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Evaluation of Mechanical Properties and Structure of 1100-Al Reinforced with Zro_2 Nano-Particles via Accumulatively Roll-Bonded

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Abstract

In this study, aluminium metal composites reinforced with Zirconium dioxide (ZrO_2) nano-particles in different of volume percentage are manufactured through accumulative roll bonding. The results indicate that with the application of 10 ARB cycles and the composite microstructure shows excellent ZrO_2 particle distribution in the Al matrices. The X-ray diffraction results also showed that nanostructured Al/ZrO_2 Nanocomposite with the average crystallite size of 48.6 nm was successfully achieved by employing 10 cycles of ARB process. According to the results of this study, the tensile, hardness, and elongation properties of the Al/ZrO_2 composite are determined for 0.50, 0.75 and 1 vol.% ZrO_2.

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Keywords: ARB; nanocomposites; ZrO_2; nano-particles.

1. Introduction

Severe plastic deformation (SPD) is considered as an effective tool for production of bulk ultra-fine grained (submicron-grain sized 100nm<d<1μm) or nanostructure (<100 nm) on the different metals, Tsuji et al. (2003), Lee (2002). There are several methods used to production ultra-fine grained materials, Valiev et al. (2000), Wang (2010) than accumulative roll bounding (ARB) have been developed, Tsuji et al. (2003), Lee (2002). ARB is of the SPD

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methods proposed by saito et al. (2003), Tsuji et al. (2003) to achieve ultra-high strain in metallic materials without changing the specimen dimension. The roll bonding technique has been extensively used to fabricate metals matrix composite (MMC) because of its cost effectiveness and efficiency. The addition of ceramic reinforcements such as carbides and oxides to form MMC enhances the properties such as elastic modulus, strength, wear resistance, and high-temperature durability, Shu and Tu (2001). Metal matrix composites are broadly used in components of various pieces of industrial equipment, Liu et al. (2007). At present, many types of MMC are fabricated via roll bonding, including Al/SiC, Jamaati et al. (2011), Al/Al_2O_3, Jamaati and Toroghinejad (2010), Al/B_4C ,Yazdani and Salahinejad (2011), Al/TiO_2, Soltani et al. (2012) and Al/W_P ,Amirkhanlou et al. (2013). On the other hand, Zirconium oxide (ZrO_2) has attracted considerable attention because of its diverse practical applications in fuel-cell technology, as a catalyst or catalyst support, oxygen sensor, nanoelectronic devices, thermal–barrier coating, ceramic biomaterial. ZrO_2 nanostructures are of significant current interest in preparing piezoelectric, electro optic, dielectric, and nanocomposite materials, Khorramie et al. (2012), Li et al. (2004). The aim of this study was to produce the high-strength and highly-uniform metal matrix composites reinforced with different content of nanoparticles of ZrO_2 (Al/NanoZrO_2) by the ARB process. Microstructures and mechanical properties by XRD, FESEM and tensile strength of the composites were alsoinvestigated.

2. Experimental procedures

In this study, Al (1100) sheet was used and the chemical composition and some mechanical properties of the Al used have been mentioned in Tables 1. It was cut into 120mm×50mm×1mm pieces, parallel to the sheet rolling direction. These strips were annealed at 753 K in ambient atmosphere for 120min.

Table 1. The chemical composition and mechanical properties of the Al used.

Materials	chemical composition	Sheet dimensions(l.w.t) (mm×mm×mm)	Elongation(%)	Yield strength	crystallite size
Commercial Al sheet	0.18Si, 0.37Fe, 0.13Cu,0.02Mn, 99.48Al, 0.01 others	120×50×1	43	89 MPa	43μm

Figure 1 shows the SEM image of the used ZrO_2 Nano-particles in this work. The composite production of ZrO_2 nanoparticles with equal to 0.50, 0.75 and 1.0vol.% were used and has been applied to a strain equal to 0.8 (Reduction actions equal 50%). The tensile test samples were machined from the ARBed strips, according to the ASTM E8M standard, to get oriented along the rolling direction. The gauge width and length of the tensile test samples were 6 and 25 mm, respectively.

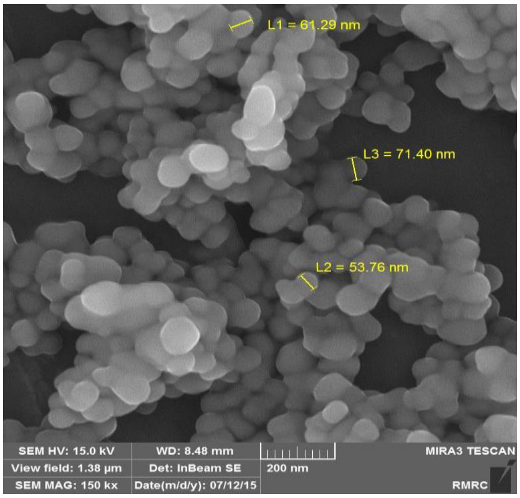

Fig. 1. shows the FESEM micrograph of ZrO_2 nanoparticles powder used.

The tensile tests were performed at room temperature at an initial strain rate of $8.3\times10^{-4}s^{-1}$. The total elongation of the samples was determined as the difference between gauge lengths before and after testing.The X-ray pattern of the manufactured Al/Nano-ZrO_2 composite was recorded with an X-ray diffractometer (XRD). The result was used for the microstructural characterization. The crystallite size of the specimen was calculated from the XRD patterns applying the Williamson–Hall method, Monzen et al. (2011), Williamson (1953).

3. Results and discussion

3.1. Microstructure

Figure 2 shows SEM images of the composite structure produced with 1.0vol% in different cycles of the ARB process. Reinforcement particles distribution is very important because it is very effective in the properties of composites produced, Jamaati and Toroghinejad (2010), Yazdani and Salahinejad (2011). Reinforcement particles play an important role in strain hardening and microstructure grain refinement and can be effective in modifying the microstructure in different ways which include: a) barriers to dislocation motion, b) differences in coefficient of thermal expansion between matrix and reinforcement particles and c) increased dislocations by Orowan mechanism based on which ceramic particles act as an obstacle in the path of dislocation motion and by dislocation passing around the particle Orowan loop is formed and the strength is increased, Jamaati and Toroghinejad (2010), Kitahara et al. (2011). According to the film theory, it can be said that two sheet surface oxide layers develop cracks during rolling, and by rolling vertical force new matrix materials are extruded through the cracks. Now it can be said that in the presence of ZrO_2 between sheets of aluminum, matrix particle can be extruded through the clusters. Fig. 2a displays image of the composite structure produced. The particle-free areas (circles) together with cluster areas and reinforcement particle agglomeration are marked with square lines. During the ARB process, elongation is caused in the rolling direction because of the reduced sectional area. This phenomenon causes the clusters being drawn in the rolling direction and the expansion created helps to break down the clusters resulting in gradual removal of clusters and areas devoid of reinforcement particles for a homogeneous structure to be created. Optimizing the properties of the composite particularly achieving suitable combination of high strength and ductility requires a relatively high volume fraction and fine reinforcement particles. According to the reference reports, Jamaati et al. (2011), the effect of reinforcement particle size on the micro scale and stated that although larger reinforcement particles will reach more uniform distribution faster than smaller reinforcement particles, the composite with smaller reinforcement particles will have higher strength after all. It can also be stated that with increasing number of cycles, reinforcement particle distribution in the matrix is improved and the distance between reinforcement particles increases leading to the strength increase. Use of reinforcement nanoparticles can play the role of fine reinforcement particles. Fine reinforcement particles tend to non-uniform distribution and the creation of clusters and their agglomeration Jamaati et al. (2011). There is a direct relationship between the local volume fraction of reinforcement particles and the formation of defects that cause damage. Under external load, concentrated clusters of reinforcement particles may bring about non-uniform stress distribution in the composite produced. Significant three-dimensional stress is created in areas of clusters which is much larger than the applied stress which leads to faster formation and propagation of cracks. The flow of plastic material in the center of clusters of particles is suspended because of high hydrostatic stresses causing cracks to germinate in these areas, Yazdani and Salahinejad (2011), Amirkhanlou et al. (2013), Jamaati, and Toroghinejad (2010). Therefore reinforcement nano-particle distribution in the matrix is very important. Fig. 2b shows image of the composite structure produced in the final cycle (cycle 10) that, as is evident in the end after the 10 cycles of the ARB, a structure with almost uniform ZrO2 reinforcement particle distribution in aluminum matrix is achieved. On the other hand, according to Williamson–Hall method and the resulting XRD graph of the composite samples made with 10 cycles of ARB, average crystallite size equal to 1 vol% has been 48.6.

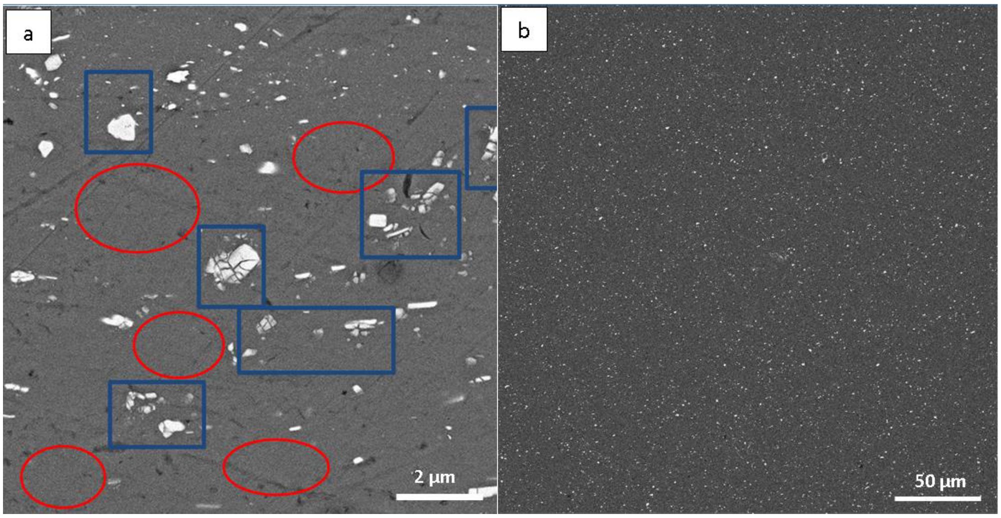

Fig. 2. shows the FESEM micrograph of microstructure produced nano-composite during ARB (a) some areas of agglomerated reinforcing particles and areas free of particles and particle clusters; (b) the structure of Nano-composites reinforced with particles of ZrO_2 at cycle 10.

3.2. Mechanical properties

Figure 3 shows image of tensile strength-number of cycles for composite sample produced by the ARB in different volume percentages. The mechanical properties of composite sheets produced are highly impressed by each cycle. Tensile strength in Al1100 sheets is equal to 89 MPa before the ARB process. As it can be seen in Fig. 3, the tensile strength of composites produced after 1 cycle ARB process for 0.5, 0.75 and 1.0 vol% increased to 121.5, 119 and 115 Mpa respectively. As it is evident, the tensile strength shows a higher rate of increase in the primary cycles and a lower rate of increase in the last cycles. According to the reference reports, Sun et al. (2010) ,tensile strength changes in the ARB process are controlled by two important strengthening mechanisms that include: 1) strain hardening by forming dislocations; in the first step, strain hardening due to the increased dislocation density resulting from the deformation shall be noted that bring about an increase in strength. This factor plays an important role in the early stages of the ARB in such a way that increasing ARB stages and producing the fine structure and improving the grain size will gradually reduce its impact. 2) Grain refinement by recrystallization mechanisms; following the ARB process, fine-graining is very effective in the final stages of the process. The effect of shear strain created during ARB process of roller friction, sample and reinforcement particles increases equivalent strain and strength. Finally for the final cycle (cycle 10) ARB process it can be seen that the tensile strength for 1.0 vol% have increased to 191.5 Mpa.

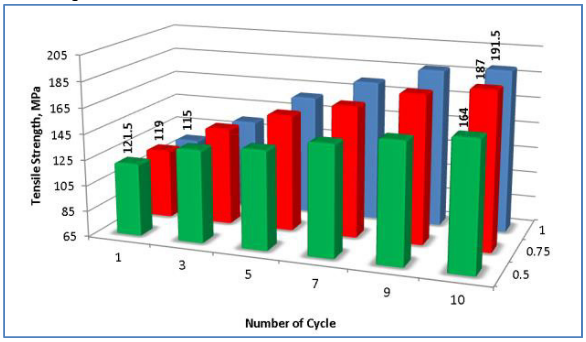

Fig. 3. shows image of tensile strength-number of cycles for produced composites by ARB process.

Figure 4 shows image of the elongation-number of cycles changes for the composite samples produced by ARB process. Elongation of the aluminum sheet used is 43 before the ARB process. As seen in this figure also by the exercise of the first cycle, elongation for 1.0 vol% has reduced to 10.1 Mpa. By increasing the number of cycles, sufficient connection will be established between sheets of aluminum and reinforcing particles, which increases the mechanical properties of the samples especially elongation, Govindaraj et al. (2013). With the increasing number of cycles, elongation decreases in the beginning and then increases continuously for 1.0 vol.% which have increased to 8.6. One of the factors that affect the tensile strength and elongation in the samples is proper connection of sheets in the presence of reinforcing particles and proper reinforcing particles distribution, as well as the decreased porosity. The presence of porosity is a very important effect on the mechanical properties of the composite sample produced. In fact, the presence of porosity, especially in the vicinity of the reinforcing particles causes a sharp reduction in tensile strength and elongation, Jamaati et al. (2014), Jamaati et al. (2014).

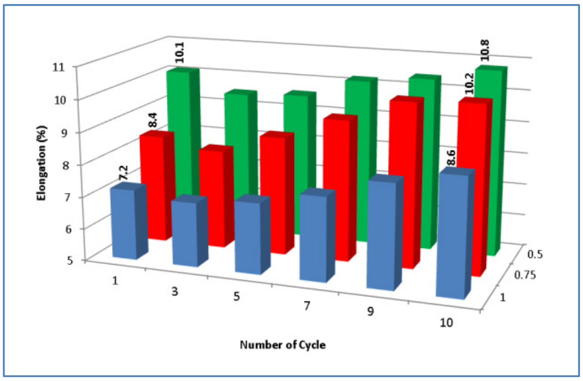

Fig. 4. shows image of elongation-number of cycles for produced composites by ARB process.

On the other hand, due to the significant difference in thermal expansion coefficient between the reinforcing particles (7×10^{-6}/K) and the aluminum matrix (23.86×10^{-6}/K) during cold rolling process, dislocations cause heat stress at the intersection of reinforcing particles and matrix, therefore, tensile strength increases and elongation decreases , Liu et al. (2012).

4. Fracture surface

Figure 5 shows SEM image of the fracture surface of Al/ZrO_2 nanocomposite tensile test produced by 1.0 vol% by ARB process. Fracture surface in the first pass is in the form of ductile fracture with deep holes in the direction of stretching with matrix having a gray surface with holes almost similar in spheroid form , Alizadeh and Samiei (2014). It should be noted that fracture is first caused by micro void formation and then micro cracks join and cause emissions and ultimately create shear failures in angles related to the tension , Eizadjou et al. (2009). Fig. 5a shows a fracture surface of a composite sample produced by 1 vol.% in the first cycle with deep and stretched pores. By increasing the number of ARB cycles fracture will change to shear mode and the number, size, depth and direction of the pores will change as well , Eizadjou et al. (2009). Fig. 5b shows the composite sample produced by 1 vol.% in the final cycle (cycle 10), which can be seen that the number, size, depth and direction of the pores are very different compared to the initial state (first pass).

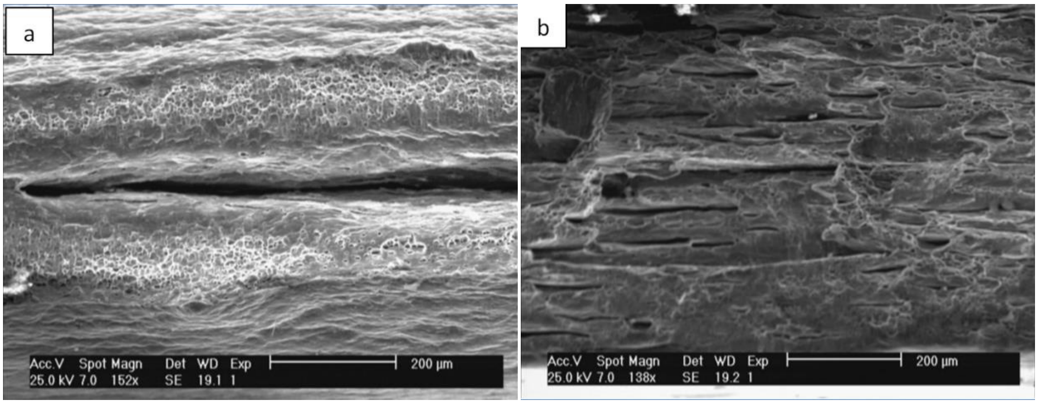

Fig. 5. shows the fracture surfaces of Nano-composites in (a) the first cycle; (b) the end cycle, respectively.

5. Conclusions

Al/Nano-ZrO_2 composites were manufactured through 10 cycles of cold roll-bonding process, which is an attempt to use pure metal particle-reinforced AMMCs. The microstructure and mechanical properties of the composites were investigated. The conclusions can be summarized as follows:

Proper distribution of reinforcing particles ZrO_2 in aluminum is obtained during 10 cycles of ARB process.

Composite strength produced increased and the strength to 1vol.% ZrO_2 was obtained 191.5 MPa which is 2.15 times higher than ARB-free aluminum sheet.

Elongation of the composite produced decreased in the first cycles and then increased as ARB process cycles continued. In the end, the elongation for in 0.5, 0.75 and 1.0 vol.% was obtained 10.8, 10.2 and 8.6, respectively.

XRD analysis results for the composite produced show that the crystallite size after 10 cycles of ARB process in 0.5, 0.75 and 1.0 vol.% is 85.5, 55.7 and 48.6, respectively.

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