The Effect of Deformation Activation Volume, Strain Rate Sensitivity and Processing Temperature of Grain Size Variants

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Abstract—The activation volume of 6082T6 aluminum is investigated at different temperatures for grain size variants. The deformation activation volume was computed on the basis of the relationship between the Boltzmann’s constant k, the testing temperatures, the material strain rate sensitivity and the material yield stress grain size variants. The material strain rate sensitivity is computed as a function of yield stress and strain rate grain size variants. The effect of the material strain rate sensitivity and the deformation activation volume of 6082T6 aluminum at different temperatures of 3-D grain are discussed.

It is shown that the strain rate sensitivities and activation volume are negative for the grain size variants during the deformation of nanostructured materials. It is also observed that the activation volume vary in different ways with the equivalent radius, semi minor axis radius, semi major axis radius and major axis radius. From the obtained results it is shown that the variation of activation volume increase and decrease with the testing temperature. It was revealed that, increase in strain rate sensitivity led to decrease in activation volume whereas increase in activation volume led to decrease in strain rate sensitivity.

Keywords—Nanostructured materials, grain size variants, temperature, yield stress, strain rate sensitivity, activation volume.

I. INTRODUCTION

Despite the great interest in severe plastic deformation (SPD) during past years, these deformation mechanisms are still uncertain [1]. Great research work with various SPD techniques and conditions gives different models for developed high angle boundaries (HABs) and structure refinement [1]. Some of the developed models extend the continuous evolution of dislocation structures by the crystallography glide from low and moderate strains. An alternative method describes the SPD as discontinuous due to localized flow inside shear bands (SBs) of non-cry stalllographic orientations [1]. Segal’s [1] original contributions provoked the scientific community to transform the microstructure of a material deformed by SPD [2]. The grain sizes of the microstructure deformed by SPD vary due to the processing routes. The varying grain size has contributed to the present controversy on nanomaterials mechanical properties [3].

The micro-mechanisms of size dependent strengthening are commonly explained by dislocation starvation effect application at nanoscale [4], [5]. High strain rate sensitivity (SRS) and low activation volume has been observed by [6]. Although nanoscale materials are being considered for different applications due to their enhanced mechanical properties, their rate limiting processes of activation volume remain “lack of deep understanding” that has called for many investigations now [6]. Most researchers have demonstrated the relationship between SRS and activation volume without taking into consideration the stochastic nature of grain size variants on the activation volume [7]-[14]. Most recent findings on the relationship between SRS and activation volume is only limited with the equivalent radius of the grain during grain refinement (with the equivalent radius defined as the radius of an equivalent sphere or cycle obtained by the displacement method of volume/area measurement). It is therefore necessary to model qualitatively the activation volume as a function of grain size variants during grain refinement. However the models of activation volume that dealt only with the equivalent radius ignored the stochastic nature of grain size variants during grain refinement. This current paper is aimed at studying the effect of processing temperature on the activation volume and grain size for 3-D grain deformed by Accumulative Roll-Bonding (ARB) and Equal Channel Angular Pressing (ECAP). The proposed models are tested with data from grain deformation in nanocrystalline aluminum samples.

II. METHODOLOGY

The characteristic equation of SRS which relates material yield stress$\sigma (r)$ and strain rate $\dot{\varepsilon}$ is given by [7].

$$m = \frac{\log (\sigma (r_1))}{\log (\sigma (r_2))} = \frac{\sigma (r_1)}{\sigma (r_2)}$$

where $\sigma (r_1)$ and $\sigma (r_2)$ are the flow stresses corresponding to instantaneous strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, and $m = SRS$

The activation volume for plastic deformation which is directly related to the physical mechanism of deformation is given by [15]

$$V_a = \frac{kT}{\rho \sigma (r)}$$

where $k$ is the Boltzmann constant, $T$ is the temperature, $\rho$ is the density, and $\sigma (r)$ is the flow stress at strain $r$. The activation volume $V_a$ is a measure of the energy required to create a dislocation in the material, and is inversely proportional to the material's strain rate sensitivity $m$.
\[ V = \frac{\sqrt{3}K_B T}{m \sigma(r)} \]  

(2)

where \( K_B \) is the Boltzmann constant, \( T \) temperature and \( m \) is the strain rate sensitivity. Equation (2) revealed that, the smaller activation volume the higher strain rate sensitivity. The activation volume as given in (2) is determined by a relationship of the values \( K_B, T, m \) and \( \sigma(r) \). The strain rate sensitivity \( (m) \) varies with the increasing testing temperature on grain size variants. All these activities account for the complexity of the dependence of the activation volume value on the testing temperature.

The material yield stress \( \sigma(r) \) on nanomaterial’s grain subjected to plastic deformation is given by [16].

\[ \sigma(r) = \sigma_0 + A \left( \frac{1}{r} \right)^{\frac{1}{3}} - B \left( r^{-1} \right) - C \left( \frac{1}{r^{1.5}} \right) \]  

(3)

where \( \sigma_0 = \sigma_0 + K_1 \) is bulk yield stress, \( A = K_j \) is HPR proportionality constant, \( B = K_2 \frac{2nH_m}{RT} \), \( C = K_3 \frac{2nH_m}{RT} \), \( K_j \) is a constant, \( h \) is atomic diameter in the case of metal, \( H_m \) is the bulk melting enthalpy, \( R \) is ideal gas constant, \( T \) is the room temperature, \( K_j > 100 \), and \( \sigma_0 > 10K_1 \).

By employing the different models of strain \( \varepsilon \) for 3-D grain during grain refinement, the strain rate \( \dot{\varepsilon} \) for \( r, r_1, r_2 \) and \( r_1 \) during grain refinement are defined as

\[ d(\dot{\varepsilon}) = \frac{d(\varepsilon)}{dt} \quad \text{and} \quad d(r) = \frac{d(r)}{dt} \]  

(4)

where \( r_1 \) is local critical grain size, \( Z \) and \( D \) are Constants, \( dW(t) \) is increment of the Wiener process, \( V_t = \tau r_1^3 \) define rate of grain breakage, \( \dot{M} = M_0 \left( 1 + \frac{CD}{r_1} \right) \), \( CD = 4\left( H_m(\ln(h_0)) / (\varepsilon(f)) (T) \right) \), \( T_m = T[\ln(m_0/m) \text{ and } M_0 = M_0 \exp(-T_0(\ln(f)) / T)] \).

\[ d(\dot{\varepsilon}) = d\left( \frac{\varepsilon}{r_1} \right) = \frac{\left( \text{Ratio}, \frac{dr}{dt} \right)}{r_1} \]  

(5)

\[ d(\dot{\varepsilon}) = d\left( \frac{\varepsilon}{r_1} \right) = \frac{\left( \text{Ratio}, \frac{dr}{dt} \right)}{r_1} \]  

(6)

where \( O \) and \( I \) are constants

\[ d(\dot{\varepsilon}) = d\left( \frac{\varepsilon}{r_1} \right) = \frac{\left( \text{Ratio}, \frac{dr}{dt} \right)}{r_1} \]  

(7)

Equations (1)-(7) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) and also employing the lognormal distribution of grain size [17].

### III. RESULTS AND DISCUSSION

![Fig. 1 (a)-(d) Plots of yield stress and strain rate at different temperatures and SRS calculated at the slopes of the grain size variants. Some of the plots of yield stress and strain rate at different temperature and SRS calculated at the slopes of the grain size variants are found in [19]](Image)

To test the models proposed in this report, the data from (nanocrystalline) aluminum sample (some of which are found in other reports: [18]) are used, \( M_0 = 0.01nm^2s^{-1}, m = 4, CC = 12, a = 0.90, D = 10^4, h_0 = 0.25nm, T_m(\varepsilon) = 933.47K, CV_0 = 0.3, \text{Ratio}_a = 0.81, \text{Ratio}_b = 1.071, H_m(\varepsilon) = 10.71KJmol^{-1}, \sigma_\theta = 16.7MPa, K_j = 1.3, \sigma_0 = 15.40MPa, K_d = 1301.77MPa nm^{-1/2}, R = 8.31JK^{-1}mol^{-1}, T_0 = 300K, K_0 = 1.381023J/K. \) The additional data obtained from this work are \( O = 0.0035, l = 1.1, r_{c1} = 1.95r, \)
The activation volume with temperature is shown in Fig. 2 for six temperatures. It is observed that, at a temperature of 400°C different activation volume are revealed for the grain size variants. From the different activation volume revealed at a temperature of 400°C the material activation volume is lower for radius measured along r3 since the grain curvature for r3 is higher when compared with the curvatures of r2 and r1. When the testing temperature increased from 400°C to 500°C the activation volume is still lower along r1 and r3 increased along r and r2 whereas it is higher along r since the grain curvature of r3 and r1 is higher when compared with the curvatures of r2 and r. The increased in activation volume with increased in testing temperature could also be rationalized based on the fact that during grain refinement of 6082T6 aluminum there is the martensitic (crystal structure) state. And the grain size variants are characterized with lower grain curvature. It has been revealed that, the SRS tends to increase with temperature on grain size variants due to higher grain curvature, whereas the effect of temperature on activation volume decreased with higher grain curvature, the obtained results is similar to that observed by [15].

V. THE ACTIVATION VOLUME (V) AND GRAIN SIZE VARIANTS

The main reasons for the increased and decreased in activation volume is due to different grain curvatures on the grain size variants as already explained. It is observed from Fig. 3 that the activation volume vary with grain size variants due to different grain curvatures. It is observed from Fig. 3 that at a grain size of 20nm different activation volume are revealed for the grain size variants. From the different activation volume revealed at a grain size of 20nm the activation volume is lower for radius measured along r3, r1 and r2 whereas it is higher along r since the grain curvature of r is lower than the curvatures of r3, r1 and r2. It is observed at a grain size of 40nm that, the activation volume decreased when measured along r1 and r whereas it increased along r and r2 due to higher grain curvatures of r1 and r2.
curvature of \( r \) and \( r_2 \). It is also observed at a grain size of 60nm to 80nm that, the activation volume increased along \( r \) and decreased along \( r_1, r_2 \) and \( r_3 \). It is further observed at a grain size of 100nm that the activation volume decreased along \( r_1, r_2 \) and \( r_3 \). The results in Fig. 3 revealed increased and decreased of activation volume due to different grain curvature on grain size variants. However the smooth transition of grain size variants at different temperatures cannot be under looked as the obtained results revealed transition at different temperature from negative activation volume as temperature increased on the grain size variants.

VI. CONCLUSIONS

The current work was aimed at studying the effect of processing temperature on activation volume for grain size variants. To achieve that, the model of activation volume for plastic deformation which is directly related to the physical mechanism of deformation given by [15] was modified to be applicable to 3-D grain. The model of SRS was also modified to be applicable to 3-D grain. The stochastic natures of the grain size variants were also taken into consideration.

It can be concluded that, the activation volume characterizes the stress sensitivity of dislocation velocity which is related with the dislocation process during grain refinement. This is also based on the thermally activated plastic deformation process of grain size variants, the dislocation velocity also depend on the activation energy and the shear stress acting on the dislocation. These activities are characterized by different grain curvatures of grain size variants during grain refinement.

The effect of deformation temperature led to different activation volume due to different grain curvatures on the grain size variants. It was also observed that the activation volume of the grain size variants decreased and increased with increasing temperature. It can also be concluded that, increased in SRS led to decrease in activation volume whereas increased in activation volume led to decrease in SRS due to different grain curvature.

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REFERENCE