Mechanical Properties of Aluminum–4043/Nickel-coated Silicon Carbide Composites Produced via Stir Casting

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Abstract- In this study, Al-4043/Ni-coated SiC composite was developed via stir casting process and the mechanical properties of the composites investigated. The composites were produced with varying SiC reinforcement fraction between 5-25 wt%. The microstructure of the composites was characterized using optical microscope and tensile properties of the composite with the monolithic Al-4043 alloy were assessed using a universal testing machine. The composite hardness was assessed using a Brinell hardness testing machine, energy required to break the composite was assessed using Charpy impact testing machine and the wear rate of the composites were evaluated using a Rubin Disc machine. The composites were characterized to possess Al-SiC eutectic microstructure with SiC solid solution precipitates and SiC particles uniformly distributed in the Al matrix. The density of the composites was found to linearly increase with increasing SiC reinforcement fractions. The tensile strength, yield strength and elastic modulus were found to increase with increasing SiC reinforcement fraction and highest values obtained for composite with 25 wt% SiC were 350 MPa, 254 MPa and 13.4 GPa respectively. However, the elongation of the composite with the highest reinforcement was lowest at a value of 10%. The hardness, compressive strength and impact energy of the composites increased significantly as composite with 25 wt% SiC possessed 76 HB, 184 MPa and 48 J respectively. The wear resistance of the Al-4043/SiC composites with highest SiC reinforcement was found to be eleven times that of the monolithic Al-4043 alloy.

Keywords Metal Matrix Composite, Aluminum, Silicon carbide, Nickel coating, Mechanical properties, Wear, Hardness, Impact.

1. Introduction

Advances in technology has placed a demand on the development of novel engineering materials which would possess high strength to weight ratio, excellent toughness, high wear- and corrosion-resistant properties such that these materials can easily replace heavy ferrous alloys in automobile, aerospace, turbomachinery, nuclear, defence and other industrial applications. For example, in automobile industries, the reduction of fuel consumption as well as greenhouse gas emissions is of great concern and can be achieved through the use of light metal alloys or composites for the development of some vehicle parts such as engine block, piston, connecting rod, brake disc, and car bodies amongst others. In light of this, Natarajan *et al.* [1] proposed the use of Aluminum metal matrix composites as brake disc material to replace the conventional grey cast iron. Metal-Matrix composites, especially the particulate reinforced ones, have been reported as a suitable material for various engineering applications where high stiffness-to-weight ratio, significant weight reduction, improved wear resistance and high thermal stability are desired when compared to unreinforced monolithic alloy [2,3]. Aluminum-silicon carbide (Al-SiC) composites have been found promising as engineering structural materials owing to its excellent properties and are produced via either solid phase (powder metallurgy, hot isostatic pressing etc) or liquid phase (squeeze casting, stir casting etc) processing routes. These Al/SiC composites are being developed using different Al alloys as matrix and are subjected to both microstructural examination and mechanical tests.

In a recent study, Moses *et al.* [4] developed Al-6061/SiC composites with varied SiC content from 5-15 wt.% using stir casting approach and examined the microstructure and mechanical properties of the composites. It was reported that the presence of the SiC reinforcement in the composites improved the microhardness to 105 HV and tensile strength to 220 MPa as recorded for composite with 15 wt.% SiC. In another similar study, Balasubramanian and Maheswaran [5] investigated the mechanical resistance behavior of AA6063/SiC composites with reinforcement fraction ranging 5-15 wt.% SiC produced via stir casting, and observed an increased resistance against indentation with 860 N/mm^2 as highest hardness value and tensile load with 175 MPa as highest tensile strength for the highest reinforcement fraction. The examination of the composites under SEM revealed that the addition of SiC initiated cleavage facets and led to brittle fracture when subjected to tensile forces with minimal elongation, and low material removal under sliding load. Rahman and Rashed [6] investigated the microstructure, mechanical properties and wear characteristics of as-cast Al/SiC composites with varied SiC composition ranging 5-20 wt.%. It was reported that maximum hardness of 45 HV and tensile strength of 77.6 MPa were obtained from composite possessing 20 wt.% SiC reinforcement and also had the lowest cumulative mass loss during wear experiment. Selvam et al. [7] fabricated Al MMC reinforced with varying fractions of SiC and Fly ash with addition of magnesium during a modified stir casting technique and the wetting of the SiC and Fly ash particles was enhanced by the presence of the magnesium. The addition of the Fly ash was reported to have prevent the dissolution of the SiC_p and formation of Al_4C_3, and the hardness and tensile strength of the Al matrix were significantly improved with increase in reinforcement fraction employed. In another study, Anand and Gowda [8] disclosed, upon fabrication of Al MMCs with varying SiC reinforcement fractions, that the composite hardness, tensile strength and compressive strength improved with increasing SiC wt.% reinforcement fraction with highest values of tensile strength 136 MPa, compressive strength 656 MPa and hardness 68 HB reported for Al MMC with 8 wt.% SiC reinforcement. Hassan *et al.* [9] developed Al-6063/SiC MMCs via stir casting and evaluated their mechanical properties. It was reported that the tensile, compressive and impact strengths improved by 48%, 43% and 79% respectively when compared to that of the monolithic alloy.

Previous work on the development and characterization of Al/SiC composites have acknowledged that the mechanical properties of the composites are enhanced by the inclusion of reinforcement in the Al matrix. Moreover, the degree of enhancement of the mechanical and wear resistant properties is dependent on the SiC reinforcement fraction employed for the production of the Al metal matrix composites. The formation of Al_4C_3 phase has been noted to be undesirable, as it limits the composite mechanical performance, and was found to be prevented by using Fly ash and particle wetting with the matrix enhanced with the addition of magnesium to the Al melt during casting. However, it has been noted that previous researches have concentrated on the use of Al-6000 series alloy and uncoated SiC particle as reinforcement, hence in this study, Al-4043 alloy was reinforced with nickel coated SiC particles to produce Al MMCs via stir casting technique and the mechanical and wear resistant properties characterized. Al-4043 alloy is majorly used as filler material and was considered as it contains high silicon content thus, a good wetting of the embedded SiC reinforcement particles is anticipated and better mechanical and tribological properties achieved.

2. Materials and Methods

2.1. Materials

The materials used for the fabrication of the Al-SiC composites were aluminum (Al-4043) alloy ingots, as shown in Figure 1, obtained from System Metal Industries Ltd. Aba, Nigeria and silicon carbide powder with angular morphology, typical of water atomization and having a particle size range of 10 – 60 μm, was supplied by Logitech Materials Company, UK.

Fig. 1. Aluminum Al-4043 alloy ingots used in the study.

2.2. Nickel-Coating of Silicon Carbide Particles

In order to prevent interfacial reaction which could result in the formation of Al_4C_3 phase, the SiC powder particles were coated with nickel using a model-12A4D vacuum coating machine, made by Hind High Vacuum Company Limited, Bangalore. The SiC particles were cleansed using acetone and a 10g/l H_2SO_4 acidic solution for 10mins and 7mins respectively. Thereafter, the SiC particles were immersed in a solution of 0.5g/l $PdCl_2$ and 3ml/l HCl for 15 mins to activate their surfaces. The cleansed and dried SiC particles were gently dispersed in the vacuum chamber of the machine. The nickel coating was carried out in the vacuum at temperature range of 80-86^oC. The coating took place for 75mins to achieve an approximately 15 µm Ni-coating thickness on SiC particles in the vacuum chamber which is anticipated to be sufficient to prevent rapid dissolution and formation of the deleterious Al_4C_3 phase around the particles in the Al matrix.

2.3. Stir casting of Al- Ni-Coated SiC Composites

Aluminum alloy (Al-4043) was used as matrix reinforced with Ni-coated SiC particles. The MMCs were fabricated by melting the aluminum (Al-4043) alloy in an improvised furnace (black smith hearth furnace) then the reinforced Nickel coated SiC particles were added and stirred slowly. Thermocouple was utilized during the melting process to measure temperature. Aluminum (Al-4043) alloy was first preheated to 450°C for 45 mins before melting and Ni-coated SiC powder were preheated to 900°C for 30 mins to remove moisture in the powder for better wettablility. The furnace temperature was first raised above the melting point of aluminum to 720°C in order to melt the matrix completely and then it was allowed to decrease to temperature below the melting temperature (540^oC) to keep the slurry in a semi-solid state. At this stage, the preheated SiC particles were added into the aluminum slurry and mechanically agitated. The composite slurry was then reheated to a fully liquid state and stirred for 8 mins to ensure the formation of a homogenous mixture. The furnace temperature was controlled within 720±10°C. After melting, slurry mix was poured into a prepared mould, as shown in Figure 2, with pouring temperature maintained at 680^oC.

Fig. 2. Cast preparation by pouring the Al/SiC slurry from the crucible into the mould.

Cast composites with varying SiC reinforcement fractions were produced ranging from 5 – 25 wt.% SiC and a cast sample of Al-4043 alloy only was also produced as a control sample during the casting process.

2.4. Mechanical characterisation

The cast samples were characterised using a Model 0524011 Maker Optical microscope to examine the composite microstructure and to be able to establish a microstructure-composition-property relationship for the Al-4043/Ni-coated SiC composites. Prior to microstructural examination, samples of the composites were mounted in a conductive resin and polished to a 1 µm Ra finish. The samples were prepared from the cast composite for mechanical characterisation. Tensile test specimens were prepared according to BS:EN 10002 and the tensile properties of the composite specimens were investigated using a M-500 25 kN Gunt, Tensiometer (Hamburg) equipped with a Model 3542 Epsilon Technology Extensometer for elongation measurement. The density of the composites was assessed using eureka can and water. The composite hardness was established using a model LM 2481T Wilson hardness tester (USA) with an applied load of 981 N (100 kgf) over a spherical indenter with a diameter of 1.59 mm. Circular wear specimens with a height of 30 mm and 40 mm diameter were prepared and a model K93500 Rubin Disc machine was employed for the wear test. Each specimen was subjected to sliding abrasion wear test for 10mins at 200 rpm using a coarse SiC paper with grit size P-220 and weight differentials after the test were used to establish the wear rate of each sample. The compressive strength of the composites was established using a compression testing machine and the Charpy impact strength and toughness of the composites was assessed using a Model 9050 Avery Impact testing machine with maximum impact energy of 300 J and a hammer velocity of 5.24 ms^{-1}. Three repetitions of each test conducted were made for each sample with same reinforcement composition to assess standard error that may be associated with the experimentation.

3. Results and Discussion

3.1. Composite microstructure

Figure 3 shows the optical micrograph of the cast Al-4043/15 wt.% SiC composite and the SiC particles were observed to be uniformly distributed in the composite. The microstructure of the composite matrix is characterized by Al-SiC eutectics. The SiC solid solution precipitates were seen as the filament-like or whisker structures which are randomly oriented to reinforce the Al solid solution matrix. The formation of Al_4C_3 phase was not observed and this suggested that the Ni coating prepared on the SiC particles before casting had prevented the formation of this deleterious phase. However, it has been presumed that if SiC particle dissolution had occurred during casting, the presence of Ni in the Al melt would have promoted the formation of the Al-SiC eutectic microstructure while the carbon could act as interstitial solid solutions in the Al matrix and the SiC precipitates [10]. It was also observed that the area density of the whiskers and the particle reinforcements increases with increasing wt.% SiC employed to produce the cast Al-4043/SiC composites. Few pores were also observed which is presumably due to gas entrapment during casting and few agglomerations of SiC particles was observed which may be absolutely inevitable but can be ameliorated by optimising the stirring operation during casting.

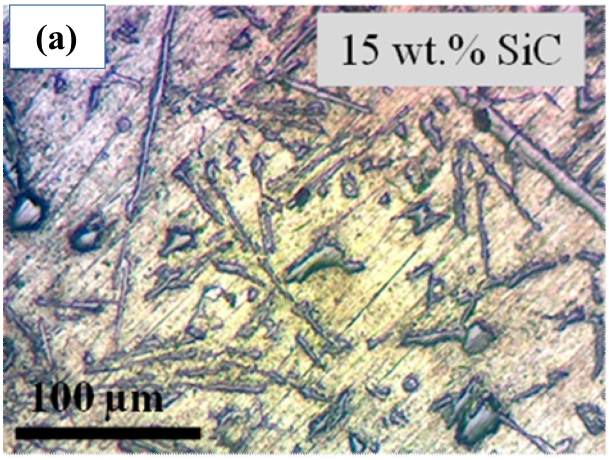

Fig. 3. Optical micrograph of cast Al-4043/15 wt% SiC composite.

3.2. Tensile properties

Having assessed the microstructure of the Al-4043/SiC composites formed, the mechanical properties of the composites can be discussed. Figure 4 shows the stress-strain curves for the Al-4043/SiC composites with varying SiC reinforcement fraction and Al-4043 alloy. The tensile strength of the cast Al-4043 alloy was obtained as 100 MPa which is lower than that of wrought Al-4043 alloy (145 MPa) [11] and strength of 140 MPa obtained for AlSi7 alloy produced via squeeze casting [12]. This may be directly attributed to the presence of pores in the cast which led to partial densification of the cast. Upon the subjection of the cast to tensile forces, the pores act as stress concentrators in the cast to accelerate the failure of the alloy. Moreover, the tensile strength of the cast Al-4043 alloy was found to improve with increasing SiC reinforcement fraction with the tensile strength ranging between 110 – 130 MPa for composite with reinforcement fraction ranging between 5 – 15 wt.% SiC. However, the tensile strengths of Al-4043/SiC composites with reinforcement fraction of 20 wt.% and 25 wt.% were significantly higher with tensile strength of 220 MPa and 350 MPa respectively. It is worthy to note that the composites with higher SiC reinforcement fraction such as 25 wt.% could not withstand high level of strain before breaking when compared to composite with 5 wt% SiC reinforcement. The yield strength and elastic modulus of the composites were found to increase with increasing SiC reinforcement fraction as shown in Figure 5. The yield strength and elastic modulus of the cast Al-4043 alloy was found to be 74 MPa and 5596 MPa respectively and these were found to increase quadratically to yield strength 254 MPa and elastic modulus 13,399 MPa for Al-4043/25 wt.% SiC composite.

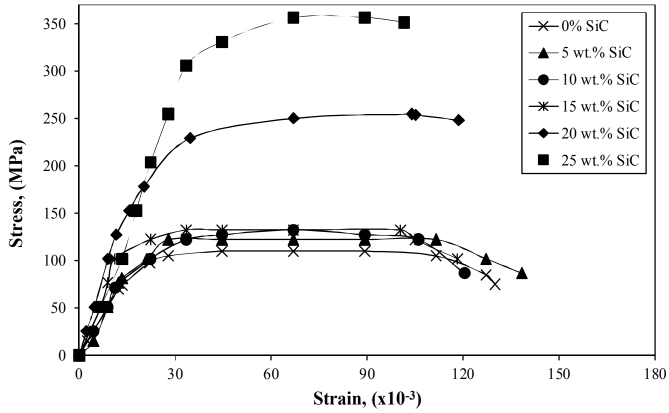

Fig. 4. The stress-strain curves for the Al-4043/SiC composites with variation in wt.% reinforcement.

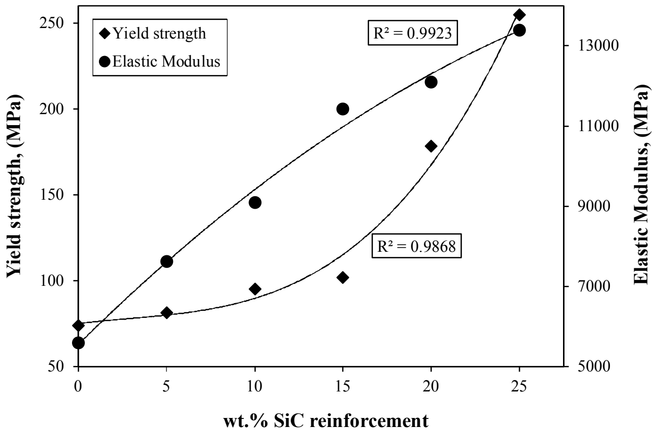

Fig. 5. Increase in yield strength and elastic modulus with increasing wt.% SiC reinforcement.

The elastic modulus result which is a measure of material stiffness was corroborated by the stress-strain curves in Figure 5, as the SiC reinforcement fraction increases, the strength of the composite increases too due to increasing SiC solid solution precipitates and uniformly distributed SiC particles which are responsible for effective load bearing capability. Figure 6 shows the elongation recorded for the tensile samples and the corresponding densities of their Al-4043/SiC composites. Whilst, density of composite increases linearly, the elongation was found to decrease exponentially with increasing SiC reinforcement fraction employed during casting. The cast Al-4043 alloy was found to possess 29.5% elongation when subjected to tensile load, however, the composite with the highest SiC fraction in this study (25 wt.% SiC) possessed 10% elongation due to the resistance provided by the reinforcing elements (SiC whiskers and SiC particles in the matrix) against deformation. The elongation values obtained in this study were greater than those recorded for Al-6061/SiC MMCs [13], this was attributed to the different elongation values of the matrices used with monolithic Al-4043 alloy having 22% [11] and Al-6061, 17% [14].

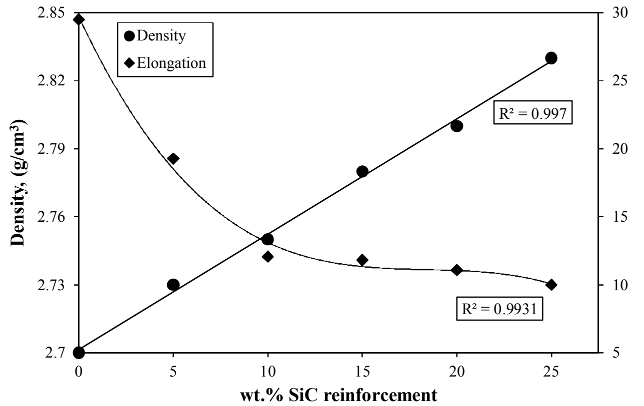

Fig. 6. An increase in density and decrease in elongation of the composites with increasing wt.% SiC reinforcement.

3.3. Composite hardness and wear rate

Figure 7 shows the variation in the Brinell hardness and wear rate of the Al-4043/SiC composites with increasing SiC reinforcement fraction. Whilst the composite hardness was found to increase with increasing reinforcement fraction, the wear rate was found to decrease exponentially. The hardness of the cast Al-4043 alloy was 30 HB which is less than that of the wrought alloy (39 HB) [11] and was raised to 76 HB when 25 wt.% SiC was added to the Al matrix which is more than 100% hardness improvement. However, the hardness value of squeeze-cast Al-MMC with 15 wt.% SiC was reported as 97 HB [12], which is higher than those observed in this study. This is due to near improved densification of cast Al-MMC produced via squeeze casting than stir casting employed in this study. The wear rate of the cast Al-4043 alloy was measured to be 33 x 10^{-11} m^3/s which was drastically reduced to 3 x 10^{-11} m^3/s with a 25 wt.% SiC reinforcement fraction in Al matrix. This indicated that the composite with 25 wt.% SiC reinforcement fraction is eleven (11) times wear resistant when compared to the monolithic Al-4043 alloy.

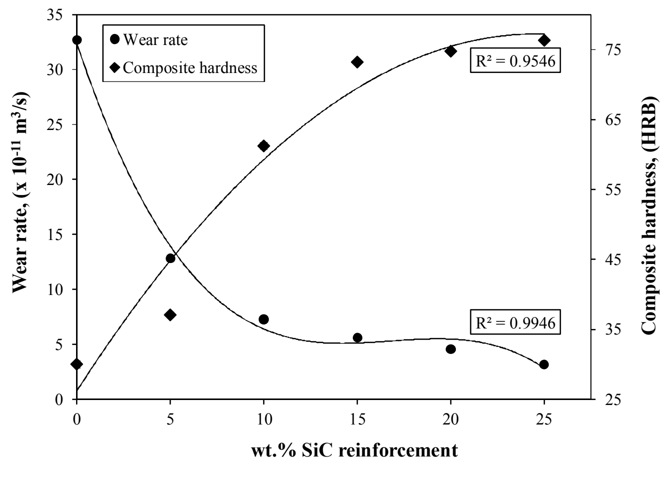

Fig. 7. A decrease in wear rate and an increase in hardness of Al-4043/SiC composites with increasing wt.% SiC reinforcement.

The improvement in wear resistance can be anchored on the increase in composite hardness and elastic modulus as the SiC reinforcement fraction employed increases. Increased resistance to indentation and improved material stiffness are central to abrasion resistance of the Al-4043/SiC composites.

3.4. Compressive and impact properties

Figure 8 shows the compressive strength and the impact energy requirement of the Al-4043/SiC composites. In both case, the compressive strength and the impact energy vary linearly with the SiC reinforcement fraction in the composites. The amount of energy absorbed by the cast Al-4043 alloy to yield was 40 J and was raised to 48 J for composite with a 25 wt.% SiC reinforcement fraction. This is indicative of increased toughness of the composites with increasing reinforcement fraction as the composites absorb more energy to deform plastically without fracture. The compressive strength of the Al-4043 alloy was found to be 144 MPa, which increased to 184 MPa with a 25 wt.% SiC reinforcement fraction. This indicated that the composites have improved resistance to deformation under compressive load when compared to the unreinforced monolithic Al-4043 alloy.

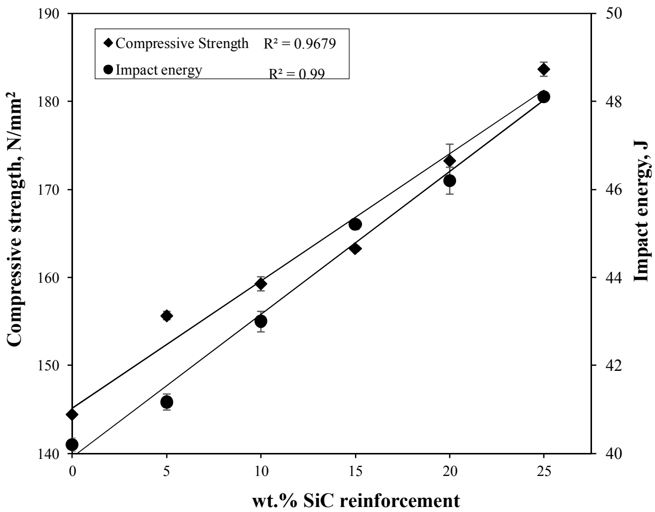

Fig. 8. An increase in compressive strength and impact energy of composite with increasing wt.% SiC reinforcement.

4. Conclusion

In this study, the mechanical properties of Al-4043/SiC composites with varying Ni-coated SiC reinforcement fraction have been successfully investigated. The composites were characterized to possess Al-SiC eutectic microstructure with SiC solid solution precipitates and SiC particles uniformly distributed in the Al matrix. The density of the composites was found to linearly increase with increasing SiC reinforcement fractions. The tensile strength, yield strength and elastic modulus were found to increase with increasing SiC reinforcement fraction and highest values obtained for composite with 25 wt.% SiC were 350 MPa, 254 MPa and 13.4 GPa respectively. However, the elongation of the composite with the highest reinforcement was lowest at a value of 10%. The hardness, compressive strength and impact energy of the composites increase significantly as composite with 25 wt'.% SiC possessed 76 HB, 184 MPa and 48 J respectively. The wear resistance of the Al-4043/SiC composites with highest SiC reinforcement was found to be eleven times that of the monolithic Al-4043 alloy.

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