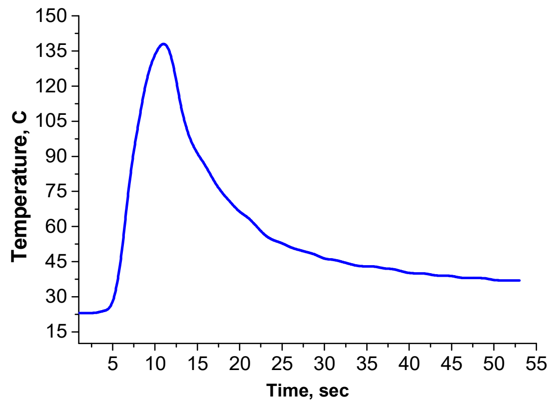


Figure 3. Plot of Mg-temperature (°C) vs. LE-process time (sec).

Figure 4. The obtained magnesium plate after lateral extrusion (LE): the beginning of the plate (I), the end of the plate (II).

Figure 3 shows the results of the experiment on measuring the temperature of magnesium during LE-deformation. The plot reveals that the temperature of magnesium at the beginning of the process was about 23°C (the ambient temperature). It is seen that metal has been gradually heated up to 140°C with deformation process.

The effect of the deformation-induced heating on the plasticity of magnesium can be judged by the shape and state of the obtained plate. Figure 4 demonstrates two parts of one Mg-plate (part I is the beginning of the plate, and was cut from the right side of part II). Part I has an irregular shape and severely cracked edges. At the same time, part II of the obtained plate seems to be smoother, without cracks at the edges. It can be concluded that at the beginning of deformation the metal has low plasticity due to low temperature of metal.

It is known that magnesium has hcp-lattice [8, 9]. This means that the metal has insufficient number of the slip systems for plastic deformation. Magnesium deformation occurs mainly along the basal planes <0001>. To activate the additional slip systems, deformation treatment is mostly performed at temperatures above 150°C. In our case, the temperature at which metal can flow easily through the rectangular channel is achieved during the deformation process. Gradual heating of the material takes place due to the large amount of energy that is transferred to the material during SPD. Temperature increase, especially in the zone of deformation localization, has a positive effect on the plasticity of the material and causes the migration of the boundaries of fragments, which especially occur in pure metals with a low melting point [11].

Conclusions

In this work, the deformation-induced heating of magnesium during LE-process was evaluated by both theoretical and experimental methods. For theoretical estimation, we have used mechanistic approach according to which, temperature of magnesium during LE is about 75°C. Computer simulation in DEFORM-3D software has shown that temperature of metal at SPD can reach up to 114°C. As for the experimental measurements, in this case, temperature of Mg in the deformation localization zone has grown during the LE-process up to ~ 140°C.

Acknowledgments
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