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Effect of SiC content on dry sliding wear, corrosion and corrosive wear of Al/SiC nanocomposites

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Abstract: The corrosion, corrosive wear and dry sliding wear of nanocomposites, are extremely complicated and involve various chemical, physical and mechanical factors. The aim of this work is to investigate the effects of nanosized SiC content on the hardness, dry sliding wear, corrosion and corrosive wear of Al/SiC nanocomposites synthesized by mechanical milling cold pressing and hot extrusion. The corrosion resistance of these composites in 3% NaCl solution was investigated by electrochemical polarization testing and their dry sliding as well as corrosive wear resistance in the same solution was evaluated using a pin-on-disc tester. The microstructures of the samples and their worn surfaces were examined using scanning electron microscopy. It was shown that the dry sliding wear and corrosion resistance of these nanocomposites were improved with the increase of SiC content. It was concluded that due to the lubrication effect of the solution, both the friction coefficient and frictional heat that might soften the material were reduced. In addition, the improved strength of the nanocomposites combined with their better corrosion resistance contributed to their increased corrosive wear resistance, compared with the base alloy. The prominent wear mechanism in the unreinforced alloy was adhesive wear, in the Al/SiC nanocomposites, the wear mechanism changed to abrasive.

Key words: Al 6061; SiC; nanocomposite; mechanical milling; corrosion; dry sliding wear; corrosive wear

1 Introduction

Aluminum-based metal matrix composites (AMCs) are good candidates for automotive market, thermal management applications and aerospace industry due to their high specific modulus, superior strength, excellent wear resistance, and high thermal conductivity [1−6]. The mechanical properties of nanometric dispersion strengthened metal matrix composites are far superior to those of their micrometric counterparts with a similar or higher volume fraction of particulates [7,8]. For example, MA et al [8] reported higher yield strength and ductility for Al/1%Si−N−C (volume fraction) nanocomposite as compared with those of Al/15%SiC (volume fraction) microcomposite.

However, the main requirement for achieving the improved properties in the particulate reinforced composites is a homogeneous distribution of particles in the matrix alloy [9]. This issue is more critical for AMCs reinforced with nano-sized particles in which agglomeration and clustering are inevitable when ordinary processing such as casting methods are used [10,11]. Powder metallurgy (P/M) techniques do not have the typical drawbacks of casting routes for fabrication of AMCs [12,13], but the problem of clustering of nano-particles in conventionally P/M processed AMCs still persists [14,15]. Mechanical milling is a useful method for fabrication of nano-composites with a uniform distribution of nanoparticles in the matrix [15−21]. In addition, this technique is capable of converting the grain size of the matrix alloy to nano-sized scale and these nanocrystalline materials exhibit high thermal stability [15].

Recently, considerable interest has been paid to extend the use of AMCs in the marine environments [22]. This demands investigating the corrosion as well as erosion–corrosion characteristics of the composite materials in a simulated marine environment. A few studies in the literature reported the corrosive wear behavior of Al alloys and composites [23−25]. ZHANG and LI [23] studied the effect of yttria addition on the

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wear resistance of aluminum under dry and corrosive conditions. They found that the dispersed yttria particles were effective in enhancing both the dry and corrosive wear resistances of the aluminum matrix. RAMACHANDRA and RADHAKRISHNA [24] reported that the slurry erosive wear resistance of Al/SiC composites increased with increased SiC content. This was attributed to the passive layers formed on the surface of the specimens acting as protective layers against the attack of slurry. They also analyzed the slurry erosive wear behavior of Al/2%Si (mass fraction) alloy reinforced with fly ash in another study [25], and noticed that the reinforcing particles enhanced the slurry erosion wear resistance of the composites.

CANDAN and BILGIC [26] reported that addition of SiC particles to Al−4%Mg (mass fraction) could improve the corrosion resistance of the composites over the base alloy in 3.5% NaCl (mass fraction) solution. On the other hand, KIOURTSIDIS and SKOLIANOS [27] reported the enhanced pitting corrosion of aluminum AA2024/SiC composites in 3.5% NaCl solution.

The corrosive wear is accompanied with acceleration of degrading the surface and generally results in more damage due to the wear-corrosion synergy as compared to ordinary wear. The possible presence of corrosion products such as oxide scales on the surface of material during corrosive wear may or may not play a negative role in corrosive wear, depending on the properties of the oxide and its adherence to the substrate [28].

Despite the importance of corrosive wear behavior of AMCs, studies on Al/SiC nanocomposites are rather limited. The objective of the current investigation is to study the corrosion rate, dry sliding and corrosive wear of Al/SiC nanocomposites to gain a better understanding of the aforementioned phenomenon to be used for optimization of these AMCs for improved performance.

2 Experimental

Nitrogen gas-atomized Al 6061 powder particles (38−63 μm), having the nominal chemical composition as given in Table 1, were co-milled with 1%, 2% and 3% (volume fraction) of nano SiC particles (25−50 nm, Plasma-Chem Co., Germany) using a laboratory planetary ball mill (PM−2400), a hardened stainless steel vial and hardened steel balls (φ=10 mm) in argon for 20 h [29]. The ball to powder mass ratio and rotational speed were 15:1 and 300 r/min, respectively while 1.5% (mass fraction) of stearic acid was used as the process control agent (PCA). Figure 1 shows a typical TEM micrograph of the used nano SiC powder particles.

The resultant powder mixtures were cold pressed at a constant pressure of 750 MPa in a steel die on a single acting 45 t hydraulic press, while graphite was used as the die lubricant. Dimensions of the compacts were 25 mm in diameter and 15 mm in height. Green compacts were hot extruded at 500 °C, being held for 45 min at the same temperature using the same hydraulic press at a ram speed of 36 mm/min with the extrusion ratio of 11:1. The surfaces of the cross-sectioned samples were examined using a Hitachi S−2700 scanning electron microscope (SEM) and transition electron microscope (TEM) (Philips CM30, Poland). Hardness of the cross-sectioned bars was measured using a Rockwell-B hardness (HRB) tester with a maximum load of 100 kg (Zwick, Roell ZHR, Germany), and the average value of five hardness measurements conducted on each specimen was considered. The corrosion resistance of the samples was evaluated via the Tafel curves obtained from electrochemical measurements in 3% NaCl solution. Each specimen was connected to a copper wire and mounted in epoxy resin in such a way that a surface area of 1 cm^2 of the sample could be exposed to the testing solution. This surface was ground with silicon carbide papers up to 800-grit, and cleaned with acetone. A saturated calomel electrode (SCE) was used as the reference electrode and a platinum plate having the area of 1 cm^2 was used as the counter electrode. The corrosion current density was determined using the Tafel extrapolation method.

Dry sliding wear tests were performed at the temperature around 25 °C using a CSEM high temperature tribometer (pin-on-disk). A 3 mm diameter Si_3N_4 ball was used as the pin and all the tests were performed at a sliding speed of 1 cm/s along a circle path

Table 1 Chemical composition of 6061 aluminum alloy (mass fraction, %)

Mg	Si	Fe	Cu	Cr	Al
1.12	0.64	0.48	0.33	0.04	Bal.

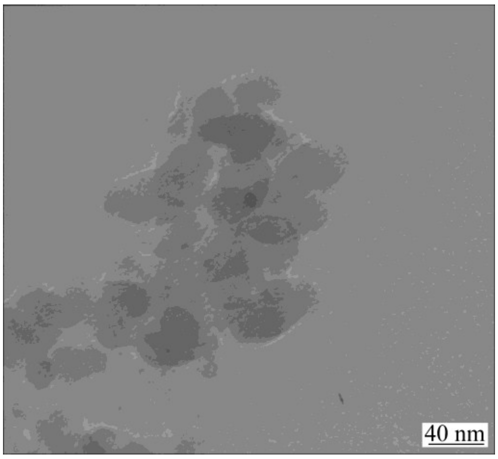

Fig. 1 Typical TEM micrograph of used nano SiC powder particles

of 2.0 mm in diameter under a normal load of 2 N for 2000 rotations, corresponding to a sliding distance of 12.6 m. Corrosive wear tests were performed using the same pin-on-disc apparatus with an attached container filled with 3% NaCl solution. A Zeiss white light scanning system was used to analyze the wear track, from which the corresponding volume loss was determined. The worn surfaces of samples subjected to either dry sliding or corrosive wear were examined using a Camscan MV2300 scanning electron microscope.

3 Results and discussion

Figure 2 shows a typical TEM image of an Al 6061 powder particle co-milled with 2% (volume fraction) of nano SiC particles, confirming that the SiC nanoparticles were homogeneously distributed in the Al mixture before powder consolidation. As shown in the SEM micrograph of the polished surface of Al/2%SiC nanocomposite (Fig. 3), the SiC nanoparticles (white spots) were also distributed uniformly in the matrix of the hot-extruded sample. The uniform distribution of the reinforcing particles in the matrix of composites contributes to their improved mechanical and tribological properties [16,30,31]. Our extensive metallographic studies revealed no evidence of the presence of pores or cracks in the composites. In fact, the measured porosity values of hot extruded samples were mostly less than 0.3% and full densification was achieved for most of these samples.

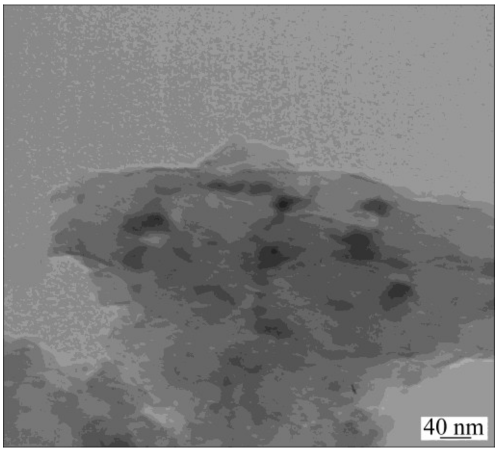

Fig. 2 Typical TEM image of Al/2%SiC nanocomposites powder

Figure 4 shows that the increased volume fraction of SiC nanoparticles resulted in increased hardness of Al/SiC nanocomposites. Similar results have also been reported by other researchers [16,32]. ZOLRIASATEIN et al [16] reported more than 5 times increase in the hardness of Al−2%Cu (mass fraction) alloy by addition of 20% Al_3Mg_2 (mass fraction) nanoparticles. ALIZADEH and TAHERI-NASSAJ [32] reported that addition of 4% B_4C (mass fraction) nanoparticles resulted in about 4 times increase in the hardness of Al−2%Cu alloy. These results are attributed to the presence of hard ceramic nanoparticles acting as load-supporting components in the nanocomposites and contributing to their increased hardness.

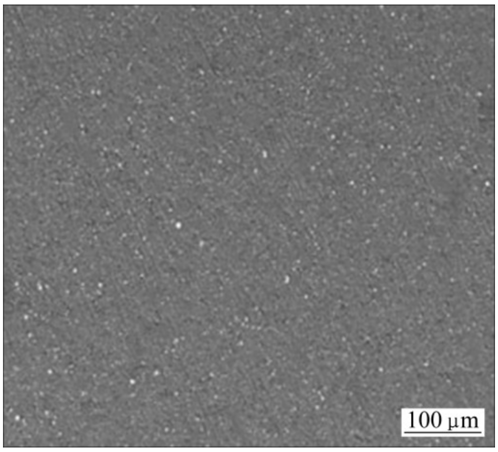

Fig. 3 Typical SEM micrograph of polished surface of hot extruded Al/2%SiC nanocomposite

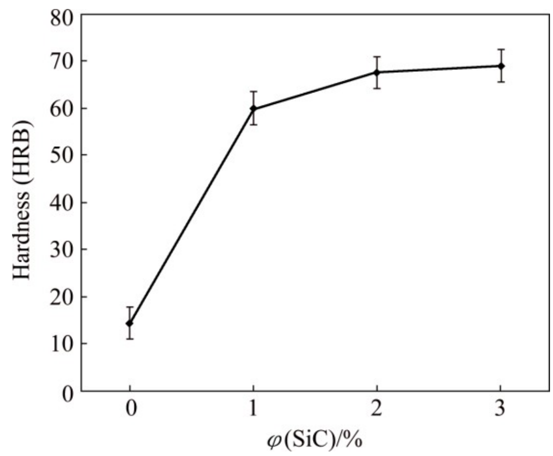

Fig. 4 Variation of hardness values of Al/SiC nanocomposites with their SiC content

The variation of dry sliding volume loss of Al/SiC nanocomposites with their SiC content is shown in Fig. 5. The nanocomposite containing 3% SiC (volume fraction) exhibited the minimum wear loss value being approximately 77% lower than that of the base alloy. According to the Archard equation, the dry sliding wear resistance of materials is proportional to their hardness [33]. Therefore, the increased dry sliding wear resistance of Al/SiC nanocomposites with their SiC content can be attributed to the increased percent of the hard SiC particles. Similar results have also been reported by other investigations [16,31,34]. WALCZAK et al [34] reported about 3 times lower wear damage for AlSi9Mg/20%SiC (20 μm) (volume fraction) composite as compared to the base alloy. ZOLRIASATEIN et al [16] realized a significant improvement in tribological performance of aluminum alloy when reinforced with 20% (mass fraction) of nano-sized Al_3Mg_2 particles. This improvement was mainly attributed to the higher hardness of the nanocomposite as compared with that of the base alloy. Besides, in Al/SiC nanocomposites, SiC particles acted as load-supporting constituents and reduced the plastic deformation in the surface layer, thereby reducing the wear damage.

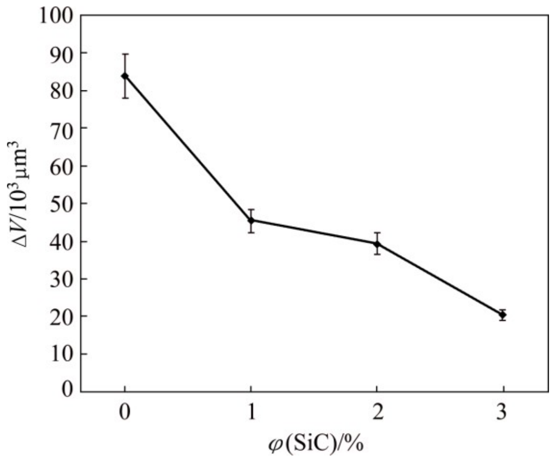

Fig. 5 Variation of dry sliding volume loss of Al/SiC nanocomposites with their SiC content

The decreased coefficient of friction with the increased volume percent of SiC for Al/SiC nanocomposites is shown in Fig. 6. These results were consistent with other reports [34]. The minimum value of coefficient of friction obtained for Al/3%SiC nanocomposite were 32% lower than that of the base alloy. The increased SiC nanoparticles resulted in decreased real contact area of pin and the composites disc and thereby the value of friction coefficient was decreased.

According to Figs. 5 and 6, addition of only 3% SiC to the matrix alloy results in a major decrease in wear loss together with a significant decrease in the friction coefficient of the samples. THAKUR and DHINDAW [35] evaluated the interfacial characteristics in particulate reinforced metal matrix composites by correlating interparticle distance with wear and friction. Therefore, the improved dry sliding wear properties obtained in the present study can be partially attributed to the uniform distribution of the nano-sized SiC particles as well as good interfacial characteristics achieved by mechanical milling and hot extrusion.

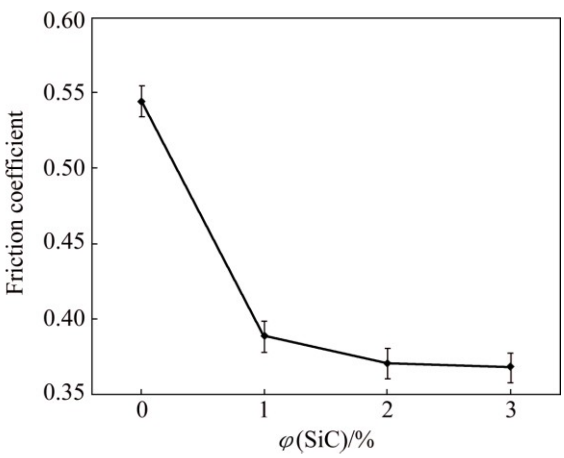

Fig. 6 Variation of dry sliding friction coefficient of Al/SiC nanocomposites with their SiC content

SEM micrographs of dry sliding worn surfaces of the samples are shown in Fig. 7. As illustrated, the base alloy experienced severe wear with massive plastic deformation (Fig. 7(a)). The plates on the worn surface could be an indication of the involved adhesive wear. However, the worn surface of Al/2%SiC nanocomposites (Fig. 7(b)) showed smaller grooves with a slight plastic deformation at the edges of the grooves. Incorporation of SiC particles into the aluminum matrix resulted in increased hardness (Fig. 4), which reduced plastic deformation. These results can be explained by considering the converted wear mechanism from adhesive wear to mostly abrasive wear by SiC particles addition to the matrix alloy.

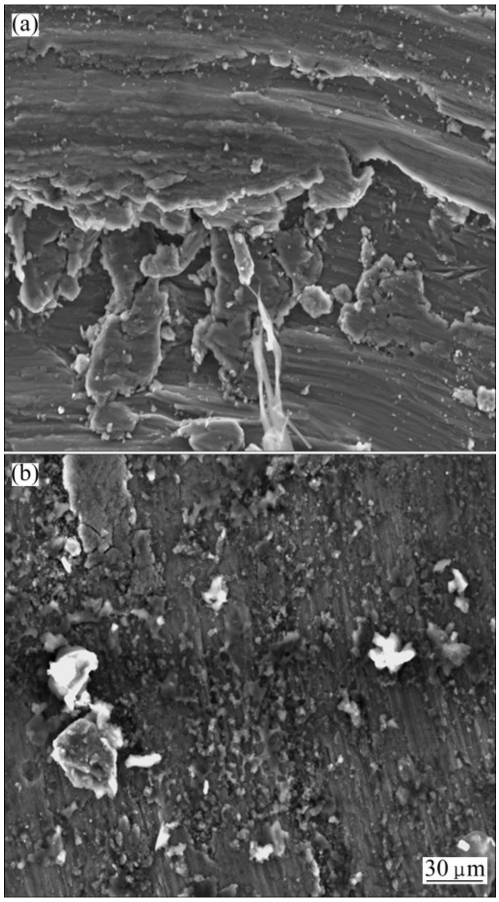

Fig. 7 Typical SEM micrographs of worn surfaces of base alloy (a) and Al/2%SiC nancomposite (b)

The polarization curves of Al/SiC nanocomposites as well as that of the matrix alloy (Al 6061) tested in 3% NaCl solution are shown in Fig. 8. The variation of the corrosion rate of these nanocomposites with their SiC content is presented in Fig. 9. These results confirmed that the SiC nanoparticles addition increased the corrosion potential of the matrix alloy, due to non-reactivity of a part of the material (nano SiC particles) with the corrosive solution. Similar observations on AMCs have been reported by other investigators [27,36]. MAHMOUD et al [36] studied the corrosion behavior of Al/Al_2O_3 and Al/SiC nanocomposites in 1 mol/L HCl solution and found lower corrosion rates for both composites as compared with the matrix alloy. They attributed these results to the inertness of both SiC and Al_2O_3 nanoparticulates. Therefore, they remained unaffected by the acid medium during the corrosion tests.

The other reason for decreased corrosion rate of composites with increased SiC content, as shown in Fig. 9, was the low conductivity of the SiC nanoparticles. Therefore, the increased fraction of SiC was

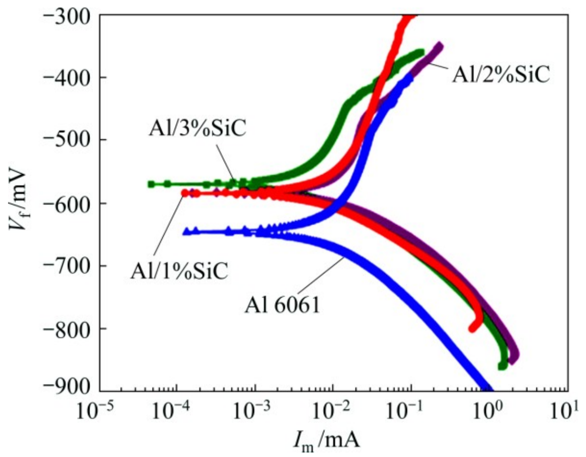

Fig. 8 Tafel polarization curves of Al 6061 and Al/SiC nanocomposites in 3% NaCl solution

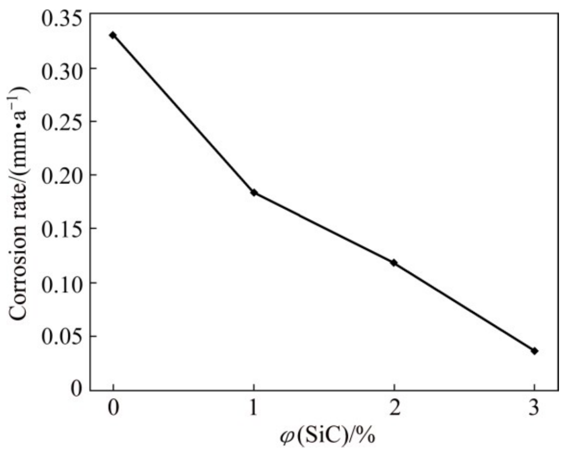

Fig. 9 Corrosion rate of Al/SiC nanocomposites in 3% NaCl solution

accompanied with decreased area of conductive aluminum that was exposed to the corrosive solution.

The decreased corrosive wear loss of Al/SiC nanocomposites with their SiC content in 3% NaCl solution is presented in Fig. 10. Again, similar to dry sliding wear, the increased corrosive wear resistance of Al/SiC nanocomposites with their SiC content can also be attributed to the increased percent of the hard SiC particles. It must be noted that the corrosion potential of Al/SiC nanocomposites is higher than that of the base alloy (Fig. 8), and thereby the lower corrosion rate of the former also contributed to the improved corrosive wear resistance of the composite materials.

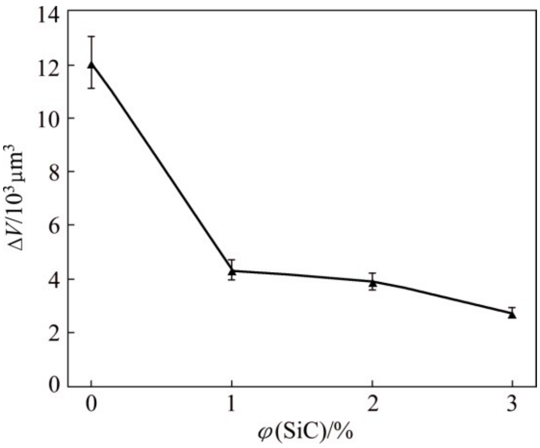

Fig. 10 Variation of corrosive wear loss of Al/SiC nanocomposites with their SiC content in 3% NaCl solution

A comparison between Fig. 5 and Fig. 10 reveals that the corrosive wear loss values of all the samples in 3% NaCl solution are lower than those of dry sliding at any SiC particle loading. These results can be attributed to the lubrication effect of the solution in reducing both the friction and frictional heat that may soften the material. In addition, wear debris that could act as abrasive particles could be removed readily by the liquid [23]. Thus, although the corrosive solution can result in corrosion-wear synergy, the above-mentioned other beneficial effects could be predominant. The variation of the friction coefficient of Al/SiC nanocomposites with their SiC content in 3% NaCl solution is presented in Fig. 11. The friction coefficient was indeed decreased by increased SiC content due to the increased hardness of composites.

Figure 12 shows SEM images of worn surfaces of the reference sample (Al 6061) and Al/2%SiC nancomposite both tested in 3% NaCl solution. The worn surfaces of both samples exhibited many grooves, but they were shallower as compared with those tested in dry wear (Fig. 7). The study of the worn surface morphologies indicated a gradual transition in the wear mechanisms from delamination to abrasive wear as a

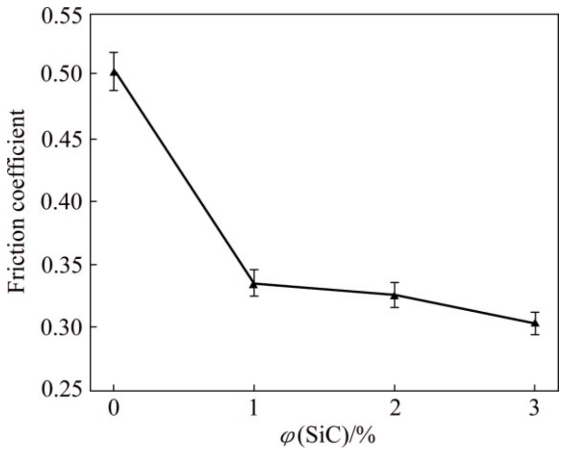

Fig. 11 Variation of friction coefficient of Al/SiC nanocomposites with their SiC content in 3% NaCl solution

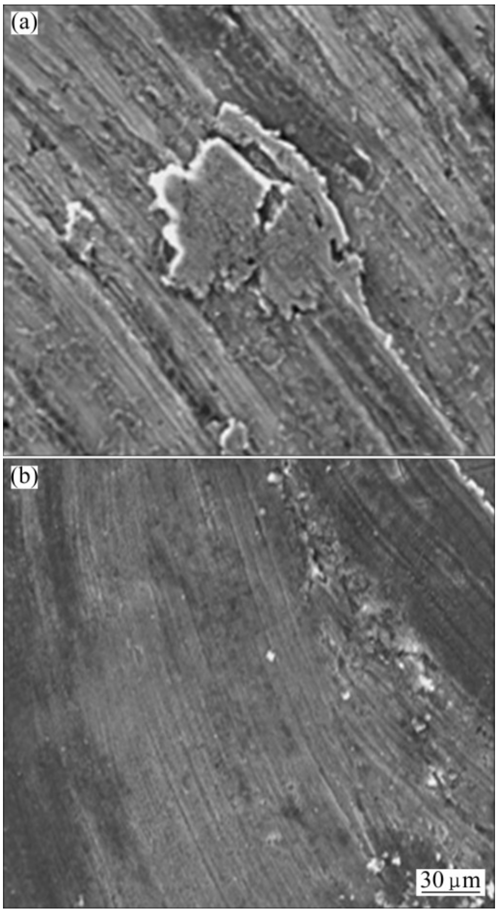

Fig. 12 Typical SEM micrographs of worn surfaces of base alloy (a) and Al/2%SiC nanocomposite (b) in 3% NaCl solution

result of the increased SiC content. As shown in Fig. 12(a), the base alloy experienced adhesion and delamination wear, which is deduced from the flow of materials along the sliding direction. Narrow grooves, as a characteristic of the abrasion wear mechanism, can be seen on the worn surface of the Al/2%SiC nanocomposite (Fig. 12(b)). The presence of SiC nanoparticles in the matrix restricted the flow of metal during sliding and created parallel narrow grooves. In comparison with the abrasive wear, the delamination type of wear led to a more severe wear damage. These SEM observations are in good agreement with the quantitative results of volume loss tests for the Al 6061 and Al/2%SiC specimen, as shown in Fig. 10. The SEM studies also revealed the presence of some oxide fragments on the worn surface of Al/2%SiC nanocomposites. This implies the role of SiC nanoparticles addition in suppressing corrosion and thus wear-corrosion synergy.

4 Conclusions

The effects of nanosized SiC content on the hardness, dry sliding wear, corrosion and corrosive wear of Al/SiC nanocomposites synthesized by mechanical milling is investigated. It is demonstrated that the increased SiC content results in increased hardness of the nanocomposites. The observed increase in the corrosion resistance in Al/SiC nanocomposites with their SiC content is attributed to the fact that nano SiC particles do not chemically react with the corrosive solution. The Al/SiC nanocomposites, as compared with the base metal, exhibited higher wear resistance and lower friction coefficient in both dry and corrosive media. The increased SiC content of such nanocomposites resulted in increased dry sliding and corrosive wear resistance as well as the decreased friction coefficient of the materials. The corrosive wear loss of all the samples in 3% NaCl solution were lower than those of dry sliding at any SiC particle loading. These results were confirmed by SEM studies of the worn surfaces and were attributed to the lubrication effect of the solution, which reduces both the friction and frictional heat that may soften the material. In addition, wear debris that could act as abrasive particles could be removed readily by the liquid. SEM studies of the worn surfaces revealed that in the unreinforced alloy, the prominent wear mechanism was adhesive wear. However, in the Al/SiC nanocomposites, the wear mechanism changed from adhesive to abrasive.

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SiC 含量对 Al/SiC 纳米复合材料干滑动磨损、腐蚀以及腐蚀磨损行为的影响

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摘　要：纳米复合材料的腐蚀、腐蚀磨损以及干摩擦磨损行为非常复杂，受化学、物理和机械等多方面因素影响。采用机械球磨、冷压和热挤压技术制备 Al/SiC 纳米复合材料，研究纳米 SiC 含量对材料硬度、干滑动磨损、腐蚀和腐蚀磨损行为的影响。采用电化学极化测试研究了复合材料在 3% NaCl 溶液中的抗腐蚀性能。采用盘-销装置研究了复合材料的干滑动磨损和在 3% NaCl 溶液中腐蚀磨损性能。利用扫描电子显微镜研究了材料及磨损表面的显微组织。结果表明，随着 SiC 含量的增加，纳米复合材料的干滑动摩擦和抗腐蚀性能均得到提高。由于溶液的润滑作用，使材料软化的摩擦因数和摩擦生热均降低。与基体合金相比，纳米复合材料的强度和抗腐蚀性能提高，因此其抗腐蚀磨损性能也提高。对于未增强的基体合金，其磨损机理为黏着磨损，而对于 Al/SiC 纳米复合材料，磨损机理转变为磨粒磨损。

关键词：6061 铝合金；碳化硅；纳米复合材料；机械球磨；腐蚀；干摩擦磨损；腐蚀磨损

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