Journal of Materials, Processing and Design (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/jmpd.2025.090112
ISSN 2516-0923 Vol. 9 Num. 1

Research Progress of Metamorphic Treatment of Hypereutectic Aluminum-Silicon Alloys

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Keywords: Hypereutectic Aluminum-Silicon Alloys; Silicon Phase; Refinement

Abstract: Hypereutectic aluminum-silicon (Al-Si) alloys are widely employed in high-end engineering applications, such as automotive engine pistons and aerospace structural components, due to their advantageous properties including low thermal expansion coefficient, high specific strength, excellent castability, and superior wear resistance. The mechanical performance of these alloys is critically influenced by the morphological characteristics of silicon phases, particularly the size, distribution, and geometric features of primary silicon crystals and eutectic silicon networks. This review systematically evaluates recent international research advancements in microstructure optimization of hypereutectic Al-Si alloys. It comprehensively discusses various modification strategies, such as non-rare-earth element modification, rare-earth compound modification and composite modification systems combining multiple alloying elements. Additionally, advanced processing techniques are analyzed, including rapid solidification technologies, ultrasonic vibration treatment during solidification, mechanical stirring processes and high-temperature melt treatment. These approaches have demonstrated effectiveness in refining silicon phase morphologies and improving alloy performance. However, significant challenges remain in achieving uniform microstructure refinement for large-scale castings, particularly in maintaining phase stability during industrial production. Future research should prioritize the development of novel modification systems and integrated processing technologies that can simultaneously optimize both primary and eutectic silicon phases.

1. Introduction

High-silicon aluminum alloys (HSAs) are characterized by their inherently low coefficient of thermal expansion (CTE), high specific strength, superior wear resistance, and excellent casting performance. These unique property combinations render them ideal candidates for high-temperature structural applications such as engine cylinders and pistons that require continuous operation under extreme thermal and mechanical loads. Their lightweight nature further enhances their appeal in aerospace and automotive industries where weight reduction is critical for fuel efficiency and performance optimization[1]. Compared to hypoeutectic and eutectic Al-Si alloys, hypereutectic Al-Si alloys exhibit distinct advantages, including lower CTE, higher tensile strength, enhanced wear resistance from primary silicon particles[2–4].

These attributes have positioned hypereutectic Al-Si alloys as the material of choice for next-generation automotive piston systems. The mechanical performance of these alloys is fundamentally dependent on the microstructural characteristics of silicon phases, specifically size distribution of primary silicon crystals, morphology of eutectic silicon networks and Spatial arrangement of silicon phases within the aluminum matrix[5–8]. Extensive research has demonstrated that melt modification during casting can effectively refine both primary and eutectic silicon morphologies, leading to significant improvements in mechanical properties. Recent advancements in this field include alloying strategies (e.g., non-rare-earth element modification, rare-earth compound modification and composite modification systems combining multiple alloying elements), process innovations (e.g., rapid solidification techniques, inoculation with ceramic nanoparticles and ultrasonic vibration during solidification) and microstructure-property correlations (e.g., quantitative analysis of silicon phase parameters using image processing, computational modeling of solidification kinetics and in-situ characterization of phase evolution during thermal cycling).

While these methods have achieved notable progress in microstructure optimization, challenges remain in achieving uniform modification across large-scale castings and maintaining stability during industrial production. Future research should focus on developing multifunctional modifier systems and integrated processing technologies that can simultaneously refine both silicon phases while ensuring scalability for mass production. Emphasis should also be placed on exploring novel alloy design approaches leveraging machine learning and high-throughput experimentation to accelerate material development.

2. Spoilage Treatment

2.1 Non-rare earth metamorphic agents

P is widely recognized as an effective refining agent for hypereutectic Al-Si alloys, capable of significantly modifying primary silicon morphology during melt processing[9–11]. Industrially, phosphorus is typically introduced through master alloys such as Al-P, Cu-P, or via direct addition of red phosphorus/phosphate salts. Recent investigations have systematically characterized its refinement mechanisms [12,13]. Shi et al. [14] reported that adding 0.8 wt.% elemental P to A390 Al-Si alloy induced dramatic microstructural changes. As shown in Figure 1, quantitative analysis revealed primary silicon size reduction from 40-50 μm to 10-20 μm, accompanied by morphological transformation from angular polygonal particles to rounded globules. This microstructural refinement translated to significant mechanical property improvements, with ultimate tensile strength increasing from 178 MPa to 219 MPa. X-ray diffraction (XRD) analysis identified the formation of AlP intermetallic compounds, which served as heterogeneous nucleation sites promoting equiaxed primary silicon growth. Zhang et al. [15] demonstrated synergistic effects of Sr modification in Al-20Si alloy systems. Combined Sr addition (0.02-0.04 wt.%) reduced primary silicon size by 40-60%, altering morphology from dendritic to compact globular structures. The resultant reduction in sharp silicon protrusions improved interfacial bonding between primary silicon and aluminum matrix, as confirmed by scanning electron microscopy (SEM) analysis. This morphological optimization led to a 12-15% enhancement in thermal conductivity, critical for heat dissipation applications like engine components.

However, optimal P content must balance refinement efficiency with potential deleterious effects such as increased porosity or formation of brittle intermetallics [16]. Current research focuses on developing composite modifier systems and advanced processing techniques to achieve precise control over primary silicon size distribution and morphology.

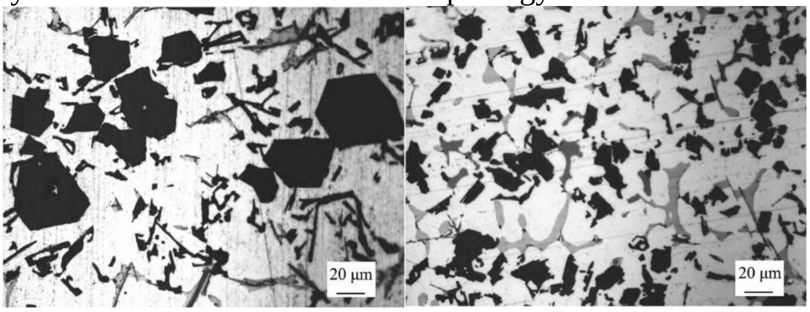

Fig.1 Microstructure of A390 alloy before and after 0.8% P densification [14].

2.2 Rare earth metamorphic agents

China's abundant rare earth (RE) resources provide a unique advantage for developing environmentally friendly modification technologies for Al-Si alloys. Rare earth elements exhibit excellent modifying efficiency in hypereutectic Al-Si systems while maintaining clean production characteristics [17–19]. Fang et al. [20] systematically investigated the effect of ytterbium (Yb) addition on the microstructure and properties of Al-20Si alloy. Their results demonstrated that optimal Yb content (0.6 wt.%) induced significant microstructural evolution: Primary silicon particles transformed from irregular polygonal/bulk shapes with sharp edges to nearly spherical globules. As shown in Figure 2, Average primary silicon size reduced from 242 μm (unmodified) to 75 μm (69% reduction). The morphological improvement suppressed stress concentration at particle-matrix interfaces. The modification mechanism involves the formation of RE-rich intermetallic compounds (Al_3Yb) acting as heterogeneous nucleation sites, the suppression of silicon growth through solute segregation at solid-liquid interfaces and the reduction in surface energy of primary silicon via RE adsorption.

These microstructural improvements resulted in enhanced mechanical properties, including increased tensile strength and ductility. At present, a large amount of research focuses more on optimizing multi-RE element combinations and exploring synergistic effects with other modifiers to achieve comprehensive microstructure control.

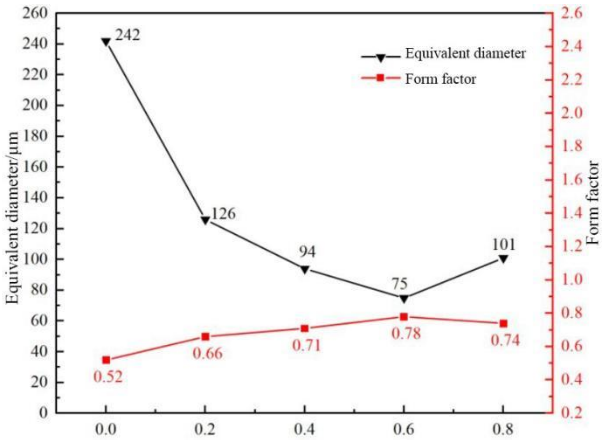

Fig. 2 Effect of rare-earth Yb metamorphism on the size and shape factors of incipient Si in hypereutectic Al-Si alloy [20].

2.3 Compound metamorphic agents

In recent years, scholars both domestically and internationally have conducted extensive research on composite densifiers. These agents exhibit a more comprehensive refining effect on both primary and eutectic silicon compared to traditional single-type densifiers, which can only produce a densification effect on either primary or eutectic silicon[21,22]. Teng et al. [23] added varying mass fractions of Al-10% LaCe intermediate alloy to Al-25Si alloys. As shown in Figure 3, it can be observed in the XRD diffraction pattern that new multiphase is generated in the alloy after the modification treatmentand and it was found from the experimental results that the optimal addition of LaCe was 1.0 wt.% for Al-25Si alloys. At this concentration, the refining effect on primary silicon was most pronounced, and the morphology of eutectic silicon transformed from acicular to granular. However, when the LaCe addition exceeded 1.0 wt.%, the refining effects on both primary and eutectic silicon became less effective, leading to a coarsening tendency in grain size. He et al. [24] introduced a fixed mass fraction of LaCe densifier and different mass fractions of P into Al-25Si alloys. They discovered that the densification effect on primary silicon was optimal at a P addition of 0.8%. The morphology of primary silicon changed from coarse five-petal star and irregular polygonal shapes to fine polygonal and plate-like structures, with the average grain size decreasing from 150 μm~200 μm to 30 μm~50 μm. Eutectic silicon, initially distributed as long needles, showed a significant reduction in distribution density. Mechanical property tests revealed substantial improvements in tensile strength and hardness after densification treatment.

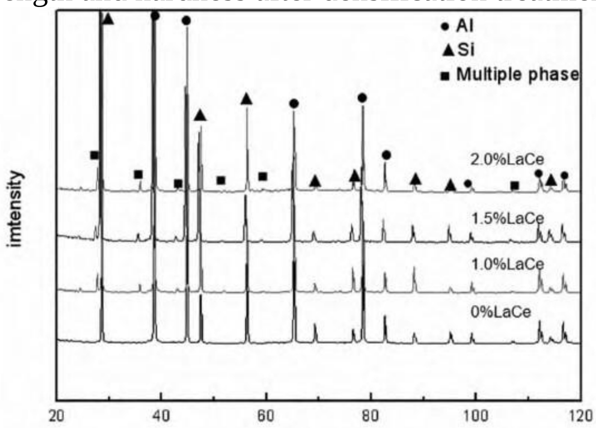

Fig. 3 XRD patterns of Al-25%Si alloy samples with different LaCe additions [23].

3. Improved preparation process

3.1 Rapid solidification

Rapid solidification is an innovative casting method commonly used in alloy preparation. Its advantage lies in simultaneously refining both eutectic and primary silicon, significantly enhancing the performance of the alloy microstructure [25–27]. However, the process is complex and requires sophisticated equipment. Common rapid solidification methods include powder metallurgy, jet deposition, and melt rotation. Xue et al. [28] investigated the effects of sand cooling, metal-type cooling, and water-cooled metal-type cooling on primary silicon in Al-20Si alloys. They found that cooling rate significantly influenced the size of primary silicon; faster cooling rates resulted in smaller silicon grains. Water-cooled cooling reduced the size of primary silicon to 23.08% of that achieved by sand cooling. Additionally, the sizes of eutectic silicon and α-Al exhibited similar decreasing trends. Li et al. [29] prepared Al-20Si specimens using continuous extrusion with jet deposition and observed that both primary and eutectic silicon were refined in the deposited billet. Primary silicon appeared in straight lines or arcs, while eutectic silicon was diffusely distributed within the α-Al matrix. The primary silicon size was approximately 2 μm, and eutectic silicon reached the nanometer level. The microstructure evolution process of the alloy during the spray forming process is shown in Figure 4.

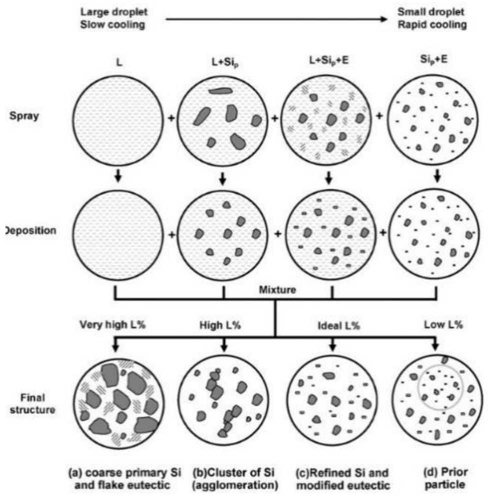

Fig. 4 Microstructure evolution of hypereutectic Al-Si alloys in injection molding [29].

3.2 Ultrasonic treatment

Ultrasonic vibration treatment is another widely used method for refining silicon phases in Al-Si alloys. The effects of various factors on the fibrous microstructure are typically investigated by altering ultrasonic vibration time, power, air-vibration ratio, and the timing of ultrasound introduction during the melting process [30,31]. Wei et al. [32] applied ultrasound with a power of 1600W at 750℃ for melt treatment of Al-24Si. Compared to untreated samples, the average size of primary silicon decreased by 45.3%, 50.3%, and 44% respectively, depending on holding times, and the hardness of the Al-Si alloy increased. Chen et al. [33] examined the influence of ultrasound powers ranging from 600W to 2000W on the primary silicon fiber structure of Al-25%Si alloys. They found that the average equivalent diameter of primary silicon first decreased and then increased, achieving the best refining effect at 1200W, with an equivalent diameter of 33.2 μm. Figure 5 is a schematic diagram of the ultrasonic melt processing system.

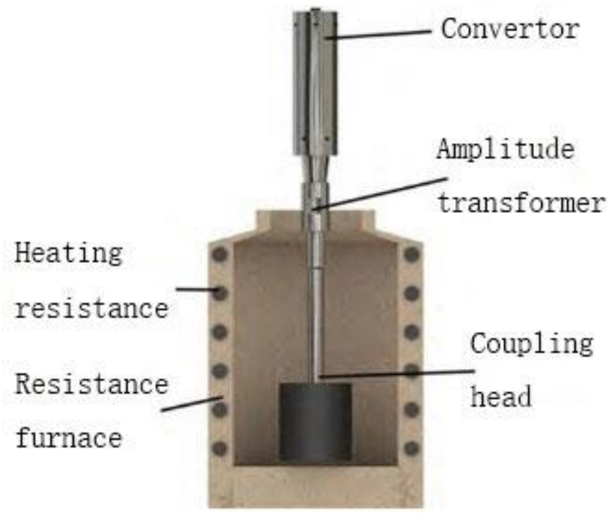

Fig. 5 Schematic diagram of ultrasonic melt processing system [32].

3.3 Mechanical stirring

Semi-solid-state mechanical stirring takes advantage of external forces to vigorously stir the particles within the microstructure. This vigorous action effectively refines the primary silicon, bringing about a notable improvement in its quality and characteristics. This approach is not only straightforward to implement but also highly cost-effective. Due to these advantages, it proves to be eminently suitable for large-scale industrial production on a mass scale[34]. Zhuang et al. [35] dedicated their efforts to investigating the profound impact of mechanical stirring on the microstructure of primary silicon in Al-30Si alloys. Their meticulous research led to significant discoveries. As shown in Figure 6, they determined that to achieve the refinement of primary silicon, higher stirring speeds in combination with lower temperatures were necessary. This specific combination of conditions disrupts the growth of coarse primary silicon particles, facilitating the formation of a finer and more homogeneous microstructure. Conversely, when it comes to the spheroidization of primary silicon, which involves transforming the shape of the primary silicon into a spherical form, a different set of conditions is required. Specifically, higher stirring speeds in conjunction with higher temperatures are essential. The elevated temperatures promote the diffusion of atoms within the alloy, which in turn enables the primary silicon particles to gradually assume a spherical shape. This transformation not only enhances the mechanical properties of the alloy but also positively influences its castability and machinability.

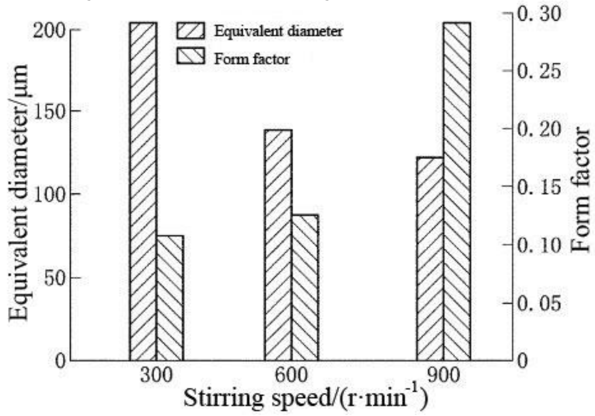

Fig.6 Effect of stirring speed on size and shape factors of unmetamorphosed primary Si [35].

3.4 Melt superheat treatment

Melt superheat treatment is one of the simplest and most effective methods for refining microstructures through controlled manipulation of melt temperature[36]. This technique involves superheating the alloy melt to an elevated temperature, holding it for a specified duration, and subsequently pouring it [37]. The process is straightforward and highly controllable, effectively refining the microstructure and enhancing various properties. Recently, this research direction has attracted significant attention from scholars worldwide. Yang et al. [38] investigated the effect of melt superheating on the microstructure and morphology of primary silicon in Al-18Si alloys. They found that when the alloy was superheated to 1050 ℃ for 1 hour, the primary silicon phase solidified uniformly as fine lumps, with the average diameter decreasing from 155 μm to 43 μm. Lu et al. [39] examined the impact of melt superheat treatment on the microstructure of Al-30Si alloys. Four melts with different superheat levels were prepared, held at these temperatures, and then cast after cooling to 950 ℃. Results indicated that as the superheat level increased, the size of the primary crystalline silicon decreased; however, five-petal star-like primary silicon morphologies persisted. Meanwhile, eutectic silicon retained its elongated, needle-like morphology.

3.5 Electromagnetic stirring

Pulsed magnetic fields (PMFs) can significantly enhance solidification structures; however, they can also induce violent motion in the liquid metal, leading to instability and splashing of the molten metal. This instability can result in poor solidification, incorporation of impurities, and entrapment of gases [40]. Chen et al. [33] investigated the effect of pulsed magnetostatic oscillation on the solidification behavior and properties of Al-25Si alloy. As shown in Figure 7, they found that the equivalent diameter of primary silicon initially decreased and then increased with the rise in peak pulse current at various current levels but constant frequency. The smallest average size of primary silicon was approximately 40.1 μm at a peak pulse current of 350A, which is notably smaller than the untreated Si alloy's average size of 130.2 μm. Additionally, as the pulse frequency increased while maintaining a constant peak pulse current, the average equivalent diameter of primary silicon also increased. Notably, at a pulse frequency of 20Hz, the average size of primary silicon reached its minimum value of 43.3 μm.

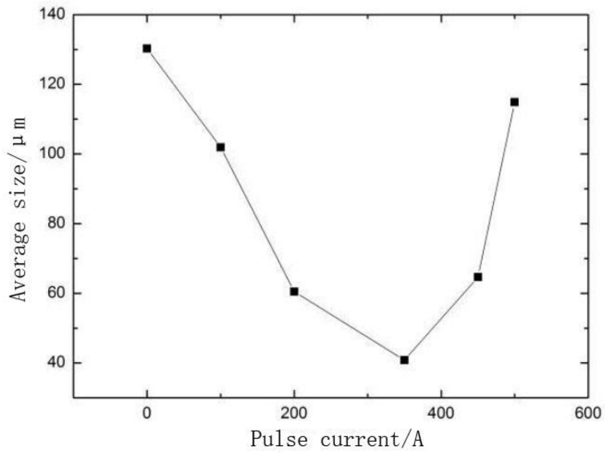

Fig.7 Variation of average size of primary silicon at different currents [33].

4. Other methods

4.1 Heat treatment

Heat treatment is frequently employed to refine the silicon phase microstructure of Al-Si alloys[41]. Liang et al. [42] investigated the impact of homogenization annealing on the microstructure and properties of Al-17Si alloy. Their findings indicated that after annealing, the eutectic silicon morphology significantly improved, transitioning from coarse needles to fine spheres. This change resulted in a more homogeneous distribution of eutectic silicon, reduced hardness, and enhanced plasticity. An effective homogenization annealing process involves maintaining the billet at 480 ℃ for 4 hours, followed by furnace cooling.

4.2 Squeeze casting

The continuous extrusion process offers a remarkable and highly significant advantage in the form of rapid and continuous molding [29]. Zhang et al. [1] carried out an in-depth and meticulous examination to explore the effects that are exerted by the extrusion temperature and the extrusion speed on the microstructure as well as the mechanical properties of the extruded parts which were fabricated from semi-solid Al-25Si billets. As shown in Figure 8, at an extrusion temperature precisely set at 460 ℃ and an extrusion speed precisely maintained at 6 mm/s, the extruded Al-25Si alloy components demonstrated extremely favorable elongation properties. To be more specific, they boasted a specific elongation rate amounting to 3.2%, and successfully managed to achieve a tensile strength reaching up to 132.3 MPa. When the extrusion temperature was deliberately reduced to 420 ℃, the mechanical properties of the alloy successfully reached their most optimal and outstanding performance level. Throughout this process, the tensile strength notably rose to 135.7 MPa, although it should be noted that the elongation experienced a relatively slight decrease to 2.95%.

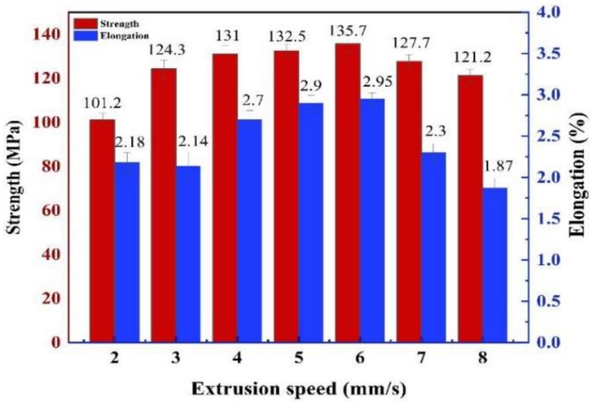

Fig.8 Mechanical properties of extruded parts at different extrusion speeds at extrusion temperature of 420 ℃ [1].

5. Conclusions

In recent years, research on hypereutectic Al-Si alloys has yielded significant results. Researchers have conducted extensive work on refining the silicon phase through the use of metamorphic agents and improvements in preparation processes, leading to notable enhancements in the microstructure and mechanical properties of these alloys. However, certain advanced preparation techniques such as ultrasonic treatment, electromagnetic stirring, and rapid solidification are not suitable for producing large-size castings due to their high equipment and technology requirements and inconsistent quality.

The addition of metamorphic agents stands out as a simple, feasible, and relatively stable method with controllable preparation processes. This approach has garnered significant attention from researchers in recent years. However, like other methods, it has inherent limitations: its effectiveness in refining the silicon phase is relatively limited, typically targeting only one form of silicon, such as eutectic or primary silicon, during the refinement process.

Therefore, developing a metamorphic agent or process that can simultaneously refine both eutectic and primary silicon phases to achieve superior mechanical and various properties is crucial. Such advancements would better meet the demands of the automotive industry for hypereutectic Al-Si alloys and facilitate large-scale industrial application. This remains a key area for future research.

Acknowledgements

Guangxi Science and Technology Major Program (Grant nos. AA23062026, AA23062036, AA24206035); Guangxi Minzu University Xiangsi Lake Youth Scholar Innovation Team (2023GXUNXSHQN04); Campus Level Talent Introduction Research Launch Project of Guangxi Minzu University (2021KJQD29)

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