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The Effect of Strain on Elongation to Failure in Nanostructured Material Produced by ARB Process

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Abstract

In this paper, a nanostructured material was produced by accumulated roll bonding (ARB) process after several cycles. The grain dislocation motion and grain boundaries migration motion and angular curvature of the grain boundaries increases during ARB cycles. The material was subjected to different straining condition during ARB passes and the grain dislocation, grain boundaries migration and grain curvature varies as the material gets elongated. The optimal condition of straining the material during elongation was revealed for maximum elongation to failure, which led to 100% elongation. Though the maximum elongation during material straining was revealed at a higher strain rate during ARB process, the factors that affect straining was revealed to be grain boundaries and grain dislocation motion and the material temperature. The main reason for the elongation to failure was alluded due to that the material was deformed through plasticity to elasticity leading to varying and grain angles curvature that moved from higher angular curvature to lower angular curvature which led to property enhancement and elongation to failure during ARB cycles.

Keywords: Elongations, strain, temperature, ultra-fine grain and ARB cycles

1. INTRODUCTION

The automotive industry is in high demands of nanocrystalline aluminum alloy sheets produced by ARB and this nanostructured sheet must have high strength and good formability. Several severe plastic deformation (SPD) techniques are useful in producing nanocrystalline aluminum ultra-grain refinement. There are several SPD techniques such as high-pressure torsion (HPT) [1-33]. Equal-channel angular pressing (ECAP) [22-44]. Cyclic extrusion and compression (CEC), and accumulative roll bonding (ARB) [33-44]. Among all these SPD approaches, the ARB technique is notable for producing nanostructured materials with larger dimensions. Most ARB processed sheets shows extremely high strength but very poor elongation during tensile tests [14]. This is due to the method of imposing strain on the material and due to the method of heat treatment of the material during ARB process and this is sometimes affected by the material used as solid solution hardening and working hardening process being used and therefore there is a great need in hardening by ARB and straining which is also impacted by the rolling temperature during ARB process.

There is plenty of research reports on the properties of ARB-processed metals. Some of these reports revealed the happening of super-plasticity in a material during straining process by ARB being related to an equivalent strain of about 3.9 at a temperature of about 200 °C, at the same time straining ranges from 200 to 400 °C [14]. Few researchers also studied the structure, ductility, and strength of a processed material by ARB during an equivalent strain of 4.8 at room temperature [14]. The properties of microstructure changes in the material during straining in different ARB passes at room temperature [14]. Several research studies revealed interesting findings that as material straining increases, the temperature in the material increases and elongation increases during ARB process due to increases in the imposed stress in the material that led to larger uniform elongation in the material. However, the study only reported the tensile properties in limited specimen, specifically, if the specimen was being strain and annealed after 7 ARB cycles [1-14]. To clarify the strain effect imposed by ARB on the material tensile properties after change in temperature during varying ARB cycles should be investigated. The aim of the current study is to understand how induced strain during ARB effects uniform elongation at varying process temperature.

2. MATERIALS AND METHODS

The materials were deformed by the ARB setup as shown in Fig.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 were 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 gets the variables of grain elongation and the elongation of principal deformation direction along the elongation lengths along the major axis r3, semi major axis r1 and semi minor axis r2 as shown in figure 1 (a-b)

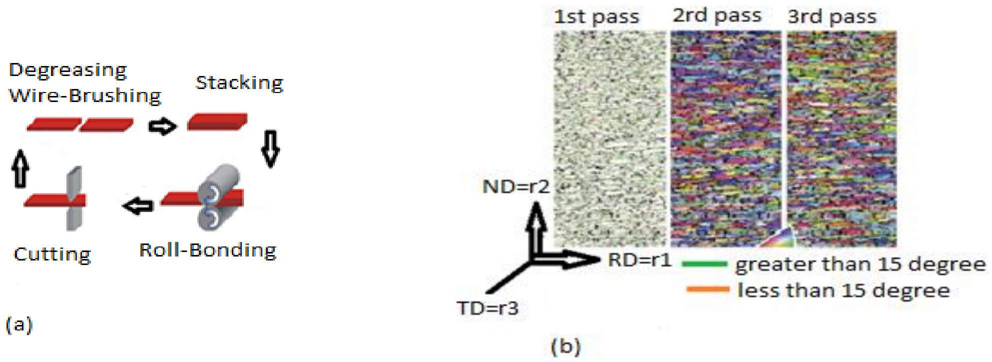


Figure 1: (a) ARB process and (b) grain elongation on different ARB passes after TEM observation [14]

Models Derivation

The model for grain elongation in 3-D grain was defined by Sob et al [14] given as

$$Elongation = \frac{3\pi r_0 r_1^4}{r_2 r_3 r^3}(r - r_0) \qquad (1)$$

By employing the different experimental observations for r, r_1, r_2 and r_3 during grain refinement, the following set of grain size variant evolutions (given in expressions (5)-(8)) were established for *3-D* grain.

Moving now to other mechanical properties, the model of the yield stress given by Reversed Hall-Petch Relationship (RHPR) as modified by Zhao [9] is given by

$$\sigma(r) = \sigma_0' + A\left(r^{-\frac{1}{2}}\right) - B\left(r^{-1}\right) - C\left(r^{-\frac{3}{2}}\right) \qquad (2)$$

where $\sigma_0' = \sigma_0 + K_t$ is bulk yield stress, $A = K_d$ is HPR proportionality constant, $B = K_t[2hH_m / RT_r]$, $C = K_d[2hH_m / RT_r]$, K_t 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_r is the room temperature, $K_d > 100K_t$ and $\sigma_0 > 10K_t$.

The models of strain evolution for nanocrystalline material for the different approaches of measuring grain size evolution given in expressions (5)-(8) [13] are

$$d\varepsilon_1 = d[dr_1 / r_1] = d\left(M\left(\frac{1}{r_{1c}}\right)\left(\frac{1}{r_1}\right) - \frac{1}{r_1^{\,2}}\right)dt + \frac{CDdW(t)}{r_1} - \frac{ZV_1 r_1^{\,2} d(t)}{r_1} \qquad (3)$$

$$d\varepsilon_3 = d[dr_3 / r_3] = d\left(\frac{Ratio_1 dr_1}{r_3}\right) \qquad (4)$$

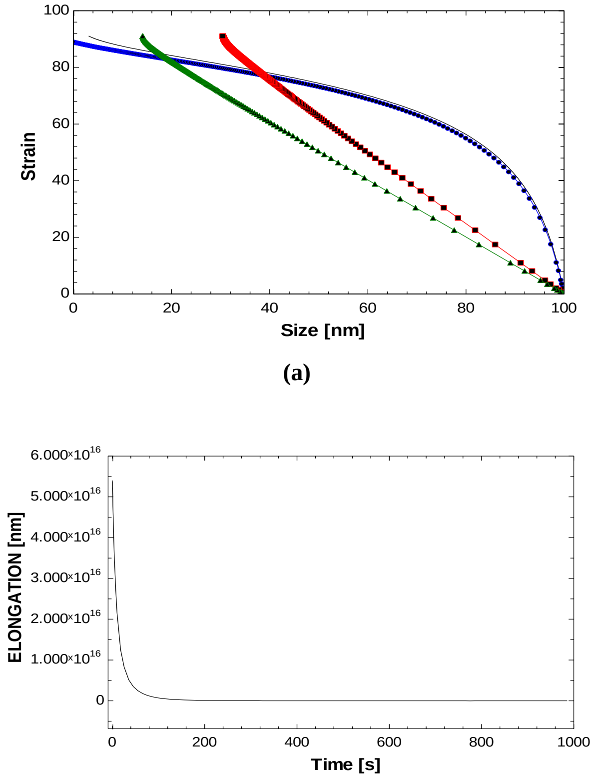
$$d\varepsilon_r = d[dr \;/ r\;] = d\left(\frac{-Ordt + IdW(t)}{r}\right) \qquad (5)$$

$$d\varepsilon_2 = d[dr_2 / r_2] = d\left(\frac{Ratio_2 dr}{r_2}\right) \qquad (6)$$

Equations (1) to (13) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) while employing the lognormal distribution of grain size.

RESULTS AND DISCUSSION

To test the models proposed in this paper, the data from (nanocrystalline) aluminum sample (some of which are found in other papers [6]) are used, which are $M_0' = 0.01 nm^2 s^{-1}$, $m=4$, $CC=12$, $a=0.90$, $D=10^{-4}$, $h_0=0.25nm$, $T_m(\infty)=933.47K$, $CV_0=0.3$, $H_m(\infty)=10.71KJMol^1$, $\sigma_0'=16.7MPa$, $K_t=1.3$, $\sigma_0=15.40MPa$, $Kd=1301.77MPa\_nm^{1/2}$, $R=8.31JK^{-1}mol^{-1}$ and $T_r=300K$. The additional data obtained for this work are $O=0.0035$, $I=1.1$, $r_{c1}= 1.95r$, $r_0=100nm$, $Z=0.4$ $Ratio_1=0.81$, $Ratio_2=1.071$, and $\tau_1 =$ 0.000008. The obtained results are presented in the plots below.

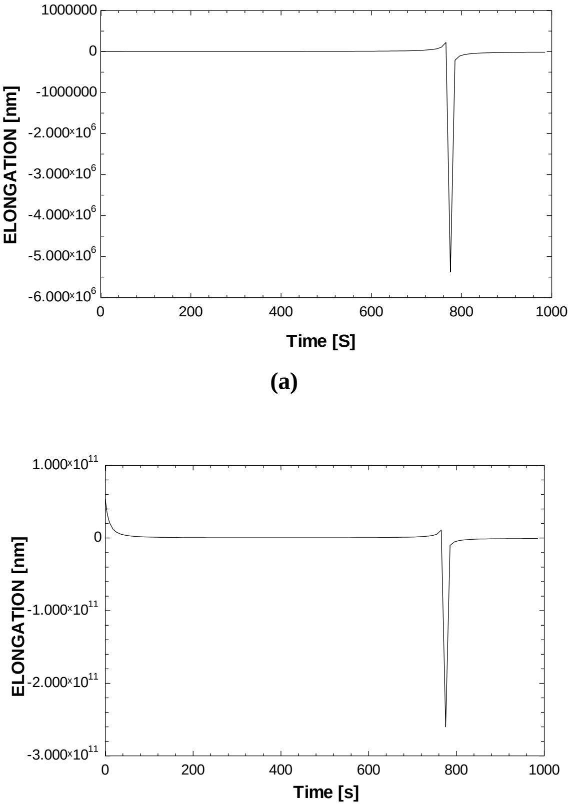


(a)

(b)

Figure 2 (a) the evolution of strain against size during elongation, (b) the evolution of elongation against time during ARB process

It is observed as shown in Fig.2 (a) that the material strain increases as the material sizes decreases during ARB process. This is because the material will experience more strain when the grain sizes are smaller since the dislocation motion, grain boundaries, grain curvatures and grain boundaries migration experience more pressure due to straining as the material sizes get smaller. During grain refinement by ARB process more dislocation motion, grain boundaries migration and higher grain curvature are being created as the strain in the material increases. During this process, the strain impacts elongation positively during ARB process. As the strain in the material continues to increase beyond the material elastic region, the strain imposed on the material exceed the elastic limit of the material and the material experiences elongation to failure which is seen as plasticity when the material start failing physically as shown in Fig.3 (a-b)



(a)

(b)

Figure 3 (a-b) the evolution of elongation during failure against time during ARB process

The results in Fig.3 (a-b) shown elongation failure during ARB when the material was already strain beyond elasticity. It is observed from Fig.3 (a-b) that when the material was strain beyond the elastic region, the property of elongation does not increase with time during ARB cycles. It is observed that as the material was strain beyond elasticity, the elongation remains constant before the material experienced failure in elongation during ARB as shown in Fig. 3 (a-b). The reason for the elongation to failure was because, as the material was deformed through plasticity to elasticity the grain angles migration created higher angles curvature which led to property enhancement. And as the material was further strain through plasticity the grain angles curvature changes from higher angles curvatures to lower angles curvatures which affect material elongation leading to elasticity and material failure as shown in Fig. 3 (a-b).

CONCLUSION

The aim of the current study was to investigate the effect of strain on elongation to failure during ARB. To achieve this objective, the effects uniform elongation at varying strain and temperature was investigated during ARB process. It was shown that the material strain increases during ARB cycles as the material sizes decreases. This was mainly due to higher dislocation motion, grain boundaries, grain curvatures and grain boundaries migration that experience more pressure due to straining at smaller grain sizes. It was also shown that as the strain in the material continues to increase beyond the material elastic region, the strain imposed on the material exceed the elastic limit of the material and the material experiences elongation to failure. The main reason for the elongation to failure was alluded since as the material was deformed through plasticity to elasticity the grain angles migration created higher angles curvature which led to property enhancement and as more straining takes place through plasticity the grain angles curvature changes from higher angles curvatures to lower angles curvatures which affected material properties and led to elongation to failure.

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