© DEC 2025 | IRE Journals | Volume 9 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I6-1712586

Influence of Silicon Content on the Microstructural, Thermal and Tribological Behavior of Cast Al–Si Piston Alloys

NINGAPPA CHANDARAGI[1], PRAVEEN KUMBAR[2], RAMESH[3], SHANKARA J R[4], R. V. KURAHATTI[5]
[1, 2, 3, 4]*Student, Department of Mechanical Engineering, Basaveshwar Engineering College Bagalkot, India*
[5]*Professor, Department of Mechanical Engineering, Basaveshwar Engineering College Bagalkot, India*

Abstract- This study investigates the influence of silicon content (10, 15 and 20 wt.%) on the microstructural, thermal and tribological behaviour of cast Al–Si piston alloys. The microstructure transitioned from hypoeutectic (Al-10Si) to near-eutectic (Al-15Si) and hypereutectic (Al-20Si) with a progressive increase in primary Si particle volume. Hardness improved with increasing Si due to the combined strengthening from eutectic and primary silicon phases. In contrast, thermal conductivity and diffusivity decreased with higher Si content, while specific heat increased. Tribological testing at 3.0 m/s demonstrated that wear rate rose with load for all alloys; however, the Al-15Si alloy showed the lowest wear rate owing to its optimally distributed silicon phases. The Al-10Si alloy exhibited the highest wear rate, while Al-20Si showed intermediate performance due to micro-cracking around coarse primary Si particles. Overall, Al-15Si offered the best balance of thermal–mechanical properties and wear resistance, indicating its suitability for high-load piston applications.

Key words: Al–Si Piston Alloys; Microstructure; Hardness; Thermal Properties; Wear Rate

I. INTRODUCTION

The automobile and transportation industry has played a crucial role in the advancement of modern society; however, it has also contributed significantly to environmental challenges such as global warming and rising emissions [1]. To address these issues, automotive manufacturers continue to focus on lightweight materials that improve fuel efficiency and engine performance. Aluminium, being the second most widely used metal globally, has become a dominant choice in this direction, with nearly 85–90% of cast components in the automotive sector produced from aluminium–silicon (Al–Si) alloys [2].Al–Si alloys are broadly classified into hypoeutectic (<12 wt.% Si), eutectic (12–13wt.% Si), and hypereutectic (14–25 wt.% Si) categories based on silicon concentration. Among these, Al-12 wt.% Si alloys commonly referred to as piston alloys have gained widespread industrial application due to their excellent abrasion resistance, corrosion resistance, low thermal expansion coefficient, and high strength-to-weight ratio [3]. However, most Al–Si alloys exhibit reduced tensile and fatigue performance at elevated temperatures (>232 °C), which limits their direct use in high-temperature piston applications [4]. To overcome this drawback, alloying elements such as Ni, Cu, Mg, and Fe are deliberately incorporated to enhance mechanical and thermal stability under severe engine operating conditions [5].

Previous studies have extensively investigated the effect of Si morphology and alloy chemistry on the mechanical and tribological performance of Al–Si piston alloys. Increasing silicon content improves hardness, tensile strength, and wear resistance due to the presence of hard primary and eutectic Si particles [6,7]. Alloying additions further modify the response of these alloys: for example, increases in Cu and Ni enhance strength but reduce thermal conductivity, leading to elevated piston crown temperatures [8], whereas squeeze casting and heat treatment can restore thermal conductivity without compromising strength [9]. Magnesium additions, on the other hand, decrease impact strength and thermal conductivity, with higher Mg content intensifying this effect [10]. Conversely, increasing Cu concentration from 1 to 3.5 wt.% enhances hardness, tensile properties, and the coefficient of thermal expansion by promoting primary Si formation and widening the solidification range [11]. These findings highlight the complex interaction between alloying elements, phase evolution, and processing techniques in tailoring piston alloy performance. The continued replacement of cast iron with aluminium alloys in piston manufacturing is driven by their superior thermal conductivity and lower density, which collectively enhance heat dissipation and improve engine efficiency [12-13]. Nevertheless, there exists a trade-off between enhanced mechanical strength and reduced thermal conductivity when multiple alloying elements are added. This challenge has motivated research into advanced casting processes, modifiers, and heat-treatment strategies to simultaneously improve strength and thermal management [14]. Thermal conductivity in aluminium alloys is particularly sensitive to the form in which alloying elements are present; solute atoms in the solid solution significantly impede heat transfer, whereas precipitated phases have a comparatively mild effect [15]. Mastering these factors is essential for the development of next-generation, high-thermal-conductivity alloys for efficient piston operation. The present study was to investige the influence of silicon content (10, 15, and 20 wt.%) on the tribological behaviour and thermal properties of Al–Si piston alloys. By correlating Si percentage with wear mechanisms, hardness, thermal conductivity, and related thermophysical characteristics, this work aims to provide a balanced understanding of material selection for high-performance piston applications.

2.1. Materials and Methods

In this study, Al–Si piston alloys were synthesized and characterized through controlled experimental procedures. The tailored made alloys procured from Fenfee Metallurgical Ltd., Bangalore, India, The alloying process was carried out in an electric resistance furnace, where the charge material was heated to 720–780 °C and held for 10–20 min to ensure complete dissolution of silicon and other alloying elements, thereby promoting compositional uniformity across the melt. The molten alloy was then poured into a preheated mold to prepare the alloys samples in the form of round bars. The elemental composition of the synthesized alloys is summarized in Table 1

Table 1: Elemental composition of alloys (wt.%)

Alloy	Si	Fe	Cu	Mg	Ni	Zn	Mn	Ti	Al
Alloy-1	10	1.2	1.5	1	0.35	0.2	0.2	0.2	Bal
Alloy-2	15	1.36	1.4	1.25	0.478	0.78	0.2	0.2	Bal
Alloy-3	20	1.22	1.1	1.1	0.2	0.7	0.2	0.2	Bal

Standard metallographic procedures were followed to prepare the samples. Grinding was performed using SiC abrasive papers from 120 to 2000 grit, followed by final polishing with alumina suspension and diamond paste (0.5–2 μm) on PSA-backed velvet cloth. The polished samples were then etched using Keller's reagent (1% HF, 1.5% HCl, 2.5% HNO_3, balance water). Sample preparation was carried out using an automatic polishing machine and microstructural observations were conducted using a Lynax optical microscope.The thermal constants and heat transfer behavior of the piston alloys were measured using a thermal constant analyzer (TPS 500 S, Hot Disk- NIT Calicut). Kapton-insulated sensors-7577 (radius 2.0 mm), 5465 (radius 3.2 mm), and 5501 (radius 6.4 mm) were used depending on the testing conditions. Bulk measurements were conducted using polished disc-shaped samples with dimensions of 3 mm thickness and 8 mm diameter (Fig. 1a). Thermal Constant Analyzer (TPS 500 S, Hot Disk) is as shown in Fig.1b.

(a)

DOI: https://doi.org/10.64388/IREV9I6-1712586

(b)

Figure 1 (a). Polished disc-shaped samples with dimensions of 3 mm thickness and 8 mm diameter (b) Thermal Constant Analyzer (TPS 500 S, Hot Disk) (NIT, Calicut)

The hardness test of piston alloys was carried out using vickers hardess testerat aapplied load of 10gand dwelling period of 10S. The dry sliding wear tests was carried on a pin-on-disc testing machine (Figure3.5) (DUCOM-Wear &Friction Monitor-TR-20LE) with a steel disk made of EN-32 material at a sliding velocity of 1.0 m/s (Disc speed- 160 rpm) and varying the normal loads of 10,20,30, and 40N.All tests were performed at room temperature with a wear track diameter of 120mm and a sliding distance of 2000 m, and were repeated three times.. Following the end of each wear test under various test conditions, wear samples were cleaned with acetone. The weight loss of a pin (W) was calculated by comparing the weight of a pin before and after each test. Equation 1 is used to compute the wear rate (WR).

$$WR = \frac{(\Delta \mathrm{W}/\mathrm{density\ of\ Composite})}{SD} mm^3/\mathrm{m} \qquad (1)$$

Microstructural observation of the worn specimens was studied by using a SEM The dry sliding wear test samples are shown in the figure 3

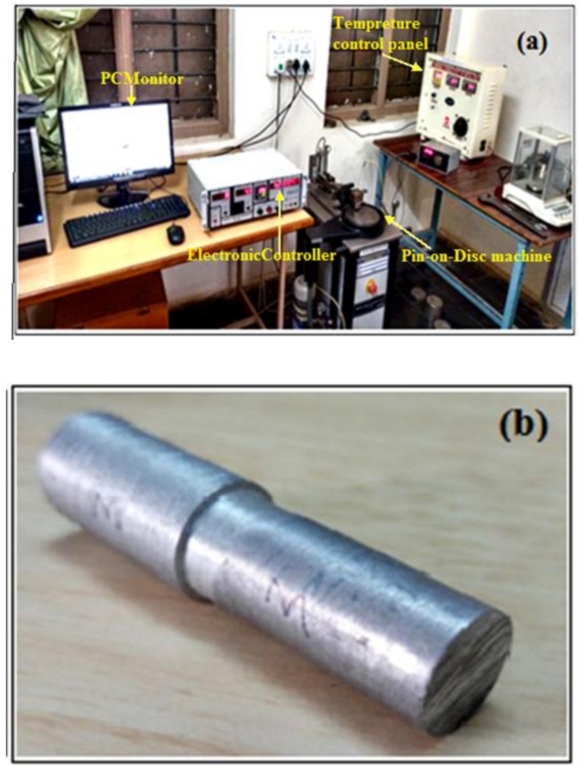

Figure 2. (a) Pin-on-Disc testing machine *and* (b) *wear* testing Pin

III. RESULTS AND DISCUSSION

Figures 3 (a)–(c) illustrate the microstructural evolution of hypoeutectic (10 wt.% Si), near-eutectic (15 wt.% Si), and hypereutectic (20 wt.% Si) Al–Si alloys. The Al-10Si alloy exhibits a dendritic α-Al matrix with fine eutectic Si particles distributed along the interdendritic regions, representing the typical solidification morphology of hypoeutectic Al–Si alloys. With an increase to 15 wt.% Si, the microstructure shifts toward a near-eutectic composition, characterized by the appearance of larger polygonal primary Si particles along with finer eutectic Si uniformly embedded in the Al matrix. At 20 wt.% Si, the alloy displays a distinctly hypereutectic structure dominated by coarse, blocky to star-shaped primary Si particles, while the eutectic Si fraction becomes comparatively lower. The progressive increase in size and density of primary Si particles with rising Si content confirms the strong influence of silicon on the solidification mode and resulting microstructure.

© DEC 2025 | IRE Journals | Volume 9 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I6-1712586

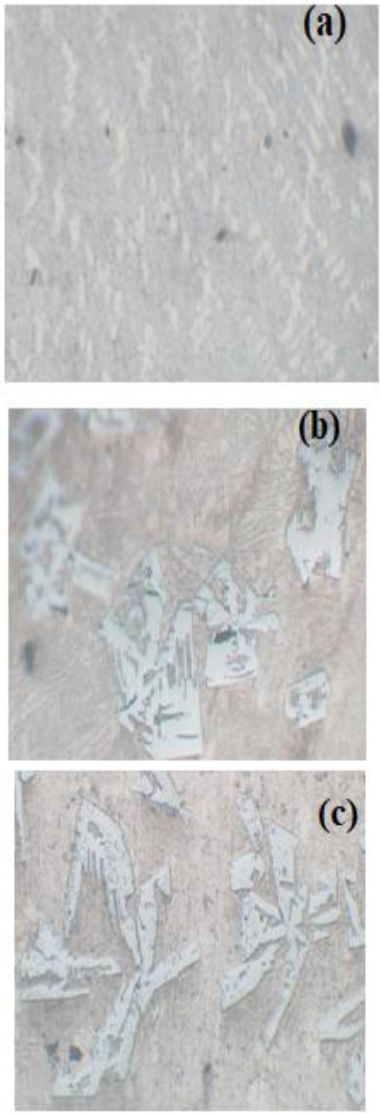

Figure 3. Optical microstructure of (a) Al-10Si,(b) Al-15Si and (c)Al-20Si alloy

3.2. Hardness test

The Vickers hardness values presented in Table 2 show a consistent increase with rising silicon content from 10 to 20 wt.%. The Al-10Si alloy exhibits the lowest hardness due to its microstructure being dominated by soft α-Al dendrites with only fine eutectic Si. In the Al-15Si alloy, the higher hardness is attributed to the increased volume fraction of Si and the appearance of polygonal primary Si particles, which enhance resistance to plastic deformation. The Al-20Si alloy records the highest hardness as its microstructure contains a large fraction of coarse primary Si particles that act as highly rigid reinforcements. Overall, the hardness trend (Al-10Si < Al-15Si < Al-20Si) aligns with the microstructural evolution, confirming that increasing Si content enhances hardness and wear resistance, although excessive primary Si may reduce ductility.

Table 2: Vickers Hardness of Al–Si Alloys

Alloy Composition	Vickers Hardness (HV)	Average
Al-10Si	82, 85, 84, 83, 86	84 ± 2
Al-15Si	94, 92, 96, 95, 93	94 ± 2
Al-20Si	108, 110, 111, 109, 107	109 ± 2

3.3.Thermal properties

Table 3 shows the thermal properties of the piston alloys, showing a clear inverse relationship between silicon content and thermal conductivity. The Al-10Si alloy records the highest thermal conductivity (123.9 W/m·K) and diffusivity (0.040 mm²/s), owing to the dominance of the continuous α-Al matrix, which offers minimal resistance to heat flow. When Si increases to 15 wt.%, both conductivity and diffusivity decrease (112 W/m·K and 0.032 mm²/s) as the formation of eutectic and primary Si phases disrupts heat-transfer pathways. The Al-20Si alloy exhibits the lowest thermal conductivity (94.5 W/m·K) and diffusivity (0.021 mm²/s) due to the large volume fraction of coarse primary Si particles, which act as non-conductive barriers and intensify phonon and electron scattering. In contrast, the specific heat increases steadily from 31.5864 to 38.6674 MJ/m³·K with rising Si content, reflecting the higher volumetric heat capacity of silicon and the increased energy required to raise the alloy temperature. Overall, the results confirm that increasing Si content reduces thermal transport but enhances heat-storage capability in Al–Si piston alloys.

© DEC 2025 | IRE Journals | Volume 9 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I6-1712586

Table 3: Thermal properties of piston alloy

Alloy	*Temperature*	*Th.Conductivity*	*Th.Diffusivity*	*Spec.Heat*
Al-10Si	25.9 °C	123.9 W/mK	0.04 mm²/s	31.5864 MJ/m³K
Al-15Si	26.0 °C	112 W/mK	0.032 mm²/s	36.1847 MJ/m³K
Al-20Si	26.0 °C	94.5 W/mK	0.021 mm²/s	38.6674 MJ/m³K
Standard Deviation	0.0 °C	0.011 W/mK	0.00 mm²/s	4.4731 MJ/m³K

3.4. Wear study

The wear behaviour of the cast Al–Si piston alloys at a sliding velocity of 3.0 m/s (Fig. 4) shows a clear dependence on both applied load and silicon content. For all alloys, the wear rate increases as the load rises from 10 N to 40 N, reflecting the typical load-sensitive transition between adhesive and abrasive wear mechanisms. Among the three compositions, the Al-15Si alloy exhibits the lowest wear rate at all loads, while the Al-10Si alloy shows the highest, particularly under higher loading conditions. The Al-20Si alloy displays intermediate behaviour, with wear values slightly above those of Al-15Si but considerably lower than Al-10Si. These differences arise from the distinct microstructures generated by varying silicon content. The Al-15Si alloy contains a balanced combination of primary and eutectic Si phases, forming a stable load-bearing skeleton that limits the real contact area during sliding. The reduced silicon content in Al-10Si results in lower hardness and insufficient reinforcement, leading to severe material removal at increased loads. Although the Al-20Si alloy has a higher amount of silicon, the presence of coarse, brittle Si particles promotes micro-cracking and delamination during wear, which marginally increases the wear rate compared with Al-15Si. Overall, the superior wear resistance of the Al-15Si alloy at 3.0 m/s highlights its suitability for high-load piston applications.

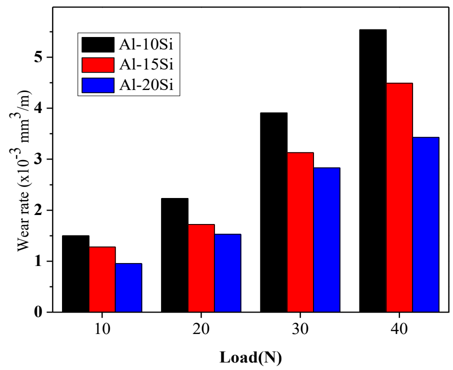

Figure 4. Wear rate of piston with applied load

The SEM worn-out surfaces of piston alloys constant sliding velocity of 3.0 m/s and a maximum applied load of 40 N are shown in Figure 5. Al-10Sialloy exhibited more severe material removal and surface damage, with prominent grooves and delamination features. This is attributed to the presence of coarse and brittle Si particles and the lack of uniform distribution within the Al matrix. In contrast, Al-15calloy 2 displayed comparatively smoother wear tracks with fewer grooves and cracks. Al-15Si alloy, maintained its integrity with finer wear grooves and shallow plastic deformation.

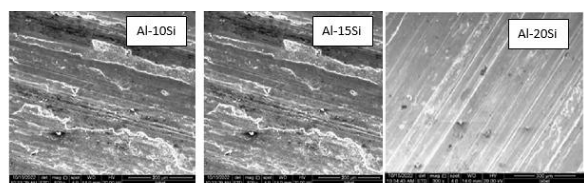

Figure 5. SEM wornout surfaces of alloys at 3.0m/s and load of 40N

The enhanced thermal stability of Al-15Si alloy microstructure played a critical role in mitigating wear damage. Al-20Si Alloy began to exhibit oxidative wear features along with deeper grooves and micro-cracks, suggesting a combined action of abrasion and oxidation. The worn surface indicated partial melting and smearing, hinting at matrix softening. Al-20Si alloy revealed fewer cracks and a more uniform wear surface, reflecting its better load-bearing capability and the effectiveness of the stir-casting method in achieving uniform particle dispersion.

IV. CONCLUSION

The present study evaluated the influence of silicon content (10, 15, and 20 wt.%) on the microstructural, thermal, and tribological characteristics of cast Al–Si piston alloys. The following conclusions were drawn

- Increasing silicon content (10–20wt.%) transformed the alloy microstructure from hypoeutectic to hypereutectic and increased the size and volume fraction of primary Si particles.
- Hardness improved with Si addition, while thermal conductivity and diffusivity decreased and specific heat increased due to silicon's heat-storage nature.
- Wear rate increased with applied load for all alloys, but its severity depended strongly on silicon content.
- Al-15Si exhibited the lowest wear rate owing to an optimum balance of primary and eutectic Si phases that enhanced load-bearing support and minimized material loss.
- Overall, Al-15Si showed the best combination of microstructural, thermal and tribological properties, confirming its suitability for high-load and high-temperature piston applications.

REFERENCES

[1] Miller, W.S., Zhuang, L., Bottema, J., Wittebrood, A.J., De Smet, P., Haszler, A., & Vieregge, A. (2000). Recent development in aluminium alloys for the automotive industry. *Materials Science and Engineering A*, 280(1), 37–49.

[2] Kaufman, J.G. (2000). *Aluminum Alloy Castings: Properties, Processes, and Applications*. ASM International, USA.

[3] Polmear, I.J. (2005). *Light Alloys: From Traditional Alloys to Nanocrystals* (4th ed.). Butterworth–Heinemann, Oxford.

[4] Samuel, F.H. (1999). Effect of alloying elements on the microstructure and properties of Al–Si piston alloys. *Journal of Materials Science*, 34(16), 3987–4001.

[5] Mathai, B., Pillai, R.M., & Pai, B.C. (2015). Influence of silicon morphology on wear performance of Al–Si alloys. *Materials & Design*, 65, 1050–1058.

[6] Dwivedi, D.K. (2005). Wear behaviour of Al–Si–Mg alloys in dry sliding conditions. *Materials & Design*, 26(5), 389–396.

[7] Li, M., Kang, H., & Zhu, X. (2018). Thermal and mechanical effects of Cu and Ni additions on Al–Si-based piston alloys. *Journal of Alloys and Compounds*, 743, 512–521.

[8] Sanil, H., Rao, G.A., & Pai, B.C. (2022). Restoration of thermal conductivity in high-strength Al–Si–Cu–Ni alloys through squeeze casting and heat treatment. *Materials Characterization*, 185, 111710.

[9] Zhang, A., Liu, C., & Sun, Y. (2023). Effect of magnesium content on impact strength and thermal characteristics of Al–Si alloys. *Journal of Materials Research and Technology*, 23, 3021–3034.

[10] Chankitmunkong, S., Chairuangsri, T., & Tongsri, R. (2019). Influence of copper content on solidification behaviour and mechanical properties of Al–Si piston alloys. *Metals*, 9(7), 815.

[11] Li, S. (2023). Heat dissipation and efficiency improvement in aluminium alloy pistons. *Applied Thermal Engineering*, 220, 119833.

[12] Inusah, S. (2024). Replacement of cast iron with aluminium alloys for high-efficiency internal combustion engines. *Journal of Energy Conversion and Management*, 307, 118501.

[13] Sanil, H., Gokuldoss, P.K., & Rao, G.A. (2022). Effect of advanced processing routes on strength and thermal performance of Al–Si piston alloys. *Journal of Materials Processing Technology*, 304, 117582.

[14] Zhang, Y., & Li, M. (2023). Correlation between solute state and heat-transfer resistance in aluminium alloys. *Progress in Materials Science*, 138, 101158.