Effect of SiC addition on the mechanical properties and wear behavior of Al-SiC nanocomposites produced by accumulative roll bonding

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Abstract
In this study, we manufactured Al and Al-SiC nanocomposites (SiC vol.% = 1, 2 and 4) using accumulative roll bonding (ARB) at room temperature. Mechanical and wear characteristic of the manufactured samples was studied. The uniform dispersion of SiC particles was achieved after five ARB cycles. The EDX mapping images reveal that the SiC reinforcement particles were homogeneously distributed into the Al matrix. After five ARB cycles, relatively small amount of nano-grains were observed in Al-SiC nanocomposite, indicating the effectiveness of the ARB process of achieving near nanostructure. It was observed that Vickers microhardness improve with increasing accumulative roll bonding cycles. Furthermore after 5 cycles, Vickers microhardness tests results showed that the highest hardness value of 66 HV is attributed to the sample containing 4 vol.% of SiC, much higher than the hardness value of the ARB-processed aluminum of 51 HV. Experimental results indicated that the wear resistance of this nanocomposite improved by increasing the number of ARB cycles due to SiC particles act as a solid lubricant.

1. Introduction

Aluminum and its alloys have been reinforced with ceramics turning into metal matrix composites (MMCs) in order to improve physical and mechanical properties [1–3]. Aluminum-based MMCs are presented widely in many applications such as aircraft, automobiles, shipbuilding, and military industries due to their high strength to weight ratio, low density, high hardness, good wear resistance, and high stiffness [4]. Composites generally possess superior wear behavior compared with unreinforced aluminum alloys, due to the incorporation of ceramic particles into the matrix of the standard alloy. The common reinforcements are SiC [5, 6], TiC [7, 8], Al2O3 [9] and B4C [10] due to the ceramic nature. Al-based metal matrix composites such as Al/SiC composites are widely applied in automotive industry as brake disks, cylinder heads and pistons [11]. Therefore, the wear behavior of this composite received considerable attention [12]. It was demonstrated the addition of ceramics such as SiC decreases the wear rates of Al-based composites [13].

Accumulative Roll-Bonding (ARB) process is one of the severe plastic deformation methods, at which two equal sized sheet materials are rolled repeatedly producing ultrafine-grained materials [14–16]. The deformed microstructure during this process plays a crucial role in affecting comprehensive properties of metals. The ARB process is a relatively upgraded new technique of SPD which is invented by Satio et al [17]. Moreover, this process has been used to manufacture MMCs with different ceramic reinforcements [18]. ARB technique has been applied to manufacture many Al-based composites such as: Al/SiC [19–23], Al/Al2O3 [24, 25], Al/TiO2 [26], Al/SiO2 [27], Al/W [28], Al/WC [29]. The main function of this process is to apply a very high plastic strain on a material, which contributes to fine the structure and increased strength without changing the dimensions of sample.
Up to date, the studies on the wear characteristics of materials processed by ARB process are rare. Kazemi Talachi et al [30, 31] and Eizadjou et al [32, 33] investigated the wear behavior of ARBed aluminum sheets. They reported that hardness of pure aluminum after ARB process increases with increasing the number of ARB cycles due to strain hardening effect and grain refinement. They also reported that the wear resistance is improved of the ARBed sheets due to the low strain hardening capability of Al and the microstructure changes including grain refinement and high angle grain creation. Recently Liu et al [34] and Darmiani et al [35] investigated experimentally the wear behavior of Al/WC and Al/SiC composites manufactured by ARB process, respectively.

The objective of this paper is investigating the mechanical and wear characteristics of Al–SiC nanocomposite fabricated by the ARB process at different cycles. The evolution of microstructure, mechanical properties and wear behavior was investigated and deeply discussed allowing better correlation between all these properties.

2. Experimental

We used Aluminum sheets (Al-1050) with the chemical composition shown in table 1 and SiC particles with 5 μm average particle size (see figure 1) as starting materials. We cut Al sheets to strips of 100 mm × 50 mm × 1 mm and heat up to 450 °C for 1 h to release internal stresses accumulated during bonding and hence reduces cracking of Al sheets. Then, we remove contaminants on the surface of the sheets using acetone. The schematic representation of the ARB process for manufacturing of the Al–SiC composite was previously reported [36, 37].

In the initial step, we distributed SiC powders at the interface between two Al sheets. We stacked the two sheets with SiC particles in between and fasten them at both ends with Al wire. We roll-bonded the fasten sheets with a 50% reduction ratio without lubrication. Consequently, SiC powders were uniformly dispersed on the irregular surfaces of two Al sheets. The irregular surfaces helps for improving particles distribution and the bonding at the zero ARB cycle due to the increase of superficial area. After that, the bonded sheets were cut into two parts and annealing at 450 °C for 1 h. In the second step, we repeated the first ARB cycle processed strip up to five cycles without adding SiC particles to improve the distribution of SiC particles and generate nanostructured grains of Al.

We investigated the microstructure and the elemental composition of the samples using FEI Sirion 200 scanning electron microscope connected with EDS unit. The investigations was conducted on the rolling direction-normal direction (RD-ND) plane. Phase composition was characterized by x-ray diffractometer (XRD-7000) with Cu Kα radiation. The crystallite size of milled powders was estimated by XRD peak

![Figure 1. SEM image of the SiC particles used.](image)

| Material       | Chemical composition (wt. %)                     | Hardness (HV) |
|----------------|--------------------------------------------------|---------------|
| Al 1050 -annealed | 0.3 Fe, 0.09 Si, 0.002 Cu, 0.003 Mg, 0.005 Mn, 0.05Ti, Al bal. | 32            |
broadening using William-Hall method as follows [30]:

\[ D = \frac{0.9 \lambda}{B \cos \theta} \]  

(1)

While the lattice strain, ε, was calculated based on the equation presented by Danilchenko et al [31] as follow:

\[ \varepsilon = \frac{B}{4 \tan \theta} \]  

(2)

Where D, B, λ and θ are crystallite size, full width at half maximum (FWHM), the wave length and peak position, respectively.

We employed Vickers microhardness test to measure the hardness on the sample surface by applying 100 g load and 15 s dwell time. For tensile specimens, we tested three sample of each batch while for hardness test at least five indentation were done for each sample.

Wear behavior of the specimens were performed using a pin-on-disk wear apparatus at room temperature. We used rectangular samples of 120 mm length and 20 mm width, where the sample length was aligned with the rolling direction. We polished the samples and cleaned them using ethanol before testing to remove any contaminants. The AISI 52100 steel (with the hardness of 63 HRC) and the sample were used as the pin and the disk, respectively. The applied loads of 2.5, 5, 7.5 and 10 N was used in the wear tests. We performed the test with 200 m sliding distance and 0.5 m s\(^{-1}\) sliding speed. To determine the wear arte, we weighted the debris of each sample using balance with 0.1 mg accuracy.

3. Results and discussion

X-ray diffraction pattern plot of the Al-SiC nanocomposites with various SiC percent are available in in figure 2. In the XRD pattern, the peaks correspond to the visible and identifiable phases whose value is dominant in the specimen. In the XRD pattern shown in figure 2, the peaks of the two phases of aluminum and SiC can be detected and observed. With respect to the intensity of the peaks, it is clear that the aluminum is higher than the rest of the other phases. The bragg peak height of SiC increases with further addition of SiC due to the higher
content of SiC particles. While the height of Al peaks decreases due to the crystallite size reduction during ARB process. The average crystallite size of Al and Al-SiC nanocomposites containing 1, 2 and 4% SiC are 55, 53, 52 and 50 nm, respectively, while its size for as received Al is 102 nm.

SEM images of the nanoparticle distribution in the Al-4%SiC nanocomposite in terms of the number of ARB cycles are shown in figure 3. In the first to third cycles, crushing and spreading of the secondary phases have occurred, and in the last cycle, only these fragmented phases have been propagated. It is also evident that the micropores in the nanocomposite have decreased significantly with the increasing number of the ARB cycles. In the nanocomposite before applying the ARB process, the nanoparticle agglomerated regions, nanoparticle free zones, and pores are evident. By applying the ARB process and by increasing the number of cycles in this process, the agglomerated and nanoparticle free zones and porosities gradually decrease and disappear in the fifth cycle. It is apparent that after five cycles of the ARB process, an appropriate distribution of SiC nanoparticles is obtained and the pores are removed. Under normal pressure of rolling, the aluminum matrix flows and extrudes through the nanoparticle clusters; thereby it results in improving the distribution of these nanoparticles.

Figure 4 shows SEM and TEM micrographs of Al-SiC nanocomposite after 5 cycles indicating 105 nm average grain size and 550 nm SiC particle size compared to 2 μm grain size of Al before rolling. This observation highlight that grains are refined during bonding process. Additionally, this observation agree well with the crystallite size observation at which the crystallite size is smaller for Al-SiC nanocomposites compared to Al.

Figure 5 shows the SEM image and EDS mapping analysis of the elements in this image of the Al-4% SiC product. As can be seen, a good distribution of the constituent phases is obtained. An elemental EDS mapping analysis shows that these constituent phases are Al, Si and C only without any observation of other undesired or phases.

Microhardness results of Al and Al-SiC nanocomposites with the number of ARB cycles are presented in figure 6. The hardness values of the products have increased with the application of the ARB process. The greatest increase in hardness occurred in the first cycle of the ARB process. In fact, most work hardening occurs in the first cycle [38–40]. With the increasing number of cycles, the slope of increasing hardness decreases so that there is no noticeable difference in hardness changes from fourth to the fifth cycle and finally, the hardness of the Al-SiC product increased about 200% rather to the hardness of the Al 1050 product. In the last cycles, the rate of dislocation generation and the disappearance of dislocations due to recovery are almost equal [41, 42]. As the number of matrix layers in the fourth and the fifth cycle increases, the distribution of hardened surfaces within the product becomes homogeneous, thus the hardness fluctuations in the four and five cycle ARBed specimens were reduced rather to the lower cycles. At the initial ARB cycles, 0, 1, 2 and 4, the increase of SiC content leads to increase of hardness due to the presence of SiC nanoparticles, which facilitates grain refinement and dislocation generation in the composite (see figure 4). For samples with 1% SiC, the hardness increases up to the fifth ARB
cycle. However, for samples with 2% and 4%, the hardness is insignificantly affected at the fifth ARB cycle. This is due to the saturation of the microstructure with ultra-fine grains after four ARB cycles for samples with 2% and 4% SiC.

Figures 7 and 8 show the wear rate as a function of applied load of ARBed aluminum and Al–SiC composite manufactured using ARB process after different ARB cycles. The wear rate decreases with increasing the number of ARB cycles for all the considered loads, figure 7. This reduced wear rate of ARBed Al is attributed to the grain refinement occurred during ARB process (see figure 4), which significantly increase the hardness and strength of the material. As a consequence, plastic deformations at the contact surface is reduced resulting in lower material removal and hence smaller wear rates. Moreover, the lower adhesion between the contacted surfaces reduces the coefficient of friction of ARBed Al samples. The same trend observed for ARBed Al was observed for Al-SiC samples, at which the wear rate is decreased with increasing the number of ARB cycles as shown in figure 8. Therefore, the wear resistance of samples is improved with increasing number of ARB cycles. The results

Figure 4. (a) SEM micrographs and (b) TEM microstructures and associated selected area diffraction (SAD) patterns of the Al–SiC composites after 5 ARB cycles.

Figure 5. Mapping analysis of Al–4% SiC nanocomposite after 5 cycles.
demonstrated that ARB process is more significant to reduce the wear rates for Al-SiC composites than Al since the wear rates of Al-SiC composites is smaller than Al sample at the same ARB cycle. During wear test for ARB-processed aluminum, deformation occurs to debris particles, which cause the wear rate increased, but for Al-SiC samples, by increasing ARB cycles, uniform distribution and SiC particle cause refinement of the debris which reduce wear rate. It can be seen that from these figures; the wear rate increases with increasing the normal load of all the tested samples. The influence of the wear load is analogues to the indentation experiment, at which the indentation depth increases with increasing applied load [43]. The wear rate dependence on the applied load follows a linear rising function for all the tested samples following Archard’s law, which states that the wear rate is proportional to the normal applied load [44].

Figure 9 shows the variations of wear rate with SiC content for ARBed Al–SiC composites. This figure shows that at all ARB cycles, the wear resistance of Al–SiC composite is higher than that of the ARBed Al samples. However, based on the available literature on this point, there is some contradict between their results and conclusions; some of them reported improvement wear resistance with increasing reinforcement content and other report the opposite trend [45]. This mainly due to the fact that in practice the wear of a material is governed by many factors [46]. The existence of reinforcement particles in the matrix decreases cause hardening of the soft
matrix reducing plasticity and deformability, which results in smaller grooves during sliding as shown in figure 10. Additionally, it increases the strength of the sample, which increases its resistance to scratches and removal of debris, and hence improves the wear resistance.

Friction coefficient of the ARB-processed aluminum and Al–SiC composite at different cycles are shown in figures 11 and 12. Generally, the coefficient of friction is increased with increasing number of ARB cycles for both materials, Al and Al–SiC composites. The coefficient of friction for ARBed aluminum is larger than Al–SiC composite at all the considered ARB cycles. Stain incompatibility at the surfaces under the pin causes delamination between contacted surfaces and the subsurface under them which facilitates the separation of debris during wear test. Therefore, ARBed Al shows higher coefficient of friction. In Al–SiC nanocomposite, SiC particle works as solid lubricant during friction process between worn surface and pin, which reduces the generated temperature due to contact. In the early ARB cycles, the distribution of SiC particles was not uniform which lead to large coefficient of friction. However, increasing the number of ARB cycles, the particles distribution became more uniform leading to reduced coefficient of friction. The presence of SiC on the worn surface reduces the deformability of the surface, which reduce the contact area and hence less friction action occurs. Additionally, the delamination due to accumulation of strains at the upper surface and temperature
difference between the worn surface and the subsurface is highly prohibited leading to less material removal [47]. Besides, the debris size in the composite is smaller than Al which indicates that the wear mechanism in this case is due to the adhesion of the hardened tribo-particles to the worn surface. These particles cling to each other and then cling to the worn surface due to the pressure on the pin, which lead to generation of smooth particles on the contacted surfaces. This surface is harder than the base material and hence lower coefficient of friction is observed.

4. Conclusions

We manufactured Al and Al–SiC nanocomposite with different SiC contents by ARB technique. The microstructure, microhardness and wear properties were investigated. The results and discussion through the manuscript lead to the following conclusions.

1. After five ARB cycles, the microstructure was uniform with homogeneously distributed SiC particle.
2. The ARB process significantly reduces the size of SiC particles.

3. The microhardness of ARB processed Al–SiC nanocomposite increased with increasing the number of ARB cycle. The rapid increment of microhardness at the initial the number of ARB cycle is due to strain hardening and the generation of more dislocations while the microhardness is became unaffected at the high number of ARB cycles due to the saturation of grain refinement.

4. The wear rate and coefficient of friction decreased with increasing the number of ARB cycle for Al–SiC nanocomposite due to SiC refinement and uniform distribution.

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