Fabrication of AA1060/Al_2O_3 Composites by Warm Accumulative Roll Bonding Process and Investigation of its Mechanical Properties and Microstructural Evolution

M. Heydari Vini*
Department of Mechanical Engineering, Mobarakeh Branch,
Islamic Azad University, Mobarakeh, Isfahan, Iran
*Corresponding author
E-mail: m.heydari@mau.ac.ir

P. Farhadipour
School of Mechanical Engineering, Iran University of Science and Technology
Tehran 16844, Iran

Received: 4 June 2017, Revised: 21 June 2017, Accepted: 22 August 2017

Abstract: Recently accumulative roll bonding (ARB) has been used as a novel method to produce particle reinforced metal matrix composites. The accumulative roll bonding as a severe plastic deformation (SPD) rolling procedure aimed at enhancing the mechanical properties of metals and alloys. The process consists in rolling series of overlapped sheets with a thickness reduction ratio (e.g. 50%). In this study, warm accumulative roll bonding (Warm- ARB) process has been used to produce Aluminum Metal Matrix Composite (AMMC: AA1060/-5% Al_2O_3). AA1060 strips were roll bonded as alternate layers up to 5 rolling passes with 300°C preheating for 5 minutes before each pass. The microstructure and mechanical properties of composites have been studied after different Warm- ARB passes by tensile test, Vickers micro hardness test and scanning electron microscopy (SEM). The results demonstrated that adding alumina particles into AMMCs improves both the strength and tensile toughness of composites. Moreover, the fracture surfaces of samples after the tensile test have been studied during various ARB cycles by scanning electron microscopy (SEM). Also, the results showed that mechanical properties such as tensile strength and average Vickers micro hardness improved with increasing the number of warm ARB cycles. Also, the elongation and tensile toughness of samples dropped in the primary cycles and improved in continuing with increasing the warm ARB cycles. Finally, warm ARB process would allow producing particle reinforced with good mechanical properties.

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

Reference: Heydari Vini, M., Farhadipour, P., "Fabrication of AA1060/Al_2O_3 Composites by warm accumulative roll bonding process and investigation of its mechanical properties", Int J of Advanced Design and Manufacturing Technology, Vol. 10/No.4, 2017, pp. 91–98.

Biographical notes: M. Heydari Vini received his PhD in Mechanical Engineering from the science and research branch of IAU in 2016. He is now assistant professor of Mechanical engineering at the Mobarakeh Branch, Islamic Azad University, Mobarakeh, Isfahan, Iran. He authored one book and many other articles on rolling, sheet metal forming and metal matrix composites. His current research focuses on metal forming, metal matrix composites, materials heat treatments and sheet metal processing. **P. Farhadipour** is received his MSc from the school of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran. His current research focuses on metal forming and metal matrix composites.

1 INTRODUCTION

Aluminum metal matrix composites (Al MMCs) have unique and desirable thermal and mechanical properties such as light weight, good wear, corrosion resistance, high strength and high modulus of elasticity and low coefficient of thermal expansion. Several methods are used to fabricate MMCs, accumulative roll bonding (ARB) [1-4], 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].

Over the past few years, ARB has been successfully used to produce multilayered structures of metal and ceramic particles in metal matrix [8], [9]. For example, Tungsten and Copper are used as metallic particles [10-13] and SiC, TiC, WC, SiO_2, B_4C, ZrO_2, TiO_2 and SiO_2 are used as Ceramic particles in MMCs [14- 17]. Using cold-ARB process has a weak bonding strength due to sever work hardening of metal layers. Reduction and temperature are two key factors which are essential precondition for an acceptable bonding of composite layers. By increasing the rolling temperature, the peeling force between composite layers enhances.

The aim of present study is to fabricate metal particle reinforced by Warm-ARB at 300°C. Because of higher temperature in comparison with cold ARB process, the material has a better flow across the composite layers and the bonding strength increases. It was attempted to manufacture AA1060/-5% Al_2O_3 MMC 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 this composite. The main incentive for these investigations is improving the mechanical properties of AA1060 with the homogenous distribution of alumina particles.

2 WARM ARB PROCESSING

The material used in this study was Al-1060 fully annealed strips. The chemical composition of this alloy are presented in Tables 1. Also, the chemical properties of alumina particles are presented in Table 2. First of all, the strip was annealed at 400°C for one hour. Two sheets in a length, width and thickness 200×50 × 2 mm were degreased in acetone for 10 minutes. For fabricating the samples in order to remove the surface oxide layer, strips fully brushed to guarantee an acceptable bonding between the layers. Al_2O_3 powder with average size 2μm were dispersed between the 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 of the sheets was uniformly covered with Al_2O_3 powders. For this purpose, two strips were stacked together and roll-bonded with 75% reduction (effective strain equal to 1.6) at 400°C without any lubrication to obtain 1 mm strip, Fig. 1(a). This initial product is called "Zero Pass or pass#0" in this study.

Table 1. The chemical composition of AA1060.

Element	Al	Si	Fe	Mg	Zn	Ti	Cu
Wt%	balance	0.25	0.03	0.03	0.05	0.03	0.05

Table 2. The mechanical and physical properties of Al_2O_3 particles.

hardness	Rapture module	Compressive strength	density	Particle size	Purity %	material
1650 $kgf.mm^{-2}$	330 MPa	2200 MPa	3.9 $gr.cm^{-3}$	2μm	99.9%	Al_2O_3

After pass#0, primary AA1060/5% Al_2O_3 sandwich was annealed again as the same condition of first annealing. This removes work hardening and improves the bonding strength of the primary sandwich. The reduction of all passes (from pass#1 to pass#5) were equal to 50% with an effective strain equal to 4. Fig. 1 illustrates the experimental setup which has been designed for Warm-ARB in this study, Fig. 1(b).

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 passes. During these five ARB passes, it is expected to have more homogeneous structure by better dispersion of the Al_2O_3 particles. After the 5th pass, the number of the powder layers is 64 within the strip. The steps of the production process of the Al/ Al_2O_3 composite have been summarized in Table 3. 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. 2). The gauge length and the width of the tensile test specimens were 25 and 6 mm, respectively. Tensile tests were conducted at 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 standard ASTM-E384 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.

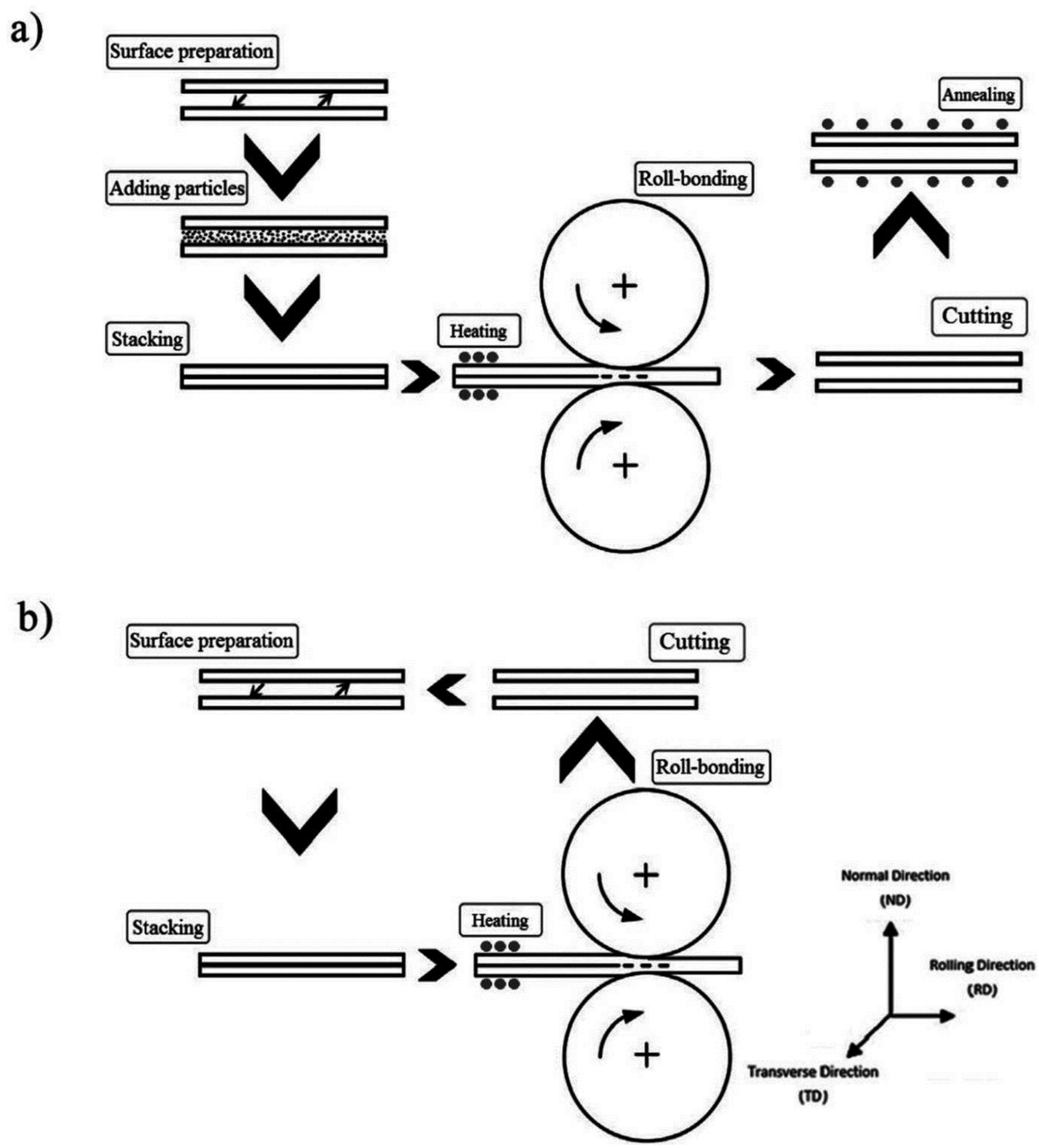

Fig. 1 Schematic illustration of the production process of the AA1060/ Al_2O_3 composite sheet (a): primary cycle (cycle#0) and (b): main cycles

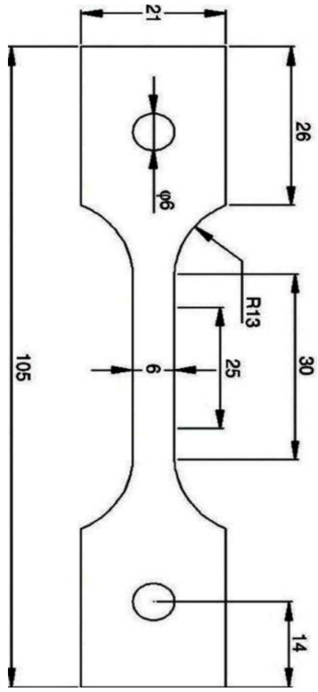

Fig. 2 Orientation of the tensile test specimens (ASTM-E8M), [18]

Table 3. Specifications of the Warm- ARB process for the production of AA1060/ 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

3 RESULTS AND DISCUSSIONS

First of all, in order to study the evolution of mechanical properties during the Warm-ARB process, 5 samples of AA1060/-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. 3). It shows that the tensile strength greatly increases by the number of passes, Fig. 3. The strength of the primary sandwich (pass#0) is equal to 82.35 MPa. Fig. 4 shows that the tensile strength is considerably increased by the first pass (144.6 MPa). But when the number of passes increases, the tensile strength remains approximately constant up to pass #5 (152.28 MPa). This behaviour can be explained based on two mechanisms. The first is due to the hardening (dislocation strengthening) [19, 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]. The 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 pass up to the 5th.

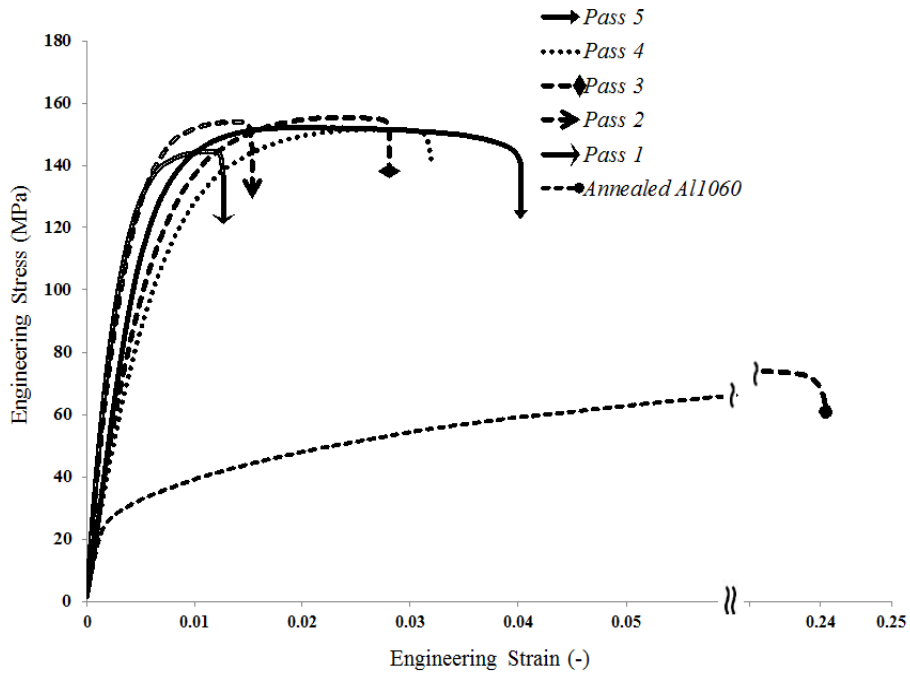

Fig. 3 Engineering stress-strain tensile test curves for Al/ Al_2O_3 composites before and after Warm-ARB

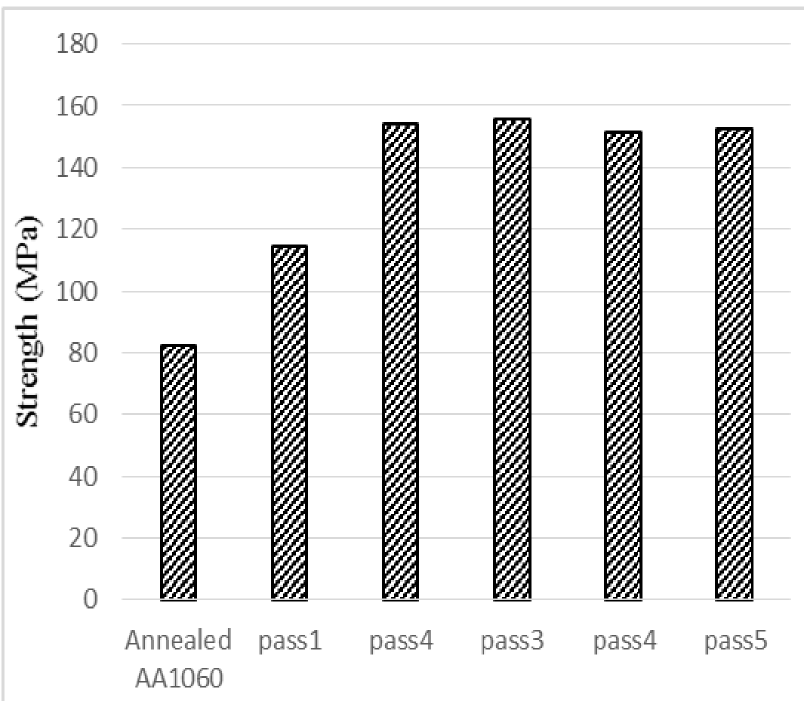

Fig. 4 Variations of the strength value of AA1060/ Al_2O_3 composites with the Warm-ARB passes

From pass#0 to pass#1, the maximum elongation decreases from 24.07% to 1.27%. So, elongation decrease can be due to the high strain hardening, weak AA1060 layers bonding, and increased number of surfaces with non-uniform reinforcement nanoparticles. But, the trend is reversed from pass#1 to pass#5. For the final Warm-ARB pass the maximum elongation value shows a value equal to 4.02% (Fig. 5). 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, 6]. For example, it has been reported that yield strength and work hardening are increased with increasing the formation of clusters whereas the elongation is significantly reduced [2], [6]. This is related to the stress concentration in the clusters, which may lead to preferential nucleation and propagation of damage in the clusters [13-14]. The difficulty of achieving the uniform distribution of particles in the matrix is one of the problems associated with the fabrication of cast composites [8].

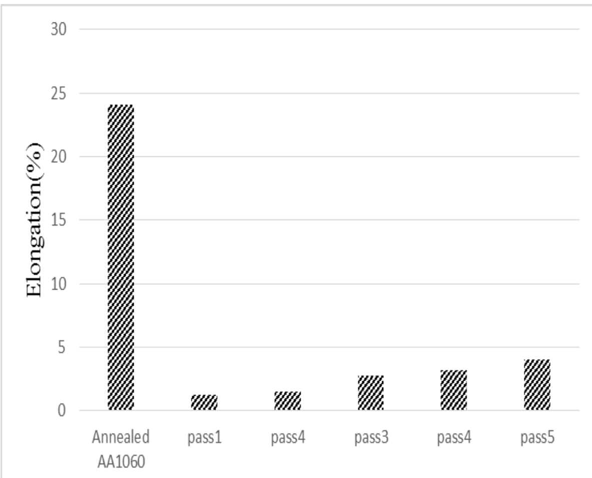

Fig. 5 Variations of the elongation value of AA1060/ Al_2O_3 composites with the Warm-ARB passes

The tensile toughness value of the composite (Fig. 6) decreases considerably from pass#0 (17.19 $j.m^{-3}\times 10^4$) to pass#1 (1.5 $j.m^{-3}\times 10^4$). This behavior is due to the stress hardening and the less mobility of dislocations [23]. There is a little increasing in the tensile toughness from pass#1 to pass#3, but it becomes faster than the pass#3 (3.62 $j.m^{-3}\times 10^4$) to pass#5 (5.51 $j.m^{-3}\times 10^4$). An increase 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 composite, (Fig. 6). This increase in tensile toughness can be justified that, by increasing the ARB, passes 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 elongation of composite.

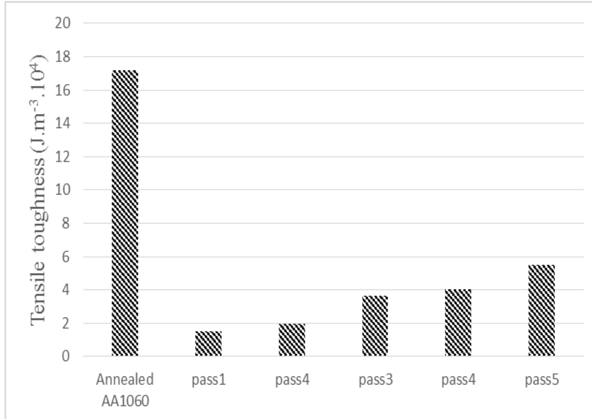

Fig. 6 Variations of tensile toughness with the Warm-ARB passes

The average Vickers micro hardness of the fabricated metal matrix composites is presented in Fig. 7 as a function of the Warm-ARB passes. It shows that from 28 HV (pass#0) to 44HV (pass#2), there is a rapid rise in the amount of average hardness while from pass#2 to 49HV (pass#5), it has a minor additional change. This minor increase is attributed to strain hardening. In other words, when the number of passes increases, dislocations saturation happens at larger strains. The saturation of the hardness is observing after higher passes and this has been reported in ultra-fine grain materials fabricated by sever plastic deformation previously [23]. 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 passes, the distribution of particles in the matrix becomes more uniformly and the percentage of porosities decreases. After a certain number of passes, the porosities are omitted and the average hardness value increases to its maximum value until the hardness saturation will be occurred afterward [22].

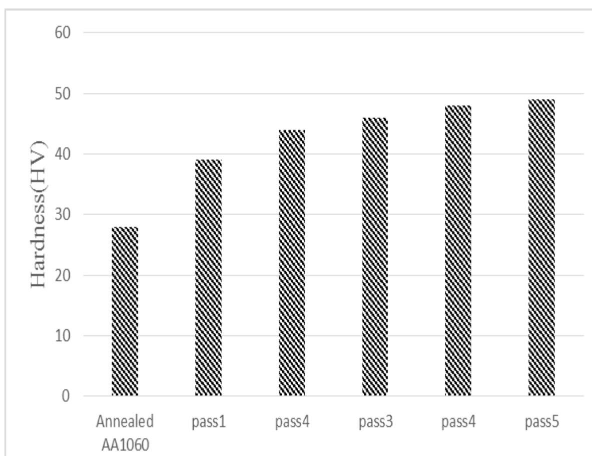

Fig. 7 Variations of Average micro-hardness values with the Warm-ARB passes

3.2. Fractography

A scanning electron microscopic (SEM) study was used in order to clarify the rupture mechanism in the primary sandwich (pass#0), #3 and #5. The fracture surfaces after the tensile test of the composites are shown in Fig. 8. The primary sandwich exhibits a typical ductile fracture and showing deep dimples (Fig. 8(a)). This is similar to other soft materials which have fracture surfaces with deep gray fibrous appearance and hemispheroidal dimples [23]. Figs. 8(b, c), clearly reveals that composite with three and five passes, exhibits a fracture surface with dimples and shear zones. By increasing the ARB passes, the fracture surface is not as deep as the earlier passes and deep dimples are shrinking slowly. At earlier passes, the fracture surfaces have deep and elongated dimples. But at higher passes, 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 [21]. Al_2O_3 powders 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 [22].

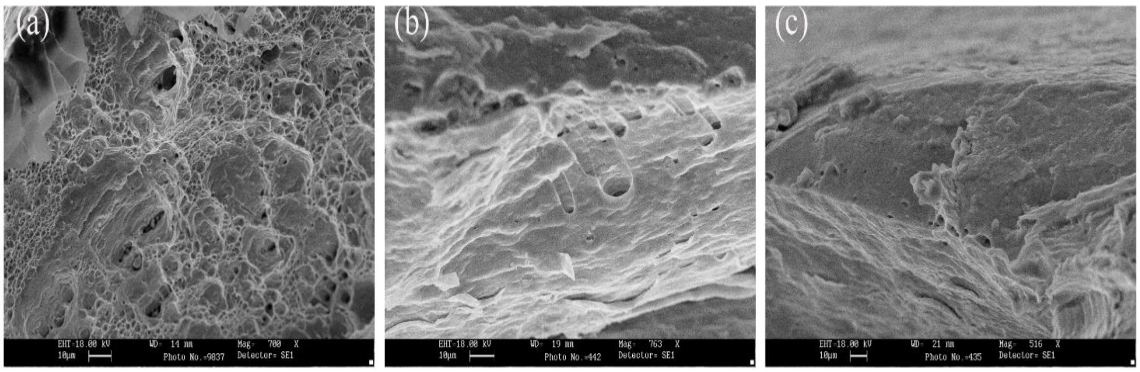

Fig. 7 The fracture surfaces after the tensile test for (a) primary composite (pass #0) and composite with (b) three and (c) five Warm-ARB passes after the tensile test

CONCLUSION

In this study, Al-1060 and fine particles of Al_2O_3 were used to produce AA1060/-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: Warm-ARB process can be used to produce high strength MMC with higher tensile toughness than conventional.

1. The microstructures revealed the clusters of Al_2O_3 particles in the Al matrix elongated in the rolling direction. As the ARB passes increase, the uniformity of clusters increases considerably.
2. The tensile strength of the composites increases with ARB passes and reaches a maximum value of 152.28 MPa after the 5^{nd} pass which was 1.84 times higher than the strength of the primary sandwich.
3. The maximum elongation of primary sandwich (annealed) is 24.07%, while after the first pass, it was reduced sharply to 1.27%. But, it increases to 4.02% after the 5^{th} pass. This means that the Al_2O_3 has an enhancing effect on the elongation after a certain number of passes.
4. The tensile toughness of primary sandwich is 17.19 $j.m^{-3}\times 10^4$ while the tensile toughness after the first pass is 1.5 $j.m^{-3}\times 10^4$ which is less than that of primary composite. By increasing the number of passes, the tensile toughness reaches to 5.51 $j.m^{-3}\times 10^4$ after the 5^{th} pass. In other words, the Al_2O_3 particles enhance the tensile toughness of composite with more passes.
5. The average micro-hardness value of AA1060/Al_2O_3 MMC increases with increasing ARB passes. This demonstrates that adding Al_2O_3 particles to Al matrix leads to an improvement of the hardness.

REFERENCES

[1] Schmidt, C. W., Knieke, C., Maier, V., Höppel, H. W., Peukert, W., and Göken, M. "Accelerated Grain Refinement During Accumulative Roll Bonding by Nanoparticle Reinforcement", Scr. Mater., Vol. 64, No. 3, 2011, pp. 245–248.

[2] Vaidyanath, L., Nicholas, M., and Milner, D, "Pressure Welding by Rolling", Br. Weld. JOUR, Vol. 6, 1959, pp. 13–28.

[3] Prasad, S. V., Asthana, R., "Aluminum Metal-Matrix Composites for Automotive Applications", Tribological considerations, Tribol. Lett., Vol. 17, No. 3, 2004, pp. 445–453.

[4] Saito, Y., Utsunomiya, H., Tsuji, N., and Sakai, T., "Novel Ultra-high Straining Process for Bulk Materials-Development of the Accumulative Roll-Bonding (ARB) Process", Acta Mater, Vol. 47, No. 2, 1999, pp. 579–583.

[5] Korbel, A., Richert, M., and Richert, J., "The Effects of Very High Cumulative Deformation on Structure and Mechanical Properties of Aluminium", in: Proc. Second RISO Int. Symp., Metall. Mater. Sci., 1981, pp. 14–18.

[6] Yin, J., Lu, J., Ma, H., and Zhang, P., "Nanostructural Formation of Fine Grained Aluminum Alloy by Severe Plastic Deformation at Cryogenic Temperature", J Mater Sci., Vol. 39, 2004, pp. 2851–4.

[7] Kok, M., "Production and Mechanical Properties of Al_2O_3 Particle-Reinforced 2024 Aluminium Alloy Composites", J. Mater. Process. Technol.,Vol. 161, 2004, pp. 381–387.

[8] Liu, C. Y., Wang, Q., Jia, Y. Z., Zhang, B., Jing, R., Ma, M. Z., Jing, Q., and Liu, R. P., "Effect of W Particles on the Properties of Accumulatively Roll-Bonded Al/W Composites", Mater. Sci. Eng. A, Vol. 547, 2012, pp. 120–124.

[9] Farhadipour, P., Heydari Vini, M., and Loghmanian, M. R., "A New Rolling Force Model for an Actual Reversing Cold Rolling Strip Mill", Int J Advanced Design and Manufacturing Technology, Vol. 8, No. 2, June - 2015, pp. 73-80.

[10] Alizadeh, M., Talebian, M., "Fabrication of Al/Cup Composite by Accumulative Roll Bonding Process and Investigation of Mechanical Properties", Mater. Sci. Eng. A, Vol. 558, 2012, pp. 331–337.

[11] Lu, C., Tieu, K., and Wexler, D., "Significant Enhancement of Bond Strength in the Accumulative Roll Bonding Process Using Nano-Sized SiO_2 particles", J. Mater. Process. Technol., Vol. 209, No. 10, 2009, pp. 4830–4834.

[12] Alizadeh, M., "Comparison of Nanostructured Al/B_4C Composite Produced by ARB and Al / B_4C Composite Produced by RRB Process", Materials Science & Engineering A, Vol. 58, No. 2, 2010, pp. 578–582.

[13] Liu, C. Y., Wang, Q., Jia, Y. Z., Zhang, B., Jing, R., Ma, M. Z., Jing, Q., and Liu, R. P., "Evaluation of Mechanical Properties of 1060-Al Reinforced with WC Particles via Warm Accumulative Roll Bonding Process", Materials and Design, Vol. 43, 2013, pp. 367–372.

[14] Ipek, R., "Adhesive Wear Behaviour of B_4C and SiC Reinforced 4147 Al Matrix Composites (Al/B_4C-Al/SiC)", J. Mater. Process. Technol, 2005, pp. 162-163.

[15] Bogucka, J., "Influence of Temperature of Accumulative Roll Bonding on the Microstructure and Mechanical Properties of AA5251 Aluminum Alloy", Arch. Metall. Mater., Vol. 59, No. 1, 2014, pp. 16–20.

[16] Rezayat, M., Akbarzadeh, A., and Owhadi, A., "Production of High Strength Al–Al_2O_3 Composite by Accumulative Roll Bonding", Compos. Part A Appl. Sci. Manuf., Vol. 43, No. 2, 2012,pp. 261–267.

[17] Milner, J. L., Abu-farha, F., Bunget, C., Kurfess, T., and Hammond, V. H., "Grain Refinement and Mechanical Properties of CP-Ti Processed by Warm Accumulative Roll Bonding", Materials Science & Engineering A, Vol. 561, 2013, pp. 109–117.

[18] Astm, "E8/E8M Standard Test Methods for Tension Testing of Metallic Materials 1", Annu. B. ASTM Stand. 4, 2010, pp. 1–27.

[19] Rezaei, M. R., Toroghinejad, M. R., and Ashrafizadeh F., "Production of Nano-Grained Structure in 6061 Aluminum Alloy Strip Byaccumulative Roll Bonding", Materials Science and Engineering A., Vol. 529, 2011, pp. 442– 446.

[20] Alizadeh, M., Paydar, H., and SharifianJazi, F., "Structural Evaluation and Mechanical Properties of Nanostructured Al/B_4C Composite Fabricated by ARB Process", Composites: Part B., Vol. 44, 2013, pp. 339–343.

[21] Jamaati, R., Toroghinejad, M. R., "Manufacturing of High-Strength Aluminum/Alumina Composite by Accumulative Roll Bonding", Mater. Sci. Eng. A, Vol. 527, No. 16, 2010, pp. 4146–4151.

[22] Alizadeh, M., Paydar, M. H., "Study on the Effect of Presence of TiH_2 Particles on the Roll Bonding Behavior of Aluminum Alloy Strips", Mater Des., Vol. 30, 2009, pp. 82–86.

[23] Jamaati, R., Toroghinejad, M. R., "Manufacturing of High-Strength Aluminum/Alumina Composite by Accumulative Roll Bonding", MATER. SCI. ENG. A, Vol. 527, 2010, pp. 4146–4151.