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Investigation of Influence of Variations of Ageing Conditions on Aluminium-Silicon: Pathway to Tailored Mechanical Properties

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ABSTRACT: This study focuses on the investigation of the influence of the variations of ageing conditions on the mechanical properties of ferrosilicon-silicon carbide reinforced Aluminium metal matrix composites. The ageing temperature, reinforcement percentage volume fractions and ageing time of the composite were systematically varied during fabrication stages by keeping the Aluminium and Ferrosilicon compositions constant while varying the percentage volume fractions of Silicon Carbide (SiC). The samples produced were machined into hardness, impact and tensile tests specimens. Then the specimens were subjected to laboratory based accelerated solution heat treatment, quenching and artificial ageing. Array of comprehensive mechanical properties examination and characterization in line with the appropriate specifications of the American Society for Testing and Materials Standard manuals were conducted to determine the influence of ageing on the material's strength, hardness, impact toughness and stress-strain characteristics. The study revealed significant enhancement in the mechanical properties of the material and the findings would provide valuable insight into the ageing behaviour of Aluminium-Silicon, thus, enabling the optimization of the material's performance for use in diverse engineering applications.

KEYWORDS: Aluminium-silicon, temperature, percentage volume fractions of reinforcement element, time, mechanical properties.

1.0 INTRODUCTION

The investigation of the influence of variations of ageing conditions on the mechanical properties of aluminum-silicon (Al-Si) is a subject of immense significance. Ageing treatments contribute to the modification and fine-tuning of the mechanical characteristics

And performance of materials and influence properties such as hardness, tensile strength, impact toughness and resilience. The examination of the volume fractions and corresponding precipitates formed during ageing deepens the understanding of the microstructural changes and their correlations with mechanical behaviour (Baumli, 2020).

The ageing process involves heat treatments designed to induce the precipitation of strengthening phases to enhance the material's mechanical performance (Nturanabo *et al.*, 2020). Volume fractions examination provides a quantitative knowledge of the changes in the arrangement and grain size distribution of the composite's precipitates which enables the identification of optimal aging condition for predicting and tailoring of the mechanical responses to facilitate the development of high-performance materials (Gang *et al.*, 2019).

In the last decades, efforts to develop environmentally friendly materials with robust beneficial mechanical properties have led to the integration of different constituents and elements into aluminium-based alloys to enhance their properties. These combinations of constituent elements lead to the emergence of composites made up of many phases that possess the attributes of their constituent elements, which replace monolithic and binary materials formerly utilized in production of engineering assembly such as aircraft, spaceship, ocean liners, automobile vehicles, and engineering structures in other sectors (Pise *et al*., 2019).

Numerous researches have given useful directions regarding the general consequences of ageing on aluminium-based alloys and composites (Baumli, 2020; Masyrukan & Darmawan, 2021). In Pogatscher *et al.* (2011); Werinos *et al.* (2015) and Banhart *et al* (2011), the age-hardening process involves three main steps: solution heat treatment, quenching, and ageing. It involves heating the alloy to dissolve precipitates, cooling it to room temperature, and reheating it to enhance properties. Artificial ageing is a controlled heat treatment process used to accelerate the precipitation of alloying elements in Aluminum Matrix Composites, enhancing their mechanical properties and offering greater control (Polmear *et al.*, 2017; Porter *et al.*, 2021; Masyrukan & Darmawan, 2021). Natural ageing is a slow process where alloying elements or reinforcing particles strengthen over time without external heat treatment, improving material properties over extended periods, making it useful in long-term service conditions (Polmear *et al.*, 2017 and Porter *et al.* 2021).

In the study of suppressed negative effects of natural ageing by pre-ageing in SiC_p/6092Al composites, pre-ageing improved the hardness of the natural aged samples and showed a stronger pre-aged effect than the 6092Al alloy base sample (Zhu *et al.*, 2021). The ageing process of alloying metals is influenced by temperature and time. Temperature promotes fine precipitates, while time influences precipitation growth and maturation. The optimal ageing time balances desired properties with potential over-ageing, ensuring a balance between desired properties and over-ageing. (Clyne, 2000; Viswanatha *et al.*, 2021; Caballoro *et al.*, 2020 and Rajaram *et al.*, 2022).

Ye *et al.* (2019) studied the effects of SiC particle size on mechanical properties of SiC reinforced Aluminium metal matrix composite. The study found that increasing strain rate enhances composite yield strength, with smaller SiC particles having superior mechanical properties. The material's load response behavior is attributed to compact interfaces and larger tension. The study also investigated precipitation hardening's effects on Al-SiC's tensile, fatigue, and fracture toughness. Vemba and Ganesan (2019) reported that the material exhibited maximum mechanical properties at peak aged conditions. Rawat *et al.* (2020) examined the mechanical properties of heat-treated Al-SiC composite and reported enhancement in impact and tensile strengths. The investigation noted that low percentage volume fractions of SiC in the range of 2 – 6wt% resulted in a 6.5% decrease in the material's hardness. The cyclic stress properties of Al-Si alloy reinforced with 10wt% of SiC was studied by Tiwari *et al.* (2019). The reinforced composite under T_6 temper conditions showed inferior ultimate tensile strength and low offset yield strength compared to the base alloy. However, after heat treatment, both materials showed improved mechanical properties and resistance to fatigue crack growth. Further investigation is needed to tailor the material's properties for safe engineering applications.

2.0 MATERIALS AND METHODS

Materials: Silicon carbide, Ferrosilicon, 16mm Aluminium bare conductor, Moulding boxes, Silica sand, Bentonite Polishing and etching materials, Pyrometer, Mechanical Stirrer, Crucible, Electrical Resistance Furnace, Alpha Duromter Hardness Tester, TecQuipment Universal Tensile Testing Machine.

Methods:

Samples Production

The specimens were fabricated using a mixture of ferrosilicon particulates and silicon carbide particles. The aluminium was obtained from 16mm bare electrical conductors and placed in a graphite crucible under an electrically powered heating system. 4g of NaCl powder was used as a melting flux cover to reduce aluminium oxidation. The temperature was raised to 720°C, and the molten metal was stirred to maintain a homogenous distribution of alloying components. 400g of charged components were used to produce the alloy. Silicon carbide was raised to 1000°C to cause interfacial oxidation. The alloy was cooled to just below its liquid state temperature of 580°C, keeping the slurry semi-solid. The reheated SiC particles were introduced and mechanically stirred, despite the difficulty of automated mixing in its semi-solid condition. The composite slurry was reheated to 720°C before being automatically mixed for 20 minutes at 150rpm average spinning rate. The furnace temperature was regulated and sustained between 730°C and 740°C, while the mixture was kept at around 720°C during and pouring.

Solution Heat Treatment, Quenching and Ageing of the Samples

The test specimens were made to undergo a solution heat treatment in a furnace heated to a temperature of 500°C and was allowed to stand at this temperature for 180 minutes in order to dissolve any soluble elements or compound that may have been present and to create a homogeneous solid solution. Immediately preceding the solution heat treatment, the specimens were then rapidly quenched by cooling in water preheated to 65°C in order to lock the aluminium atom in a supersaturated state. Artificial aging was performed on test samples using age-hardening agent (Magnesium) and reheating at 100°C, 200°C, and 300°C temperatures for 60-660 minutes. The samples were quenched and analyzed for aging characteristics, followed by tensile and impact tests at peak aging times.

Determination of Mechanical Properties

Hardness: TecQuipment Universal Hardness Tester (Alpha-Duometer) was deployed for the determination of the hardness values of the as-cast and age-hardened specimens in line with ASTM E18-22 standard criteria. The Rockwell hardness on the "B" scale was estimated using the Rockwell Hardness B (HRB) scale expression shown on Equation 2.1.

$$\mathrm{HRB} = 100 - \frac{\mathrm{h_s}}{\mathrm{h_o}} \tag{2.1}$$

The statistical analysis utilized the L8 Taguchi Robust parameter design of experiment methodology to investigate the influence of temperature, SiC percentage volume fractions and ageing time on the hardness property of aged material. An orthogonal array for the design ensured equal distribution of three factors-three levels combinations across the experimental runs. The determination of the signal-to-Noise ratio was determined using the expression:

$$S/N = -10*\text{Log}_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{Y_i}{\bar{Y}}\right)^2\right) \qquad (2.2)$$

Where: n is the number of exponential runs.

Y_i represents the response (output) for the i-th experimental run.

$\bar{Y}$ is the average of all responses (Nwoke *et al.*, 2017).

Throughout the experimental runs, diligent data collection procedures were employed to capture the variations in the response variables. A comprehensive data analysis, using Signal-to-Noise Ratios (SNR) and analysis of variance (ANOVA) was carried out to discern significant factors and potentials interactions, in order to identify key factors influencing the hardness of the aged composites using the "larger the better" signal-to-noise values indications.

Tensile Characteristics: The TecQuipment Universal Testing Machine was used to examine the tensile properties of As-cast samples and peak-aged materials, conforming to ASTM E8 and E8M standards. The testing process began with a small initial load, gradually increasing until failure occurred.

Impact Strength: The laboratory study used a TecQuipment Hardness Tester to investigate impact strength on as-cast and peak-aged samples. The test used a standard cylinder impact test sample with a 45-degree opening angle. The pendulum was calibrated before mounting the test sample, and the scale showed the angle at which the pendulum made before the specimens fractured, indicating the energy absorbed in causing the cracks.

3.0 RESULTS AND DISCUSSION

3.1 Hardness Properties Examination

The behaviour of the aged composites with respect to time for the five different volume fractions of the SiC reinforcement phases in the metal-matrix composites are as shown on the graphical plot displayed in Figures 3.1.

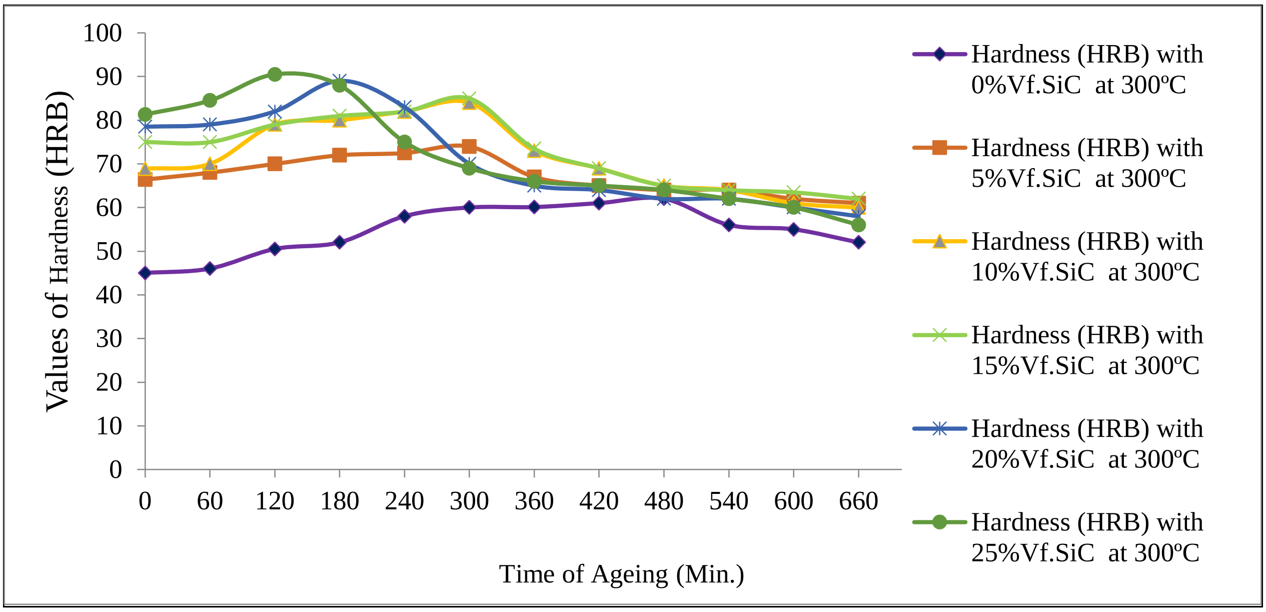

Fig. 3.1: Hardness versus Ageing Time at 300℃

Figures 3.1 illustrate the hardness values of composites at different temperatures during the ageing process show a surge in values, followed by a decline after reaching peak ageing time. Elevated ageing temperatures lead to faster attainment of peak hardness due to the faster rate of precipitates in second-phase materials. The behavior of hardness (HRB) varies with percentage volume fractions of SiC at 300°C over different ageing times. Higher SiC content generally corresponds to higher hardness values. The age hardening characteristics mirror those reported by Cinkilic *et al.* (2020), Pradica (2020), and Viswanatha (2021).

3.2 Analysis of Ageing Process

The "Larger the Better" Criterion Signal-to-Noise Ratios Analysis: This criterion was selected for the investigation due to its alignment with the objective of maximizing the performance the material being studied. In mechanical engineering materials optimization processes that utilize Taguchi method or other robust design techniques, the goal is often to maximize and; or improve certain characteristics of materials such as strength, hardness, toughness and stiffness (Gonfa *et al.*, 2022). Generally, higher values of SN ratio indicate better performance and quality. Consequently, when analyzing SN ratio, selecting 'the larger the better" allows for enhancement of these properties to optimize design process.

3.3 Hardness (HRB) SN Ratios versus Temperature, %V_f of SiC and Time

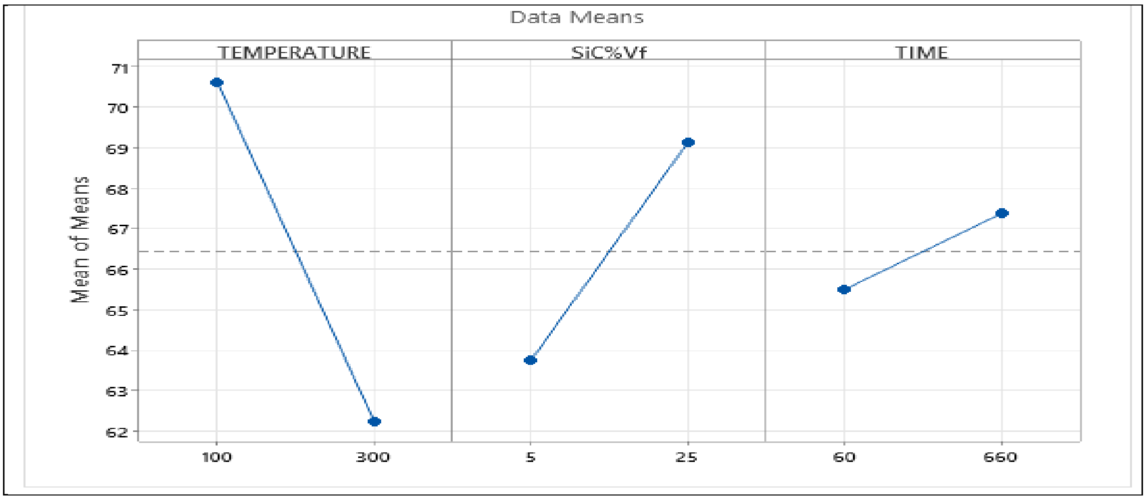

Fig. 3.2: Main Effects for SN Ratios of Hardness Values (HRB)

Figure 3.2 shows the relationship between temperature, %V_f of SiC, ageing time, and their interactions on hardness Signal to Noise (SN) ratios. The study reveals that temperature and %V_f of SiC are the most influential factors in explaining the variation in the material's hardness values, with time having a minimal influence at a short run. Elevating temperature leads to a 0.5198 rise in the material's SN ratio, while decreasing temperature and time results in a 0.3120 decrease. The Response for Means reveals that temperature, percentage volume fractions of SiC, and time have a significant impact on hardness. At 100ºC, hardness is 70.63HRB, while at 300ºC, it decreases to 62.25HRB. At 25%V_f of SiC, hardness increases to 69.13HRB, while at 60 minutes, it increases to 65.50HRB. Ageing temperature has the highest rank, followed by percentage volume fraction of SiC and ageing time.

3.4 Hardness with Percentage Volume Fractions of SiC

Plot 3.4 indicates the measure of the extent of hardness of both the as-cast and aged composites. The hardness values of both the as-cast and aged samples are seen to exhibit an upward trend as the percentage volume fractions of SiC in the material increase. This trend is attributed to the rise in the magnitude of hardness and brittleness within the ceramic particulates present in the composites.

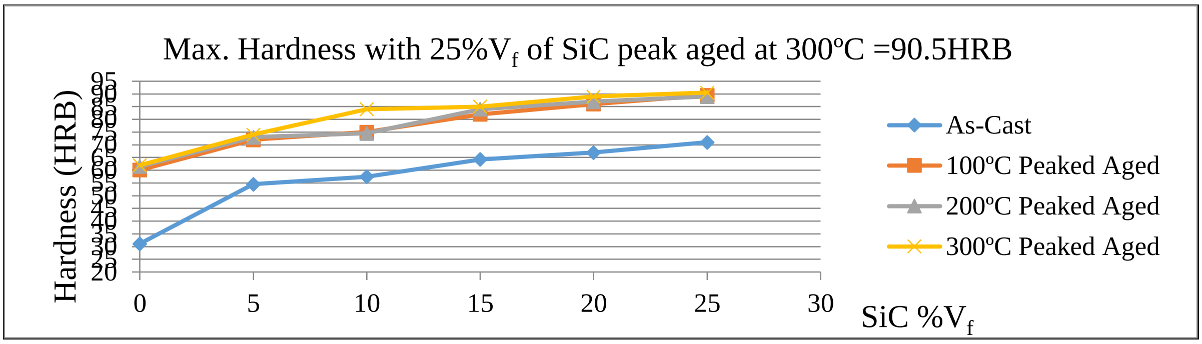

Fig. 3.4: Hardness Versus %V_f of SiC

The hardness of aged composites varies with SiC incorporation percentages. The material reinforced with 25% SiC increases from 71.0HRB to 90.5HRB at 300oC, suggesting optimal hardness for applications. Precipitation hardening enhances the mechanical properties of the composite due to the presence of reinforcement particles of SiC which promotes peak hardness at shorter ageing time and the peak hardness obtained for the materials at the various ageing temperatures is in line with earlier observations of Doddapaneni *et al.* (2023), Chandradess *et al.* (2021), Mane and Shantharaja (2021) and Farokhpour *et al*. (2022).

3.5 Yield Strength of $Al_4C_3$3FeSi Composites

The yield strength across different ageing temperatures for various percentage volume fractions of Silicon carbide is displayed on plot 3.5.

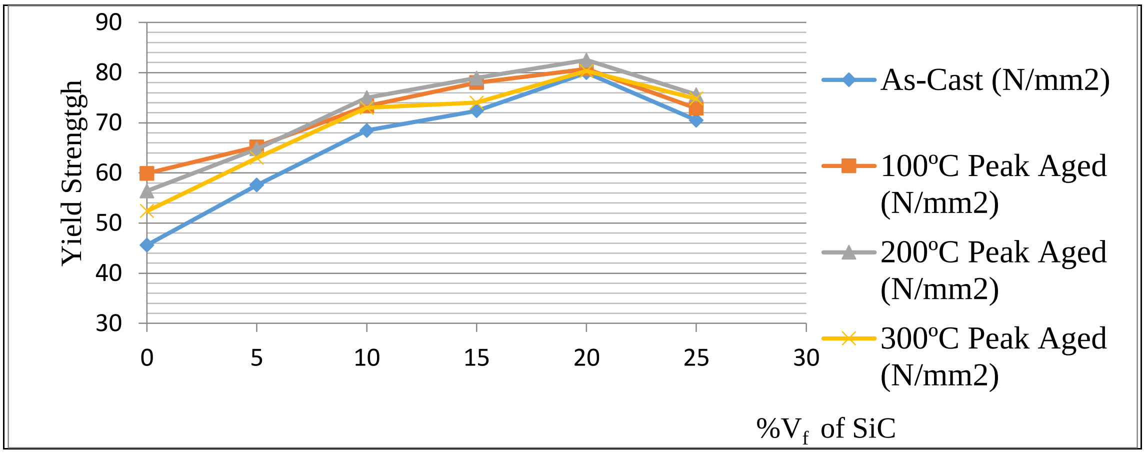

Fig. 3.5: Yield Strength Versus %V_f of SiC

The addition of SiC to composites increases yield strength across all ageing temperatures, possibly due to improved reinforcement and structural integrity. At 100°C peak aged conditions, yield strength increases, but plateaus at 200°C and 300°C. Composites with 20% SiC content show the highest yield strength, suggesting an optimal balance between ageing temperatures. Beyond 20% SiC reinforcement, yield strength declines, possibly due to processing conditions, microstructural variations, or experimental uncertainties. The findings herein corroborate that of Ye *et al.* (2019) who reported increase in yield strength with corresponding increase in strain rate of composites with smaller percentage volume fractions of SiC.

3.6 Tensile Strength of Al_4C_33FeSi Composites

Figure 3.6 shows the tensile strength behaviour of the composites with varying percentage volume fractions of SiC at different ageing temperatures.

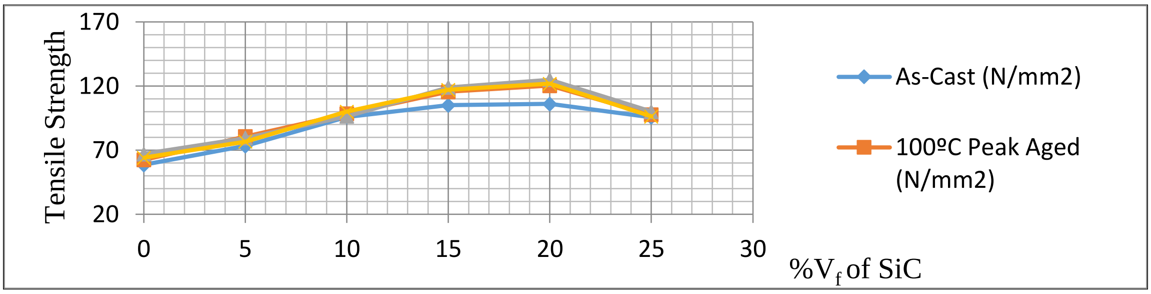

Fig. 3.6: Tensile Strength Versus %V_f of SiC

The addition of SiC reinforcement increases tensile strength across all ageing temperatures, contributing to improved mechanical properties. Composites with 20% SiC content achieve maximum tensile strength of 106.12N/mm^2, 120.43N/mm^2, 125.00N/mm^2, and 121.85N/mm^2, respectively. However, between 200°C and 300°C, tensile strength plateaus. The optimal SiC content is 20%, suggesting that further increases may not significantly enhance tensile strength. The material's stress resistance initially increases, reaching a peak at a strain of 0.03. As strain increases, it decreases slightly, indicating a yielding behavior. As strain increases, stress resistance rises from 30.63 N/mm^2 to 36.08 N/mm^2, then slightly decreases to 35.18 N/mm^2, indicating a potential yielding point. The trend of the curves is seen to obey the general Al-Si/SiC pattern as reported by Singh *et al.* (2014) and Sabry *et al. (*2020).

4.0 CONCLUSION

The study reveals that variations in ageing conditions can significantly impact the mechanical properties of Al-Si MMCs. SiC reinforcement significantly enhanced the mechanical properties of AMMC, showing resistance to ageing-induced degradation. The Taguchi 'Larger the Better' Signal-to-Noise Ratio analysis revealed the influences of volume fractions of SiC, ageing temperature, and time on the material's mechanical hardness property. The composite samples showed an upward trend with increasing SiC percentage, while the time to reach peak hardness decreased with increased in temperature. The maximum yield strength of the material occurred at 200°C ageing temperature with 20% SiC composition. The impact energy of aged material increased at 100°C peak aged condition but decreased at higher ageing temperatures. Young's Modulus values increased with SiC reinforcement, enhancing composite stiffness and mechanical properties. However, excessive SiC reinforcement negatively affected impact toughness, especially in dynamic loading applications.

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