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Aluminum-matrix composites reinforced with E-glass fibers by cross accumulative roll bonding process

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Abstract

In this research, the structure and mechanical properties of 1050 aluminum strips reinforced with E-glass fibers, processed by the cross accumulative roll bonding (CARB) process, were investigated from microscopic, hardness, tensile and peeling viewpoints. The results indicated that the incorporation of the glass fibers in the Al matrix increases strength and micro-hardness but decreases elongation. In addition, it was realized that some of these fibers are broken and changed to short fibers during the CARB process. The presence of the glass fibers strongly also reduces the bond efficiency of the Al strips, typically from 50% to 5%. To compensate this deleterious effect, it was found that at least 25% should be increased to the normal thickness reduction used in CRAB.

Keywords: Cross accumulative roll bonding; Metal matrix composites; E-glass fiber; Peeling test: Mechanical properties

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1. Introduction

Researchers are always looking for new advanced materials for engineering applications. In this regard, metal matrix composites (MMCs) are suitable candidates due to the capability of controlling their properties [1]. These materials are made from two or more constituents and provide new properties [2, 3], where properties of MMCs are a function of constituents' properties. Some of these properties, such as specific strength and corrosion resistance are provided by the metal matrix; in contrast, the reinforcements determine some others like hardness, specific strength and wear resistance [3, 4].

The reinforcements can be used in the forms of particle, whisker, or fiber. Carbon fibers and glass fibers have be used by some researchers for the production of MMCs [5,6]. MMCs reinforced by carbon fibers are expensive due to the high cost of carbon fibers [6]. In comparison with carbon fibers, glass fibers have low cost because their raw materials are more cheap and available. In addition to flexibility, strength and stiffness, glass fibers have high melting point, considerable resistance to chemical attack, low susceptibility to moisture absorption, and high thermal stability [7]. Because of these promising properties, they are taken into account as a good candidate to reinforce structural composites. The MMCs reinforced with these fibers can be used in automotive, aerospace, aircraft, and electronic industries [2, 3, 6, 7].

When glass fibers are used as the reinforcement in MMCs, some challenges like poor bonding between the glass fibers and matrix, changes in the length of the fibers during fabrication, and the inappropriate distribution of the fibers should be addressed. The employment of a suitable process for the fabrication of MMCs reinforced with glass fibers can help solve some of these challenges. There are some traditional methods to fabricate fiber-reinforced MMCs, such as casting, metal spraying, liquid metal infiltration, diffusion bonding, and powder metallurgy [8]. Casting and powder metallurgy are typically used to fabricate short fiber-reinforced MMCs. In recent years, cross accumulative roll bonding (CARB) has been used for fabrication of particle-reinforced MMCs [9-11]. To produce MMCs, the following advantages can be assigned to CARB: (1) the potential to produce composites in the form of sheets, (2) the ability to produce composites with nanocrystalline and ultrafine grained (UFG) structures, and (3) having relatively simple processing and low cost. In this process, reinforcement particles are dispersed between several sheets and a layered sandwich is prepared. The prepared sandwich is rolled with a thickness reduction bigger than fifty present. The rolled sample is cut in the middle, stacked on each other and then is rolled again but at a 50% thickness reduction. This process is repeated several times. During rolling, due to the increase in the number of layers, flow of layers in the rolling direction, and flow of layers in the normal direction, the particles are distributed homogenously in the matrix [11]. Bonding between layers in the presence of the reinforcement is an essential parameter affecting the mechanical properties of the fabricated composites [12].

To the best of our knowledge, there are no scientific reports on the fabrication of Al/E-glass fibers composites by the CARB process. The main purpose of this paper is to investigate the feasibility of fabricating glass fiber-reinforced aluminum-matrix composites by the CARB process. Aiming at the optimization of the mechanical characteristics, the effect of the glass fibers addition on the bonding, microstructural and mechanical properties of the produced composites were also evaluated.

2. Experimental procedure

2.1. Sample preparation

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2.1.1. Sample preparation for peeling tests

1050-aluminum strips with the dimension of 200×40×3 mm^3 were prepared by a shearing machine. The surfaces of the strips were cleaned and one side of them was wire-brushed. About 10 vol% E-glass fibers with the length of 200 mm and the diameter of 13 μm were putted on the surface of a strip and fixed, and then another strip was placed on the fibers. The chemical composition of the used E-glass fiber is listed in Table 1. A sandwich includes two Al strips and one fiber layer between them was prepared, while both end of the sandwich were fastened by steel wires. Fifteen sandwiches were fabricated with the same method and prepared for the roll bonding process. The prepared sandwiches were rolled with various thickness reduction values (30-80 %) by a rolling machine. The rolling speed was selected to be 5 rpm, where the loading capacity and rolls diameter were 30 tons and 30 cm, respectively.

2.1.2. Fabrication of composites

Eight sheets of commercially 1050 aluminum alloy with the length of 250 mm, the width of 100 mm, and the thickness of 0.4 mm were prepared by a shearing machine. The sheets were cleaned by acetone and dried at atmosphere. Brushing was done by a wire brush on both sides of the sheets, except the lower and upper sheets which were brushed on one side. E-glass fibers were arranged on the surface of the sheets and fixed. Aluminum layers were stacked on each other, while glass fibers were between them. The result of this arrangement was a sandwich including eight layers of Al and seven layers of the glass fibers. The prepared sandwich was rolled by a laboratory rolling machine. The rolled sample was cut into two equal parts and after surface preparation and stacking on each other was rolled again, while it was rotated 90º around normal direction (ND). This process was repeated eight times.

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The product of this process was an aluminum matrix composite reinforced with the E-glass fibers.

2.2. Sample characterization

Peeling test samples were prepared by a wire cut machine from the roll-bonded sandwiches, according to ASTM-D1876-01. An Instron tensile test machine was used to perform peeling tests. After the tests, the rolling direction-transverse direction (RD-TD) surfaces of the peeled samples were investigated by a VEGA3 TESCAN scanning electron microscope (SEM).

The microstructural examination was also done on the rolling direction-normal direction (RD-ND) plane of the composite samples by an optical microscope and SEM. The mechanical properties of the fabricated Al/E-glass composites were evaluated by tensile and micro-hardness tests. JIS-5 (1/5 miniaturized) was used for the preparation of the tensile test specimens. In this standard, the specimen is dog-bone shaped with the length and width of 50 and 15 mm, respectively, and the gage length and width of 10 and 5 mm, respectively. The samples were prepared in the rolling direction at various CABR cycles. The strain rate during the tensile tests was about 0.5 mm/min. Micro-hardness testing by a Leitz machine was used on the samples fabricated at various CABR cycles. The applied load and holding time were 20 g and 10 s, respectively. The hardness tests were carried out on the RD-ND plane on five points and the average value of them was calculated.

3. Results and discussion

Fig. 1a shows the variations of peeling force versus peeling distance for a roll-bonded Al/Al strip after 50 % reduction in thickness. As can be seen, at the beginning of the peeling test, the peeling force increases to a maximum value and then exhibits a saw-toothed shape. It is noticeable that the mean peeling force is reported as the typical result of the peeling test (dash line in Fig. 1a). The main mechanisms of bonding between the strips during roll bonding are joint recrystallization, diffusion bonding, energy barrier surface, and surface film theory [13-15]. The surface film mechanism is more compatible for bonding of Al strips. In this mechanism, atom-to atom bonding is crated during cold roll bonding processes [13]. During this process, the opposing scratch-brushed surfaces, which are brittle, are exposed to cracking due to the rolling pressure. The virgin metal is extruded through opposite cracks and metallic bonds are created between two virgin metals, leading to bonding between two strips [13]. An important parameter representing the bonding level between two Al strips is the average bond strength. Fig. 1b depicts the effect of the thickness reduction on the average bond strength of two Al strips. The average bond strength was calculated by following equation [13]:

$$Average\ bond\ strength = \frac{Average\ load}{Bond\ width}\left(\frac{N}{mm}\right) \quad (1)$$

where the average load was determined from peeling force versus peeling distance curves, as shown in Fig. 1a with a dashed line. The bond width was selected to be 25 mm in this research. As it can be seen in Fig. 1b, the average bond strength is increased by increasing the thickness reduction and bonding between the strips becomes stronger. In fact, the increase of the thickness reduction results in the increase of cracks width, number of cracks, and amount of extruded virgin metals, thereby enhancing the bond strength [13].

To investigate the effect of the E-glass fibers on the bonding properties of the Al strips, the roll bonding process was carried out in the presence of the E-glass fibers. Fig. 2a shows the variations of peeling force versus peeling distance for a roll-bonded Al/E-glass fiber/Al strip after 50 % reduction in thickness. The trend of this curve is similar to Fig. 1a; however, the peeling force value is different. The comparison of Figs.1b and 2a shows that at the same thickness reduction, the peeling force of the Al/Al strips is bigger than that of the Al/E-glass fiber/Al strips. This means that the presence of the glass fibers between the Al strips decreases bonding between them. Bonding between two strips is created when an energy barrier overcomes [16]. It has been reported that surface contaminations (grease, dust, and adsorbed water vapor) increase the energy required for the bond formation. E-glass fibers behave like surface contaminations and inhibit successful bonding between two Al strips. Accordingly, to achieve an acceptable bond strength between Al strips in the presence of E-glass fibers, it is essential to increase the rolling pressure or thickness reduction. Fig. 2b shows the effect of the thickness reduction on the average bond strength of two Al strips in the presence of the E-glass fibers. It is obvious that by increasing the thickness reduction, the bond strength is increased. By increasing the thickness reduction, more cracks are created and more atoms gains the energy required for successful atom-to-atom bonding.

The fracture surfaces of the Al/E-glass fiber/Al specimens after the peeling tests at different thickness reductions are demonstrated in Fig. 3. There are three regions in the fracture surfaces: (α) bonded regions during the cold roll bonding process which have been debonded after the peeling test, (β) fibers regions, and (γ) fiber track regions (regions where the fibers have been separated from the surface). During the rolling process, two forces are applied on the strips, a horizontal force (x-direction) and a vertical force (y-direction). The vertical component applies a pressure on the Al strips and fibers. Accordingly, Al is flowed in the y-direction and surrounds the fibers. This dictates that the fibers are embedded in the Al matrix due to this pressure. In addition, the Al matrix is flowed and the fibers are stretched in the x-direction. However, the fibers are a ceramic material and have a limited elongation;

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hence, they are broken and changed to short fibers. As it can be seen in Fig. 3, by the increase of the thickness reduction, the "α" regions is increased. The increase of these regions cause to increase the bond strength (see Fig. 2b). In fact, by the increase of the thickness reduction, more fibers are embedded in the Al matrix (see Fig. 3e). Also, the fibers are further broken down and their length decreases.

Figs. 3b and c indicates the fracture surfaces of the Al/E-glass fiber/Al specimen after the peeling test at a higher magnification. As it is seen, some of the fibers are not in their places (region 1). Indeed, they are connected on the opposite surface which have been detached from the visible surface during the peeling test. Some of the fibers have left their places, but they present in the fracture surface (region 2). The last group of the fibers has placed in the Al matrix strongly (region 3). In these regions, bonding between the Al matrix and E-glass fibers is stronger, as is shown in Fig. 3c. It is noticeable that during the roll bonding process, fibers may crush due to the rolling pressure, creating some glass particles. These particles which are seen in the fracture surface (Fig. 3b) can increase the strength of the composite during the CARB process [9,17].

The bond efficiency (η) of the Al strips with and without the E-glass fibers in the various thickness reductions was calculated by the following equation [18]:

$$\eta = \frac{S_b}{K\prime}\left(\ln\frac{1}{1-R_t}\right)^{-n} \qquad (2)$$

where S_b is the bond strength, R_t is reduction in thickness, and K' is a constant value determined by [18]:

$$K' = \left(\frac{2}{\sqrt{3}}\right)^{n} K \qquad (3)$$

where n and k are plastic constants. n and K of the used Al matrix were determined by tensile tests to be 0.229 and 142 MPa, respectively. Fig. 4 shows the bond efficiency (η) of the Al strips. According to Eq. 2, the bond efficiency is proportional to the bond strength; hence, the bond efficiency is increased by increasing the bond strength. From this figure, it can be concluded that first, there is a threshold thickness reduction which lower than that the bond efficiency is zero, i.e. bonding does not occur. Second, by increasing the thickness reduction, the bond efficiency is increased and reaches a maximum value. Third, the presence of the glass fibers between the Al strips decreases the bond efficiency, whereas the trend of the changes in the bond efficiency versus thickness reduction is similar for both the samples (with and without the E-glass fibers). The threshold value of the thickness reduction for the Al strips without the glass fibers is about 30 % and for Al strips with the glass fibers is about 45 % i.e. about 1.5 times. It has been reported that in the thickness reductions lower than the threshold value, there is not enough force to create cracks in the surfaces of the strips [13, 19]. Therefore, cracks cannot be created, or if they are created, the number of them is low, they are shallow, and their openings are tight. The virgin metal cannot be extruded through cracks and bonding does not occur. However, by increasing the thickness reduction, the bond efficiency is increased. In the presence of the glass fibers, the thickness reduction of 45 % is enough for the creation of high and deep cracks, but the glass fibers prevent form passing of the virgin metal and bonding between them. Hence, the successful bonding occurs in higher thickness reductions. In fact, the glass fibers increase the activation energy required for a successful bonding [19].

According to the reported results, to obtain a successful bonding between the Al strips in the presence of the E-glass fibers, a thickness reduction higher than 65 % is required. For this purpose, the thickness reduction of about 69 % was selected in the first cycle of CARB. In this cycle, the thickness of the prepared sandwich was decreased from 3.2 mm to 1 mm by the rolling machine. In the next cycles, the thickness reduction of 50 % was applied to fabricate Al/E-glass fiber composites. Because after the first CARB cycle, there are no fibers between the Al strips and according to Fig. 4, this thickness reduction is enough to create a successful bonding between the Al strips. Fig. 5 shows the optical microstructure of the Al/E-glass fiber composite fabricated by one and eight cycles of CARB. As can be seen, in the first cycle, the glass fibers present a layer feature between the Al layers. In this cycle, bonding between the Al layers is not suitable and there are some bonded and unbonded areas. Fig. 6 shows the SEM image of the composites fabricated by one and eight cycles of CARB. From Fig. 6a, it is obvious that there are some big porosity between the fibers, so that they are close at the higher cycles of CARB due to the rolling pressure and flowing of Al in these pores. According to Fig. 6b, in some areas, bonding between the Al strips is not created due to the presence of the E-glass fibers, because the fibers have increased the activation energy required for successful bonding. In whatever way, most of these unbonded areas disappear at the next cycles of CARB. But the presence of these unbonded areas in the composite deteriorates the mechanical properties of the fabricated composites at the initial cycles [20]. By increasing the CARB cycles, in each cycles, the length of the Al strips approximately becomes two times due to the horizontal component of the frictional force. Also, the thickness of the strips becomes half due to the rolling pressure in each cycle. In addition, at each cycle, the number of layers becomes twice due to the stacking of the layers on each other. These factors lead to the more uniform distribution of the glass fibers in the Al matrix at the final CARB cycles, as shown in Figs. 5b and 6c.

The tensile stress-strain curves of the annealed pure Al, CARBed monolithic Al after eight cycles, and composites fabricated at the various cycles of CARB are shown in Fig. 7. It is seen that by increasing the CARB cycles, the strength of the composite samples is increased. The mechanism of the strength increase during the CARB process has been frequently reported [21,22]. Strain hardening in the initial CARB cycles and grain refining in the final CARB cycles are two main mechanisms explaining the increase of strength [21,22]. These mechanisms are active in both monolithic Al and composite samples during the CARB process. Additionally, in the composite samples, the glass fiber reinforcements increase the strength. Since the strength and the Young's modulus of the E-glass fibers embedded within the Al matrix are greater than those of Al, the fibers increase the strength. As indicated in Fig. 7, the strength of the composite fabricated by eight cycles of CARB is about 1.2 times higher than that of the monolithic Al, due to the presence of the E-glass fibers. Also, the strength of the fabricated composite is about 3.4 times higher than that of the pure Al, due to the application of the CARB process and the presence of the E-glass fibers. The high strength of the fabricated composites makes it promising to use in automotive and aerospace industries.

It is noticeable that the interfacial bonding between the Al matrix and E-glass fibers has a large impact on the tensile properties of the fabricated composites. To investigate the bonding behavior of the matrix and reinforcements, SEM images were provided form the tensile fracture surfaces of the composite samples fabricated at the various cycles of CARB (Fig. 8). As can be seen in Fig. 8a, an extensive pull-out has occurred for the fibers. Generally, the interfacial bonding between the Al matrix and E-glass fibers can be evaluated by the fiber pull-out level of a fractured surface [3]. Due to pull-out, the interfacial bonding between the matrix and fibers is not strong, resulting in a decrease in the tensile strength of the composite. Fig. 8 shows that by increasing the CARB cycles, the pull-out of the fibers decreases and it is expected that the tensile strength is increased. In fact, by increasing the CARB cycles, interfacial adhesion becomes stronger, resulting in the breakage of the glass fibers close to the fracture plane of the Al matrix during the tensile tests (see Fig. 8d).

Despite the fact that the CARB process increases the strength of the samples, it decreases elongation. Fig. 9 indicates the elongation of the annealed pure Al, monolithic Al, Al/E-glass fiber composites at various cycles of CARB. As it is obvious, the elongation of the monolithic Al and composite samples is lower than that of pure Al. The severe reduction of elongation is the characteristic of the ARB process, which is attributed to high strain hardening and the presence of some porosity and disbonding area between layers [22, 23]. The comparison of the monolithic and composite samples shows that the elongation of the monolithic sample is slightly higher. As mentioned above, the glass fibers decrease the bond efficiency of the layers during the CARB process; increasing the disbonded areas. These areas are preferred places for the initiation of cracks during the tensile tests and can decrease the elongation. Also, due to the weak interfacial bonding between the matrix and some glass fibers (see Fig. 8), the elongation is decreased. The brittleness of the E-glass fiber also is one of the effective parameters on the decrease of elongation [3].

From Figs. 7 and 9, it can be found that by increasing the CARB cycles, the elongation of the fabricated composite is increased, which is in consistent with the literature [23-25]. The fracture surface of the fabricated composite samples after the first cycles of CARB (Fig. 8a) consists of Al matrix/E-glass fiber debonding, delaminated layers, and micro cracks. These defects result in the initiation of cracks and the descent of the elongation of the composite samples fabricated at the initial CARB cycles. According to Fig. 8a, the fracture surface consists of flat areas and dimples, showing a mixture of ductile and brittle fracture. By increasing the CARB cycles, delaminated layers, cracks, and the fraction of unbonded matrix/E-glass fibers are decreased, and the fraction of dimples and consequently elongation are increased [24].

Table 2 tabulates the Vickers micro-hardness of the pure Al and fabricated monolithic Al and Al/E-glass fiber composites as a function of CARB cycles. The trend of the micro-hardness changes in two materials is similar. At the initial CARB cycle, the increase of micro-hardness is considerable, which is attributed to the strain hardening effect [26]. In these cycles, the density of dislocations is sharply increased and their interaction results in the increase of micro-hardness [26, 27]. After the initial cycles, the increase of micro-hardness is gradual due to the decrease of the strain hardening effect [26, 27]. At the final cycles, grain boundary strengthening is responsible for the increase of micro-hardness [26]. As can be seen in Table 2, the micro-hardness of both materials at the initial CARB cycles is almost equal and then the micro-hardness of the composite samples increases more sharply. This is attributed to the presence of the glass fibers in the Al matrix and their homogenous distribution [3, 28, 29].

4. Conclusions

In this work, an attempt was made to fabricate Al/E-glass fibers composites by the CARB process. The effect of the E-glass fibers on the bonding properties of Al strips was investigated because of its impact on the mechanical properties of the composites. The microstructural and mechanical properties of the roll-bonded strips and composite sample were also examined. The results were concluded as follows:

1. The presence of the E-glass fibers strongly decreased the bond strength and weld efficiency of the Al strips during cold roll bonding.

2. By increasing the thickness reduction, the bond strength and weld efficiency of the Al strips were increased.

3. To create an acceptable bonding between the Al strips in the presence of the E-glass fibers, at least 25% thickness reduction should be increased. In this case, the optimum thickness reduction level was about 72%.

4. By increasing the CARB cycles, the pull-out of the fibers was decreased, and the breakage of the glass fibers occurred close to the fracture plane of the Al matrix.

5. The tensile strength and micro-hardness of the fabricated composites increased by increasing of the CARB cycle. Also, the strength and hardness of the fabricated composites were higher than those of monolithic Al.

6. The elongation of the composites after the final cycles of CARB was lower than that of the monolithic Al. Also, by increasing the CARB cycles, the elongation of the composites was increased.

7. The CARB process was found to be a feasible method to fabricate short glass fiber reinforced composites.

References

[1] J.W. Kaczmar, K. Pietrzak, W. Wlosinski, The production and application of metal matrix composite materials, J. Mater. Process. Technol. 106 (2000) 58–67.

[2] P. Nageswara, R. Kotaiah, D. Venkateswarlu, Study on Mechanical Property of Aluminium 6061 with E Glass Fiber Reinforced Composite, Appl. Mech. Mater. 877 (2018) 50-53.

[3] S. Seshan, A. Guruprasad, M. Prabha, A. Sudhakar, Fibre-reinforced metal matrix composites -a review, J. Indian Inst. Sci. 76 (1996) 1-14.

[4] V. Kavimani, K. Soorya Prakash, T. Thankachan, Experimental investigations on wear and friction behaviour of SiC@r-GO reinforced Mg matrix composites produced through solvent-based powder metallurgy. Compos Part B: Eng 162 (2019) 508-521.

[5] L.G. Hou, R.Z. Wu, X.D. Wang, J.H. Zhang, M.L. Zhang, A.P. Dong, B.D. Sun, Microstructure, mechanical properties and thermal conductivity of the short carbon fiber reinforced magnesium matrix composites, J. Alloy. Compd. 695 (2017) 2820-2826.

[6] A. Samanta, Q. Wang, H. Ding, A novel selective laser melting process for glass Fiber-reinforced metal Matrix Composites, Manuf. Lett. 18 (2018) 27-30.

[7] P. Bhuyan, H. Singh, L. Kumar, N. Sharma, D. Panda, D. Verma, S.N. Alam, Development of Cu-E-Glass Fiber Composites by Powder Metallurgy Route, Mater. Sci. Eng. 115 (2016) 3-12.

[8] T.W. Chou, A. Kelly, A. Okura, Fibre-reinforced metal-matrix composites, Composites. 16 (1985) 183-190.

[9] M. Alizadeh, E. Salahinejad, A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes, J. Alloy. Comp. 620 (2015) 180-184.

[10] M. Alizadeh, Strength prediction of the ARBed Al/Al_2O_3/B_4C nano-composites using Orowan model, Mater. Res. Bull. 59 (2014) 290-294.

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

[12] M. Alizadeh, Effects of temperature and B_4C content on the bonding properties of roll-bonded aluminum strips, J. Mater. Sci. 47 (2012) 4689–4695.

[13] M. Eizadjou, H. Danesh Manesh, K. Janghorban, Mechanism of warm and cold roll bonding of aluminum alloy strips, Mater. Des. 30 (2009) 4156-4161.

[14] H.A. Mohamed, J. Washburn, Mechanism of solid state pressure welding, Welding Research Supplement, 55 (1975) 302-310.

[15] V. Yousefi Mehr, M.R. Toroghinejad, A. Rezaeian, The effects of oxide film and annealing treatment on the bond strength of Al–Cu strips in cold roll bonding process, Mater. Des. 53 (2014) 174-181.

[16] H.Y. Wu, S.Y. Lee, J.Y. Wang, Solid-state bonding of iron-based alloys, steel-brass, and aluminum alloys. J. Mater. Proc. Technol. 75 (1998)173–179.

[17] M. Alizadeh, M.H. Paydar, High-strength nanostructured Al/B_4C composite processed by cross-roll accumulative roll bonding, Mater. Sci. Eng. A. 538 (2012) 14–19.

[18] H.R. Madaah Hosseini, A.H. Kokabi, Cold roll bonding of 5754-aluminum strips, Mater. Sci. Eng. A. 335 (2002) 186–90.

[19] M. Alizadeh, M.H. Paydar, Study on the effect of presence of TiH_2 particles on the roll bonding behavior of aluminum alloy strips, Mater. Des. 30 (2009) 82-86.

[20] M. Alizadeh, M.H. Paydar, Fabrication of Al/SiC_P composite strips by repeated roll-bonding (RRB) process, J. Alloy. Compd. 477 (2009) 811–816.

[21] 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.

[22] X. Huang, N. Kamikawa, N. Hansen, Strengthening mechanisms in nanostructured aluminum, Mater. Sci. Eng., A. 484 (2008) 102–104.

[23] S. Mansourzadeh, M. Hosseini, E. Salahinejad, A.H. Yaghtin, Cu-(B_4C)p metal matrix composites processed by accumulative roll-bonding, Prog. Nat. Sci.: Mater. Int. 26 (2016) 613-620.

[24] M. Eizadjou, H. Danesh Manesh, K. Janghorban, Microstructure and mechanical properties of ultra-fine grains (UFGs) aluminum strips produced by ARB process, J. Alloy. Compd. 474 (2009) 406-415.

[25] H. Yu, H. Wang, C. Lu, A.K. Tieu, H. Li, A. Godbole, X. Liu, Microstructure evolution of accumulative roll bonding processed pure aluminum during cryorolling, J. Mater. Res. 31 (2016) 797-805.

[26] M. Shaarbaf, M.R. Toroghinejad, Nano-grained copper strip produced by accumulative roll bonding process, Mater. Sci. Eng., A. 473 (2008) 28–33.

[27] A. Yazdani, E. Salahinejad, Evolution of reinforcement distribution in Al–B_4C composites during accumulative roll bonding, Mater. Des. 32 (2011) 3137–3142.

[28] K. Shirvani Moghaddam, S.U. Hamim, M. Karbalaei Akbari, S.M. Fakhrhoseini, H. Khayyam, A.H. Pakseresht, E. Ghasali, M. Zabet, K. Shahzad Munir, S. Jiag, P. Davim, M. Naebe, Carbon Fiber Reinforced Metal Matrix Composites: Fabrication Processes and Properties, Composites, Part A. 92 (2017) 70-96.

[29] Vinayashree, R. Shobha, Study on Mechanical Property of Aluminium 6061 with E Glass Fiber Reinforced Composite, Appl. Mech. Mater. 877 (2018) 50-53.

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Figures

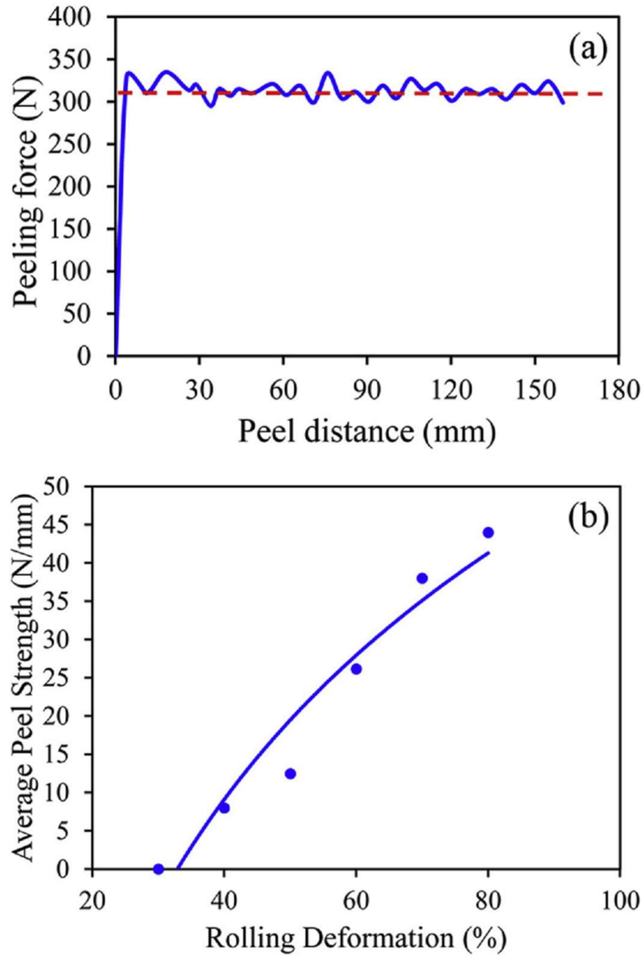

Fig. 1. Variation of (a) peeling force vs. peel distance for the roll-bonded pure Al strips at the thickness reduction of 50% and (b) average peel strength vs. thickness reduction for the roll-bonded pure Al strips.

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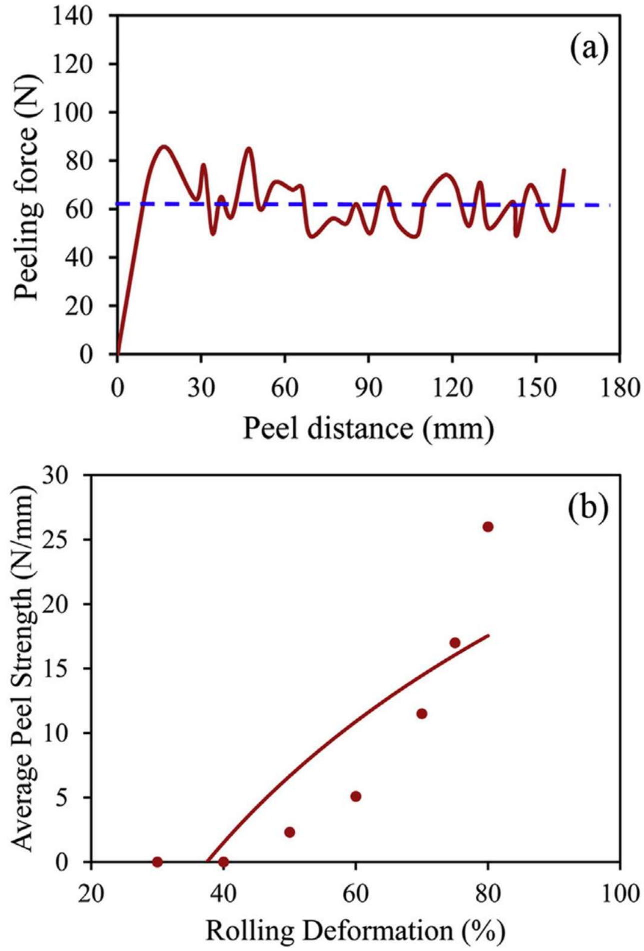

Fig. 2. Variation of (a) peeling force vs. peel distance for the roll-bonded Al strips in the presence of the E-glass fibers at the thickness reduction of 50% and (b) average peel strength vs. thickness reduction for the roll-bonded Al strips in the presence of the E-glass fibers.

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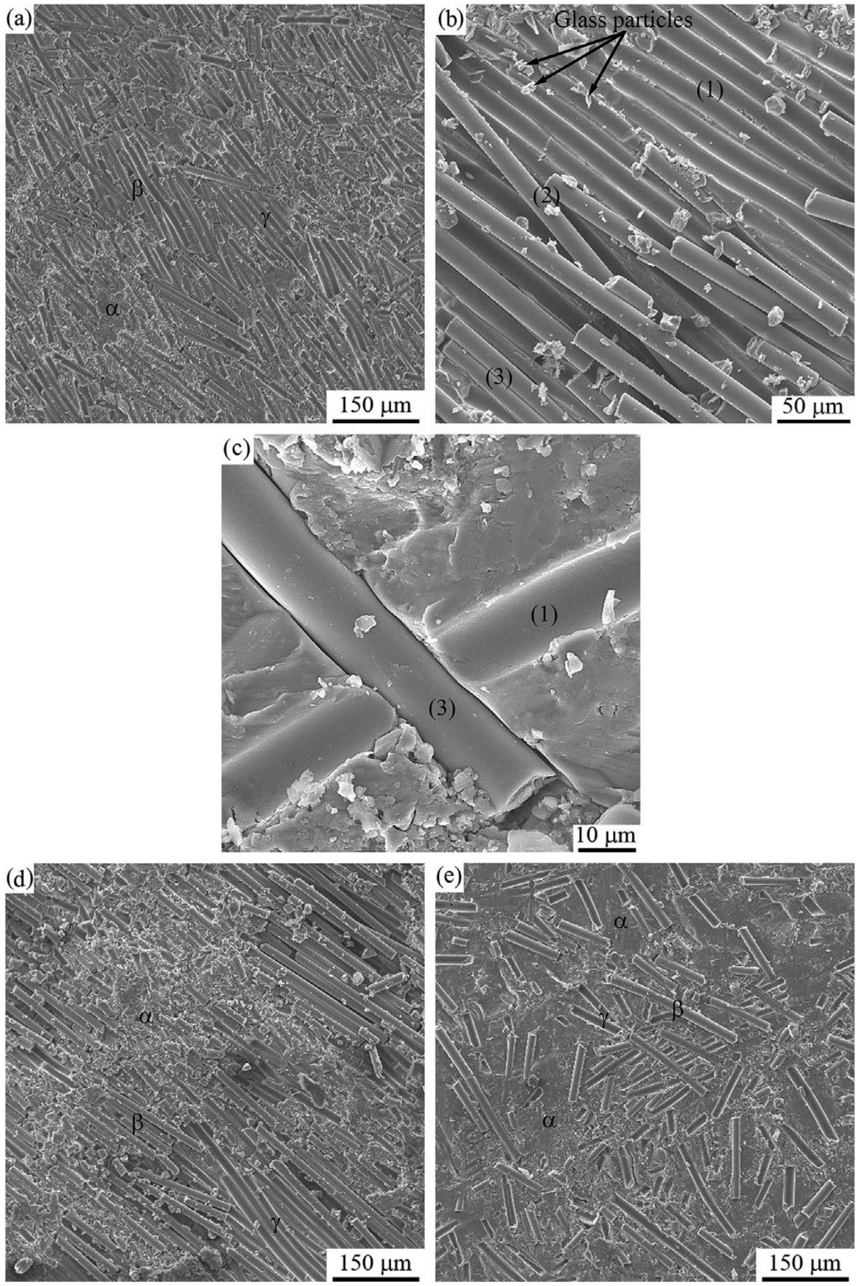

Fig. 3. Back-scatter SEM micrograph of the fracture surfaces of the Al/E-glass fiber/Al specimens after the peeling tests at different thickness reductions: (a, b, and c) 50%, (d) 70%, and (e) 80%.

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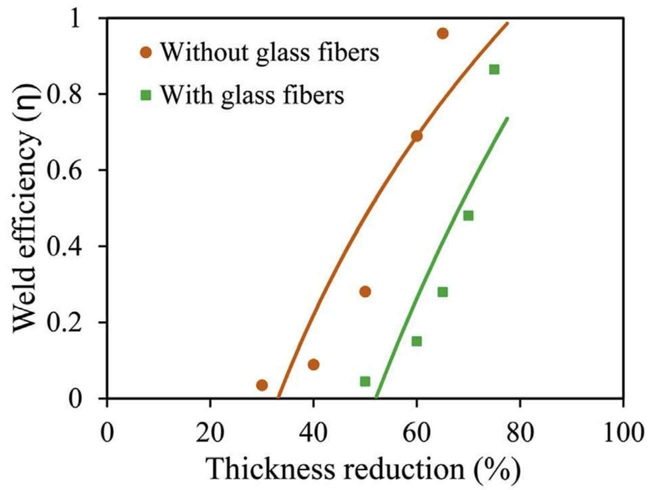

Fig. 4. Variation of the bond efficiency of the Al strips vs. thickness reduction, with and without the E-glass fibers.

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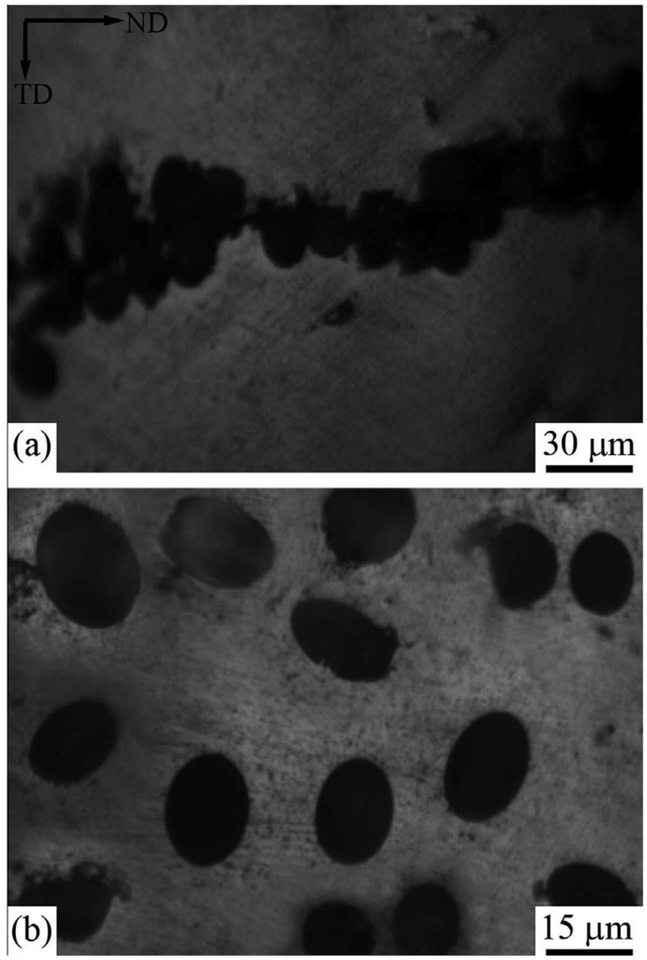

Fig. 5. Optical micrograph of the Al/E-glass fiber composites fabricated by (a) first and (b) eight cycles.

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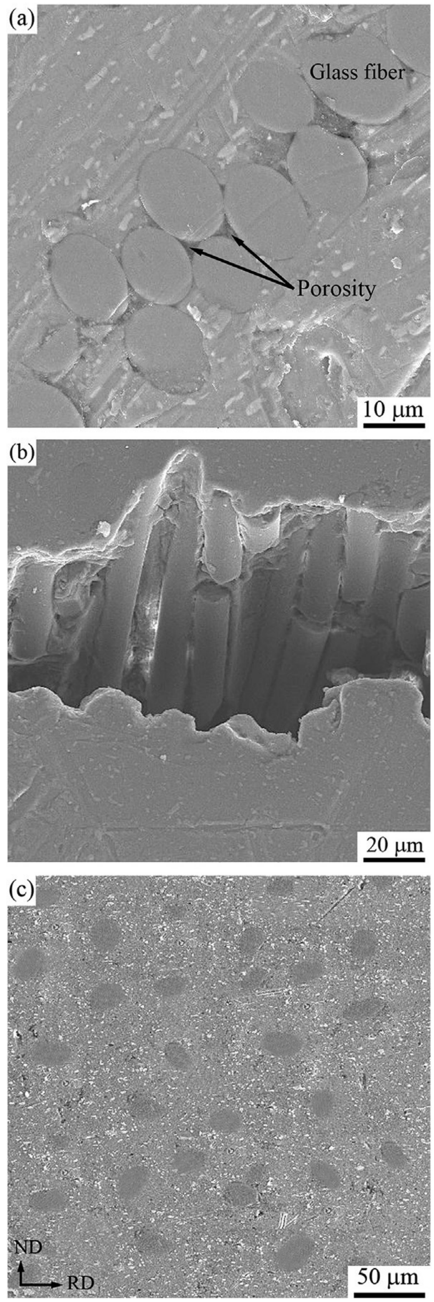

Fig. 6. SEM micrograph of the Al/E-glass fiber composites fabricated by the first and eight cycles: (a) the connection of two Al layers in the presence of the fibers and porosity between the fibers at the first cycle, (b) the disconnection of two Al layers in the presence of the fibers at the first cycle, (c) the distribution of the fibers in the Al matrix after the eight cycles.

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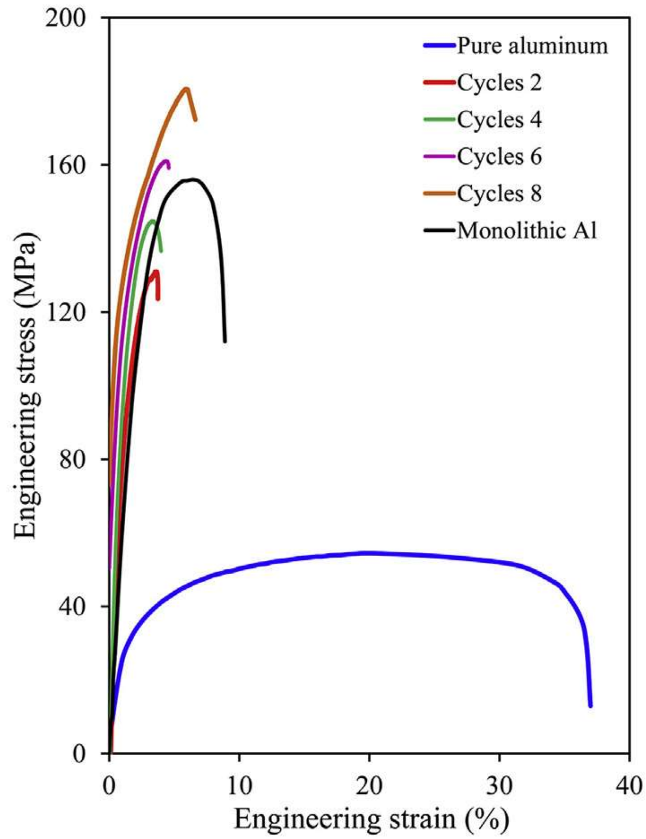

Fig. 7. Engineering stress-strain curves of the pure Al and Al/E-glass fiber composites fabricated by various CARB cycles.

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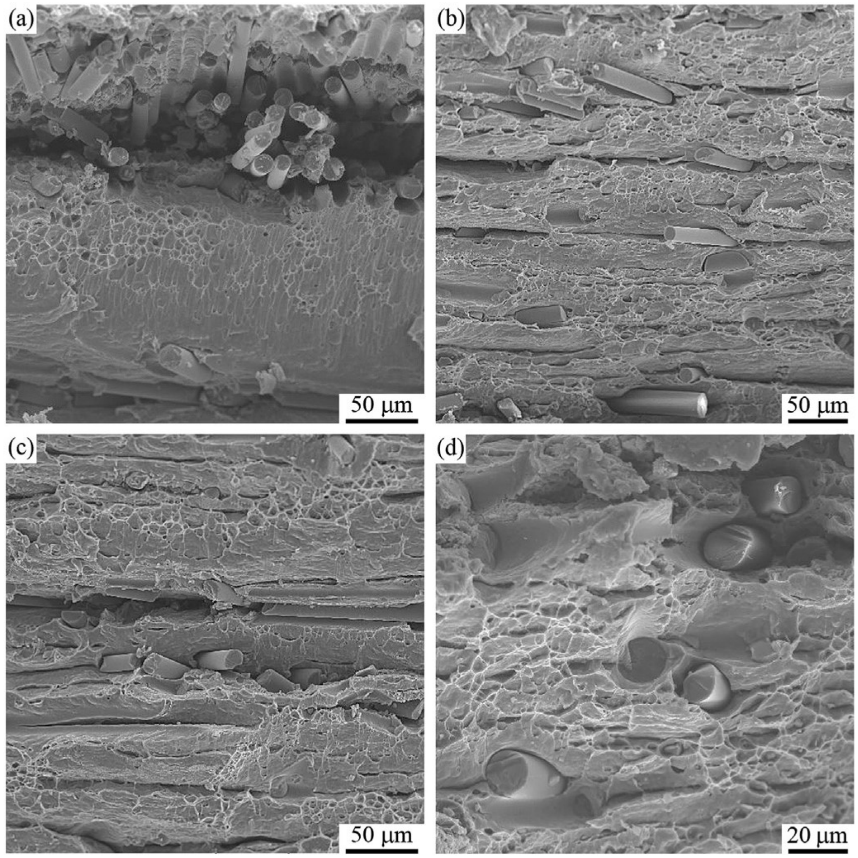

Fig. 8. SEM micrograph of the fracture surface of the Al/E-glass fiber composites fabricated by (a) first, (b) forth, and (c, d) eight cycles after the tensile tests.

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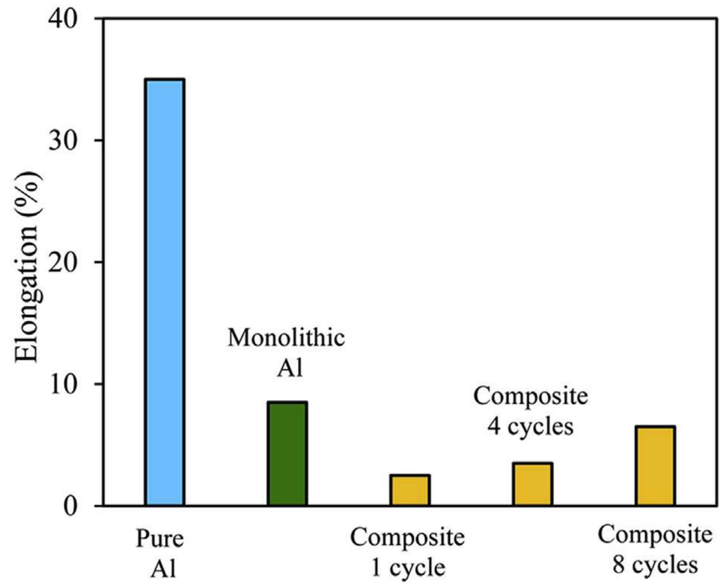

Fig. 9. Elongation of the pure Al, monolithic Al and Al/E-glass fiber composites fabricated by various CARB cycles.

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Tables

Table 1. Chemical composition of the E-glass fibers used.

	Component					
	SiO_2	CaO	Al_2O_3	MgO	B_2O_3	Na_2O+K_2O
wt%	53	17.5	16	4.5	8	1

Table 2. Micro-hardness of the monolithic Al and Al/E-glass fiber composites as a function of CARB cycles.

Samples	Number of cycles					
	0 (Pure Al)	1	3	5	7	9
Monolithic Al	23.5 ± 1.5	41.0 ± 2.0	46.5 ± 1.5	52.3 ± 1.7	51.5 ± 1.5	51.5 ± 2.5
Composite	23.3 ± 1.7	40.5 ± 1.5	47.6 ± 1.4	59.5 ± 1.5	69.4 ± 1.6	73.5 ± 3.5