ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)

10.24425/afe.2024.149271

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Microstructure and Mechanical Properties of the EN AC-AlSi12CuNiMg Alloy and AlSi Composite Reinforced with SiC Particles

G.G. Sirata *, K. Wacławiak, A.J. Dolata
Department of Materials Technologies, Faculty of Materials Engineering,
Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland
* Correspondence contact: e-mail: goftilagudeta@gmail.com

Received 13.09.2023; accepted in revised form 22.03.2024; available online 05.06.2024

Abstract

There is growing interest in developing more advanced materials, as conventional materials are unable to meet the demands of the automotive, aerospace, and military industries. To meet the needs of these sectors, the use of advanced materials with superior properties, such as metal matrix composites, is essential. This paper discusses the evaluation of microstructural and mechanical properties of conventional eutectic EN AC-AlSi12CuNiMg aluminum alloy (AlSi12) and advanced composite based on EN AC-AlSi12CuNiMg alloy matrix with 10 wt% SiC particle reinforcement (AlSi12/10SiC_p). The microstructure of these materials was investigated with the help of metallographic techniques, specifically using a light microscope (LM) and a scanning electron microscope (SEM). The results of the microstructural analysis show that the SiC particles are uniformly distributed in the matrix. The results of the mechanical tests indicate that the tensile properties and hardness of the AlSi12/10SiC_p composite are significantly higher than those of the unreinforced eutectic alloy. For AlSi12/10SiC_p composite, the tensile strength is 21% higher, the yield strength is 16% higher, the modulus of elasticity is 20% higher, and the hardness is 11% higher than unreinforced matrix alloy. However, the unreinforced AlSi12 alloy has a percentage elongation that is 16% higher than the composite material. This shows that the AlSi12/10SiC_p composite has a lower ductility than the unreinforced AlSi12 alloy. The tensile specimens of the tested composite broke apart in a brittle manner with no discernible neck development, in contrast to the matrix specimens, which broke apart in a ductile manner with very little discernible neck formation.

Keywords: Metal matrix composites (MMCs), Mechanical properties, SiC particle reinforcement, Microstructure analysis, Fractography

1. Introduction

Aluminum alloys have been widely used in various industries, mainly in the automotive and aerospace sectors [1–3], due to their properties such as low density, thermal conductivity, stiffness, higher corrosion and wear resistance, formability, and low coefficient of thermal expansion [4]. In the automotive industry, engine parts, such as cylinder heads and pistons, are generally made of Al-Si alloys. These parts are often subjected to high temperatures and stress variations due to the conversion of chemical energy into mechanical energy [5]. At elevated temperatures, the mechanical properties of the Al-Si alloy deteriorate and reduce the performance of the structure [6,7]. Therefore, it is essential to enhance the mechanical properties of Al-Si alloy and increase its resistance to temperature and load variation for this type of application. Reinforcing the alloy with a suitable reinforcement material is one way to enhance the material's mechanical properties. It provides additional strength and stability to the alloy, making it more resistant to temperature and stress variations.

Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are inexpensive reinforcement materials commonly used to reinforce aluminum alloys. Other ceramic particles such as silicon oxide (SiO_2), titanium carbide (TiC), titanium diboride (TiB_2), aluminum nitride (AlN), zirconium diboride (ZrB_2), and silicon nitride (Si_3N_4) are also used to reinforce the aluminum alloy [8–10]. These ceramic phases are very durable and hard. Due to their low density and strong specific mechanical properties, aluminum matrix composites (AMCs) reinforced with SiC particles are among the most favorable materials for lightweight applications. Compared to unreinforced aluminum alloys, SiC-reinforced aluminum matrix composites exhibit higher strength, stiffness, creep resistance, and wear resistance [11–15]. Due to their favorable properties, SiC-reinforced aluminum matrix composites are gradually replacing traditional aluminum alloys in many applications involving operation under complex and harsh conditions [10,16].

Efficient processing techniques enhance a uniform dispersion of SiC particles and a strong interfacial bonding between the reinforcement material and the matrix [8,17,18]. Two main processing techniques used to fabricate AlMC materials are melt metallurgy (liquid state) and powder metallurgy (solid-state) [8,19]. The melt metallurgy category involves the incorporation of preheated reinforcements into the molten metal matrix, followed by an appropriate mixing method and casting process [20]. This process includes several methods, such as stir casting [21,22], squeeze casting [23], and centrifugal casting [24]. In melt metallurgy processes, the wetting of reinforcing material by the molten matrix material plays a crucial role in achieving good mechanical properties [19].

On the other hand, powder metallurgy involves the compaction and sintering of powdered matrix and reinforcement materials to form a solid composite with desired mechanical properties [25,26]. Each manufacturing technique has its advantages and limitations in terms of cost, production efficiency, and the ability to modify the microstructure and properties of AMCs. For example, powder metallurgy (solid-state) confers favorable mechanical properties to AlMC. However, this production technique is characterized by its high cost and unsuitability for large-scale manufacturing [27,28]. Melt metallurgy (liquid state) is preferred for fabricating AMCs because of its simplicity, cost-effectiveness, ease of adaptation, and suitability for large-scale manufacturing [29].

Among various liquid-state processing techniques, the stir-casting process is the most widely used method for producing AMCs [30]. The stir-casting process involves stirring molten metal with reinforcement particles to distribute them homogeneously in the matrix material. The stirring action of this technique improves the bond between the metal matrix and the reinforcing particles, as indicated by previous studies [31–33]. In the overall procedures of stir casting manufacturing, it is essential to consider the numerous factors that can adversely affect the mechanical properties of AMCs. These factors, including porosity, undesirable chemical reactions, poor wettability of reinforced particles with the molten metal, etc., can negatively affect the composite's mechanical properties [34]. The presence of non-uniformly distributed SiC particles in the matrix can lead to the formation of defects, i.e., the accumulation of particles in certain regions. These defects can reduce the tensile strength, ductility, fatigue strength, hardness, and toughness of the composite material [30,35]. In addition, the presence of porosity in AMCs can lead to a decrease in density and an increase in vulnerability to crack propagation. On the other hand, insufficient wettability between the reinforced particles and the molten metal can lead to inadequate bonding, thus decreasing the load transfer capacity between the SiC particles and matrix and the overall mechanical performance of the composite.

Numerous studies have incorporated silicon carbide (SiC) particles as a reinforcing material within an aluminum matrix composite. Tamer Ozbenet et al. [36] investigated the mechanical and machining properties of an aluminum matrix composite (Al-MMC) fabricated with silicon carbide (SiC) particles. The AMC material showed an improvement in tensile strength, hardness, and density with an increasing reinforcement ratio. However, a corresponding drop in impact toughness was observed in their study. In their study, Ozden et al. [37] examined the impact behavior of particle-reinforced aluminum matrix composites (AMC) made of aluminum (Al) and silicon carbide (SiC) at different temperatures. The particle clustering, particle cracking, and poor bonding between matrix and reinforcement significantly influence the impact behavior of the composites. These results imply that temperature variations do not significantly affect the impact behavior of aluminum matrix composites.

Shuvho et al. [38] studied the mechanical behavior of an aluminum matrix composite reinforced with SiC, Al2O3, and TiO2. Their study revealed that the reinforced aluminum matrix composite exhibits higher hardness, tensile strength, and yield strength than the base alloy. Zhang Peng et al. [39] investigated the impact of particle clustering on the mechanical response of aluminum matrix composites. The authors suggest that elastic deformation is less sensitive to clustering than plastic deformation and that early clustering promotes interface disconnection and void formation.

Pawar et al. [17] studied the mechanical properties of aluminum matrix composites reinforced with silicon carbide (AMC) particles to fabricate power transmission elements, such as gears, which are subjected to a continuous load. The authors used two manufacturing methods, i.e., casting and powder metallurgy. They presented that powder metallurgy is better for achieving uniform distribution of reinforcement particles but is not as economical as the casting method.

Studying the mechanical properties of AMMC at elevated temperatures is essential to understanding its behavior under various operational conditions during its use [40]. However, few studies have been reported on the tensile properties of AlSi12/10SiCp composites at elevated temperatures. In this work, the tensile properties of EN AC-Al Si12CuNiMg alloy and AlSi12CuNiMg/10SiCp composite were investigated at room temperature and elevated temperatures ranging from 150 °C to 350 °C. The effect of temperature on tensile properties was described. The fracture behavior of the composite at elevated temperatures has also been studied. In addition, this article presents the microstructure of the AlSi12CuNiMg alloy and the AlSi12CuNiMg/10SiCp composite.

2. Materials and Methods

In this study, eutectic EN AC-AlSi12CuNiMg aluminum alloy (AlSi12) was used as the matrix material and 10 wt% SiC particles were used as the reinforcement. The chemical composition of the investigated matrix alloy was measured by optical emission spectroscopy (OES) and presented in Table 1.

The aluminum ingot was initially melted in a furnace. The temperature of the resistance furnace was set at 720 °C. When the desired temperature was reached, a constant volumetric flow of 2 l/min of argon gas was used to prevent the aluminum alloy from chemically interacting with the oxygen and nitrogen in the air. A trowel was used to gently remove the slag. The SiC reinforcement particles were then weighed according to the specifications of the experiment and preheated to 600 °C in a preheating chamber. Preheating was carried out to ensure proper mixing of the reinforcement, to remove moisture and air trapped between the reinforcement particles, to reduce the temperature gradient between the reinforcement particles and the molten alloy, and to remove impurities from the reinforcement particles. The mixture was then poured into a mold and cooled before removing the samples.

Table 1.
The determined chemical composition of eutectic EN AC-Al Si12CuNiMg alloy matrix (wt%)

Fe	Si	Cu	Mg	Zn	Mn	Ti	Ni	Al
0.4	11.4	1.27	1.24	0.18	0.18	0.04	1.48	rest

2.1. Microstructure Observation

Both the matrix alloy and the composite were subjected to microstructure studies. Metallographic samples were taken from the cast aluminum alloy and the composite. A standard metallographic procedure was used to polish the samples. Waterproof SiC emery papers with grit sizes up to 2000 were used to polish the surface of the samples. Then, polishing was continued using a 3 µm and 1 µm diamond suspension on a disc polisher until a mirror-like surface was obtained. This was done to allow for better microstructural observation. A light microscope (LM) and a scanning electron microscope (SEM) working with an X-ray spectrometer (VP S-3600N HITACHI, EDS from THERMO NORAN) were used to perform microstructural analysis.

2.2. Mechanical Properties: uniaxial tensile and hardness test

A uniaxial tensile test was performed to determine the basic mechanical properties of the fabricated cast alloy and its composites. Tensile test specimens with dimensions of 60 mm in length and 10 mm in diameter were cut from the cast eutectic alloy and AlSi12/10SiC$_p$ composite. Using the Zwick/Roel Z100 universal testing machine, these specimens were subjected to tensile tests in accordance with ISO 6892-1. Figure 1 shows the tensile test set up during the elevated temperature tensile test. During the load application, data on the specimen's elongation was recorded with the help of a clip-on extensometer that was placed in the elastic zone. The strain rate was held constant at 0.0067 1/s throughout all the tests. The specimens were loaded in a uniaxial direction with a tensile force until they fractured. The data on load elongation was recorded with the help of the TestXpert software. An average of five results was taken as the results of each tensile test result. Finally, the tensile properties of conventional aluminum alloys and AlSi composite were analysed. The prepared tensile specimens are shown in Figure 2.

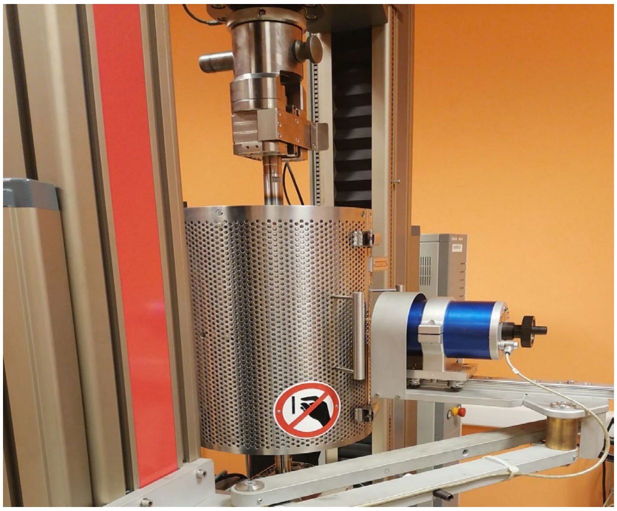


Fig. 1. Tensile test setup

Fig. 2. Tensile specimens

In accordance with the standard test method ISO 6506-1, an axial load of 2450 N was applied for 15 seconds using a Brinell hardness tester to measure the hardness of the aluminum alloy as well as prepared composite. Figure 3 shows the hardness specimens.

Fig. 3. Specimens for the hardness test

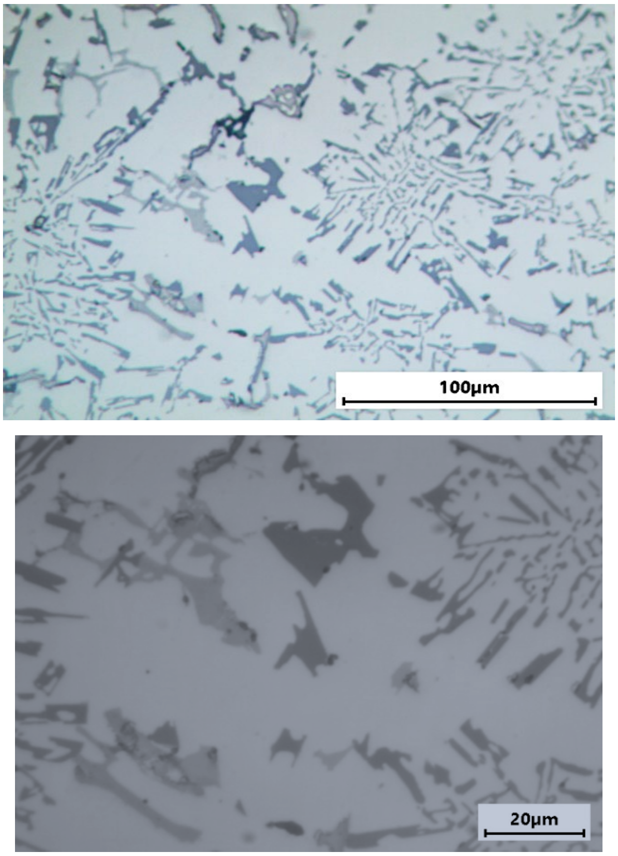


Fig. 4. LM images of the EN AC-Al Si12CuNiMg alloy at different magnification

3. Results and Discussion

3.1. Microstructure of the matrix EN AC-AlSi12CuNiMg alloy

The LM and SEM micrographs of the investigated cast EN AC-AlSi12CuNiMg alloy are shown in Figures 4 and 5 respectively.

To determine chemical composition of microstructural components in AlSi12 alloy, the point analysis was performed. Example results of EDS diagrams and quantitative point analysis of chemical composition for individual microstructure components of the base eutectic Al-Si alloy are presented in Figure 5. As it can be seen, the microstructure of the base AlSi12 eutectic alloy consists mainly of the primary phase (α_{Al}), needle-like $\alpha_{Al}+\beta_{Si}$ eutectic mixture (its amount depends on the Si content in the Al alloy), and plate-like Si primary crystals in the shape of polyhedrons. Moreover, the presence of the Cu, Mg, Ni, Mn, and Fe elements results in the formation of various intermetallic compounds correlated with the chemical composition of the eutectic Al-Si alloy. The Al_2Cu and Mg_2Si phases and more complex compounds in different systems like Al-Ni-Cu, Al-Fe-Si Al-Fe-Mn-Si, were identified in the microstructure. The morphology of Si phases can change after modification and heat treatment. In addition, the cooling rate influences the microstructural composition's size, morphology and distribution, including intermetallic phases.

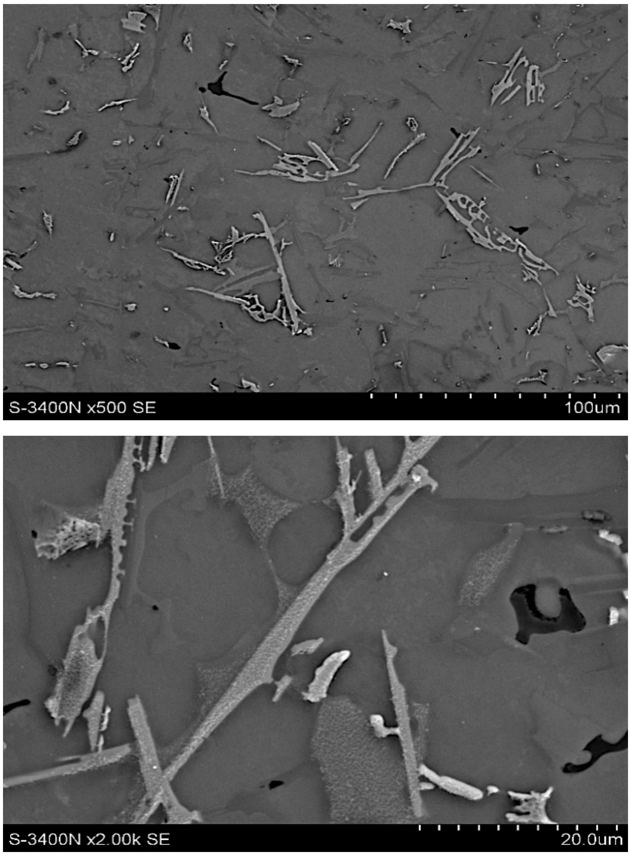


Fig. 5. SEM micrographs of the EN AC-Al Si12CuNiMg alloy at different magnification

3.2. Microstructure of the EN AC-Al Si12CuNiMg -10 wt% SiC composite

The micrographs of the EN AC-Al Si12CuNiMg/SiC composites are shown in Figures 3 and 4. The microstructure of the AlSi composite consisted of several phases, including matrix-Al, Si and intermetallic phases. The intermetallic phases were formed by the combination of Mg, Ni, Fe, Cu, and Al, which significantly improved the base alloy's high-temperature properties [41,42].

The SiC particles appear as dark spots and are uniformly dispersed throughout the aluminum matrix. Some porosity could be observed around the structures of reinforcement particles. The eutectic Si phase was heterogeneously nucleated in the form of needles on the surface of the reinforcement, as shown in Figures 6 and 7 and mentioned in reference [16]. Due to the formation of intermetallic compounds at the interface, the SiC particles are also observed to have a strong bond with the aluminum matrix, as stated in the literature [43]. The added SiC particles significantly affect the grain refinement of the base alloy. This is because the grain size of the (Al) + (Si) eutectics is noticeably finer than that of the base alloy.

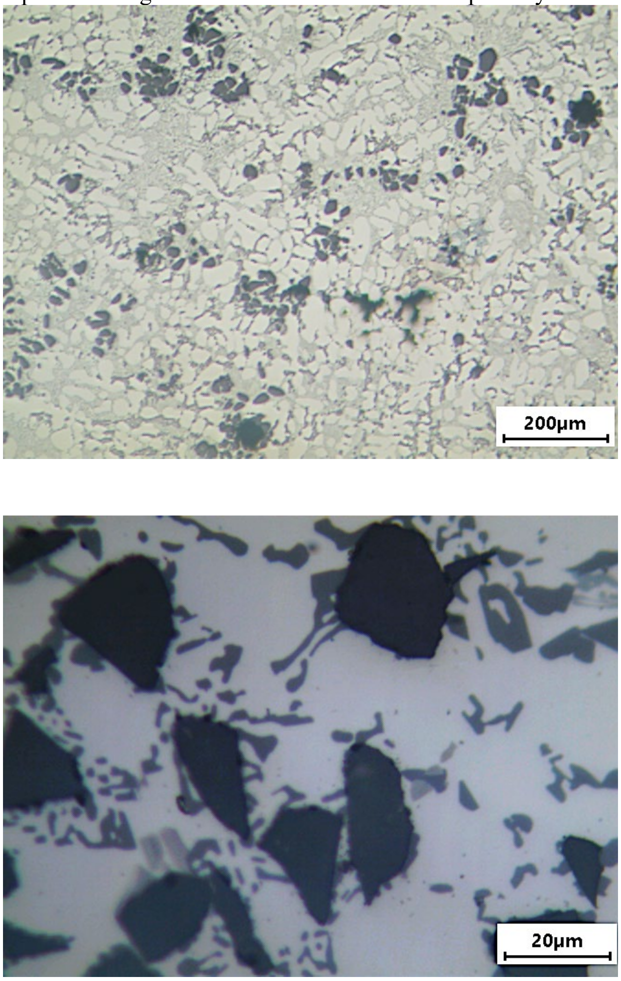


Fig. 6. LM micrographs of the AlSi12CuNiMg/SiCp composite

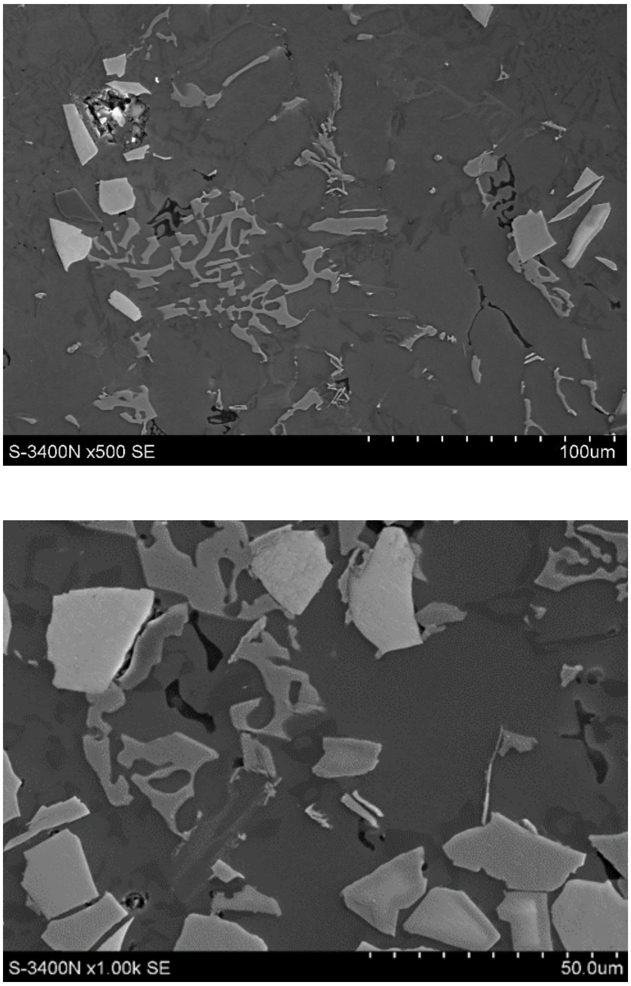


Fig. 7. SEM micrographs of the EN AC-Al Si12CuNiMg/SiC composite at different magnification

3.3. Mechanical properties - tensile properties and hardness measurement

The addition of 10 wt% of SiC particles have a substantial impact on the tensile properties of the produced composites. Therefore, it is important to test materials at room and elevated temperatures. Table 2 shows the test results of the EN AC-Al Si12CuNiMg alloy and SiC-reinforced composite at room temperature. The room temperature tensile test results show that SiC-reinforced composite has a higher base tensile strength than non-reinforced alloys. The yield strength, ultimate tensile strength, and modulus of elasticity of SiC-reinforced composites are 17%, 20%, and 6% higher than those of the unreinforced alloy.

Table 2.
Tensile properties of EN AC-Al Si12CuNiMg alloy and AlSi composite determined at room temperature

Materials	Yield Strength (MPa)	Tensile Strength (MPa)	Young Modulus (GPa)	Elongation (%)
EN AC-Al Si12CuNiMg	120 ± 6	140 ± 12	73 ± 5	0.57 ± 0.1
AlMMC	145 ± 8	175 ± 8	78 ± 4	0.5 ± 0.12
Change (%)	>17	> 20	>6	<20

The excellent interfacial bonding between the matrix and the reinforcement could be a reason to improve the tensile properties of the composites. On the other hand, the EN AC-Al Si12CuNiMg alloy showed a 20% higher percentage elongation. This implies that the SiC-reinforced composite has a low ductility compared to the matrix alloy.

Figure 8 shows the tensile strength of both the EN AC-Al Si12CuNiMg alloy and its composite at various temperatures. The values presented are the average of three test results with their error bars. The graph clearly shows the decrease in tensile strength with increasing temperature. For example, the tensile strength of EN AC-Al Si12CuNiMg alloy at normal temperature is 140 MPa, but at 150 °C and 200 °C, it decreases to 125 MPa and 120 MPa, respectively. From normal temperatures to 150 °C and 200 °C, the tensile strength decreases by about 5% and 15%, respectively. In addition, the tensile strength of the matrix alloy decreases by 20-50% for the temperature ranges between 250 and 350 °C. In the case of the composite material, the tensile strength decreased by about 3-6% for the temperature ranges of 150-200 °C compared to the result at normal temperature. However, for the temperature ranges between 150 and 350 °C, the tensile strength of the composite was reduced by about 17% to 50%. This shows that the decrease in tensile strength at low and moderate temperatures is negligible; however, when the temperature exceeds 250 °C), both materials' tensile strength deteriorates significantly.

The strength of the composite decreases with increasing temperature similar to that of an unreinforced aluminium alloy. This is likely because the matrix material becomes softer at high temperatures, which reduces its capability to support the reinforcing particles. Additionally, as the temperature increases, more atoms diffuse within the material, causing decreased cohesion between the matrix and reinforcement. This leads to a decrease in the strength of the composite material because the bonding between the two components weakens at elevated temperatures. These factors combined lead to a decrease in the strength of the AMM (Aluminium Matrix Material) composite material to a similar extent as the unreinforced aluminium alloy.

Figure 9 shows a plot of the yield strength and fracture strain of the SiC-reinforced composite and the unreinforced alloy vs. temperature. The average values of the three test results are shown in this graph. The yield stress was reduced by 8% from normal temperature to 200 °C in the case of the EN AC-Al Si12CuNiMg alloy. At 350 °C, however, it dropped by about 50%. In the case of EN AC-Al Si12CuNiMg/10%SiC composite, it was dropped by 4% from its normal temperature to 200 °C. But it dropped by about 40% at 350 °C. This implies a rapid decrease in the yield strength of both the matrix alloy and composite at temperatures above 200 °C.

On the other hand, the fracture strain of the EN AC-Al Si12CuNiMg alloy increases rapidly for temperatures above 200 °C, while the fracture strain of the composite increases slowly. This relates to the ductility properties of the EN AC-Al Si12CuNiMg alloy and the composite. The unreinforced alloy has a higher fracture strain at both low and elevated temperatures. The ductility of both the unreinforced alloy and the composite increases with temperature.

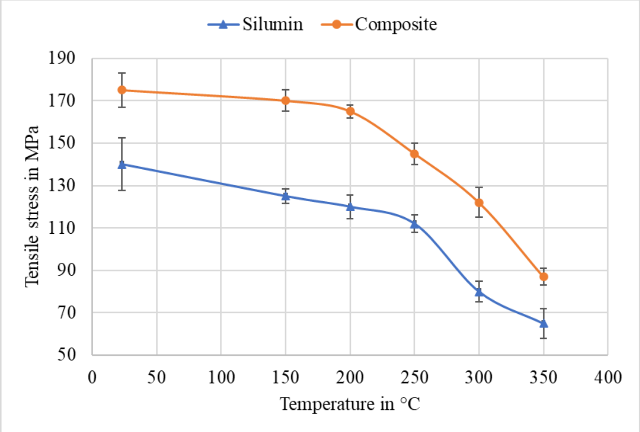


Fig. 8. Tensile strength of EN AC-Al Si12CuNiMg alloy and composite at various temperatures

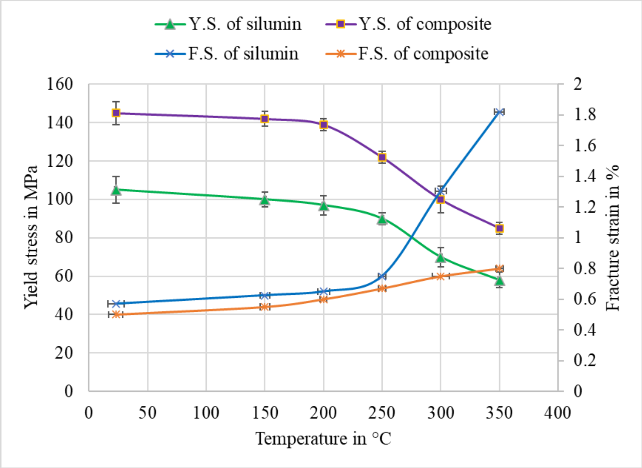


Fig. 9. Yield strength and fracture strain of EN AC-Al Si12CuNiMg alloy at various temperatures

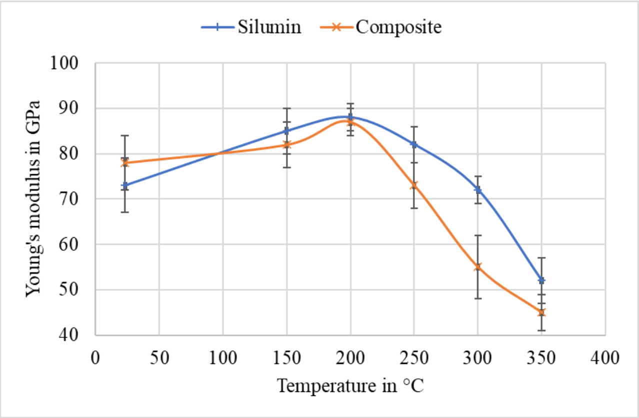


Fig. 10. Young modulus of EN AC-Al Si12CuNiMg alloy and composite at various temperatures

Young's modulus can be used to measure the resistance of materials to axial deformation. The operating temperature of materials can have an impact on Young's modulus. Figure 10 shows how temperature affects the Young's modulus of the matrix alloy and the SiC-reinforced composite. The average Young's modulus of the three test results was plotted against temperature. The study shows that Young's modulus of the EN AC-Al Si12CuNiMg alloys increases from room temperature up to about 200 °C and then starts to decrease as the temperature increases. The same pattern was observed for the SiC-reinforced composite. The SiC-reinforced composite exhibited a more significant decrease in Young's modulus over a higher temperature range than the EN AC-Al Si12CuNiMg alloy.

Figure 11 shows the average hardness value of the five test results with their error deviation. It is observed that there is a remarkable improvement in the hardness of the composite when compared with EN AC-Al Si12CuNiMg alloy. An improvement of 15% is observed in the hardness of the composite when compared with the unreinforced alloy. The strong bond between the matrix material (AlSi12CuNiMg) and the silicon carbide (SiC) particles could be the reason for the increased surface hardness value of the composite specimens. SiC, a hard reinforcement, renders the inherent property of hardness to the matrix material, thereby enhancing its resistance to deformation. It is an experimentally proven fact that the hardness of the matrix material can be improved significantly by adding hard reinforcement into a soft ductile matrix material like aluminum alloy [44]. The hardness behavior of composite is also affected by grain refinement of matrix alloy and fine and even distribution of reinforced particles. Reduction in grain size always enhances the hardness of the composites. The smaller the grain size, the higher the obstructions for dislocation motion, thereby improving the resistance to plastic deformation, resulting in increased hardness [45]. This characteristic of SiC could be the cause of the increased hardness of the composite specimens.

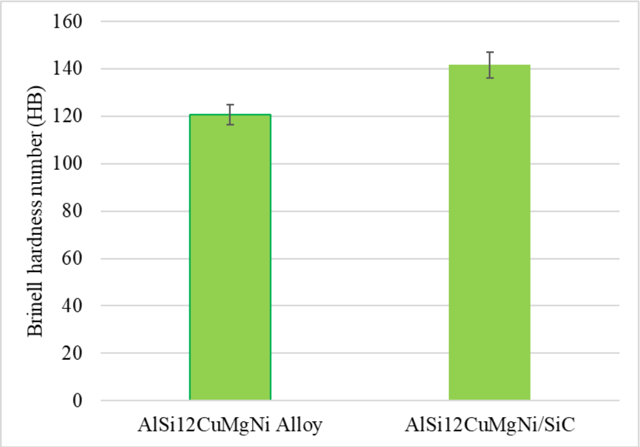
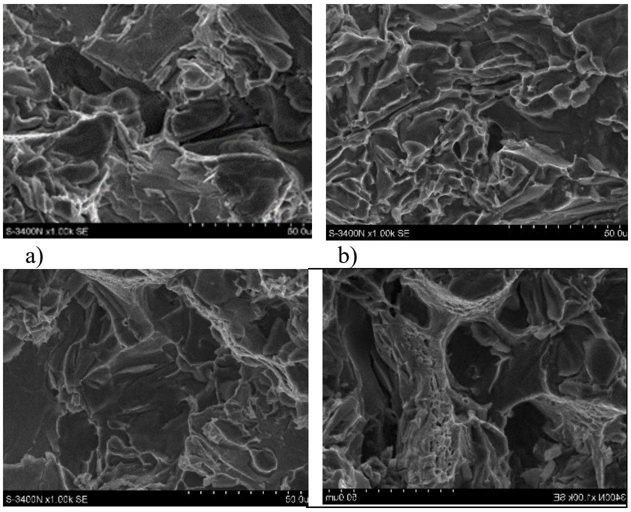


Fig. 11. Brinell hardness number (BHN) for unreinforced alloy and composite

3.3. Tensile Fractography

Fractographic analysis of the matrix alloy and composite material was carried out for tensile fracture tested at various elevated temperatures. Figure 12 shows the EN AC-Al Si12CuNiMg alloy fractographies at various temperatures. The result showed that the test temperature directly influenced the fracture behavior of the matrix alloy and composite material. The room temperature tensile fracture of the matrix alloy shows small dimples and a few cleavage planes, indicating the semi-brittle behavior of the matrix alloy. However, as the temperature increases from room temperature to 150, 250, and 350 °C, the size of the dimples increases, and the fracture surface of the matrix alloys changes from semi-brittle to ductile. The presence of larger dimples on the fracture surface indicates larger plastic deformation during fracture.

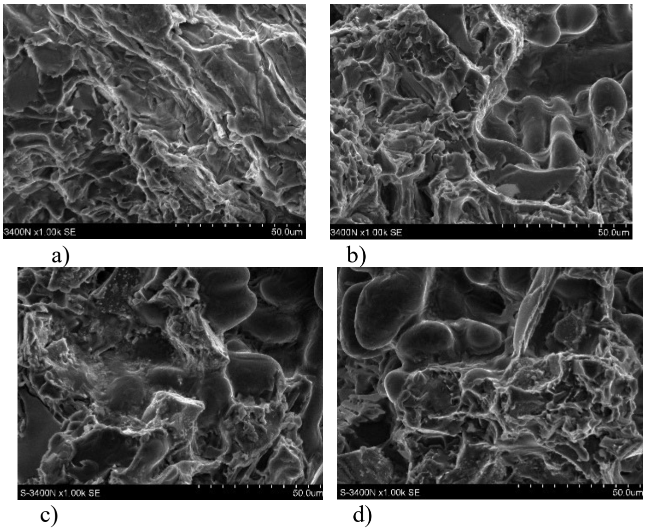


a) b)

c) d)

Fig. 12. Fractography of matrix alloy specimens tested at a) room temperature, b) 150 °C, c) 250 °C, and d) 350 °C

On the other hand, the fracture properties of the composite material depend on the properties of the reinforcement, matrix, and interface, as well as on the test temperature. Figure 13 shows the fractographies of the composite at various temperatures. Fractographic observation shows that the composite material exhibits a brittle fracture mode at room temperature, with a fracture surface characterized by cleavage planes. This is due to the presence of the SiC particle reinforcement, which is very hard and brittle. Since the alloy is semi-ductile at room temperature, the crack can initiate at the interface between the matrix and the reinforcement and propagate through the reinforcement. As the temperature rises from room temperature to 150 °C, 250 °C, and 350 °C, the fracture mode becomes semi-ductile. This is because the matrix alloy becomes more ductile at higher temperatures, allowing cracks to propagate more slowly. The degree of plastic deformation of the composite material also increases with temperature.



a) b) c) d)

Fig. 13. Fractography of the composite specimens tested at a) room temperature, b) 150 °C, c) 250 °C, and d) 350 °C

4. Conclusions

In this study, the structure and mechanical properties of EN AC-Al Si12CuNiMg alloy and EN AC-Al Si12CuNiMg 10 wt% SiC composite materials produced by stir casting were investigated. Optical and SEM analyses showed that the composites had a more refined microstructure, a clear interface, and a good bond between the matrix and reinforcement. The SiC particles were uniformly distributed in the matrix. These contribute to the improvement of the mechanical properties of the composite, as observed during the mechanical properties test. Tensile test results showed that the composite material has higher tensile strength and yield strength, a higher Young's modulus, and lower ductility than an unreinforced alloy. A considerable improvement in the hardness of the composite by 20% compared to the unreinforced alloy was also observed. This indicates that reinforcement with SiC particles significantly improves the overall mechanical properties of the composites, except ductility, especially at elevated temperatures. As a result, reinforced composites can be used in applications that require high strength in harsh environmental conditions, replacing unreinforced alloys. For example, the ability of SiC-reinforced composites to maintain their mechanical properties at elevated temperatures also makes them suitable for use in high-temperature applications, such as engine components in the aerospace and automotive industries. The fractographic investigation also shows that the composite material exhibits a smaller dimple size than the unreinforced material. The smaller dimple size observed in the composite material implies a lower degree of ductility than the unreinforced alloy. This could be due to a strong bond between the matrix and the reinforcement, which prevents plastic deformation.

References

[1] Rashnoo, K., Sharifi, M. J., Azadi, M. & Azadi, M. (2020). Influences of reinforcement and displacement rate on microstructure, mechanical properties and fracture behaviors of cylinder-head aluminum alloy. *Materials Chemistry and Physics*. 255, 123441, 1-13. DOI: 10.1016/j.matchemphys.2020.123441.

[2] Azadi, M., Winter, G., Farrahi, G.H. & Eichlseder, W. (2015). Comparison between isothermal and non-isothermal fatigue behavior in a cast aluminum-silicon-magnesium alloy. *Strength of Materials*. 47(6), 840-848. DOI: 10.1007/s11223-015-9721-4.

[3] Aybarc, U., Dispinar, D. & Seydibeyoglu, M.O. (2018). Aluminum metal matrix composites with SiC, Al 2 O 3 and graphene–review. *Archives of Foundry Engineering*. 18(2), 5-10. DOI: 10.24425/122493.

[4] Arora, A., Astarita, A., Boccarusso, L. & Mahesh, V.P. (2016). Experimental characterization of metal matrix composite with aluminium matrix and molybdenum powders as reinforcement. *Procedia Engineering*. 167, 245-251. DOI: 10.1016/j.proeng.2016.11.694.

[5] Farokhpour, M., Parast, M.S.A. & Azadi, M. (2022). Evaluation of hardness and microstructural features in piston aluminum-silicon alloys after different ageing heat treatments. *Results in Materials*. 16, 100323, 1-11. DOI: 10.2139/ssrn.4162353.

[6] Sirata, G.G., Wacławiak, K. & Dyzia, M. (2022). Mechanical and Microstructural Characterization of aluminium alloy, EN AC-Al Si12CuNiMg. *Archives of Foundry Engineering*. 22(3), 34-40. DOI: 10.24425/afe.2022.140234.

[7] Kurzawa, A. & Kaczmar, J.W. (2017). Bending strength of EN AC-44200–Al2O3 composites at elevated temperatures. *Archives of Foundry Engineering*. 17(1), 103-108. DOI: 10.1515/afe-2017-0019.

[8] Lijay, K.J., Selvam, J.D.R., Dinaharan, I. & Vijay, S.J. (2016). Microstructure and mechanical properties characterization of AA6061/TiC aluminum matrix composites synthesized by in situ reaction of silicon carbide and potassium fluotitanate. *Transactions of Nonferrous Metals Society of China*. 26(7), 1791-1800. DOI: 10.1016/S1003-6326(16)64255-3.

[9] Lakshmipathy, J. & Kulendran, B. (2014). Reciprocating wear behavior of 7075Al/SiC in comparison with 6061Al/Al2O3 composites. *International Journal of Refractory Metals and*

Hard Materials. 46, 137-144. DOI: 10.1016/j.ijrmhm.2014.06.007.

[10] Jayashree, P.K., Gowrishankar, M.C., Sharma, S., Shetty, R., Hiremath, P. & Shettar, M. (2021). The effect of SiC content in aluminum-based metal matrix composites on the microstructure and mechanical properties of welded joints. *Journal of Materials Research and Technology*. 12, 2325-2339. DOI: 10.1016/j.jmrt.2021.04.015.

[11] Dolata-Grosz, A., Dyzia, M., Śleziona, J. & Wieczorek, J. (2007). Composites applied for pistons. *Archives of Foundry Engineering.* 7(1), 37-40. ISSN (1897-3310).

[12] Moćko, W. & Kowalewski, Z.L. (2011). Mechanical properties of A359/SiCp metal matrix composites at wide range of strain rates. *Applied Mechanics and Materials.* 82, 166-171. https://doi.org/10.4028/www.scientific.net/AMM.82.166.

[13] Dolata, A.J. & Dyzia, M. (2014). Effect of Chemical Composition of the Matrix on AlSi/SiC p+ C p Composite Structure. *Archives of Foundry Engineering.* 14(1), 135-138. ISSN (1897-3310).

[14] Wysocki, J., Grabian, J. & Przetakiewicz, W. (2007). Continuous drive friction welding of cast AlSi/SiC (p) metal matrix composites. *Archives of Foundry Engineering.* 7(1), 47-52. ISSN (1897-3310).

[15] Li, R., Pan, Z., Zeng, Q. & Xiaoli, Y. (2022). Influence of the interface of carbon nanotube-reinforced aluminum matrix composites on the mechanical properties–a review. *Archives of Foundry Engineering*. 22(1), 23-36. DOI: 10.24425/afe.2022.140213.

[16] Dolata, A.J., Mróz, M., Dyzia, M. & Jacek-Burek, M. (2020). Scratch testing of AlSi12/SiCp composite layer with high share of reinforcing phase formed in the centrifugal casting process. *Materials.* 13(7), 1685, 1-17. DOI: 10.3390/ma13071685.

[17] Pawar, P.B., & Utpat, A.A. (2014). Development of aluminium based silicon carbide particulate metal matrix composite for spur gear. *Procedia Materials Science*, 6, 1150-1156. DOI:10.1016/j.mspro.2014.07.187.

[18] Miracle, D.B. (2005). Metal matrix composites–from science to technological significance. *Composites science and technology,* 65(15-16), 2526-2540. DOI: 10.1016/j.compscitech.2005.05.027.

[19] Dyzia, M. (2017). Aluminum matrix composite (AlSi7Mg2Sr0. 03/SiCp) pistons obtained by mechanical mixing method. *Materials.* 11(1), 42, 1-14. DOI: 10.3390/ma11010042.

[20] Sahoo, B.P.,& Das, D. (2019). Critical review on liquid state processing of aluminium based metal matrix nano-composites. *Materials Today: Proceedings.* 19, 493-500. DOI: 10.1016/j.matpr.2019.07.642.

[21] Yar, A.A., Montazerian, M., Abdizadeh, H. & Baharvandi, H.R. (2009). Microstructure and mechanical properties of aluminum alloy matrix composite reinforced with nano-particle MgO. *Journal of alloys and Compounds.* 484(1-2), 400-404. DOI: 10.1016/j.jallcom.2009.04.117.

[22] Kumar, B.A. & Murugan, N. (2012). Metallurgical and mechanical characterization of stir cast AA6061-T6–AlNp composite. *Materials & Design.* 40, 52-58. DOI: 10.1016/j.matdes.2012.03.038.

[23] Peng, L.M., Han, K.S., Cao, J.W. & Noda, K. (2003). Fabrication and mechanical properties of high-volume-fraction Si3N4-Al-based composites by squeeze infiltration casting. *Journal of Materials Science Letters.* 22(4), 279-282. DOI: 1022356413756.

[24] Rajan, T.P.D., Pillai, R.M., & Pai, B.C. (2008). Centrifugal casting of functionally graded aluminium matrix composite components. *International Journal of Cast Metals Research.* 21(1-4), 214-218. DOI: 10.1179/136404608X361972.

[25] Chen, H.S., Wang, W.X., Li, Y.L., Zhang, P., Nie, H.H. & Wu, Q.C. (2015). The design, microstructure and tensile properties of B4C particulate reinforced 6061Al neutron absorber composites. *Journal of Alloys and Compounds.* 632, 23-29. DOI: 10.1016/j.jallcom.2015.01.048.

[26] Rohatgi, P.K. & Schultz, B. (2007). Lightweight metal matrix nanocomposites–stretching the boundaries of metals. *Material Matters.* 2(4), 16-20.

[27] Torralba, J.D., Da Costa, C.E. & Velasco, F. (2003). P/M aluminum matrix composites: an overview. *Journal of Materials Processing Technology.* 133(1-2), 203-206. DOI: 10.1016/S0924-0136(02)00234-0.

[28] Suryanarayana, C. & Al-Aqeeli, N. (2013). Mechanically alloyed nanocomposites. *Progress in Materials Science. 58*(4), 383-502. DOI: 10.1016/j.pmatsci.2012.10.001.

[29] Taha, M.A. (2001). Practicalization of cast metal matrix composites (MMCCs). *Materials & Design.* 22(6), 431-441. DOI: 10.1016/S0261-3069(00)00077-7.

[30] Maurya, M., Maurya, N.K. & Bajpai, V. (2019). Effect of SiC reinforced particle parameters in the development of aluminium based metal matrix composite. *Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy.* 06(03), 200-206. DOI: 10.5109/2349295.

[31] Sharma, P., Sharma, S. & Khanduja, D. (2015). A study on microstructure of aluminium matrix composites. *Journal of Asian Ceramic Societies.* 3(3), 240-244. DOI: 10.1016/j.jascer.2015.04.001.

[32] Chandra, D., Chauhan, N. R. & Rajesha, S. (2020). Hardness and toughness evaluation of developed Al metal matrix composite using stir casting method. *Materials Today: Proceedings.* 25, 872-876. DOI: 10.1016/j.matpr.2019.12.026.

[33] Kaviyarasan, K., Kumar, J.P., Anandh, S.K., Sivavishnu, M. & Gokul, S. (2020). Comparison of mechanical properties of Al6063 alloy with ceramic particles. *Materials Today: Proceedings.* 22, 3067-3074. DOI: 10.1016/j.matpr.2020.03.442.

[34] Subramanya Reddy, P., Kesavan, R. & Vijaya Ramnath, B. (2017). Evaluation of mechanical properties of aluminum alloy (Al2024) reinforced with silicon carbide (SiC) metal matrix Composites. *Solid State Phenomena.* 263, 184-188. DOI: 10.4028/www.scientific.net/SSP.263.184.

[35] Nair, S.V., Tien, J.K. & Bates, R.C. (1985). SiC-reinforced aluminium metal matrix composites. *International Metals Reviews.* 30(1), 275-290. https://doi.org/10.1179/imtr.1985.30.1.275.

[36] Ozben, T., Kilickap, E. & Cakır, O. (2008). Investigation of mechanical and machinability properties of SiC particle reinforced Al-MMC. *Journal of Materials Processing*

Technology. 198(1-3), 220-225. DOI: 10.1016/j.jmatprotec.2007.06.082.

[37] Ozden, S., Ekici, R. & Nair, F. (2007). Investigation of impact behaviour of aluminium based SiC particle reinforced metal–matrix composites. *Composites Part A: Applied Science and Manufacturing*. 38(2), 484-494. DOI: 10.1016/j.compositesa.2006.02.026.

[38] Shuvho, M.B.A., Chowdhury, M.A., Kchaou, M., Roy, B. K., Rahman, A. & Islam, M.A. (2020). Surface characterization and mechanical behavior of aluminum based metal matrix composite reinforced with nano Al2O3, SiC, TiO2 particles. *Chemical Data Collections.* 28, 100442. DOI: 10.1016/j.cdc.2020.100442.

[39] Peng, Z. & Fuguo, L. (2010). Effects of particle clustering on the flow behavior of SiC particle reinforced Al metal matrix composites. *Rare Metal Materials and Engineering.* 39(9), 1525-1531. DOI: 10.1016/S1875-5372(10)60123-3.

[40] Kurzawa, A. & Kaczmar, J.W. (2017). Impact strength of composite materials based on EN AC-44200 matrix reinforced with Al2O3 particles. *Archives of Foundry Engineering.* 17(3), 73-78. DOI: 10.1515/afe-2017-0094.

[41] Azadi, M., Bahmanabadi, H., Gruen, F. & Winter, G. (2020). Evaluation of tensile and low-cycle fatigue properties at elevated temperatures in piston aluminum-silicon alloys with and without nano-clay-particles and heat treatment. *Materials Science and Engineering: A.* 788, 139497, 1-16. DOI: 10.1016/j.msea.2020.139497.

[42] Li, Y., Yang, Y., Wu, Y., Wang, L. & Liu, X. (2010). Quantitative comparison of three Ni-containing phases to the elevated-temperature properties of Al–Si piston alloys. *Materials Science and Engineering: A.* 527(26), 7132-7137. DOI: 10.1016/j.msea.2010.07.073.

[43] Dolata, A.J., Dyzia, M. & Boczkal, S. (2016). Structure of interface between matrix alloy and reinforcement particles in Al/SiCp+ Cgp hybrid composites. *Materials Today: Proceedings.* 3(2), 235-239. DOI: 10.1016/j.matpr.2016.01.063.

[44] Keshavamurthy, R., Mageri, S., Raj, G., Naveenkumar, B., Kadakol, P.M. & Vasu, K. (2013). Microstructure and mechanical properties of Al7075-TiB2 in-situ composite. *Research Journal of Material Sciences.* 1(10), 6-10. ISSN 2320- 6055.

[45] Moustafa, S.F. (1995). Wear and wear mechanisms of Al-22% Si/A12O3f composite. *Wear.* 185(1-2), 189-195. DOI: 10.1016/0043-1648(95)06607-1.