e-ISSN: 3104-3860
المجلد الأول، العدد الثالث، 2025

Effect of Mould Preheating on the Quality of Re-melt Aluminum Alloy Cylinder Blocks: Experimental and Simulation Study

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دراسة تأثير إعادة تسخين قالب السباكة على جودة المنتج المصنع من سبيكة الألومنيوم المعاد تدويرها والمستخدمة في تصنيع كتلة الأسطوانات لمحرك الاحتراق الداخلي: دراسة معملية ومحاكاة

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Received: 20-04-2025; Accepted: 17-06-2025; Published: 14-07-2025

Abstract

This study investigates the effect of mold preheating on mold filling, cooling behavior, and defect formation during the casting process of recycled aluminum silicon alloy, and the experimental was combined with simulation using ProCAST software. The results showed that pouring molten metal into an unheated mold result in significant defects, such as misruns and incomplete sections. The primary cause is the rapid heat loss from the molten metal to the cold mold walls, leading to premature solidification and incomplete cavity filling, achieving only 52.8% fill in the unheated case. On the other hand, preheating the mold to 250 °C resulted in nearly complete filling (98%) due to reduced thermal gradients, slower cooling rates (starting from –714 K/s), and more uniform solidification. Simulation results confirmed the experimental findings, illustrating the detrimental effects of rapid solidification in cold molds, including high cooling rates (up to –2000 K/s) and extensive shrinkage porosity, especially in central and upper regions of the casting. Overall, the findings highlight that mold preheating is a vital parameter in casting aluminum alloys, improving surface finish, dimensional accuracy, and mechanical performance by ensuring complete mold filling and minimizing solidification-related defects such as misruns and porosity.

Keywords: Aluminum alloys, Casting, Preheating, Simulation

الملخص

في هذه البحث تمت دراسة تأثير تسخين قالب السباكة على جودة المنتج المسبوك من حيث ملئ القالب وسلوك عملية تدفق المصهور ومعدل تبريده. أجريت هذه الدراسة على سبيكة الألومنيوم سيلكون المستخدمة في تصنيع كتلة الأسطوانات لمحرك الاحتراق الداخلي حيث تم إعادة تدويرها (صهرها). أجريت الدراسة بطريقة معملية وكذلك بطريقة المحاكاة باستخدام برنامج ProCAST. بينت النتائج عدم امتلاء القالب الذي لم نقم بتسخينه قبل عملية الصب، وذلك بسبب معدلات التبريد السريعة عند جدار القالب البارد والذي أدى الي تصلب المصهور بشكل سريع قبل اكتمال امتلاء القالب محققا نسبة امتلاء 52% تقريبا من حجم القالب. ومن ناحية أخرى عند صب المصهور في قالب تم تسخينه مسبقا لاحظنا امتلاء القالب بالكامل تقريبا وبنسبة 98 % مشكلا الجزء المراد تصنيعه، وبمعدل تبريد للمصهور ابطئ من السابق والذي سمح بتدفقه خلال مجرى القالب. اكدت عملية المحاكاة نتيجة التجربة المعملية وكذلك حدد معدلات التبريد في كلتا الحالتين، ووضحت التصلب السريع للمصهور خاصة عند جدران القالب الباردة وبمعدل تبريد سريع جدا حوالي – 2000 K/s ، كما وضحت الصور المتحصل عليها من برنامج المحاكاة تكون حالة الانكماش المسامي في هذه الحالة خاصة في المنطقة المركزية العليا للمسبوك. لخص البحث أهمية تسخين القالب قبل اجراء عملية السباكة لسبيكة الألومنيوم سيلكون مما يضمن اكتمال امتلاء القالب كما يحسن الخواص الميكانيكية للمنتج وذلك بضمان عدم تكون العيوب المجهرية الناتجة من التصلب السريع مثل المسامية.

الكلمات الدالة: أعادة تسخين القالب، سباكة المعادن، سبائك الألومنيوم، محاكاة

1. Introduction

Aluminium alloys are the preferred material for pistons in both gasoline and diesel engines due to their specific characteristics: low density, high thermal conductivity, simple net-shape fabrication techniques (casting and forging), easy machinability, high reliability, and very good recycling characteristics. Al-Si casting alloys are chosen often to produce engine parts due to their great castability, where silicon plays an important role particularly having high thermal properties increases the fluidity (Davis, 1993; Stefanescu, Davis, & Destefani, 1988).

The demand for sustainable metal casting practices has led to a growing interest in the recycling and reuse of automotive components, particularly aluminum-based engine parts. Now a day's most of engine parts commonly manufactured from aluminum-silicon alloys such as pistons, cylinder blocks, etc., are frequently recast to reduce material waste and extend the lifecycle of automotive components (Kermanidis, 2020). Among the critical parameters influencing the quality of recast components is mold temperature, which directly affects defect formation, incomplete filling, porosity, and shrinkage. It also influences the microstructure, surface finish, and dimensional accuracy of the final component. Low fluidity in the liquid metal makes it becomechallenging to fill complex casting moulds, particularly those with thin parts. Defects like short runs or miss-runs are caused by poor fluidity, which makes it difficult for the molten metal to flow fully and precisely fill the mould cavity, especially in the thin areas (Campbell, 2015). Mould preheating has been widely recognized as a technique to enhance metal flow, reduce thermal shock, and minimize casting defects such as shrinkage porosity, cold shuts, and miss-runs. It plays a pivotal role in improving the metallurgical bonding between the molten metal and the mould surface, thus ensuring higher integrity of the final casting (Ingle & Sorte, 2017). Previous studies have explored the thermal interaction between molten metal and mould surfaces. Akhyar et al. (Akhyar, Ali, & Pahlevi, 2025) emphasized that preheating reduces the rate of solidification, leading to more uniform structures and minimizing internal stresses, they also demonstrated through experimental technique that increasing mould temperature up to 250 °C led to a more homogeneous temperature field, reducing casting defects and improving overall mechanical performance. Gunasegaram et al. (Gunasegaram, Farnsworth, & Nguyen, 2009) reported a significant reduction in shrinkage porosity when preheating permanent moulds for aluminium-silicon alloys at temperatures 365 °C. On the other hand, excessive preheating of the mould can lead to grain coarsening and undesirable microstructural evolution, especially in aluminium-silicon alloys where controlled solidification is crucial (LI ET AL., 2023; TEFERI, KOLHE, TSEGAW, & FATOBA, 2025; VLACH & CAIS, 2022). Moreover, computational modelling has become an indispensable tool for predicting the behaviour of metal during solidification. Finite Element Method (FEM)-based tools such as ProCAST enable visualization of temperature gradients, flow patterns, and defect locations in complex castings, helping optimize mold and process parameters before actual production (KHAN & SHEIKH, 2016).

In this study, a consumed cylinder block was repurposed and melted to make an engine core plug. Casting was conducted under two conditions: without mold preheating (room temperature) and with preheating. The effects of mold temperature on casting quality were analyzed by comparing physical casting defects and porosity, identified using optical microscopy, as well as measuring the dimensional shrinkage ratio. Furthermore, the study incorporated numerical simulations using ProCAST software to evaluate the solidification behavior and predict defect distribution for both casting conditions. By combining experimental and computational approaches, the work aims to provide insights into the influence of mold preheating on casting quality and to validate simulation tools in replicating real casting outcomes. The study contributes to the optimization of casting parameters in aluminum alloy recycling processes and offers practical implications for industries seeking to reuse and remanufacture automotive engine components with improved consistency and performance.

2. Experimental Procedure and Simulation

A consumed car engine cylinder block of Chevrolet Optra 2008 was used in the present study as a material alloy. The chemical composition of the alloy was determined using FOUNDARY-MASTER Pro emission spark spectrometer. Table 1 shows the chemical composition of the cylinder block alloy. The steel permanent mold is designed and drawn according to a core plug readymade from a Chevrolet Optra 2008 car, as shown in Figure 1, using SolidWorks 2024 software.

Table 1. Chemical composition of the cylinder block alloy

Element	Cr	Zn	Mg	Mn	Cu	Fe	Si	AL
Wt.%	`0.0260	0.714	0.257	0.151	2.59	0.762	11.5	Bal.

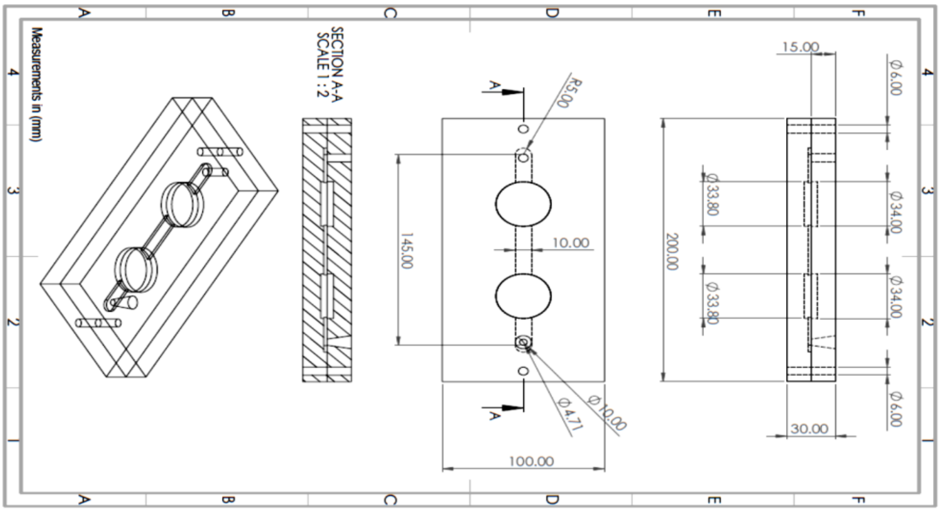

Figure 1. Mold design drawing.

The mould was fabricated from steel, via milling machine, which is shown in Figure 3. The block was cut into small pieces, then melted in an electrical furnace equipped with a graphite crucible, and then poured into the mould at 790 ^{o}C, at room temperature without preheating the mould, and then with preheat the mould at 250 ^{o}C. Furthermore, defect analysis was performed to identify the various casting defects, porosity was conducted via optical microscope, and shrinkage ratio of product was measured. The casting components were fabricated three times with 6 components in each trail. Due to the experimental design, two types of results were obtained (with and without mould preheating). The experimental results were compared with the simulation results of casting processes using ProCAST 2022 software, for both casting conditions, with and without preheating the mold.

Figure 2. The fabricated mould.

3. Results and Discussion

The first sample of casting, without preheat the mold showed incomplete molten metal into the mould, as shown in Figure 3.

Figure 3. Pouring without preheat the mold (incomplete filling).

Pouring molten metal into a mould without preheating can lead to incomplete filling of the mould cavity, resulting in a "Misrun" or "incomplete casting". This occurs because the cold mould causes the molten metal to cool and solidify prematurely, preventing it from completely filling the mould's intricate details. A cold mold absorbs heat from the molten metal, causing it to cool and solidify faster than it would in a preheated mold. This rapid cooling can lead to the metal freezing before it can reach all parts of the mold cavity, particularly thin sections or intricate details. The result is a casting that is not fully formed, with missing sections or rounded edges where the metal solidified before filling the mold completely, called Misrun Defect (Papanikolaou & Saxena, 2021). Preheating the mold helps to mitigate this issue by reducing the temperature difference between the molten metal and the mold, allowing for more complete filling and a sounder casting, as we can see in Figure 4, after preheating the mould up to 250 °C, the molten metal was infill the whole cavities. Therefore, preheating the mold is a crucial step in metal casting to ensure proper mold filling and prevent defects like Misruns.

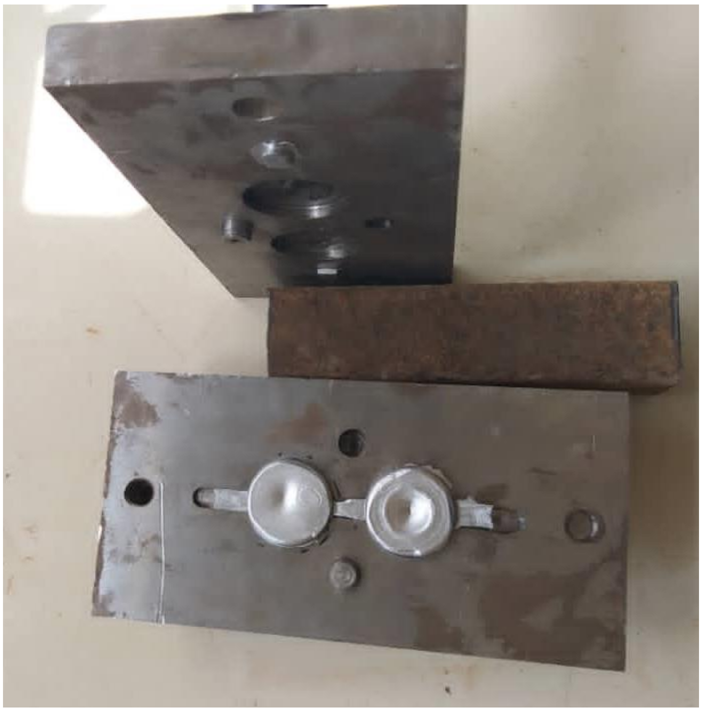

Figure 4. Complete filling after pouring the molten metal into the preheated mold.

The experimental results were confirmed via simulation, as shown in Figure 5, the cooling rate of molten metal during solidification for both situations, (a) without preheat (incomplete filling), and (b) preheat (completely filling).

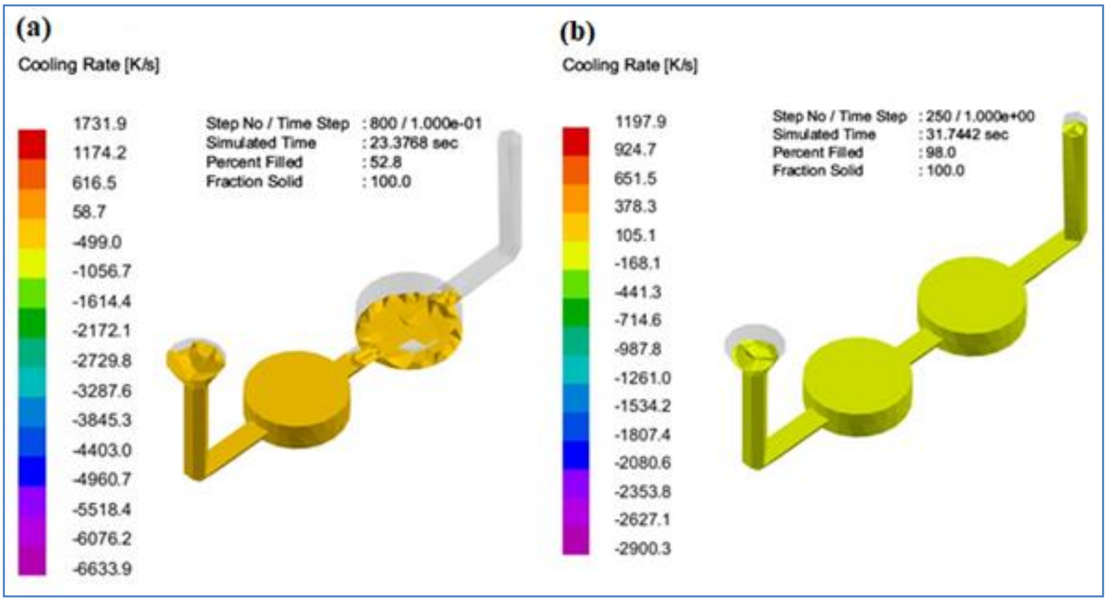

Figure 5. Cooling rate of the molten into the unheated mold.

The results clearly demonstrate the significant influence of mold preheating on the cooling behavior and overall quality of the casting process. In the case where the mold was not preheated, the molten alloy experienced extremely rapid cooling upon contact with the cold mold walls. This is evident from the high negative cooling rate values (around - 2000 K/s) observed in the simulation. Such rapid cooling induces immediate solidification at the mold-metal interface, which can obstruct the flow of the remaining molten into the mold cavity. Consequently, the mold filling was incomplete (only 52.8% filled), and the final solidified part is expected to contain serious defects such as cold shuts, Misruns, and incomplete sections. The rapid formation of a solidified shell at the metal–mold interface can result in premature freezing, thereby preventing complete mold filling and promoting surface discontinuities (Campbell, 2015). Furthermore, (Ravi, 2005) emphasized that in permanent mold casting, the mold's thermal state directly affects the casting fluidity and internal quality. When casting is done in an unheated mold, there is insufficient time for the molten metal to fully conform to the cavity shape before solidifying, leading to dimensional inaccuracies and increased porosity risk. Otherwise, the casting simulation with mold preheating at 250 °C, revealed a vastly improved outcome. The metal showed more uniform cooling (cooling rate starting from - 714 K/s), and the mold cavity was nearly completely filled (98% filled). Preheating the mold reduces the temperature gradient between the molten metal and the mold wall, slowing down the heat transfer rate and allowing the molten metal to flow more smoothly and reach all areas of the mold before the onset of solidification.

Preheated moulds before casting processes enhance the castability of aluminum alloys and lead to improved surface finish and dimensional accuracy. Moreover, the controlled solidification conditions improve microstructural homogeneity, reduce internal stresses, and reduce shrinkage porosity (de Medeiros et al., 2025). The simulation of shrinkage porosity further reinforces the critical influence of mold thermal conditions on casting quality, Figure 6. In the non-preheated mold condition, significant levels of shrinkage porosity are observed, particularly concentrated in the central and upper regions of the casting cavity (with around 40 %), which indicates severe void formation. These voids result from inadequate feeding of the solidifying metal due to early solid skin formation caused by rapid heat extraction into the cold mold, and the mold extracts heat very quickly from the molten alloy, leading to localized early solidification. This restricts the ability of the remaining liquid metal to flow and compensate for volumetric contraction that occurs during solidification, thus forming shrinkage cavities (Campbell, 2015). It has been reported that the lower mold temperatures drastically increase the likelihood of shrinkage porosity, especially in areas distant from the gating system or risers (He & Chen, 2022), and the insufficient feeding leads to poor metallurgical integrity and significantly affects the mechanical performance of the final component. In contrast counterpart simulation with mold preheating exists; it is well-established that preheating the mold improves the feeding of molten metal during the final stages of solidification, which allows the molten alloy to flow into areas undergoing contraction, thereby minimizing shrinkage-related defects, Figure 6 (b). In addition, mould preheating reduces the thermal gradient between the mold and the metal, extending the time available for feeding and enabling more controlled and directional solidification. Shrinkage defects can significantly impair the mechanical properties of the casting products, especially in applications requiring pressure resistance or structural load-bearing. Therefore, preheating the mold proves to be a critical parameter for controlling shrinkage porosity and ensuring higher casting quality.

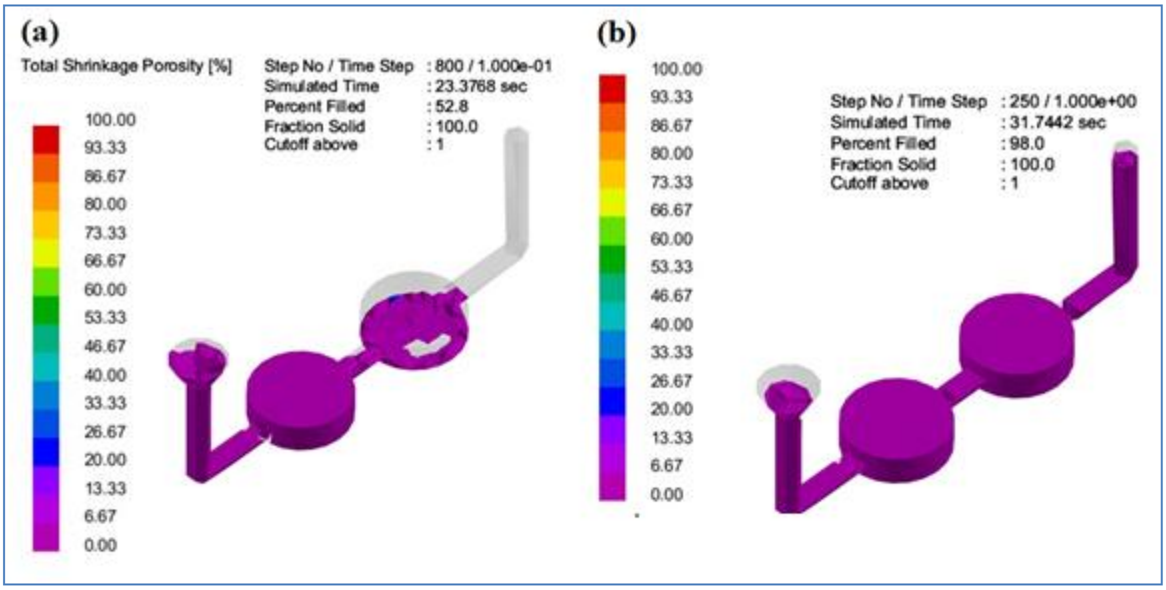

Figure 6. Total shrinkage porosity of: (a) unheated mold. 2; (b) preheated mold.

Furthermore, mould temperature control is essential in aluminum alloys casting to manage dendrite formation, grain size, and porosity. A mold that is too cold results in fine dendrite structures with higher brittleness and potential shrinkage cavities. In contrast, moderate preheating promotes the formation of a more uniform grain structure and reduces the formation of solidification-related defects (Sigworth, 2011).

Comparison Between Preheated and Non-Preheated Conditions

The table below shows the main results extracted from the study for both metal pouring conditions (with and without mold preheating):

Table 2. Comparison Between Preheated and Non-Preheated Conditions

Property / Condition	Without Mold Preheating	With Mold Preheating (250°C)
Filling Rate	52.8%	98%
Cooling Rate	Up to -2000 K/s	Starts from -714 K/s
Shrinkage Porosity	Around 40% (central and upper regions)	Low / Improved
Common Defects	Misruns, incomplete sections, shrinkage porosity	Fewer defects, improved surface finish and dimensional accuracy

4. Conclusion

Both the visual evidence from experimental and simulation established literature converge on the conclusion that mold preheating is essential for enhancing mold filling, reducing casting defects, and improving the overall quality of cast aluminum components. In addition, the experimental observations confirmed the simulation predictions, with castings from preheated moulds exhibiting better surface finish, fewer porosity defects under microscopy, and more consistent shrinkage measurements.

Recommendations

Based on the results, it is strongly recommended to apply mold preheating as an essential step in aluminum alloy casting processes, especially when recycling engine cylinder blocks. To ensure the best product quality, the following should be considered:

Optimal Preheating Temperature: This study found that 250°C was highly effective in achieving nearly complete mold filling and reducing defects. However, further research should be conducted to precisely determine the optimal temperature, as excessive heating can lead to grain coarsening and undesirable microstructural developments.

Precise Heating Control: Uniform mold heating must be ensured to avoid localized thermal gradients that could affect casting quality.

Leveraging Simulation: The use of simulation software like ProCAST has proven effective in predicting solidification behavior and defect distribution, allowing for optimization of mold design and process parameters before actual production. Simulation can help identify the best preheating conditions for different mold geometries and metals.

Continued Research: Research should continue to improve aluminum alloy recycling processes, focusing on the impact of other variables such as pouring temperature, pouring rate, and gating system design to further enhance casting quality and reduce waste.

Training and Best Practices: Foundry workers should be trained on the importance of mold preheating and its techniques, and encouraged to apply industrial best practices to ensure consistent production of high-quality products.

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