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Ageing on mechanical and microstructural properties of aluminum-silicon metal matrix composites: A review

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Abstract

This review examines the impact of ageing on the mechanical and microstructural properties of Aluminum-Silicon (Al-Si) Metal Matrix Composites (MMCs), extracting broader perspectives from experimental and theoretical studies. Al-Si MMCs have gained significant attention in various industries as a pivotal material in advanced engineering applications due to their excellent strength, exceptional thermal stability, corrosion resistance, lightweight nature and wear resistance properties. Nevertheless, the long-term performance of the composites is significantly influenced by thermal and mechanical ageing phenomena, which alter their microstructural configuration and mechanical integrity. Thus, fundamental ageing mechanisms such as precipitation hardening, coarsening of reinforcement particles, matrix-reinforcement, interfacial reactions and micro-crack initiation are explored in relation to ageing conditions, percentage volume fractions of reinforcement and alloying elements. Further emphasis is placed on the correlation between microstructural evolutions; including grain refinement, intermetallics phase transformation and particles distribution, noting their influences on the tensile strength, hardness, wear resistance and fatigue behaviour of the composites. More so, various ageing treatments such as natural, laboratory accelerated (artificial) and over-ageing influence dislocation movements and interfacial bonding; thereby affecting overall performance of the material. In addition, emerging trends in nano-structured MMCs and advanced ageing models for prediction of materials' performance are discussed. Thus, this review provides a foundational understanding for materials engineers and researchers aiming to tailor Al-Si MMCs through controlled ageing for improved service performance and lifecycle efficiency; as the findings herein underscore the critical role of optimized ageing treatments in enhancing the reliability and longevity of Al-Si MMC components in automotive, aerospace and structural applications. Future research directions are proposed, focusing on hybrid reinforcement systems and real-time monitoring of ageing-induced degradation in engineering systems.

Keywords: Al-Si Metal Matrix Composites; Ageing; Mechanical Properties; Microstructural Configuration; Precipitation Hardening; Composite Degradation

1. Introduction

Aluminium-Silicon Metal Matrix Composites (Al-Si MMCs) which is typically reinforced with silicon particles and other ceramic phases are widely used in critical components within the automotive, aerospace, and structural sectors where reliability and durability under service conditions are vital [1]. As such, understanding the long-term performance of Al-Si MMCs is important in order to ensure structural integrity and service life extension of engineering components. One of the most critical factors affecting the reliability of Al-Si MMCs is ageing. The time-dependent phenomenon occurs as a result of thermal or mechanical exposure of the material; resulting to significant changes in both the mechanical behaviour and microstructural characteristics [2]. Ageing influences key performance indicators of a material such as hardness, tensile strength, fatigue resistance, and wear properties through precipitation hardening, dislocation

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movement, inter-facial de-cohesion, and microstructural coarsening mechanisms [3]. This investigation aims to provide a comprehensive synthesis of the current knowledge on the effects of ageing on the mechanical and microstructural properties of Al-Si MMCs. The scope covers natural and laboratory accelerated ageing processes, their influences on microstructural evolution, and the resulting implications for mechanical performance. Based on compiled and analyzed results from recent studies, the review offers critical insights into ageing mechanisms and material behaviour under various ageing conditions. The significance of this work lies in its potential to guide future materials design and ageing treatment optimization, thereby improving the reliability, safety, and performance of Al-Si MMCs in advanced engineering applications.

2. Review of Ageing on Al-Si MMCs System

Ageing influences the mechanical and microstructural behavior of Al-Si MMCs, affecting performance metrics of hardness, strength, ductility, fatigue life, creep resistance and thermal stability. The consolidation of findings from experimental, empirical, and simulation-based studies which assess property degradation mechanisms, compare ageing responses across different alloy grades and reinforcement types in order to identify how processing parameters influence the long-term reliability of these composites in critical applications; provide direction for materials selection, component design, and lifecycle management strategies especially for the development of more ageing-resistant and thermally stable composite Al-Si systems.

2.1. Al-Si Metal Matrix Composites

Aluminium–Silicon Metal Matrix Composites (Al-Si MMCs) evolves as a class of advanced materials engineered by the combination of ductile aluminium alloy matrix with silicon (Si) particles as reinforcing phases [4]. In the report of [5], ceramic materials such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) constitute other reinforcements of Al. Generally, reinforcements are introduced to enhance specific material properties such as strength, wear resistance, thermal stability, and stiffness, without significantly compromising weight or ductility. The composition of Al-Si MMCs typically includes 5–25% silicon content or lower, with additional ceramic or ferro-silicon particulates introduced to meet design needs [6]. The aluminium matrix provides good machinability, thermal conductivity, and toughness, while the silicon phase contributes to improved wear resistance and dimensional stability due to its hardness and inertness [7]. Silicon carbide and other ceramic reinforcements further enhance load transfer capabilities and elevate the composite's resistance to creep, oxidation, and thermal expansion [8]. In [6], silicon particularly, plays a dual role as a reinforcing agent and a microstructure modifier; in that, it refines the eutectic structure and reduces shrinkage during casting. When distributed evenly, silicon enhances hardness, reduces thermal expansion, and helps stabilize the microstructure during heat treatment or service exposure [9][10]. The ceramic particulates serve as barriers to dislocation movement and contribute to grain refinement by acting as heterogeneous nucleation sites. Due to this favorable combination of properties, Al-Si MMCs are widely utilized in high-performance applications. In the automotive industry, they are used for engine blocks, brake discs, cylinder liners, pistons, and connecting rods, where lightweight and thermal stability are essential. In the aerospace sector, their high strength-to-weight ratio and corrosion resistance make them suitable for structural panels, landing gear, and high-speed rotating parts. Structural applications include load-bearing components in bridges, frames, and aerospace-grade architectural panels, where the combination of mechanical reliability and resistance to deformation under thermal stress is crucial [11]. Despite their advantages, the long-term performance of Al-Si MMCs is significantly influenced by ageing phenomena. Over time, exposure to heat and mechanical stress can lead to changes in microstructure such as coarsening of precipitates, formation of brittle intermetallics, and interfacial degradation; which negatively affect mechanical properties like strength, fatigue resistance, and ductility [12]. This has created a critical need for deeper insight into how Al-Si MMCs behave under ageing conditions - both natural and artificial; to ensure durability, reliability and service life extension.

2.2. Ageing Phenomena in Metal Matrix Composites

2.2.1. Definition and Classification of Ageing

[13] refers to ageing as the time-dependent evolution of a material's microstructure and properties as a result of exposure to thermal or mechanical conditions. It is especially relevant in precipitation-hardened alloys and composites, where phase transformations and diffusion-controlled changes occur over time [14]. In the investigation of Al-Si Metal Matrix Composites (MMCs) ageing properties, [15] observed that ageing plays a critical role in defining mechanical stability, hardness, tensile strength, and fatigue performance of the composite. Typically, ageing is classified into three main types: (i) Natural ageing (NA) which occurs at ambient temperatures after solution heat treatment and involves slow precipitation of solute atoms and dislocation locking over extended periods [16]. (ii) Artificial ageing (AA) which involves controlled heat treatment at elevated temperatures (usually 100–200°C for aluminium alloys) to accelerate

precipitation hardening. It is often optimized for maximum hardness and strength [17]; and (iii) Thermal ageing (TA) that refers to changes induced by prolonged exposure to high service temperatures. Unlike artificial ageing, it can lead to overageing, precipitate coarsening, and degradation of mechanical properties [18]. Each ageing method influences the distribution and morphology of precipitates, which in turn affects the performance of the Al-Si MMC.

2.2.2. Comparison of Ageing in MMCs vs. Conventional Alloys

While ageing affects both monolithic aluminium alloys and metal matrix composites, the presence of reinforcements in MMCs introduces additional complexities [19]. In conventional aluminium alloys, ageing primarily influences the precipitation of intermetallic compounds such as Mg_2Si, Al_2Cu, or Al_3Ni [20]. However, in MMCs, the matrix-reinforcement interface acts as an active site for nucleation, and differential thermal expansion can generate residual stresses that accelerate diffusion and precipitation kinetics. Furthermore, ceramic reinforcements like SiC or Al_2O_3 tend to hinder dislocation motion and reduce grain boundary mobility, leading to more thermally stable microstructures. However, this can also localize stress during ageing and potentially initiate microcracks or interfacial debonding under prolonged thermal exposure [21]. In comparison, conventional alloys age more uniformly and predictably, without the added complexity of matrix–particle interactions.

2.2.3. Thermodynamics and Kinetics of Ageing in Al-Si Systems

The ageing behaviour of Al-Si MMCs is governed by diffusion-controlled precipitation, interface reactions, and the thermodynamic stability of the matrix and reinforcement phases [15]. Thermodynamically, ageing begins when the supersaturated solid solution (obtained after solution treatment) seeks equilibrium via the nucleation and growth of precipitates. This evolution is driven by the reduction in Gibbs free energy and modulated by temperature and alloy composition [22]. In Al-Si MMCs, the kinetics of ageing are influenced by the distribution and type of reinforcement, which alters atomic diffusion pathways. For example, the presence of hard particles like SiC can act as sinks or sources for solute atoms and affect precipitate nucleation rates. Additionally, ageing kinetics in these composites are sensitive to processing history, particle clustering, and interfacial bonding quality [15]. Typically, artificial ageing brings about a three-stage hardness profile which includes under-aged (incomplete precipitation), peak-aged (optimal properties), and over-aged (coarsened precipitates and declining properties) [23][24]. The comprehension of the various kinetic models including Avrami equations or Johnson-Mehl-Avrami-Kolmogorov (JMAK) models can assist in the prediction of these transitions and guide the optimization of ageing cycles [25][26].

2.3. Mechanisms of Ageing in Al-Si MMCs

The ageing mechanisms in Aluminium–Silicon Metal Matrix Composites (Al-Si MMCs) are governed by complex interactions between the aluminium matrix, silicon particles, and added ceramic reinforcements during thermal or service exposure [15]. These mechanisms determine how the material's microstructure evolves over time and are directly linked to changes in its mechanical performance.

2.3.1. Precipitate Nucleation and Growth

In heat-treatable Al-Si alloys, artificial ageing induces the precipitation of metastable phases such as Guinier–Preston (GP) zones and θ' (Al_2Cu), which strengthen the matrix via precipitation hardening. In MMCs, these precipitates nucleate both homogeneously within the matrix and heterogeneously at dislocations or near reinforcement interfaces [15][27]. Reinforcing particles such as SiC and Al_2O_3 often act as heterogeneous nucleation sites, accelerating the precipitation kinetics compared to unreinforced alloys [21]. However, prolonged exposure to elevated temperatures can cause over-ageing, where precipitates coarsen and lose coherency with the matrix. This coarsening leads to decreased obstacle strength against dislocation motion, thereby reducing tensile strength and hardness.

2.3.2. Matrix–Reinforcement Interfacial Degradation

Another significant mechanism is the thermal instability at the matrix–reinforcement interface, especially under cyclic or prolonged thermal ageing. Differential thermal expansion between aluminium and reinforcement phases induces interfacial stresses that can lead to de-bonding, void formation, or micro-cracking [19][20]. These microstructural defects act as stress concentrators, deteriorating fatigue life and fracture toughness. In particular, chemical reactions at the interface such as the formation of brittle inter-metallic compounds (e.g., Al_4C_3 in Al–SiC systems) can further weaken the interface, reduce load transfer efficiency and introduce embrittlement [12].

2.3.3. Coarsening of Eutectic and Primary Silicon Particles

Ageing also affects the morphology of silicon within the composite. Eutectic and primary Si particles may undergo coarsening and spheroidization during thermal exposure, especially at high temperatures. This morphological change reduces their effectiveness in impeding dislocation motion and contributes to a decline in yield strength and wear resistance [15][28][29]. In [30], the coarsening follows Ostwald ripening principles, where smaller particles dissolve and redeposit onto larger ones to minimize system energy. The resulting reduction in particle counts and increase in average particle size reduces the mechanical interlocking between the matrix and reinforcement.

2.3.4. Grain Boundary Relaxation and Softening

At elevated temperatures, dislocation recovery and grain boundary relaxation become prominent. The stored energy from deformation is gradually relieved, causing a reduction in dislocation density. In composites, where reinforcement particles impede recrystallization, ageing may instead trigger localized softening and grain boundary sliding, leading to time-dependent deformation (creep) and dimensional instability [31].

2.3.5. Precipitation Hardening and Particle Coarsening

Ageing in Al-Si MMCs is primarily driven by precipitation hardening, where finely dispersed precipitates (e.g., Mg_2Si in Al-Si-Mg systems) hinder dislocation motion, enhancing strength. However, over time, these precipitates coarsen, reducing their effectiveness and leading to softening and strength loss [15][32]. The kinetics of coarsening is accelerated at higher temperatures, contributing to the decline in peak-aged mechanical performance.

2.3.6. Dislocation Pinning and Movement

The introduction of ceramic particles such as SiC impedes dislocation mobility through Orowan looping and particle pinning mechanisms. During thermal ageing, dislocation density can either increase due to thermal mismatch stress or decrease due to recovery processes, affecting overall ductility and work-hardening capacity [33].

2.3.7. Phase Transformations and Intermetallic Formation

Ageing can promote phase transformations and the formation of brittle intermetallics (e.g., Al-Fe-Si phases), particularly at grain boundaries. These phases may reduce toughness and accelerate crack propagation under stress [21][34].

2.3.8. Matrix-Reinforcement Interface Reactions

At elevated temperatures, diffusion-driven reactions at the matrix-reinforcement interface can result in interfacial debonding or the formation of reaction layers. This weakens load transfer efficiency and contributes to early failure in thermally aged composites [35].

2.3.9. Thermal Stability and Creep Deformation during Prolonged Exposure

Under long-term thermal exposure, creep mechanisms such as grain boundary sliding and dislocation climb become prominent. The thermal instability of the matrix or weak interface zones may cause microstructural degradation, impairing long-term load-bearing capabilities [36].

2.4. Effects of Ageing on Mechanical Properties

[15] observed that ageing treatments significantly influence the mechanical performance of Al-Si Metal Matrix Composites (MMCs), as they alter the internal microstructure and interfacial bonding dynamics.

2.4.1. Hardness Variation

Artificial ageing leads to a distinct hardness profile characterized by an initial increase (under-aged), a peak (peak-aged), and a decline (over-aged). Peak hardness results from the uniform dispersion of fine precipitates that impede dislocation movement. Prolonged thermal exposure causes precipitate coarsening and loss of coherency, reducing hardness [18].

2.4.2. Tensile Strength and Ductility

Tensile strength improves with ageing due to matrix strengthening from precipitation. However, over-ageing reduces strength and can increase brittleness. Ductility often decreases slightly at peak ageing due to reduced plastic flow, while excessive ageing may lead to ductile-to-brittle transitions [15][32].

2.4.3. Fatigue Resistance and Fracture Behaviour

Ageing affects fatigue life through changes in micro-crack initiation and propagation paths. Interfacial weakening, void formation, and silicon particle coarsening under ageing degrade fracture toughness and enhance crack sensitivity under cyclic loading [20][32].

2.4.4. Wear and Abrasion Resistance

Well-aged Al-Si MMCs exhibit improved wear resistance due to higher hardness and stronger interfaces. However, over-ageing can promote particle pull-out and interfacial degradation, increasing surface wear under abrasive conditions [37].

2.4.5. Creep Response and Load-Bearing Ability

Thermal ageing impacts long-term dimensional stability and creep resistance. Grain boundary softening and dislocation recovery at elevated temperatures reduce the composite's ability to sustain constant loads over time, particularly in high-temperature applications [34][38][39]. It may be deduced that the combined effects of precipitate evolution, interfacial degradation, and matrix softening result in reduction in hardness and tensile strength after peak ageing, diminished fatigue resistance due to interfacial voids and cracks, loss of creep strength and dimensional stability under prolonged exposure; and changes in fracture toughness associated with silicon coarsening and interfacial weakening. An in-depth understanding of these mechanisms is essential for optimized ageing treatments, suitable reinforcement materials selection and the improvement of the design of Al-Si MMCs for long-term applications.

2.5. Effects of Ageing on Microstructural Properties

Ageing induces critical microstructural transformations in Al-Si MMCs that directly influence their mechanical behavior and long-term reliability.

2.5.1. Grain Growth and Refinement

Prolonged ageing promotes grain coarsening in the aluminium matrix due to dislocation recovery and grain boundary migration. This leads to reduced strength and thermal stability [40].

2.5.2. Particle Distribution and Morphology

Silicon and ceramic reinforcements may coarsen or undergo conversion of carbide structures into spherical form, especially at elevated temperatures in order to increase ductility and machinability. Uniform distribution achieved in the as-cast or heat-treated state becomes disrupted with ageing, weakening load transfer efficiency [41].

2.5.3. Interfacial Evolution

The matrix–reinforcement interface experiences stress due to thermal mismatch. Ageing can cause interfacial de-bonding, voids, or the formation of brittle intermetallics such as Al_4C_3 in SiC systems, thus degrading mechanical bonding [42][43].

2.5.4. Precipitate Nucleation and Growth

Ageing accelerates the formation of strengthening precipitates (e.g., GP zones, θ'), which initially improve hardness. Over time, these precipitates coarsen and lose coherency, diminishing their strengthening effect [44].

2.5.5. Microstructural Instabilities

With extended ageing, voids, microcracks, and stress concentrators develop, particularly near particle-matrix interfaces and grain boundaries [45] reported that these instabilities compromise fatigue life and fracture resistance.

2.6. Influence of Ageing Parameters

The ageing response of Al-Si Metal Matrix Composites (MMCs) is significantly influenced by processing variables and material characteristics, which govern precipitate behavior, interface stability, and overall property retention [1][15].

2.6.1. Ageing Temperature and Duration

Elevated temperatures promote rapid precipitate growth, potentially leading to overageing and loss of hardness, while lower temperatures with extended durations favor fine, coherent precipitate formation [32]. Peak ageing conditions vary depending on alloy system and reinforcement.

2.6.2. Type and Volume Fraction of Reinforcement

Ceramic reinforcements such as SiC and Al_2O_3 enhance stiffness and wear resistance but also influence thermal conductivity and ageing kinetics. Increased reinforcement volume fraction improves strength but may promote interfacial stress and micro-crack formation during ageing [12].

2.6.3. Alloying Elements and Matrix Composition

Elements like SiC, Cu and Mg in aluminium matrices support age hardening via formation of θ′ or β′ precipitates. Their concentration determines the rate and extent of strengthening during artificial ageing [21][34].

2.6.4. Cooling Rates and Heat Treatment Cycles

Rapid quenching suppresses premature precipitation, allowing controlled ageing. optimized solutionizing and artificial ageing cycles are crucial for achieving peak mechanical performance [18].

2.7. Characterization Techniques for Ageing Studies

Comprehensive evaluation of ageing in Al-Si MMCs requires advanced characterization techniques to assess microstructural evolution and mechanical performance over time.

2.7.1. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM)

SEM provides insights into particle-matrix interfaces, microcracks, and surface degradation post-ageing. TEM reveals nano-scale precipitates and dislocation structures critical for understanding precipitation hardening and over-ageing effects [46][47].

2.7.2. X-ray Diffraction (XRD)

XRD detects phase transformations, lattice strain, and intermetallic compound formation during ageing, allowing correlation of crystallographic changes with mechanical behavior [34].

2.7.3. Differential Scanning Calorimetry (DSC)

DSC identifies heat absorption or release associated with precipitation, phase dissolution, and thermal events during ageing. It helps pinpoint ageing windows and phase stability [32].

2.7.4. Thermogravimetric Analysis (TGA)

TGA monitors mass changes under controlled heating, useful for detecting thermal degradation, oxidation, or moisture loss in the matrix or interface over long-term ageing [48].

2.7.5. Microhardness and Tensile Testing

These mechanical methods track hardness and strength changes over ageing cycles, indicating peak ageing or overageing conditions [14][15][18].

2.7.6. Creep Testing

Essential for evaluating long-term load-bearing capacity, creep testing measures strain under constant stress and temperature. It reveals time-dependent deformation and helps predict service life under elevated conditions [35].

2.8. Case Studies and Comparative Analysis

Several experimental studies have explored the influence of ageing on various Al-Si MMC systems, offering valuable comparative insights.

2.8.1. Experimental Studies

[32] investigated Al6061-SiC composites and found peak hardness at 175 °C after 10 hours of artificial ageing. Similarly, [15][49] reported improved wear resistance and tensile strength in Al-Si MMC post-ageing, with diminishing returns beyond peak conditions. [23] observed that over-ageing led to coarsened precipitates and weakened particle-matrix bonding, affecting fracture toughness. Studies on Al-7Si-0.3Mg reinforced with 10% SiC revealed enhanced micro-hardness and creep resistance after ageing ([50].

2.8.2. Grade-Based Comparison

In [15], different percentage volume fractions SiC gives different Al-Si grade and each grade show varying sensitivity to ageing. High Si content alloys tend to resist coarsening better, while Al-Mg-Si matrices benefit more from precipitation hardening. Thus, reinforcement type and volume fraction further modulate property shifts.

2.9. Ageing Models and Predictive Approaches

Accurate prediction of the ageing behavior of Al-Si MMCs is essential for optimizing design and maintenance of high-performance components. This section outlines empirical, computational, and life-prediction models used to describe and forecast ageing-related changes in mechanical and microstructural properties.

2.9.1. Empirical Models for Ageing Response

Empirical models are widely used to establish relationships between ageing parameters (e.g., time, temperature) and property evolution such as hardness or tensile strength. These models often take the form of time-temperature-transformation (TTT) or time-temperature-property (TTP) curves, and are derived from regression analysis of experimental data [32][51][52][53]. Hardness H as a function of ageing time t can often be fitted using a parabolic law:

$$H(t) = H_o + Kt^n \qquad \dots\dots \quad (1)$$

where k and n are material-specific constants [54].

2.9.2. Computational Simulations and Phase-Field Models

Finite Element Analysis (FEA) and phase-field models simulate microstructural evolution during ageing, capturing effects such as precipitate nucleation, growth, and coarsening. These models provide insights into local stress distributions, diffusion behavior, and interface stability [44][55]. They are especially valuable for heterogeneous MMC systems with complex reinforcement distributions.

2.9.3. Life Prediction Models for MMC Components

Predictive models for service life integrate creep laws (e.g., Norton's law), damage accumulation theories, and microstructural degradation trends. These are used to estimate the time to failure or allowable operating periods under thermal and mechanical loads [56][57]. Such models help define inspection intervals and component replacement schedules in aerospace or structural applications.

2.10. Applications and Engineering Implications

The ageing behavior of Al-Si Metal Matrix Composites (MMCs) has critical implications for component design, material selection, and lifecycle management in engineering applications [8][15].

2.10.1. Design Considerations for Ageing-Prone Components

In applications such as brake rotors, cylinder liners, and structural panels, design engineers must account for potential degradation in properties like hardness, tensile strength, and fatigue resistance over time. Ageing-induced embrittlement and interface weakening require design safety factors, thermal shielding, or reinforcement optimization to ensure reliability under long-term service conditions [15][18][21].

2.10.2. Ageing Resistance as a Selection Criterion

Material selection for high-performance components increasingly considers ageing resistance alongside cost, machinability, and weight. Al-Si MMCs with thermally stable reinforcements (e.g., SiC, Ferro-Si) and controlled matrix compositions are preferred in aerospace and automotive sectors for their retention of mechanical strength post-ageing [15][32].

2.10.3. Lifecycle Optimization Strategies

Lifecycle strategies such as optimized heat treatment schedules, scheduled inspections, and protective coatings are employed to extend service life. Predictive maintenance models based on empirical ageing data help avoid unexpected failures, especially in mission-critical aerospace and defense systems [35][58].

2.11. Challenges and Research Gaps

Despite significant progress in understanding the ageing behaviour of Al-Si MMCs, several persistent challenges and research gaps hinder the establishment of universally applicable conclusions and design strategies [59].

2.11.1. Limitations in Existing Ageing Data for MMCs

Most studies on ageing of Al-Si MMCs are restricted to specific alloy compositions, reinforcement types, and ageing temperatures, limiting the generalizability of findings. There is a noticeable lack of long-term ageing data under realistic service conditions, especially for components exposed to variable thermal and mechanical loads [60]. In [61], many investigations focus only on peak hardness or strength, often neglecting fatigue, creep, and wear behaviour during extended ageing. However, [62][63] delve into the innovation that deployed neuro-symbolic programming to predict the rate of wear and fatigue of Al metal matrix composite.

2.11.2. Inconsistencies Due to Processing Differences

Processing techniques such as stir casting, powder metallurgy, and squeeze casting introduce significant variability in matrix-reinforcement bonding, particle dispersion, and porosity [64][65][66]. These microstructural differences affect how composites respond to ageing, leading to inconsistent results across studies. Furthermore, the influence of pre-ageing thermal history is frequently overlooked, contributing to contradictory observations.

2.11.3. Need for Standardised Ageing Protocols

Currently, no unified ageing protocols exist for evaluating MMCs, making cross-study comparisons difficult. Standardized ageing cycles, test conditions, and reporting formats are necessary to build a consistent database and facilitate material benchmarking. International collaboration and interdisciplinary research could play a key role in formulating such protocols.

2.12. Future Perspectives and Research Directions

To enhance the performance and reliability of Al-Si Metal Matrix Composites (MMCs) in ageing-prone environments, emerging research is exploring novel materials, monitoring technologies, and sustainable processing techniques.

2.12.1. Development of Hybrid and Nano-Reinforced Al-Si MMCs

Future studies are expected to focus on hybrid reinforcements combining microscale SiC or Al_2O_3 with nanoscale particulates (e.g., CNTs, graphene) to improve mechanical strength and thermal stability during ageing [33][67][68][69][70] Nano-reinforcements can significantly suppress grain growth and delay coarsening of precipitates, enhancing the long-term structural integrity of the composites.

2.12.2. Integration of Real-Time Monitoring During Service Ageing

[71][72] argued that smart sensing technologies such as embedded strain gauges and acoustic emission monitoring offer real-time tracking of ageing-related degradation. These methods, combined with AI-based predictive algorithms, may enable condition-based maintenance and failure prediction for Al-Si MMC components in aerospace and automotive sectors

Advanced Post-Processing and Ageing Treatments: Advanced techniques like laser surface treatment, friction stir processing, and cryogenic ageing are being explored to modify surface microstructures and enhance resistance to wear and thermal degradation [73][74]. These processes can refine grains, redistribute reinforcements, and increase interfacial bonding.

2.12.3. Sustainable and Energy-Efficient Ageing Control

As environmental concerns grow, research is increasingly directed at low-energy thermal treatment methods and recyclable composite systems [75][76][77]. Thus, other strategies including localized ageing, induction heating, and optimized thermal cycles aim to reduce energy consumption while maintaining desired mechanical properties are being devised.

3. Conclusion

This review has comprehensively examined the effects of thermal ageing on the mechanical and microstructural behavior of Aluminium-Silicon Metal Matrix Composites (Al-Si MMCs), highlighting the critical role of ageing in determining performance durability in automotive, aerospace, and structural applications. Ageing influences key mechanical properties such as hardness, tensile strength, ductility, fatigue resistance, and creep response, largely through microstructural changes including precipitate evolution, grain coarsening, interface degradation, and the formation of micro-voids. Current knowledge underscores that ageing response is significantly affected by factors such as alloy composition, type and volume fraction of reinforcements, heat treatment schedules, and cooling rates. Advanced characterization techniques like SEM, TEM, XRD, and DSC have enabled in-depth understanding of these transformations. However, a lack of standardized ageing protocols, limited long-term service data, and inconsistencies due to processing variability present ongoing challenges. Empirical and computational models have been developed to simulate and predict ageing behavior, yet most of the analysis remain as material-specific and are not universally applicable. Research on real-time ageing monitoring, hybrid/nano-reinforced MMCs, and sustainable thermal treatment methods are still in its infancy.

3.1. Potential Avenues for Future Research

Based on the critical insights and knowledge gaps identified in this review, the following recommendations are proposed to guide future research. Researchers and industrial practitioners may develop standardized test framework and ageing models including unified testing procedures, ageing cycles, and reporting formats to ensure consistency and comparability of ageing data across different Al-Si MMC systems. Hybrid and Nano-Reinforced MMCs may be developed by intensifying research on the synthesis and characterization of hybrid and nano-reinforced Al-Si MMCs to improve thermal stability, interface bonding, and resistance to ageing-induced degradation. Moreso, the integration of Smart Monitoring Systems may be integrated by embedding sensors and developing AI-driven predictive tools to enable real-time monitoring of ageing behavior in service, enhancing component safety and reliability. Engineers may adapt Lifecycle based design strategies by incorporating ageing resistance as a key criterion in material selection and component design, especially in aerospace and automotive sectors where performance degradation poses critical risks. A multi-scale modeling and simulation systems with advanced modeling tools combining phase-field, FEA, and data-driven methods may be deployed to predict long-term ageing effects and optimize materials design.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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