# Mechanical and wear properties evaluation of Al/Al$_2$O$_3$ composites fabricated by combined compo-casting and WARB process

Mohamad Heydari Vini[*1] and Saeed Daneshmand[2a]

[1]*Department of Mechanical Engineering, Mobarakeh Branch, Islamic Azad University, Mobarakeh, Isfahan, Iran*
[2]*Department of Mechanical Engineering, Majlesi Branch, Islamic Azad University, Majlesi, Isfahan, Iran*

**Abstract.** Compo-casting method is one of the popular technique to produce metal based matrix composites. But, one of the main challenges in this process is un-uniform spreading of reinforced subdivisions (particles) inside the metallic matrix and the lack of desirable mechanical properties of the final produced composites due to the low bonding strength among the metal matrix and reinforcement particles. To remove these difficulties and to promote the mechanical properties of these kind of composites, the WARM ARB technique was utilized as supplementary technique to heighten the mechanical and microstructural evolution of the casted Al/Al$_2$O$_3$ composite strips. The microstructure evolution and mechanical properties of these composites have been considered versus different WARM ARB cycles by tensile test, average Vickers micro hardness test, wear test and scanning electron microscopy (SEM). The SEM results revealed that during the higher warm- ARB cycles, big alumina clusters are broken and make a uniform distribution of alumina particles. It was shown that cumulating the forming cycles improved the mechanical properties of composites. In general, combined compo-casting and ARB process would consent making Al/Al$_2$O$_3$ composites with high consistency, good microstructural and mechanical properties.

## 1. Introduction

Currently the use of aluminum matrix composites (AMCs) is felt in several productions such as automobile, aerospace, vessels and chemical productions. These needed properties are such as high strength, good wear resistance, good chemical resistance, light weight, high elastic modulus and low thermal expansion coefficient (Jamaati and Toroghinejad 2010). Amid the engineering methods for the production of metal matrix composites (MMCs), compo-casting is generally popular for its simplicity, cost efficiency and its capability for producing in large and industrial scales. The compo-casting process is a variation of the stir casting in which the ceramic or oxide particles are added to the molten metal or alloy and stirred (Amirkhanlou *et al.* 2011, Heydari Vini

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*Corresponding author, Ph.D., Assistant Professor, E-mail: m.heydari@mau.ac.ir
[a]Ph.D., Associate Professor, E-mail: S.daneshmand@iaumajlesi.ac.ir

*et al*. 2017). Although the compo-casting process is a cost efficient process for producing MMCs, but there are some restrictions in the final produced composites such as porosity formed during the process which makes low mechanical properties, non-uniform dispersion of reinforced particles and generating zones with free and high amount of particles amount and finally low bonding strength among the reinforced particles and metal matrix due to the low amount of the compression of metal matrix around the particles (Saito *et al*. 2017). So, it is essential to progress the mechanical properties of these composites with a supplementary forming process which high amount of plastic strain. On the other hand, combining the compo-casting process with a sever plastid deformation (SPD) is a good idea. There are several sever plastic deformation processes to produce ultra-fine grain (UFG) materials such as powder metallurgy, accumulative roll bonding (ARB) (Saito *et al*. 2017), cyclic extrusion compression (CEC) (Heydari Vini and Daneshmand 2020), multi-axial forging and so on among these processes. ARB process proposed by Saito *et al*. (2017) to achieve ultra-high strain in sheet metals without changing the specimen dimension. Totally based on the recent investigations done, there are two main kinds of reinforcement particles used for production of MMCs. The first group are metallic particles such as Tungsten and Copper (Liu *et al*. 2012, Alizadeh and Talebian 2012). The second group are ceramic particles such as $Al_2O_3$, TiC, SiC, $SiO_2$, $B_4C$ and WC (Lu *et al*. 2009, Alizadeh 2010, Liu *et al*. 2013, Ipek 2005). Also, the main reason using $Al_2O_3$ particles as reinforcement particles in this study is that $Al_2O_3$ has the most hardness value in ceramics after the natural diamond based on the Mohs scale of mineral hardness (Farhadipour *et al*. 2017). To overwhelmed the above-mentioned difficulties compo-casting process of $Al/Al_2O_3$ composites, we recommend combined compo-casting and warm accumulative roll bonding (WARM ARB) process together at 300°C as its novelty. Increasing the rolling temperature allows the aluminum matrix to have a better flow around the $Al_2O_3$ particles which improves the bonding among the aluminum matrix and $Al_2O_3$ particles as reinforcement. The purpose of this study is to produce $Al/Al_2O_3$ composite samples with highly unchanging spreading of $Al_2O_3$ particles in Al MMCs contains high mechanical properties.

## 2. Experimental procedure

### 2.1 Materials

During this paper, AA 1050 and $Al_2O_3$ particles with average size 1μm were elected as the matrix and the reinforcement, individually.

### 2.2 Fabrication of cast composites

AA1050/5 Wt. % $Al_2O_3$ composites were formed by compo-casting process. The average size 5 micrometer is chosen due to the agglomeration effect of particles with the smaller size. Diagram of the experimental sequences utilized in the making of the cast composites is displayed in Fig. 1. In each test, about 1500g of AA1050 was melted in a graphite crucible of 2kg capacity, and the temperature of the molten aluminum was elevated to 750°C. For having an unchanging temperature state, the molten aluminum alloy was reserved at the fixed temperature for around three minutes. Then, the melt was enthused at 600 rpm using a graphite propeller with the injection of $Al_2O_3$ particles in a pure argon (99.99%) atmosphere. Afterward end of the injection and after a constantly cooling with an average cooling rate of 4.5°C/min, the temperature of the final molten alloy is 750°C and then cast hooked on a steel die located under the heater.
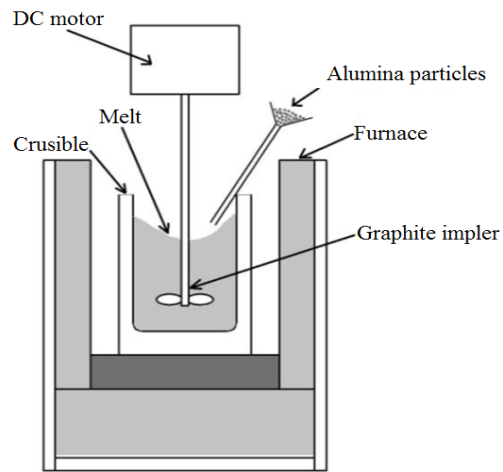
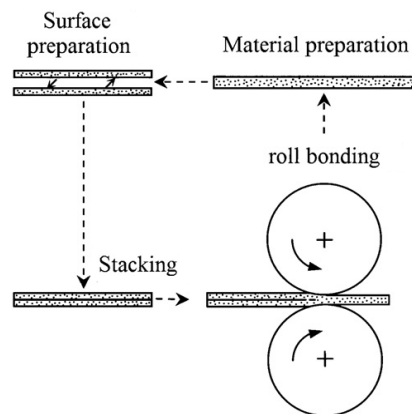Fig. 1 Diagram of the experimental set-up secondhand in making of the cast Al/Al₂O₃ composites



Fig. 2 Diagram design of ARB

## 2.3 Accumulative roll bonding (ARB) process

Afterward making as stir cast composites, samples with 100 mm length, 50 mm width and 2 mm height, were machined. Then, the samples were fully annealed at 450°C for 2h before the ARB process. Nest, the samples were degreased in acetone bath for 15 minutes. In direction to eliminate the surface oxide layer, the surfaces of samples were fully brushed to guarantee an acceptable bonding between the layers. Then, two strips were stacked together to achieve 4 mm thickness and roll-bonded with 50% reduction (effective strain equal to 0.8) at 300°C minus any lubrication to acquire 2 mm thickness.

The roll diameter and the rolling speed ($\omega$) were 170 mm and 40 rpm. The composite produced after one cycle of ARB was cut into two parts and preheated at 300°C for 5 minutes. In the next stage (Fig. 2), two strips of MMC were loaded each other after surface cleaning. The fabricated sample was cut into two strips and a rolling process with a 50% of thickness reduction repeated up to eight cycles. Increasing the plastic strain during the cumulative rolling leads to a
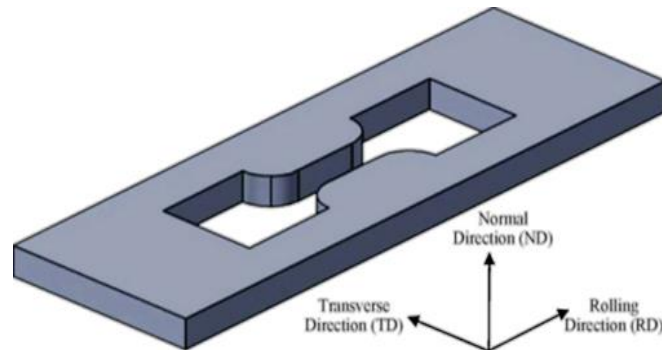
Fig. 3 Orientation of the tensile test specimens

better dispersion of the powder particles. The tensile test specimens were prepared according to the ASTM-E8M standard which along the longitudinal direction in 25 and 6 mm dimensions, (Fig. 3). The tensile strain for conducting the tensile test was $1.67 \times \frac{10^{-4}}{sec}$ on a Hounds field H50KS testing machine. Also, the standard ASTM-E384 was utilized for doing the hardness test. Moreover, to perform the wear test on the composite samples the wear tests performed on a pin on flat wear-testing machine with a constant rotation speed of 38 rpm. The length of each round was 16 cm and normal load (Fn) of 50 N at room temperature without lubrication with the total distance of 100 m.

## 3. Results

### 3.1 Tensile strength

Fig. 4 displays the tensile strength values of composite samples versus dissimilar ARB cycles. The strength of the annealed Al is 81.3 MPa and for the sample with two cycles of ARB is equal to 161.6 MPa which is a rapid increasing rate. Afterward according to Fig. 4, the tensile strength remains approximately constant by cumulating the number of cycles up to eight (162 MPa). This trend is also similar to the yield strength. Two mechanisms can clarify this behavior, (I): strain hardening (dislocation strengthening) at low number of cycles and (II): grain boundary strengthening mechanism by growing the cycles due to the production of ultra-fine grain aluminum matrix (Heydari Vini *et al*. 2017, Sedighi *et al*. 2016). In the second stage, local strain hardening around the alumina particles is a main object for growing the strength hardening (Heydari Vini *et al*. 2017). Alumina particles can initiate slip systems in the aluminum matrix close its together layers which their density and the amount of local strain hardening in them expands by cumulating the plastic strain up to the 8th cycle.

Fig. 4 displays the elongation of samples against the ARB cycles. As can be seen in Fig. 4, there is a rapid drop from the annealed Al (23.25 %) to cycle #2 (1.72 %). This rapid drop can be ascribed to the stress hardening due to plastic and the less movement of dislocations [3]. This trend revers from cycle#2 up to cycle#8 where it reaches to its maximum value (7.26%). This improving behavior can be attributed to three mechanisms: (I) increasing the uniformity of particles through the matrix, (II) enhancement of the bond strength between the Al matrix and alumina particles and
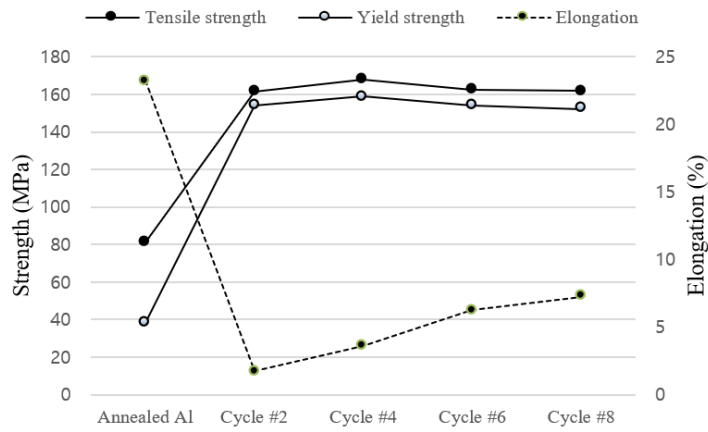
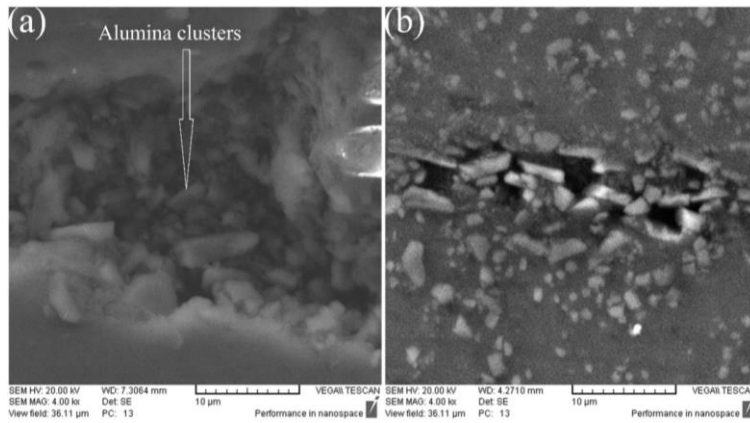Fig. 4 Mechanical properties of the Al/Al₂O₃ composites



Fig. 5 SEM micrograph expressive of Al₂O₃ cluster through the Al matrix with (a) one and (b) eighth cycles of ARB, respectively
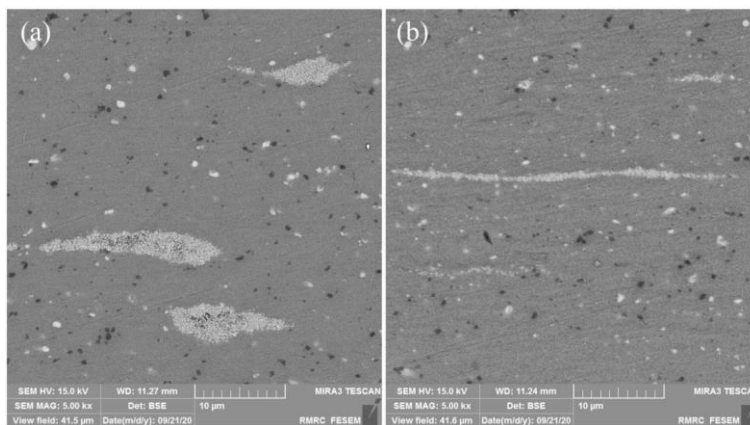


Fig. 6 Dispersion of Al₂O₃ particles through the Al matrix, (a) as-cast composite and (b) eighth cycles of ARB, respectively
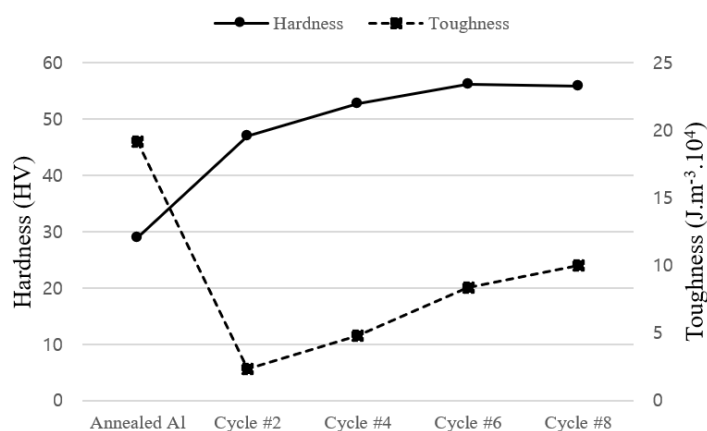
Fig. 7 The average Vickers micro-hardness and tensile toughness

(III) breaking of particle clusters and reducing the absorbencies in the structure. Figs. 5 and 6 compare the SEM micrographs of the agglomerations in the aluminum matrix of composite samples with one and eight cycles of ARB. The micrograph for the eight cycle processed sample shows small cluster which means the smaller grain size of Al matrix and a unvarying dispersal of alumina particles in the structure. On the other hand, at higher amounts of plastic strain, the porosities in the clusters are eliminated.

Fig. 7 shows the tensile toughness value of samples versus the ARB cycles. According to Fig. 7, tensile toughness value drops severely from the annealed Al (19.2 $j.m^{-3} \times 10^4$) up to cycle#2 (2.36 $j.m^{-3} \times 10^4$) and then begins to grow slightly from cycle #2 to cycle #6 (8.34 $j.m^{-3} \times 10^4$). But, this trend becomes slower than before from cycle #6 to cycle #8 (10.02 $j.m^{-3} \times 10^4$). Growing values of the strength and strain amplitudes during the ARB process is the main reason for increasing in the tensile toughness of compocasted Al/Al$_2$O$_3$ composites.

### 3.2 Hardness test

The average Vickers micro hardness and tensile toughness of composite samples versus various ARB cycles are shown in Fig. 7. As can be seen in Fig. 6, the average micro hardness has an increasing rate from the annealed Al up to cycle #4 and then remains approximately constant with a minor additional change up to cycle #8. The initial increasing stage of the average Vickers micro hardness is linked to the strain hardening and cumulating the dislocations density inside the crystalline lattice (Heydari Vini *et al*. 2017). By increasing the number of cycles up to eight, the hardness is saturated (Su *et al*. 2014). Dislocations saturation occurs at larger plastic strains (Heydari Vini *et al*. 2017, Su *et al*. 2014). It seems that due to the locking mechanism of dislocations occurs at higher plastic strains which creates a unvarying spreading of particles through the alloy matrix.

### 3.3 Fractography

Figs. 8(a) and 8(b) clearly shows the SEM fracture surface of samples with two and four cycles. In the fracture surface of samples at earlier cycles, the fracture surface contains deep and elongated
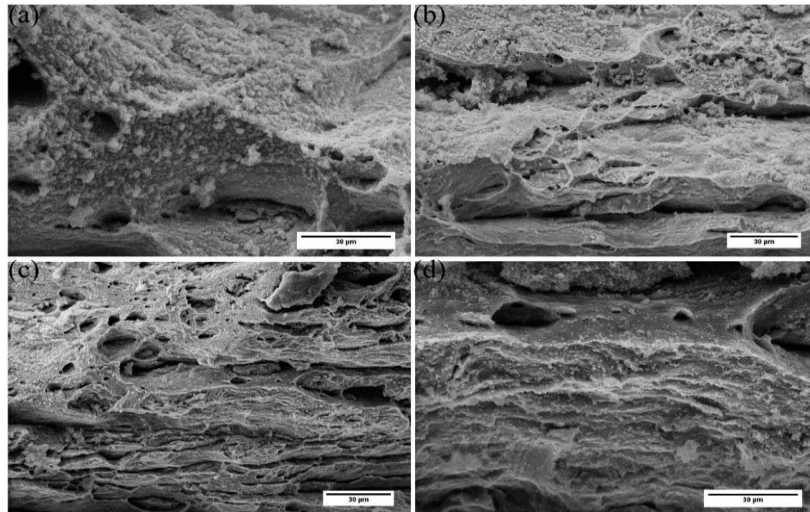
Fig. 8 The fracture surfaces after the tensile test for composite samples with (a) two, (b) four, (c) six and (d) eight cycles of ARB process, respectively
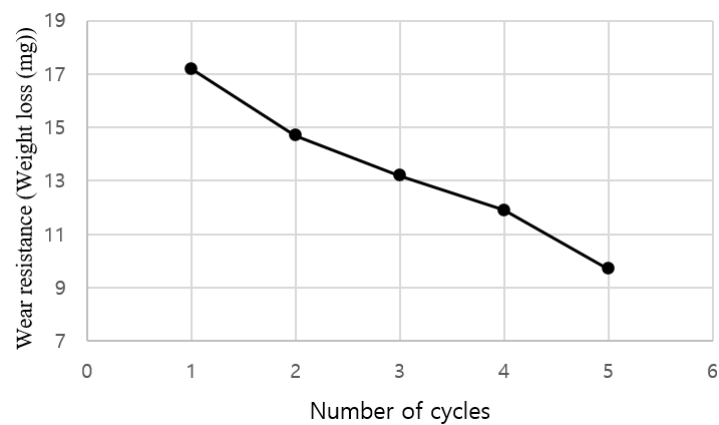


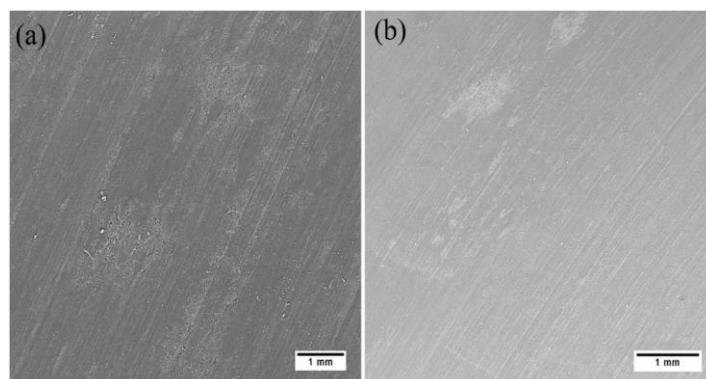Fig. 9 Wear resistance (Weight loss) in sliding wear for Al–Al₂O₃ composite at different cycles



Fig. 10 SEM microphotographs of worn surface of composite samples after (a) Cycle #1 and (b) Cycle #8

## 4. Wear test

Fig. 9 displays the weight loss of Al processed after various cycles. Weight loss Fig. 9 shows weight loss of composite samples produced with one and eight ARB cycles after the wear test. Also, Fig 9 shows the morphology of the worn surface of composite samples after one and eight cycles. According to Figs. 9 and 10 the weight loss of composite with one cycle is more than sample fabricated via eight cycles. In the other words, debris particles formed at the initial cycles cause the mass loss increased and by increasing the plastic strain due to the ross at higher number of cycles, uniform distribution of Al2o3 particle leads to the reduction of weight loss.

## 5. Conclusions

1. Combined compo-casting and WARM ARB procedure can be secondhand to produce high strength AMCs than conventional.

2. SEM results revealed that by increasing the number of ARB cycles, the spreading of particles rises considerably.

3. The UTS of samples reaches a maximum value of 162 MPa after the 8nd cycle which is about two times more than annealed Al.

4. The maximum elongation of the annealed Al is 23.25 % which drops to 1.72% for the sample with two cycles. Then, it improves to 7.26% after the 8th cycle. This means that the alumina can has an enhancing effect on the elongation after a certain number of cycles.

5. The tensile toughness of the annealed Al is 19.2 $j.m^{-3} \times 10^4$ which drops to 2.36 $j.m^{-3} \times 10^4$ for the sample with two ARB cycles and then it enhances to 19.2 $j.m^{-3} \times 10^4$ for the eight cycle processed sample. In other words, the alumina particles can improve the tensile toughness of composites with more cycles.

6. The hardness value improves with the ARB cycles due to the presence of reinforcement phase.

7. The results revealed that the composites with alumina particulates have better wear resistance property compared to annealed base alloy.

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