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An investigation into the wear behavior of aged Alumix321/SiC composites fabricated by hot pressing

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ABSTRACT: Aerospace or automobile industries need materials that have a combination of several features such as lightness, high strength, corrosion and wear resistance. With ceramic particulates reinforcement, the properties of aluminum alloys can be greatly improved. The aim of this study is to investigate the effect of precipitation age hardening and the mass percentage of SiC particles on hardness and wear resistance of the 6061 aluminum matrix composites produced by hot pressing. Composites were solution treated at 530 °C for 1.5 h and then artificially aged at 160 °C for 18 h. The ball-on-disc wear test was carried out under 2N load using an alumina ball as the counterpart. The density of the composites was calculated according to Archimedes principle. Porosity tended to increase with increasing SiC reinforcement. Hardness and wear resistance of composites were improved by SiC particles and aging. Maximum hardness and minimum wear loss was obtained heat treated sample that contains 20 wt.% SiC reinforcement.

KEYWORDS: Aging; Alumix321; 6061 Al alloy; Composite; SiC; Wear

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RESUMEN: *Investigación sobre el comportamiento al desgaste de los compuestos Alumix321/SiC envejecidos y fabricados por prensado en caliente*. La industria aeroespacial y del automóvil están necesitadas de materiales que combinen varias características, tales como bajo peso, elevada resistencia mecánica, alta resistencia a la corrosión y al desgaste. Las propiedades de las aleaciones de aluminio se pueden mejorar enormemente mediante el refuerzo utilizando partículas cerámicas. El objetivo de este estudio es analizar el efecto del envejecimiento por precipitación en el endurecimiento y el porcentaje de masa de partículas de SiC en la dureza y resistencia al desgaste de los compuestos de matriz de aluminio 6061, fabricados mediante prensado en caliente. Los compuestos se trataron en solución a 530 °C durante 1,5 h y luego se envejecieron artificialmente a 160 °C durante 18 h. La prueba de desgaste mediante un disco de bola se llevó a cabo con una carga 2 N y utilizando una bola de alúmina. La densidad de los compuestos se determinó de acuerdo con el principio de Arquímedes. La porosidad aumentó a medida que se incrementó el refuerzo de SiC. La dureza y la resistencia al desgaste mejoraron con las partículas de SiC y el envejecimiento. La dureza máxima y la pérdida de desgaste mínima se obtuvieron en muestras tratadas térmicamente que contenáin un 20% en peso de refuerzo de SiC.

PALABRAS CLAVE: Aleación aluminio 6061; Alumix321; Compuesto; Desgaste; Envejecimiento; SiC

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1. INTRODUCTION

Metal matrix composites (MMCs) are composites that comprising reinforcement of several one or more materials made of the metal structure. Metals are reinforced with hard particles such as SiC, B_4C, TiC, and Al_2O_3 to enhance mechanical properties such as hardness, Young's modulus, and yield strength. Today, aluminum metal matrix composites (AMMCs) are widely used in many areas such as aerospace, automobile, structural applications and electronic industries because of their lightness, corrosion resistance, low coefficient of thermal expansion, favorable machinability and enhanced mechanical properties (Laska and Kazior, 2012; Knowles *et al.*, 2014; Hassani *et al.*, 2014; Wu and Kim, 2015; Soltani *et al.*, 2017; Salman, 2017; Ulvi Gezici *et al.*, 2018; Jiang *et al.*, 2019).

AMMCs can be manufactured by different techniques. For instance, Soltani *et al.* (2017) produced Al-SiC composites with stir casting. Powder metallurgy is another technique to produce metal matrix composites with a high homogeneity (Salman, 2017). The researchers have focused on mechanical and microstructural properties of AMMCs produced by hot pressing (Ogel and Gurbuz, 2001; Tang *et al.*, 2004; Gu, 2006; Suśniak *et al.*, 2015).

Karabacak *et al.* (2017) have produced Al2024-B_4C nanocomposite by hot pressing. They reported that the increased reinforcement ratio enhanced hardness, tensile strength and density of the composite. In contrast, there are fewer studies about the tribological properties of hot-pressed AMMCs. Nassef and El-Hadek (2015), produced Al-Al_2O_3 composites and investigated their dry sliding wear behavior. Bedir (2007), applied pin-on-disc wear test to Al–Cu–SiCp and Al–Cu–B_4Cp composites using abrasive papers fixed to a disc.

In case of using a heat treatable aluminum alloy, the matrix phase experiences solution treatment that involves the excess dissolution of the precipitates under hot pressing conditions (Wierszyłłowski *et al.*, 2005; Wang *et al.*, 2017) and perform less mechanical strength than expected in despite of hard reinforcement particles. The artificial aging heat treatment may overcome this undesired result of hot pressing. The novelty of the present study is to investigate the effect of both the amount of SiC reinforcement and aging treatment on mechanical properties and wear behavior of hot pressed Alumix321-SiC composites.

2. MATERIALS AND METHODS

2.1. Sample preparation

In this study, Alumix 321 coded pre-alloyed powders, from ECKA were used as a matrix material (Table 1). Alumix 321 contains magnesium and silicon as the main alloying elements. The powders produced by using gas atomization technique have an average size of 63 μm. The densities of Alumix 321 and SiC are 2.69 $g\cdot cm^{-3}$ and 3.31 $g\cdot cm^{-3}$ respectively.

The SiC particulates were dispersed in the matrix with 5, 10 and 20 % by weight. Powders were mixed with 3D shaker-mixer (Turbula T2F) for 30 min. Then mixed powders were loaded into a steel die and produced with a unidirectional hot press. Schematic illustration of the hot pressing unit is shown in the Fig. 1.

The production steps of the Alumix321/SiC powder composites followed the order of cold pressing at room temperature under 100 MPa for 30 s and hot pressing at 500 °C under 300 MPa for 1 h. The produced Alumix321/SiC bulk composite was cut into 20×20×10 mm^3 pieces. The aging process is applied to a portion of the hot pressed samples, while maintaining only a portion of hot-pressed state. A portion of hot pressed composites were solution treated at 530 °C for 1.5 h and then artificially aged at 160 °C for 18 h. Then all specimens were mechanically ground using abrasive SiC papers of increasing grade and finished with 1200 grit. They were polished with 6 and 3 μ diamond suspension and then cleaned with ethanol.

2.2. Characterization: Density and Microstructure

The density of the Alumix321/SiC composites was calculated using water displacement approach (Archimedean density, Buoyancy method). The theoretical density of Alumix321/SiC composites was calculated using the rule of mixtures. Samples were weighed in the air (W_a) then dropped in the water and weighed again (W_w) The actual densities were calculated according to $\rho_a = [W_a / (W_a - W_w)] \times \rho_w$ equation.

Where ρ_a is the actual density, W_a is the mass of the sample in the air, W_w is the mass of the sample in water and ρ_w is the density of water. The samples were weighed using a digital balance with an accuracy of 0.1 mg.

TABLE 1. Chemical composition of Alumix 321 (6061 Al) powder

Element	Mg	Si	Cu	Fe	Bi	Sn	V	Al
wt.%	1.31	0.5	0.32	0.10	0.01	0.03	0.01	Balance

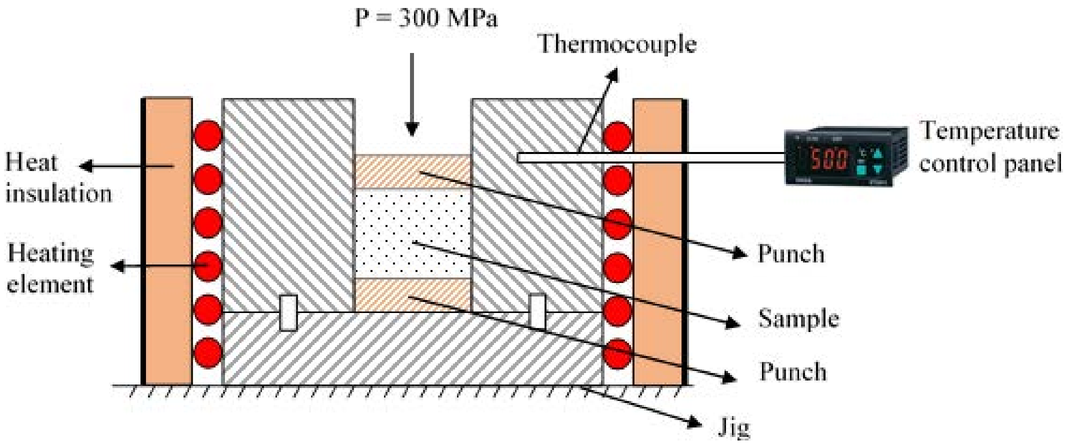

FIGURE 1. Schematic illustration of hot pressing system.

Optical, stereo microscopes and scanning electron microscope (SEM) were employed for microstructural examinations of Alumix321/SiC composites. Homogeneity of distribution of SiC particles was observed by optical microscope. Samples were investigated under a stereo microscope after the wear test.

2.3. Hardness test

The hardness values of the samples were determined by a Brinell Hardness Tester (Duravision 2000 EMCO Test) and the mean of at least ten measurements was recorded at a load of and 6.25 kgf with 2.5 mm steel ball. The test was carried out at room temperature and the measurements were observed at least 10 different locations to increase reliability.

2.4. Wear Testing

Wear tests were carried out on the CSM instruments ball-on-disc wear-test unit (Fig. 2). The sliding distance was 200 m for each specimen. Alumina balls were used as an abradant counterpart and the contact load was set to 2N. The ceramic ball has a diameter of 6 mm. The tests were performed under a dry condition at room temperature. The dry sliding system was selected as tribosystem. Determination of the wear loss was carried out by calculating the volume loss. The depth of the trace was calculated by a profilometer on this trace and volume loss was found. Wear traces were examined by using SEM.

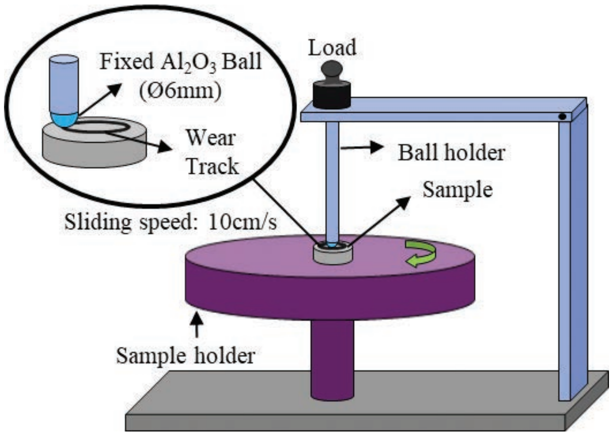

FIGURE 2. Schematic model of ball-on-disc wear-test unit.

3. RESULTS AND DISCUSSION

3.1. Microstructure and Density

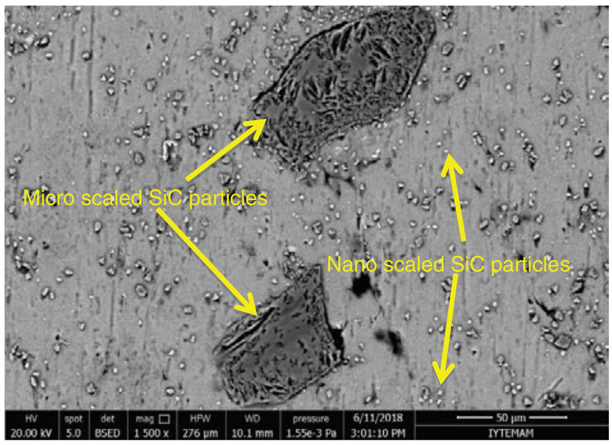

FIGURE 3. SEM image of Alumix 321+5 wt.% SiC: Micro and nano scaled SiC particles.

Microstructure of the composites consists of micro and nano scaled SiC particles embedded in a heat treatable Alumix321 matrix (Fig. 3). Optical microscopy revealed that the Alumix321 powders tended to form grains around the SiC particles that act like nucleation sites (Fig. 4).

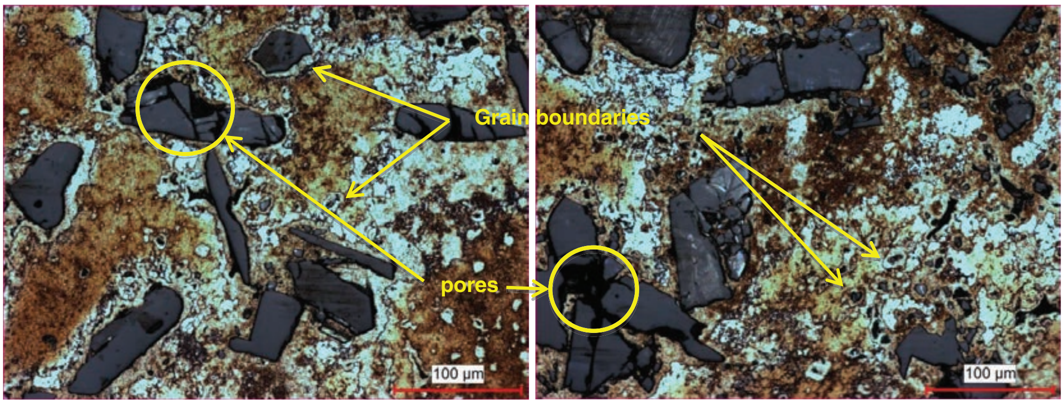

FIGURE 4. Microstructure of Alumix 321 + 20 wt.% SiC.

During the pressing process SiC particles tend to redistribute and gather together due to their low plastic deformation ability (Wang *et al.*, 2017). In the case of adding 20 wt.% SiC particles, local reinforcement accumulation increased by clustering because of the resistance of SiC against plastic deformation. Due to these clusters, the voids between the SiC particles were not closed during sintering and were increased the porosity (Fig. 4). The changes in density of the produced composite samples at 500 °C and under 300 MPa pressure are given in Table 2. As it is seen, the percentage of relative densities varies between 97.5–99.3% depending on the amount of reinforcement. The lowest percentage of relative density was observed in 20 wt.% SiC reinforcement composite. The reason of this can be referred to the increase of interface gap ratio between particle/matrix and particle/particle. Especially, particle agglomeration has limited the effect of sintering and cause of the gaps in the regions that have a high particle concentration. Table 2 also indicates that the porosity tended to increase with the increasing SiC reinforcement. The percentage of porosity that is which was 0.74 in Alumix 321, increased to 2.49 with the increase of the reinforcement. This observation is line with the study of Mazahery *et al.* (2009). Mazahery *et al.* (2009) observed an increase in porosity of A356/nano-Al_2O_3 composites with increasing the volume fraction of Al_2O_3. As the number of particles in the matrix increases, gap ratios are also increased (Mazahery *et al.*, 2009).

Images of volume fraction calculations of composites are given in Fig. 5. According to the weight percentage values of composites, theoretical volume fraction was calculated for each sample. Average volume fractions of SiC particles obtained by the image analysis of Clemex software were found to be close to the theoretical values (Table 3). It can be stated that SiC particles exhibited nearly uniform dispersion in the Alumix321 matrix.

3.2. Hardness and Wear

The change in the hardness values of the samples is shown in Fig. 6. Hardness values increased with the increasing SiC reinforcement ratio in Alumix321 matrix. Altinkok and Koker (2004) produced aluminum matrix composites reinforced with Al_2O_3/SiC particles by stir casting (Altınkok and Koker, 2004). They observed that hardness and tensile strength of composites are strongly dependent on reinforcement that inhibits the movement of dislocations. In fact, in present study the porosity increased by increasing the amount of reinforcement and it was expected that it would decrease the hardness. However, the change in the porosity is very small in comparison with the increase of the reinforcement ratio. Therefore, the

TABLE 2. Theoretical and hot pressed density values of the composites

Compositions	Theoretical Density ($g\cdot cm^{-3}$)	Hot pressed Density ($g\cdot cm^{-3}$)	Percentage of porosity (%)	Percentage of relative density (%)
Alumix321 + 0 wt.% SiC	2.69	2.67	0.74	99.26
Alumix321 + 5 wt.% SiC	2.72	2.66	2.20	97.80
Alumix321 + 10 wt.% SiC	2.75	2.71	2.18	97.82
Alumix321 + 20 wt.% SiC	2.81	2.74	2.49	97.51

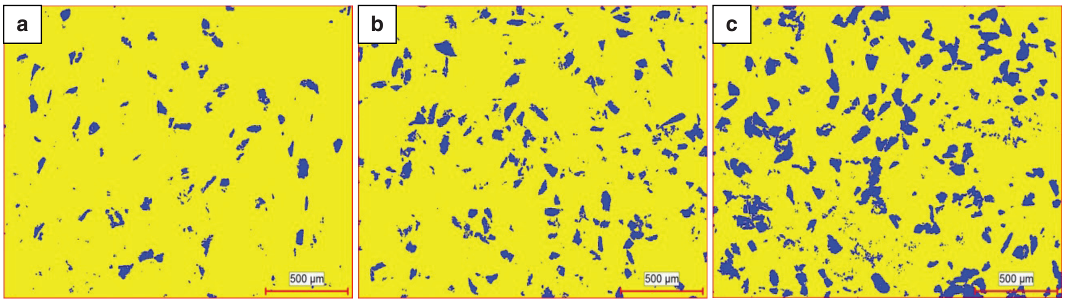

FIGURE 5. Volume fraction of SiC particles: a) 5 wt.% SiC, b) 10 wt.% SiC, and c) 20 wt.% SiC.

TABLE 3. Volume fraction of SiC particles

SiC (wt.%)	Theoretical Volume Fraction	Image Analysis
5%	4.25%	3.91 ± 0.5 %
10%	8.56%	9.31 ± 1.1 %
20%	17.37%	17.23 ± 0.9 %

effect of SiC particles on the hardness of the composite plays a more decisive role than the effect of porosity caused by the clusters of these particles on hardness. In addition, mechanical properties of composites were enhanced by precipitation age hardening. The hardness of the Alumix321/SiC composites increased between 21–26% after the aging process. Mechanical properties of Al-Mg-Si alloys can be enhanced by aging treatment that is applied in order to precipitate the Mg_2Si hardening phases (Elangovan and Balasubramanian, 2008; Ozturk *et al.*, 2010; Ahmad and Bakar, 2011). Mg_2Si precipitates hinder the movement of the dislocations (Wang *et al.*, 2017) and improve the mechanical properties of composites by strain hardening.

Cui *et al.* (2016) reported that the role of SiC reinforcement is not limited with increasing the dislocation density. The interface between the SiC particles and aluminum matrix also provides nucleation sites for Mg_2Si precipitates during the aging process (Cui *et al.*, 2016). Although they asserted that increasing volume fraction of SiC supports this phenomenon, the findings of the present study revealed that the more homogeneous distribution and the less porosity are required for this phenomenon to be actualized as expected. The hardness of unreinforced powder metal product increased about 21% after aging treatment. The percentage of hardness increment achieved its maximum value in the sample reinforced with 5 wt.% SiC and started to stepdown with increased SiC reinforcement (Fig. 6). It was thought that the clusters of SiC particles increase the porosity and decrease the interface between

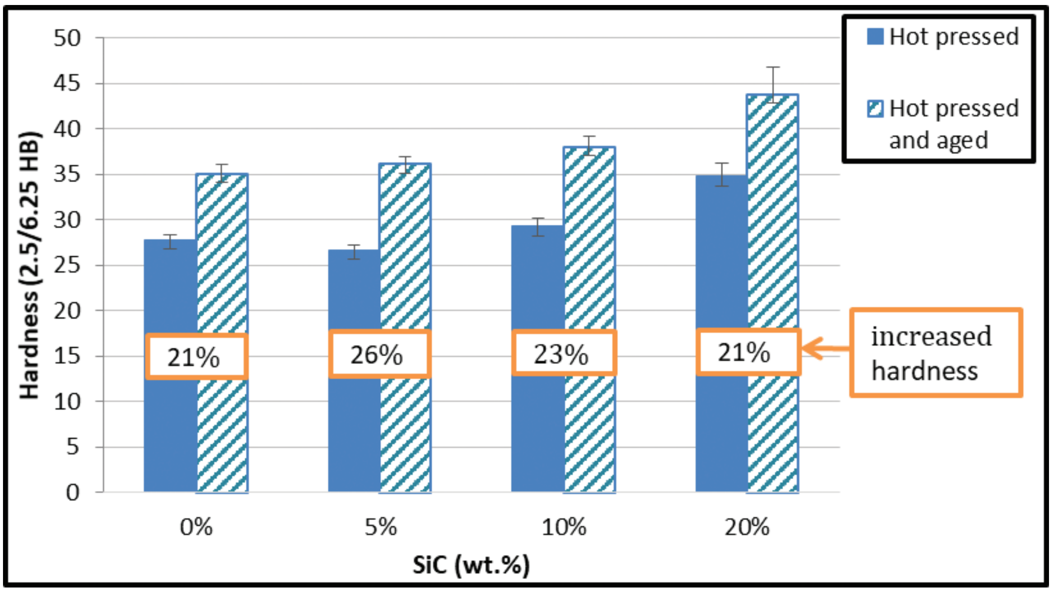

FIGURE 6. Hardness values of composites before and after aging.

Alumix321 matrix and SiC particle. Consequently, the encouraging effect of SiC particles on the nucleation of Mg_2Si during the aging process went down.

The volume losses of the composites before and after the precipitation age hardening are shown in Fig. 7. It is obvious that the SiC reinforcement increased the wear resistance of the Alumix321 matrix composites reducing the volumetric material loss between 32–63%. Aging treatment contributed to the wear resistance of the Alumix321/SiC composites. Volume loss of unreinforced Alumix321 powder product was decreased about 13% by aging treatment. The most significant reduction in volume loss that was calculated as 35% was observed in Alumix321 composite reinforced with 5 wt.% SiC. Unexpectedly, the composite reinforced with 20 wt.% SiC performed almost no reduction in volume loss after precipitation age hardening despite of achieving the maximum hardness values upon others. In general, the harder a material is, the more wear resistant it is. But in terms of composite materials, wear resistance is not only related with hardness but also with the type, amount and distribution of reinforcement and interaction between the reinforcement particles and matrix. In this context, the clusters of SiC particles may cause an undesired condition for wear resistance while a harder matrix may reduce the material loss. For instance, aging reduces ductility when increasing the strength of heat treatable aluminum alloys (Reis *et al.*, 2012). A harder Alumix321

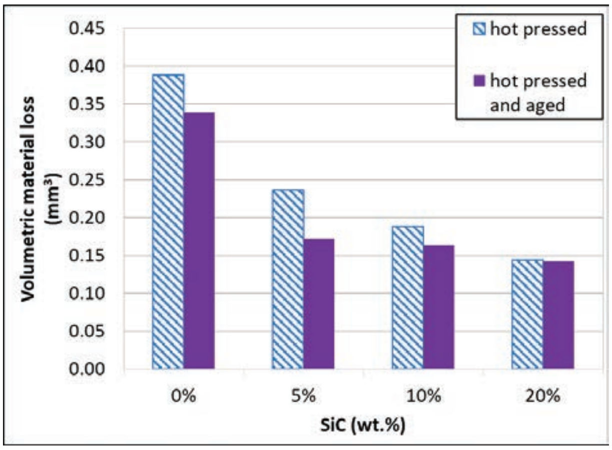

FIGURE 7. Volume losses of the samples after the wear test.

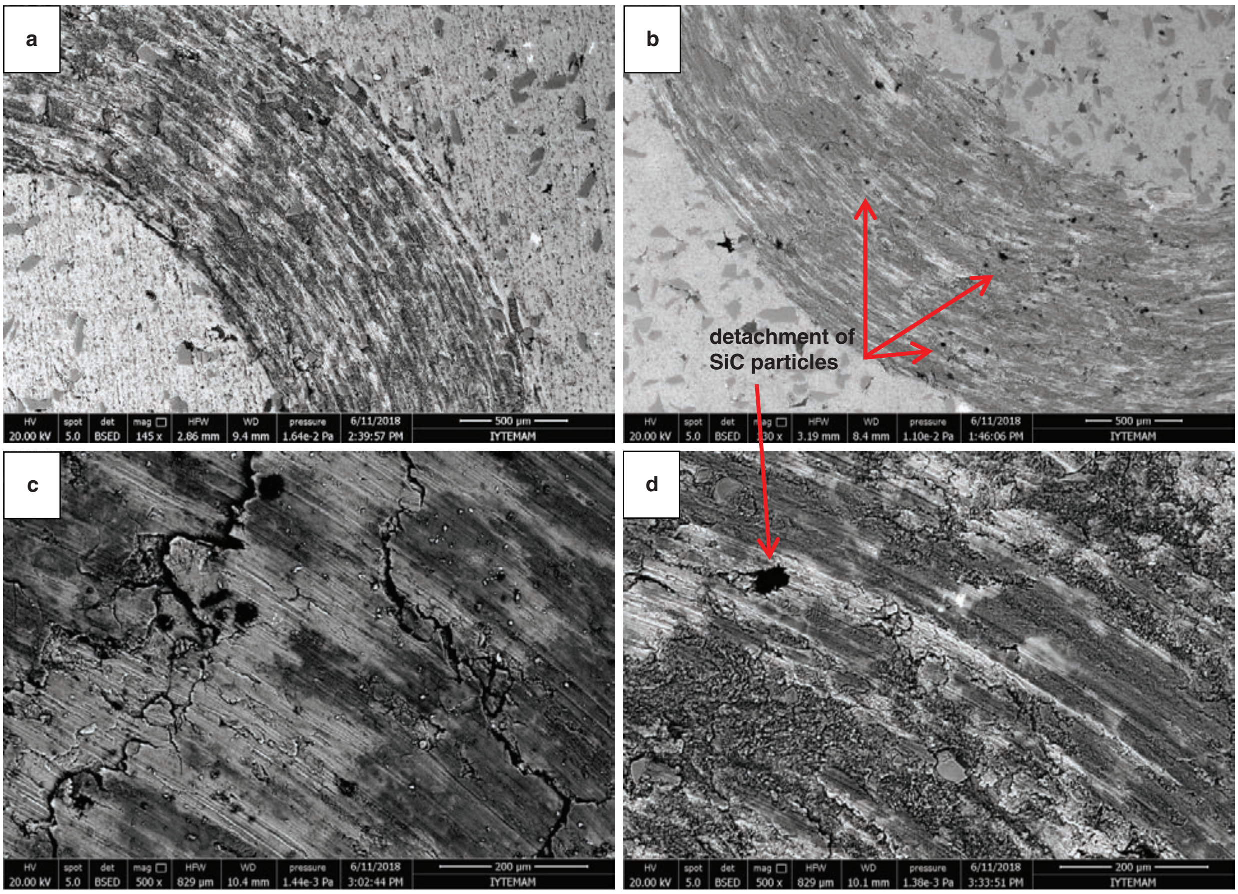

FIGURE 8. Worn surface of: a) 10 wt.% SiC composite without aging, b) aged 10 wt.% SiC composite, c) aged and unreinforced sample, and d) 5 wt.% SiC composite without aging.

matrix with a low ductility and SiC particles resist to abradant such as aged Alumix321 + 5 wt.% SiC composite. However, low ductility of the aged Alumix321 matrix did not exhibit the expected wear performance by increased SiC amount due to the formation of SiC clusters that decrease the contact surface between Alumix321 matrix and reinforcement particles. Decreased contact surface with a less ductile matrix would cause detachment of SiC reinforcement easily during the wear test (Fig. 8b).

Worn surfaces of Alumix321/SiC composites involve scratches that indicate the abrasive wear (Fig. 8). The alumina ball smeared the Alumix321 matrix during the wear test. Plastic deformation occurred as a consequence of smearing and the Alumix321 matrix experienced strain hardening that caused the formation of cracks due to the induced brittleness (Fig. 8c and 8d).

4. CONCLUSIONS

Alumix321/SiC composites were produced successfully by hot pressing. The density of composite without SiC particles is 99.26 %. The effect of the ratio of the SiC reinforcement and aging treatment can be summarized as follows:

- In the Alumix321 matrix, the SiC reinforcement exhibited a close distribution of homogeneity. The density of SiC reinforced composites varies between 97.82–97.51%. Increased fraction of SiC reinforcement diminished the compressibility and caused an increase of porosity in Alumix321/SiC composites.
- Maximum hardness value was achieved at composites with 20 wt. % SiC reinforcement. The hardness of composites tended to increase with increasing SiC content.
- As the amount of SiC wt.% in matrix was increased, the wear resistance of the samples increased. 20 wt.% SiC containing sample was showed the maximum wear resistance.
- Aging treatment has improved the hardness of Alumix321/SiC composites by 21–25% in comparison with the non-heat treated condition. However, the amount of reinforcement has not exhibited a significant effect on wear rate in case of applying heat treatment. When the hardness and wear test results are analyzed for all samples, 5 wt.% SiC reinforcement is found to be sufficient for aged Alumix321/SiC composites for wear resistance.

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