Microstructure and mechanical properties of Al/Cu/Mg laminated composite sheets produced by ARB process

Davood Rahmatabadi¹, Moslem Tayyebi², Ramin Hashemi^{1*}, Ghader Faraji³

¹School of Mechanical Engineering, Iran University of Science and Technology, PO. Box 16765-163, Tehran, Iran

²Department of Material Engineering, Sahand University of Technology, PO. BOX 51335/1996, Tabriz, Iran

³School of Mechanical Engineering, College of Engineering, University of Tehran, PO Box: 515-14395, Tehran, Iran

*Corresponding author: E-mail: rhashemi@iust.ac.ir (R. Hashemi) Tel.: +98-21-77240540, Fax: +98-21-77240540

Abstract

In the present study, Al/Cu/Mg multi-layered composite was produced by accumulative roll bonding (ARB) through seven passes, and the microstructure and mechanical properties were evaluated. The microstructure investigations showed that plastic instability occurred for the both copper and magnesium reinforcing at the primary sandwich. Also, a composite with the perfectly uniform distribution of copper and magnesium reinforcing layers were prepared at the last pass. By increasing the number of ARB cycles, the microhardness of the layers including aluminum, copper, and magnesium was significantly increased. The ultimate tensile strength of the sandwich was enhanced continually and reached to the maximum value of 355.5 MPa. This strength value was about 3.2, 2 and 2.1 times higher than that of the initial value of strength for aluminum, copper and magnesium sheets, respectively. Investigation of the tensile fracture surfaces during the ARB process indicated that by increasing the number of the ARB passes, the fracture mechanism changed to shear ductile at the seventh pass.

Keywords: Multi-layered composite, Al/Cu/Mg, Accumulative roll bonding, Fractography, Mechanical Properties, Microstructure.

1. Introduction

Metal matrix composites (MMC) have broad and various applications. The strength, hardness, thermal conductivity, wear resistance, creep resistance and dimensional stability of MMC are improved compared to the base metal [1, 2]. Aluminum due to good engineering properties, simple processing, and low density is a metal that regarded highly to manufacturing the composites [3, 4]. Magnesium is a lightweight metal with hexagonal close packing (HCP) structure that has many applications in the medical, automotive and aerospace industries [5-7]. Copper is also one of the metals with high electrical and thermal conductivity and excellent formability. A composite consisting of three metals of aluminum, copper, and magnesium, can provide a variety of properties such as high strength, light weight, and good thermal and electrical conductivity. Several methods are used for manufacturing multilayer composites. One of the top-down strategies includes severe plastic deformation (SPD) processing methods. By now, various SPD processes such as equal channel angular pressing (ECAP) [8-11], high pressure torsion (HPT) [8, 12-14], multi-axial forging (MAF) [15], repetitive forging [16], tubular channel angular pressing (TCAP) [17, 18], cyclic extrusion compression (CEC) [19, 20], and accumulative roll bonding (ARB) [21, 22] have been proposed as effective SPD methods successfully applied to various materials. The common feature of these techniques is that the shape and dimension of the sample are approximately constant after processing so that there is no geometric limitation for the applying of very high plastic strains [23]. Among these processes, accumulative roll bonding has some unique features, such as: (1) unlike the ECAP, CEC and HPT processes which require forming machines with large capacity and expensive dies, the ARB process can be performed by a conventional rolling mill without any particular die [23], (2) in comparison to the other methods, the productivity of the ARB process is relatively high because this process implies the potential of industrial upscaling to a continuous production of ultrafine-grained (UFG) metallic sheets or plates [21]. In the recent years, the ARB process was used to produce many multilayer composites with different and similar materials such as Al/Cu [24], Al/Zn [25], Al/Mg [26], Al/Ni [27], Cu/Ni [28] and Al/Ti [29]. Also, there were limited researches in producing metal matrix composites by more than two different material that it can be noted Al/Ti/Mg [30], Al/Zn/Cu [31] and Al/Ti/Nb [32] and Al/Ni/Cu [33].

In the present study, Al/Cu/Mg multilayer composite were produced by ARB process through seven passes at the room temperature without using lubricant. Then, the microstructure and mechanical properties of the produced multi-layered composite were evaluated after different ARB cycles.

2. Experimental Procedure

2.1 Materials

The materials employed in this study include commercially pure Al, Copper, and AZ31B Mg alloy. Table 1 demonstrates chemical composition, mechanical properties and primary dimension of these materials.

Table 1. Specifications of primary materials

Material	Chemical Composition (%)	Ultimate tensile strength (MPa)	Micro hardness (HV)	Primary dimension (mm)
Al 1050	Al 99.17, Mg 0.05, Fe 0.4, Cr 0.2, Si 0.25, Mn 0.05, Zn 0.05, Ti 0.03	110.5	34	120*50*1
Pure Cu	Cu 99.9, Fe 0.006 and other element were balanced	179.5	74.5	120*50*1
Mg AZ31B	Mg 95.8, Al 3, Zn 1, Mn 0.2	170.35	67.3	120*50*1.5

2.2 ARB process

Fig. 1(a) demonstrates the schematic illustration for producing a primary sandwich. At first, a primary sandwich was fabricated, and then the accumulative roll bonding process was carried out. To fabricate the primary sandwich, at first, six aluminum sheets, one Cu sheet, and one Mg sheet were prepared at same dimensions. Then, these sheets were degreased in acetone, dried in the air, and were scratch brushed and stacked on each other as shown in Figs. 1(a). Then, the sheets were assembled as a sandwich stack. To prevent slippage, the stack was clamped using copper wires at the edges. Finally, a 60% reduction in thickness was applied to fabricate the primary sandwich. The thickness of the sandwich stacks reached 8.5 mm from 3.1 mm using the rolling process at room temperature as shown in Figs. 1(a). Also, the real samples of the prepared stacked and the produced primary sandwich shown in Figs 2(a) and 2(b).

Fig. 1(b) demonstrates the schematic illustration of the ARB process. The surface preparation was performed in the multi-steps such as degreasing by acetone, drying in the air, and roughening by circular stainless steel wire brush. Finally, the roll-bonded sheets with a 50% reduction in thickness value were created after clamping. The ARB process was repeated for seven cycles. The process was performed using a laboratory rolling mill with 107 mm in roller diameters at room temperature, in which no lubricant was used. After the seventh pass, a multilayer composite with 1024 layers was processed (Fig 1(c)).

2.3 Microstructure

The microstructures of the processed specimens after different ARB cycles were evaluated by optical microscopy (OM). Specimens after each pass were cut using a wire cut electro discharge machining in the parallel to

the rolling direction. Then, they were grinding using the sandpaper numbers 100 to 5000 and they were also polishing by use of a mixture of alumina powder with a particle size of 0.3 μm , water, and soap. Finally, polishing by alcohol and alumina without using water was done to remove the magnesium oxide layers. Also, tensile fracture surfaces after uniaxial tensile test were viewed using the scanning electron microscope (SEM) model VEGA TESCAN. XRD measurements were carried out on the RD–TD plane of the ARB processed sheets. The XRD experiments were performed by an X-ray diffractometer (XRD, Bruker Advance D8) using Cu $k\alpha$ radiation ($\lambda=0.15406$ nm). The X-ray was operated at 40 kV, 0.5 Step Size and 40 mA and the data were collected at room temperature with a 2θ range between 30 and 90. The Williamson–Hall formula and X'Pert High Score software were used to analyze the XRD data.

2.4 Mechanical properties

Mechanical properties of Al/Cu/Mg multi-layered composite fabricated through the ARB process were investigated by uniaxial tensile tests and microhardness measurements. The uniaxial tensile test samples were prepared for the unprocessed sheets and ARB processed sheets oriented along the rolling direction according to the JISZ2201 standard. The gauge length and width of the tensile test specimens were 11.6 and 3 mm, respectively. The uniaxial tensile tests were performed at an initial strain rate of 0.5 mm/min at room temperature using SANTAM tensile testing machine. The Vickers microhardness tests were done for initial, and ARBed samples using JENUS apparatus under a load of 200 gr applied for 10 s. Microhardness tests had been implemented to the aluminum, copper and magnesium layers at ten different points randomly on the cross-sections perpendicular to the rolling direction. Then, for each aluminum, copper and magnesium layers, the minimum and maximum hardness values were disregarded.

3. Results and discussion

3.1 Microstructure

Fig. 3 illustrates the microstructure of Al/Cu/Mg multi-layered composite after the ARB process. The difference in the flow properties of the metal matrix and reinforcing causes, occurrence of the plastic instability (fracture and necking) during processing by ARB process [30, 31]. By increasing the applied strain, the plastic instability was observed in the copper and magnesium layers (Fig. 3a and 3c). Copper layers were continuous and coherent in an aluminum matrix at the end of the first cycle, but the plastic instability was observed in the magnesium layers of the primary sandwich. Due to high formability and work hardening of aluminum compared to both reinforcing layers (copper and magnesium), the large plastic strain was applied to aluminum and also high reduction thickness was observed in the aluminum layers with significantly work hardening. However, reinforcing layers deformed harder than aluminum layers and inevitably, bearing plastic instability. In the last investigations reported that reinforcing distribution was non-uniform in the early ARB passes due to non-uniform strain because of friction between the roller and sample and also between layers due to the difference in flow properties [24, 30, 34]. By increasing the number of ARB cycles, the difference of flow properties between matrix (aluminum) and

reinforcing (copper and magnesium) reduced. This caused to prepare a multi-layered composite with a uniform distribution of both Cu and Mg layers within the Al matrix (Fig. 3h).

Fig. 4 demonstrates the thickness variations for both copper and magnesium reinforcing layers at different passes of the ARBed Al/Cu/Mg composite. Because of applying high strains, the thickness of copper and magnesium layers at the early ARB passes decreased sharply. Then, the thickness of copper and magnesium layers reduced with a lower slope because of fracturing layers and reducing the formability [24, 30, 34]. It can be seen that the highest rate of thickness reduction of magnesium and copper layers occurred at the first and second pass, respectively. Finally, the thicknesses of copper and magnesium layers of 1000 and 1500 μm at the initial sample were reduced to ~ 18 and 30 μm after the seventh cycle of ARB process, respectively.

Fig. 5 shows the typical XRD patterns of Al/Cu/Mg composite after a primary sandwich and seven ARB cycles. XRD analysis showed that by increasing the number of ARB cycles, new peak was not added to previous peaks and that showed, there was not a new phase or a new combination. This phenomena was predictable since the production of composites was at room temperature. Also, due to low strain rates and relatively low speed of roller mill, much heat did not create and this heat was less than the activation energy necessary to produce the intermetallic compounds [35]. Crystallite size for the Al matrix after a primary sandwich rolling and seventh ARB cycle were determined to be 208 and 132 nm, respectively. Deformation mechanisms in the microstructures of multi-phase materials exhibit strong obstacles against the movement of dislocations because of different interfaces between the phases [36]. According to the conducted research at the ARB process, the structural changes and creating ultrafine grains were independent of the type of metals, and also the average of grain size for the different materials were different [22]. These differences could be attributed to stacking fault energy, processing temperature, strain rate, and so on. During the severe plastic deformation at the low temperatures, the boundaries areas with high deviation angle were created by two mechanisms: a) expansion borders that existed from the beginning in the material and b) the production of new high-angle boundaries by dividing grain [37, 38].

3.2 Mechanical properties

Fig. 6 illustrates the microhardness variation of copper, magnesium and aluminum layers individually at various ARB passes. As shown, it is apparent that by increasing the number of the ARB passes, microhardness of all layers (copper, magnesium, and aluminum) increased. The microhardness values of Cu, Al and Mg layers after the first pass were increased about 1.86, 1.77, and 1.6 times compared to the initial samples, respectively. Accordingly, a sharp rise in the microhardness at the early cycles of ARB process could be attributed to the work hardening, dislocations density increasing and the formation of a new subgrain boundaries [24, 25, 33, 39]. Then, by increasing the number of ARB passes from the second to the fifth pass, it led to increase in the value of microhardness of all layers. Though, the rate of microhardness increase was less than early cycles. This may be because, the work hardening and grain refinement were larger at early cycles of SPD processing [40, 41]. At the intermediate passes, the rate of work hardening was less than the initial passes [4, 33]. Finally, from the fifth to the seventh passes, the

microhardness reached a saturated value resulted from saturation in the grain size. At the last pass, the value of microhardness of aluminum, copper and magnesium layers reached to 77.4HV, 146.1HV and 121.5HV, respectively. By comparing them with the initial samples, the value of microhardness of aluminum, copper and magnesium layers increased 2.15, 1.96 and 1.80 times, respectively. The main reason of increasing microhardness was grain refinement [24, 25, 33, 39].

The engineering stress–strain curves of initial unprocessed strips were displayed in Fig 7. Also, the engineering stress–strain curves of the multilayer composite Al/Cu/Mg after the ARB process were shown in Fig. 8. By raising the number of the ARB cycles, the strength increased and the elongation decreased at first and then the elongation increased. Fig. 9 demonstrates the variation of tensile strength and elongation of the multilayer composite Al/Cu/Mg processed by ARB through different cycles. The tensile strength increased continuously up to seventh cycle. The maximum value of the tensile strength was achieved after the last cycle of ARB process and it was reached 355.5 MPa. This strength value was 3.2, 2 and 2.1 times higher than that of the initial aluminum, copper and magnesium sheets, respectively. Also, at first, from the primary sandwich, the elongation decreased and then it increased continuously up to seventh cycle. Researchers reported that several major factors, including work hardening, grain refinement, shape, type and size of the particles, the amount of applied deformation, quality of bonding layers, and distribution of reinforcements [4, 25, 33, 39, 42] could have effects on changes of the tensile strength of metal matrix composites. At the early ARB passes, strengthening was mainly due to work hardening, the formation of low angle subgrain boundaries and increasing the density of dislocations [4, 24, 25, 33, 43]. Then, the mechanism of strengthening was mainly due to grain refinement. At the last cycle of ARB process, the value of strength increased due to the fine-grained microstructure and the distribution of the copper reinforcements.

Table 2 compares the strength and ductility of multilayered Al/Cu/Mg composite achieved from the present study with those from previous works. It could be realized from Table 2 that the elongation of composite without using particle reinforcement was higher than that of with using particle reinforcement because the strength of interfaces of powder/metal was weaker. The powder/metal interface was good places for germination of crack and defects for initiation of fracture. It could also be realized that using two phase hcp structure caused further reduce of the elongation. Also, higher ductility was obtained from Al/Cu/Mg ARB processed composite in comparison with those from previous studies. The reason for this was probably due to the grain refinement, and higher bond strength between the layers which was almost more than previous studies, including Al/Ti/Mg, Al/Cu/Ni, Al/Cu/Mn, Al/Cu/Al₂O₃ and Al/Cu.

Table 2. The comparison of strength and ductility of the multilayered composite obtained in present study with those from previous works.

Materials	Maximum value of UTS (MPa)	Maximum value of El (%)	ARB cycle	Reference
-----------	-------------------------------	----------------------------	-----------	-----------

Al/Cu/Mg	355.5	8.4	7	This study
Al/Ti/Mg	335.9	2.3	4	[30]
Al/Cu/Ni	346	7.8	11	[33]
Al/Cu/Zn	290	15	4	[31]
Al/Cu/Mn	355	6.9	9	[4]
Al/Cu/Al ₂ O ₃	361	5	7	[42]
Al/Cu	365	7.93	5	[24]
Al/Cu	385.5	7.3	7	[44]

3.3 Fractography

Fig. 10 illustrates the tensile fracture surfaces of Cu and Mg sheets after the uniaxial tensile testing. The basic fracture mechanism of Al, Cu, and Mg was a ductile, ductile, and brittle fracture, respectively. The basic fracture mechanism of the most coarse-grained metals with fcc and hcp crystal structures were ductile and brittle fractures, respectively [30]. Fig. 11 shows the tensile fracture surfaces of Al/Cu/Mg multi-layered composite at Al, Cu, and Mg layers after the primary sandwich. As shown, debonding was seen between interfaces of Al/Mg at the primary sandwich. Also, lamellar structure exhibited up to the fourth cycles, (see Fig 11(c)). By increasing the number of ARB cycles, bonding between layers was stronger, and it could also be seen that lamellar structure decreased, though still lamellar structure was considered after sixth and seventh cycles [42]. It could also be seen that the fracture surfaces at the seventh pass exhibited shear ductile mode [30].

4. Conclusions

In the present study, Al/Cu/Mg multi-layered composite was fabricated through the accumulative roll bonding process up to seven cycles, and the results were concluded as follows:

- Plastic instability was observed in the magnesium and copper layers of the primary sandwich and second cycles, respectively.

- The thickness of copper and magnesium layers from 1000 and 1500 μm of the initial sample was reduced to ~ 18 and $30 \mu\text{m}$ after the seventh cycle of ARB cycles, respectively.
- By increasing the number of ARB cycles to the seventh cycle, the multi-layered composites with 1024 layers, Cu and Mg uniform distribution were processed.
- By increasing the number of ARB cycles, the values of microhardness for third aluminum, copper and magnesium layers were increased.
- The tensile strength of the sandwich was enhanced continually, and the maximum value of 355.5 MPa was achieved.
- The tensile fracture surfaces of the produced composite from second to fourth pass were a lamellar structure with depending on the interfaces and the fracture mechanism changed to shear ductile for aluminum finally.

References

- [1] D. B. Miracle, S. L. Donaldson, S. D. Henry, C. Moosbrugger, G. J. Anton, B. R. Sanders, N. Hrivnak, C. Terman, J. Kinson and K. Muldoon, *ASM handbook*: ASM International Materials Park, OH, USA, 2001.
- [2] M. H. Vini, M. Sedighi, M. Mondali, Mechanical properties, bond strength and microstructural evolution of AA1060/TiO₂ composites fabricated by warm accumulative roll bonding (WARB), *Int. J. Mater. Res.*, 108(2017), No. 1, p. 53.
- [3] H. Rahimi, M. Sedighi and R. Hashemi, Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, *Part L: J. Mater. Des. Appl.*, (2016). Doi: 10.1177/1464420716655560
- [4] M. Alizadeh and M. Samiei, Fabrication of nanostructured Al/Cu/Mn metallic multilayer composites by accumulative roll bonding process and investigation of their mechanical properties, *Mater. Des.*, 56(2014), p. 680.
- [5] K. Wu, H. Chang, E. Maawad, W. Gan, H. Brokmeier and M. Zheng, Microstructure and mechanical properties of the Mg/Al laminated composite fabricated by accumulative roll bonding (ARB), *Mater. Sci. Eng., A*, 527(2010), No. 13, p. 3073.
- [6] P. Asadi, G. Faraji and M. K. Besharati, Producing of AZ91/SiC composite by friction stir processing (FSP), *Int. J. Adv. Manuf. Technol.*, 51(2010), No. 1-4, p. 247.
- [7] G. Faraji, O. Dastani and S. A. A. Mousavi, Effect of process parameters on microstructure and micro-hardness of AZ91/Al₂O₃ surface composite produced by FSP, *J. Mater. Eng. Perf.*, 20(2011), No. 9, p. 1583.
- [8] R. Z. Valiev, R. K. Islamgaliev and I. V. Alexandrov, Bulk nanostructured materials from severe plastic deformation, *Progress. Mater. Sci.*, 45(2000), No. 2, p. 103.
- [9] R. Z. Valiev and T. G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, *Progress. Mater. Sci.*, 51(2006), No. 7, p. 881.
- [10] R. Z. Valiev, N. Krasilnikov and N. Tsenev, Plastic deformation of alloys with submicron-grained structure, *Mater. Sci. Eng., A*, 137(1991), p. 35.

- [11] A. Azimi, S. Tutunchilar, G. Faraji and M. B. Givi, Mechanical properties and microstructural evolution during multi-pass ECAR of Al 1100–O alloy, *Mater. Des.*, 42(2012), p. 388.
- [12] G. Sakai, Z. Horita and T. G. Langdon, Grain refinement and superplasticity in an aluminum alloy processed by high-pressure torsion, *Mater. Sci. Eng., A*, 393(2004), No. 1, p. 344.
- [13] A. P. Zhilyaev and T. G. Langdon, Using high-pressure torsion for metal processing: fundamentals and applications, *Progress. Mater. Sci.*, 53(2008), No. 6, p. 893.
- [14] Z. Horita, D. J. Smith, M. Furukawa, M. Nemoto, R. Z. Valiev and T. G. Langdon, An investigation of grain boundaries in submicrometer-grained Al-Mg solid solution alloys using high-resolution electron microscopy, *J. Mater. Res.*, 11(1996), No. 08, p. 1880.
- [15] J. Yin, J. Lu, H. Ma and P. Zhang, Nanostructural formation of fine grained aluminum alloy by severe plastic deformation at cryogenic temperature, *J. Mater. Sci.*, 39(2004), No. 8, p. 2851.
- [16] A. Babaei, G. Faraji, M. Mashhadi and M. Hamdi, Repetitive forging (RF) using inclined punches as a new bulk severe plastic deformation method, *Mater. Sci. Eng., A*, 558(2012), pp. 150.
- [17] G. Faraji, K. Abrinia, M. Mashhadi and M. Hamdi, An upper-bound analysis for frictionless TCAP process, *Arch. Appl. Mech.*, 83(2013), No. 4, p. 483.
- [18] G. Faraji, M. M. Mashhadi and H. S. Kim, Tubular channel angular pressing (TCAP) as a novel severe plastic deformation method for cylindrical tubes, *Mater. Lett.*, 65(2001), No. 19, p. 3009.
- [19] M. Richert, H. Stüwe, J. Richert, R. Pippan and C. Motz, Characteristic features of microstructure of ALMg5 deformed to large plastic strains, *Mater. Sci. Eng., A*, 301(2001), No. 2, p. 237.
- [20] J. Richert and M. Richert, A new method for unlimited deformation of metals and alloys, *Al.*, 62(1986), No. 8, p. 604.
- [21] Y. Saito, H. Utsunomiya, N. Tsuji and T. Sakai, Novel ultra-high straining process for bulk materials—development of the accumulative roll-bonding (ARB) process, *Acta Mater*, 47(1999), No. 2, p. 579.
- [22] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai and R. Hong, Ultra-fine grained bulk aluminum produced by accumulative roll-bonding (ARB) process, *Scr. Mater.*, 39(1998), No. 9, p. 1221.
- [23] H. Pirgazi, A. Akbarzadeh, R. Petrov and L. Kestens, Microstructure evolution and mechanical properties of AA1100 aluminum sheet processed by accumulative roll bonding, *Mater. Sci. Eng., A*, 497(2008), No. 1, p. 132.
- [24] M. Eizadjou, A. K. Talachi, H. D. Manesh, H. S. Shahabi and K. Janghorban, Investigation of structure and mechanical properties of multi-layered Al/Cu composite produced by accumulative roll bonding (ARB) process, *Comp. Sci. Technol.*, 68(2008), No. 9, p. 2003.
- [25] R. N. Dehsorkhi, F. Qods and M. Tajally, Investigation on microstructure and mechanical properties of Al–Zn composite during accumulative roll bonding (ARB) process, *Mater. Sci. Eng., A*, 530(2011), p. 63.
- [26] H. Chang, M. Y. Zheng, C. Xu, G. D. Fan, H. G. Brokmeier and K. Wu, Microstructure and mechanical properties of the Mg/Al multilayer fabricated by accumulative roll bonding (ARB) at ambient temperature, *Mater. Sci. Eng., A*, 543(2012), p. 249.
- [27] A. Mozaffari, H. Danesh Manesh and K. Janghorban, Evaluation of mechanical properties and structure of multilayered Al/Ni composites produced by accumulative roll bonding (ARB) process, *J. Alloys Compd*, 489(2010), No. 1, p. 103.

- [28] M. Tayyebi and B. Eghbali, Study on the microstructure and mechanical properties of multilayer Cu/Ni composite processed by accumulative roll bonding, *Mater. Sci. Eng., A*, 559(2013), p. 759.
- [29] H. P. Ng, T. Przybilla, C. Schmidt, R. Lapovok, D. Orlov, H.-W. Höppel and M. Göken, Asymmetric accumulative roll bonding of aluminium–titanium composite sheets, *Mater. Sci. Eng., A*, 576(2013), p. 306.
- [30] P. D. Motevalli and B. Eghbali, Microstructure and mechanical properties of Tri-metal Al/Ti/Mg laminated composite processed by accumulative roll bonding, *Mater. Sci. Eng., A*, 628(2015), p. 135.
- [31] M. M. Mahdavian, L. Ghalandari and M. Reihanian, Accumulative roll bonding of multilayered Cu/Zn/Al: An evaluation of microstructure and mechanical properties, *Mater. Sci. Eng., A*, 579(2013), p. 99.
- [32] R. Zhang and V. L. Acoff, Processing sheet materials by accumulative roll bonding and reaction annealing from Ti/Al/Nb elemental foils, *Mater. Sci. Eng., A*, 463(2007), No. 1–2, p. 67.
- [33] A. Shabani, M. R. Toroghinejad and A. Shafyei, Fabrication of Al/Ni/Cu composite by accumulative roll bonding and electroplating processes and investigation of its microstructure and mechanical properties, *Mater. Sci. Eng., A*, 558(2012), p. 386.
- [34] G. Min, J.-M. Lee, S.-B. Kang and H.-W. Kim, Evolution of microstructure for multilayered Al/Ni composites by accumulative roll bonding process, *Mater. Lett.*, 60(2006), No. 27, p. 3255.
- [35] R. Snyder, R. Jenkins, Introduction to X-ray powder diffractometry: Wiley-Interscience, 2012.
- [36] A. Pineau, A. A. Benzerga and T. Pardoen, Failure of metals III. Fracture and fatigue of nanostructured metallic materials, *Acta Mater.*, (2015).
- [37] Z. Xing, S. Kang and H. Kim, Structure and properties of AA3003 alloy produced by accumulative roll bonding process, *J. Mater. Sci.*, 37(2002), No. 4, p. 717.
- [38] N. Hansen, X. Huang, R. Ueji and N. Tsuji, Structure and strength after large strain deformation, *Mater. Sci. Eng., A*, 387(2004), p. 191.
- [39] A. Mozaffari, H. D. Manesh and K. Janghorban, Evaluation of mechanical properties and structure of multilayered Al/Ni composites produced by accumulative roll bonding (ARB) process, *J. Alloys Compd.*, 489(2010), No. 1, p. 103.
- [40] H. Abdolvand, G. Faraji, M. B. Givi, R. Hashemi, M. Riazat, Evaluation of the microstructure and mechanical properties of the ultrafine grained thin-walled tubes processed by severe plastic deformation, *Met. Mater. Int.*, 21(2015), No. 6, p. 1068.
- [41] G. Faraji, M. Mashhadi, A. Bushroa and A. Babaei, TEM analysis and determination of dislocation densities in nanostructured copper tube produced via parallel tubular channel angular pressing process, *Mater. Sci. Eng., A*, 563(2013), p. 193.
- [42] V. Y. Mehr, A. Rezaeian and M. R. Toroghinejad, Application of accumulative roll bonding and anodizing process to produce Al–Cu–Al₂O₃ composite, *Mater. Des.*, 70(2015), p. 53.
- [43] M. Sedighi, M. H. Vini and P. Farhadipour, Effect of Alumina Content on the Mechanical Properties of AA5083/Al₂O₃ Composites Fabricated by Warm Accumulative Roll Bonding, *Powder Metall. Met. Ceram.*, 55(2016), No. 7-8, p. 413.

Preprint of: [Davood Rahmatabadi](#) , Moslem Tayyebi, Ramin Hashemi & Ghader Faraji. (2018). Microstructure and mechanical properties of Al/Cu/Mg laminated composite sheets produced by ARB process. International Journal of Minerals, Metallurgy and Materials. DOI: [10.1007/s12613-018-1603-x](#)

- [44] V. Y. Mehr, M. R. Toroghinejad and A. Rezaeian, Mechanical properties and microstructure evolutions of multilayered Al–Cu composites produced by accumulative roll bonding process and subsequent annealing, *Mater. Sci. Eng., A*, 601(2014), p. 40.

Figure 1. Schematic illustration of ARB for processing Al/Cu/Mg multilayered composite.

Figure 2. Primary sandwich (a) after rolling (b) before rolling.

Figure 3. The microstructure of ARB processed Al/Cu/Mg multi-layered composite (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles, (f) fifth cycles (g) sixth cycles and (h) seventh cycles.

Figure 4. Thickness variations of copper and magnesium layers at different cycles of ARB processed Al/Cu/Mg composite

Figure 5. XRD pattern of the nanostructured Al/Cu/Mg metallic multilayer composite after primary sandwich and seven ARB cycle.

Figure 6. Microhardness variation of aluminum copper and magnesium layers individually at different cycles of ARB processing of Al/Cu/Mg composite.

Figure 7. Engineering stress-strain curves of primary materials.

Figure 8. Engineering stress-strain curves of ARB processed Al/Cu/Mg composite.

Figure 9. Variations of the tensile strength and elongation of Al/Cu/Mg composite processed via different cycles of ARB.

Figure 10. Tensile fractured surfaces of initial sheets before ARB process (a) Mg and (b) Cu.

Figure 11. Tensile fractured surfaces of Al/Cu/Mg multi-layered composite: (a) primary sandwich and after (b) first cycle, (c) second cycles (d) third cycles, (e) fourth cycles and (f) fifth cycles.