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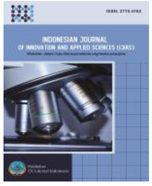

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Effect of pouring temperature on fluidity, porosity, density, and microstructure of Al-Si alloy in gravity die casting

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ABSTRACT

The growing demand for lightweight aluminium components necessitates improved quality control in casting, particularly for aluminium–silicon (Al–Si) alloys produced via gravity die casting. This study systematically investigates the effect of pouring temperature on the fluidity, porosity, density, and microstructure of an Al–Si alloy using a gravity iron die mold with varying section thicknesses. Casting experiments were conducted at pouring temperatures of 600°C, 650°C, and 700°C to simulate thin-wall casting conditions. Fluidity was evaluated by measuring flow length, while density and porosity were determined using Archimedes' principle. Microstructural evolution was characterized via optical microscopy. The results demonstrate that increasing the pouring temperature significantly enhances fluidity, enabling the complete filling of progressively thinner sections. However, higher temperatures also lead to increased porosity and reduced density, particularly in thicker sections, due to prolonged solidification times and reduced cooling rates. Microstructural analysis reveals that higher pouring temperatures and larger section thicknesses promote coarser α-Al dendrites, larger β-Si particles, and increased intermetallic phase aggregation; conversely, lower pouring temperatures and thinner sections result in finer, more homogeneous microstructures. These findings highlight the critical trade-off between mold-filling capability and internal casting quality, emphasizing the importance of optimizing pouring temperature in the gravity die casting of Al–Si alloys.

INTRODUCTION

The demand for aluminium casting alloys has increased significantly recently, particularly in the automotive, aerospace, and electrical/electronic industries, driven by the need for lightweight structures, improved energy efficiency, and reduced emissions (Asghar et al., 2025; Simões, 2025; Yin et al., 2026). Aluminium alloys are widely recognized for their advantageous combination of low density, high specific strength, good corrosion resistance, and excellent recyclability, making them ideal candidates for modern engineering applications (Li et al., 2023; Niu et al., 2022; Sun, 2023). Among the various aluminium alloy systems, aluminium–silicon (Al–Si) alloys represent the most important group of casting alloys, accounting for nearly 90% of all aluminium castings produced worldwide due to their superior castability, favourable solidification behaviour, and good mechanical performance (Haga et al., 2021; Niu et al., 2022).

Gravity die casting, also referred to as permanent mold casting, is one of the most widely used manufacturing processes for producing aluminum alloy components with high dimensional accuracy and excellent surface quality (Timelli &

Bonollo, 2007; Zhang, Wang, Li, et al., 2021). In this process, molten metal is poured into a reusable metal mold under the influence of gravity, allowing the mold cavity to fill from bottom to top. Compared with sand casting, gravity die casting offers improved mechanical properties, better repeatability, smoother cast surfaces, and higher material efficiency, making it suitable for producing structural and functional components for transportation and industrial applications (Campbell, 1988). However, achieving high-quality castings using gravity die casting requires careful control of processing parameters, particularly when producing thin-walled components.

One of the most critical characteristics governing casting quality in aluminum alloys is fluidity, which refers to the ability of molten metal to flow and fill a mold cavity before solidification occurs (Erzi et al., 2024; Han, 2022). Fluidity plays a decisive role in determining mold-filling capability, surface integrity, dimensional accuracy, and internal soundness of cast components, especially for thin-wall and complex geometries (Campbell, 1988; Niu et al., 2022). Insufficient fluidity can lead to casting defects such as misruns, cold shuts, and incomplete filling, resulting in high rejection rates and increased production costs (Di Sabatino, 2008; Ergün Songül & Dispinar, 2025; Erzi et al., 2024). Therefore, understanding the factors influencing fluidity is essential for the foundry industry, particularly in applications requiring lightweight and thin-section castings.

Fluidity is not an intrinsic material property but a complex technological characteristic arising from the interaction between molten metal flow and solidification kinetics under specific casting conditions (Han, 2022; Han & Zhang, 2020). It is typically evaluated by measuring the distance molten metal can flow through a narrow channel before solidification under conditions of rapid heat extraction and high thermal gradients (Erzi et al., 2024; Haga et al., 2021). Several parameters influence fluidity, including pouring temperature, mold temperature, cavity thickness, alloy composition, melt cleanliness, viscosity, surface tension, and mold material (Han & Zhang, 2020; Júnior et al., 2022). Due to the coupled nature of these factors, fluidity behavior remains one of the most challenging aspects of aluminum casting to predict and control accurately.

Extensive research has been conducted to investigate the influence of alloy composition and solidification behavior on the fluidity of aluminum alloys. Silicon content has been shown to improve fluidity by lowering the liquidus temperature and delaying dendrite coherency during solidification (Engler & Knarbakk, 2021; Haga et al., 2021; Niu et al., 2022). The effects of alloying additions such as Fe, Cu, Zn, rare-earth elements, and nanoparticle reinforcements on fluidity have also been widely reported (Chen & Li, 2024a; Durmus et al., 2025; Niu et al., 2019). Additionally, numerical and experimental studies have demonstrated that mold material and cooling conditions significantly affect flow arrest mechanisms during die casting (Bang et al., 2022; Bazhenov et al., 2021; Han & Zhang, 2020). Despite these efforts, fluidity is often examined as an isolated parameter, without systematic correlation to other critical quality indicators such as porosity, density, and microstructure.

Pouring temperature is widely recognized as one of the most influential process parameters affecting melt superheat, viscosity, surface tension, and solidification rate (Han, 2022; Niu et al., 2022). Increasing pouring temperature generally enhances fluidity by extending the liquid lifetime of the melt and delaying the onset of solidification (Becker et al., 2018; G. Zou et al., 2022; Han, 2022). However, excessive pouring temperature may also lead to undesirable effects, including increased hydrogen absorption, oxidation, grain coarsening, segregation of alloying elements, and porosity formation, which can degrade mechanical properties and internal quality (A. Samuel et al., 2021; G. T. Zou et al., 2020). Therefore, although pouring temperature is frequently adjusted in industrial practice to improve mold filling, its broader influence on casting quality remains insufficiently understood.

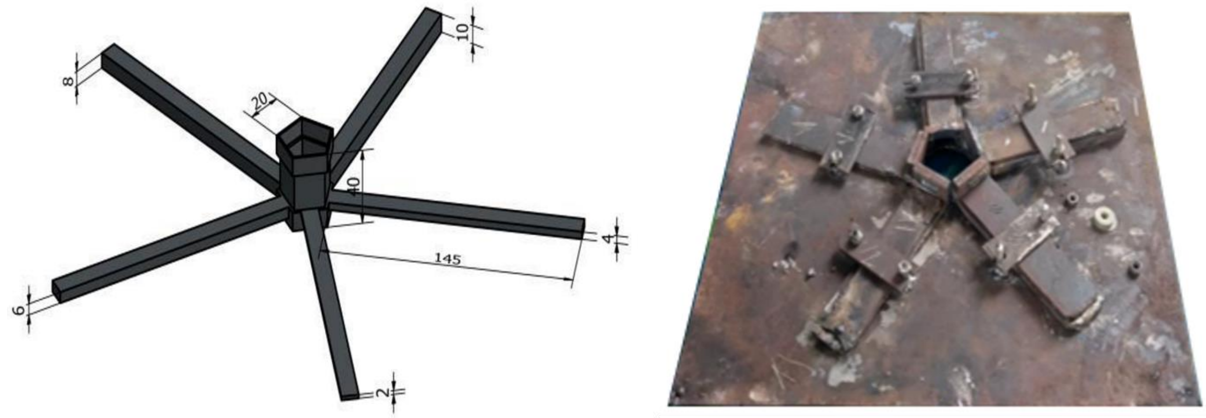
There is limited systematic understanding of how pouring temperature simultaneously affects fluidity, porosity, density, and microstructure in Al–Si alloys under gravity die casting conditions. Many previous studies have focused on high-pressure die casting or sand-casting processes, which involve different heat transfer characteristics and feeding behavior compared with gravity iron molds (Han & Zhang, 2020; Rao et al., 2023). Moreover, porosity and density are often discussed independently of fluidity, despite their strong interdependence through solidification behavior and feeding efficiency (A. Samuel et al., 2021; E. Samuel et al., 2025). Fluidity-focused investigations rarely integrate microstructural evolution, even though it directly governs mechanical performance.

To address these limitations, the present study investigates the influence of pouring temperature as a single dominant processing variable on the fluidity, porosity, density, and microstructure of an aluminum–silicon alloy cast using a gravity iron die mold. Casting experiments were conducted at three different pouring temperatures (600°C, 650°C, and 700°C) using molds with varying strip thicknesses to simulate thin-wall casting conditions. Fluidity was quantified by measuring the flow length of molten metal in each strip, while density and porosity were determined using Archimedes' principle. Microstructural evolution was examined using optical microscopy to correlate phase morphology and grain size with thermal conditions.

METHODS

Research Design

This study employed an experimental research design to investigate the influence of pouring temperature on the fluidity behavior, density, porosity distribution, and microstructural characteristics of Al–Si alloy castings produced by gravity die casting. The overall experimental procedure consisted of four sequential stages: material preparation, casting experiment, specimen characterization, and data analysis.



(a) Mold dimension (b) The actual mold of the fluidity test.

Figure 1. Design and dimensions of the fluidity testing mold

The independent variable in this study was the pouring temperature, which was varied at three levels (600, 650, and 700 °C), while the mold geometry and casting conditions were maintained constant throughout the experiments. The response variables included strip fluidity length, density, porosity content, and microstructural features. Three specimens were produced for each pouring temperature to ensure experimental repeatability and improve statistical reliability.

Figure 2. Fluidity cast

After casting, density measurements were performed using Archimedes' principle to determine the porosity level of the cast specimens. Microstructural observations were subsequently conducted using optical microscopy after standard metallographic preparation. The relationships between pouring temperature, mold filling capability, porosity formation, and microstructural evolution were then analyzed to evaluate the influence of casting temperature on the quality of Al–Si alloy castings.

Materials and Experimental Arrangement

The material employed in this investigation was a commercial Al–Si casting alloy. Its chemical composition, determined before the experiments, is presented in Table 1. Silicon was the major alloying element, accompanied by minor amounts of Cu, Fe, Mg, Mn, Ni, Ti, Cr, Sn, and Ca, which are commonly found in commercial casting alloys and influence fluidity, solidification behavior, and microstructural development.

The experimental setup consisted of a gravity die casting system equipped with a strip fluidity mold fabricated from low-carbon steel. The mold dimensions are shown in Figure 1a. The mold was designed to evaluate the filling capability of molten metal through strip channels having different cavity thicknesses of 10, 8, 6, 4, and 2 mm while maintaining a constant strip width of 4 mm. This configuration enabled the assessment of molten alloy fluidity under different solidification conditions.

The alloy was melted in a gas-fired crucible furnace using a low-carbon steel crucible. Melt temperature was continuously monitored using a K-type thermocouple to ensure accurate pouring conditions. Before each casting operation, the mold cavity was coated with a thin graphite layer to minimize adhesion between the casting and the mold after solidification. The molten alloy was then poured into the non-preheated mold at three different pouring temperatures of 600, 650, and 700 °C. Three casting trials were carried out at each pouring temperature to improve the reproducibility of the experimental data.

After solidification, the strip castings were removed from the mold and sectioned into density specimens at 2.5 cm intervals starting from the riser end toward the chill end (Figure 2). Density measurements were performed according to Archimedes' principle. The porosity content was estimated indirectly using the expression.

$$\text{Porosity} = \frac{D_s - D}{D}$$

where D_s represents the density of the reference specimen, and D is the measured density of the test specimen. Three specimens from each experimental condition were analyzed to obtain representative porosity values.

Microstructural characterization was performed using an inverted metallurgical microscope (Metkon IMM 902, Turkey). Samples were sectioned from the strip castings and mounted in epoxy resin to facilitate handling during metallographic preparation. The specimen surfaces were sequentially ground using silicon carbide abrasive papers with grit sizes ranging from 100 to 1000, followed by polishing with alumina suspension and final diamond polishing to obtain a mirror-like surface finish. Before microscopic observation, the polished specimens were etched using Keller's reagent consisting of 10 mL HF, 15 mL HCl, 25 mL HNO_3, and 50 mL H_2O. The resulting micrographs were subsequently analyzed to evaluate the influence of pouring temperature on grain morphology and casting defects.

Table 1. Chemical composition of material

Chemical elements	Composition (%)
Al	84.00
Si	11.82
Cu	1.477
Fe	0.838
Mn	0.141
Mg	0.91
Cr	0.02
Ni	0.631
Sn	0.01
Ti	0.048
Ca	0.011

RESULTS AND DISCUSSION

Fluidity

Figure 3 presents the fluidity length of the aluminium–silicon alloy measured under die casting conditions at pouring temperatures of 600°C, 650°C, and 700°C. The results show a clear and systematic increase in total fluidity length with increasing pouring temperature, reaching 397 mm at 600°C, 423 mm at 650°C, and 483 mm at 700°C. This trend demonstrates that pouring temperature is a dominant process parameter governing molten metal flow in die casting. At 600°C, molten metal flows only through strip thicknesses of 10, 8, and 6 mm, with measured fluidity lengths of 140 mm, 138 mm, and 119 mm, respectively, while no flow is observed in 4 mm and 2 mm strips. Increasing the pouring temperature to 650°C enables additional flow through the 4 mm strip (13 mm), although flow is still absent in the 2 mm strip. At 700°C, complete flow through all strip thicknesses is achieved, including the thinnest 2 mm strip, confirming that higher pouring temperature significantly enhances mold-filling capability. This behaviour is consistent with previous studies reporting that increased superheat delays flow arrest by extending the time available before dendrite coherency occurs in Al–Si alloys (Han, 2022; Niu et al., 2022; G. T. Zou et al., 2020).

The increase in total fluidity length from 397 mm at 600°C to 483 mm at 700°C in Figure 3 is consistent with the established finding that flow length increases as pouring temperature increases, and it also aligns with the broader thermal-parameter dependence captured by a fitted relationship linking fluidity to pouring and mold temperatures (G. Zou et al., 2022). The strong dependence of fluidity on thermal input in this study is further supported by spiral-test results showing that fluidity length rises markedly as pouring temperature increases and also increases with mold temperature, reinforcing that higher thermal head extends flow before solidification (de Medeiros et al., 2025; Wang et al., 2025). The fact that complete filling of the thinnest 2 mm section occurs only at 700°C agrees conceptually with the view that fluidity behaviour is not simply inversely proportional to the solidification interval, and that fluidity length can increase when solidus-related constraints are reduced in hypoeutectic *Al–Si* alloys (Niu et al., 2019; Song et al., 2020).

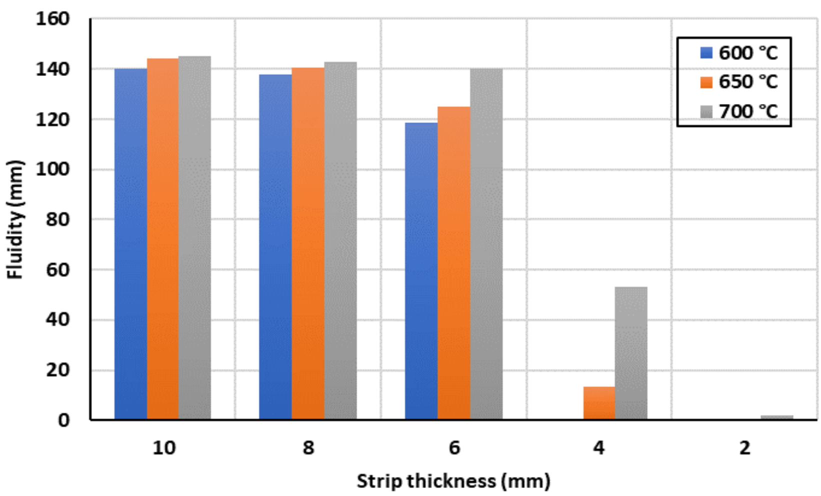


Figure 3. Fluidity of Al-Si Alloy at various pouring temperatures

The variation of fluidity length with strip thickness at each pouring temperature highlights the strong interaction between melt flow and heat extraction. For all pouring temperatures, fluidity decreases as strip thickness decreases, indicating that thinner sections impose more severe thermal gradients and accelerate solidification. At 600°C, the absence of flow in 4 mm and 2 mm strips indicates premature flow arrest caused by rapid heat loss and early dendritic network formation. At 650°C, partial filling of the 4 mm strip suggests that increased superheat is sufficient to delay solidification but remains inadequate for the thinnest section. At 700°C, the molten metal successfully flows through all strip thicknesses, demonstrating that sufficient thermal energy is available to overcome flow choking even under severe cooling conditions. This thickness-dependent behaviour agrees with flow-choking mechanisms reported under die casting conditions, where flow arrest occurs once the solid fraction reaches a critical threshold controlled by local cooling rate and section geometry (Campbell, 1988; Haga et al., 2021; Han & Zhang, 2020). The results further confirm that thin-wall castings require higher pouring temperatures to achieve complete filling, as widely reported in aluminium casting literature (Campbell, 1988; Niu et al., 2022).

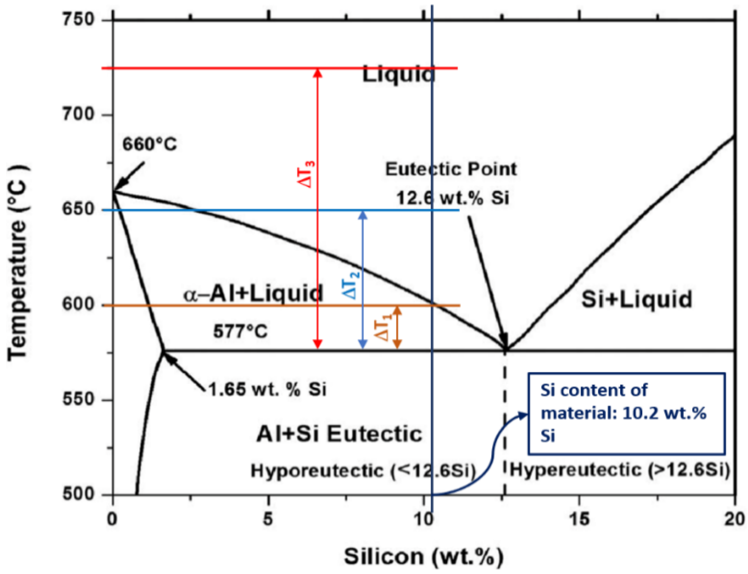


Figure 4. Phase diagram of Al-Si Alloy

The enhancement of fluidity with increasing pouring temperature is closely associated with changes in the solidification range of the alloy. The solidification ranges at pouring temperatures of 600°C, 650°C, and 700°C are 23°C (ΔT_1), 73°C (ΔT_2), and 123°C (ΔT_3), respectively, as shown in Figure 4. A wider solidification range implies a longer duration for the transformation from liquid to solid, allowing the molten metal to remain fluid for an extended period. At 600°C, the narrow solidification range promotes rapid dendrite interlocking, resulting in early flow arrest, particularly in thin sections. In contrast, at 700°C, the significantly wider solidification range prolongs the fluid life of the melt, enabling greater filling length and successful flow through all strip thicknesses. In addition, higher pouring temperatures reduce melt viscosity and surface tension, facilitating faster and longer flow within the mold cavity. The role of melt superheat—defined as the temperature difference between the pouring temperature and the liquidus temperature—is therefore critical, as numerous studies have shown a near-linear increase in fluidity with increasing melt temperature for aluminium alloys (Han, 2022; Niu et al., 2022; Vatankhah Barenji, 2022; G. T. Zou et al., 2020). These findings confirm that pouring temperature strongly governs fluidity through its combined influence on thermophysical properties and solidification kinetics.

Porosity

Figure 5 illustrates the influence of pouring temperature on the porosity of the Al–Si alloy at different strip thicknesses (10, 8, 6, and 4 mm). The results clearly demonstrate that porosity increases proportionally with increasing pouring temperature for all strip thicknesses. At a strip thickness of 10 mm, the porosity values are approximately 1.10% at 600°C, 1.85% at 650°C, and 2.30% at 700°C, indicating a strong temperature dependence of pore formation. A similar trend is observed for thinner sections, although the absolute porosity levels decrease with decreasing strip thickness. This temperature-dependent increase in porosity is consistent with previous studies reporting enhanced hydrogen solubility and prolonged liquid lifetime at higher pouring temperatures in *Al–Si* alloys (A. Samuel et al., 2021; G. T. Zou et al., 2020).

At a thickness of 8 mm, porosity decreases to approximately 0.38% at 600°C, while remaining relatively high at 1.50% at 650°C and 2.20% at

700°C. Further reduction in strip thickness to 6 mm results in porosity values of approximately 0.18%, 0.75%, and 1.60% at 600°C, 650°C, and 700°C, respectively. At the smallest thickness of 4 mm, porosity is not detected at 600°C, whereas values of approximately 0.55% at 650°C and 1.50% at 700°C are recorded. These results confirm that thicker casting strips consistently exhibit higher porosity content, reflecting the combined influence of section geometry and thermal conditions during solidification, as also reported in prior investigations on Al–Si cast alloys (A. Samuel et al., 2021; E. Samuel et al., 2025).

Figure 5 further demonstrates that porosity increases with increasing strip thickness at all pouring temperatures. Thicker strips consistently exhibit higher porosity than thinner ones, highlighting the strong influence of section geometry on porosity formation. This trend is associated with longer solidification times in thicker sections, which reduce cooling rates and limit effective interdendritic feeding during the final stages of solidification. Previous studies have reported a near-linear relationship between solidification time and porosity content in aluminium alloy castings, confirming that prolonged solidification promotes both shrinkage porosity and gas pore coalescence (A. Samuel et al., 2021; E. Samuel et al., 2025). Consequently, although pouring temperature plays an important role, strip thickness—through its effect on solidification time—exerts significant control on porosity evolution.

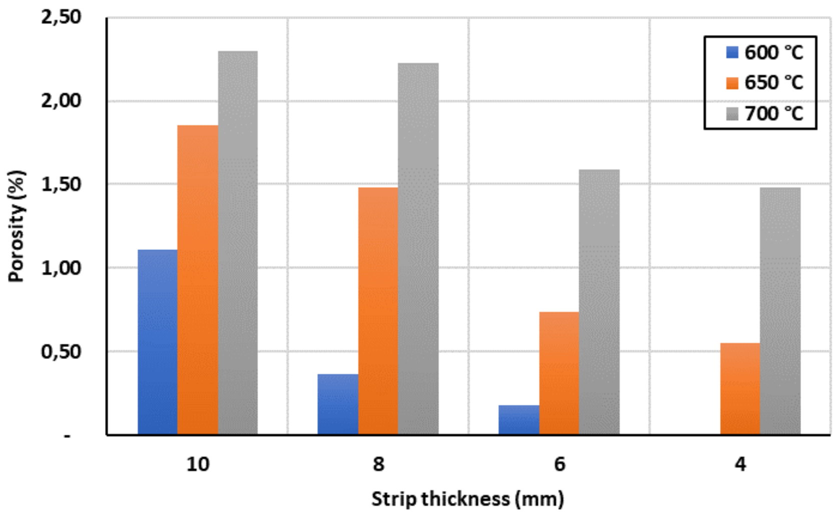


Figure 5. Porosity of Al-Si Alloy at various pouring temperatures

Although solidification time is a key thermal parameter influencing porosity formation, the results in Fig. 5 indicate that it cannot solely account for the magnitude and distribution of porosity in *Al–Si* alloy castings. Porosity development is governed by the combined effects of multiple thermal parameters, including cooling rate, thermal gradient, solidus front velocity, feeding behaviour, and their interactions during solidification. The observed increase in porosity with both pouring temperature and strip thickness suggests that an insufficient cooling rate plays a dominant role in pore formation. Therefore, to reduce porosity content and improve casting density and overall quality, it is essential to enhance cooling rate and optimize heat extraction conditions rather than relying on a single parameter such as solidification time. Similar conclusions have been reported in previous investigations emphasizing that porosity control in aluminium alloy castings requires integrated thermal management strategies (A. Samuel et al., 2021; E. Samuel et al., 2025; G. T. Zou et al., 2020).

The porosity response in Figure 5, where porosity varies with pouring temperature and thickness and can rise under prolonged solidification, is consistent with observations that higher thermal conditions increase solidification time, coarsen dendrites, enlarge interdendritic spacing, and increase porosity and shrinkage defects compared with lower thermal conditions (de Medeiros et al., 2025). The presence of shrinkage-related porosity in this work under certain thermal–feeding conditions is comparable to tomography-based evidence showing that large pores at 700°C in air-melted alloys reflect shrinkage porosity due to incomplete flow during solidification, even when the casting temperature is relatively high (Mathew et al., 2021).

Density

Figure 6 shows the variation in density of the *Al–Si* alloy cast at pouring temperatures of 600°C, 650°C, and 700°C for different strip thicknesses. A clear trend is observed in which density decreases with increasing pouring temperature at a given strip thickness. For instance, at a strip thickness of 10 mm, the density drops from about 2.67 g/cm³ at 600°C to 2.65 g/cm³ at 650°C and then to 2.64 g/cm³ at 700°C. Similar behaviour is evident at 8 mm and 6 mm thicknesses. This reduction in density at higher pouring temperatures is commonly associated with increased porosity formation due to higher hydrogen solubility and prolonged liquid lifetime before solidification, as widely reported for *Al–Si* alloy castings (A. Samuel et al., 2021; G. T. Zou et al., 2020).

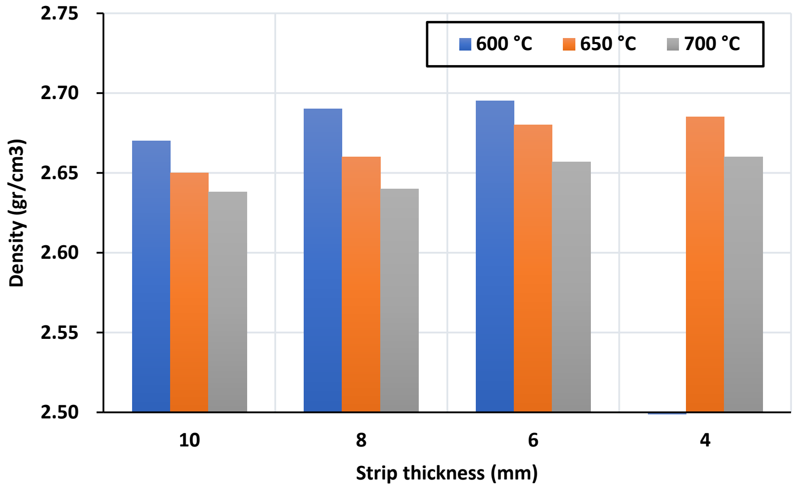


Figure 6. Density of Al-Si Alloy at various pouring temperatures

At a constant pouring temperature, Figure 6 indicates that density slightly increases with decreasing strip thickness. At 600°C, density increases from approximately 2.67 g/cm³ at 10 mm to 2.69 g/cm³ at 8 mm, reaching a maximum of ≈2.70 g/cm³ at 6 mm. A similar trend is observed at 650°C and 700°C. This behaviour is attributed to faster cooling rates in thinner sections, which reduce solidification time and suppress the formation of shrinkage and gas porosity. Previous studies have shown that reduced section thickness enhances heat extraction and feeding efficiency, resulting in higher density and improved internal soundness of aluminium alloy castings (A. Samuel et al., 2021; E. Samuel et al., 2025).

The density trends observed in Figure 6 are consistent with the porosity behaviour reported in Figure 5. Higher pouring temperatures and larger strip thicknesses promote increased porosity, which directly reduces the effective density of the castings. Since density is inversely related to the volume fraction of internal voids, the decrease in density at elevated pouring temperatures confirms that porosity is the dominant factor controlling densification in *Al–Si* alloy castings. Similar correlations between porosity content and density reduction have been extensively reported in the literature for *Al–Si* alloys solidified under low cooling rate (A. Samuel et al., 2021; E. Samuel et al., 2025). The observed inverse relationship between porosity and density is consistent with the principle that pore morphology and distribution govern severity, and with the mechanism that platelet-like intermetallic precipitation can restrict melt flow locally and promote shrinkage cavities when interdendritic feeding becomes obstructed (Ergün Songül & Dispinar, 2025; Khan et al., 2021; A. Samuel et al., 2021).

Although pouring temperature and strip thickness have a clear influence on density, the results in Figure 6 indicate that density is governed by the combined effects of multiple thermal parameters, including cooling rate, solidification time, thermal gradient, and feeding behaviour.

Higher pouring temperatures and thicker sections extend solidification time and reduce cooling rate, increasing the likelihood of shrinkage and gas porosity formation. Conversely, thinner sections solidify more rapidly, leading to improved feeding efficiency and higher density values. These observations support previous findings that achieving high density in aluminium alloy castings requires optimization of overall solidification conditions rather than control of a single processing parameter (E. Samuel et al., 2025; Yu et al., 2022). Therefore, enhancing the cooling rate and optimizing heat extraction remain essential strategies for improving the density and quality of *Al–Si* alloy castings.

Microstructure

Figure 7 shows the optical microstructures of the Al–Si alloy cast at pouring temperatures of 600°C, 650°C, and 700°C for two different strip thicknesses (6 mm and 10 mm). The as-cast microstructure is dominated by two primary phases: the bright α-Al phase, which forms the matrix of the alloy, and the dark *β-Si* phase, which is embedded within the aluminium matrix. In addition to these primary phases, secondary intermetallic phases identified as *Al–Si–Cu–Mg* compounds are observed to be dispersed at several locations within the microstructure. Such phase constituents are typical of Al–Si casting alloys and are known to play a decisive role in controlling mechanical properties and casting quality (Niu et al., 2022). The phase constitution observed in Figure 5 is consistent with previously reported microstructures of *Al–Si* alloys produced under conventional casting conditions (Al-Helal et al., 2012; Choudhary et al., 2024; Niu et al., 2022).

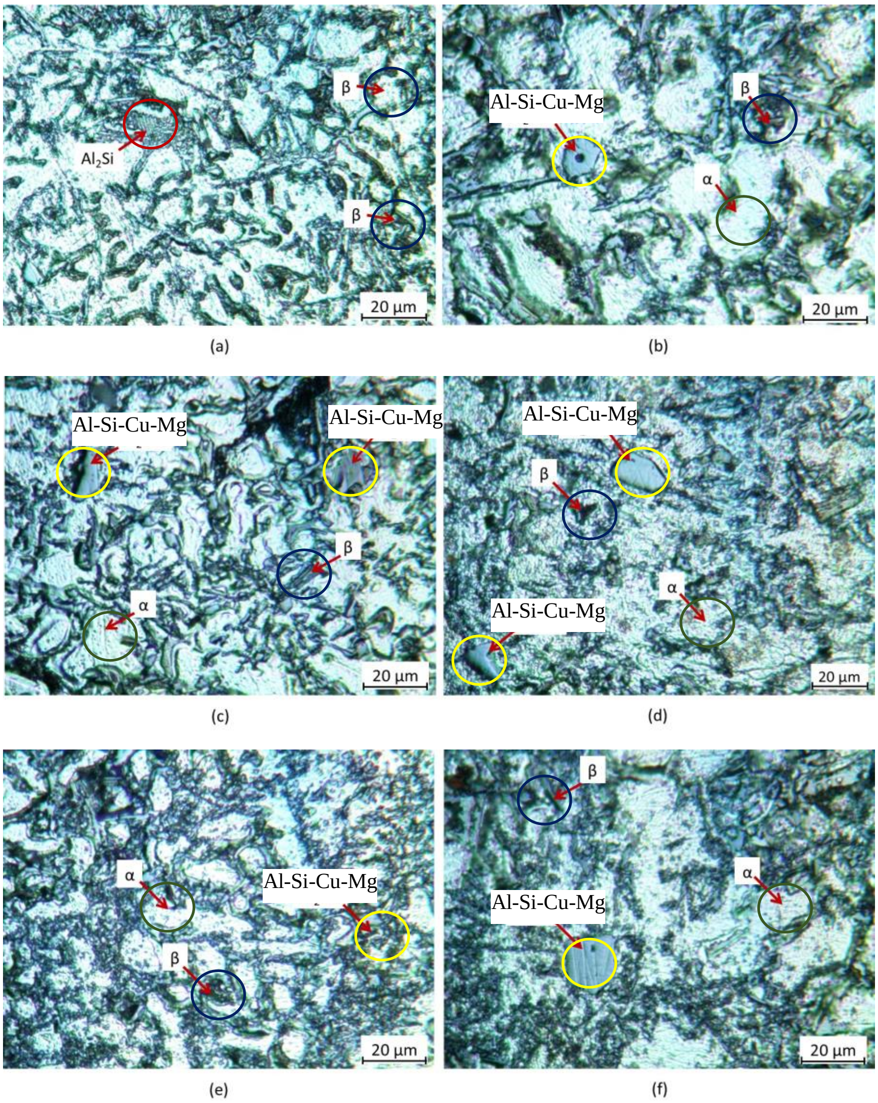


Fig. 7. Microstructure of specimen of Al-Si Alloy at various pouring temperatures of in two different casting thickness 650 °C [(a), (b)]; 600 °C [(c), (d)]; and 700 °C [(e), (f)].

A clear influence of the pouring temperature on microstructural refinement is evident in Figure 7. At a pouring temperature of 600°C, the primary α-Al grains and β-Si particles are relatively fine, and the *Al–Si–Cu–Mg* intermetallic phases are more uniformly distributed within the matrix. When the pouring temperature is increased to 650°C and 700°C, the microstructure becomes progressively coarser, characterized by larger *α-Al* dendrites, coarser *β-Si* particles, and aggregation of the secondary intermetallic phases. This microstructural coarsening is attributed to a decrease in solidification rate and cooling rate at higher pouring temperatures, which allows extended time for grain growth and elemental segregation. Similar temperature-dependent coarsening of *α-Al* and *β-Si* phases has been widely reported in *Al-Si* alloys and is commonly associated with slower heat extraction and prolonged solidification intervals (Ferreira et al., 2019; Han, 2022; Jahangiri et al., 2017), (G. T. Zou et al., 2020).

Figure 7 further reveals that casting thickness strongly affects microstructural refinement. For a given pouring temperature, the 10 mm thick sections exhibit coarser *α-Al* grains, larger *β-Si* particles, and more pronounced dendritic structures compared with the 6 mm thick sections. This behaviour is directly related to the slower cooling rate and longer solidification time in thicker sections, which promote grain coarsening and silicon particle growth. In contrast, thinner sections experience faster heat extraction, resulting in finer dendrites, smaller silicon particles, and a more homogeneous microstructure. These observations are consistent with established solidification theory for *Al–Si* alloys, where increased cooling rate is known to refine grain size and suppress excessive silicon growth (Chen & Li, 2024b; A. Samuel et al., 2021; E. Samuel et al., 2025).

The combined effects of pouring temperature and strip thickness on microstructural evolution have important implications for casting quality. Coarser *α-Al* dendrites, larger *β-Si* particles, and aggregated intermetallic phases observed at higher pouring temperatures and larger thicknesses are generally associated with reduced mechanical performance and increased susceptibility to porosity formation. Conversely, the finer and more homogeneous microstructures obtained at lower pouring temperatures and thinner sections are favourable for improved mechanical properties, although excessively low pouring temperatures may result in incomplete mold filling and increased internal stresses (G. Zou et al., 2022; G. T. Zou et al., 2020). These results confirm that microstructure in *Al–Si* alloy castings is governed by the combined influence of pouring temperature and cooling rate, and that optimal casting quality requires a balanced control of thermal conditions rather than reliance on a single processing parameter (Jin et al., 2020; G. T. Zou et al., 2020). Therefore, improving cooling rate and optimizing heat extraction remain essential strategies for achieving dense and high-quality *Al–Si* alloy castings.

Coupled Influence of Pouring Temperature and Strip Thickness on Fluidity, Microstructure, Porosity, and Density of Al–Si Alloy Castings

The combined analysis of fluidity (Figure 3), microstructure (Figure 7), porosity (Figure 5), and density (Figure 6) demonstrates that pouring temperature and strip thickness exert a coupled and competing influence on the solidification behaviour and quality of the *Al–Si* alloy. Increasing the pouring temperature from 600°C to 700°C significantly enhances fluidity, enabling the molten alloy to fill progressively thinner sections, with complete filling of all strip thicknesses achieved only at 700°C. This improvement in fluidity is attributed to increased melt superheat, reduced viscosity and surface tension, and delayed dendrite coherency, which extend the available flow time prior to solidification (Han, 2022; Niu et al., 2022; G. Zou et al., 2022).

However, the enhanced fluidity at higher pouring temperatures is accompanied by pronounced microstructural coarsening, as observed in Figure 7. At 600°C, the microstructure is characterized by finer primary α-Al grains and smaller *β-Si* particles, with *Al–Si–Cu–Mg* intermetallic phases distributed more uniformly. In contrast, pouring temperatures of 650°C and 700°C lead to coarser *α-Al* dendrites, larger and more irregular *β-Si* particles, and aggregation of intermetallic phases. This microstructural evolution is a direct consequence of reduced solidification rate and prolonged solidification time at higher pouring temperatures, which allow extensive grain growth and elemental segregation (Han, 2022; Niu et al., 2022; G. T. Zou et al., 2020).

Strip thickness further modulates these effects. Thicker sections (10 mm) exhibit slower cooling rates and longer solidification times than thinner sections (6 mm), resulting in coarser grains, larger silicon particles, and more pronounced dendritic structures. Conversely, thinner sections solidify more rapidly, producing finer dendrites and a more homogeneous microstructure. These observations are consistent with well-established solidification principles for Al–Si alloys, where cooling rate strongly governs grain size, silicon morphology, and intermetallic distribution (A. Samuel et al., 2021; Zhang, Wang, Zhou, et al., 2021).

The microstructural coarsening observed at higher pouring temperatures and greater strip thickness directly correlates with the porosity behaviour shown in Figure 5. Porosity increases with both pouring temperature and strip thickness, reflecting the combined effects of increased hydrogen solubility at elevated temperatures and reduced feeding efficiency during prolonged solidification. Coarser dendritic networks restrict interdendritic feeding and promote shrinkage porosity, while slower cooling facilitates gas pore growth and coalescence (A. Samuel et al., 2021; G. T. Zou et al., 2020). This phenomenon explains why improved fluidity does not translate into improved internal soundness at higher pouring temperatures.

The influence of porosity is clearly reflected in the density results presented in Figure 6. Density decreases with increasing pouring temperature at a given strip thickness and slightly increases with decreasing strip thickness. For example, the highest density values are obtained at 600°C and moderate thicknesses, where porosity is minimized and microstructural refinement is maximized. Since density is inversely related to the volume fraction of internal voids, these trends confirm that porosity—rather than incomplete filling—is the dominant factor governing densification in the present *Al–Si* alloy castings (A. Samuel et al., 2021; E. Samuel et al., 2025).

Overall, the integrated results reveal a fundamental trade-off inherent to aluminium alloy casting. Higher pouring temperatures improve fluidity and ensure complete mold filling, particularly in thin-wall sections, but simultaneously promote microstructural coarsening, increased porosity, and reduced density. Lower pouring temperatures favour finer microstructures, reduced porosity, and higher density but may lead to insufficient fluidity and incomplete filling. Therefore, optimal casting quality in Al–Si alloys requires a balanced process window in which pouring temperature and section thickness are carefully optimized to achieve sufficient fluidity while maintaining refined microstructure, low porosity, and high density. This conclusion is fully consistent with established findings in aluminium casting literature and highlights the necessity of integrated thermal and solidification control rather than reliance on fluidity enhancement alone (Niu et al., 2022; A. Samuel et al., 2021; G. Zou et al., 2022).

CONCLUSION

This study systematically investigated the influence of pouring temperature on the fluidity, porosity, density, and microstructure of an Al–Si alloy cast using a gravity iron die mold with varying strip thicknesses. Based on the experimental results and integrated analysis, the following conclusions can be drawn.

First, pouring temperature was identified as a dominant parameter governing the fluidity behaviour of the *Al–Si* alloy. Increasing the pouring temperature from 600°C to 700°C resulted in a significant increase in total fluidity length, enabling complete filling of progressively thinner sections. Complete flow through all strip thicknesses, including the thinnest 2 mm section, was achieved only at 700°C, confirming that sufficient melt superheat is essential to overcome rapid heat extraction and flow arrest in thin-wall castings.

Second, the enhancement in fluidity at higher pouring temperatures was accompanied by a systematic increase in porosity. Porosity increased with both pouring temperature and strip thickness, indicating that prolonged liquid lifetime and reduced cooling rate promote gas pore growth and shrinkage porosity formation. Thicker sections consistently exhibited higher porosity due to longer solidification times and limited interdendritic feeding, whereas thinner sections benefited from faster cooling and reduced pore formation.

Third, density measurements showed an inverse relationship with porosity. Density decreased with increasing pouring temperature at a given strip thickness and increased slightly with decreasing thickness. These results confirm that porosity is the primary factor controlling densification in Al–Si alloy castings under the present conditions, rather than incomplete mold filling.

Fourth, microstructural observations revealed that pouring temperature and strip thickness strongly influence phase morphology and grain size. Lower pouring temperatures and thinner sections produced finer α*-Al* grains, small β*-Si* particles, and a more homogeneous distribution of *Al–Si–Cu–Mg* intermetallic phases. In contrast, higher pouring temperatures and thicker sections led to coarser dendritic structures, larger silicon particles, and increased phase segregation, which are detrimental to casting quality.

Overall, the results demonstrate a fundamental trade-off between fluidity and internal quality in gravity die casting of Al–Si alloys. Higher pouring temperatures make it easier for the mold to fill, but they also make the microstructure coarser, the porosity higher, and the density lower. Therefore, optimal casting quality cannot be achieved by maximizing fluidity alone. Instead, a balanced processing window must be established in which pouring temperature and section thickness are carefully optimized to ensure adequate fluidity while maintaining refined microstructure, minimal porosity, and high density. These findings provide practical guidance for the production of high-quality, thin-walled Al–Si alloy castings in gravity die casting applications.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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