

WEAR AND HEAT CHARACTERIZATION OF BOTH THE AS-CAST AND HEAT EXPOSED SPECIMENS FOR AL/SiC PARTICULATE COMPOSITES

M. M. Dewidar¹, Khalil. A. Khalil^{1,2}, and Sug-Won Kim²
¹Department of Mechanical Design and Materials, High Institute of Energy, South Valley University, Aswan, Egypt
²Division of Advanced Materials Engineering, RIAMD, Chonbuk National University, Jeonju 561-756, South Korea

(Received June 15, 2006 Accepted August 30, 2006)

ABSTRACT– *This Study is to investigate on the wear characterization and heat resistance of aluminum/silicon carbide (Al/SiC) with different particles (3, 5, and 10 μm) composites manufactured by duplex process, which consists of squeeze-infiltration and squeeze casting. Also, this study is to investigate the effect of alloying element (Ni) on the microstructure, wear behavior and heat resistance of Al/SiC composite. Owing to the increase in interfacial area between SiC particles and matrix in both the as-cast and heat exposed specimens (at 250 °C and 350 °C for 5hr), the decrease in nano-SiC particles size resulted in the increase in the hardness of composites. And in case of 3 μm SiC reinforced Al composites as compared with other composites, the highest density of dislocation was generated during manufacture. Composite with 3 μm SiC has the lowest wear amount among composites reinforced with 5 and 10 μm SiC. Heat resistant property was improved with increasing Ni addition content (wt.) in Al/SiC composites. The wear resistance at 200 °C in argon gas on composite was greater than those at 200 °C and room temperature in the as-composites.*

1. INTRODUCTION

Metal matrix composite materials are advanced materials, which combine tough metallic matrix with a hard ceramic or soft reinforcement to produce composite materials [1]. These materials have superior properties compared to the monolithic materials and can be tailorable to a specific applications [2]. In recent years the aerospace, military and automotive industries have been promoting the technological development of composite materials to achieve good mechanical strength/density and stiffness/density ratios. Nano-ceramic particle reinforced composites have the good characteristics that are good formability, lower fabrication cost, good heat and wear resistance due to unique particle's properties and dispersion compared with the fiber reinforced composites. Al–SiC composites offer isotropic improvements in structural properties over their corresponding base alloys at a reasonable cost, particularly as they can often be produced and formed via conventional metallurgical routes [3]. In addition to their increased specific stiffness and strength over monolithic alloys, Al–SiC composites have been selected for specific engineering applications for their improved smooth specimen fatigue resistance over unreinforced alloys [4-8]. It is now well understood that the reinforcement content and nature of its distribution in the matrix of the composite have profound influence on the performance of composites [9-11]. However, it is difficult to make the homogeneous distribution of particles in the Al-matrix in case of subseive size (below 10 μm) particle. Therefore, a new duplex

process has been developed to produce Al matrix composite with homogeneous distribution of subseive size particles. In present study, the characteristics of the heat resistance and alloying element effects in SiC reinforced Al matrix composites manufactured by duplex process were investigated by using Optical Microscope (OM), X-Ray Diffractometer (XRD), Differential Scanning Clorimetry DSC and Scanning Electronic Microscope (SEM). Also, wear characteristics at ambient, elevated temperature (200 °C) and 200 °C -Ar were investigated.

2. EXPERIMENTAL PROCEDURES

In the first stage for preparing the precomposite, starting material (Pure Al) was melted in electric furnace with other alloys of Al-25%Si, Al-50%Cu under argon atmosphere at 740°C. The chemical composition of the initial matrix alloy is given in **Table 1**. Ni element was added to examine effects of alloying element on hardness and wear resistance. In squeeze infiltrating die, (3, 5, and 10 μm) SiC bed was preheated up to 600 °C and then the melt was poured into the die at 700 °C. To infiltrate by squeeze at 680 °C, the hydraulic ram was used to apply a pressure of 50 MPa to the molten metal until completion of eutectic reaction. In the second stage, the matrix alloy was melted in electric furnace with pre-composite for designed 10wt% SiC reinforced Al matrix alloy at 720 °C, mechanically agitated at 600 rpm and then solidified under pressure of 75MPa until 500 °C. SEM and OM were used to investigate the distribution of SiC particles. Hardness was measured on the B scale with steel ball indenter and a 100 kg major load in Rockwell hardness tester. All specimens were tested to investigate the wear characteristics such as wear loss amount and the morphology of worn surface by using a TE88P wear tester of the pin on disc type under the conditions (final load: 100N, sliding distance: 4000 m, sliding speed: 0.64 m/s, room temperature (RT) and elevated temp.: 200 °C with and without Argon gas).

Table 1. The chemical composition of the initial matrix alloy.

Element	Si	Cu	Fe	Mg	Al
Wt.%	7.77	2.72	0.55	0.28	Bal.

3. RESULTS AND DISCUSSION

3.1 Microstructures And Sic Particles Distribution

In general, when adding into the melt, the subsieve size SiC floats onto the surface of the melt, because of large specific surface. Therefore, it is difficult to make the composite reinforced homogeneously subsieve size particle of under 10 μm . But the wettability of particle of 3, 5 and 10 μm , used in this study was improved due to formation of activated surface on SiC surface through squeeze infiltrating process for making the pre-composite. So, in order to make subsieve size (under 10 μm) SiC distribution homogeneously, duplex process which consists of squeeze infiltration process (1st step) and squeeze casting was used for making specimens used in this study.

The optical micrographes of Al/10wt.% SiC composites fabricated by duplex processing were shown in **Figure 1**. The SiC particles was generally distributed homogeneously due to the formation of active surface on SiC of the precomposite fabricated by squeeze infiltrating process and the microstructures became finer due to an increase in the cooling rate by applying pressure of a squeeze casting. However, compare with other specimens reinforced with particle of 5, 10 μm SiC, a dispersion uniformity of 3 μm SiC reinforced composite appeared low because of the pushing effect in growing dendrite arm and great coalescencing force between particles with great specific surface.

Figure 2 shows optical micrographs of Ni added composites. The distribution of SiC particles became homogeneous by the addition of Ni in composite. This is because Ni addition makes the increase in eutectic temperature, as a result mushy zone is shortened.

By the addition of finer SiC particle in aluminum matrix, the distribution of SiC particle became inhomogeneous. But the distribution of SiC particle became homogeneous with not only an addition of Ni but also with an increase of Ni content.

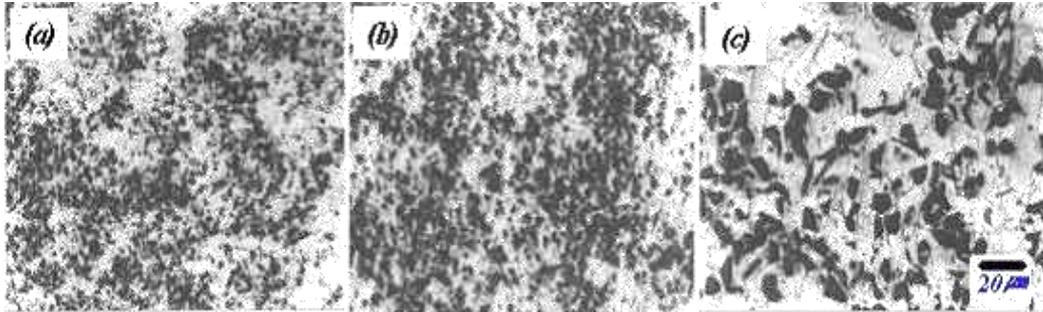


Figure 1. Optical microstructures of final composites with various SiC, size (a) 3 μm (b) 5 μm (c) 10 μm .

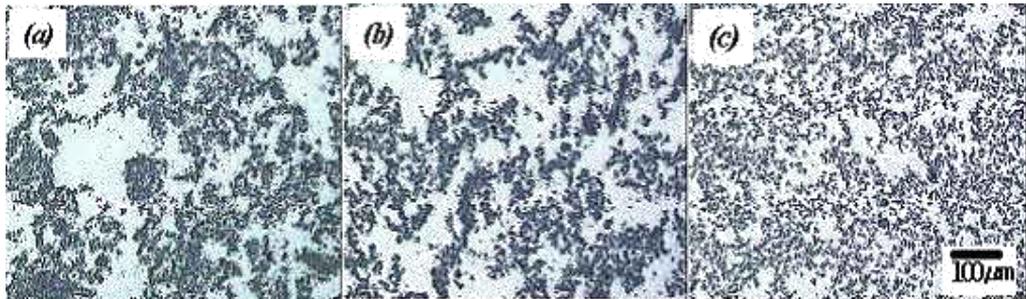


Figure 2. Variation of microstructures with Ni addition in 5 μm SiC reinforced composite (a) 5 μm (b) 5 μm -1%Ni (c) 5 μm -3%Ni.

3.2 Hardness

The changes of hardness in Al/SiC composite with the various particle sizes and addition of Ni before and after heat exposure were shown in **Figure 3**. In **Figure 3(a)**, a composite reinforced by SiC has higher hardness compare to a cast non-reinforced. It is caused by a particle dispersion reinforcement by SiC. A hardness increases with the size of SiC become more finer. This is because the formation of dislocation by the difference of heat expansion coefficient between SiC and Al matrix [12]. A hardness of heat exposed specimens at 250°C for 5hr is higher than as-cast specimens. This is because a formation of aging precipitation by heat exposure. It is thought that hardness is increased by the formation of θ' phase and $\lambda(\text{Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_5)$ [12]. The reason of increasing the hardness at 3 μm is because the formation of precipitations is formed more rapidly by high dislocation density.

Also at **Figure 3(b)**, hardness value was increased continuously with addition of Ni. Because of eutectic temperature was increased by addition of Ni, α -Al become more

finer. Also the reason of increasing the hardness is because the intermetallic compound of NiAl_3 , and NiAl_2 [13] which is more securer and harder at the high temperature was formed.

3.3 XRD

Intermetallic compound was identified by XRD in order to observe the compound behavior during heat exposure and the results were shown in **Figure 4**. Only aging precipitation of Al_2Cu appeared at Ni non-addition composite. But 3%Ni added Al/SiC composite formed intermetallic compound of NiAl_3 which is stable at high temperature as well as Al_2Cu .

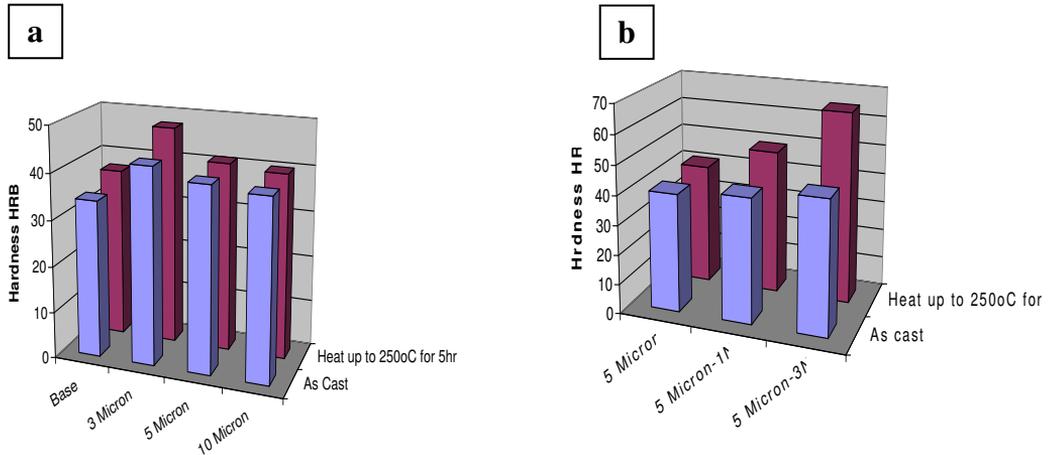


Figure 3. Hardness of as-cast and heat-exposed specimens at 250oC for 5hrs
a) without Ni addition, and b) with Ni addition

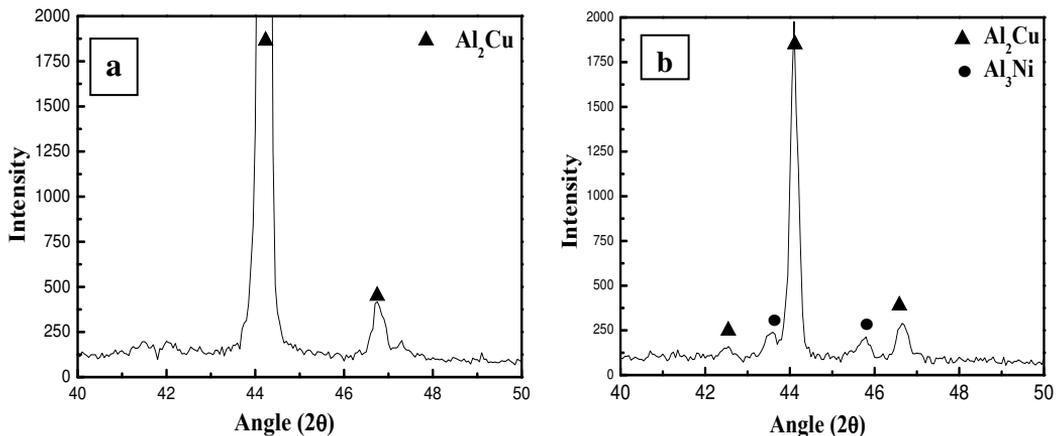


Figure 4. X-ray diffraction analysis of heat exposed specimens at 250°C for 5hr,
(a) Al-7.76Si-2.75Cu-0.28Mg/10wt.%SiCp, and
(b) Al-7.76Si-2.75Cu-0.28Mg-3Ni/10wt.%SiCp.

Figure 5 shows the elemental dot mapping results of the specimen using SEM. **Figure 5(a)** shows the morphology of 3% Ni added composite, (b) of Al dot mapping, (c) of Ni dot mapping and (d) of Cu dot mapping. As a result of the elemental dot mapping, it could be confirmed that the formation of intermetallic compounds consisted of Al, Ni and Cu elements.

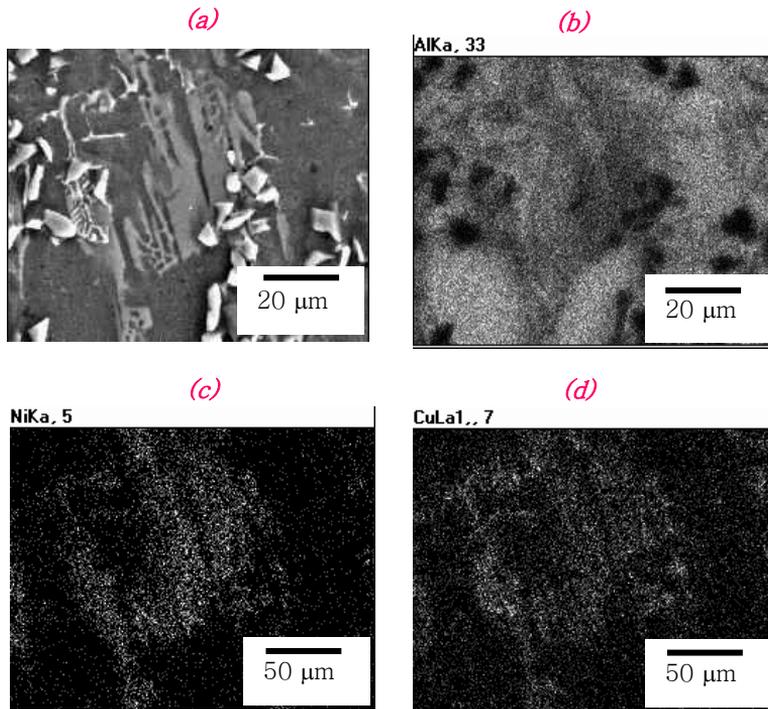


Figure 5. Dot mapping of intermetallic compounds (a) SEM (3%Ni) (b) Al dot mapping (c) Ni dot mapping, and (d) Cu dot mapping.

3.4 Wear Behavior of As-Cast and Heat Exposed Specimens at room temperature

Figure 6(a) shows the wear amount of heat exposed composite and as-composite. Wear amount of composite (3 μm) has less than that of composite (5 μm), because SiC (3 μm) was acted as lubricant agent during abrasive wear. Also, wear resistance of heat exposed specimen for 5hr at 250°C was improved more than as-composite. This is because the hardness was increased by aging effect caused by heat exposure for 5hr at 250°C. The composite exposed at 350°C for 5hr appeared large wear amount more than that of non-heat exposed specimen. It is considered because Si of α -Al was diffused into a near eutectic region, so its hardness was decreased. **Figure 6(b)** showed the changes of wear amount according to heat exposure temperatures (250°C, 350°C) and Ni addition. Wear amount of composite (5 μm) added 3wt%Ni has less than that of composite (5 μm). The wear amount of heat exposed specimen for 5hr at 250°C decreased than that of R.T and 350°C. This is because hardness is increased by the formation of θ' phase and $\lambda(\text{Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_5)$ [12] during heat exposure at 250°C. It is confirmed through worn surface and debris as shown in **Figure 8**. Worn surface of 5 micron heat-exposed at 350°C appeared adhesive wear and worn debris became coalescenceing (**Figure 8**). **Figure 7** shows the variation of worn surface and debris

according to particle sizes in composites reinforced various particles. The worn surface of base alloy appeared the abrasive and fusion wear phenomenon. The worn surface of 3M has abrasive morphology of very smooth type. Abrasive wear mechanism appears because of the separated SiC acted as a lubricant on worn surface while wear is processing. Also debris of 10 micron was formed as bloky type broke out worn surface which caused by the adhesive and friction wear mechanism.

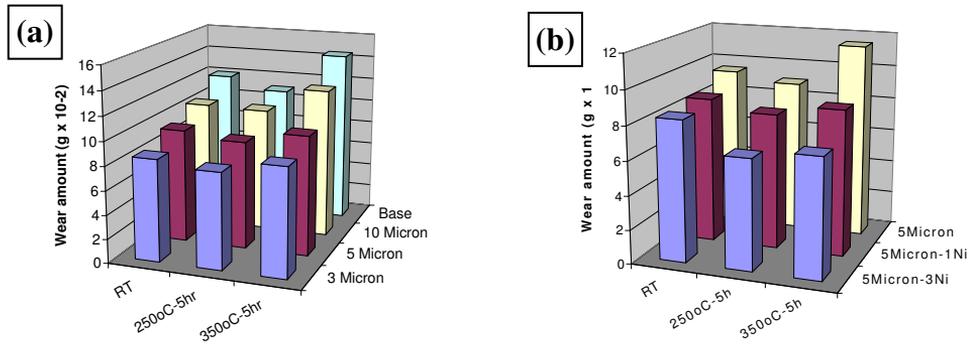


Figure 6. Wear amount after heat exposure at 250°C and 350°C for 5hrs a) Al/SiC composites, and b) composite with Ni addition.

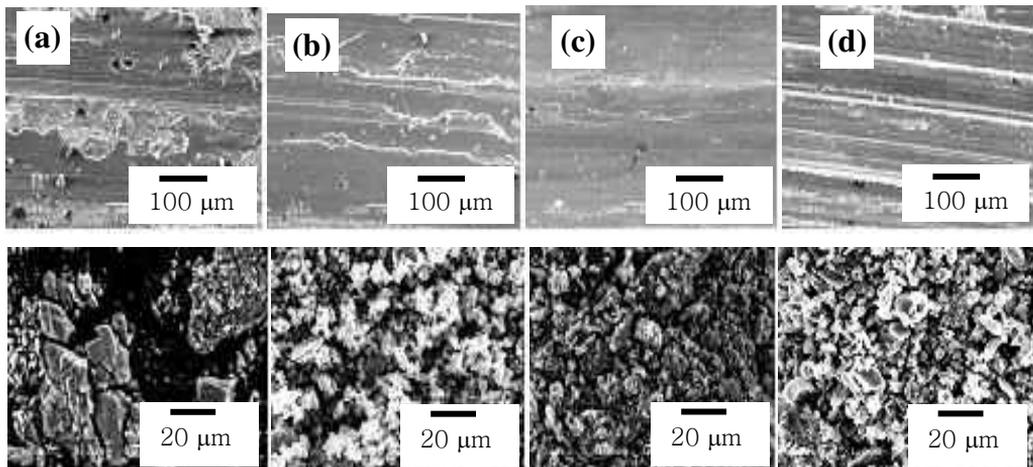


Figure 7. SEM of worn surface and debris in alloy composites with different SiC particle size in matrix alloy (a) base alloy (b) 3M (c) 5M and (d) 10M.

3.5 Wear Behavior of As-Cast and Heat Exposed Specimens at Elevated Temperature

Figure 9 (l) shows the results of wear test of 3μm composite under the various conditions. As shown in this figure, the wear amount in specimen increased drastically at elevated temperature, compared with room temperature. The worn surface morphology of 200°C-Ar wear specimen shows adhesive and abrasive wear phenomena, otherwise adhesive and fusion morphologies were appeared that the debris was formed coarsely in case of 200°C wearing specimen. Using SEM and OM, the reason of significant decrease in wearing amount when purging argon gas was

clarified by **Figure 9 (II)**. As shown in **Figure 10(II)**, the tribological layer (30-60 μm thickness) with agglomerate of SiC reinforcement was form in worn surface and 3-4 μm Al_2O_3 layer in the edge of its layer was form. The hardness of tribological layer is two times higher than that of the as-cast and higher hardened layer prevents worn surface from wearing. As a result, wear amount of 200°C-Ar composites decreased than that of 200-composites. Without Ar gas purging during wear test at 200°C, the tribological layer was not formed, instead ferro-oxide layer (Fe_2O_3 : 7-8 μm thickness) was formed. This is because that the matrix temperature of composite during wear test without Ar gas became higher than that of composite with Ar gas purging, and the matrix became softer.

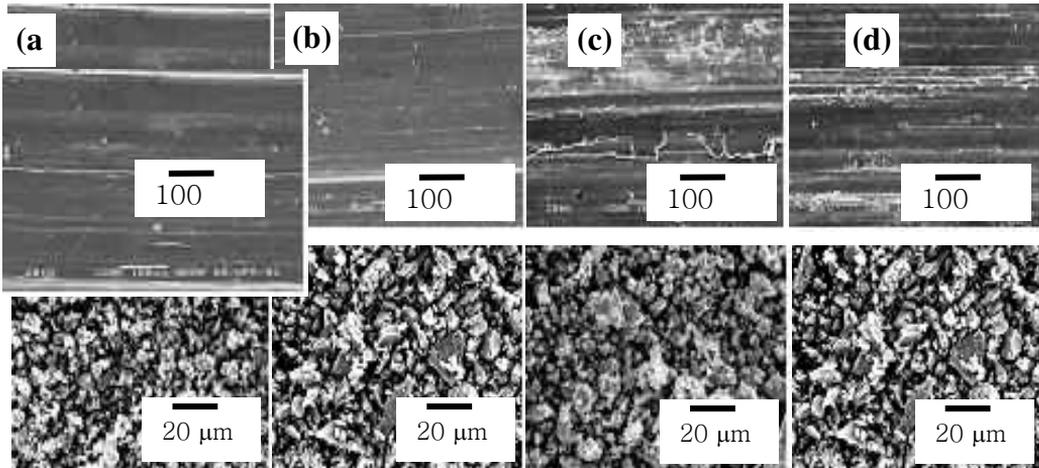


Figure 8. SEM of worn surface and debris according to different exposure temperatures for 5hr (a) 5M-250°C (b) 5M-3Ni-250°C (c) 5M-350°C and (d) 5M-3Ni-350°C.

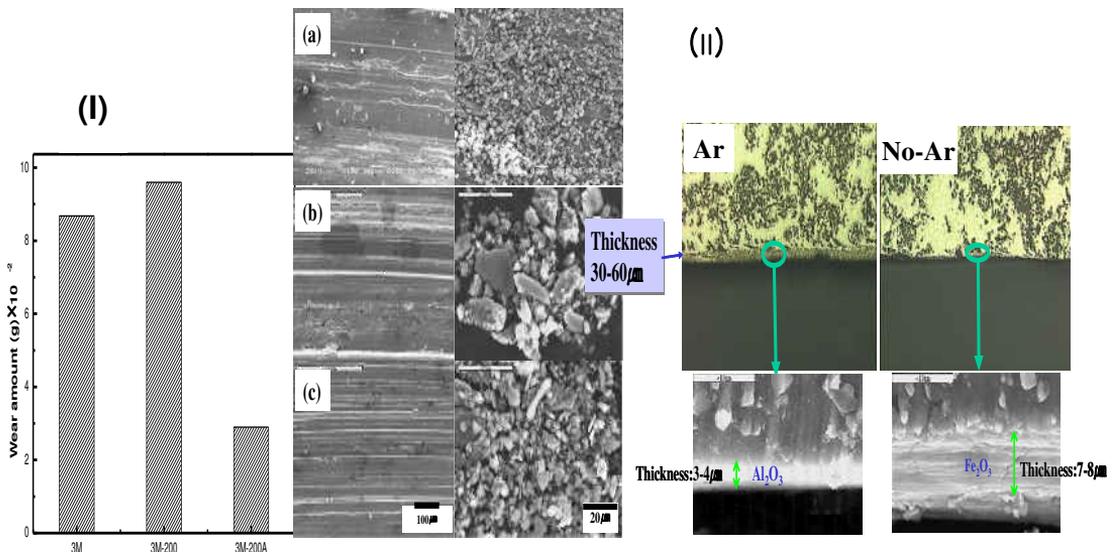


Figure 9. Wear amount and OM, SEM of worn surface and debris according to the wear conditions in 3 μm composite (a) R.T (b) 200 °C, and (c) 200 °C -Ar.

Figure 10 shows the relationship between wear amount, SEM of worn surface, and debris of composites according to wear conditions. In this figure, (a) is under the atmosphere of room temperature, (b) 200°C (c) 200°C-Ar gas. The 3 μm SiC composite experienced with exposure of 250°C before wear test was used in wear test as shown in **Figure 10**. Also the wear amount of 200°C composite was greater than those of as-composite and 200°C-Ar composite. The wear behavior of 200°C-Ar composite was dominated by the mixture of adhesive and abrasive wear mechanism, otherwise that of 200°C composite was dominated by fusion wear mechanism. The debris of 200°C composite was larger than those of both as-composite and 200°C-Ar composite. As shown in the photos, tribo-layer consisted of mixture of SiC agglomerate was formed on the surface of composite when purging with Ar gas. Without Ar gas, tribo-layer as mentioned above was not formed, instead Al and Fe oxides layer was found.

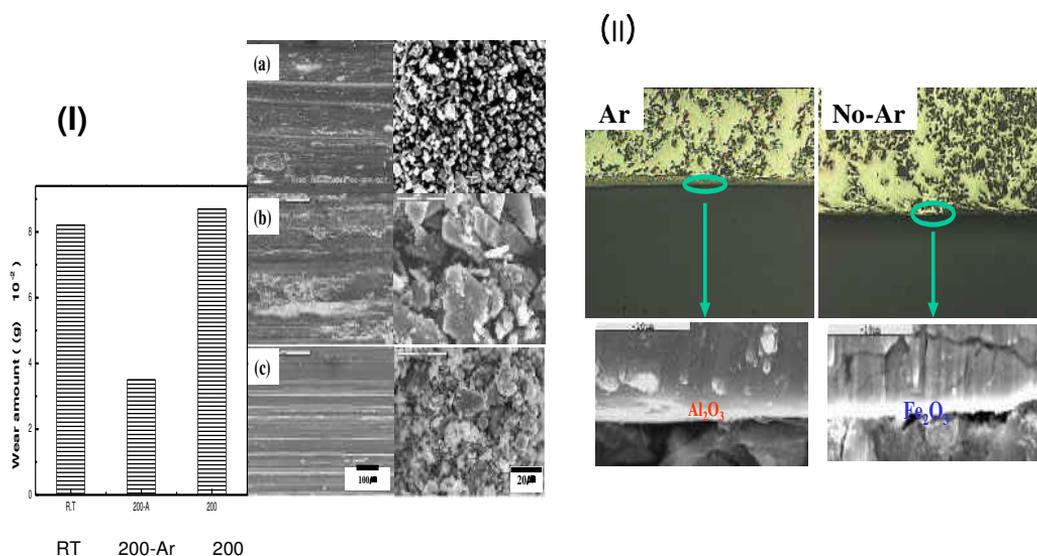


Figure 10. SEM of worn surface and debris according to the wear conditions in 3 μm composite after exposure at 250 °C for 5hr. (a) R.T (b) 200 °C (c) 200 °C –Ar.

4. CONCLUSIONS

The following conclusions can be derived from the results presented above:

- 1- The composite of Al as a matrix and SiC with size (3, 5, and 10 μm) as reinforce with homogeneous distribution was fabricated by duplex process.
- 2- In the composites (Al/10wt%SiCp) manufactured by Duplex process, the sliding wear characteristics under conditions of ambient temperature, 200°C and 200°C-Ar gas and microstructures were studied using OM, SEM.
- 3- The hardness of Al/SiC composites increased with the decrease in SiC particle size and with Ni addition in both the as-cast and the as-heat exposed states.
- 4- In Al composite reinforced with 10wt.% SiC, wear amount decreased with the decrease in particle size. The wearing amount of 200°C composite was greater than those of as-composites and 200°C-Ar composite

REFERENCES

- [1] M. K. Surappa, "Aluminum matrix composites: challenges and opportunities," *Sadhana*, 2003; 28: 319–334.
- [2] J. Goni, I. Mitxelena, and J. Coletto, "Development of low coat metal matrix composites for commercial applications," *Mater Sci Technol*, Vol. 16, 2000, pp 743–746.
- [3] A. Pardo, M.C. Merino, S. Merino, F. Viejo, M. Carboneras and R. Arrabal, "Influence of reinforcement proportion and matrix composition on pitting corrosion behaviour of cast aluminium matrix composites (A3xx.x/SiCp)," *Corrosion Science*, Vol. 47, 2005, pp. 1750-1764.
- [4] J.A. Garcia-Hinojosa, C. González R., J.A. Juárez I. and M.K. Surrapa, "Effect of grain refinement treatment on the microstructure of cast Al–7Si–SiCp composites," *Materials Science and Eng. A*, Vol. 386, 2004, pp. 54-60.
- [5] S. W. Kim, U. J. Lee, S. W. Han, D. K. Kim and K. Ogi, "Heat treatment and wear characteristics of Al/SiC_p composites fabricated by duplex process," *Composites Part B: Engineering*, Vol. 34, 2003, pp. 737-745
- [6] E. P. Medécigo, M. I. Canul, M. R. Reyes and A. Gorokhovskiy, "Effect of processing parameters on the production of bilayer-graded Al/SiC_p composites by pressureless infiltration," *Materials Letters*, Vol. 56, 2002, pp. 460-464.
- [7] S. S. Joshi, N. Ramakrishnan, H. E. Nagarwalla and P. Ramakrishnan, "Wear of rotary carbide tools in machining of Al/SiCp composites," *Wear*, Vol. 230, 1999, pp. 124-132.
- [8] R. Rodríguez-Castro, R. C. Wetherhold and M. H. Kelestemur, "Microstructure and mechanical behavior of functionally graded Al A359/SiC_p composite," *Materials Science and Engineering A*, Vol. 323, 2002, pp. 445-456
- [9] M. I. Pech-Canul, R. N. Katz and M. M. Makhlof, "Optimum conditions for pressureless infiltration of SiC_p preforms by aluminum alloys," *Journal of Materials Processing Technology*, Vol. 108, 2000, pp. 68-77.
- [10] X. -P. Zhang, L. Ye, Y. -W. Mai, G. -F. Quan and W. Wei, "Investigation on diffusion bonding characteristics of SiC particulate reinforced aluminium metal matrix composites (Al/SiC_p-MMC)," *Composites Part A: Applied Science and Manufacturing*, Vol. 30, 1999, pp. 1415-1421.
- [11] M. Muratoğlu and M. Aksoy, "Abrasive wear of 2124Al–SiC composites in the temperature range 20–200 °C," *Journal of Materials Processing Technology*, Vol. 174, 2006, pp. 272-276.
- [12] I. Dutta, S. M. Allen, and J. L. Hafley, "Effect of reinforcement on the aging response of cast 6061 Al–Al₂O₃ particulate composite," *Met Trans*; 22 A, 1991, pp 2553–2563.
- [13] J. Y. Uan, L. H. Chen, and T. S. Lui, "On the extrusion microstructural evolution of Al–Al₃Ni in situ composite," *Acta Mater*, 49, 2001, pp. 313–320.

خصائص البري ومقاومة الحرارة لمادة مركبة من الالومنيوم ومسحوق كبريد السليكون

هذه المقالة تهدف إلى بحث خصائص البري لمادة مركبة من الالومنيوم ومسحوق كبريد السليكون الذي تم إضافته بأحجام 3, 5, 10 ميكرون وقد تم صناعة هذه المادة بطريقة مزدوجة حيث تتكون من خطوتين التسريب مع العصر و السباكة مع العصر. كذلك فإنه تم دراسة تأثير إضافة مادة النيكل بنسب مختلفة علي التركيب البنائي وعلي سلوك البري والمقاومة للحرارة لهذه المادة المركبة. وقد أثبتت الدراسة أن إضافة مسحوق كبريد السليكون بأحجام صغيرة أدى إلي زيادة الصلادة للمركب في حالته التي تم الحصول عليه من السباكة بدون معالجات أو بعد معالجته حراريا عند درجة حرارة 250 أو 350 درجة مئوية ولمدة خمس ساعات, كما أظهرت النتائج بأن الكثافة قد زادت للمركب في حاله استخدام مسحوق كبريد السليكون بقطر 3 ميكرون, وكذلك فإن كمية المعدن المفقودة نتيجة البري كانت هي الأقل عند استخدام ذات المسحوق بذات القطر. من ناحية أخرى فقد تحسنت خاصية مقاومة المركب للحرارة عند اضافته النيكل, وقد أوضحت النتائج بأن مقاومة البري لهذا المركب عند درجة حرارة 200 درجة مئوية وفي وجود محيط من غاز الارجون قد زادت عنها في حالة إجراء التجارب عند درجة حرارة الغرفة أو عند ذات درجة الحرارة ولكن بدون غاز الارجون.