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Mechanical and Wear Properties of Al-Ni_p Composites Produced by ARB Process

H. Baharipour, H. Danesh Manesh* and F. Ghanbari Mardasi
Department of Materials Science and Engineering, School of Engineering, Shiraz University, Shiraz, Iran

Abstract: In this research, Al-Ni particle composite strips are formed by accumulative roll bonding (ARB) process using Al strips and Ni powder. The rule of ARB cycles and volume percentage (Vol%) of Ni powder on the microstructure, wear resistance and mechanical properties of the formed composites are investigated. According to the tensile test results, the yield stress and tensile strengths of the Al -Ni $_{(p)}$ composites tend to increase with rising of the ARB cycles. Ductility of the ARB samples significantly decreased in the first cycle of the ARB process and then elevated lightly from the second pass of the ARB. Furthermore, the yield stress and tensile strengths of the Al - Ni (p) composites with different vol% of Ni powder, increased with increasing the amount of Ni Powder. Also the hardness and wear resistance of produced composites were investigated. Micro hardness and wear resistance of these composites increased with increasing the number of ARB cycles and the amount of Ni particles content during ARB Process.

Keywords: Accumulative roll bonding (ARB), Metal matrix composites (MMCs), Particle-reinforcement, Electron microscopy

1. Introduction

Aluminum is the second most plentiful metallic element on earth and it is well suited for many of the engineering applications due to its light weight, appearance, mechanical properties, and ease of fabrication. However, pure Al is extremely poor in strength and hardness and this is one of the major limitations as far as the end application is concerned. There are many established ways to improve the strength and hardness of Al, such as: precipitation hardening, dispersion hardening and composite hardening [1].

Herein, Al metal matrix composites are considered as a group of new advanced materials due to their light weight, high strength, high specific modulus, low coefficient of thermal expansion and good wear resistance properties [2]. A combination of these excellent properties is not available in a conventional material [2, 3]. In this respect, SiC, Al_2O_3, TiC and B_4C particles have been used as ceramic reinforcement particles to produce Al metal matrix composites [4, 5]. These composites can be produced by different manufacturing methods, most of which have high product cost. Therefore, it becomes an essential task to establish new manufacturing method to produce these composites with economical cost [6]. ARB seems to be an excellent alternative method in which recently has been utilized for production of Al/Ni metal matrix composite [7]. The most advantage of this method is its ability to create high strengths ultra-fine grain structures composite sheets form [6]. Kitazono et al. [8] used this method to impose TiH_2 particles into the aluminum matrix in order to manufacture the closed - cell aluminum foams. Mozaffari et al. [7] produced ultra-fined grain structure metal matrix composites by ARB method. The ARB process consists of two steps. First, roll bonding carries out to impose appropriate particles reinforcement into the base metal. For this purpose, the sheets degrease and scratch brushes, the powder deposits on the lower sheet

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*Corresponding author (daneshma@shirazu.ac.ir)

surface and then the sheets are stacked and roll bonded. At the second step, accumulative roll bonding process carries out to improve the dispersion of particles reinforcement in the metal matrix to create an ultra-fined grain structure [7, 9, 10].

The aim of the present work is to evaluate the feasibility of the ARB process for fabricating ultra-fined grain Al base composites with submicron Ni particles and then evaluates hardness, strength, wear resistance and micro structure of the products.

2. Experimental Procedure

2.1. Materials used

In this research, 1050 Al alloy strips with length of 250 mm, width of 50 mm and 1mm thickness were used as metal matrix and a pure grade Ni powder with an average particle size of 60 µm was prepared as reinforced particles. Figure 1 shows the SEM image (BS) of Ni powder and Table 1 illustrates the chemical composition of the Al strip.

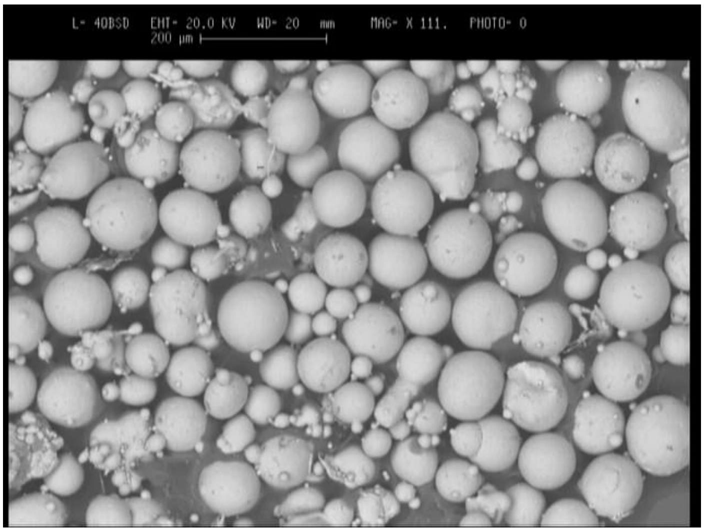

Fig. 1. SEM image of the used Ni powder.

Table 1. specification of the used aluminum strips.

Al	Si	Fe	Bi	Cu	Mn	element
99/5	0/04	0/12	0/1	0/005	<0/001	٪ percent

2.2. Accumulative Roll Bonding Process

Accumulative roll bonding (ARB) method was used to fabricate the Al-Ni $_{(p)}$ composites. For this proposal, first the strips were degreased by acetone and scratch brushed with a 90 mm diameter stainless steel circumferential brush equipped with 0.35 mm wire diameter and 14 ms^{-1}surface speed. Then the prepared strips were laid over each other to achieve a 2 mm thick sample, while Ni powders were dispersed between them. Nickel powders were dispersed on the strip surface beneath by mechanical agitation of a 20µm mesh sieve. The both sides of stacked strips were fastened by steel wires and then roll bonded with 66 % reduction in thickness at room temperature. The early investigation confirms that the 66% reduction in thickness is fairly adequate for an appropriate bonding between the two aluminum strips [7]. The roll bonded strips were cut in half, degreased and scratch brushed the same as before. The half strips surfaces were stacked over each other (without any Ni particles between them) and roll bonded by 50% reduction in thickness, Von Misses equivalent strain of 0.8. Figure 2, schematically shows the desired ARB process. After seven cycles of accumulative roll bonding process, the Al matrix composites

with well dispersed Ni particles were produced. The roll passes carried out without any lubrication, by a laboratory rolling mill with 150 mm rolls diameter, 15 RPM rolling speed and 15 tons load capacity.
In order to investigate the rule of Ni particles, three different volume percent of Ni particles (between 1 to 3Vol %) were used.

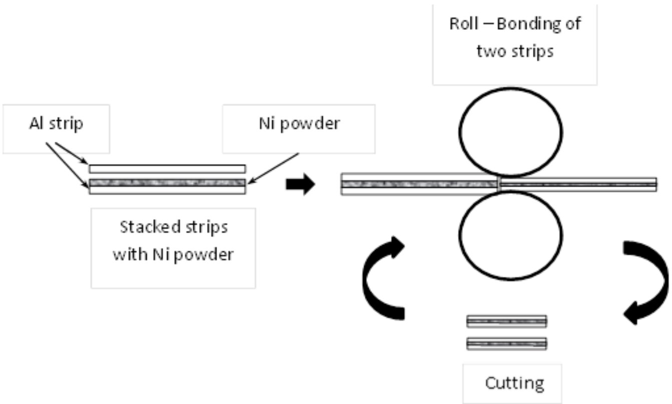

Fig. 2. Schematic illustrations of the ARB process for production of Al/Ni composites.

2.3. Tensile Test

Tensile tests were carried out by a universal testing machine at room temperature at a strain rate of 8.3×10^{-4} s^{-1}. The test samples were prepared according to one fifth of the JIS-5 standard dimensions, oriented along the rolling direction as shown in Fig. 3. The gauge length and the width of the tensile test specimens were 10 and 5 mm, respectively. The true strain incremental and elongation of the specimens were measured from the difference in the gage length.

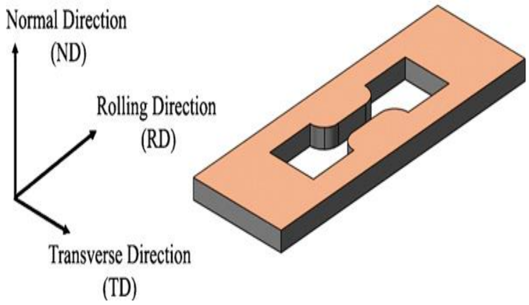

Fig. 3. Orientation of the tension specimens prepared after each ARB cycle.

2.4. Microhardness Test

Vickers microhardness (HV) tests were performed along the transverse direction (RD–ND plane) of the ARB processed samples by using a 25 grams load for 15 sec. The mean value of ten measurements taken at randomly different selected points was reported.

2.5. Wear Test

Friction and wear performance of specimens were evaluated with a pin-on-disc test machine. The 5mm×2mm×10mm dimension samples were prepared by wire cutting from the ARBed samples. A load of 25N was applied with slide speed of 0.04m/s for a distance of 100 m. The used counter face was St52100.

3. Result and Discussion

3.1. Microstructure observation

Figure 4 shows the SEM microstructures of the composites processed with 2Vol. % of $Ni_{(p)}$ after the first, third and seventh cycles of the ARB. All SEM microstructures were observed along the transverse direction (RD–ND plane) of the rolling samples. Figure 4a evidences clearly that the aluminum layers were coherent just in the first cycle of sandwich production and there is one cue of Ni particles between two layers of aluminum strips. Figure 4c obviously indicates that by increasing the number of cycles, the Ni particles is well dispersed uniformly from the interfaces to the bulk of the aluminum matrix and that no any void remains around the Ni particles. In addition the discontinuities between the aluminum layers are disappeared as the result of closure of the porosities in these regions and the aluminum layers are well bounded for the given reduction in thicknesses.

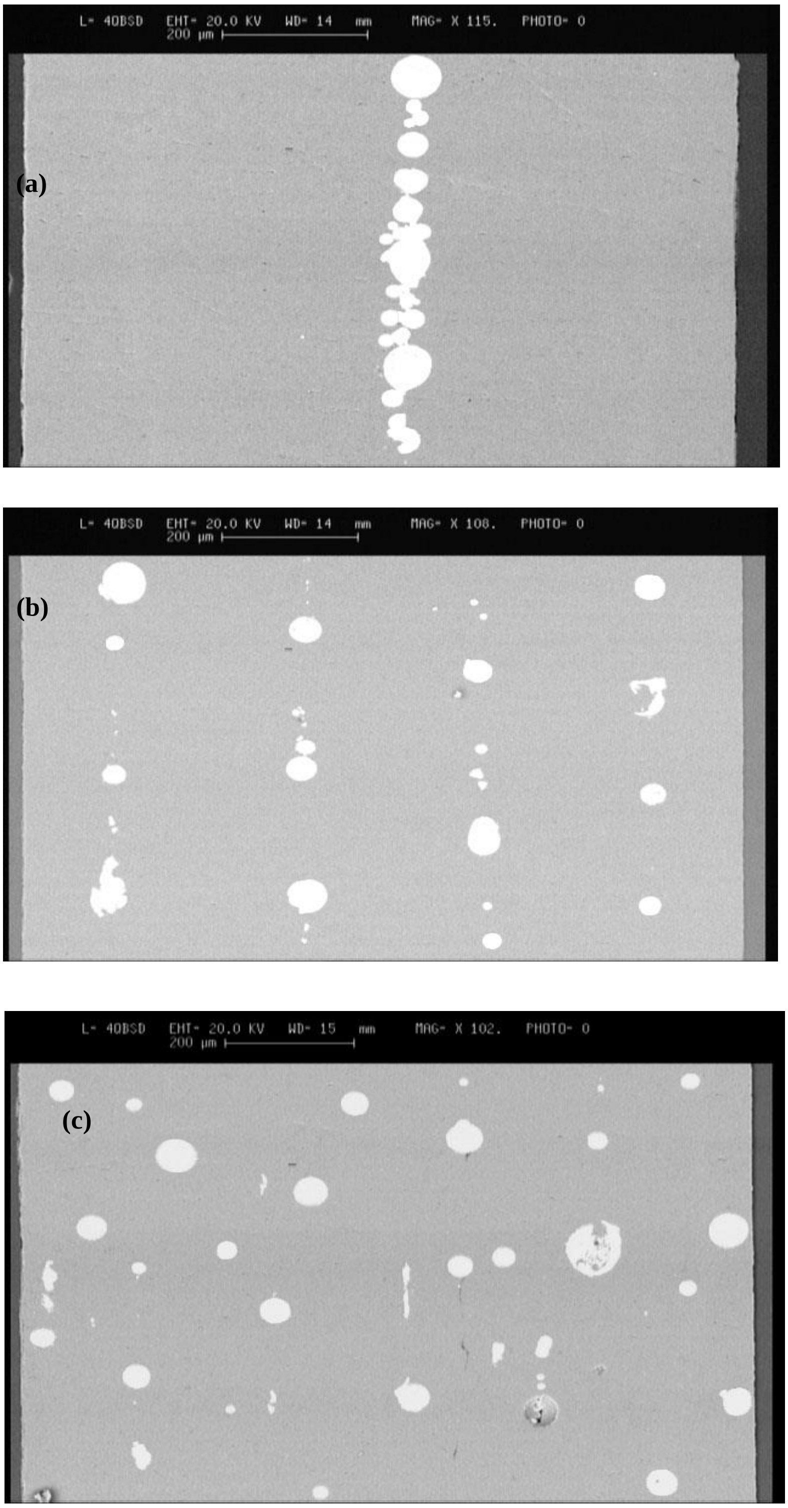

Fig. 4. SEM microstructure of Al/2 Vol % Ni composites after a) the first, b) the third and c) the seventh cycles of ARB process.

3.2. Evaluation of mechanical properties

3.2.1. Effects of ARB Cycles

Figure 5 demonstrates the variations in yield stress, tensile strength and total elongation of produced Al-Ni $_{(p)}$ composites with respect to the ARB cycles for 2 Vol.% amount of Ni $_{(p)}$. Regarding to this figure, the yield stress and tensile strength of the samples increased with increasing of the ARB cycles. The yield stress of the material varies in a similar trend like tensile strength as a function of ARB cycles. It has been reported that strength variations in accumulative roll bonding process are governed by two main strengthening mechanisms: (a) strain hardening by dislocations and (b) grain refinement [11-13]. Strain hardening or dislocation strengthening play a main role in increasing the strength in the initial stages of ARB process, while at higher stages, higher strength is achieved by grain refinement. As a matter of fact, due to formability and hardenability of aluminum, it can say that after the fourth cycle of ARB, the strengthening mechanism is mostly due to the evolution of the grain structure and formation of ultra-fined grains (grain boundary strengthening mechanism) and the strain hardening mechanism becomes less dominant. Also as like as other ARB processed materials [14, 15] the elongation of produced samples decreased intensively, because of declining of dislocations mobility as well as existent of small number of shear bounds. Besides, the cracks can simply formed and propagate at the interfaces between Ni particles and aluminum matrix. This causes the elongation of the composites decreased in compare to pure aluminum. Then again, as Figure 4 shows, a gradual slight rising of elongation by increasing the ARB cycles is observed, because of improving aluminum layer bonding, more uniform Ni particles distribution and elimination of voids around the Ni particles in higher ARB cycles. Moreover, grain refinements, such as dynamic recovery and recrystallization and high angle grains generation can also be a reason of the elongation enhancement by increasing the ARB cycles.

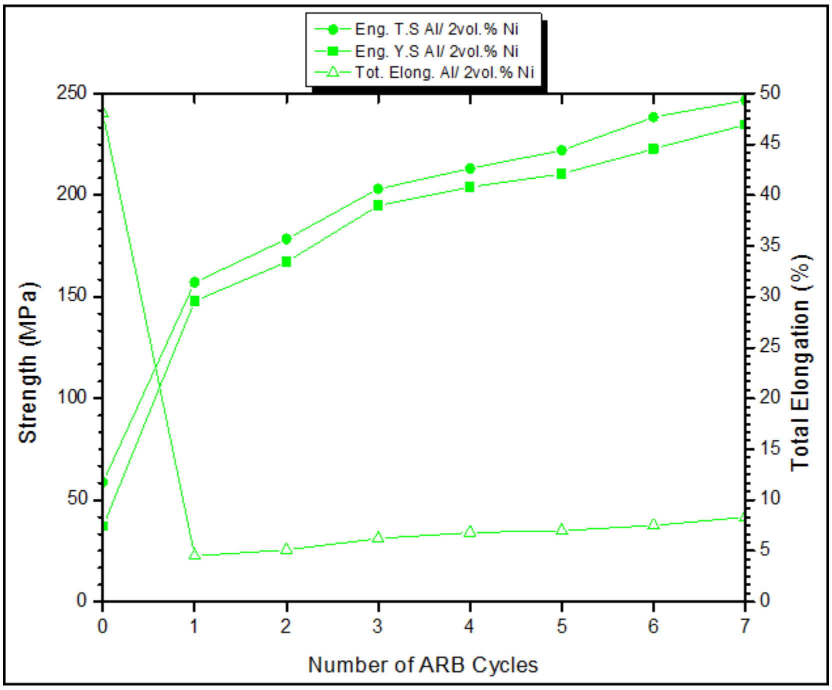

Fig. 5. Variations of tensile strength, yield stress and elongation of Al/ 2 Vol % Ni composite and pure aluminum versus umber of ARB cycles.

3.2.2. Effects of volume percent of Ni $_{(p)}$

The effect of volume percentage of Ni particles on the tensile strength of the roll bounded Al-Ni composites is shown in Fig. 6. Paying attention to this figure, it can be found that the strength of the samples increased with increasing the volume percentage of the Ni particles up to 2 Vol% in all the cycles of ARB, while for higher particle percentage (i.e. 3 Vol%) the tensile strength of the composite falls down noticeably. In fact, the hard and relatively non deformable Ni particles reinforced the aluminum matrix and caused the activation of the slip systems of the aluminum matrix. As the result, the dislocation density and strain hardening of the matrix will increase. In the other words, the existence of the hard Ni particles cause many dislocations to generate at the particle- matrix interfaces and accommodate the strain compatibility between these two phases; consequently this phenomenon increases the tensile strength of the products. Decreasing the tensile strength for 3 Vol% of Ni particles is because of reducing the bonding strength between the aluminum layers.

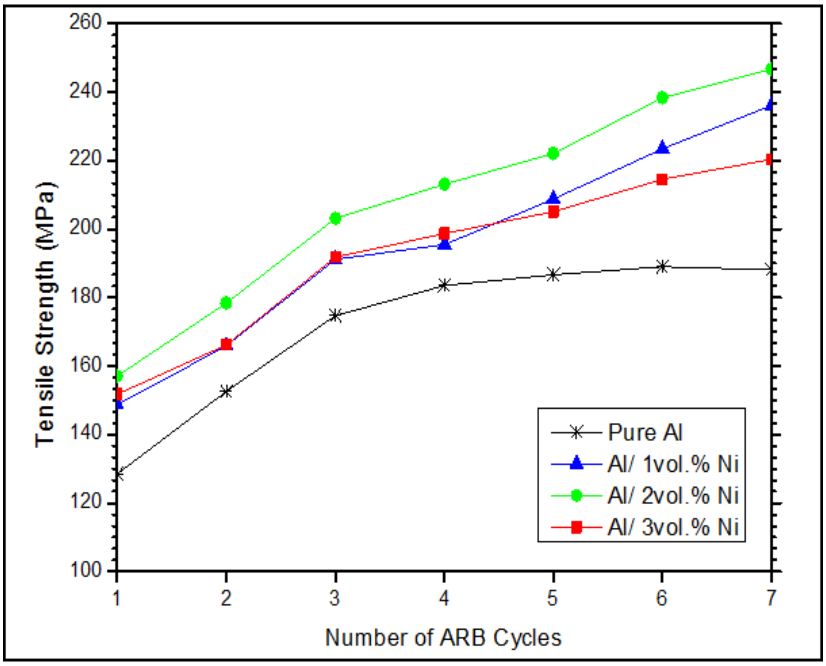

Fig. 6. Variations of tensile strength of produced Al/Ni composites and pure aluminum with number of ARB cycles at different Vol% of Ni particles.

3.3. Evaluation of microhardness

Figurer 7 compares The Vickers microhardness of the pure Al and the Al -Ni composites as a function of the ARB cycles. A remarkable increase in the hardness of all samples can be seen after the first ARB pass. The microhardness of the composite samples is still increasing remarkably for the further ARB passes, while for pure aluminum sample a very little change in hardness is observed with subsequent straining. The rapid increase in the microhardness at relatively low strains (after the first cycle) is attributed to strain hardening and finally saturating at high strains by further ARB cycles. The saturation of the microhardness is reported in ultra-fine grain materials fabricated by severe plastic deformation [11, 16]. This is due to the fact that the materials reached to a steady - state dislocations density [16, 17]. In case of the composites samples, again the existence of the hard Ni particles influence the dislocation generation at the particle-matrix interfaces and causes an extra gradual rise in the microhardness of the samples with further ARB cycles as has happened for the tensile strength of the composite products. Figure 7 also indicates that the microhardness of the composite samples have risen with Vol % of the Ni particles, that expected to be due to the present of larger amount of hard Ni particles in the metal matrix [18].

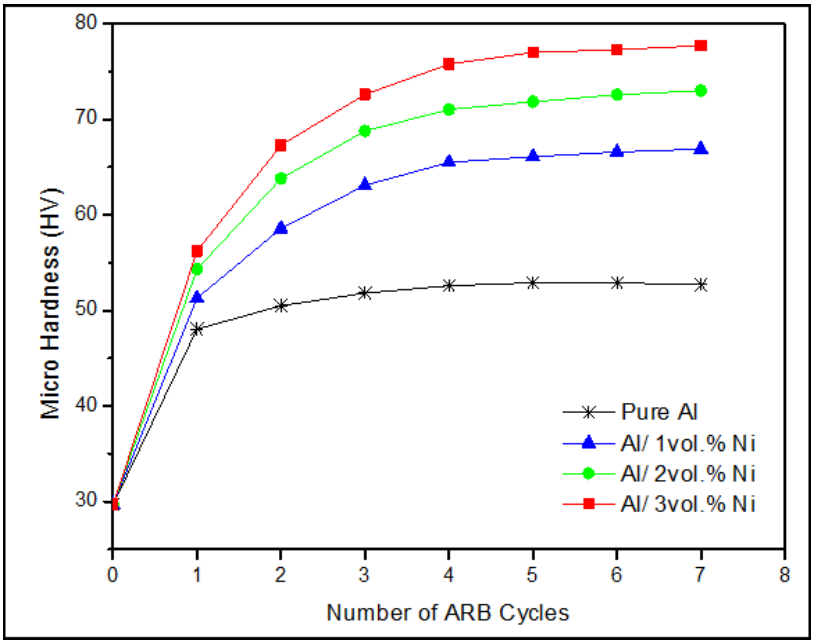

Fig. 7. Variations of microhardness of Al/Ni composites versus ARB cycles.

3.4. Wear properties

Figure 8 shows the wear rate variations of the produced Al -Ni composites and pure aluminum versus number of ARB cycles. Again it can be seen that for both pure and all the composited samples the wear rate increased severely after the first cycle of ARB process. The interesting point is that the trend of wear resistance disparity with the number of ARB cycles is identical in all the samples, so that the wear rate increased rapidly after the first cycle of ARB and decreased gradually up to third pass, then raised gradually once more in the subsequent cycles. Obviously, strain hardening capability, microstructure and evolution of the samples by ARB cycles change wear behaviors of the samples [19, 20]. The decrease of samples ductility after the first pass causes a rapid increment in the wear rate [21]. The wear rate of the ARBed samples is increasing till the third cycle due to increasing of the samples microhardness. Finally from the fourth ARB cycle the wear rate increased gradually because of creation and increasing of non-equilibrium high energy and unstable grain boundaries [22]. The unstable grain boundaries usually have low recrystallization temperature and rotate or coalescence easily with local imposed strain, as can happening on a wearing surface and can cause a rapid growth of the recrystallized grains at the subsurface. If so, there would be a strain incompatibility between the wearing surface with large recrystallized grains and the subsurface with non-equilibrium ultra-fine grain. This incompatibility could cause a delamination of the deformed surface layer which results in a high wear rate. Regarding Figure 8, the wear rate of the samples decreased with increasing the contained of Ni particle at all ARB cycles, this is again due to increasing the hardness of samples with higher Vol % of Ni particles.

The SEM images of the worn surfaces of the aluminum 2 Vol % Ni composite in the first, third and seventh cycles of the ARB process are shown in Fig. 9a-c. The worn surface of a sample with high wear rate capacity shows broad surface deformation traces and scratch marks, while a sample with low wear rate exhibit less surface deformation and scratches. The higher wear rate of the first ARB cycle is due to the low strain hardening effect that causes a thick surface deformation layer during sliding wear and delamination of the deformed layer as shown in Fig. 9a. The surface morphology image of the ARBed sample after the third cycle, Fig. 9b, exhibits the abrasive wear with scratch marks and little surface deformation is observed. The higher wear rate can be seen at the seventh cycle of the ARB process with broad surface deformation traces and few scratch marks (Fig. 9c).

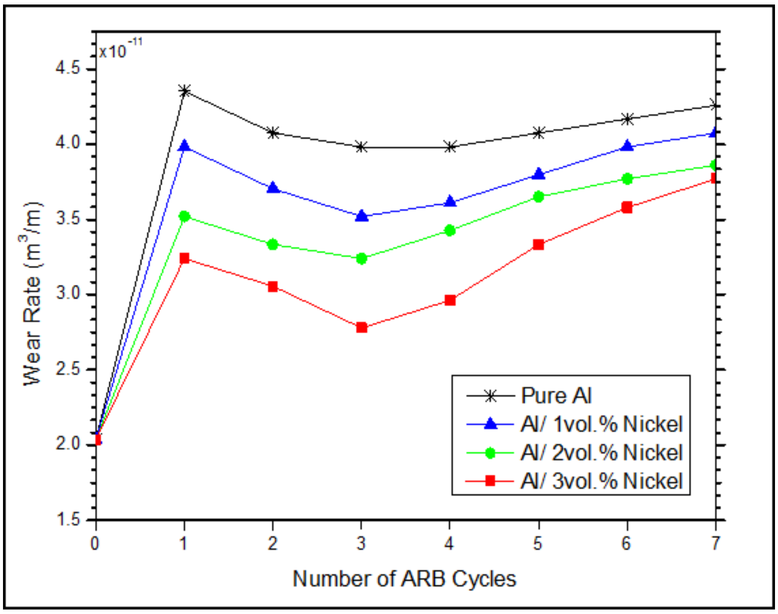

Fig. 8. Variation of wear rate of ARBed Al/Ni composites and pure aluminum with number of ARB cycles.

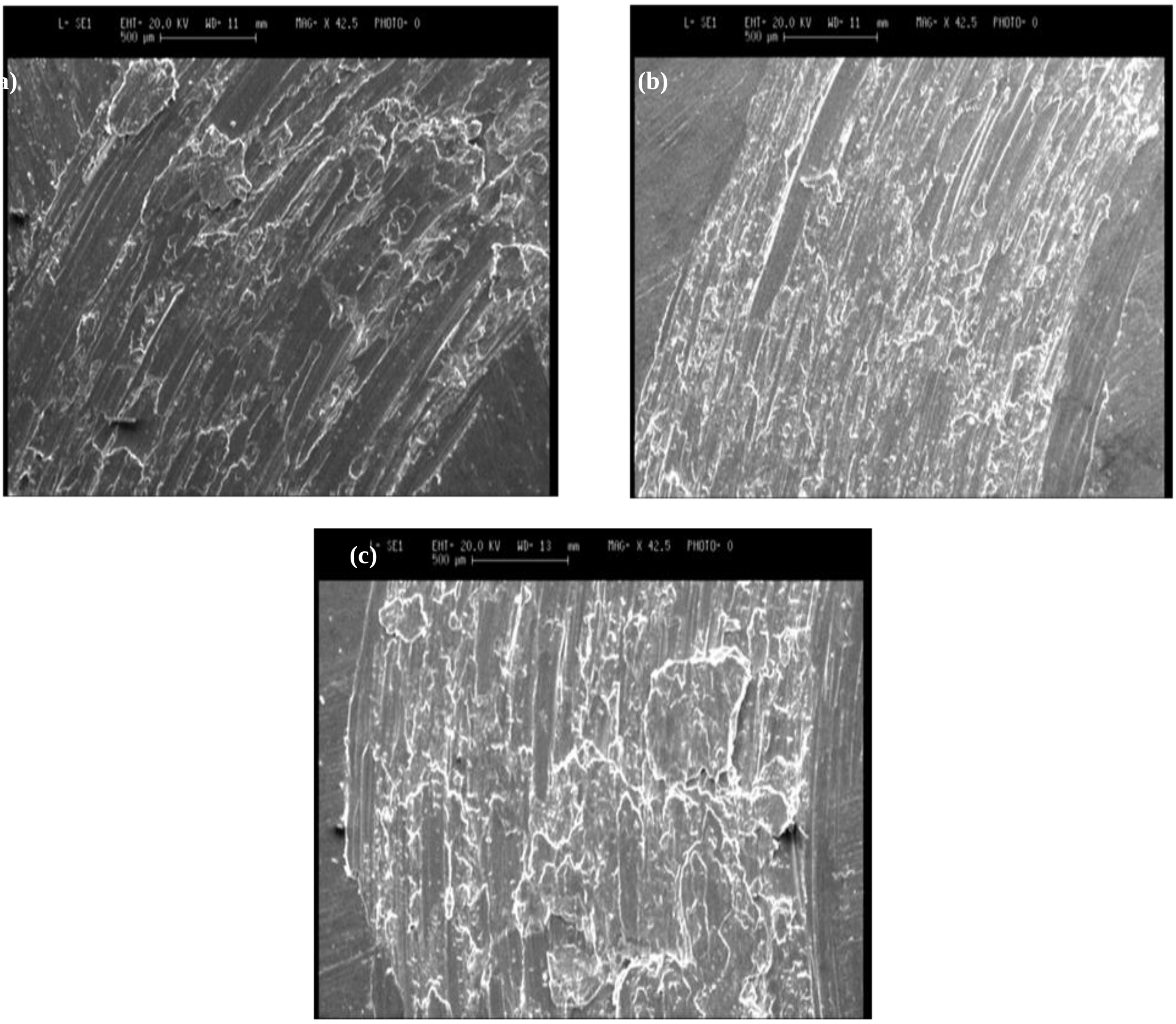

Fig. 9. SEM images of worn surfaces of Al- 2Vol. % Ni composite at a) the first, b) the third and c) the seventh cycles of ARB process.

4. CONCLUSION

In this research, for the first time, the Al-Ni particles composites were produced by Accumulative Roll Bonding process. The following conclusions were achieved:

1- The Ni particles were distributed uniformly in the aluminum matrix with increasing the ARB cycles.

2- The yield stress and tensile strength of the produced composites, for any Vol% of Ni particles, significantly increased at the first ARB cycle and then risen gradually with the ARB cycles up to the seventh cycle.

3- The elongation of the produced composites, for all Vol % of Ni particles, greatly fell down in the first cycle and then increased gradually up to the seventh cycle of the ARB process.

4- The microhardness of produced composites improved with the increase of the ARB cycles and the Vol% of the Ni powders.

5- The wear resistance of the ARBed samples enhanced with ARB cycles up to the third cycle, and then decreased in the further cycles.

5. References

[1] M. F. Ashby and D. R. H. Zones, *Engineering materials*, 2, Butterworth-Heinemann, 2nd edition, (1998).

[2] J.W. Kaczmar, K. Pietrzak and W. Wlosinski, The production and application of metal matrix composite materials, *Journal of Materials Processing Technology*, 106(2000) 58–67.

[3] H.Y. Wang, Q.C. Jiang, Y. Wang, B.X. Ma and F. Zhao, Fabrication of TiB_2 particulate reinforced magnesium matrix composites by powder metallurgy, *Materials Letter*, 58(2004) 3509–3513.

[4] V.K. Lindroos and M.J. Talvitie, Recent advances in metal matrix composites, *Journal of Materials Processing Technology*, 53(1995) 273–284.

[5] M. Alizadeha and M.H. Paydar, High-strength nanostructured Al/B4C composite processed by cross-roll accumulative roll bonding, *Materials Science and Engineering: A*, 538(2012) 14–19.

[6] S. Abis, Characteristics of an aluminium alloy/Alumina Metal Matrix composite, *Composite. Science and Technology*, 35 (1989) 1–11.

[7] A. Mozaffari, M. Hosseini and H. DaneshManesh, Al/Ni metal intermetallic composite produced by accumulative roll bonding and reaction annealing, *Journal of Alloys and Compounds*, 509(2011) 9938– 9945.

[8] K. Kitazono, E. Sato and K. Kuribayashi, Novel manufacturing process of closed-cell aluminum foam by accumulative roll-bonding, *Scripta Materialia*, 50(2004) 495–8.

[9] A. Yazdani, E. Salahinejad, J. Moradgholi and M. Hosseini, A new consideration on reinforcement distribution in the different planes of nanostructured metal matrix composite sheets prepared by accumulative roll bonding (ARB), *Journal of Alloys and Compounds*, 509(2011) 9562–9564.

[10] R. Jamaati and M.R. Toroghinejad, Manufacturing of high-strength aluminum/alumina composite by accumulative roll bonding, *Materials Science and Engineering: A*, 527(16-17) (2010)2320–2326.

[11] Z.P. Xing, S.B. Kang and H.W. Kim, Structure and properties of AA3003 alloy produced by accumulative roll bonding process, *Jornal of Materials Science*, 37(2002) 717–722.

[12] X. Huang, N. Kamikawa and N. Hansen, Strengthening mechanisms in nanostructured aluminum, *Materials Science and Engineering: A*, 483–484 (2008)102–104.

[13] N. Hansen, X. Huang, R. Ueji and R. N. Tsuji, Structure and strength after large strain deformation, *Materials Science and Engineering: A*, 387–389(2004) 191–194.

[14] M. Hosseini and H. Danesh Manesh, Immersed friction stir welding of ultrafine grained accumulative roll-bonded Al alloy, *Materials & Design*, 31(2010) 4786–4791.

[15] M. Alizadeh, M.H. Paydar, Fabrication of nanostructure Al/SiC_P composite by accumulative roll-bonding (ARB) process, *Journal of Alloys and Compounds*, 492(2010) 231–235.

[16] M. Alizadeh, Comparison of nanostructured Al/B_4C composite produced by ARB and Al/B4C composite produced by RRB process, *Materials Science and Engineering: A*, 528(2010) 578–582.
[17] M. Shaarbaf and M.R. Toroghinejad, Nano-grained copper strip produced by accumulative roll bonding process, *Materials Science and Engineering: A*, 473(2008) 28–33.
[18] M. Barmouza, M.K.B. Givia and J. Seyfi, On the role of processing parameters in producing Cu/SiC metal matrix composites via friction stir processing: Investigating microstructure, microhardness, wear and tensile behavior, *Materials Characterization,* 62(2011) 108–117.
[19] Y.S. Kim, J.S. Ha and D.H. Shin, Sliding wear characteristics of ultrafine-grained non-strain-hardening aluminum-magnesium alloys, *Materials Science Forum*., 475–479(2005) 401–404.
[20] Y.S. Kim, T.O. Lee and D.H. Shin, Microstructural Evolution and Mechanical Properties of Ultrafine Grained Commercially Pure 1100 Aluminum Alloy Processed by Accumulative Roll-Bonding (ARB), *Materials Science Forum*, 449–452(2004) 625–628.
[21] M. Eizadjou, H. DaneshManesh, K. Janghorban, Microstructure and mechanical properties of ultra-fine grains (UFGs) aluminum strips produced by ARB process, *Journal of Alloys and Compounds*, 474(2009) 406–415.
[22] A. KazemiTalachi, M. Eizadjou, H. DaneshManesh and K. Janghorban, Wear characteristics of severely deformed aluminum sheets by accumulative roll bonding (ARB) process, *Materials Characterization,* 62(2011) 12–21.