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(Research Article)

Ageing kinetics and precipitation hardening behavior of aluminum-silicon: A volume fractions examination approach

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Abstract

This work examines the ageing kinetics and precipitation hardening behaviour of ferrosilicon-silicon carbide reinforced aluminium metal matrix composites (AMMCs) with particular focus on the influence of varying the percentage volume fractions (%V_f) of reinforcement, ageing temperature and time on the material's behaviour. The investigation systematically analyzed different %V_f of silicon carbide (SiC) of the AMMCs fabricated using dual stir casting technique; to examine the ageing kinetics, precipitation hardening behaviour and their impacts on the material's mechanical properties so as to identify optimal ageing conditions for maximizing the performance of the composites. Percentage volume fraction and distribution of SiC particulates within the microstructure significantly affected the ageing kinetics and precipitation hardening behaviour; as higher %V_f of reinforcement led to a pronounced hardening effect which enhanced composite's hardness by 45.98% and the yield strength by 46.28%. The activation energy of diffusion of the material increased with higher %V_f of SiC from 3508.508 J/mol at 0%V_f of SiC to 9170.342 J/mol at 25%V_f of SiC. This observed increment in activation energy follows the complex and enhanced diffusion pathway of Al-Si atoms, resulting in higher activation energy for the sustenance of the diffusion processes. The acceleration to precipitation hardening dropped with corresponding increase in ageing time. Thus, the precipitates hardening ratio (R) decreased from 0.9 with 5%V_f of SiC to 0.6 with 25%V_f of SiC at 100°C ageing temperatures. A 15-20 %V_f of SiC offered a good balance between accelerated ageing kinetics and manageable activation energy, providing efficient hardening without excessively high diffusion barriers.

Keywords: Ageing kinetics; Precipitation hardening; Activation energy of diffusion; Acceleration to precipitation; Reinforcement distribution; Enhanced mechanical properties; Aluminium-silicon

1. Introduction

The developments of advanced materials with enhanced mechanical properties to meet the demand of modern engineering applications have remained a subject of concern in the field of engineering. Among the various techniques of enhancing the properties of materials especially aluminum silicon system, ageing remains one of the subjects of investigation and utilization. The capability of ageing to alter materials' behaviour has been widely reported and understanding ageing kinetics with associated precipitation hardening characteristics of aged materials is significant in materials design.

Aluminium-silicon (Al-Si) metal matrix composites (MMCs) have garnered significant attention due to their favorable combination of lightweight and high strength [1], [2] and [3]. Its metal matrix composites (MMCs) are engineered by combining aluminium with reinforcing components to create a new material with improved properties [2] and [3]. The

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addition of silicon (Si) in aluminium matrix composites enhances fluidity and resistance to hot cracking, while iron (Fe) reduces casting defects and improves mechanical properties such as tensile strength, yield strength, and hardness at elevated temperatures [4]. Both silicon and iron play crucial roles during solidification, influencing microstructure and mechanical properties [5]. Silicon, when dispersed within the aluminium matrix, forms a eutectic structure, enhancing the composite's properties [6]. Al-Si MMCs exhibit diverse properties depending on constituent phases and volume fractions, with variations noted by [7] and [8]. Integrating ferrosilicon (FeSi) and silicon carbide (SiC) into aluminium matrix further improve mechanical performance, making the emergent material suitable for use in automotives, aerospace and other high-stress environments [9] and [10].

Ageing is a process that evolves material properties over time leading to physical, chemical, thermal, and environmental changes; and age-hardening is a heat treatment process that enhances the mechanical characteristics of certain alloys [11], [12], [13], [14], [15] and [16]. The typical age-hardening process involves heating of the alloy to a high temperature to dissolve precipitates, rapidly cooling the alloy to room temperature to “freeze” the dissolved elements in a supersaturated solid solution; and reheating the alloy to a temperature lower than its solidification temperature to allow the formation of fine precipitates, which contributes to the increase of hardness [17], [18] and [19]. Ageing treatments have a significant impact and contribution in the modification and fine-tuning of the mechanical characteristics and performance of materials, in order to influence properties such as hardness, tensile strength, and impact toughness [20] and [21].The examination of the volume fractions (V_f) and corresponding precipitates formed during ageing deepens the understanding of the microstructural changes and their correlations with mechanical behaviour [2]

The ageing process of alloying metals such as aluminium metal composites (AMCs) is influenced by temperature and time [22]. An optimal temperature range balances the desired strengthening effects with potential drawbacks like over-ageing [23] and [24]. Longer ageing times lead to larger, well-developed precipitates, increasing strength and hardness [25]. Over-ageing can result from excessive temperature or prolonged exposure, reducing the effectiveness of strengthening mechanisms; and determination of optimal ageing time balances desired properties with potential over-ageing under controlled [26]. One of the mechanisms of structural materials ageing is the mechanism of related penetration of atomic hydrogen, or other gasses in the atomic state which formed micro cavities thoroughly by structural imperfections inside the materials [27]. The primary precipitate in Al-Si alloys is often a phase rich in silicon, such as the theta (θ) phase. This phase nucleates and grows during the ageing process and strengthens the alloy by impeding the movement of dislocations and resulting in the improvement of the material’s mechanical properties [17], [18] and [28].

However, the optimization of the ageing processes to achieve maximum hardness and strength remains a challenge. The ageing kinetics and precipitation hardening behaviour of these reinforced composites are influenced by various factors, including the percentage volume fractions of the reinforcements [27]. A deep understanding of how different proportions of FeSi and SiC affect the ageing process and the resulting microstructural changes are essential for tailoring the heat treatment processes to enhance the material’s properties [29].Precipitation hardening heat treatment process enhances the strength and hardness of aluminum alloys and the process involves a temperature and time dependent equilibrium solid-solubility attribute [30]. Volume fractions examination provides a quantitative knowledge of the changes in the arrangement and grain size distribution of the composite’s precipitates; their precise correlation with mechanical properties and the kinetics of phase transformations which enables the identification of optimal ageing conditions [31].

The evolution of microstructural changes in materials as a result of heat treatment, mechanical deformation, or environmental conditions, often lead to formation of precipitates or phases, which can be observed and analyzed using optical microscopy, electron microscopy, and diffraction methods [10] and [23]. Chemical composition process of manufacturing and the type of heat treatment determine the mechanical properties of aluminum alloys and composites. The formation of metastable phases during the process of ageing by heat treatment enhances the properties of a material [32]. Kinetic analysis focuses on identifying the kinetic equation controlling precipitation. Non-isothermal heat treatment is crucial for alloy and metal matrix composite ageing [33], [34] and [35].

In [36], the Arrhenius equation for diffusion is given as:

$$D = D_o \exp\left(\frac{-E}{RT}\right) \ldots\ldots\ldots (1)$$

where: D is the Diffusion coefficient.

D_o is the material constant.

E = activation energy for diffusion (J/mol).
R = Universal Gas constant (8.314J/mol K).
T = Absolute temperature (K).

The Equation (1) when presented in logarithmic form is expressed as in Equation (2).

$$\ln D = \ln D_o - \left(\frac{E}{R}\right)\frac{I}{T} \dots\dots\dots\dots\dots(2)$$

The substitution of D with ln $\frac{I}{t}$ produces a straight line with slope - $\frac{E}{R}$ enabling the calculation of the activation energy (E) of which t is the time to peak hardness and the graph is a plot of ln $\frac{I}{t}$ against $\frac{I}{T}$ for specific ranges of temperature. In the kinetic analysis of precipitation reactions in AI-SI alloys during ageing, various theories and formulas are employed to characterize the evolution of microstructure overtime. These theories provide the framework for evaluation of kinetic aspects of precipitation hardening reaction in Al-Si during ageing. The validation and application of these models support the optimization of ageing conditions of the microstructure and mechanical properties of Al-Si/AMCs [32], [36], [37] and [38].

This study is grounded on the need to enhance the mechanical properties of Al-Si MMCs through deepened understanding of the influence of variation in reinforcements' volume fractions on ageing kinetics and precipitation hardening behaviour of the ferrosilicon-silicon carbide reinforced aluminium matrix for the optimization of the ageing processes in order to achieve superior mechanical properties suitable for high performance applications.

2. Material and methods

The materials utilized during the investigation are 16mm aluminium bare conductor, ferrosilicon, silicon carbide, bentonite, sodium chloride, magnesium, diamond suspension paste, aluminium chloride, mechanical stirrer, crucible, pyrometer, ageing furnace, molding boxes, silica sand and water. Others are universal testing machine, alpha-durometer hardness tester and digital weighing balance.

Samples preparation: Aluminium ferrosilicon (Al-FeSi) was chosen as the matrix material and SiC was used as reinforcement. The composites were fabricated using dual stir casting technique to ensure uniform distribution of reinforcements. Different percentage volume fractions of SiC in the range of 5%, 10%, 15%, 20% and 25% by volume were produced and machined to the required standard tests sample sizes; to investigate their effect on the ageing kinetics and precipitation hardening behaviour of the material.

Ageing process: The composite samples were subjected to solution heat-treatment at 500°C for three hours to dissolve the alloying element in the matrix. Thereafter, the samples were rapidly quenched in water preheated to 65°C to retain the supersaturated solid solution. Then the quenched samples were made to undergo laboratory accelerated ageing at 100°C, 200°C and 300°C for durations ranging from one hour to eleven hours; and the ageing kinetics were studied.

Characterization techniques: Rockwell hardness tests were conducted on the aged samples to measure the hardness and the hardening effect of different volume fractions of the reinforcement was evaluated. Based on the experimental results, the optimal ageing conditions for different volume fractions of SiC reinforcement were determined.

3. Results and discussion

3.1. Activation Energy (E_a)

The Arrhenius equation as well as Avrami exponent were used to analyze the kinetics characteristics and crystallization parameters of Aluminum-based system of metal matrix composites [34], [35], [36].This study obtained the curve of the activation energy, $\mathbf{E_a}$ with corresponding percentage volume fractions (%V_f) of SiC as shown in tables 1 and 2; and their plots are displayed on figures 1 and 2 respectively.

Table 1 %V_f of SiC with Corresponding Activation Energy

%Vf. of SiC addition	Activation energy, Ea
0	3508.508
5	4061.389
10	4831.2654
15	5962.8008
20	6928.0562
25	9170.342

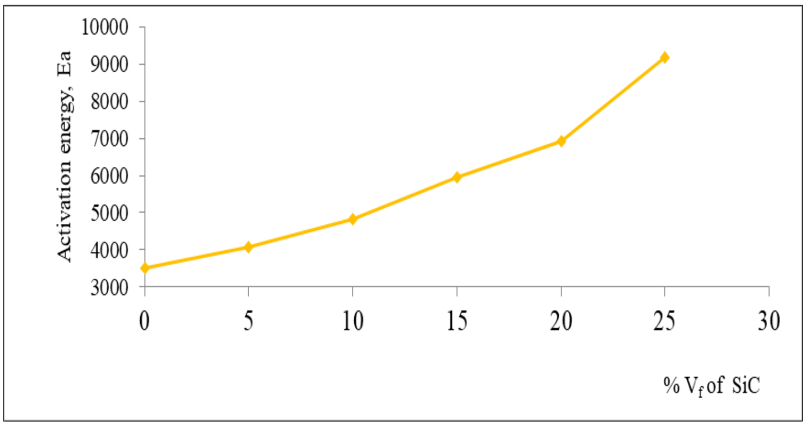

Figure 1 Activation Energy versus %V_f of SiC

The trend indicates that higher volume fractions of SiC reinforcement accelerated the ageing process, reducing the time required to achieve peak hardness. This acceleration may be attributed to the increased density of nucleation sites provided by the SiC particles, which facilitated quicker precipitation of strengthening phases. The activation energy of diffusion increased with higher percentage volume fractions (%V_f) of SiC from 3508.508 J/mol at 0% V_f to 9170.342 J/mol at 25% V_f. This rise in activation energy suggests that as the volume fraction of SiC increased the energy barrier for atomic diffusion also increased; thus, creating a more complex and restrictive environment for diffusion and further necessitating higher energy for atoms to move and form precipitates.

The reduced peak ageing times with higher SiC volume fractions highlights the effectiveness of SiC in enhancing the hardening kinetics of Al-Si MMCs which is beneficial for applications requiring rapid hardening as the hardening kinetics is seen to be enhanced. The increase in activation energy with higher SiC content indicates a more robust and thermally stable composite structure. The higher energy barrier suggests that these composites might retain their properties better at elevated temperatures, which is advantageous for high-temperature applications.

The plot further suggests that optimizing the percentage volume fraction of SiC can tailor the ageing behavior of Al-Si MMCs. For instance, a 15-20% V_f of SiC might offer a good balance between accelerated ageing kinetics and manageable activation energy, providing efficient hardening without excessively high diffusion barriers.

Table 2 Natural logarithm of (1/t) with corresponding absolute (1/T)

1/T	Ln(1/t) for 0%V_f of SiC	Ln(1/t) for 5% V_f of SiC	Ln(1/t) for 10%V_f of SiC	Ln(1/t) for 15%V_f of SiC	Ln(1/t) for 20% V_f of SiC	Ln(1/t) for 25% V_f of SiC
0.0027	-10.3859	-10.2681	-10.1350	-9.9804	-9.7981	-9.2500
0.0021	-10.1346	-9.9804	-9.7981	-9.5750	-9.2873	-8.6000
0.0017	-9.9804	-9.7981	-9.5750	-9.2873	-9.0000	-8.1887

The natural logarithm of the inverse of precipitation hardening time ($\ln\frac{1}{t}$) and the inverse of absolute ageing temperature ($\frac{1}{T}$) is displayed on table 2; and the corresponding plot is shown on figure 2.

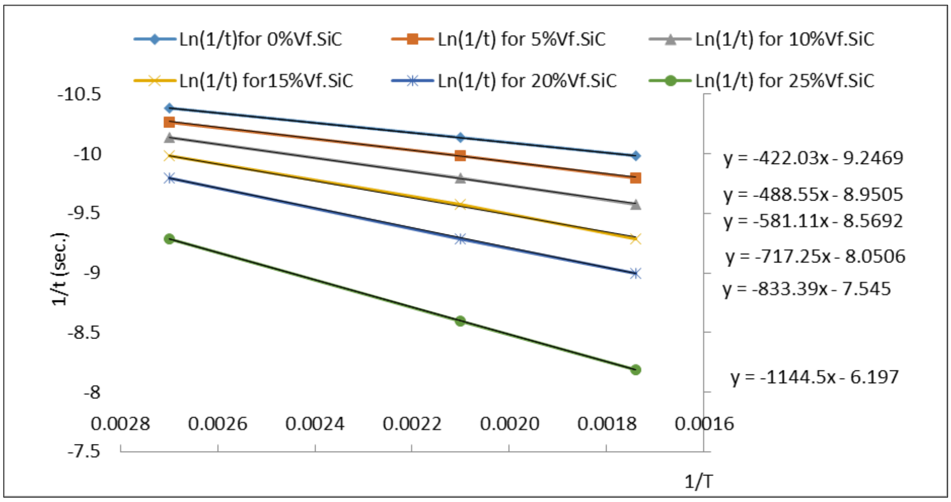

Figure 2 $\ln\frac{1}{t}$ (sec.) versus $\frac{1}{T}$(K).

In figure 2, the values of diffusion coefficients are organized by volume fractions of SiC reinforcement (0%, 5%, 10%, 15%, 20%, 25%). Each condition shows a clear trend where diffusion coefficients values increase (become less negative) as the percentage volume fraction of SiC increases. This trend is consistent across the different ageing conditions and corresponds to different temperatures. At 100 °C ageing temperature, an increase %V_f of SiC resulted in the corresponding decrease in peak ageing time. The less negative diffusion coefficient (D) values indicate that the time to reach peak hardness decreases with increasing volume fractions of SiC. For instance, moving from -10.3859 at 0%V_f to -9.2873 at 25%V_f shows a consistent trend of reduced ageing time as the reinforcement increases. This suggests that higher SiC content accelerates the ageing process, which aligns with the slope of the graph showing reduced peak ageing times with increased SiC volume fractions. Consequently, the following can be deduced:

- *Effect of Ageing Conditions*: Across all conditions, the trend remains consistent, indicating a robust relationship between the volume fraction of SiC and the ageing kinetics. The exact values of diffusion coefficients vary across conditions, which likely represent different temperatures or other ageing parameters. However, within each condition, increasing %V_f of SiC always results in a higher diffusion coefficient.
- *Reinforcement Effect on Diffusion*: The increase in diffusion coefficients with higher SiC content implies enhanced nucleation rates and faster precipitation of strengthening phases due to the presence of more SiC particles, which act as nucleation sites.
- *Optimization of Ageing Process*: For practical applications, understanding this relationship helps in optimizing the volume fraction of SiC to achieve desired mechanical properties more efficiently. Higher SiC content could be preferred for applications requiring rapid hardening.

The ability to reduce ageing time by increasing SiC content can be advantageous in manufacturing, reducing processing time and costs. The increased activation energy with higher SiC content suggests more energy is required for diffusion, indicating a potential trade-off between accelerated ageing and the thermal stability of the material.

3.2. Precipitation Hardening Ratio (R)

The precipitation hardening rate (R) of the AMC particles was obtained by taking the ratio of the time to peak hardening for the cold-worked material (t_pH_c) and the time for peak hardening for the as-machined material (t_pH_m) at different ageing temperatures and SiC volume fractions compositions. The plot of the precipitation hardening ratio against percentage volume fraction of reinforcement is as displayed on figure 3.

Table 3 Acceleration to Precipitation hardening of varying %Vf. of SiC

%Vf. of SiC	Acceleration to precipitation hardening (R) at 100ºC	Acceleration to precipitation hardening (R) at 200ºC	Acceleration to precipitation hardening (R) at 300ºC
0			
5	0.90	0.75	0.63
10	0.80	0.75	0.63
15	0.70	0.63	0.50
20	0.70	0.63	0.38
25	0.60	0.50	0.25

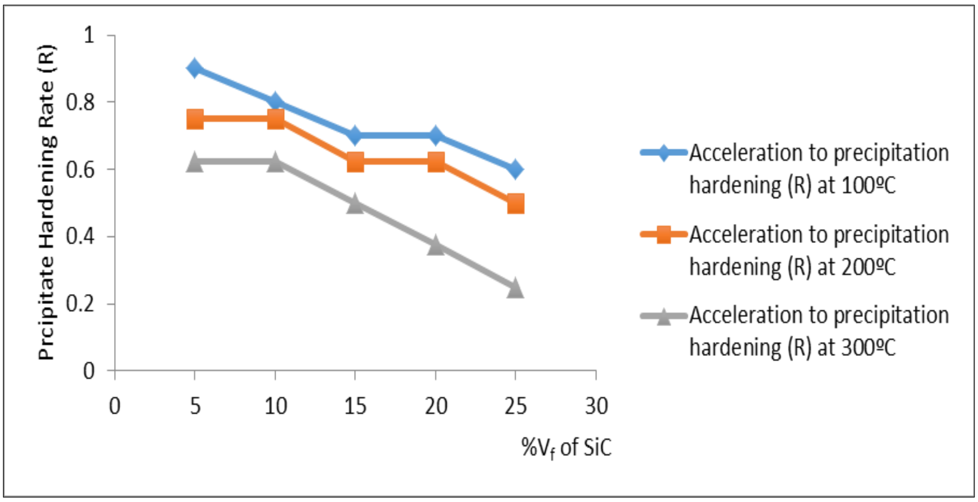

Figure 3 Hardening Rate versus %Vf of SiC

The precipitates hardening ratio (R) and peak aged time at different temperatures (100ºC, 200ºC, 300ºC) for ferrosilicon-silicon carbide reinforced aluminum metal MMCs impregnated with varying percentage volume fractions (%Vf) of silicon carbide (SiC), reflects the efficiency of the precipitation hardening process, with higher values indicating more effective hardening. The Peak Aged Time (Hrs) is the time required to reach peak hardness at each specified temperature. The precipitates hardening ratio (R) decreases as the volume fraction (Vf) of SiC increases for all temperatures. For example, at 100°C, R decreased from 0.9 (5% Vf) to 0.6 (25% Vf).

This trend indicates that while the addition of SiC reinforcements initially improves the hardening process, excessive SiC content may reduce the efficiency of precipitation hardening. The peak aged time consistently decreased with increasing SiC volume fractions. At 100°C, the peak aged time reduces from 10 hours (0% Vf) to 6 hours (25% Vf). This trend is observed across all temperatures, indicating that higher SiC content accelerates the ageing process. The precipitates hardening ratio and peak aged time data show that the ageing process is highly temperature-dependent. Higher temperatures (e.g., 300°C) generally result in shorter peak aged times across all volume fractions. This suggests that higher temperatures enhance the diffusion and precipitation processes, leading to quicker hardening.

The reduced peak aged times with higher SiC volume fractions are beneficial for industrial applications requiring faster processing times. The presence of SiC particles accelerates the nucleation and growth of precipitates, leading to quicker hardening, while higher SiC content reduces ageing time, it also lowers the precipitates hardening ratio. This indicates a trade-off where the addition of SiC speeds up the ageing process but may compromise the efficiency of hardening if the volume fraction is too high. The observation suggests that there is an optimal range of SiC volume fractions (potentially around 15-20%) where the benefits of accelerated ageing are maximized without significantly compromising the hardening ratio.

3.3. Effects of Precipitation Hardening on Mechanical Characteristics

3.3.1. Hardness

The result of the peak aged values of hardness of the composites on scale "B" of Rockwell hardness test is as tabulated in table 4.

Table 4 Values of Hardness (HRB) of the As Cast and Aged Composites with Percentage Fractions of Silicon Carbide

% V_f of SiC	**As-cast**	**100°C Peak aged**	**200°CPeak aged**	**300°C Peak aged**
0	31.10	60.10	61.50	62.00
5	54.50	72.00	73.00	74.00
10	57.50	75.00	74.50	84.00
15	64.30	82.00	84.00	85.00
20	67.00	86.00	87.00	89.00
25	71.00	89.50	89.00	90.50

The corresponding plot is displayed on figure 4.

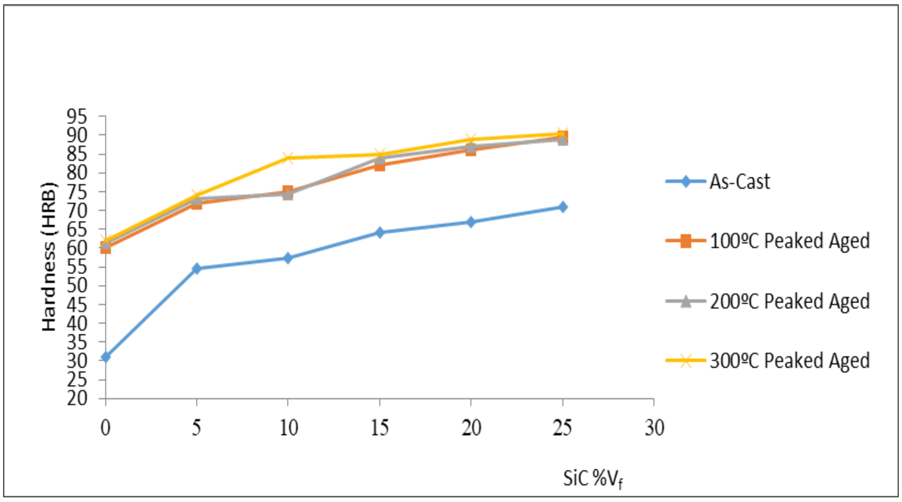

Figure 4 Hardness Versus %V_f of SiC

Table 4 and Figure 4 indicate the measure of the extent of hardness of both the as-cast and aged composites. Based on the results, the hardness values of both the as-cast and aged samples exhibit an upward trend as the percentage volume fraction of SiC in the material is increased. This trend is attributed to the rise in the magnitude of hardness and brittleness within the ceramic particulates present in the composites.

Table 5 Hardness with corresponding ageing temperature

Ageing Temperature (ºC)	**Hardness of As Cast (HRB)**	**Hardness of 5%V_f of SiC (HRB)**	**Hardness of 10%V_f of SiC (HRB)**	**Hardness of 15%V_f of SiC (HRB)**	**Hardness of 20%V_f of SiC (HRB)**	**Hardness of 25%V_f of SiC (HRB)**
	31.10	54.50	57.50	64.30	67.00	71.00
100	60.10	72.00	75.00	82.00	86.00	89.50
200	61.50	73.00	74.50	84.00	87.00	89.00
300	62.00	74.00	84.00	85.00	89.00	90.50

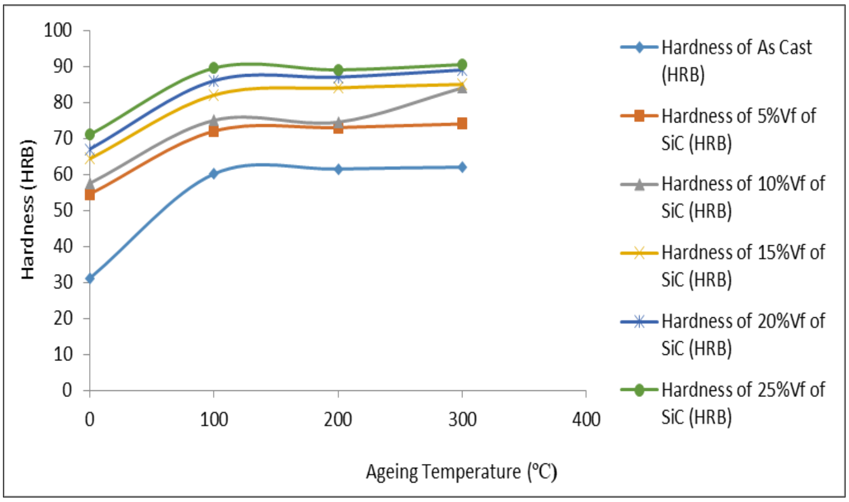

Figure 5 Hardness versus Ageing Temperature

The addition of SiC significantly increases the hardness of the composite materials, with a significant increase observed at 100°C. The as-cast material's hardness nearly doubles, and the 25%V_f of SiC composite reached 89.5 HRB. At 200°C, the hardness slightly increased, but less pronounced than at 100°C. The 10%V_f of SiC composite's hardness decreases slightly, possibly due to over-ageing effects. At 300°C, all composites show slight increments which seemingly suggest microstructural stability.

Based on the study, larger SiC concentration increased hardness at all aging temperatures, suggesting that it is useful for strengthening aluminum matrix. The temperature ranges where the most of the increases are seen are 0°C to 100°C, with minor decreases occasionally occurring at higher ageing temperatures (200°C to 300°C). Higher SiC volume fractions and higher ageing temperatures are advantageous for achieving maximal hardness. The highest hardness (90.5 HRB) is shown by the 25%V_f of SiC composite peak aged at 300°C, which is the ideal temperature for maximal hardness. The results provide important information on the best compositions and treatments to provide the requisite mechanical characteristics, which is important for applications requiring high-strength materials.

The behaviour of the material's hardness property with corresponding ageing time for the varying percentage volume fractions of SiC reinforcements are displayed in figure 6.

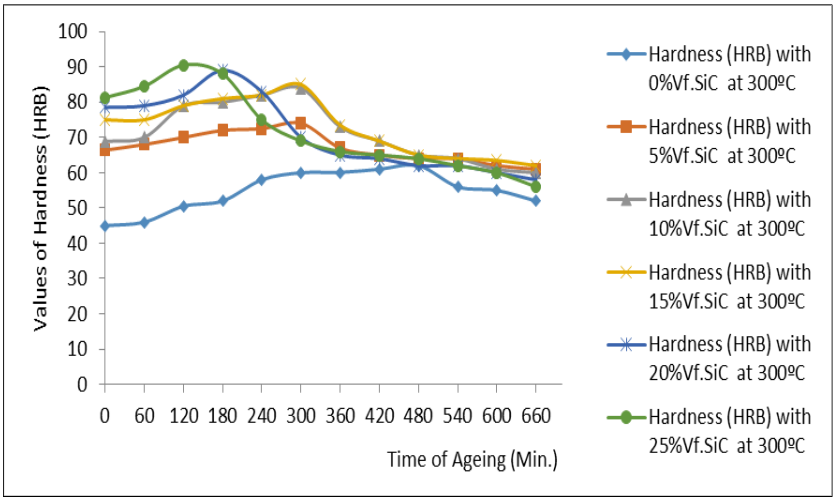

Figure 6 Hardness versus Ageing Time (Min)

The trend in figure 6 illustrates a notable surge in the values of hardness recorded from each grade of composite at all temperatures in the beginning of the ageing process. Subsequently, there is a decline after attaining the peak ageing time which indicates over ageing condition. Notably, at elevated ageing temperatures, the materials attain peak hardness in a shorter period. This accelerated attainment is attributed to the faster rate in which precipitates of the second-phase materials contributed to the increment of hardness values, revealing a shorter time for achieving peak hardness as the ageing process progresses sequentially from 100°C to 200°C and to 300°C. The age hardening characteristics mirror those reported by [23], [30] and [39]. In essence, hardness exhibits a continuous increase during ageing, reaching a maximum before subsequently decreasing due to over ageing. An intriguing observation is that, within the reinforced aluminum alloy metal-matrix composite system, an increase in the percentage volume fractions of SiC results in a consistent reduction in the time required to attain peak hardness.

At different aging temperatures, the hardness values of the aged composites almost mirror one another with corresponding percentage volume fractions of SiC incorporations. 90.50HRB is the maximum hardness shown in Figures 4, 5 and 6. Both the hardness of 90.5HRB in the plot of hardness versus percentage volume fractions of SiC and the hardness of 90.5HRB in the plot of hardness versus ageing time indicate the point of optimization for maximum hardness of the material. The hardness of the material in the plot of hardness versus ageing temperature with 25%Vf of SiC peak aged at 300°C mirrors the other two plots. 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 [13], [40], [41] and [42].

3.3.2. Signal-to-Noise Ratios of Hardness of Composites.

The data was organized in a factorial design to evaluate the effects of these factors on the Signal-to-Noise Ratio (SNR) of the hardness measurements. Tables 6 and 7 show the means of the SNR for hardness (HRB) as a function of three variables: temperature (T) in degree Celsius (°C), volume fraction (V_f, multiplied by 0.05), and time (t, in minutes, multiplied by 0.6).

Table 6 Mean Response of Hardness Signal-to-Noise Ratio with Time

Time (Min.)	HRB	S/N Ratio	Mean response, ỹ
60	58	10.95	68.2
360	79	8.27	
660	64	10.10	
360	73	8.95	
660	63	10.23	
60	75	8.72	
660	61	10.51	
60	75	8.72	
360	66	9.83	

Table 7 Mean Response of Hardness Signal-to-Noise Ratio with Temperature

Means of SNR of HRB	T (°C)	V_f (%) x0.05	t (mins.) x0.6
100	9.77	10.14	9.46
200	9.30	9.07	9.02
300	9.69	9.55	10.28

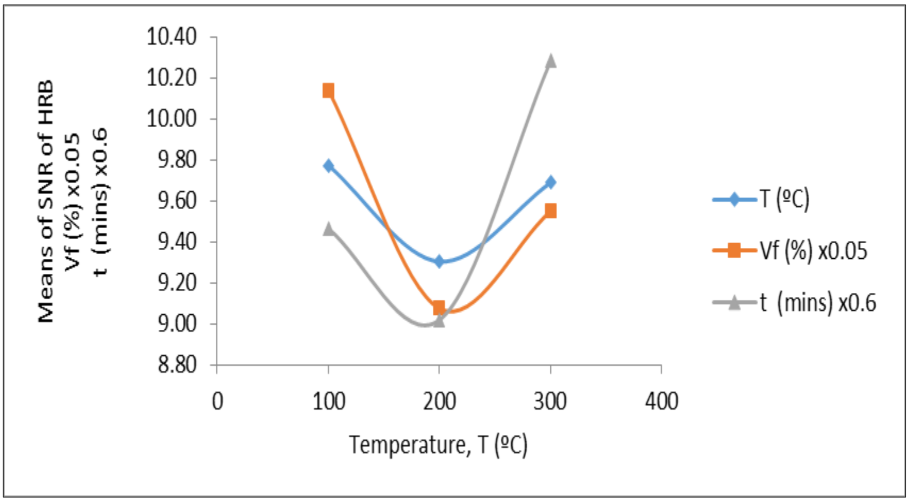

Figure 7 Means of SNR of Hardness (HRB) versus Ageing Temperature (ºC)

The SNR values for hardness measurements at different temperatures are 9.77, 9.30, and 9.69, respectively. The highest SNR is at 100°C, indicating the most consistent measurements. The lowest SNR is at 200°C, indicating increased variability. At 300°C, the SNR is 9.69, indicating an improvement in consistency. SNR values varied for different volume fractions, with the highest SNR at the 5%volume fraction setting indicating the best consistency. SNR values also varied for different ageing times, with the highest SNR at the 660 minutes time setting indicating the best consistency.

At 100℃, hardness measurements exhibited the maximum degree of uniformity. The results are likewise rather constant at 300℃, with the greatest fluctuation observed around 200℃. The most reliable hardness readings were obtained with the 5% volume fraction setting, or SNR of 10.14. The most variable volume fraction option is the 15%V_f, whereas the 25%V_f setting exhibited an intermediate level of consistency. The hardest readings are consistently obtained at the 11hours time setting (SNR = 10.28), indicating that this is the best ageing period to reduce variability. The greatest fluctuation is shown in the 360 minutes time setting, suggesting that the material may not have achieved a stable condition; thus moderate consistency was provided by the 60 minutes time setting.

The optimal parameters for consistency in aluminum-silicon carbide composites are the 5% volume fraction setting (10.14) and the 660 minutes time setting (10.28), with the ideal aging time found by focusing on the 360 minutes and 660 minutes time settings. These parameters enhance the reliability and dependability of hardness measurements of the material in engineering applications.

3.3.3. Yield Strength of FeSi-SiC AMMCs.

Table 8 contains the results of yield strength of the AMMCs at corresponding ageing temperatures while figure 8 displays the corresponding plot of the data set.

Table 8 Yield Strength of FeSi-SiC AMMCs with varying Temperature

Ageing Temperature (℃)	**Yield Strength of As Cast (HRB)**	**Yield Strength of 5%V_f of SiC (HRB)**	**Yield Strength of 10%V_f of SiC (HRB)**	**Yield Strength of 15%V_f of SiC (HRB)**	**Yield Strength of 20%V_f of SiC (HRB)**	**Yield Strength of 25%V_f of SiC (HRB)**
	45.60	57.57	68.46	72.38	79.98	70.50
100	59.90	65.20	73.35	78.00	80.75	72.90
200	56.40	64.80	75.00	78.91	82.50	75.60
300	52.40	63.00	73.00	74.00	80.34	74.80

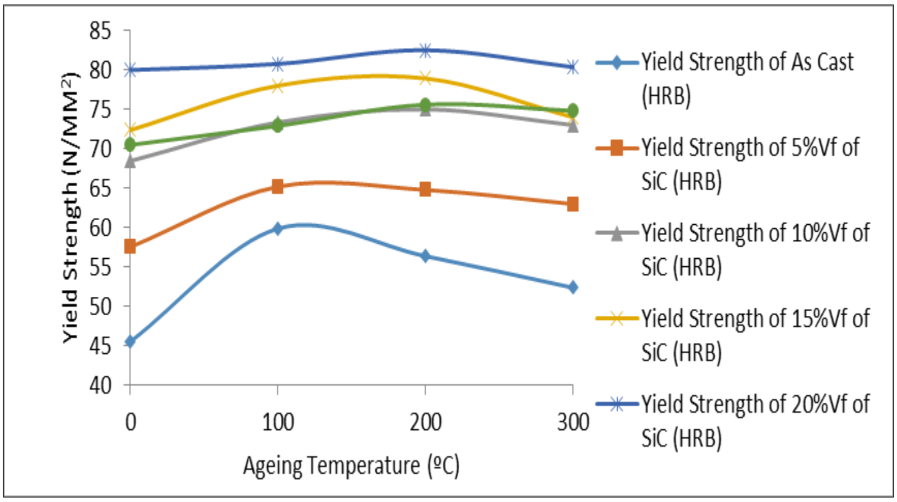

Figure 8 Yield Strength of FeSi-SiC AMMCs versus Ageing Temperature

The trends of the plot in figure 8, show that yield strength of the as-cast composite increased with ageing temperature, peaking at 75 HRB at 200°C and slightly declining at 300°C. With 5%V_f of SiC, the yield strength increased to 65.2 HRB at 100°C, then falls to 64.8 HRB at 200°C and 63 HRB at 300°C. Yield strength is seen to rise steadily with temperature at 10%V_f of SiC, reaching a peak of 75 HRB at 200°C and a minor decline to 73 HRB at 300°C. The yield strength increased from 72.38 HRB at as-cast condition to 75.6 HRB at 200°C with 15%V_f of SiC, then gradually declined to 74 HRB at 300°C. With 25%V_f of SiC, yield strength increased from 70.5 HRB to 75.6 HRB at 200°C, then gradually declined to 74.8 HRB at 300°C.

The overall pattern suggests that yield strength increased with increased SiC volume fractions at all aging temperatures. At all temperatures, the maximum yield strength is consistently provided by the 20%V_f of SiC reinforced material specimen. There is an ideal ageing temperature for strengthening, since yield strength was seen to improve with temperature up to 200°C. The yield strength tends to decline beyond 200°C, most likely as a result of the effects of over-aging, which result in some strength reduction.

20%V_f of SiC is the ideal SiC content for reinforcement as it offers the maximum yield strength at all temperatures. These are the ideal conditions for yield strength. 200°C is the ideal ageing temperature to maximize yield strength. For the majority of composites, this temperature yields the maximum strength. Yield strength decreases at temperatures higher than 200°C, indicating that the material qualities start to deteriorate after attaining their maximum hardness due to thermal degradation.

4. Conclusion

- The study provided a comprehensive understanding of how varying the percentage volume fractions of FeSi and SiC reinforcements influenced the ageing kinetics and precipitation hardening behaviour of Al-Si MMCs. The activation energy of diffusion of the material increased with higher %V_f of SiC from 3508.508 J/mol in the as-cast condition to 9170.342 J/mol with 25% V_f of SiC.
- There is a clear, consistent relationship between SiC volume fraction and ageing kinetics, providing valuable insights for optimizing the reinforcement content in Al-Si MMCs for various engineering applications. The precipitates hardening ratio (R) decreased from 0.9 with 5% V_f of SiC to 0.6 with 25% V_f of SiC at 100°C ageing temperatures.
- A 15-20%V_f of SiC offered a good balance between accelerated ageing kinetics and manageable activation energy, providing efficient hardening without excessively high diffusion barriers. Thus, this study might contribute to the design and heat treatment processes for developing high-performance composite materials tailored to specific engineering applications.
- The composite's hardness increased from 62HRB in the as-cast condition to 90.5HRB when peak aged at 300°C for 2hours; and the yield strength improved by 46.28%. These might also guide the development of optimized ageing process for tailoring the mechanical properties and processing times for Al-Si MMCs in specific engineering applications.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there exists no conflict of interest.

Author's contribution

All authors contributed equally to thus work.

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Data availability statement

The data that supports the findings of this investigation are available upon request from the corresponding author.

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