FRACTURE, FATIGUE AND FAILURE ANALYSIS ON ELONGATION IN ANOCRYSTALLINE MATERIAL DEFORMED BY ARB PROCESS

P. B. SOB¹ & M. PITA²

¹Department of Mechanical Engineering, Faculty of Engineering and Technology, Vaal University of Technology,
Vanderbijlpark 1900, Private Bag X021, South Africa

²Department of Mechanical and Industrial Engineering, Faculty of Engineering and Technology, University of South Africa

ABSTRACT

Imposing strain during ARB process by forcing external and internal grain sizes of conventional material dimensions to nanometer scale by top down that gives rise to enhanced materials. This impacts the resistance and ductility due to material cracking which negatively impact on material properties such as elongation to failure from useful elongation that usually enhanced mechanical properties. Several parameters characterized fracture, fatigue and failure to elongation during ARB process. Recent studies also revealed some information on the scientific origins of lack of ductility in a material, resistance due to fracture and the main factors govern fatigue resistance in a material during property enhancement. In the current study, the strain model was optimized during material fatigue by ARB process. Different fracture, fatigue and failure mode analysis was revealed due to ARB process and their impact on material properties was revealed. Their different intrinsic mechanisms being used to enhance material hardening and material strain rate sensitivity during production so as to delay necking and improve grain-boundary cohesion which resist intergranular cracks or voids in a material are revealed. It was shown that, the extrinsic manufacturing methods are utilized by hybridizing the produced material with another material to delocalize material deformation process and that is commonly used in stretchable electronics. It was also revealed that the initiation in material fatigue crack being enhanced by a fine structure, but at the expense of greater crack fatigue growth rates during material deformation process. The extrinsic toughening through hybridization process during material deformation allows arresting or bridging cracks during ARB process.

KEYWORDS: Fracture, Fatigue, Failure, Elongation And Nanostructure Material.

Received: Feb 16, 2021; **Accepted:** Mar 06, 2021; **Published:** Apr 01, 2021; **Paper Id.:** IJMPERDJUN202110

INTRODUCTION

For over decades now, there have been several research investigations on the advancement of fatigue and fracture mechanism during accumulative roll bonding in most metallic alloys industry [1-2]. Several research investigations on the recent advances in the material fracture, fatigue and failure analysis on elongation during ARB process in metallic alloys typically involves microstructural scales within tens of nanoscale being used in microscopic conventional analysis [1-2]. Recent studies show that the most system in the physical and fractural mechanics in metals materials in Nano-scale dimension [1-3]. Other research findings also shown the mechanical behaviour of fracture, fatigue and failure analysis on elongation during ARB process have a main focus on material mechanism of deformation during ARB process, and this is always done with limited attention to fracture process during deformation [1-4]. The material resistant to fracture process during ARB process is being reported to be very weak and it is mostly quantified by limited ductility process or it is quantified by very low material fracture

toughness [1-9].

These are critical issues that greatly impacts material properties during ARB process and it must be solved in order to create a viable application of nanostructured metallic materials in most industries since material failure to elongation has limited the practical application of nanomaterials in most industries. Several microstructural analysis and characteristics of internal microstructure in metallic structures involving submicron dimension in “2D” films or “1D” wires at submicron characteristic in internal microstructure sizes revealed more complex microstructural in terms of material elongation process and material fracture analysis during ARB process. Material fracture mechanics of 1D and 2D material structure are very complex in a sense due to the fact that, both the microstructure and the general system characteristic in lengths generally affect the material failure and elongation process during ARB. Practically these factors facilitate properties enhancement process in community sector that produced bulk nanostructured metals for various applications. The material properties are greatly impacted by processing temperature during ARB process.

Nanomaterials are very sensitive to temperature and therefore they are very sensitive even in low temperature. Materials with static fracture crystalline material was initially addressed with a little consideration in some of the critical issues relating to the environment such as varying temperature that effects on metallic glasses. Most often, material fracture is addressed from the general material failure mode process and that often includes pre-crack, under different static conditions. This involves material ductility by plastic localization. Most material fatigue processes are always treated in the process of material resistance to crack initiation process and the tendency of the crack that usually propagate from a pre-existing crack during ARB process.

Most material failure process involves basic process in material science. Most of this methods focused on the specific materials methods of imposing stress/strain and rate of material deformation process as addressed in this research paper. The specific method of imposing stress/strain and rate of material deformation provides more information on the mechanisms in metals with nanoscale dimensions and this revealed the critical parameters between useful elongation and elongation to failure during failure, fatigue and failure analysis on elongation to failure during ARB process as revealed in this study. These aspects in material useful elongation and elongation to failure are critically during operation. Some studies focused on “local approach” to fracture during elongation and failure mechanisms in relation to microstructure and their physical phenomena during ARB. Several results in the damage of material and cracking resulting to specific deformation process developed in metals during the ARB process. This problem must be properly addressed since for over decades now, the opening applications on different engineering fields where optimal strength.

This comes with a backdrop of several key issues that impacts the processing methods in industrial application and structural applications process, such as ductility that are low in terms of elongation that are uniform and strain fracture which impact material and the resistant of the material to cracking when the material is used in several structural applications. The low strain hardening properties in this material are the reason for the limited resistance to plastic and elongation that are uniform. In several materials, damages and cracks are reported and the critical issue is predominance of material intergranular mechanisms due to extreme material stress build-up in the grain- boundaries (GBs) of the material and due to the presence of processing defects during ARB process. Recent research work revealed an approach of recovery material ductility by introducing heterogeneities at multiple scales and by favouring rate sensitivity in nano-twinned (NT) metals [9] or in hybrid nano-structuring strategies being used in the bimodal or multi- modal grain size distributions and in multi-phase alloys being graded as single or multiphase systems, multi-layered metallic composites, generation of

controlled internal stress distributions, and combination of solute additives as solutions for property enhancement. This doesn't always lead to property enhancement as the main problem is to model the optimal properties that led to material stability and control useful elongation. Therefore, material fracture, Fatigue and failure analysis on Elongation during ARB process is complex and complicated and therefore it is difficult to control useful elongation and elongation to failure during ARB process.

METHODOLOGY

Modeling Fracture, Fatigue and Failure Analysis on Elongation During ARB Process

To model fracture, fatigue and failure mode during elongation by ARB process, it is important to model the processing parameters that impacts fracture, fatigue and failure during elongation and these parameters includes low material ductility in uniform elongation process and strain fracture in the material which negatively impact material capabilities and material resistance to crack. Figures 1 (a-d) depicts an ARB process, the different directions of grain refinement during ARB, and microstructural cracks that impacts fracture, fatigue, and failure mode as shown by [10]. The results that are shown in Fig 1 (e) show the different possibility of cracks propagation during elongation by ARB process.

Figure 1. (a) Accumulative Roll Bonding Process (b) Material Deformed by Accumulative Roll Bonding after Cycles (c) Material Elongated Grains Sizes after Accumulative Roll Bonding Cycles (D)Cracks Images of the Deformed Material Captured by TEM [11]and (e) The System Schematic Showing Material Crack tip during Propagating of Cracks Along Different Approaches of Measuring.

The material damage evolution is shown in Figure 1 (d) and the damage propagates along different surfaces in the material during elongation by ARB process and this impacts the material properties. The mechanism on generic structural and phenomena that impact the unique combination of enhanced yield strength, fracture toughness and toughening

mechanism during ARB was utilized in the study by using the fundamental relationship between fracture toughness (K_{IC}^σ), shear modulus (G), Poisson's ratio (ν) and specific surface energy (γ_e) during ARB as given as

$$K_{IC}^\sigma = \sqrt{\frac{4G\gamma_e}{(1-\nu)}} \quad (1)$$

In this regards the research studied high volume of fracture processes on varying grain size boundaries in the nanocrystalline materials. Modelling started at nanocrack tip being the major element of the carriers of fracture in the materials. This brought a particular interest and focus on the proper understanding of the mechanisms for nano-crack generation, fracture toughness and toughening mechanism at the grain size variants and their correlation with plastic deformation processes which is known to be mediated by grain boundaries during ARB cycles.

The theoretical model developed and proposed in this study describes the nucleation, growth of nanocracks, fracture toughness and toughening mechanism on grain size variants during ARB process. Modeling initially started from the Ilya model [14] in which we consider basic statements of the model which gives the relationship between fracture toughness (K_{IC}^σ), shear modulus (G), Poisson's ratio (ν) and specific surface energy (γ_e) of nc materials is given as

$$K_{IC}^\sigma = \sqrt{\frac{4G\gamma_e}{(1-\nu)}} \quad (1)$$

The specific surface energy has an impact on fracture, material fatigue and elongation during ARB. This depends on the applied tensile load on the material and the change in temperature during ARB process given as

$$\gamma_e = \gamma - T \frac{\Delta\gamma}{\Delta T} \quad (2)$$

Where γ = surface tension, T = temperature, $\Delta\gamma$ = change in surface tension and ΔT = change in temperature. $\Delta T = T_m - T_{m,b}$ where T_m = is the melting temperature of nc materials and $T_{m,b}$ = is the bulk melting temperature, $T_m = T_{m,b}(1 - a/r)$, $a > 0$, is a dimensional factor which depends on the shape of the material. The different approaches of elongation during crack propagation as shown in Fig. 1 (e) depends on the tensile load during feed rate by ARB and this is affected by the volume of the material subjected to deformation process. The material volume of the 3-D material subjected to feed rate as shown in Fig.1 (a-c) can be model to obtained the equivalent radius by relating the equivalent volume through $(4/3)\pi r^3 = V = (4/3)\pi r_1 r_2 r_3$, and achieve $r^3 = V/r_1 r_2 r_3$ which gives the relationship between r and (r_1, r_2, r_3) which are the possible direction of fracture propagation during elongation by ARB. Elongation during ARB process causes fracture, fatigue and failure during ARB process due to varying strain during ARB. The mode of strain due to varying grain sizes distribution and varying feed rate can be modelled by looking at the Whang model of varying strain rate on rolling speed as given as

$$Y(s) = [(\alpha\mu b)^2 h \dot{\epsilon} \left(1 - \exp\left(-\frac{s\dot{\epsilon}}{\dot{\epsilon}}\right)\right) + \sigma^2 \exp\left(-\frac{s\dot{\epsilon}}{\dot{\epsilon}}\right)] \quad (3)$$

Where $Y(s)$ is the flow stress, ε is strain, $\dot{\varepsilon}$ is strain rate, μ is the material modulus of rigidity, b is the burger vector, h is the hardening coefficient, which stands for the growth rate dislocation density, α is the material constant, s is the softening coefficient which stands for the decreasing rate of dislocation density and σ is the creep stress. Equation (3) greatly depends on deformation resistance stress at different strain and strain rates on grain dislocation principle during ARB process and it impacts material fracture, fatigue, and elongation of nanocrystalline material during ARB. The rate of propagation in the material during ARB process depends on the tensile force on the system under compressive force or compression pressure. The model of material compressive force and stress during ARB process as defined by Karman is given as

$$(\sigma + p) dt + t d\sigma + 2q dx = 0, \quad p' = p - \frac{q}{2} \frac{dt}{dx} \quad (4)$$

Where p' is compression pressure, σ is the horizontal stress, p is the rolling normal pressure, q is the shear stress and t is the strip thickness. From the Zhao (Zhao et al 2006;472) model, the yield stress on that practically impacts useful yield stress being given as Hall Petch Relationship HPR to Reverse Hall Petch Relationship RHPR as:

$$\sigma(r) = \sigma' + A \left(r^{-\frac{1}{2}} \right) - B(r^{-1}) - C(r^{-\frac{3}{2}}) \quad (5)$$

Where $\sigma' = \sigma_0 + k_t$ is the 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 the atomic diameter in the case of metal, H_m is the bulk melting enthalpy, R is the ideal gas constant, T_r is the room temperature, $k_d > 100k_t$ and $\sigma_0 > 10k_t$. The model of the HPR to the RHPR can be modified to study material useful elongation and elongation to failure, which are impacted by material fracture, fatigue and elongation during ARB process.

RESULTS AND DISCUSSION

Our proposed models are tested with data from (nanocrystalline) aluminum sample [17-19] $\gamma = 0.98 \pm 0.21 Jm^{-1}$, [17-19] $G=169GPa$, $v=0.23$ [28] $M0'=0.01nm2s^{-1}$, $m=4$, $rc1=1.95r$, $CC=12$, $a=0.90$, $D=10^{-4}$, $h0=0.25nm$, $Tm(\infty)=933.47K$, $CV0=0.3$, $Hm(\infty)=10.71KJmol^{-1}$, $\sigma_0'=16.7MPa$, $Kt=1.3$, $\sigma_0=15.40MPa$, $Kd=1301.77MPa_{nm}^{1/2}$, $R=8.31JK^{-1}mol^{-1}$ and $Tr=300K$. The additional data obtained for this work are $O=0.0035$, $I=1.1$, $r0=100nm$, $Z=0.4$, $Ratio1=0.81$, $Ratio2=1.071$, and $\tau_1=0.000008$. Some data were obtained through curve fitting of the empirical data from the different measures of the sizes. The obtained results are presented in the plots below.

Figure 2 (a) Yield Stress and Size During Elongation (b) Strain and Time During Elongation and (c) Elongation against Time during ARB Process

The Deformation process and deformation mechanisms in NC by ARB process and UFG multiphase grain in bimodal grain distribution impact fracture, material fatigue and elongation process due to continuous network of small grains, which led to property enhancement (useful elongation) as the yield strength in the material increases as shown in Figure 2 (a) to an optimal yield strength of 360 MPa before material failure takes place being seen after a grain size of 40 nm, 20 nm and 10 nm depending on the approaching of observation which is practically elongation to failure as material failure takes place during ARB due to material fatigue. During this process the strain in the material was steadily increased as shown in Figure 2 (b) and off course, the system elongation during elongation to failure is shown in Figure 2 (c). The elongation to failure is as a result of material fatigue due to monotonic deformation by ARB process and this was due to low angle grain curvature that negatively impacted the material properties. Low angle grain curvature gave low material properties and high angle grain curvature gave high strength and material property and this is related to the grain sizes and larger grain and smaller grain sizes gave low and high curvature angles during ARB. Most often in material refinement process, high yield strength at bigger grains brings isotropic strain hardening contribution during ARB process. More so, a bigger kinematic strain hardening contributed to strength mismatch in small and large grains and that impact the material yield stress and elongation. This is impacted by grain aggregate and higher order boundary conditions on GBs on plastic flow during ARB. The deformation mechanisms during ARB process in multi-phase microstructures impact fracture and material fatigue analysis since it acts as a stronger obstacle to dislocation motion due to different interfaces that existed between different phases during ARB and these are the factors that impacts elongation and material strain rate due to the feed rate of the material during ARB as shown in Figure 3

Figure 3: (a-b) Useful Elongation Against Time During ARB Process (c-d) Elongation to Failure Against Time During ARB Process (e) Strain Rate Against Size During ARB Process and (f) Energy Against Size During ARB Process.

During deformation by ARB process, dislocation motion due to different interfaces exists between different phases and these interfaces are always stronger than GBs regarding dislocation transmission for property enhancement. A strong back stress is being generated and the material gets elongated during ARB cycles due to the different strength and different phases and this led to the accumulation of high densities of GNDs which impacted material elongation and properties as shown in Figure 3 (a-b) which is useful elongation and the elongation led to property enhancement. During the process the material sizes decrease and material yield stress increases and strain handing takes place during ARB cycles leading material slip transfer process from one phase to another phase and this slip transfer process depends on the crystallography nature and orientation relationship in the material during ARB process. In some materials, the lower grain boundaries easily became higher grain boundaries leading to optimal yield stress in the material which further lead to material failure or elongation to failure as shown Figure 3 (c-d) during ARB process. This is always impacted by the nature of work hardening in material multi-phased due to TRIP effect. Most often, thick multilayer material has better resistance to slip transmission during ARB process across the interphase boundaries and this constitutes a dominant factor that determines the maximum strength of the material multilayer during ARB process.

A significant increase in yield strength with decreasing grain sizes led to microstructure size change that elongated as shown in Figure 3(a-b). This was accompanied by a drop in ductility or elongation when the material yielded due to material fatigue and subsequent elongation to failure during ARB process as shown in Figure (c-d). Figure 3 (c-d) shows time evolution of the variation of elongation to failure (or total elongation during ARB cycles). Material elongation at fracture depend on the intensity of the compressive force applied on the material since elongation is impacted by several internal and external forces therefore it is important to know that the use of the elongation to failure during grain refinement also depend on the material a ductility index mixes the material ability to resist necking and resistance to damage accumulation during ARB and these factors are better quantified by the material true fractural strain during feeding rate by ARB process. The intricate mechanisms of material plasticity during elongation by ARB in nanostructured material ultimately impart rate-dependent hardening behaviour during elongation process. Most models of damage due to fatigue and fracture which depend on material deformation are based on the explicit rendering of dislocation slip, dislocation motion, and twinning are critical parameters that broaden the interpretation useful elongation to elongation to failure as shown in this paper.

CONCLUSION AND RECOMMENDATION

The current paper was aimed at studying the impacts of fracture, fatigue and their impact on useful elongation and elongation to failure during ARB process. To achieve the objective, the different model of fracture and strain during ARB process was established and their impacts on elongation were revealed during deformation process. The impacts on imposing strain during ARB process and their impact on property enhancement was discussed. It was shown that elongation is impacted by major parameters such as fracture and fatigue that characterised material useful for elongation and elongation to failure during ARB process. The obtained results show that material fatigue crack initiation is enhanced by a fine structure, but at the expense of larger fatigue crack growth rates during deformation process. The extrinsic toughening through hybridization process during material deformation allows arresting or bridging cracks during ARB process. It was also shown that, a bigger kinematic strain hardening contributed to strength mismatch in small and large grains and that impact the material yield stress and elongation. It was also revealed that, deformation mechanisms during

ARB process in multi-phase microstructures impact fracture and material fatigue analysis since it acts as a stronger obstacle to dislocation motion due to different interfaces that existed between different phases during ARB

REFERENCES

1. A. Pineau, A.A. Benzerga, T. Pardoen, *Acta Mater.* 107 (2016) 424e483.
2. A. Pineau, D.L. McDowell, E.P. Busso, S.D. Antolovich, *Acta Mater.* 107 (2016) 484e507.
3. H. Gleiter, *Prog. Mater. Sci.* 33 (1989) 223e315.
4. M.A. Meyers, A. Mishra, D.J. Benson, *Prog. Mater. Sci.* 51 (2006) 427.
5. K.S. Kumar, H. Van Swygenhoven, S. Suresh, *Acta Mater.* 51 (2003) 5743e5774.
6. BM, Karthik, et al. "Coated and uncoated reinforcements metal matrix composites characteristics and applications–A critical review." *Cogent Engineering* 7.1 (2020): 1856758.
7. J.R. Greer, J.T.M. De Hosson, *Prog. Mater. Sci.* 56 (2011) 654e724.
8. M. Dao, L. Lu, R.J. Asaro, J.T.M. De Hosson, E. Ma, *Acta Mater.* 55 (2007) 4041.
9. Shrivastava, D. E. E. P. T. I., and M. M. Malik. "Enhancing efficiency of organic light emitting diodes through doping of cadmium sulphide nanocrystals." *Int. J. Nanotechnol. Appl* 4.1 (2014).
10. M.D. Uchic, P.A. Shade, D.M. Dimiduk, *Ann. Rev. Mater. Res.* 39 (2009) 361e386.
11. X. Li, Y. Wei, L. Lei, K. Lu, H. Gao, *Nature* 464 (2010) 877e880.
12. WEBO, WILSON, et al. "NANOCELLULOSE AND THEIR COMPOSITES." *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* 10, 3, Jun 2020, 793-800
13. P.B. Sob and M. Pita (2020). *Stochastic effect of fracture toughness and toughening mechanism on nanocrystalline material size variants produced by accumulative roll bonding*. 2020 IEEE 11th International Conference on Mechanical and Intelligent Manufacturing Technologies. ISBN: 978-1-7281-5331-5.
14. Figueiredo, R. B., & Kawasaki, M., and Langdon, T. C., "The mechanical properties of ultrafine-grained metals at elevated temperatures. *Rev. Adv. Mater. Sci.* 19 (1/2), 1–12, 2009.
15. ISRAFIL, BAHRAM ISMAILOV. "An analysis and control of dynamic processes in mechanical parts of power equipment." *International Journal of Mechanical and Production Engineering Research and Development* 8.5 (2018): 347-352.
16. Nezami, Mohsen, and Mozghan Rahi. "Fragility Analysis of Existing Steel Building and Possible Rehabilitation by Fuzzy Expert Systems Under Blast and Dynamic Loads." *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD) ISSN (P)* (2016): 2249-6866.
17. Oladeebo, J. O. "Analysis of Factors Affecting Technical Inefficiency of Smallholder Farmers in Nigeria: Stochastic Frontier Approach." *International Journal of Economics, Commerce and Research* (2013): 21-28.