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Modeling the temperature rise in high-pressure torsion

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ABSTRACT

Experiments and finite element modeling were used to estimate the temperature rise during high-pressure torsion. The results show the temperature rise is dependent upon the material strength, the rotation rate, the sample radius, the heat capacity and the volume of the anvils. A general relationship is derived which predicts the temperature rise in samples of different geometries processed using different anvil sizes. A simplified version of the equation is presented for general use.

1. Introduction

Severe plastic deformation (SPD) techniques [1] have been extensively used to refine the grain structure in metallic materials. The large amounts of plastic deformation applied to the samples lead to the introduction of internal defects in the crystalline structure of the materials but also produce significant heating. Among the various SPD techniques, Equal-Channel Angular Pressing (ECAP) [2] and high-pressure torsion (HPT) [3] are the most common. It was shown experimentally that the temperature rise during ECAP may reach ~70 K in a high strength aluminum alloy when pressing at a speed as high as 18 mm s^{-1} [4]. Later, Finite Element Modeling (FEM) was used to estimate the temperature rise during ECAP and the results agreed well with the experimental values [5]. Other similar experimental results were also reported [6] together with a heat transfer analysis [7]. Nevertheless, it is important to note that the temperature rise in ECAP occurs abruptly and there is a gradual cooling after crossing the shearing zone. This means in practice that the temperature rise is not incremental during multiple passes. By contrast, the deformation during HPT is continuous and therefore the temperature is expected to continue rising while processing is maintained. Accordingly, it is important to determine the temperature rise for samples processed to large numbers of turns in HPT, especially for high strength materials processed at high rotation rates.

The temperature rise, ΔT, during plastic deformation is given by the following relationship [8]:

$$\Delta T = \frac{0.9}{C} \int \sigma \, d\varepsilon \tag{1}$$

where C is the heat capacity of the sample ($C = \rho C_p$ where ρ is the density and C_p is the specific heat capacity), σ is the flow stress, ε is the plastic deformation and the fraction of plastic deformation work converted into heat is assumed as 0.9. Early reports estimated temperature rises of ~300 K [9] and ~400 K [10] during HPT processing of an aluminum alloy and a Cu-based metallic glass, respectively. However, these calculations failed to include the heat loss to the massive HPT anvils. Later, experiments were conducted to determine the temperature rise in the anvils during HPT processing of different materials [11] and these values were used in FEM to estimate the temperature rises in the samples [11,12]. Through these calculations, it was shown that the temperature rise is proportional to the sample strength and the rotation rate [11,12] and a graphical representation was used to estimate the temperature rise at any time in a typical HPT facility [12]. Nevertheless, this approach failed to incorporate the effect on temperature rise of either the size of the anvils or the size of the workpiece. Accordingly, the present calculations were conducted with the objective of deriving a general relationship to predict the temperature rise during HPT processing when all variables are included.

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2. Experimental procedure and modeling

In order to critically evaluate the temperature rise during HPT processing, samples of titanium grade 2 with a 5 mm radius and a 0.8 mm thickness were processed at rotation rates of 1 rpm and 0.2 rpm under a pressure of 6.0 GPa at room temperature using an HPT facility operating under quasi-constrained conditions [12,13]. The anvils used in the experiments have diameters of 50 mm and heights of ~30 mm. The surface of the anvil has a conical shape at an inclination of ~5° to avoid contact between the anvils during processing. Marks were scribed on both surfaces of the sample before processing and these marks exhibited perfect alignment after HPT processing which shows no slippage had occurred. The temperature rise in the anvil was tracked during processing by placing a K-type (chromel–alumel) thermocouple within the center of the anvil at 10 mm from the contact surface of the anvil with the sample.

Simulations of HPT processing were performed using the FEM DEFORM 2D 10.0 software (Scientific Forming Technologies Corporation, Columbus, OH). The geometries and meshes of the anvils and the workpiece used in this study are depicted in Fig. 1. Since HPT exhibits axial symmetry, the model was simplified to a two dimensional situation considering only the axial and radial directions. The simulations considered sticking conditions between the sample and the anvils on the top and bottom surfaces which means no slippage was allowed in these surfaces. A coefficient of friction of 0.6 [14] was considered in the contact between the sample and the anvils in the area of material outflow. The simulations considered workpieces with different values for the radius, r_w, and thickness, h_w, anvils with different volumes, V, and different rotation rates, ω. Further details on the modeling parameters and the boundary conditions were given earlier [12]. The thermal conductivity and heat capacity of the anvils were taken as 42 W m^{-1} K^{-1} and 3.72 MJ m^{-3} K^{-1}, respectively, where these values were selected from the library of the software for the tool steel.

The material of the workpiece was titanium grade 2 with a thermal conductivity of 20 W m^{-1} K^{-1} and a thermal capacity of 2.36 MJ m^{-3} K^{-1} [15]. The flow stress was considered constant and taken as the saturation stress, 940 MPa [16]. Additional simulations were carried out considering the early variation in flow stress in the strain-hardening regime of the material and the results showed the difference in temperature rise is not significant. This shows that considering the flow stress as constant during HPT does not compromise the prediction of temperature rise.The value of the flow stress was considered as a constant since the HPT processing is expected to impose a sufficiently large level of deformation that the flow stress saturates in the early stages leading to only minor variations in the flow stress during the later stages of processing.

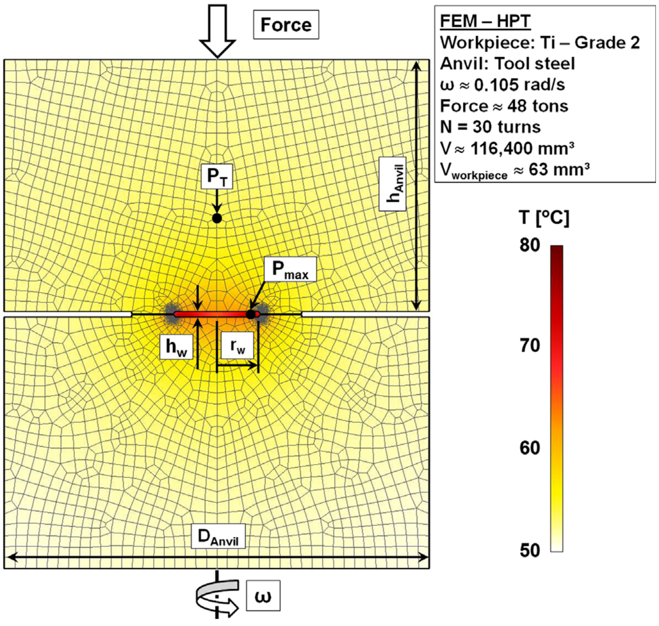

Fig. 1. Illustration of geometry of anvils and workpiece used in the simulations. The distribution of temperature is shown for a specific processing condition.

3. Results and discussion

3.1. Validation of the simulation model

Fig. 2 shows the temperature plotted as a function of time for the experimental HPT processing of titanium at two different rotation rates together with the simulation values. The temperature in the experiments was recorded within the anvils and the temperature in the simulations was estimated both in the anvils and in the workpiece. It is readily apparent that the values of the temperatures in the simulations agree very well with the values observed in the experiments at both rotation rates, thereby confirming the general validity of the model. It is also clear that the temperature in the workpiece follows the same general trend as in the anvils but with a shift towards higher values. The earlier simulations also showed good agreement with experimental data for the temperature rise during HPT [12].

3.2. General trend of temperature rise

Further simulations were conducted in order to evaluate the effect of rotation rate, workpiece radius and thickness and the anvil volume on the temperature evolution and the results were then analyzed in order to provide a general trend. The overall trend of the temperature evolution during HPT can be explained in terms of heat generation, heat storage and heat dissipation. Thus, in the very early stage of deformation the heat generated by plastic deformation of the workpiece is mostly stored in the workpiece leading to a rapid increase in temperature. This leads to an initial temperature rise which is incorporated as ΔT_0. Following this early stage, the temperature gradient between the workpiece and the anvil leads to heat transfer so that the heat generated in the

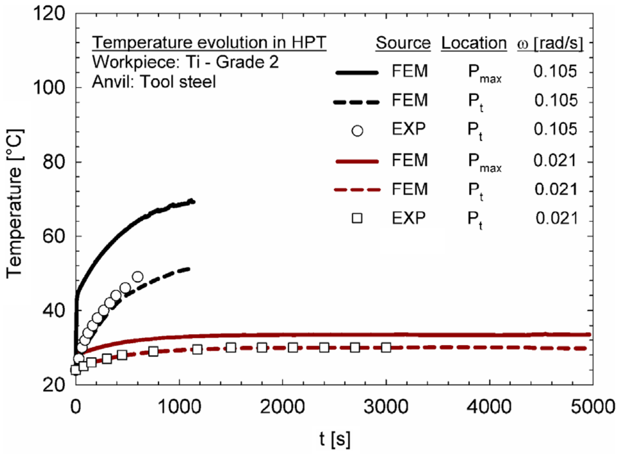

Fig. 2. Temperature evolution as a function of time using experimental data for titanium grade 2 processed at rotation rates of 1.0 rpm (0.105 rad s^{-1}) and 0.2 rpm (0.02 rad s^{-1}). The dashed and continuous lines represent, respectively, the temperature predicted in the simulation in the anvil, P_t, and in the workpiece, P_{max}.