Malaysian Journal of Microscopy 2026 22(1) 337-359

MALAYSIAN JOURNAL OF MICROSCOPY

Journal homepage: https://malaysianjournalofmicroscopy.org

REVIEW ARTICLE

HYPEREUTECTIC Al–Si ALLOYS: CHALLENGES, MECHANISMS, AND ADVANCED SOLUTIONS – A COMPREHENSIVE REVIEW

Altameemi Ali Mohammed[1,2], Tuty Asma Abu Bakar[1,*], Mohd Ayub Sulong[1], Mohammed Rasheed[3], Aqeel Ahmed Bhutto[4], Hamidreza Ghandvar[5]

[1]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[2]Mechanical Power Technical Engineering Department, Al-Amarah University College, Maysan, Iraq.
[3]Production Engineering & Metallurgy College, University of Technology- Iraq, Baghdad 10066, Iraq.
[4]Mechanical Engineering Department, MUET SZAB Campus, Khairpur Mirs 66020, Pakistan.
[5]Department of Mechanical Engineering, School of Engineering, New Uzbekistan University, Movarounnahr Street 1, Mirzo Ulugbek District, Tashkent, 100000, Uzbekistan.

Abstract. Hypereutectic Al–Si alloys are widely used in automotive and aerospace applications due to their excellent wear resistance, low thermal expansion, and high strength-to-weight ratio. However, their performance is strongly influenced by microstructural features, particularly the morphology, size, and distribution of silicon phases, which remain critical challenges in achieving optimal mechanical and corrosion properties. This review addresses the existing research gap by providing a comprehensive analysis of microstructural evolution, processing parameters, and performance-enhancement strategies for hypereutectic Al–Si alloys. The review highlights the influence of silicon content, typically above 12.3 wt.%, on solidification behaviour, nucleation, and defect formation, including porosity and cracking. Emphasis is placed on the transformation of eutectic silicon from coarse plate-like or needle-like structures to refined fibrous or spheroidized morphologies through alloying additions and heat treatment processes. These modifications significantly improve mechanical performance, wear resistance, and corrosion behaviour. Furthermore, the role of processing techniques, including casting methods, cooling-rate control, and heat treatment (e.g., T6), is critically discussed in relation to microstructural refinement and property optimisation. The significance of this review lies in integrating findings from previous and recent studies to provide clear insights into microstructure–property relationships and practical guidelines for alloy design and processing. Future research directions are also outlined, focusing on advanced manufacturing techniques, hybrid reinforcement strategies, and computational modelling to further enhance alloy performance. This review serves as a valuable reference for researchers and engineers working on the development of high-performance Al–Si alloys.

Keywords: Hypereutectic aluminium silicon alloys, common issues, challenges, solutions.

Article Info

Received 13 January 2026
Accepted 4 May 2026
Published 8 June 2026

***Corresponding author: tuty@utm.my**

ISSN: 1823-7010, eISSN: 2600-7444

1. INTRODUCTION

Aluminium-Silicon (Al-Si) alloys are among the most essential materials and are used in numerous applications, including internal combustion (IC) engines in automobiles. The piston of an IC engine is considered a crucial component in the automobile manufacturing industry. The automobile piston must withstand heat and have sufficient strength to resist the gas pressure and reaction forces generated by combustion in the automobile engine. Therefore, selecting a lightweight material that can withstand high inertia and thermal forces is crucial. Such material should endure mechanical and thermal forces and resist distortion caused by these forces. The material of the piston should have good wear qualities so that its hardness is not affected by the operating temperatures [1].

Currently, research is actively developing on engine downsizing as the most effective solution for reducing fuel consumption and emissions. Pressure boosters are utilised to maintain the output power [1]. The high pressure through pressure boosters produced high stresses and distortion vectors in the combustion chamber. High stresses and distortion vectors could lead to premature failure of the piston material. Consequently, the application of high-strength, thermally stable, and durable materials becomes imperative. In this regard, Al-Si alloy is the most used material in the automotive industry for piston manufacturing. Al-Si alloys exhibit better thermal distortion resistance, enhanced strength, improved wear resistance, higher hardness, and a lower coefficient of thermal expansion [2]. It is well established that the mechanical and physical properties of Al–Si alloys are strongly governed by the morphology, size, and distribution of eutectic silicon particles. Previous studies have shown that finer, more uniformly distributed silicon phases significantly enhance tensile strength and hardness, whereas coarse, plate-like silicon structures reduce ductility and promote crack initiation. In addition, the silicon content and processing conditions, including heat treatment and casting techniques, play a crucial role in controlling microstructural evolution and overall performance.

Several studies have reported that increasing silicon content improves strength and wear resistance due to the presence of hard silicon phases; however, excessive silicon may adversely affect ductility and machinability. In the automotive industry, these alloys are lightweight, suitable for high-temperature applications, and preferred for internal combustion (IC) engines. Aluminium pistons are commonly made by casting or forging and are applied in the piston-ring/cylinder-liner system, where they influence power output, lubricant use, and component wear. It has been reported that increased cylinder liner wear leads to higher oil consumption, which adversely affects engine performance, increases emissions, and reduces overall fuel efficiency. Pistons are preferred for materials that have low friction, are lightweight, and exhibit high wear resistance. Generally, cast iron has been used in the automotive manufacturing industry to produce pistons. A progressive shift towards the use of Al-Si alloys for piston manufacturing leads to greater efficiency and material cost benefits. However, aluminium alloys are preferred for pistons in diesel and gasoline engines due to their specific characteristics. Al-Si-Mg Alloys are selected for use because they have some of the most important advantages compared to other materials (i.e., reinforced), such as larger stiffness, better strength, lightweight, and a high coefficient of thermal expansion [3].

There are various materials available for manufacturing pistons; however, selecting the right alloy remains challenging, as some engines perform better with aluminium alloys, while others do not. Therefore, reviewing the different alloys used in piston manufacturing and classifying them by engine type is essential. Understanding the mechanical properties of these materials enables researchers to identify the most suitable alloy for each engine application.

However, despite these studies, several limitations remain in the current understanding of hypereutectic Al–Si alloys. Despite extensive research on Al–Si alloys, there remains a lack of comprehensive understanding of the combined effects of silicon morphology, processing parameters, and alloying elements on the overall performance of hypereutectic Al–Si alloys. The novelty of this review lies in integrating these aspects to provide a unified perspective on microstructure–property relationships. Therefore, the main objective of this review is to systematically analyse the influence of microstructural features, processing conditions, and modification techniques on the mechanical, wear, and corrosion behaviour of hypereutectic Al–Si alloys, as well as to identify current challenges and future research directions.

In automotive applications, Al–Si alloys are commonly used in the form of Al–Si–Mg and Al–Si–Cu systems due to their excellent combination of castability, strength, and thermal stability. The mechanical properties of these alloys are strongly influenced by both alloy composition and heat treatment conditions. The most widely applied heat treatment is the T6 process, which consists of solution treatment typically carried out at approximately 520–540 °C, followed by rapid quenching and artificial ageing at 150–200 °C. This process promotes precipitation of strengthening phases such as Mg_2Si and Al_2Cu, which significantly enhance hardness and tensile strength. Furthermore, the composition of Al–Si alloys used in automotive components generally ranges from 6–12 wt.% Si for eutectic alloys and above 12 wt.% Si for hypereutectic alloys, where higher silicon content improves wear resistance and reduces thermal expansion.

The addition of alloying elements such as Mg, Cu, and Ni further enhances mechanical and thermal performance, making these alloys suitable for applications such as pistons, cylinder heads, and engine blocks. The combined effects of composition, heat-treatment parameters, and processing conditions play a critical role in controlling the microstructure and achieving the desired mechanical and corrosion properties. The influence of composition and heat-treatment parameters on the performance of Al–Si alloys has been widely reported in the literature and is summarised in Table 1.

Table 1: Summary of previous studies on Al–Si alloys

Author(s)	Year	Alloy Composition (wt.%)	Fabrication / Treatment	Key Findings (Strength, Hardness, CTE, etc.)
Tenekedjiev. [4]	1990	AlSi0.5–AlSi7Mg	Casting + anodizing	Lower Si content improved oxide thickness and uniformity
Labisz. [5]	2008	AlSi9Cu3, AlSi12	HPDC casting + anodising	Lower Si alloys produced thicker anodised layers
Forn. [6]	2007	A357 (Al–7Si–Mg)	Thixocasting + anodizing	Refined Si morphology improved coating uniformity
Zeren & Karakulak [7]	2008	Near eutectic Al–Si + Ti	Casting + Ti addition	Ti addition, refined grains, increased hardness and strength
Jaradeh & Carlberg [8]	2005	Al alloys + Ti	DC casting	Ti promoted grain refinement and improved mechanical properties
Kumar et al. [9]	2010	Al–Ti system	Particle addition	Al_3Ti particles improved strength via dispersion strengthening
Fratila-Apachitei. [10]	2003	Al–Si alloys	Hard anodising	Si particles caused defects and localised corrosion in the oxide layer
Chaukea [11]	2014	Al–8Si	Rheo-HPDC + anodizing	Corrosion initiated at the Si/Al interface due to the potential difference
Mohedano [12]	2015	Al–Si alloys	PEO anodising + sealing	Improved corrosion resistance with optimised oxide layer
Samuel [13]	2020–2024	Al–Si (6–17 % Si)	Casting + modification + heat treatment	Tensile strength: ~100–250 MPa, Hardness: ~70–130 HV, improved with refinement

2. SYSTEMATIC REVIEW FRAMEWORK OF HYPEREUTECTIC Al–Si ALLOYS

Figure 1 presents the systematic review framework adopted in this study, illustrating the methodological flow. The framework begins with the classification of Al–Si alloys, followed by the identification of key challenges associated with hypereutectic alloys, a discussion of corresponding solution strategies, and, finally, highlights of future research directions for high-performance applications.

To gain a deeper insight into the referred research, hypereutectic Al-Si alloys are systematically reviewed in this work. Hypereutectic Al-Si alloys are emerging materials with numerous applications, including those in automobile engines. To further strengthen this review, common issues have been identified from numerous research articles published between 2008 and 2025. To attract readers, possible solutions to the common issues of hypereutectic Al-Si alloys are sought through research articles sourced from renowned publishing agencies. Finally, conclusions are drawn from the reviewed work. This structured approach ensures a comprehensive and logical analysis of the existing literature, enabling clear identification of research gaps and potential avenues for advancing hypereutectic Al–Si alloys.

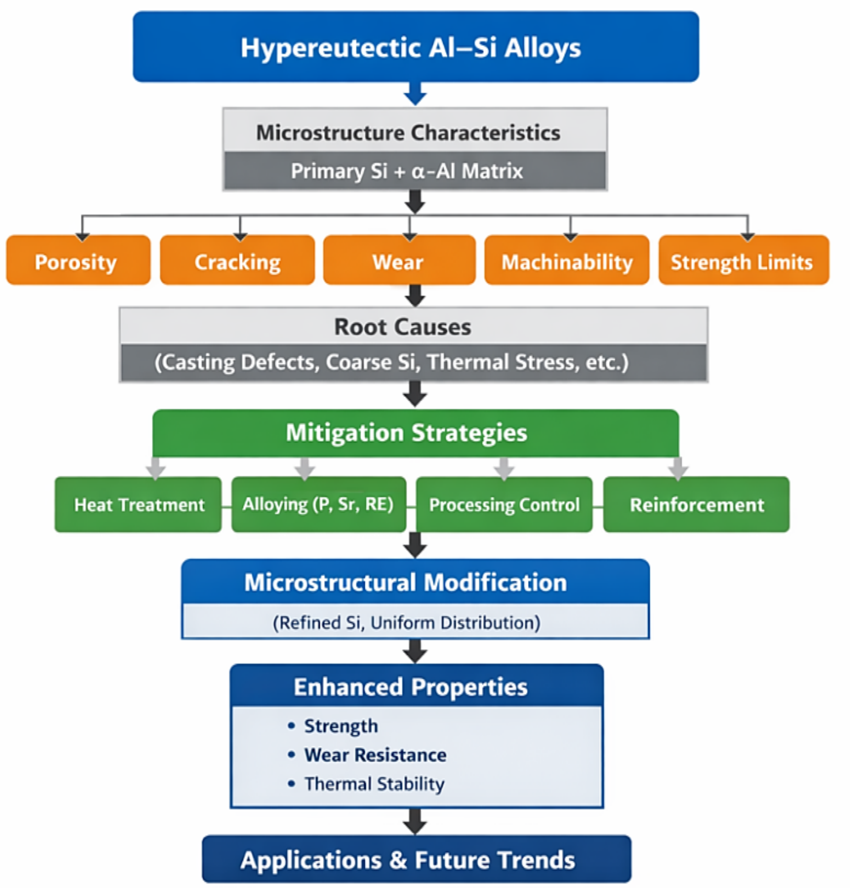

Figure 1: Schematic flowchart illustrating the structure of the review

3. COMMON ISSUES IN HYPEREUTECTIC AL-SI ALLOYS

Hypereutectic Al-Si alloys are well-known for their numerous characteristics, which make them suitable for a wide range of applications. Yet, their poor performance at elevated temperatures is undesirable, limiting their applications in some cases [4]. Unlike hypoeutectic alloys such as A356, hypereutectic Al–Si alloys are characterised by the presence of primary silicon particles, which significantly influence solidification behaviour, porosity formation, and mechanical properties.

The primary applications of Al MMCs are in the automotive, aviation, and aerospace industries, and their use is increasing due to their numerous superior characteristics. However, conventional techniques such as stir casting and powder metallurgy are still used to produce various aluminium alloys and composites. Al-Si alloys, containing silicon as the main alloying element, have numerous applications in the transportation industry due to their improved resistance to cracking, higher tensile strength, and ability to withstand high thermal loads. The characteristics of Al-Si alloys are chiefly determined by their composition, heat treatment, and casting parameters [5].

Hypereutectic Al-Si alloy, with its high specific stiffness, low coefficient of thermal expansion, low density, high-temperature resistance, and wear resistance, exhibits several striking characteristics that make it particularly suitable for the transport industry. These striking characteristics of hypereutectic Al-Si alloys make them suitable to produce connecting rods, pistons, cylinders, and rocker arms [6]. However, producing these automobile parts using conventional casting techniques could lead to numerous constraints, including porosity, cracking, wear, and reduced strength in hypereutectic Al-Si alloys. Detailed discussions of these constraints are presented in the headings below. The severity of these issues is strongly dependent on silicon content, cooling rate, and processing conditions, which collectively control nucleation, grain growth, and defect formation in hypereutectic Al–Si alloys.

3.1 Porosity

Hypereutectic Al-Si alloys are prone to porosity, which can occur during casting owing to a higher weight percentage of Si. The presence of porosity reduces the material's strength and mechanical properties, as shown in Figure 2 [7]. Although A356 is a hypoeutectic Al–Si alloy (~7 wt.% Si), it is included here as a reference material to illustrate the general effect of porosity on tensile properties, which is also applicable to hypereutectic Al–Si alloys.

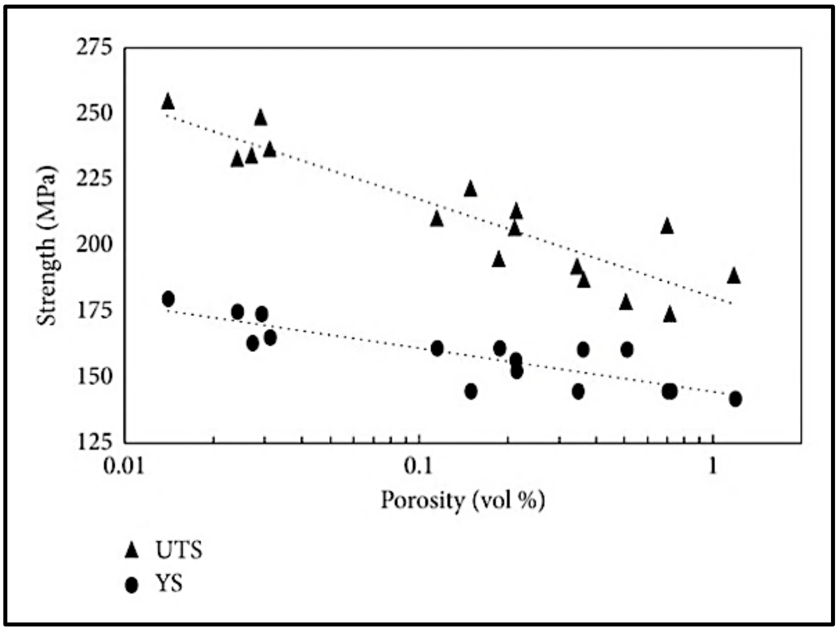

Figure 2: Reduction of tensile properties of A356 (hypoeutectic Al–Si alloy) with porosity volume fraction, presented for comparative understanding of porosity effects in Al–Si systems [7]

It should be noted that, although the data correspond to a hypoeutectic alloy, similar porosity-induced degradation mechanisms are also observed in hypereutectic Al–Si alloys, particularly due to casting-related defects. In hypereutectic Al–Si alloys, the increased silicon content (>12 wt.%) significantly influences solidification behaviour by promoting the formation of primary silicon particles prior to the eutectic reaction. These primary Si particles act as heterogeneous nucleation sites; however, excessive growth can lead to a non-uniform distribution and localised stress concentrations. During solidification, the presence of large primary Si particles restricts the feeding of liquid metal, thereby increasing the likelihood of shrinkage porosity. In addition, a high silicon content reduces fluidity during later stages of solidification, further contributing to gas entrapment and pore formation. The combined effects of restricted liquid flow, uneven solidification, and thermal gradients result in increased porosity, ultimately degrading mechanical properties and structural integrity. Figure 3 presents the microstructure of a hypereutectic Al–Si alloy, showing coarse primary silicon particles distributed within the α-Al matrix and porosity formed during solidification. The morphology and size of the silicon particles, together with the distribution of pores, highlight the influence of high silicon content and solidification conditions on microstructural defects and overall material performance [14].

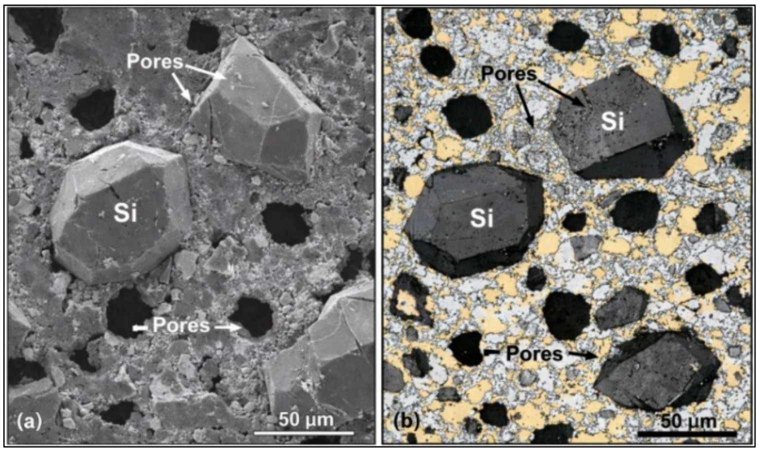

Figure 3: (a – b) Microstructure of hypereutectic Al–Si alloy showing porosity and coarse primary silicon particles [14]

3.2 Cracking

These alloys tend to crack during casting and subsequent heat treatment due to their high silicon content and associated thermal stresses [8]. The presence of cracks can reduce the material's overall strength and lead to premature failure, as shown in Figure 4 [9].

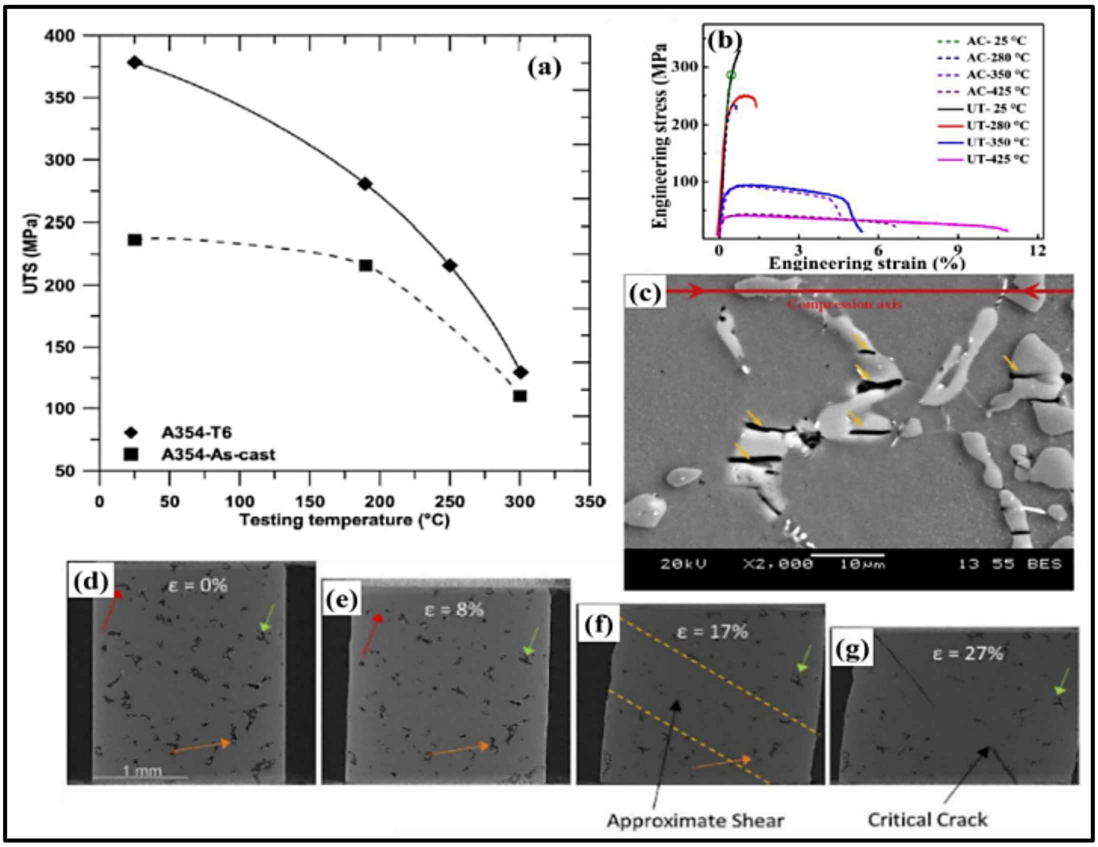

Figure 4: (a) UTS of as-cast A354 alloy and T6 heat treatment, (b) Tensile stress–strain curves for as-cast Al-Si piston and ultrasonic melt treatment, (c) Crack initiation Al-7%Si alloy, and (d–g) Porosity and damage evaluation of an L-PBF Al-10%Si-Mg alloy [9]

3.3 Wear resistance

While hypereutectic Al-Si alloys are known for their good wear resistance, they can still experience wear under certain conditions, particularly in high-temperature applications. The wear rate with respect to load has been improved for eutectic and hypereutectic Al-Si alloys, as observed by [10], as shown in Figure 5. This can lead to reduced component lifespan and increased maintenance costs.

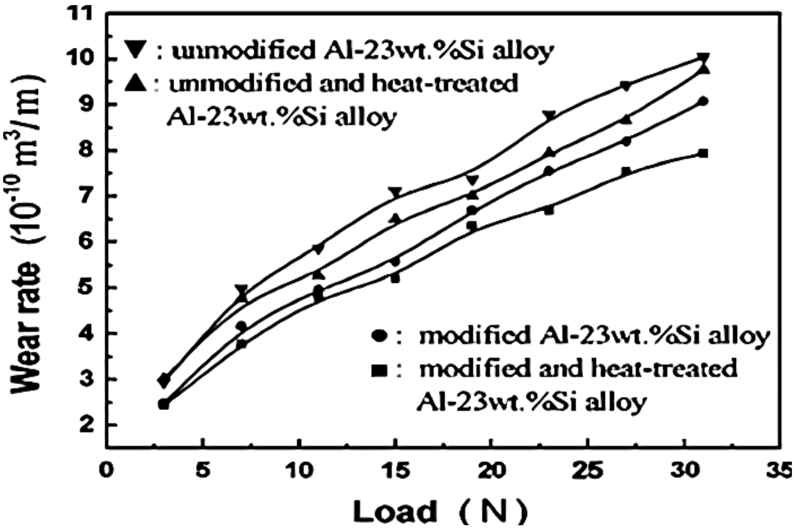

Figure 5: Wear Rate Results with context to Load for Hypereutectic Al-Si alloy [10]

3.4 Machinability

Hypereutectic Al-Si alloys are classified based on the weight percentage of Si in them and typically have a high weight percentage of Si (>12.3 %) [15]. A high Si content in hypereutectic Al-Si resulted in machining difficulties. Numerous unwanted consequences, such as time-to-cut, processing time, and cost, are constraints for hypereutectic Al-Si alloys due to their high Si content [9].

3.5 Strength of Hypereutectic Al-Si Alloy

The high weight percentage of Si in hypereutectic Al-Si resulted in better wear (Figure 6), better thermal stability, and good strength (Figures 7 and 8). Furthermore, the high weight percentage of Si in hypereutectic Al-Si alloy differentiates it in terms of the above characteristics from hypoeutectic and eutectic Al-Si alloys (hypoeutectic and eutectic Al-Si alloys) [16]. Additionally, a possible solution to mitigate the strength constraints of hypereutectic Al-Si alloy is to optimize grain refiners, modify the microstructure, adjust alloying contents, and implement heat treatment, among others.

Nonetheless, numerous other characteristics (beyond mechanical strength) identify specific applications for hypereutectic Al-Si alloys. For instance, some applications require improved thermal stability, while others focus on reducing the wear rate under applied load. In such applications, the value of mechanical strength is not significantly practical; thus, it appears that mechanical strength is not as important as other characteristics of hypereutectic Al-Si alloys. Yet, the applications where mechanical strength is a prime consideration require the importance of improving strength to be investigated and mitigated. The strength of the hypereutectic Al-Si alloy can be further enhanced through various methods, including the addition of reinforcement, adjustment of processing parameters, alteration of alloying contents, and heat treatment (Figure 7) [17,18]. Ultimately, the suitability of hypereutectic Al-Si alloys for a particular application will depend on a variety of factors, including the specific requirements of the application, the operating conditions, and the available materials. Therefore, evaluating these factors is vital for achieving significant improvements in the strength of hypereutectic Al-Si alloys.

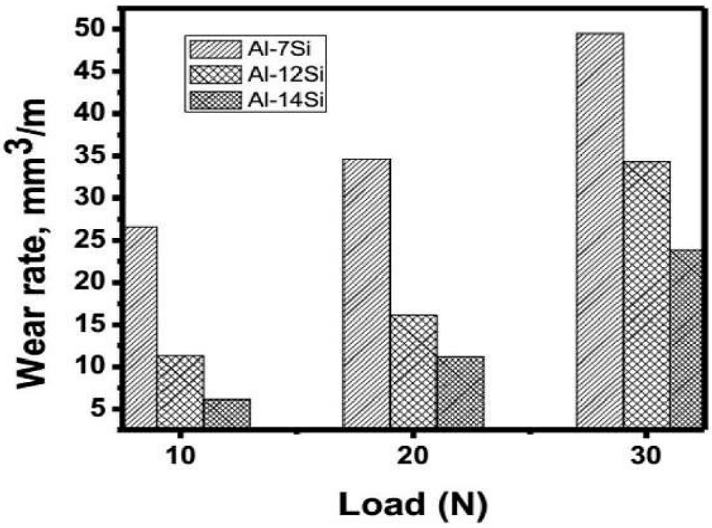

Figure 6: Wear rate analysis of Hypoeutectic, Eutectic, and Hypereutectic Al-Si alloys [16]

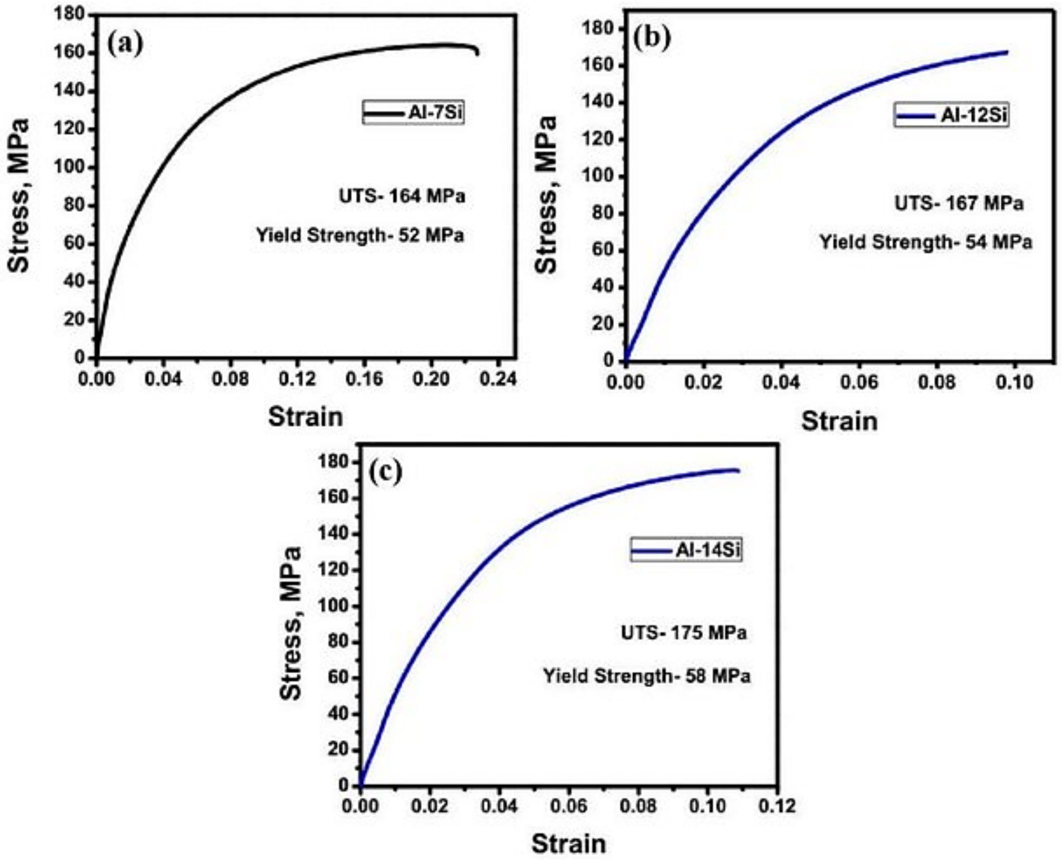

Figure 7: (a) Hypoeutectic alloy, (b) Eutectic alloy, and (c) Hypereutectic alloy showing strength comparison [16]

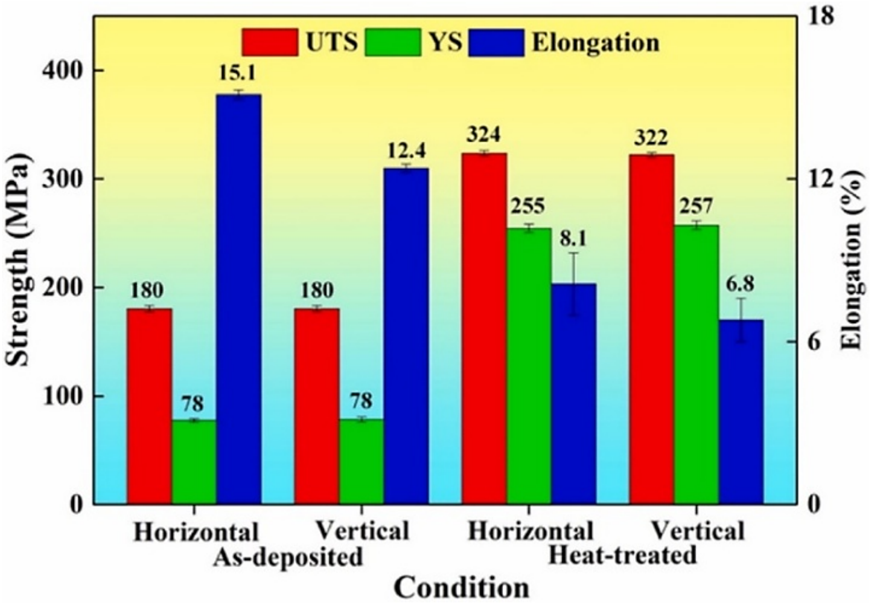

Figure 8: Tensile strength of piston alloy through heat treatment [17]

4. POSSIBLE SOLUTION METHODS TOWARDS ISSUES IN HYPEREUTECTIC Al-Si ALLOYS

This review emphasises recent developments reported between 2022 and 2025, particularly in advanced casting techniques such as high-pressure die casting (HPDC), microstructural control, and alloy design. Numerous strategies have been utilised to overcome the aforementioned issues in hypereutectic Al-Si alloys. Recent advancements in high-pressure die casting (HPDC) have significantly improved the quality of hypereutectic Al–Si alloys. Studies published between 2022 and 2025 highlight that HPDC enables better control of solidification rates, reduced porosity, and enhanced microstructural uniformity. Furthermore, advanced variants such as vacuum-assisted HPDC and rheo-die casting have demonstrated improved mechanical properties by minimising gas entrapment and refining silicon morphology. These developments indicate that modern casting technologies play a critical role in overcoming the traditional limitations of hypereutectic Al–Si alloys. For instance, heat treatment techniques improve the microstructure of the Al-Si alloy, enhancing its tensile strength.

Figure 9 shows the microstructure improvement of Al-Si-Cu and Al-Si-Mg alloys due to the heat treatment technique [19]. Before heat treatment, the microstructure of Al–Si alloys is characterised by coarse primary silicon particles and eutectic silicon in plate-like or needle-like forms distributed within the α-Al matrix. The addition of Cu leads to the formation of Al_2Cu intermetallic phases during solidification, which strengthen but may also promote micro segregation. In contrast, Mg addition results in the formation of Mg_2Si phases, which influence nucleation behaviour and refine the eutectic silicon morphology. These alloying elements alter solidification kinetics by enhancing heterogeneous nucleation and restricting grain growth, resulting in a more refined, uniform microstructure. Consequently, the initial microstructure prior to heat treatment plays a crucial role in determining the final mechanical properties and the effectiveness of subsequent heat-treatment processes. The heat treatment of both alloys improved the Si grain morphology and the fine-grained structure of α-Al and Si, ultimately enhancing the hardness and mechanical strength of the alloys. According to Ozen et al. [20], the quenching heat treatment improved the alloy's microstructure by forming α-Al and fine silicon-rich particles in the eutectic phase. Xu et al. [21] concluded that solution heat treatment resulted in a microstructure with α-Al, a smaller particle size, and well-distributed Si particles. As illustrated in Figure 9, these microstructural modifications are further enhanced after heat treatment, resulting in finer silicon morphology and improved mechanical performance.

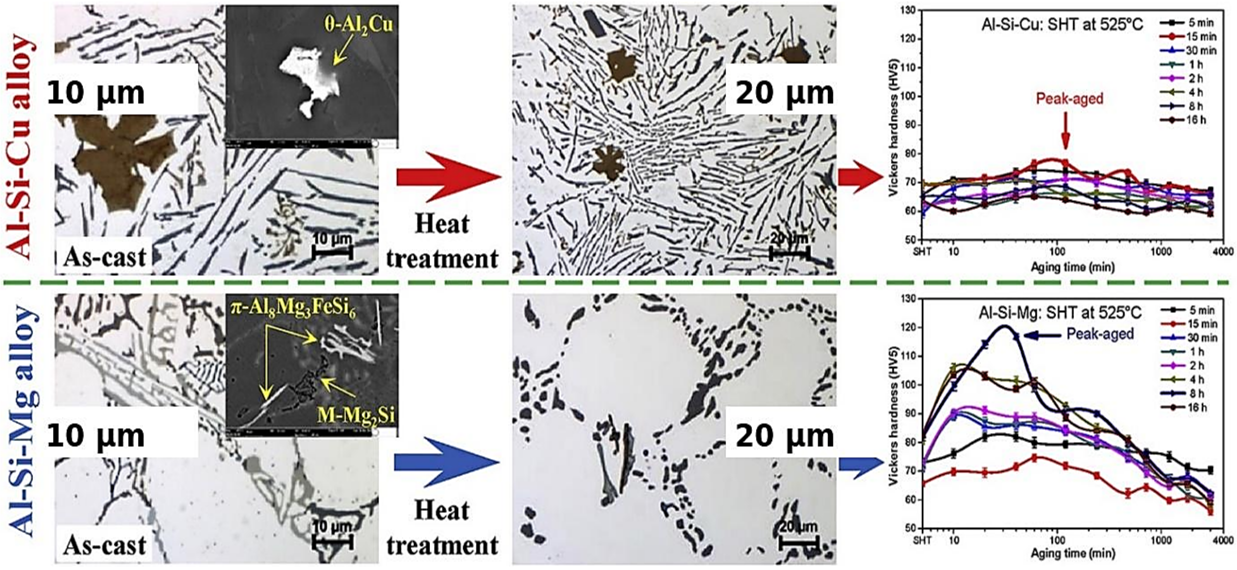

Figure 9: Microstructure evolution of Al–Si alloy (a) as-cast condition showing coarse Si morphology and (b) after heat treatment showing refined and spheroidized silicon particles [19]

Detailed discussions of possible solutions to overcome porosity, cracking, and improve wear resistance, machinability, and strength in hypereutectic Al-Si alloys are presented below.

Al–Si alloys are commonly classified by silicon content as hypoeutectic (<12.3 wt.% Si), eutectic (≈12.3 wt.% Si), or hypereutectic (>12.3 wt.% Si). In engineering practice, hypereutectic alloys typically contain about 14–25 wt.% Si, depending on the target application. Although increasing Si content generally improves hardness, wear resistance, and thermal stability, excessively high Si levels may promote the formation of coarse primary silicon, brittleness, reduced ductility, and poor machinability [20,21]. Therefore, an optimum silicon range, often around 16–20 wt.% for many automotive applications, is preferred to balance performance and processability. Numerous studies have reported that microstructural refinement and silicon morphology control significantly influence the mechanical and corrosion properties of hypereutectic Al–Si alloys [17,22,23].

Figure 10 presents the microstructural evolution of the Al–Si alloy before and after heat treatment. In the as-cast condition (Figure 10(a)), coarse and angular primary silicon particles are observed within the α-Al matrix, indicating non-uniform solidification.

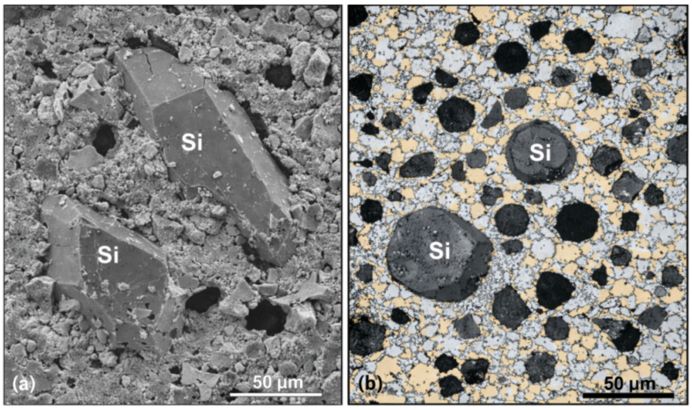

Figure 10: Microstructure evolution of Al–Si alloy (a) as-cast condition with coarse and angular primary silicon (Si) particles and (b) after heat treatment exhibiting refined and spheroidized silicon morphology within the α-Al matrix [19]

After heat treatment (Figure 10(b)), the silicon particles become refined and spheroidized, resulting in a more homogeneous microstructure [19], and modified the functional and mechanical properties owning to the heat treatment [24]. This transformation improves mechanical properties by reducing stress concentration sites and enhancing structural integrity.

4.1 Porosity

The microstructure of hypereutectic Al–Si alloys can exhibit various grain and silicon morphologies, including needle-like, plate-like, dendritic, rosette, and fibrous structures. These morphologies are strongly influenced by alloy composition, particularly silicon content, as well as solidification conditions such as cooling rate and nucleation behaviour. High silicon content promotes the formation of primary silicon particles and eutectic structures, which can appear as coarse plate-like or needle-like morphologies in slow cooling conditions. In contrast, higher cooling rates increase nucleation density and suppress excessive grain growth, leading to finer, more uniform, and fibrous or rosette-type structures. The control of microstructure is closely related to nucleation and growth mechanisms during solidification. Increased nucleation sites, either through rapid solidification or the addition of grain refiners, result in refined grain structures and improved silicon distribution. Conversely, low nucleation rates combined with slow cooling promote the growth of coarse dendritic and irregular silicon phases, which act as stress concentrators and reduce mechanical performance. Therefore, controlling silicon morphology and grain structure through composition, cooling rate, and processing parameters is essential to enhance strength, wear resistance, and corrosion behaviour in hypereutectic Al–Si alloys.

Porosity is undesirable in Al casting alloys, and it can be mitigated through optimising casting parameters, such as mould design, casting speed, and pouring temperature [7]. Hao et al. [17] concluded that increasing the pouring temperature improved the grain morphology of the Si and provided a better microstructure for the Al-Si alloy, as shown in Figure 11. Vijayan et al. [16] observed that increasing the pouring temperature to a certain limit could improve the strength of the Al-Si alloy; however, increasing it further could reduce the strength of the Al-Si alloy (Figure 12).

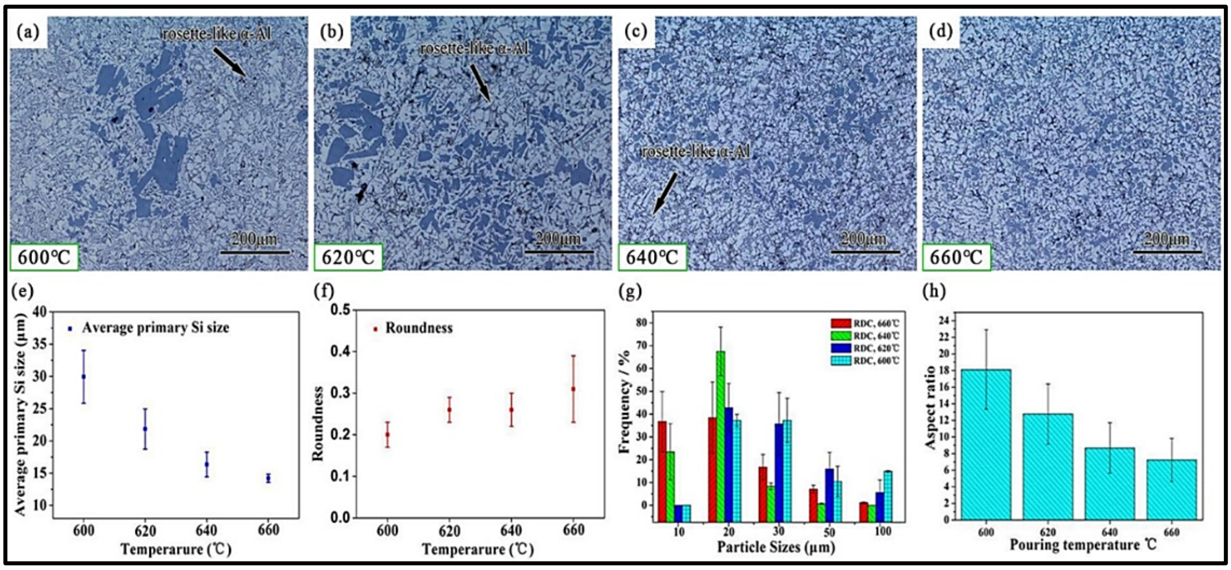

Figure 11: Refinement of particle size in context to pouring temperature [17]

Another way to overcome the porosity of casting aluminium alloys is using grain refiners or degassing agents. Refined morphologies such as fibrous or rosette silicon structures are particularly desirable, as they improve load distribution, reduce crack initiation, and enhance overall mechanical performance. Figures 12 (a)–(d) presents the influence of pouring temperature on the microstructure of hypereutectic Al–Si alloy. At 600 °C and 620 °C, coarse and irregular primary silicon particles are observed, whereas at higher temperatures (640 °C and 660 °C), the microstructure becomes finer and more uniformly distributed, with the formation of rosette-like α-Al structures. This indicates that increasing pouring temperature enhances nucleation and reduces silicon particle size, leading to improved microstructural uniformity and potential enhancement in mechanical properties.

Figure 13 presents different silicon morphologies in hypereutectic Al–Si alloys, including (a) needle-like, (b) plate-like, and (c) fibrous/rosette structures. The needle-like and plate-like silicon morphologies are typically associated with coarse and brittle microstructures formed under slow cooling conditions, which act as stress concentrators and reduce mechanical performance. In contrast, the fibrous or rosette morphology represents a refined silicon structure resulting from modification techniques or higher cooling rates, leading to improved strength, ductility, and wear resistance. These variations clearly demonstrate the strong dependence of alloy performance on silicon morphology and distribution [23].

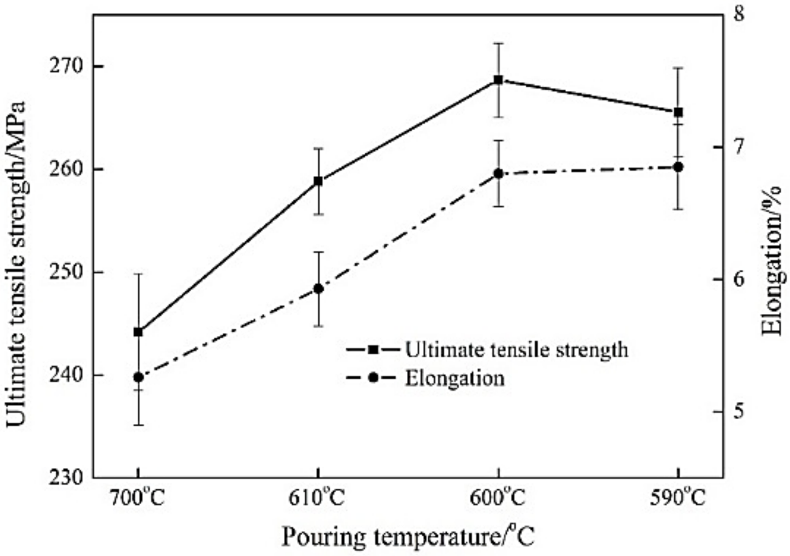

Figure 12: Pouring temperature effect on tensile strength [16]

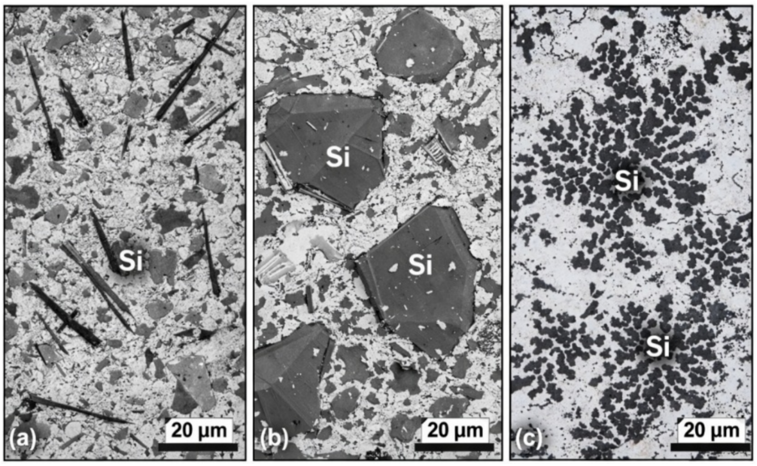

Figure 13: Different silicon morphologies in hypereutectic Al–Si alloys: (a) needle-like, (b) plate-like, and (c) fibrous/rosette structures [23]

4.2 Cracking

Cracking can be minimised by controlling the cooling rate during casting and heat treatment, as well as by modifying the alloy composition to reduce the thermal stresses [8]. Another way to reduce the cracking is to use a fine grain size during the casting of Al-Si alloys. Figure 14 shows the cracked region of an Al-Si alloy, where uniformity in the crack was observed and compared to the coarse grain size. It is noted that achieving homogeneous, consistent characteristics in hypereutectic Al-Si alloys is difficult during casting. The precise way of casting hypereutectic Al-Si alloys is highly significant for the reasons of the tribological surface features and even dispersion of Si particles. For example, adding small amounts of titanium or strontium can refine silicon particles and reduce the tendency to crack.

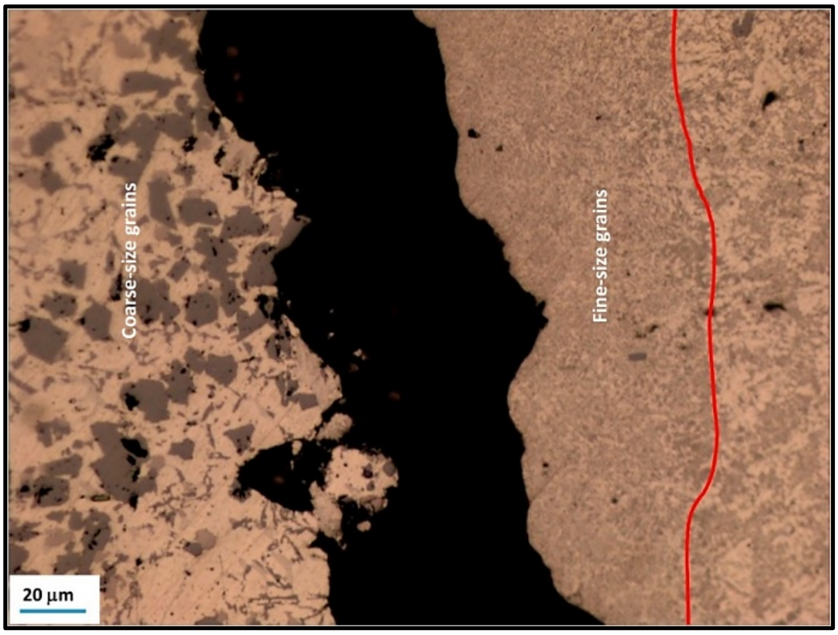

Figure 14: Crack uniformity with respect to grain size [8]

4.3 Wear resistance

Wear resistance can be improved by optimising or modifying the alloy composition, heat treatment, and processing parameters. Figure 15 shows the wear rate analysis of modified, heat-treated, un-modified and un-heat-treated Al-Si alloys. The conclusion was made that both heat-treated and modified Al-Si alloys had better wear resistance [10].

For example, increasing the amount of silicon improved wear resistance and mechanical properties. Figure 16 shows that increasing the content of Si significantly improved the tension properties (stress) of the Al-Si alloys (hypo, eutectic, and hypereutectic) [20]. Additionally, heat treatment can increase the material’s hardness and enhance its properties [10]. Figure 16 presents the stress–strain curves of hypoeutectic, eutectic, and hypereutectic Al–Si alloys, illustrating the variation in mechanical behaviour with silicon content. The hypoeutectic alloy exhibits higher ductility with lower strength, while the eutectic alloy shows a balance between strength and ductility. In contrast, the hypereutectic alloy demonstrates higher strength but reduced ductility due to the presence of primary silicon particles.

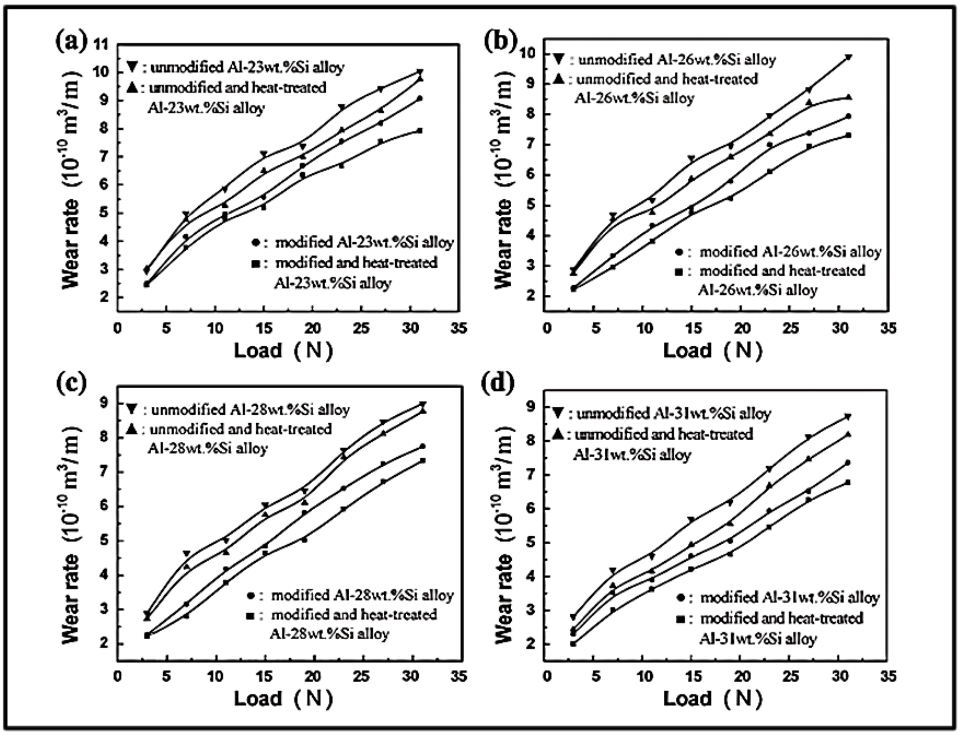

Figure 15: Wear rate analysis of different loadings: (a) Al–23 wt.% Si alloys, (b) Al–26 wt.%Si alloys, (c) Al–28 wt.%Si alloys, and (d) Al–31 wt.%Si alloys [10]

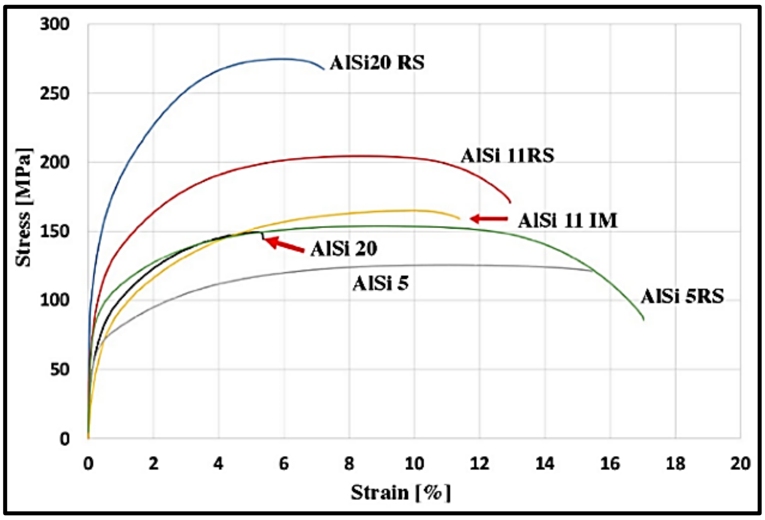

Figure 16: Stress-strain curves in context to varying Si concentration [20]
The differences in stress–strain behaviour are primarily attributed to variations in silicon morphology, distribution, and volume fraction within the alloy matrix

4.4 Machinability

Machinability can be enhanced by utilising suitable cutting tools, lubricants, and optimal machining conditions [21]. Higher cutting speeds, feed rates, and coolant flow rates can help reduce tool wear and improve machining efficiency. Figure 17 illustrates the variation in cutting force with different cutting speeds under various cutting conditions examined. However, material adhesion at the tool–chip interface, as well as the cutting forces, are influenced by the quantity of coolant used. Coolant is necessary for the quality of the surface produced [21]. The lowest surface roughness was observed for utilising nanofluid. It reduced the built-up edge as shown in Figures 18(a) and (b).

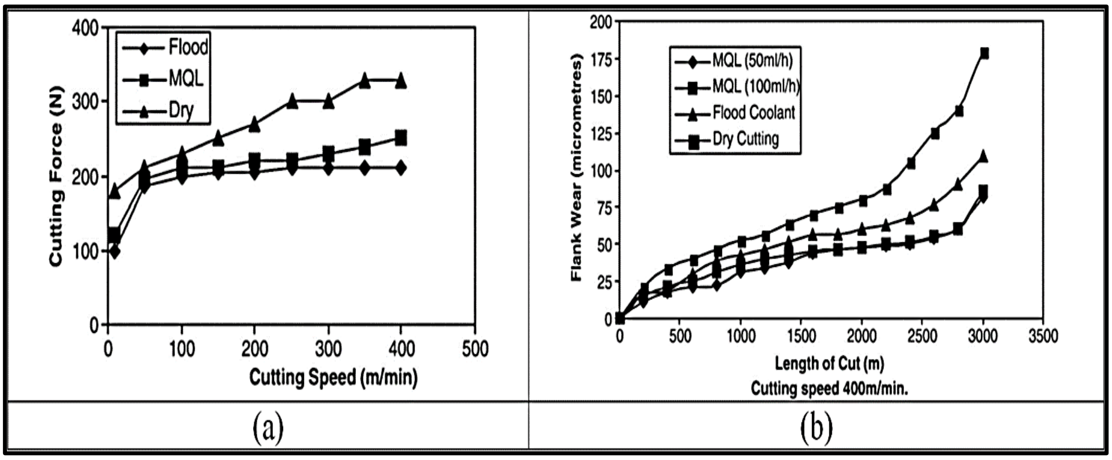

Figure 17: (a) Cutting parameters behaviour and (b) Impact on flank wear at cutting speed of 400 m/min [21]

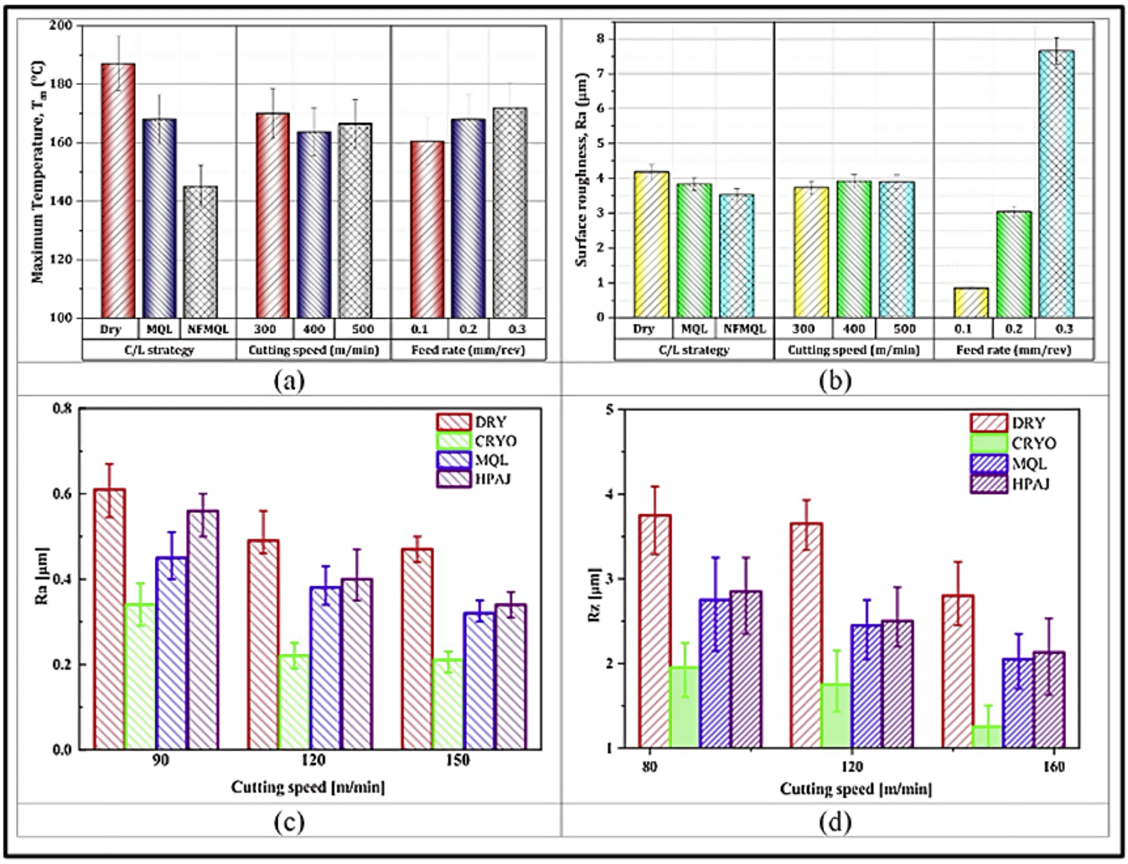

Figure 18: (a) Temperature and cutting speed, (b) Ra with coolant liquid, cutting speed, and feed rate, (c) and (d) Surface roughness (Ra and Rz) at cutting speed for coolant strategies [21]

When a nanofluid was employed, the disparity and temperature between the peaks and valleys on the surface decreased, thereby increasing the tool life. Furthermore, the results depicted in Figures 18(c) and (d) show that alternative cooling technologies may achieve reduced Ra (<0.4 μm) and Rz (<2.5 μm) values, resulting in delayed crack initiation [21]. The performance of hypereutectic Al-Si alloys can be enhanced through the careful selection of alloy composition and processing parameters, as well as through the use of advanced manufacturing techniques and processing technologies.

4.5 Strength of Hypereutectic Al-Si Alloy

The strength of the hypereutectic Al-Si alloy is a major contributor, making it suitable for numerous applications [5]. The hypereutectic Al-Si alloys are characterised by a high content of Si, typically greater than 12.3 % [11]. The strength of the hypereutectic Al-Si alloy improves mechanical properties and enhances resistance to impact, thermal, and external forces [16]. Thus, addressing the strength of the hypereutectic Al-Si alloy is crucial, and it can be improved through numerous strategies ranging from microstructural refinement, refinement of Si morphology, addition and or variation of alloying elements, processing techniques and parameters, and through using advanced computational techniques [21] to predict the strength of the hypereutectic Al-Si alloy. Figure 19 presents the influence of alloying elements on the microstructure of hypereutectic Al–Si alloys. The unmodified alloy (a) shows coarse and irregular silicon particles, while Mg (b) and Cu (c) additions promote refined and more uniformly distributed silicon morphologies [19]. These changes are attributed to improved nucleation and controlled solidification behaviour, which enhance mechanical performance and structural integrity by minimising defect formation and stress concentration sites.

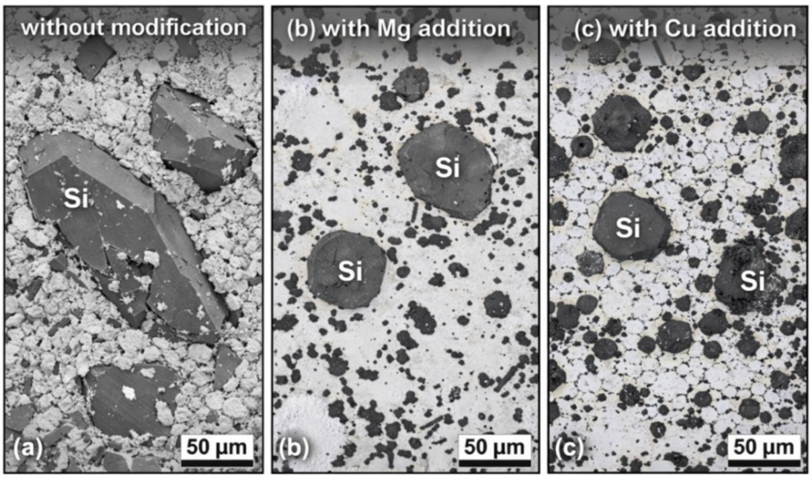

Figure 19: Effect of alloying elements on microstructure: (a) without modification, (b) with Mg addition and (c) with Cu addition, showing refined silicon morphology [19]

4.5.1 Microstructural Refinement

The microstructural evolution of the hypereutectic Al–Si alloy during solidification occurs in two distinct forms: the α-Al matrix and dendritic primary Si. The dendritic primary Si can be refined through various methods, such as adjusting cooling rates during solidification and adding grain refiners to the hypereutectic Al-Si alloy during the molten state [13]. In a few applications, grain refiners are added in powdered form and mixed into molten hypereutectic Al-Si alloy using mechanical vibration, electromagnetic stirring, or ultrasonic stirring.

Numerous grain refiners, such as Titanium, Carbon, Boron, Cerium, Phosphorus, Zinc Oxide, and Yttrium, are commonly added to the hypereutectic Al-Si alloy for microstructural refinement [25, 26]. In a few applications, binary and tertiary form grain refiners like Ti-B, Al-Ti-B, Al-Ti-C, and others are used as grain refiners to improve the microstructure of hypereutectic Al-Si alloys. Among them, Al-Ti-B has shown better results compared to Ti-B, Al-Ti, and Al-Ti-C grain refiners. Nonetheless, adding grain refiners can increase heterogeneous nucleation and result in a refined microstructure of the hypereutectic Al-Si alloy [17].

Another way to improve the microstructure of the hypereutectic Al-Si alloy is through rapid solidification techniques. The rapid solidification of the melted hypereutectic Al-Si alloy through melt spinning and spray casting can improve the microstructure through the Hall-Petch strengthening mechanism, ultimately enhancing the strength of the hypereutectic Al-Si alloy. Other techniques, such as spray forming and laser processing, are also utilised for the rapid solidification of the hypereutectic Al-Si alloy. Finally, non-equilibrium solidification can form non-equilibrium phases, and ultimately provides significant improvement in the microstructure of the hypereutectic Al-Si alloy [27]. Generally speaking, rapid solidification hinders the evolution of Si, promotes the nucleation of the elements, and results in smaller elements, including Si, and a better microstructure of the hypereutectic Al-Si alloy.

4.5.2 Modification of Si Morphology

The morphology of Si has a significant effect on the strength of the hypereutectic Al-Si alloy. The primary and dendritic shape of Si reduced the strength of the hypereutectic Al-Si alloy. The dendritic shape of Si morphology reduced the bonding between Al and other elements, thereby decreasing the crack resistance and the applied load. Thus, to form finer and smaller-sized morphology of Si is vital to achieve better strength of the hypereutectic Al-Si alloy.

The most common way to improve Si morphology is by adding grain refiners, such as phosphorus, sodium, and strontium, to the melted cast hypereutectic Al-Si alloy. The refinement of silicon morphology by elements such as phosphorus (P), strontium (Sr), and rare earth (RE) elements is governed by distinct nucleation and growth mechanisms. Phosphorus promotes heterogeneous nucleation of primary silicon through the formation of AlP particles, which act as potent nucleation sites due to their crystallographic compatibility with silicon, thereby increasing nucleation density and reducing silicon particle size. In contrast, strontium modifies the growth of eutectic silicon by poisoning the twin-plane re-entrant edge (TPRE) growth mechanism, which suppresses the faceted growth of silicon and leads to a transition from coarse plate-like or dendritic structures to fine fibrous morphology. Rare earth elements further contribute to refinement through impurity-induced growth restriction and by altering interfacial energy conditions, which hinder silicon growth and promote a more uniform and refined microstructure. These mechanisms collectively result in improved distribution, reduced particle size, and enhanced mechanical properties of hypereutectic Al–Si alloys.

Adding grain refiners refined the morphology of Si, transforming it into finer and fibrous Si morphology, and thereby improving the strength of the hypereutectic Al-Si alloy. The Si morphology of hypereutectic Al-Si alloys can be improved through the use of proper cooling rates during solidification. The optimum cooling rates could prevent the growth of Si during solidification, improve bonding strength with aluminium, and ultimately enhance the tensile strength of the hypereutectic Al-Si alloy [28]. Such refinement mechanisms are critical in controlling crack initiation, improving load transfer, and enhancing overall strength and wear resistance.

4.5.3 Addition of Alloying Elements

The hypereutectic Al-Si alloys are categorised as hypoeutectic, eutectic, and hypereutectic based on the weight percentage of Si. The weight percentage of Si is more than 12.3 in hypereutectic Al-Si alloys, in addition to other alloying elements like Cu, Mg, Fe, Ni, and others [11]. Conclusively, each alloying element has a unique impact on the physical, mechanical and thermal characteristics of the hypereutectic Al-Si alloy [16]. The addition of Cu improves mechanical strength, enhances corrosion resistance, refines the microstructure, and reduces dislocation density in the hypereutectic Al-Si alloys [29]. The addition of Mg enhanced the ductility and tensile strength of the Al-Si alloys. Furthermore, adding Mg refined the Si morphology and improved the distribution of Si in the microstructure of the hypereutectic Al-Si alloy. The reason behind such improvement is the phase formation of Mg_2Si in the microstructure of the hypereutectic Al-Si alloy [30].

4.5.4 Processing Parameters and Techniques

The strength and hardness of the casting Al-Si alloys can be controlled and improved by adjusting casting parameters, such as stirring time and stirrer rotational speed, cooling rates during solidification, and pouring temperature, in addition to heat treatment of the cast specimens. The stirring time and stirrer rotational speed control the growth of Si during melting and transform it into the eutectic phase. This step refines the size of Si morphology and improves the tensile strength and hardness of the hypereutectic Al-Si alloy. The selection of an appropriate stirring time and rotation can hinder the growth of Si and support the formation of fine and smaller Si particles. The other significant outcome of controlling the stirring time and rotation is the regulation of Si aggregation and agglomeration, thereby improving bonding strength and enhancing the resistance to deformation and mechanical strength of the hypereutectic Al-Si alloy.

The cooling rate during solidification plays a critical role in determining silicon morphology, grain size, and mechanical properties, as widely reported in the literature [14,19,17]. Faster cooling rates promote finer microstructures, whereas slower cooling leads to coarse silicon particles and reduced mechanical performance.

The pouring temperature of the cast Al-Si alloy can significantly affect its mechanical properties. It also controls the formation of porosity in the cast Al-Si alloys during the casting process. A low pouring temperature can reduce the large and coarse Si particles, ultimately improving the mechanical strength of the hypereutectic Al-Si alloy. However, further reduction in pouring temperature could lead to incomplete moulding and cast defects [31-34].

The controlled heating and cooling of metals to modify their mechanical and physical characteristics without changing the product's shape or design is known as heat treatment [11]. Enhancing the mechanical strength of metals is frequently associated with heat treatment. While there is no discernible effect on thermo-mechanical fatigue, heat treatment operations have a substantial impact on thermal, mechanical, and fatigue behaviours, particularly at room temperature. Numerous studies have demonstrated that processing parameters such as stirring speed, cooling rate, pouring temperature, and heat treatment conditions significantly influence the microstructure and performance of hypereutectic Al–Si alloys. These parameters control nucleation, grain growth, and silicon morphology, which directly affect mechanical strength, wear resistance, and corrosion behaviour. Therefore, optimisation of processing conditions is essential to achieve refined microstructures and enhanced performance, as supported by multiple experimental investigations reported in the literature [14,19,27,31,35].

5. FUTURE RESEARCH TRENDS OF HYPEREUTECTIC Al-Si ALLOY

Future research on hypereutectic Al–Si alloys should be guided by both established findings and recent advances reported in the literature. Previous studies have shown that microstructure refinement, silicon morphology control, and heat treatment optimisation are among the most effective routes for improving the mechanical and tribological performance of these alloys. More recent investigations have further highlighted the importance of advanced casting techniques, additive manufacturing, hybrid alloying strategies, and computational modelling in tailoring the microstructure and performance of hypereutectic Al–Si alloys for demanding applications [14,19,20,27,36]. Future research on hypereutectic Al-Si alloys in automotive applications will focus on several key areas to enhance performance and broaden their use.

5.1 Microstructure Optimisation

Ongoing research aims to control the size, distribution, and morphology of silicon particles through advanced casting and heat treatment techniques, enhancing mechanical properties, wear resistance, and thermal management. This trend is strongly supported by earlier and recent studies showing that refining primary Si size and improving its distribution can significantly enhance strength, wear resistance, and thermal stability [5,14,20,22,27].

5.2 Alloy Composition Modifications

Investigating the addition of alloying elements, such as chromium, copper, nickel, and rare earth elements, aims to enhance the mechanical, thermal, and casting characteristics of hypereutectic AlSi alloys, thereby expanding their applications. Recent studies have demonstrated that alloying additions such as Mg, Cu, rare earth elements, and grain refiners can effectively modify silicon morphology and improve both mechanical and physical properties [16,17,27,37].

5.3 Additive Manufacturing Techniques

Additive manufacturing techniques, such as direct metal laser sintering (DMLS) and selective laser melting (SLM), are trending techniques. The fabrication of hypereutectic Al-Si using any of these methods, and the investigation of its mechanical and other properties, are crucial. Additive manufacturing techniques can fabricate complex geometries, tailor microstructures, and reduce raw material waste. The growing interest in additive manufacturing is also supported by recent reports showing improved microstructural control and property tailoring in Al–Si-based alloys fabricated by advanced layer-wise processing routes [15,18,38].

5.4 Hybrid Reinforcement Composites

The addition of metallic, ceramic, and other rare earth elements has shown a significant effect on the tensile strength, hardness, and physical properties of the Al-Si composite. However, in addition to that, their additions have shown unwanted outcomes, including porosity, non-equilibrium thermal variations, and others [39-42]. Thus, combining different reinforcements and producing hybrid composite materials is vital in current research work. Thus, investigating the impact of adding different reinforcements in hypereutectic Al-Si is crucial to obtain tailored mechanical, physical and thermal properties. Previous and recent investigations indicate that hybrid reinforcement strategies may offer a more balanced improvement in strength, hardness, and wear resistance compared with single-reinforcement systems, although porosity and interfacial stability remain critical challenges [31].

6. CONCLUSIONS

Hypereutectic Al-Si alloys, containing more than 12 % silicon by weight, are known for their exceptional hardness, wear resistance, and high-temperature properties, making them particularly attractive for high-performance applications. The increased silicon content yields large primary silicon particles, which contribute to the alloy's unique microstructure and performance. Despite their advantages, hypereutectic Al-Si alloys face several challenges, including poor castability, high porosity, and difficulties in achieving a uniform microstructure during manufacturing, which can impact their mechanical properties and limit their industrial adoption.

Researchers have explored various strategies to address these issues, including advanced casting techniques, modifying elements, and optimising heat treatment processes. By overcoming these challenges, the performance and reliability of hypereutectic Al-Si alloys can be significantly improved, paving the way for broader utilisation in diverse applications across industries such as automotive, aerospace, and heavy machinery. As the demand for high-performance materials grows, research and development of hypereutectic Al-Si alloys is expected to intensify, focusing on new alloying elements, advanced manufacturing techniques, and microstructural optimisation.

Hypereutectic Al-Si alloys represent a promising avenue for next-generation lightweight, high-performance materials. By addressing their challenges and exploring new avenues for improvement, researchers and industry professionals can unlock the full potential of these alloys, paving the way for increased adoption in critical applications. Future developments in hypereutectic Al–Si alloys are expected to be driven by recent advances in HPDC and related casting technologies reported in the past few years. Overall, the performance of hypereutectic Al–Si alloys is strongly dependent on silicon content, microstructure, and processing conditions. Based on the reviewed studies, an optimal silicon content range of approximately 16–20 wt.% is often recommended for achieving a balance between mechanical strength, wear resistance, and thermal stability. Microstructural refinement, particularly the control of silicon morphology from coarse plate-like structures to fine fibrous or spheroidized forms, plays a critical role in improving mechanical performance and reducing defect formation. Furthermore, optimized processing parameters, including cooling rate, alloying additions, and heat treatment conditions, are essential for achieving uniform microstructure and enhanced performance.

Acknowledgements

The authors acknowledge the Ministry of Higher Education for funding this research under the Fundamental Research Grant Scheme (FRGS), Registration Proposal No: FRGS/1/2022/TK 10/UTM/02/45.

Author Contributions

Ali M.H. Altameemi, Tuty Asma Abu Bakar, Mohd Ayub Sulong; methodology, Ali M.H. Altameemi, Mohammed Rasheed, Aqeel Ahmed Bhutto; planned and conducted the tests, Ali M.H. Altameemi, Mohammed Rasheed, Tuty Asma Abu Bakar; data analysis and interpretation, and Tuty Asma Abu Bakar, Ali M.H. Altameemi, Mohammed Rasheed; prepared the manuscript. Hamidreza Ghandvar: editing and formatting. All authors have read and approved the final manuscript version.

Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest.

Compliance with Ethical Standards

The work is compliant with ethical standards.

References

[1] Haque, M. M. & Sharif, A. (2001). Study on wear properties of aluminium–silicon piston alloy. *Journal of Materials Processing Technology*, 118(1-3), 69-73.

[2] Azadi, M. & Sadegh, M. (2022). Data analysis of high-cycle fatigue testing on piston aluminum–silicon alloys under various conditions: : Wear, lubrication, corrosion, nano-particles, heat-treating and stress. *Data in Brief*, 41, 107984.

[3] Hari Sanil, T. K., Deepak, T. K. & Ravi, M. (2022). Experimental and numerical evaluation of squeeze cast Al–Si–Cu–Ni–Mg alloy for piston applications. *Materials and Manufacturing Processes*. 37(10), 1145–1155.

[4] Tenekedjiev, N. & Gruzleski, J. E. (1990). Hypereutectic aluminium-silicon casting alloys—a review. *Cast Metals*, *3*(2), 96-105.

[5] Labisz, K., Dobrzański, L. A. & Konieczny, J. (2008). Anodization of cast aluminum alloys produced by different casting methods. *Archives of Foundry Engineering*, 8(3), 45–50.

[6] Forn, A., Picas, J. A., Baile, M. T., Martin, E. & Garcia, V. G. (2007). Microstructure and tribological properties of anodic oxide layer formed on Al–Si alloy produced by semisolid processing. *Surface and Coatings Technology*, 202(4-7), 1139–1143.

[7] Zeren, M. & Karakulak, E. (2008). Influence of Ti addition on the microstructure and hardness properties of near-eutectic Al–Si alloys. *Journal of Alloys and Compounds*, 450(1-2), 255–259.

[8] Jaradeh, M. & Carlberg, T. (2005). Effect of titanium additions on the microstructure of DC-cast aluminium alloys. *Materials Science and Engineering: A*, 413–414, 277–282.

[9] Kumar, G. S. V., Murty, B. S. & Chakraborty, M. (2010). Effect of $TiAl_3$ particle size and distribution on their settling and dissolution behaviour in aluminium. *Journal of Materials Science*, 45, 2921–2929.

[10] Fratila-Apachitei, L. E., Terryn, H., Skeldon, P., Thompson, G. E. & Duszczyk, J. (2003). Influence of substrate microstructure on the growth of anodic oxide layers. *Electrochimica Acta*, 49(7), 1127–1140.

[11] Chauke, L., Mutombo, K. & Govender, G. (2014). Corrosion behaviour of anodised A356 aluminium alloy produced by rheo-high pressure die casting. *Advanced Materials Research*, 1019, 67–73.

[12] Mohedano, M., Matykina, E., Arrabal, R., Mingo, B. & Pardo, A. (2015). PEO of pre-anodized Al–Si alloys: Corrosion properties and influence of sealing. *Applied Surface Science*, 346, 57–67.

[13] Samuel, E., Tahiri, H., M. Samuel, A., Songmene, V. & H. Samuel, F. (2024). A Review on Fundamentals of Grain Refining of Al-Si Cast Alloys. In *Recent Advancements in Aluminum Alloys*. Ed. Shashanka R. (IntechOpen Book Series, United Kingdom), pp. 1-33.

[14] Jorstad, J. & Apelian, D., (2009). Hypereutectic Al-Si alloys: practical casting considerations. *International Journal of Metalcasting*, 3(3), 13-36.

[15] Sajadifar, S. V., Sharifi, E., Weidig, U., Steinhoff, K. & Niendorf, T. (2020). Performance of thermo-mechanically processed AA7075 alloy at elevated temperatures. *Metals*, 10(7), 884.

[16] Vijayan, V. & Prabhu, K. N. (2013). Review of microstructure evolution in hypereutectic Al–Si alloys and its effect on wear properties. *Transactions of the Indian Institute of Metals*, 67(1), 1–18.

[17] Hao, Z., Bojin, Q., Zewu, Q., Caiyou, Z., Zihao, J., Yubin, Z., Hongwei, L., Ruize, Z. & Baoqiang, C. (2024). Influence of heat treatment on the microstructure and mechanical properties of Al–Mg–Si alloy fabricated by double wires + arc additive manufacturing. Journal of Materials Research and Technology, 30, 910–918.

[18] Samuel, A. M., Zedan, Y., Doty, H. W., Songméné, V. & Samuel, F. H. (2021). A review study on the main sources of porosity in Al–Si cast alloys. *Advances in Materials Science and Engineering*, 2021(1), 1921603.

[19] Beroual, S., Boumerzoug Z., Paillard P. & Borjon-Piron Y. (2019). Effects of heat treatment and addition of small amounts of Cu and Mg on the microstructure and mechanical properties of Al-Si-Cu and Al-Si-Mg cast alloys. *Journal of Alloys and Compounds*, 784, 1026–1035.

[20] Ozen, G. & Giulio T. (2020). Lanthanides: a focused review of eutectic modification in hypoeutectic Al–Si alloys. *Journal of Materials Research and Technology*. 9(4), 8652–8666.

[21] Xu, C. L., Yang, Y. F., Wang, H. Y. & Jiang, Q. C. (2007). Effects of modification and heat treatment on abrasive wear behavior of hypereutectic Al–Si alloys. *Journal of Materials Science*, 42, 6331–6338.

[22] Zhu, Z., Wang, Y., Shi, D., Wang, J., Liu, Y., Wu, C. & Su, X. (2024). Optimizing the microstructure and enhancing the mechanical properties of hypereutectic Al–Si alloys by Mg addition. *Journal of Materials Research and Technology*, 32, 457–469.

[23] Jaafar, A. & Jyoti, M. (2020). Developing nano-sized fibrous eutectic silicon in hypereutectic Al–Si alloys by laser remelting. *Scientific Reports*, 10(1), 12090.

[24] Mingotti, E., Girelli, L., Tocci, M., Arcaleni, R., Dongellini, M., Ceschini, L., Gelfi, M. & Pola, A. (2025). Effect of different heat treatments on the high temperature tensile behavior and electrical/thermal conductivity of HPDC castings in high recycled content AlSi10MnMg alloy. *Journal of Alloys and Compounds*, 1049, 185446.

[25] Akkera, H. S., Reddy, N. N. K., Poloju, M., Sekhar, M. C., Yuvaraj, C. & Prasad, G. S. (2016). Fabrication of cast aluminium–silicon (Al–Si) and aluminium–magnesium (Al–Mg) alloys and their properties. *Acta Metallurgica Slovaca*, 22(4), 212–221.

[26] Hu, Z., Huo, Q., Chen, Y., Liu, M. & Chen, X. (2023). Improving mechanical property of hypereutectic Al–Si alloys via regulating microstructure by Rheo-die-casting. *Metals*, 13(5), 968.

[27] Yu, X. F., Zhang, G. Z., Wang, X. Y., Gao, Y. Y., Jia, G. L. & Hao, Z. Y. (1999). Non-equilibrium microstructure of hyper-eutectic Al-Si alloy solidified under superhigh pressure. *Journal of Materials Science*, 34(17), 4149-4152.

[28] Li, L., Li, D., Mao, F., Feng, J., Zhang, Y. & Kang, Y. (2020). Effect of cooling rate on eutectic Si in Al-7.0Si-0.3Mg alloys modified by La additions. *Journal of Alloys and Compounds*, 826, 154206.

[29] Mihaela, A., Robert, K., Judith, L., Gerald, K., Jacopo, F. & Paola B. (2020). Microstructure evolution during in-situ heating of AlSi10Mg. *Additive Manufacturing*, 36, 101605.

[30] Li, M., Li, Y. & Zhou, H. (2020). Effects of pouring temperature on microstructure and mechanical properties of A356 alloy. *Materials Research*, 23(1), e20190676.

[31] Noga, P., Skrzekut, T. & Wędrychowicz, M. (2023). Microstructure and mechanical properties of Al–Si alloys produced by rapid solidification. *Materials*, 16(15), 5223.

[32] Danil, Y. P., Maitri, K., Navneet, K., Giuseppe, P., Marina, C. V., Leonardo, R. R. D. S. & Khaled, G. (2023). Review of machinability improvement in aluminium alloys. *The International Journal of Advanced Manufacturing Technology,* 129(1), 4743–4779.

[33] Sai, T. V., Vinod, T. & Sowmya, G. (2017). A critical review on casting types and defects. *International Journal of Scientific Research in Science, Engineering and Technology*, 3(2), 463-468.

[34] Bhutto, A., Wahab, M. S., Solangi, F. A., Hussain, F., Zhou, D., Yunus Khan, T. M & Shaik, A. S., (2025). Microstructure, mechanical and physical characteristics analysis of ADC14 hypereutectic AlSi composite reinforced with Al2O3. *Alexandria Engineering Journal*, 126 (3), 303–319.

[35] Wang, Z., Xiao, Z., Tse, Y., Huang, C. & Zhang, W., (2019). Optimization of processing parameters and establishment of a relationship between microstructure and mechanical properties of SLM titanium alloy. *Optics & Laser Technology*, 112, 159-167.

[36] Xiao, W., Zizhi, Y., En, H., Juntao, M., Xiaoqing, Z., Tengfei, M. & Xiaohong, W. (2024). Effect of Al–Ti–B–Er on microstructure and properties of aluminium alloy. *Crystals*, 14(8), 695.

[37] Prigunova, A. G., Koshelev, M. V. & Borisov, A. G. (2024). Primary silicon formation in hypereutectic alloy Al–16.5% wt. Si treated in the liquid state by a changing unipolar pulsed electric current. *Materials Science and Technology*, 42 (1), 68-78.

[38] Dong, Z., Jia, B., Cheng, W., Yang, G., Wan, X., Zhao, X. & Huang, H., (2025). Heat resistant ultra-strong Al-Si alloy and its application in additive manufacturing. *Cell Reports Physical Science*, 6(8), 102774.

[39] Zhang, X., Yang, C., Li, Z., Bao, S. & Chen, Y. (2025). A comparative study of Mg-9Al-3Si high silicon magnesium alloy extruded from rapid solidification strip and conventional ingot casting processes. *Materials Chemistry and Physics*, 342, 130965.

[40] Zheng, Z., Ji, Y., Mao, W., Yue, R. & Liu, Z. (2017). Influence of rheo-diecasting parameters on hypereutectic Al–Si alloy. *Transactions of Nonferrous Metals Society of China*, 27(6), 1264–1272.

[41] Farahany, S., Hamedani, M. K., Salehloo, M., Altameemi, A. M., Ourdjini, A., Krol, M. & Ghandvar, H. (2025). The effect of bismuth and tin on mechanical and tribological performance of compocast aluminum hybrid composites reinforced with Al_2O_3, ZrO_2 and SiC. *Journal of Materials Engineering and Performance*, 34(20), 23418–23434.

[42] Farahany, S., Malekan, M., Altameemi, A. M., Nasirpour, T., Sedaghatpour, S., Pirhadi, P. & Vaziri, S. (2025). Tailoring the solidification behaviour of recycled Al–Fe–Si alloy through gadolinium additions: A thermal analysis and microstructural investigation. *Journal of Thermal Analysis and Calorimetry*, 150(18), 14009–14021.