Mechanical Properties and Microstructural Evolution of AA5083/Al_2O_3 Composites Fabricated by Warm Accumulative Roll Bonding

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Abstract: In this study, warm accumulative roll bonding (Warm- ARB) process has been used to produce Metal Matrix Composite (MMC: AA5083/-5% Al_2O_3). Starting materials were roll bonded as alternate layers up to 5 rolling cycles with 300°C preheating for five minutes before each cycle. The microstructure and mechanical properties of composites have been studied after different Warm- ARB cycles by tensile test, Vickers micro hardness test and scanning electron microscopy (SEM). The results revealed that during higher Warm- ARB cycles, breaking the layers of alumina particles led to the generation of elongated dense clusters with smaller sizes. This microstructural evolution led to improvement in the hardness, strength and elongation during the Warm- ARB process. The results demonstrated that the dispersed alumina clusters improved both the strength and tensile toughness of the composites. Finally, Warm- ARB process allowed producing metal particle reinforced with high uniformity, good mechanical properties and high bonding strength.

Keywords: Fractography, Mechanical properties, Metal-matrix composites (MMCs), Particle-Reinforced composites, Warm accumulative roll bonding

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1 INTRODUCTION

Aluminum is a lightweight and relatively weak metal. Its applications are limited when high modulus and strength are required. The demands for high-strength materials have led to the development of MMCs. Aluminum metal matrix composites (Al MMCs) are being considered as a group of new advanced materials in industries due to their light weight, good wear, corrosion resistance, high strength, high modulus of elasticity, and low coefficient of thermal expansion. In recent years, severe plastic deformation (SPD) has been introduced as a potentially successful method to obtain ultra-fine grained structures in metallic materials with the ensuing positive consequences for strength and toughness.

Several methods are used to fabricate MMCs., such as powder metallurgy [1], accumulative roll bonding (ARB) [2-4], equal channel angular pressing (ECAP) [5], [6], multi-axial forging and so on. Among these processes, ARB and CEC are known as kinds of severe plastic deformation (SPD) methods [7]. Most of the ARB production methods are based on "Cold-ARB" implemented at the ambient temperature [8], [9]. In this method, using fine particles is a common practice for producing MMC. For example, Tungsten and Copper are used as metallic particles [10], [11]. Ceramic particles in aluminum matrix such as SiC, TiC, WC, SiO_2 and B_4C are used in MMCs [12-15].

Fabricating composite by Cold-ARB process has a weak bonding strength due to sever work hardening of metal layers. For example, a large number of cracks begin to nucleate and propagate during cold rolling cycles [15]. Reduction and temperature are two key factors which are essential preconditions for an acceptable bonding of composite layers. At higher reduction of thickness, the bonding strength between two layers of composite was improved [12-17]. Very limited works are presented in literature regarding ARB at higher temperature. By increasing the rolling temperature, the peeling force between composite layers enhances.

Researchers used Warm-ARB method on commercially pure titanium. They studied the effect of number of ARB cycles on the tensile strength, grain size and micro hardness [18]. The aim of present study is to fabricate metal particle reinforced by Warm-ARB at 300°C. Because of higher temperature, the material has a better flow across the composite layers and the bonding strength increases. It was attempted to manufacture AA5083/5% Al_2O_3 MMCs with uniformly distributed alumina powder in the Al matrix and evaluate the microstructure and mechanical properties such as hardness, strength, elongation and tensile toughness of these composites. The main incentive for these investigations is enhancing the mechanical properties of AA5083 with the homogenous distribution of powder particles.

2 WARM ARB PROCESSING

The material used in this study was fully annealed Al-5083 strips. The chemical composition and mechanical properties of this alloy are presented in tables 1 and 2, respectively. Also, the mechanical and physical properties of alumina particles are presented in table 3. First of all, the strips were annealed at 400°C for one hour. Two sheets in a length, width and thickness of 200×50×2 mm were degreased in acetone for 10 minutes. For fabricating the samples in order to remove the surface oxide layer, strips were fully brushed to guarantee an acceptable bonding between the layers (Figs. 2 and 3). Al_2O_3 particles with average size of 2 μm were dispersed between two layers to obtain the primary sandwich by hot rolling process. For dispersing the Al_2O_3 particles, an ethanol base suspension with PH = 3 was prepared and was put under ultrasonic waves with 50 kHz frequency for 30 minutes in an oven. Al_2O_3 Particles were deposited and ethanol was evaporated. Finally the brushed surfaces in all the sheets were uniformly covered with Al_2O_3 particles. For this purpose, two strips were stacked together and roll-bonded with 75% reduction in thickness (effective strain equal to 1.6) at 400°C without any lubrication to obtain 1mm strip according to Fig. 3. This initial sample is called "Zero Cycle or cycle#0", in this study. Fig. 4 illustrates the experimental setup which has been designed for Warm-ARB in this study.

Table 1 The chemical composition of AA5083.

Element	Al	Cr	Si	Fe	Mn	Zn	Ti	Cu	Mg
Wt. %	balance	0.21	0.23	0.185	0.51	0.23	0.003	0.08	4.5

Table 2 The mechanical properties of AA5083

Grade	Temper	UTS (MPa)	Yield strength	Elongation%	Hardness HV
AA5083	o	290	145	29	26.3

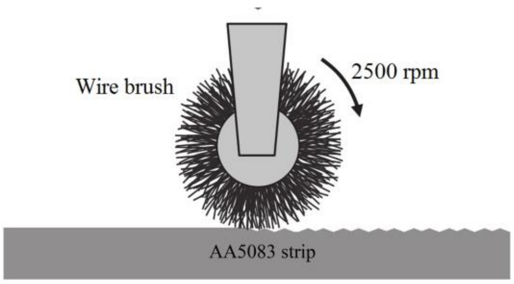


Fig. 1 Schematic illustration of the wire brushing

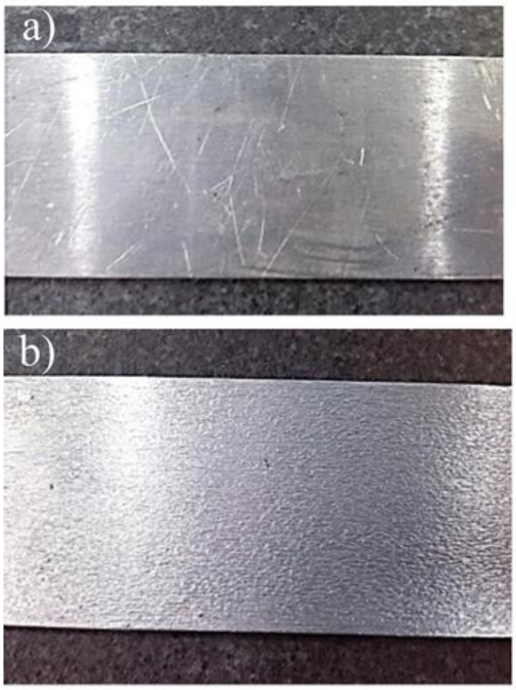


Fig. 2 The surface of the samples, (a) before brushing and (b) after brushing and.

Table 3 The mechanical and physical properties of Al_2O_3 particles

Material	Purity %	Particle size	Density	Compressive Strength	Rapture Module	Hardness
Al_2O_3	99.9%	2 µm	3.9 $gr.cm^{-3}$	2200 MPa	330 MPa	1650 $kgf.mm^{-2}$

Fig. 3 The sample fastened by steel wires before the rolling process.

After cycle#0, primary AA5083/5% Al_2O_3 sandwich was annealed again as the same condition of the first annealing. This annealing process removes the work hardening and improves the bonding strength of the primary sandwich. The reduction of all cycles (from cycle#1 to cycle#5) was equal to 50% with an effective strain equal to 4. Fig. 4 illustrates the experimental setup which has been designed for Warm-ARB process in this study.

According to Fig. 5, the roll diameter and the rolling speed (ω) were 110 mm and 40 rpm. The primary sandwich was cut into two strips and preheated at 300°C for 5 minutes. In the next step, two strips of MMC were stacked together after degreasing and wire-brushing. The roll bonded sheet was cut into two sheets, and the 50% roll-bonding process was repeated up to five cycles. During these five ARB cycles, it is expected to have more homogeneous structure by better dispersion of the Al_2O_3 particles. After the 5th cycle, the number of the powder layers is 64 within the strip. The steps of the production process of Al/ Al_2O_3 composites have been summarized in Table 4.

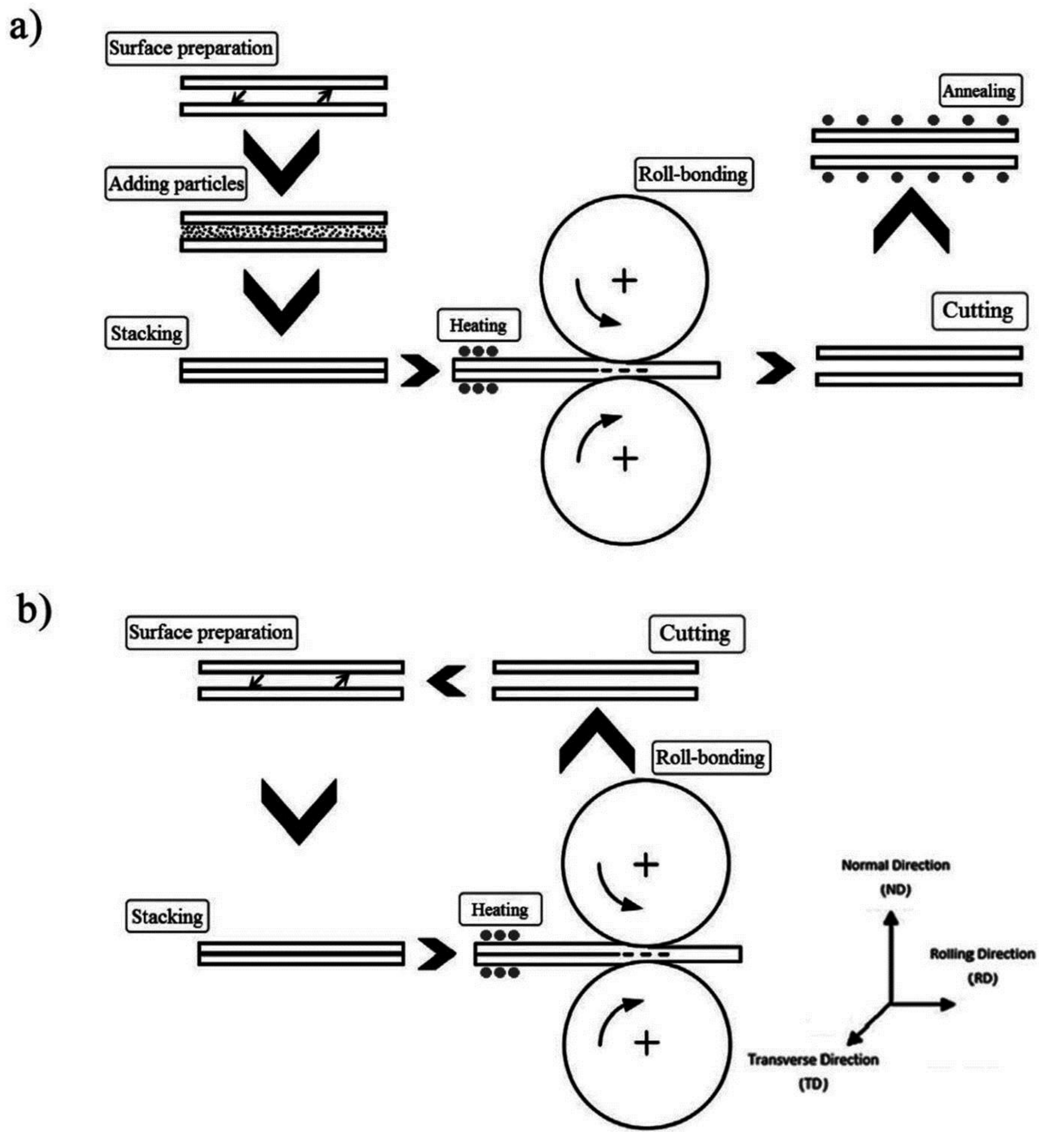


Fig. 4 Schematic illustration of the production process of the AA5083/ Al_2O_3 composite sheet (a) primary cycle (cycle#0) and (b) main cycles

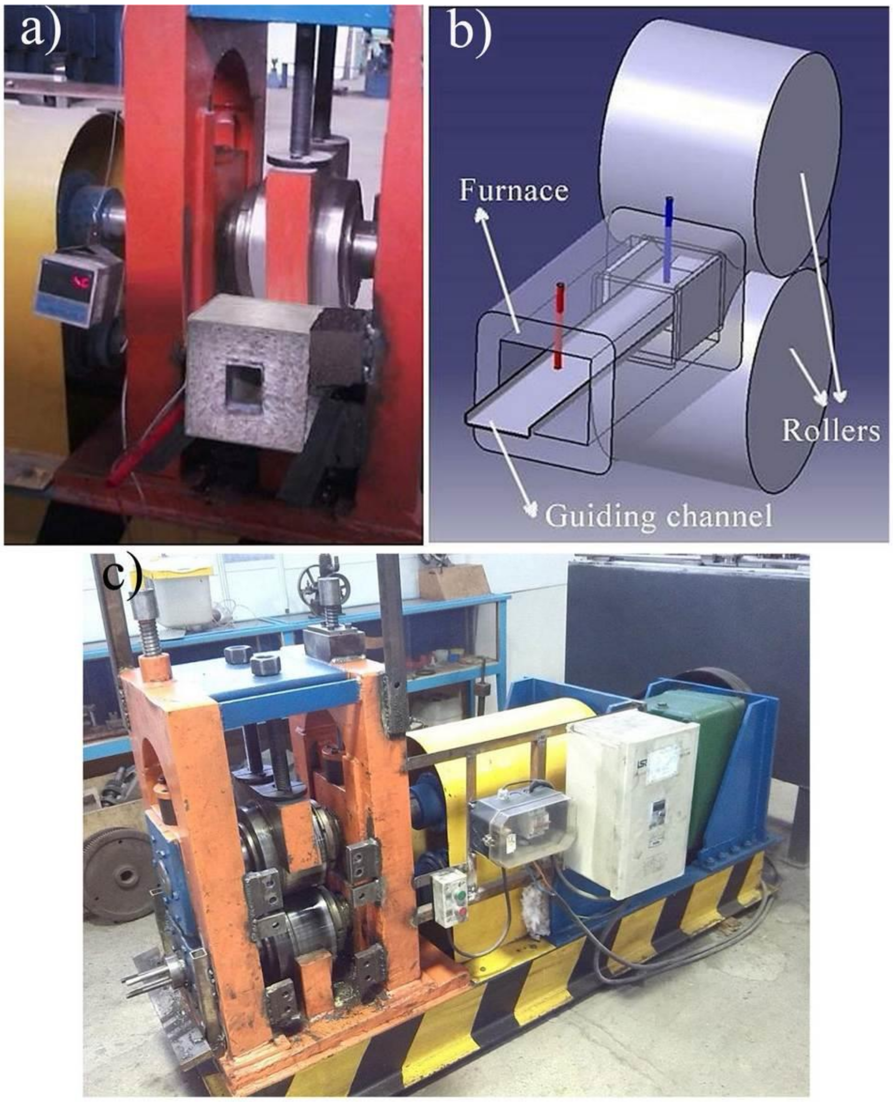


Fig. 5 Experimental setup for roll bonding process

Table 4 Specifications of the Warm- ARB process for the production of AA5083/ Al_2O_3 composites

No. of cycles	Rolling temperature (°C)	No. of Al-layers	No. of Al_2O_3 layers	Reduction in each Cycle (%)	The Al-layers thickness (µm)	Total reduction (%)	Effective strain (ε_{ef})
0*	400	2	1	75	500	75*	1.6*
1	300	4	2	50	250	50	0.8
2	300	8	4	50	125	75	1.6
3	300	16	8	50	62.5	87.5	2.4
4	300	32	16	50	31.25	93.75	3.2
5	300	64	32	50	15.625	96.87	4

* After the zero cycle, the sample is annealed at 400 °c for 1 hour; therefore, the strain exerted in the zero cycle would be removed.

The tensile test specimens were machined from the rolled strips according to the ASTM-E8M standard [18], which were oriented along the rolling direction, (Fig. 6). The gauge length and the width of the tensile test specimens were 25 and 6 mm, respectively. Tensile tests were conducted at the ambient temperature on a Hounds field H50KS testing machine at a strain rate of 1.67×10^{-4} sec^{-1}. The tensile test was repeated 3 times for each sample. The Vickers hardness test was done by ASTM-E384 standard under the load of 500 gr force in 15s on the composites. The hardness test was done on more than five points and the average number was reported. The bond strength of the bimetal strips AA5083 was measured using an Instron tensile testing machine with 100 kg load cell. The mean peeling force was measured by a clamping configuration shown in Fig. 6.

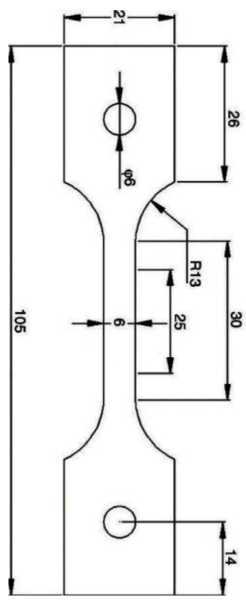


Fig. 6 Orientation of the tensile test specimens (ASTM-E8M) [18]

3 RESULTS AND DISCUSSIONS

First of all, in order to study the evolution of mechanical properties during the Warm-ARB process, 5 samples of AA5083/-5% Al_2O_3 MMCs with one up five cycles were fabricated. Then, tensile and hardness tests were carried out and finally their fracture surfaces after the tensile test specimens were examined by SEM.

3.1. Tensile strength

Engineering stress-strain curves of the ARBed samples have been obtained by tensile test, (Fig. 7). It shows that the tensile strength greatly increases by the number of cycles, Fig. 7. The strength of the primary sandwich (cycle#0) is equal to 270 MPa. Fig. 7 shows that the yield and tensile strength are considerably increased by the first cycle (420 MPa). But, when the number of cycles increases, the tensile strength remains approximately constant up to cycle #5 (498 MPa). This behaviour can be explained based on two mechanisms. The first is due to the hardening (dislocation strengthening) [20] and the second is due to the production of ultra-fine grains (grain boundary strengthening mechanism) [21].

Dispersing of Al_2O_3 particles has a main role for increasing the strength hardening in the second stage [22]. These particles activate slip systems in the Al matrix near its adjacent layers. The density and locally strain hardening of these regions increased from the first up to the 5th cycle. From cycle#0 to cycle#1, the maximum elongation decreased from 21% to 2.1%. So, this would be due to the high strain hardening, weak AA5083 layers bonding, and increased number of surfaces with non-uniform reinforcement nanoparticles. But, the trend is reversed from cycle#1 to cycle#5. For the final Warm-ARB cycle, the maximum elongation value showed a value equal to 4.2%, Fig. 8. This behavior is attributed to (I) increasing the uniformity of particles, (II) increasing the bond strength between the Al matrixes, (III) decreasing the porosities in the clusters.

The distribution of reinforcement in the matrix is one of the effective parameters influencing the properties of the samples. The non-uniformity in the reinforcement distribution can have significant effects on the mechanical properties of the composites [2], [4] and [6]. For example, it has been reported that the yield strength and work hardening are increased with increasing the formation of clusters whereas the elongation is significantly reduced [2], [4], and [6]. This is related to the stress concentration in the clusters which may lead to preferential nucleation and propagation of damage in the clusters [4], [13], and [14]. The difficulty of achieving the uniform distribution of particles in the matrix is one of the problems associated with the fabrication of cast composites [6-8].

The tensile toughness value of the composites decreased considerably from cycle#0 (49.5 $j.m^{-3}\times10^4$) to cycle#1 (7.23 $j.m^{-3}\times10^4$), Fig. 9. This behavior is due to the stress hardening and the less mobility of dislocations [23], [26]. There is a little increasing in the tensile toughness from cycle#1 to cycle#3 but this trend becomes faster than cycle#3 (10.2 $j.m^{-3}\times10^4$) to cycle#5 (18.16 $j.m^{-3}\times10^4$). An increasing in the strength and strain amplitudes of the samples during ARB process leads to increasing in the tensile toughness of the produced Al/ Al_2O_3 composites, (Fig. 9). This increasing in the tensile toughness can be justified that; by increasing the ARB cycles, the bond strength between the Al matrix and Al_2O_3 particles [11] and homogeneity of particles increase and the size of clusters decrease which can improve the tensile toughness as well as the elongation of composites.

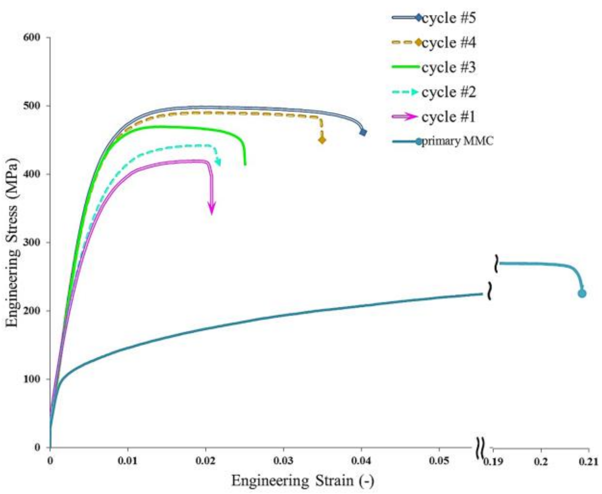


Fig. 7 Engineering stress-strain tensile test curves for Al/ Al_2O_3 composites after the Warm-ARB process

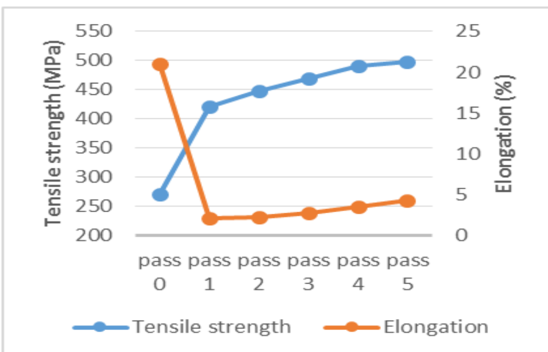


Fig. 8 Variations of the mechanical properties of AA5083/ Al_2O_3 composites with the Warm-ARB cycles

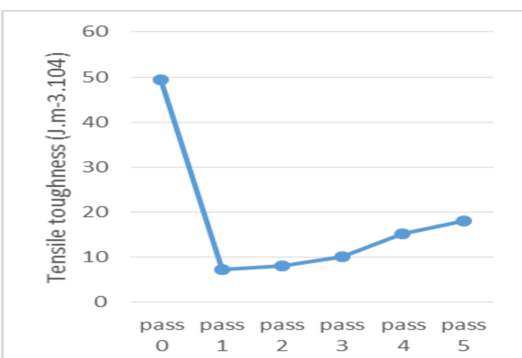


Fig. 9 Variations of the tensile toughness with the Warm-ARB cycles

3.2. Hardness test

The average Vickers micro hardness of the fabricated metal matrix composites is presented in Fig. 10 as a function of the Warm-ARB cycles. It shows that from cycle#0 to cycle#2, there is a rapid rise in the amount of average hardness while from cycle#2 to cycle#5, it has a minor additional change. This minor increase is attributed to strain hardening. In other words, by increasing the number of cycles, dislocations saturation happens at larger strains.

The saturation of the hardness is observed after higher cycles and this has been reported in ultra-fine grain materials fabricated by severe plastic deformation previously [23], [29]. This fact can be explained that after a certain plastic deformation, the materials reach to a certain steady state density of dislocations. By increasing the number of cycles, the distribution of particles in the matrix becomes more uniformly and the percentage of porosities decreases. After a certain number of cycles, the porosities are omitted and the average hardness value increases to its maximum value until the hardness saturation is occurred afterward [24].

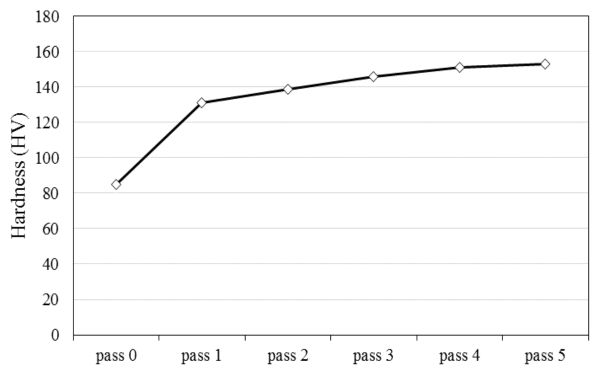


Fig. 10 Variations of the average micro-hardness values and tensile toughness with the Warm-ARB cycles

3.3. Fractography

A scanning electron microscopic (SEM) study was used in order to clarify the rupture mechanism in the primary sandwich (cycle#0), cycle#1, #3 and #5. The fracture surfaces after the tensile test of the composites are shown in the Figs. 11 and 12.

The annealed sample of AA5083 and primary sandwich exhibits a typical ductile fracture and shows deep dimples, Figs. 11 and 12(a). This is similar to other soft materials which have fracture surfaces with deep gray fibrous appearance and hemispheroidal dimples [23]. Figs. 12(c) and 12(d), clearly reveals that composite with three and five cycles, exhibits a fracture surface with dimples and shear zones.

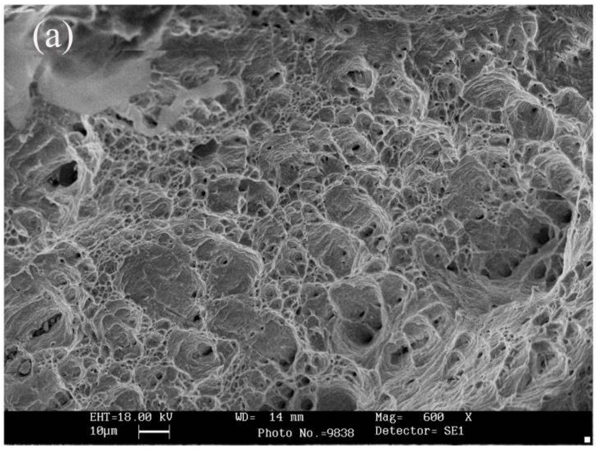
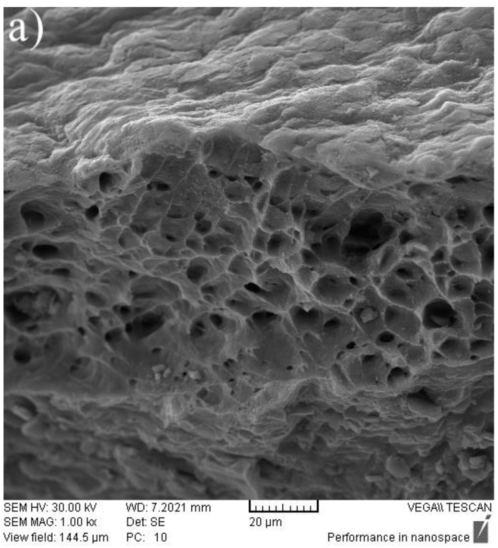
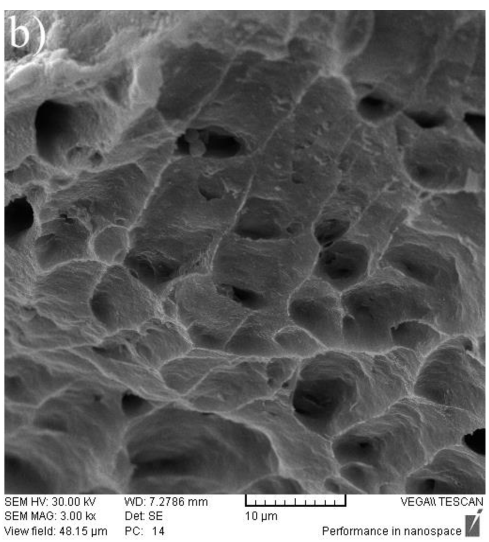
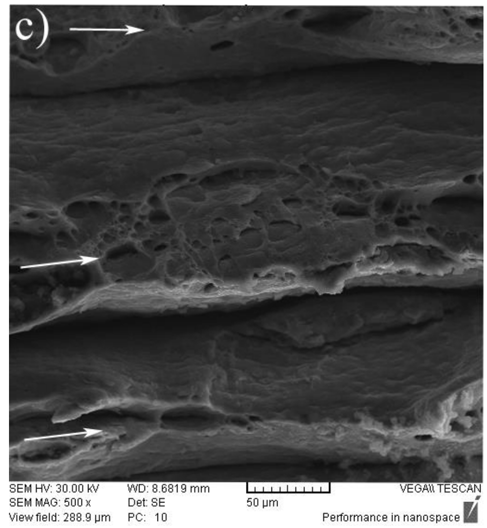


Fig. 11 The fracture surfaces annealed aluminum alloy 5083







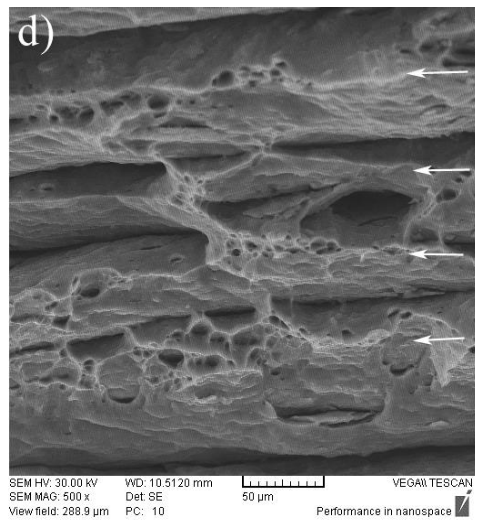


Fig. 12 The fracture surfaces after the tensile test for (a) Primary composite (cycle #0), (b) Composite with 1, (c) 3, (d) with 5 Warm-ARB cycles after the tensile test

By increasing the ARB cycles, the fracture surface is not as deep as the earlier cycles and deep dimples are shrinking slowly. At earlier cycles, the fracture surfaces have deep and elongated dimples. But at higher cycles, the main fracture surfaces do not show elongated and deep shape dimples. Deep and elongated dimples are the result of the nucleation of micro voids, their growth in the structure and finally their coalescence which is affected by shear stress [28]. Al_2O_3 particles have a significant effect on the fracture surface of composites. Their presence on the core and walls of dimples implies that these particles (agglomeration and particle-matrix interface) provided suitable sites for crack initiation and nucleation. Cracks propagate among the particle-matrix interfaces as weak places in the structure [24], [29], and [30].

4. CONCLUSION

In this study, Al-5083 and fine particles of Al_2O_3 were used to produce AA5083/-5% Al_2O_3 MMC with fine and uniform clusters of Al_2O_3 particles successfully by Warm-ARB process. The following conclusions can be highlighted briefly:

1. Warm-ARB process can be used to produce high strength MMCs with higher tensile toughness than conventional.
2. The microstructures revealed the clusters of Al_2O_3 particles in the Al matrix elongated in the rolling direction. As the ARB cycles increase, the uniformity of clusters increases considerably.
3. The tensile strength of the composites increases with ARB cycles and reaches a maximum value of 498 MPa after the 5nd cycle which was 1.84 times higher than the strength of the primary sandwich.
4. The maximum elongation of primary sandwich (annealed) is 21%, while after the first cycle; it was reduced sharply to 2.1%, while it increases to 4.2% after the 5th cycle. This means that the Al_2O_3 has an enhancing effect on the elongation after a certain number of cycles.
5. The tensile toughness of primary sandwich is 49.5 j.m$^{-3}\times 10^4$ while the tensile toughness after the first cycle is 7.2 $j.m^{-3}\times 10^4$ which is less than that of primary composite. By increasing the number of cycles, the tensile toughness reaches to 18.16 $j.m^{-3}\times 10^4$ after the 5th cycle. In other words, the Al_2O_3 particles enhance the tensile toughness of composite with more cycles.
6. The average micro-hardness value of AA5083/Al_2O_3 MMCs increases with increasing the ARB cycles. This demonstrates that adding Al_2O_3 particles to Al matrix leads to an improvement in the hardness value.

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