

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

# **A comparative study on metal-matrix composites fabricated by conventional and cross accumulative roll-bonding processes**

Morteza Alizadeh <sup>a,\*</sup>, Erfan Salahinejad <sup>b</sup>

<sup>a</sup> Department of Materials Science and Engineering, Shiraz University of Technology, Shiraz, Iran

<sup>b</sup> Faculty of Materials Science and Engineering, K.N. Toosi University of Technology, Tehran, Iran

## **Abstract**

This paper focuses on some structural and mechanical characteristics of Al–Al<sub>2</sub>O<sub>3</sub> composites produced by conventional accumulative roll-bonding (ARB) and cross accumulative roll-bonding (CARB). The obtained structures were studied by transmission electron microscopy, X-ray diffraction, and optical microscopy; typically, the reinforcement distribution on different orthogonal planes was quantitatively compared. Also, the composite samples were mechanically characterized by hardness, uniaxial tensile, and fractographic experiments. The results showed that the CARB process, compared with ARB, gives rise to somewhat more effective grain refinement. Concerning the particles dispersion, the lateral rolling planes of the CARB samples, contrary to those of the ARB composites, present a similar feature. It was also found that the hardness, yield stress, tensile strength, and elongation of the CRAB specimens are higher than those of the ARB composites.

**Keywords:** Metal matrix composites; Microstructure; Mechanical properties; Nanostructured Materials

---

\* **Corresponding Author (Morteza Alizadeh):** *Email address:* Alizadeh@sutech.ac.ir

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

## 1. Introduction

Aluminum metal-matrix composites (MMCs) are currently regarded as a group of advanced materials, due to lightweight, high strength, high specific modulus, low coefficient of thermal expansion, and good wear resistance, while a combination of these desirable properties can be hardly achieved by conventional materials. As reinforcing agents in MMCs, ceramic particles like Al<sub>2</sub>O<sub>3</sub>, SiC, B<sub>4</sub>C, WC, and TiB<sub>2</sub> are generally used [1–5].

It is known that in order to get the optimum properties of a composite, especially a suitable combination of strength and ductility, a small size and large volume fraction of the reinforcement(s) are required. Nonetheless, there is a challenge of effectively and simultaneously taking advantage of these two requirements, since small reinforcing particulates in MMCs usually tend to be agglomerated and inhomogeneously distributed through the matrix. This unpleasant feature considerably degrades the mechanical behavior of the composite [6–8]. In this regard, it has been found that severe plastic deformation processes, for example high-pressure torsion [9], equal channel angular pressing [10], and accumulative roll-bonding [11–13] can successfully improve the homogeneity of the particulate reinforcement distribution in MMCs.

In the recent years, accumulative roll-bonding (ARB) has been increasingly used to produce MMC sheets [11–14]. In addition, a modification of the conventional ARB process, namely cross-accumulative roll-bonding (CARB), was introduced to prepare this type of materials [15], in which the strip is rotated 90 ° around the normal direction between successive passes. Concerning the reinforcement distribution in MMCs fabricated by ARB, it has been found that the homogeneity is improved by increasing the number of ARB passes [12]. Also, the structural homogeneity on the rolling direction–normal direction plane of ARB-processed MMCs has been reported to be better than that on the transverse direction–

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

normal direction plane [16]. However, to our knowledge, no comparison of the reinforcement distribution has been made between ARB- and CARB-processed composites. In this paper, a comparative study is conducted on the structure and mechanical properties of Al–Al<sub>2</sub>O<sub>3</sub> composites fabricated by ARB and CARB, especially on the alumina reinforcement distribution on the different plans of the processed sheets.

## **2. Experimental procedures**

### *2.1. Materials and sample preparation*

To fabricate Al– 15 vol.% Al<sub>2</sub>O<sub>3</sub> composites by ARB and CARB, strips of annealed 1050- aluminum alloy and Al<sub>2</sub>O<sub>3</sub> powder with the average size of 3 μm was used as the raw materials.

In the first step of the CARB process, the Al strips of 0.5 mm thickness were firstly degreased in acetone and scratch brushed. The eight surface-prepared strips were stacked each other, while 1.66 vol. % Al<sub>2</sub>O<sub>3</sub> powder was dispersed at the seven interfaces of each two adjacent sheets. The product was roll-bonded with a reduction of 66% at room temperature. The well roll-bonded strip was cut into three strips and annealed at 623K for 1 h. After the surface preparation and the dispersion of 1.66 vol. % Al<sub>2</sub>O<sub>3</sub> powder between the two interfaces of each two adjacent sheets, the product was again roll-bonded with the same reduction. Then, the roll-bonded strip was cut into two strips and again annealed.

In the second step, the two obtained, surface-prepared strips were roll-bonded with a draft percentage of 50% reduction, without the alumina particles dispersion. The roll-bonded strip was cut into two strips; and after the surface treatment and without annealing, these were stacked over each other and rotated 90° around the normal direction (ND) of the previous rolling pass. The rotated strip was roll-bonded with a draft percentage of 50%

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

reduction. In fact, in this stage, the strip was rolled along the transverse direction (TD) of the prior stage. The last step of the process, i.e. cutting, surface preparation, rotation, and rolling, was repeated eight times. For comparison, Al– 15 vol.% Al<sub>2</sub>O<sub>3</sub> composites were produced by the ARB process, according to Ref. [14], where no strip rotation is conducted between successive passes.

## 2.2. Structural characterization

Transmission electron microscope (TEM) micrographs of thin foils parallel to the rolling plane (rolling direction–transverse direction or RD–TD plane), prepared by ion milling, were taken by a Philips, FEG-TEM operating at 200 kV. Additionally, the crystallite size of the matrix on the RD-TD plane surfaces of the ARB- and CARB-processed composites was determined by X-ray diffraction (XRD, D8 Bruker diffractometer, Cu K $\alpha$ <sub>1</sub> radiation,  $\lambda= 0.15406$  nm) peak profile analysis, using a step size of 0.03° and a counting time of 3s per step. The MAUD software, which employs the Rietveld refinement and the Double-Voigt approach, was used to do so.

An optical microscope was used to observe the dispersion of the Al<sub>2</sub>O<sub>3</sub> particles on the different planes of the MMCs, where the micrographs were analyzed by the radial distribution function. According to Refs. [12,17], in this quantitative analysis, circles of variable radii  $r$ , from 1  $\mu\text{m}$  to 100  $\mu\text{m}$ , were centered on a particle and the function  $H(r)$  is then determined as below:

$$H(r) = \frac{N_{ra}}{N_a} \quad (1)$$

where  $N_{ra}$  is the mean number of the particles per unit area in the circles and  $N_a$  is the mean number of the particles per unit area over the whole sample. Afterwards, the degree of

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

clustering ( $A_H$ ) was estimated by the deviation of the  $H(r)$  curves from  $H(r) = 1$  (as a random distribution of particles essentially yields  $H(r) = 1$  for any radius  $r$ ), via the area described as follows:

$$A_H = \int_{r=1\mu m}^{r=100\mu m} [H(r) - 1] dr \quad (2)$$

where to obtain a reliable result, six particles were randomly selected as the central particle on the optical micrographs of the MMCs.

### 2.3. Mechanical experiments

Vickers bulk hardness tests, with a load of 150 g, were conducted on ten random locations of the produced MMCs. Also, uniaxial tensile tests were conducted on the MMCs by an Instron testing machine at an initial strain rate of  $8.3 \times 10^{-4} \text{ s}^{-1}$ . The tensile test samples were machined from the ARBed strips oriented along the rolling direction, according to the 1/5 scale of the JIS-No. 5. Also, the fracture surfaces of tensile test specimens were evaluated by a scanning electron microscope (SEM, JEOL-JSM 6340F).

## 3. Results and discussion

### 3.1. Structural studies

The TEM micrographs of the ARB- and CARB-processed Al–Al<sub>2</sub>O<sub>3</sub> MMCs after the eighth pass are shown in Fig. 1. According to these images, the mean grain size of the aluminum matrix in the ARB and CARB samples is almost 240 and 190 nm, respectively, while nanometric grains (smaller than 100 nm) can be also observed. Fig. 2 also indicates the XRD patterns of the MMCs processed by eight ARB and CARB cycles. According the XRD peak profile analysis using the MAUD software, the average crystallite size of the matrix in

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

the ARB and CARB samples was determined to be almost 125 and 110 nm, respectively.

Clearly, the crystallites detected by the X-ray line broadening analysis are smaller than the related grains observed by TEM, due to the sub-division of the grains into the substructures (crystallites).

According to the TEM and XRD studies, the ARB and CARB processes to the eighth pass successfully develop ultrafine-grained, nanocrystalline Al– Al<sub>2</sub>O<sub>3</sub> MMCs. Structural refinement can be explained in terms of grain sub-division at the submicron scale, due to severe plastic deformation [18,19]. Furthermore, the presence of the Al<sub>2</sub>O<sub>3</sub> reinforcement particles in the aluminum matrix increases the dislocation density in the matrix during ARB and CARB. These dislocations are generated at the particles/matrix interface in order to accommodate the strain incompatibility between the two phases. On the other hand, the Al<sub>2</sub>O<sub>3</sub> particles act as obstacles to the dislocation motion, thereby leading to the dislocation accumulation and to the formation of sub-grain and then grain boundaries. Moreover, the reinforcement particles retard the dislocation motion and dynamic recovery. Note that dynamic recovery retards grain refinement during ARB through dislocation annihilation, as especially reported for pure Al [20,21].

As it can be seen from the TEM studies, the matrix grain size in the CARB composite is less than that in the ARB sample. Essentially, there are two types of boundary in ARB structures, namely lamellar boundaries (LBs) which are almost parallel to the rolling plane and short transverse boundaries which interconnect LBs. During the CARB process, LBs alternately become parallel and perpendicular to RD in successive passes, due to the strip rotation around ND, as described in the experimental section. This leads the interconnecting boundaries spacing in the CARB sample to be less than that in the ARB sample. As a result, by employing the CARB process, the aspect ratio of the interconnecting boundary spacing

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

and the lamellar boundary spacing is significantly reduced, which causes a more efficient grain refinement in comparison to ARB.

The radial distribution function, particularly the degree of clustering ( $A_H$ ), is a suitable approach to quantifying the reinforcement distribution in particulate-reinforced composites, where smaller  $A_H$  values are indicative of increased particle homogeneity. According to Refs. [12,16], by increasing ARB cycles, the reinforcement distribution homogeneity in Al-B<sub>4</sub>C MMCs fabricated by ARB is improved, as also observed for the Al–Al<sub>2</sub>O<sub>3</sub> MMCs prepared in this work. To evaluate the reinforcement distribution homogeneity in the Al–Al<sub>2</sub>O<sub>3</sub> MMCs, the  $A_H$  values on the different planes of the specimens prepared to the eight ARB and CARB pass are shown in Fig. 3. These differences can be justified by considering mechanisms governing the evolution of the reinforcement distribution on the different planes during the processes, as follows.

The evolution of the Al<sub>2</sub>O<sub>3</sub> reinforcement distribution by progression of ARB and CARB can be regarded from the following viewpoints [12]: the increase in the number of the Al and Al<sub>2</sub>O<sub>3</sub> layers, the matrix extrusion through particle clusters, and the sheet elongation due to rolling. Obviously, by progression of the ARB and CRAB processes, the number of the Al and Al<sub>2</sub>O<sub>3</sub> layers is increased, resulting in an improvement in the particle distribution along ND. On the other hand, in the early stages of the processing, the reinforcement layers are disrupted into small fragments, leaving particle clusters and reinforcement-free zones. With the processing progress, the metallic matrix is extruded and flows through the particle clusters, under the normal pressure of the rolls. The resultant shear stress leads to the cluster decomposition, thereby improving the reinforcement distribution along TD and RD. Furthermore, the sheet elongation along RD promotes the cluster expansion, as accompanied

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

by the matrix infusion between the particles, and gives rise to a more improvement in the structural homogeneity in this direction.

Comparing the degrees of clustering on the ND-RD and ND-TD planes for the ARB sample, it is realized that the homogeneity on the ND-RD plane is better than that on the ND-TD plane. In regard to the reinforcement dispersion, both of these planes take equally advantage of the mechanisms of the increase in the number of the layers and the matrix flow through the clusters. However, the mechanism of the sheet elongation has no contribution on the ND-TD plane in contrast to the ND-RD plane, because strain along TD is almost zero in the course of rolling. On the other hand, according to Fig. 3, the particle dispersion on the ND-RD and ND-TD planes (i.e. lateral planes) of the CARB-processed MMCs is relatively the same. During the CARB process, due to the strip rotation around ND, the situation of the lateral planes relative to the real rolling direction are alternately substituted for each other by progression of the process. Thus, these planes similarly benefit from all of the three mechanisms mentioned above for the evolution of the particle distribution.

In accordance with Fig. 3, the homogeneity of the particle dispersion on the lateral planes of the CARB sample is better than that on the ND-TD plane of the ARB composite and is worse than that on the ND-RD plane of the ARB sample. These differences can be justified by the fact that the lateral planes of the CARB sample take advantage of the sheet elongation mechanism every two passes, while the ND-RD and ND-TD planes of the ARB sample benefits from this mechanism in all of and none of the ARB passes, respectively. On the other hand, according to the results obtained on the RD-TD planes, it is observed that the structural homogeneity of the CARB composite is better than that of the ARB specimen. Thus, it can be inferred that the alternate substitutes of the nominal rolling and transverse

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

directions with each other in the CARB state provide a more uniform distribution of the reinforcing particulates on the ND-TD plane, as compared with ARB.

### 3.2. Mechanical evaluations

Fig. 4 illustrates the bulk hardness values of the ND-TD planes of the MMCs, showing an increasing trend by progression of the ARB and CARB processes. It can be seen that the hardness values of the CARB composites are higher than those of the ARB composite. It would be worth mentioning that the standard deviation of the hardness measurements is decreased by increasing the number of passes, which is an evidence for the reinforcement distribution improvement. Additionally, the standard deviation for the CARB samples is less than that for the ARB samples, which suggests the more homogeneity of the CARB samples, as realized and justified above. The inference of the dispersion homogeneity from the standard deviation of the hardness measurements is based on the fact that in the case of more uniformity, the contributions of the matrix and reinforcement to the measured hardness values in all indented locations are similar, leading to a lower standard deviation compared to more inhomogeneous cases.

The engineering stress–strain curves of the ARB and CARB-processed Al–Al<sub>2</sub>O<sub>3</sub> composites for different passes are shown in Fig. 5. It can be seen that the yield strength, tensile strength, and elongation increase by progression of the processes, similar to hardness. As can be also observed, these tensile characteristics for the CARB composites are higher than those for the ARB composite. The hardness and tensile behaviors of the produced composites is affected by various factors, such as bonding quality between the Al layers, strain hardening (dislocation strengthening), grain boundary strengthening, bonding quality of the Al/Al<sub>2</sub>O<sub>3</sub> interfaces, reinforcement distribution, mismatch between the coefficients of

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, *Journal of Alloys and Compounds*, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

thermal expansion of Al and ceramic particles [22–25]. These factors can explain the increase in the strength and hardness of the MMCs by progression of the ARB and CARB passes. Nonetheless, the increase in elongation by increasing the passes suggests that the effects of the improvement in the interlayer bond strength, the quality of the matrix/reinforcement interfaces, and the reinforcement distribution on tensile elongation prevails over those of the other factors which are basically deleterious to elongation. On the other hand, the improved mechanical properties of the CARB samples are attributed to their finer grain size and the homogenous distribution of the Al<sub>2</sub>O<sub>3</sub> particles, compared with the ARB-processed MMCs, as confirmed by the above structural evaluations (Figs. 1, 2 and 3).

The SEM micrographs of the fracture surfaces of the samples after the tensile tests are demonstrated in Fig. 6. As can be seen, the ductile rupture is the major fracture mechanism in the samples, as realized from typical dimples in the micrographs. The presence of some particles in the core of some of the dimples suggests that the decohesion of the particle-matrix interface plays a significant role in fracture. The lower number, smaller size, and shallower feature of dimples observed in the ARB sample are indicative of its lower ductility compared with the CARB sample, as also confirmed in Fig. 5. In contrast to the CARB sample, some particle agglomeration zones are observed in the ARB sample, which essentially has a major contribution to the measured mechanical properties.

#### **4. Conclusions**

Ultrafine-grained/nanocrystalline Al–Al<sub>2</sub>O<sub>3</sub> composites were fabricated by ARB and CARB processes. According to the radial distribution function analysis, the reinforcement dispersion on the different planes of the samples was improved in this order: ARBed ND-TD plane < CARBed ND-RD plane ≡ CARBed ND-TD plane < ARBed ND-RD plane, as

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

justified by the phenomenon of the sheet elongation in RD during the rolling process. It was also found that the RD-TD plane of the CARB composite was more homogeneous than that of the ARB sample. Based on mechanical evaluations, the hardness, yield stress, tensile strength, and elongation of the composites were increased by increasing ARB and CARB passes. These mechanical characteristics, i.e. hardness, yield stress, tensile strength, and elongation, for the CARB specimens were higher than those for the ARB-processed MMCs. The higher ductility of the CARB sample was confirmed by the fracture surface SEM observations.

### **Acknowledgments**

The authors would like to thank the Shiraz University of technology and Iran Aluminum Dishes Corporation for their technical assistance in conducting this project.

### **References**

- [1] M. Tabandeh Khorshid, S.A. Jenabali Jahromi, M.M. Moshksar, Mechanical properties of tri-modal Al matrix composites reinforced by nano-and submicron-sized Al<sub>2</sub>O<sub>3</sub> particulates developed by wet attrition milling and hot extrusion, Mater. Des. 31 (2010) 3880–3884.
- [2] R.N. Rao, S.Das, Effect of matrix alloy and influence of SiC particle on the sliding wear characteristics of aluminium alloy composites, Mater. Des. 31 (2010) 1200–1207.
- [3] K. Kalaiselvan, N. Murugan, S. Parameswaran, Production and characterization of AA6061–B<sub>4</sub>C stir cast composite, Mater. Des. 32 (2011) 4004–4009.

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, *Journal of Alloys and Compounds*, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

[4] M. Yusoff, R. Othman, Z. Hussain, Mechanical alloying and sintering of nanostructured tungsten carbide-reinforced copper composite and its characterization, *Mater. Des.* 32 (2011) 3293–3298.

[5] C. Mallikarjuna, S.M. Shashidhara, U.S. Mallik, K.I. Parashivamurthy, Grain refinement and wear properties evaluation of aluminum alloy 2014 matrix-TiB<sub>2</sub> in-situ composites, *Mater. Des.* 32 (2011) 3554–3559.

[6] T. Christman, A. Needleman, S. Suresh, An experimental and numerical study of deformation in metal-ceramic composites, *Acta Metall.* 37 (1989) 3029–3050.

[7] D.J. Lloyd, Aspects of fracture in particulate reinforced metal matrix composites, *Acta Metall. Mater.* 42 (1991) 59–71.

[8] Z. Wang, T.K. Chen, D.J. Lloyd, Stress distribution in particulate-reinforced metal matrix composites subjected to external load, *Metall. Trans. A* 24 (1993) 197–207.

[9] I. Sabirov, O. Kolednik, R. Pippan, Homogenization of metal matrix composites by high-pressure torsion, *Metall. Mater. Trans. A* 36 (2005) 2861–2870.

[10] I. Sabirov, O. Kolednik, R.Z. Valiev, R. Pippan, Equal channel angular pressing of metal matrix composites: effect on particle distribution and fracture toughness, *Acta Mater.* 53 (2005) 4919–4930.

[11] M. Alizadeh, Comparison of nano-structured Al/B<sub>4</sub>C composite produced by ARB and Al/B<sub>4</sub>C composite produced by RRB process, *Mater. Sci. Eng. A* 528 (2010) 578–582.

[12] A. Yazdani, E. Salahinejad, Evolution of reinforcement distribution in Al–B<sub>4</sub>C composites during accumulative roll bonding, *Mater. Des.* 32 (2011) 3137–3142.

[13] M. Alizadeh, H. Akbari beni, M. Ghaffari, R. Amini, Properties of high specific strength Al–4 wt.% Al<sub>2</sub>O<sub>3</sub>/B<sub>4</sub>C nano-composite produced by accumulative roll bonding process, *Mater. Des.* 50 (2013) 427–432.

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

[14] M. Alizadeh, M.H. Paydar, D. Trada, N. Tsuji, Effect of SiC particles on the microstructure evolution and mechanical properties of aluminum during ARB process, Mater. Sci. Eng. A 540 (2012) 13–23.

[15] M. Alizadeh, Processing of Al/B<sub>4</sub>C composites by cross-roll accumulative roll bonding, Mater. Lett. 64 (2010) 2641–2643.

[16] A. Yazdani, E. Salahinejad, J. Moradgholi, M. Hosseini, A new consideration on reinforcement distribution in the different planes of nano-structured metal matrix composite sheets prepared by accumulative roll bonding (ARB), J. Alloys Compd. 509 (2011) 9562–9564.

[17] P.A. Karnezis, G. Durrant, B. Cantor, Characterization of reinforcement distribution in cast Al–Alloy/SiC<sub>p</sub> composites, Mater. Charact. 40 (1998) 97–109.

[18] S.H. Lee, Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai, Role of shear strain in ultragrain refinement by accumulative roll-bonding (ARB) process, Scr. Mater. 46 (2002) 281–285.

[19] M. Alizadeh, E. Salahinejad, Processing of ultrafine-grained aluminum by cross accumulative roll-bonding, Mater. Sci. Eng. A 595 (2014) 131–134.

[20] E. Hosseini, M. Kazeminezhad, Nanostructure and mechanical properties of 0–7 strained aluminum by CGP: XRD, TEM and tensile test, Mater. Sci. Eng. A 526 (2009) 219–224.

[21] A. Rezaee-Bazzaz, S. Ahmadian, H. Reihani, Modeling of microstructure and mechanical behavior of ultra fine grained aluminum produced by accumulative roll-bonding, Mater. Des. 32 (2011) 4580–4585.

[22] J.C. Lee, K.N. Subramanian, Effect of cold rolling on the tensile properties of (Al<sub>2</sub>O<sub>3</sub>)<sub>p</sub>/Al composites, Mater. Sci. Eng. A 159 (1992) 43–50.

[23] N. Tsuji, Y. Ito, Y. Saito, Y. Minamino, Strength and ductility of ultrafine grained aluminum and iron produced by ARB and annealing, Scr. Mater. 47 (2002) 893–899.

**This is the accepted manuscript (postprint) of the following article:**

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

[24] A.H. Yaghtin, E. Salahinejad, A. Khosravifard, Processing of nanostructured metal matrix composites by a modified accumulative roll bonding method with structural and mechanical considerations, *Int. J. Miner. Metall. Mater.* 19 (2012) 951–956.

[25] Z. Zhang, D.L. Chen, Consideration of Orowan strengthening effect in particulate-reinforced metal matrix nanocomposites: A model for predicting their yield strength, *Scr. Mater.* 54 (2006) 1321–1326.

This is the accepted manuscript (postprint) of the following article:

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

## Figures

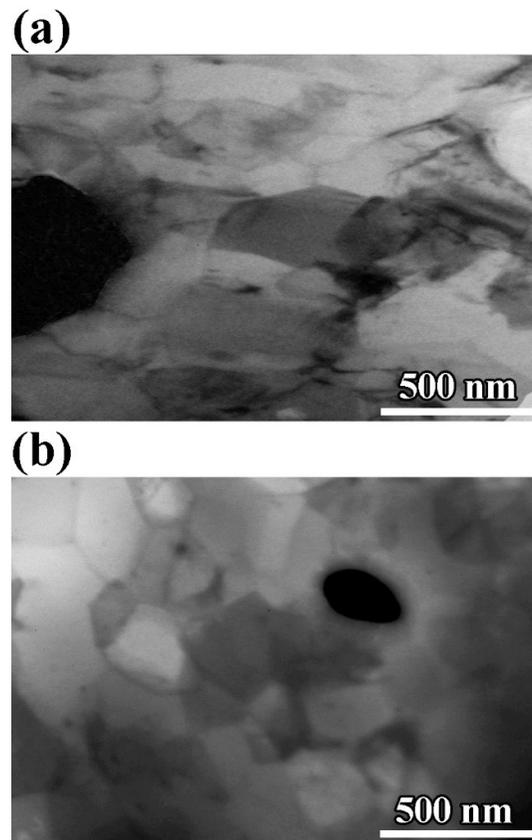


Fig. 1. TEM micrographs of the ARB (a) and CARB (b) composites processed to eight passes.

This is the accepted manuscript (postprint) of the following article:

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

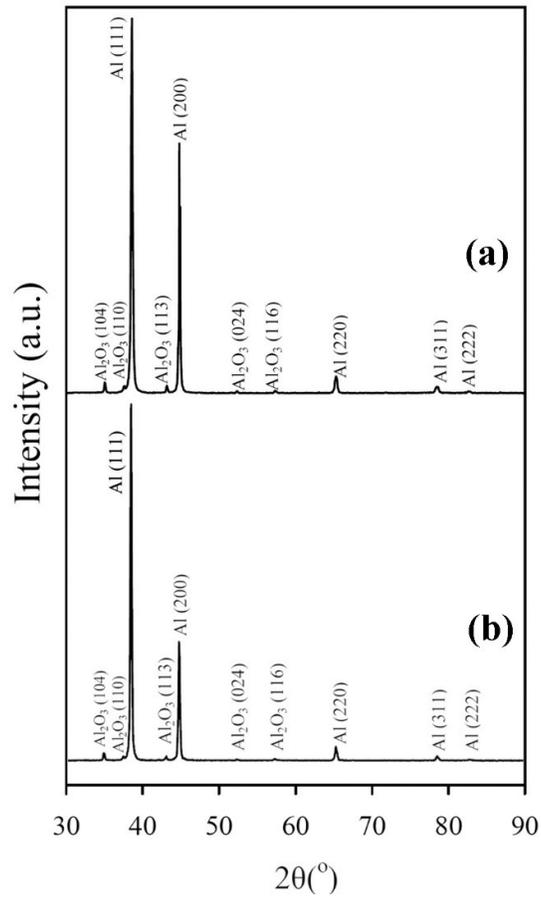


Fig. 2. XRD profiles of the ARB (a) and CARB (b) composites processed to eight passes.

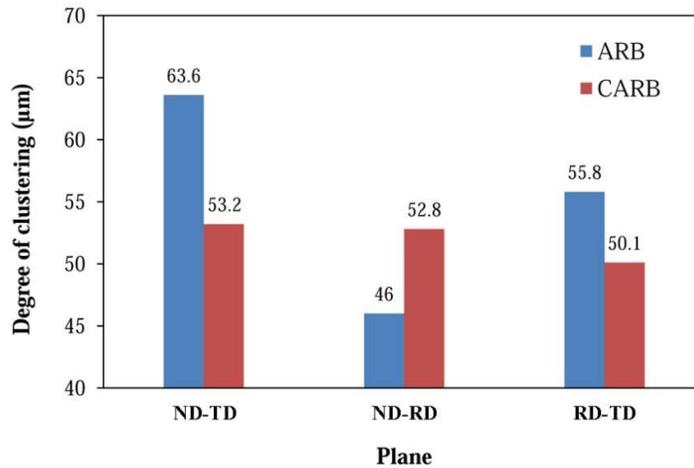


Fig. 3. Degree of clustering on the different planes of the MMCs produced to eight passes.

This is the accepted manuscript (postprint) of the following article:

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

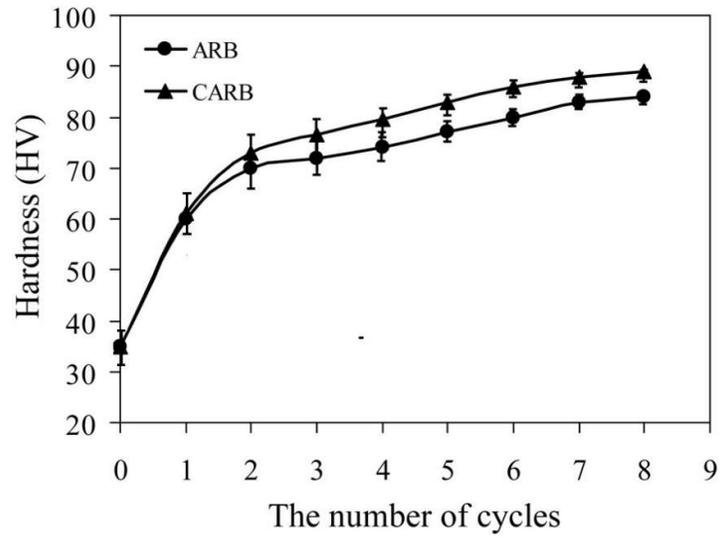


Fig. 4. Hardness values of the ARB- and CARB-processed MMCs.

This is the accepted manuscript (postprint) of the following article:

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

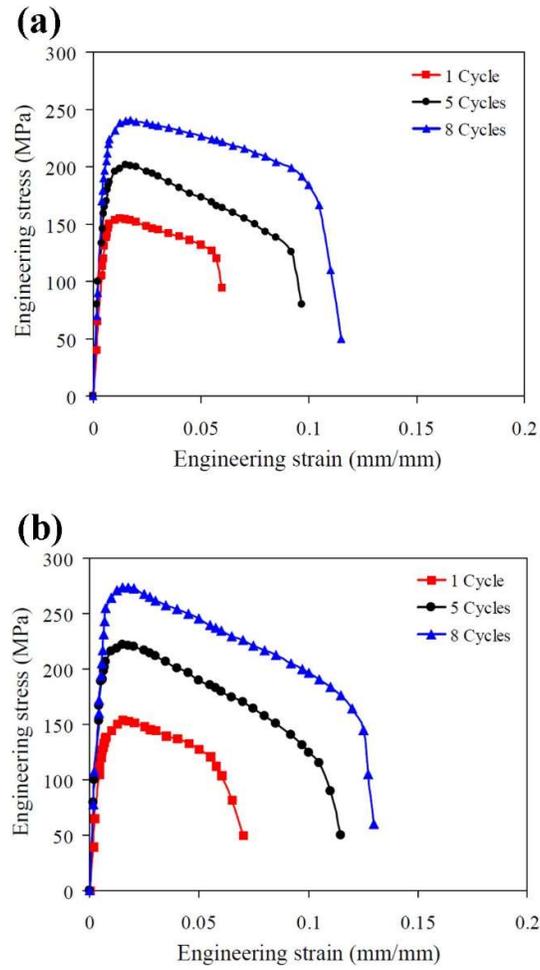


Fig. 5. Stress-strain curves of the MMCs prepared by the ARB (a) and CARB (b) processes.

This is the accepted manuscript (postprint) of the following article:

M. Alizadeh, E. Salahinejad, *A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes*, Journal of Alloys and Compounds, 620 (2015) 180-184.

<https://doi.org/10.1016/j.jallcom.2014.08.249>

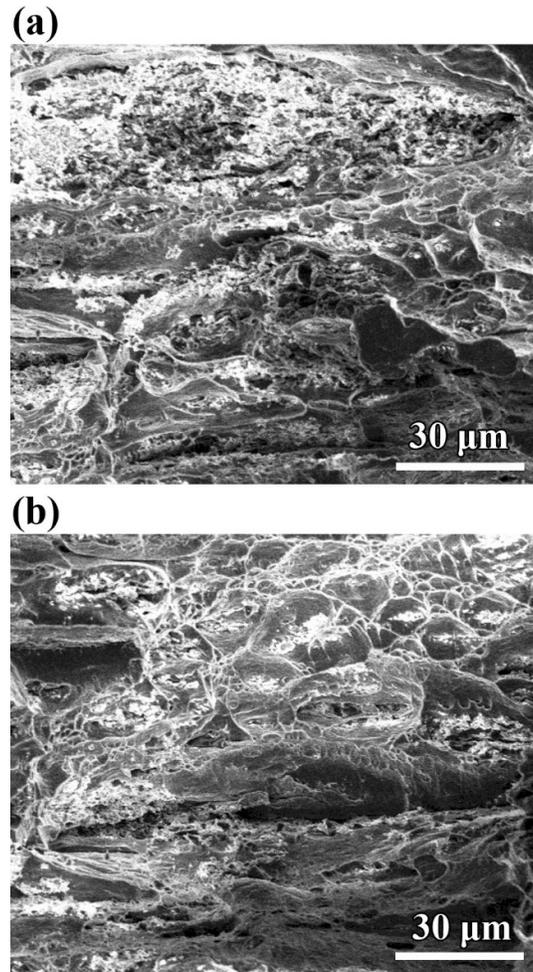


Fig. 6. SEM micrographs of the fracture surfaces of the ARB (a) and CARB (b) composites processed to eight passes after the tensile tests.