

Investigation of Heat Treatment on Silicon Carbide Composite Compared with Silicon Nitride Composite for Reinforced Aluminum Matrix

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ABSTRACT

The purpose of this study is to determine the additional effect of heat treatment on the hardness, corrosion resistance, and mechanical strength of cast aluminum matrix composites reinforced with SiC. Additionally, this study investigated the strength and hardness of both silicon carbide (SiC) and silicon nitride (Si_3N_4) reinforced aluminum composites and compared with previous research conducted in the lab, where only silicon carbide was added. Silicon nitrides are a group of advanced engineering ceramics with high strength, fracture toughness, hardness, wear resistance and good chemical and thermal stability. Due to the excellent combination of properties, silicon nitride is used in various structural applications. The effects of heat treatment will be compared to an identical but untreated cast aluminum matrix composite reinforced by SiC, and additionally to the unaltered base aluminum matrix. Accordingly, both composite samples were created from the same batch of matrix alloy in combination with SiC, melted and homogenized in an induction furnace to ensure stability and consistency of crystal structure. Microstructure and morphology analyses were conducted, the hardness was measured by the Micro Vickers hardness tester (HM-200), corrosion of the samples was tested using a salt spray chamber, and the tensile strength by a universal test machine. It was found that the heat treatment increased the hardness in the way of wear resistance of the AlSiC composite, improved the corrosion resistance, the tensile strength, and showed more favorable material properties than the unaltered test sample of the AlSiC composite.

Keywords: casting, heat treatment, salt spray, corrosion resistance, alloy, composite, ceramics, silicon carbide, silicon nitride

INTRODUCTION

As the field of manufacturing tirelessly investigates new materials that further the forefront of performance and economical pricing, focus and demand have lingered on refining and enhancing aluminum alloys. Aluminum, as a

material, demonstrates tremendously favorable properties, including outstanding corrosion resistance, low coefficient of thermal expansion, castability and machinability, in addition to its light weight.¹ This is no new discovery, however, with the aerospace and electronics industries championing aluminum-silicon alloys, especially SiC and Si_3N_4 alloys for their superior properties at their economical values. Materially, aluminum serves as the base matrix, wherein the SiC and Si_3N_4 particles disperse throughout and strengthen the overall composite, coalescing the benefits of each material to bolster the other and form an overall stronger alloy.²⁻⁴ Silicon carbide and silicon nitride, the additives to the base matrix of aluminum that this study will focus on, lend great strength and hardness to the materials they are used in. The strength of SiC stems from its tetrahedral structure, held together in a crystal lattice by the bonds between the silicon and carbon atoms.⁴ SiC has thermal stability up to 3452F (1900C), and an extremely low oxidation rate.⁵ The key components of AlSiC's strength comes from its ideal aluminum base matrix bolstered by the homogeneous distribution of SiC particles, wherein the material benefits of each material supports and enhances the other. A homogeneous distribution of particles is shown to be important for ductility, strength, fracture behaviors, and fatigue. Previous studies have shown that the silica layer which develops at the surface of the SiC or Si_3N_4 plays an important role in the corrosion resistance of both materials.⁶ SiC and Si_3N_4 previously displayed excellent corrosion resistance, performing better than corrosion resistant monolithic materials.⁷ Some testing suggests that SiC and Si_3N_4 show more consistent behavior in the corrosion process when compared to other aluminum metal matrix composites, which may also be a desirable quality for use in more corrosive environments.⁸ The additional resistance to alkalis, molten salts, or acids on the part of SiC adds another layer of corrosion resistance to the already advantageous corrosion resistance properties of aluminum, making it an absolute powerhouse of a versatile material.

In practice, however, homogeneous distribution of the particles of both additives is exceedingly difficult to

achieve through traditional means.⁹ In a previous study, induction heating was employed to better homogenize the composites, and in large part, was a success in showing superior strength, wear resistance, and hardness to the base metal control. Aluminum matrix compounds consist of the aluminum and the reinforcement, another metal or a ceramic. They are significantly improved when reinforced by ceramic particles, as hardness, Young's modulus, and tensile strength is considerably increased.¹⁰

When working with particulate reinforced composites the particle wettability, particle shape, dispersion uniformity, and particle uniformity will affect the composite's properties.¹¹ A liquidus projection of AlSiC shows isothermal sections at 3902F (2150C), 3632F (2000C), 1652F (900C), 1062F (572C), 1035F (557C), and 932F

(500C), as well as vertical sections along the Al_4C_3 -SiC and AlSiC joints.¹² AlSiC has a higher density and better corrosion resistance than a pure Al matrix.¹³ However, the pure Al performed better against corrosion than AlSiC at temperatures ranging from 122F (50C) to 167F (75C). The final composite still leaves potential enhancement of strength and ductility untapped, even after showing superior strength and hardness to the base aluminum matrix. Since the residual stresses ingrained within the casting from its cooling were still present, a possible means of relieving the composite of such stresses and enhancing its ductility, hardness, and potentially even electrical conductivity, is heat treatment. Heat treatment improves the hardness of Al compounds by 20-25%, because of the formation of intermetallic precipitates.¹⁴

Table 1. Aluminum Matrix Composition

Si	Fe	Cu	Mn	Mg	Cr
0.067%	0.085%	0.014%	0.120%	7.500%	0.0001%
Zn	Ti	Sn	Pb	Ni	Al
0.015	0.200%	0.001%	0.001%	0.008%	Rem

MATERIALS

The aluminum alloy, shown in Table 1 by its discrete parts, serves as the matrix material for this study. The SiC and Si_3N_4 with an average particle size of 50 μ m are then added to separate samples of the molten alloy from the induction furnace and homogenized. The material, composed by means of normal methods, resulted in a variety of particle shapes between batches.

METHOD

To create the test samples, the aluminum alloy was melted down in a ceramic crucible in an induction furnace (Fig. 1). The melting temperature of the base aluminum matrix was 1300F (704C) and the homogenization temperature was 1350F (732C). It took ten minutes, mixing at homogenization temperature to fully blend the composite. The melted alloy was then poured into a second ceramic crucible with the 15% SiC powder, and a third with 15% Si_3N_4 , wherein they were mixed constantly during the pour and homogenized. Following the blending process, the molten alloys were poured into a small ladle, where the mixtures cooled and solidified. The composites cooled from 1350F (732C) to 72F (22C) in twenty minutes, with 72F (22C) being the ambient temperature of the foundry.

That yields an estimated cooling rate of 63.9°F/min (35.5°C/min). Once cooled, the AlSiC was removed from the ladle and heat treated at a temperature of 250F (121C) for fifteen minutes, while the $AlSi_3N_4$ mixture was left untreated. After the heat treatment was finished, the composite sample was air cooled. All surfaces on each of the samples, including the edges, were wet ground using 120, 220, 320, 600, 1000, and 1200 grit silicon carbide papers. These samples were subsequently rinsed in distilled water followed by polishing with an alumina powder to get a bright mirror finish for the final step using a grinder and polisher (Fig. 2). Finally, these samples were degreased with acetone and then ultrasonically cleaned for ten minutes using ethanol as a medium.

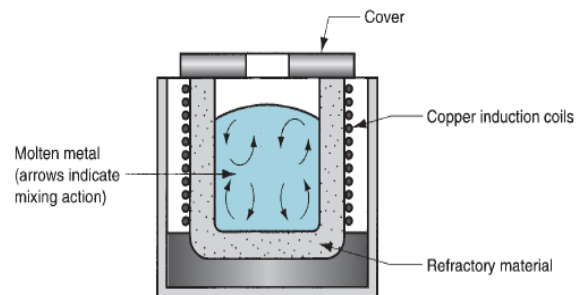


Figure 1. A schematic for an induction furnace is shown.¹⁵

EXPERIMENTAL

The composites were polished prior to observation. The hardness of the composites was measured using the Micro Vickers hardness tester (HM-200) using a specific load of 0.50 kilograms. The mean value of no less than five measurements determines the final, stated hardness value.

Tensile testing was carried out using a strain rate of two millimeters per minute at room temperature, using a computerized tensile testing machine. Samples of unaltered aluminum, and samples of the matrix material, both heat treated and untreated, are then machined by computer numerically controlled (CNC) milling to the specification shown in Fig. 3.

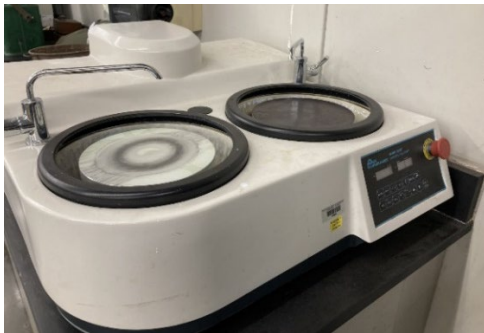


Figure 2. The polishing machine used on the samples.

Corrosion resistance of the three samples was determined by salt spray testing, over the course of 100 hours. The salt spray test was held at 1 bar of pressure, in humidity of 50%. The temperature in the salt spray chamber during the test was maintained at 132F (55C).

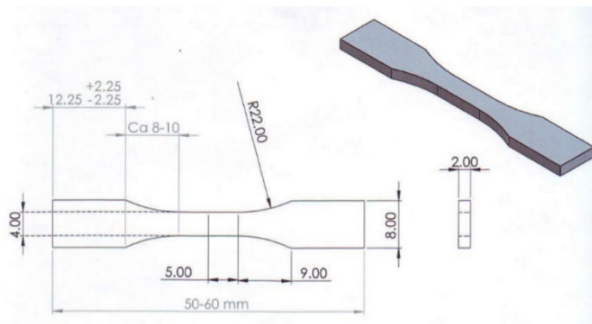


Figure 3. The dimensions of the tensile test specimen are shown.

RESULTS & DISCUSSION

MICROSTRUCTURE

Examination of the AlSiC microstructure yielded largely homogeneous distribution of SiC throughout the base matrix. Due to the high difficulty of blending the composite to achieve fully uniform SiC dispersion, a few spots of non-homogeneous mixture by way of SiC clusters were recorded (Fig. 4-6).

Scanning electron microscopy (SEM) images would be beneficial for comparison between the composite materials, but testing equipment was unable to be used for the AlSi₃N₄.

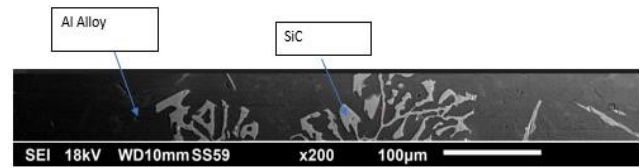


Figure 4. SEM view of Al-SiC at 200x.

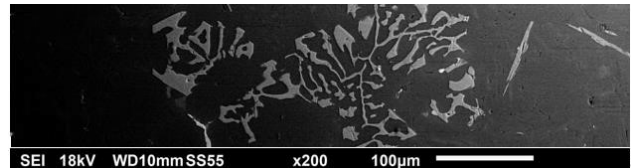


Figure 5. SEM view of Al-SiC at 200x.

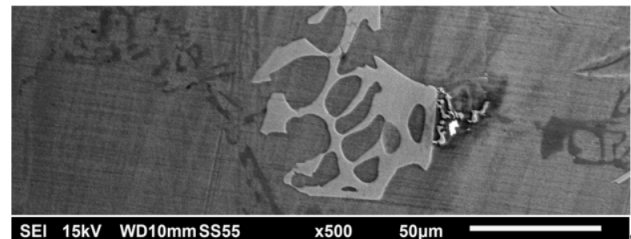


Figure 6. SEM view of Al-SiC at 500x.

HARDNESS

Hardness, namely in the way of resistance to scratch or indentation, was measured across the three different samples by a Micro Vickers hardness tester. These tests were conducted across five different areas on each of the four samples, and then averaged to determine the sample's Vickers microhardness rating. The control group of unaltered aluminum measured at 81 HV, the untreated AlSiC sample at 97 HV, the heat-treated counterpart at 109 HV, and the AlSi₃N₄ sample at 101HV.

SURFACE ROUGHNESS

A surface roughness gauge was used to find R_a (Fig. 7). This value is the arithmetic average deviation of the surface valleys and peaks as irregularities measured. It is important to observe the surface roughness of the AlSiC composite after polishing, since imperfections of the surface roughness can denote potential points of fracture or part failure later on in the lifetime of the part. Additionally, in upholding rigorous industry standards for surface finish, it is useful to observe and compare the heat treated composite sample in reference to other alternate materials.

Similar to the hardness tests, five different sections of the composite sample were tested, with the resultant roughness value derived from the mean value of the five samples (Fig. 8). The roughness value of 0.332 Ra (μm) was observed. Manufactured parts must take care to avoid irregularities in shape and sizes, as changes in geometry lead to concentrations in stress.¹⁶ In this way, surface roughness values play an important part in determining additional processing of a material, thus, the values taken for each composite should be taken into consideration when deciding what material a manufacturer should choose.

In testing, the samples of the AlSi_3N_4 composite had a smaller Ra value by a factor of 0.1 micrometers across all samples. While this difference is small, it is not negligible and points to the notion that AlSi_3N_4 may be the more suitable material depending on specific application. This preliminary result requires further investigation into the particle distribution and formation that occurred during mixing before, as well as further testing for replication before a definitive answer can be achieved.

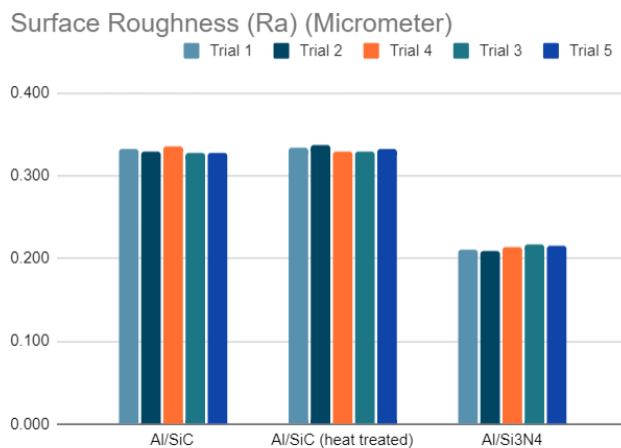


Figure 7. The surface roughness average of AlSiC before and after heat treatment, as well as AlSi₃N₄.

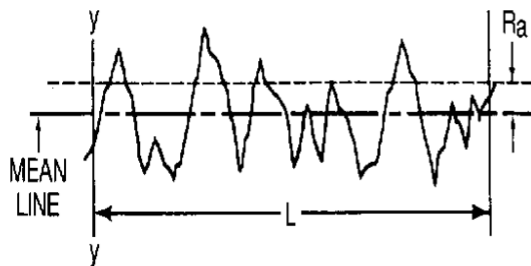


Figure 8. A visual representation of the mean surface roughness value.

TENSILE

The evolution of fine grains of the SiC is essential in the strength increase for Al. Tensile forces are transferred from the Al matrix to the SiC (Fig. 9) particles leading to the compound handling greater loads. Wettability between the particles and the matrix is an important factor in the composite's tensile strength. The addition of SiC particles to the Al matrix increased the average tensile strength of the specimens from 276.47 MPa to 307.18 MPa. This is due to the SiC particles impeding dislocation movement. The heat treated sample showed another increase with an average tensile strength of 316.76 MPa (Fig. 10). This effect is seen because of the smaller grain sizes after heat treatment. Performing the hardness and tensile tests showed a clear picture, that the monolithic material aluminum cannot compare in either hardness or tensile strength to both composites measured. The AlSi_3N_4 also outperformed the AlSiC composite in tensile strength by close to 20 MPa.



Figure 9. The computerized tensile test machine used is shown with AlSiC sample.

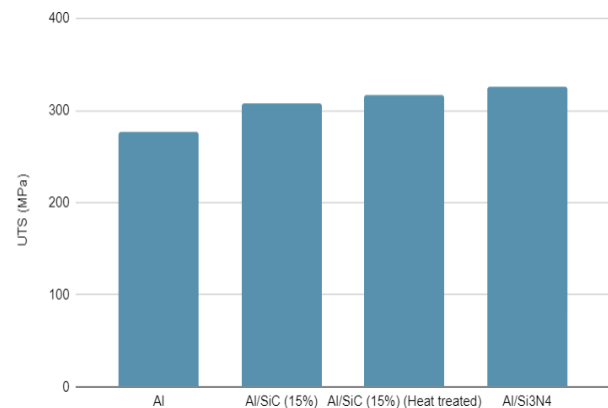


Figure 10. The ultimate strength (UTS) of Al with and without SiC reinforcement and heat treatment, as well as AlSi₃N₄ is graphed.

SALT SPRAY CHAMBER

Equipment required for this test included a spray chamber, atomizing nozzles, compressed air, method of heating the container, and a salt solution reservoir.¹⁷ This test involved a salt solution, typically a neutral 5% salt, being sprayed onto the samples (Fig. 11). The samples tested were the AlSiC composite before and after heat treatment to see how heat treatment would affect corrosion resistance.



Figure 11. The salt spray chamber used is shown.

The temperature was controlled inside the chamber. A continuous spray of the salt solution covered the samples in a mist. The samples were constantly wet and therefore affected by corrosion. The conditions for the samples in the salt spray chamber were: a pressure of 1 bar, temperature of 131F (55C), and 50% humidity. The brine reservoir capacity was 180 Liters with a 5% NaCl-Solution. The test was run for 100 hours and took the average of five samples for both AlSiC without heat treatment and a heat-treated sample. Mass loss was measured by scale, wherein the mass of the sample would be measured before the salt spray test, and then again afterwards. The samples were rinsed of residual salt in distilled water and then degreased with acetone.

Following cleaning, samples were placed on the scale and measured for total mass loss. Results show that the heat-treated sample was more resistant to general corrosion as it lost less weight than the sample with no treatment (Fig. 12). Corrosion testing results (Fig. 12) also indicated increased performance of the AlSi₃N₄ composite when compared to that of the AlSiC composite. The early weight loss of the AlSi₃N₄ was significantly less than that of the AlSiC, up to 40 hours. At that point, both composites experienced similar rates of weight loss. The chloride ions released from the NaCl dissolving in the water led to pitting. The water from the humidity added extra hydrogen which continues the pitting reaction, leading to trapping water within the pits and allowing coalescence. This result agrees with previous research done on the subject.¹⁸

Weight Loss over Time

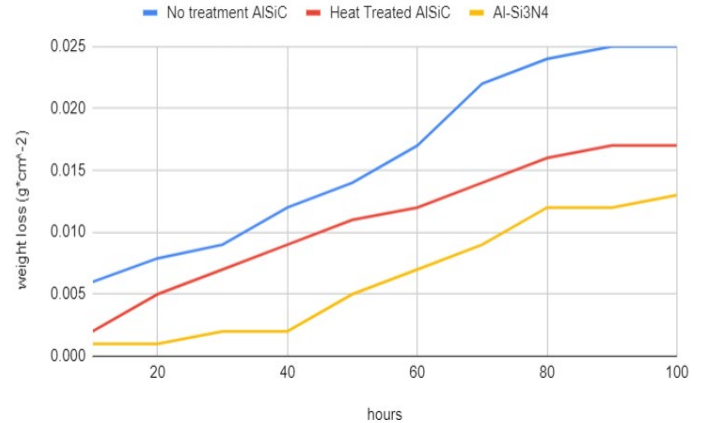


Figure 12. AlSiC with and without heat treatment as well as AlSi₃N₄ weight over time in salt spray chamber is graphed.

CONCLUSIONS

Overall, the mechanical properties of the AlSi₃N₄ outperformed those of the AlSiC composites in surface roughness, tensile strength, and corrosion resistance, while falling just short of the heat treated sample in terms of hardness. These data points are in line with previous literature, and the differences are likely due to differences in the microstructure developed through fabrication. AlSiC as an addition to aluminum alloys shows great hypothetical potential in adding hardness to an otherwise ductile and malleable material.

As shown, the hardness rating of the aluminum composite does increase favorably due to the involvement of the AlSiC, and even further so with heat treatment. The hardness and tensile tests show improvements of material properties as well in the heat treated test specimen, per greater hardness and higher tensile strength than the control group of the base aluminum alloy and the untreated composite. Corrosion resistance is also improved greatly by heat treatment, as observed by the salt spray chamber tests. Through the homogenization process, however, the SiC particles show a tendency to cluster and unevenly group throughout the cast composite. Despite the drawback of uneven dispersion of SiC particles, the addition of SiC and heat treatment still demonstrates favorable enhancements of both the base aluminum and untreated AlSiC composite.

While the AlSi₃N₄ showed more favorable properties in several categories than either the pure aluminum or both AlSiC samples, the additional cost brought by AlSi₃N₄ will make AlSiC a very promising alternative for many manufacturers.

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