THE EFFECT OF TEMPERATURE ON ELONGATION TO FAILURE IN NANOSTRUCTURED MATERIAL FABRICATED BY ARB PROCESS

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ABSTRACT

A nanostructured material was produced by accumulated roll bonding (ARB) process after several passes. The grain dislocation, grain rotation, grain curvature angles and the fraction of high angle grain boundaries increased as the ARB cycles increases. During ARB cycles, the material was observed to elongate more as the temperature in the material increases due to adiabatic warming that takes place during ARB cycles. The optimum temperature on the material was achieved for maximum elongation to failure. This causes more material elongation at higher temperature and material fatigue takes at the maximum temperature during ARB cycles. The obtained results revealed indication of material fracture surfaces in higher temperature after several ARB cycles than in lower temperature. The reason for this was due to deeper, bigger, and longer being observed in high temperature elongation than in low temperature elongation range during ARB cycles.

KEYWORDS: *Elongations, Temperature, ARB Cycles, Nanostructured & Ultra-Fine Grain*

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INTRODUCTION

Materials are called Polycrystalline when their grain sizes are less than $1.0\mu\text{m}$ and these materials also are defined as ultrafine grained (UFG) materials [1-33]. For over the years now, several researchers have showed that most UFG materials have the potentiality or capability of exhibiting a vast range of higher mechanical properties, specifically these materials have improved fracture toughness in nanostructured material with exceptional magnetic properties of the material [1-44]. Most nanostructured materials are reproduced through different techniques and most of these techniques involve the application of severe plastic deformation (SPD) [1-33]. There are different techniques of SPD processes and most of these techniques include Accumulative roll bonding (ARB), equal-channel angular pressing (ECAP), cyclic extrusion and compression (CEC), and high-pressure torsion (HPT). Among all these techniques, the ARB process is more useful due to its significant advantages such as better mass production potentials as the ARB process are easily used in realizing bulk nanostructured metals [2, 3 & 29].

During SPD process, specifically during ECAP and ARB when a load is applied to my material during deformation process, the materials grain gets elongated along more on the principal deformation direction and along other plane of deformation. More so, when applying SPD processes to deform a material, elongated grain in the main direction of deformation in the microstructure achieved [4-6]. During deformation process, the deformed material through SPD exhibits more enhanced strength than coarse grained metals [1-44]. The deformed material has high density of grain boundaries and the material is thermally unstable [1-33]. Among all the SPD, the ARB is more continuous during manufacturing and therefore the ARB does not have greater production challenges like

other SPD methods [14]. This process experiences high grain elongation and the material easily suffers from fatigue due to high elasticity and plasticity during elongation and if the material temperature is not well controlled this leads to elongation to failure being observed as material failure during ARB process [14]. In this study, the working conditions of ARB process and the deformation cycles on temperature are important parameters being investigated. These factors usually change during ARB process and impact the properties of the material thermal stability in the microstructure due to adiabatic warming. Due to the change in adiabatic warming during ARB process, the matrix and material grain boundaries mobility are impacted and therefore, the effect of temperature during ARB process impacts the properties of a material. Most nanomaterial after AR showed elongated UFG structured and they are thermally unstable at high temperature [14-55]. The aim of this paper is to investigate the effect of temperature on elongation after several ARB cycles in order to find the optimal temperature to achieve maximum elongation

2. MATERIALS AND METHODS

The materials were deformed by the ARB setup as shown in Figure 1 through the rolling mill facility. During experimentation process, the material being deformed was forced or fed through the rotating shafts in the first pass. The rolling shafts gripped the sample and forced the sample through the rollers. The deformed materials were cut into two pieces and stacked together and roll for another pass. Before stacking the material, the entire material surfaces of the strips were clean by a wire-brushed and degreased with tetrachloroethylene to achieve the desire bonding. The deformed materials were joined by using aluminum wires and the joined material was subsequently rolled for another pass. The process of “rolling, cutting, face-brushing, degreasing and stacking” was repeated for several “passes or cycles” until nanomaterials with required characteristics were produced. The initial samples and the deformed samples were examined using Transmission Electron Microscopy (TEM) to get the variables of grain elongation and the elongation of principal deformation direction along the elongation lengths along the major axis r_3 , semi major axis r_1 and semi minor axis r_2 as shown in figure 1 (a-b)

Figure 1: (a) ARB Process and (b) Grain Elongation on Different ARB Passes after TEM Observation [14]

From Figure 1 (b), the model of elongation in 2-D and 3-D can be established as defined by Sob et al [14] by relating volume and area as $A=V^{2/3}$ given in the model as,

$$Elongation = \frac{P r_0}{V^{2/3} E} \quad (1)$$

Where the initial length is given as r_0 , the Young modulus of the material during ARB is given as E , and the applied force to the system is given as P . The material model for Young's modulus (E) of nanomaterials defined by [14] is given as

$$E = \left(\frac{P}{d} \right) \left(\frac{(r^3)}{192I} \right) \quad (2)$$

Where the moment of initial can be inferred during the manufacturing of nanomaterial given as $I = \frac{\pi r_1^4}{64}$, $d = dr = (r - r_0)$, r being defined as the length or equivalent radius of nanocrystalline grain. It is practically observed during experimentation that the grain-size evolution varies at any instant during ARB and the radii of the nanomaterials during ARB can be related to the equivalent volume of the grain through $(4/3)\pi r^3 = V = (4/3)\pi r_1 r_2 r_3$. This gives

$$r^3 = r_1 r_2 r_3 \quad (3)$$

By putting expression (2) and (3) into expression (1), gives the model of elongation on a 3-D grain during ARB process given as

$$\text{Elongation} = \frac{3\pi r_0 r_1^4}{r_2 r_3 r} (r - r_0) \quad (4)$$

The effect of temperature in elongation and other parameters that affect temperature during elongation such as the change in internal energy, and change in energy in the material during elongation can be established as

$$dQ = -(T_{ex} ds - T_{ex} dP_s) \quad (5)$$

$$du = -((T_{ex} ds - T_{ex} dP_s)) \quad (6)$$

$$\Delta E = \delta \frac{4}{3} \pi r^3 + \phi(t) \sigma \left(\frac{4}{3} \pi r_0 - \frac{4}{3} \pi r^3 \right) \quad (7)$$

where T_{ex} is the external temperature and E is the internal energy in the material during elongation by ARB and this impacts the variation of grain sizes variants in the model of elongation defined by equation (4).

Equations (1-8) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) and the effect of elongation to failure during ARB passes are revealed

RESULTS AND DISCUSSION

The derived models developed in this paper was tested with data from (nanocrystalline) aluminum sample (some of which are found in other papers [6 & 14]) are used, which are $M_0' = 0.01 \text{ nm}^2 \text{ s}^{-1}$, $m=4$, $CC=12$, $a=0.90$, $D=10^{-4}$, $h_0=0.25 \text{ nm}$, $T_m(\infty)=933.47 \text{ K}$, $CV_0=0.3$, $H_m(\infty)=10.71 \text{ KJ Mol}^{-1}$, $\sigma_0'=16.7 \text{ MPa}$, $K_t=1.3$, $\sigma_0=15.40 \text{ MPa}$, $Kd=1301.77 \text{ MPa}_{\text{nm}}^{1/2}$, $R=8.31 \text{ J K}^{-1} \text{ mol}^{-1}$ and $T_r=300 \text{ K}$. The additional data obtained for this work are $O=0.0035$, $I=1.1$, $r_{cl}=1.95r$, $r_0=100 \text{ nm}$, $Z=0.4$, $\text{Ratio}_1=0.81$, $\text{Ratio}_2=1.071$, and $\tau_1=0.000008$. The theoretical simulated results are presented and discussed below.

Figure 2: (a) Elongation and Change in Temperature during ARB, (b), Energy against Elongation during Grain Refinement

It should be observed as shown from Figure 2 (a) that the natures of increase of elongation and change in temperature does not increase linearly or exponentially. This is because change in temperature in a material during elongation is affected by several parameters such as dislocation motion, grain rotation coalescence, grain boundaries migration, grain curvature angles and the fraction of high angles grain boundaries that increases during ARB cycle and affect material elongation. This is also because energy and heat are lost due to adiabatic warming and this is affected by change in grain boundaries migration that carries energy along during dislocation motion. The impacts of energy and elongation are shown in Figure 2 (b). Figure 2 (b) revealed that, during the initial process of elongation the material energy rapidly increases which was immediately followed by continuous decrease of energy as elongation increases. This was because the deformed material was being deformed by good internal energy and the internal energy was being transformed as dislocation motion took place during migration of grain particles as the material gets elongation beyond plasticity during ARB. It should be recalled that during the initial process of grain refinement that change in grain boundaries, curvature and dislocation motion led to properties enhancement when the elongation was useful before the plastic rang of the material and as soon as the material gets to its elastic region, elongation to failure begins and the energy in the material is affected as shown in Figure 3

Figure 3: (a) Energy against Sizes during Useful Elongation by ARB, (b), Energy against Sizes during Elongation to Failure by ARB

The results shown in Figure 3 (a-b) revealed energy and sizes during useful elongation and elongation to failure during ARB process. The results in Figure 3 (a) revealed deformation and useful elongation during ARB process. The material

energy increases during ARB process as the material sizes decreases from conventional material to nanostructured materials. This was because the change in dislocation motion, grain curvature and the fraction of high angle grain boundaries increase within the elastic limit of the material during ARB. Before the elastic limit of the material, the elongation is useful, and the material developed the desired property enhancement with the acceptable energy during ARB. As the deformed material exceeds its elastic region, the grain boundaries angles became lower and elongation to failure begins as the material energy starts falling as shown in Figure 3 (b). Therefore, Figure 3 (b) revealed a decrease in sizes led to decrease in energy since elongation to failure was being observed during ARB process. Therefore, the optimal energy the material can withstand before elongation to failure during ARB process has been revealed.

CONCLUSIONS

The aim of the current paper was to investigate the effect of temperature on elongation after several ARB. To achieve that, the model of elongation on temperature during ARB process was developed in order to find the optimal temperature to achieve maximum elongation. The tool of stochastic mechanics was used to model the random change in grain size and temperature during elongation. It was shown that, during the initial process of grain elongation, the material energy increases, and this was immediately followed by a decrease in energy as elongation increases. This was due to the due change in grain boundaries migration and grain curvature during ARB. It was also shown that, the material energy increases as the material sizes decreases from conventional material to nanostructured materials. This change affected temperature and elongation during ARB process. It was revealed that the change in dislocation motion, grain curvature and the fraction of high angle grain boundaries increase within the elastic limit of the material during ARB which was followed by plasticity at the optimal elongation when elongation to failure was revealed during ARB.

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