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EXPERIMENTAL STUDY ON MOLD HEATING TEMPERATURE AND TIME VARIATIONS IN LOST WAX CASTING OF PROPELLER FOR UNMANNED SURFACE VEHICLE

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Abstract. The increasing demand for high-performance propulsion systems in unmanned surface vehicles (USVs) requires propellers with high dimensional accuracy, minimal defects, and superior surface quality. Lost wax casting enables the production of complex propeller geometries; however, casting quality is strongly influenced by mold heating parameters during the burnout stage. This study investigates the effect of mold heating temperature and holding time on surface defects, density, and dimensional shrinkage of Aluminum 6061 propellers produced by the lost wax casting process. An experimental method was applied using three mold heating temperatures (660°C, 710°C, and 760°C) and three holding time variations (60–70 minutes, 120–130 minutes, and 180–190 minutes). Surface quality was evaluated through dye penetrant testing, internal integrity was assessed using density measurement based on the Archimedes principle, and dimensional accuracy was determined through shrinkage analysis. The results indicate that insufficient preheating at 660°C caused significant surface porosity, lower density, and higher shrinkage due to incomplete wax burnout. Increasing the temperature to 710°C significantly improved casting quality, with the holding time of 120–130 minutes producing minimal surface defects, relatively high density, and reduced shrinkage. Although 760°C yielded high density and low shrinkage at longer holding times, excessive thermal exposure indicated potential mold degradation. It can be concluded that a mold heating temperature of 710°C with a holding time of 120–130 minutes provides the most balanced and optimal condition for producing Aluminum 6061 propellers with improved surface integrity, internal soundness, and dimensional stability suitable for USV applications.

Keywords: Lost Wax Casting; Mold Heating Temperature; Holding Time; Aluminum 6061; Propeller Casting

1 Introduction

The rapid development of unmanned surface vehicles (USVs) has increased the demand for high-performance propulsion components, particularly propellers with complex geometry, high dimensional accuracy, and superior surface quality. As a critical component of propulsion systems, propellers directly influence hydrodynamic efficiency, vibration characteristics, and operational reliability of USVs. To meet these requirements, manufacturing methods capable of producing intricate shapes with minimal post-processing are essential. Lost wax casting, also known as investment casting, has been widely adopted for this purpose due to its ability to produce near-net-shape components with excellent surface finish and dimensional precision [1], [2].

Previous studies have demonstrated that the quality of cast products in lost wax casting is strongly influenced by process parameters during the mold heating or burnout stage. Parameters such as heating temperature, heating rate, and holding time significantly affect the removal of wax residues, oxidation of carbon

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deposits, and the mechanical strength of ceramic molds. Inadequate burnout conditions may lead to various casting defects, including porosity, surface roughness, carbon inclusions, and dimensional inaccuracies [3], [4]. Research on aluminum alloy castings has shown that improper burnout temperatures or insufficient holding times can result in incomplete wax removal and trapped gases, which subsequently degrade casting integrity and mechanical performance [5].

Several researchers have investigated the effect of burnout temperature on surface quality and porosity in investment casting of aluminum components. Studies on impellers and small marine components indicate that higher burnout temperatures generally improve mold cleanliness and reduce surface defects; however, excessively high temperatures may weaken gypsum-based molds and increase the risk of shell cracking [6], [7]. Other studies emphasize the role of holding time in ensuring complete oxidation of residual wax and stabilization of mold structure prior to pouring [8]. Despite these findings, most existing studies focus on generic cast geometries or industrial components such as pump impellers and structural parts, rather than propellers with thin blades and complex curvature [9].

Based on the current literature, a clear research gap can be identified. There is limited experimental research that simultaneously evaluates the combined effect of mold heating temperature and holding time on multiple quality indicators—namely surface defects, internal porosity, density, and dimensional shrinkage—specifically for aluminum 6061 propellers produced by lost wax casting. Moreover, comprehensive assessments that integrate non-destructive testing methods, such as dye penetrant inspection, with density measurement and shrinkage analysis remain scarce, particularly in the context of manufacturing propellers for unmanned fast boats [10], [11].

The novelty of this study lies in its systematic investigation of the interaction between mold heating temperature and holding time during the burnout stage and their influence on casting defects, density, and shrinkage of aluminum 6061 propellers. Unlike previous studies that focus on a single quality parameter, this research employs a combined evaluation approach using dye penetrant testing, Archimedes density measurement, and dimensional shrinkage analysis to provide a more holistic assessment of casting quality. Furthermore, the study is specifically oriented toward propeller manufacturing for USV applications, where dimensional accuracy and surface integrity are particularly critical [9], [12].

Therefore, the objectives of this research are to analyze the effect of mold heating temperature on surface defects of aluminum 6061 propeller castings using dye penetrant testing, to evaluate the influence of heating temperature and holding time on internal porosity and dimensional shrinkage through density and shrinkage measurements, and to determine the optimal combination of mold heating temperature and holding time that produces propellers with minimal defects, high density, and low shrinkage suitable for unmanned surface vehicle applications.

2 Method

This study employed an experimental research method to investigate the effect of mold heating temperature and holding time on casting defects, density, and dimensional shrinkage of aluminum 6061 propellers manufactured using the lost wax casting process.

2.1 Material and equipment

The material used in this study was aluminum alloy 6061, which is widely applied in marine and propulsion components due to its favorable mechanical properties, corrosion resistance, and relatively low density. Aluminum 6061 is particularly suitable for unmanned surface vehicle (USV) propellers because it offers a good balance between strength and weight while maintaining acceptable castability [9] ,[13]. Wax granules were used to fabricate wax patterns, while silicone rubber molds were employed to ensure accurate replication of the propeller geometry. The investment mold material consisted of gypsum-based investment powder specifically designed for lost wax casting applications, mixed with water at a ratio of 2.6:1, as recommended for achieving adequate mold strength and surface detail [14].

The primary equipment used in this study included an electric furnace for mold heating and burnout, a crucible furnace for aluminum melting, a vacuum chamber for mold preparation and metal pouring, digital weighing scales for density measurements, and standard dye penetrant testing kits for surface defect inspection. Dimensional measurements were performed using precision measuring tools to evaluate shrinkage after casting.

2.2 Wax pattern and mold preparation

The experimental procedure began with the fabrication of a master propeller pattern, which was used to create silicone rubber molds. Wax granules were melted and poured into the silicone molds to produce wax patterns with identical geometry and dimensions. Multiple wax patterns were assembled into a pattern assembly using a sprue with a diameter of 10 mm and a length of 9 cm, and runners with a diameter of 4 mm and a length of 2 cm to ensure consistent metal flow during pouring.

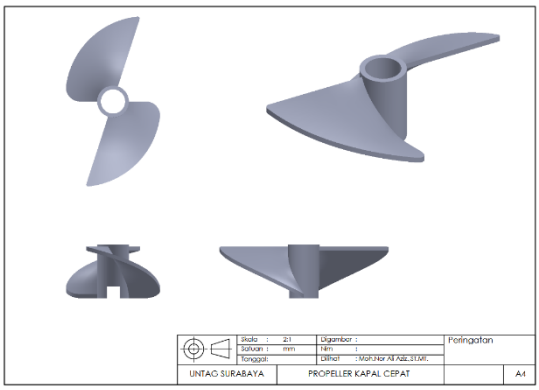


Fig. 1. Master pattern geometry modeled in SolidWorks as a reference for the manufacturing process.



Fig. 2. Silicone rubber mold utilized for forming wax master patterns in the invesment casting process.

The assembled wax patterns were placed inside a flask, after which the investment slurry was poured under vacuum conditions at a pressure of 5 bar for approximately 3 minutes to minimize air entrapment within the mold. The molds were then allowed to set and harden at room temperature before proceeding to the dewaxing and burnout stages.

2.3 Mold heating

Mold heating was conducted using an electric furnace with controlled temperature settings. The molds were subjected to three different heating temperatures: 660°C, 710°C, and 760°C. For each temperature level, three holding time variations were applied: 60–70 minutes, 120–130 minutes, and 180–190 minutes. These temperature and time ranges were selected based on prior studies indicating their relevance to effective wax removal, carbon oxidation, and mold strengthening in investment casting [3], [8].

During the heating process, molds were gradually heated to prevent thermal shock and shell cracking. After completion of the designated holding time, the molds were removed from the furnace and left in ambient conditions for approximately 10 seconds prior to metal pouring to stabilize the mold temperature.



Fig. 3. Mold heating process with different temperatures and times

2.4 Casting Procedure

Aluminum 6061 was melted in a crucible furnace and poured at a controlled temperature of 660°C, as recommended for aluminum alloy casting to ensure adequate fluidity without excessive oxidation [2]. The molten metal was poured into the preheated molds under vacuum conditions for approximately 3 minutes to improve mold filling and reduce gas entrapment.

After pouring, the molds were allowed to cool naturally for approximately 15 minutes. The investment molds were then broken to extract the cast propellers. Residual investment material adhering to the casting surface was removed using water cleaning prior to inspection and testing.

2.5 Testing and characterization

2.5.1 Dye Penetrant Test

Surface imperfections, including cracks, pinholes, and open porosity, were evaluated using the dye penetrant testing method shown in the Figure 2. This nondestructive inspection technique is widely employed to identify surface-connected flaws by enabling the penetrant liquid to infiltrate surface discontinuities, which are subsequently made visible through the application of a developer [15].



Fig. 4. Penetrant testing is performed to detect surface defects on the propeller blade.

2.5.2 Density meansurement

Density evaluation was performed based on the Archimedes principle by determining the mass of the specimens in air and when submerged in water. Differences in the measured density were interpreted as indicators of internal porosity and overall casting integrity, with reduced density values signifying a greater presence of internal voids [11].

The measurement of specimen density is done by calculating the density value based on the following equation [16].

$$\rho = \frac{W_{udara}}{(W_{udara} - W_{air})} x \rho_{air} \quad (1)$$



(a) (b)

Fig. 5. Density measurement (a) Weighing the specimen before density testing (b) Weighing the specimen while in water

2.5.1 Shringkage meansurement

Dimensional shrinkage was evaluated by comparing the volume of the wax pattern with the volume of the final cast propeller. Shrinkage percentage was calculated to assess dimensional accuracy and the influence of mold preheating parameters on solidification behavior. Shrinkage analysis is commonly used to evaluate the effectiveness of feeding and thermal control during aluminum casting processes.

Before calculating the shrinkage, it is necessary to determine the original volume and the pattern volume. Based on the density of wax granules, which is 0.89 g/cm³, the volume can be calculated using the following equation :

$$v = \frac{m}{\rho} \quad (2)$$

Shrinkage can be calculated using the formula below [4] :

$$S = \frac{(V_{pola} - V_{produk})}{V_{pola}} x 100\% \quad (3)$$

3 Results and discussion

3.1 Dye Penetrant Test

The dye penetrant test results demonstrate that variations in mold preheating temperature and holding time play a decisive role in determining the surface integrity of Aluminum 6061 propellers manufactured through the lost wax casting process. When the mold was preheated to 660 °C with a holding time of 60–70 minutes, a high density of surface defects such as pinholes and open porosity was observed. These imperfections indicate inadequate wax burnout and the entrapment of residual gases during molten metal filling.

Extending the holding time at the same temperature led to a noticeable reduction in defect frequency; however, traces of porosity were still present. This condition implies that while a longer holding duration enhances wax removal, a preheating temperature of 660 °C remains insufficient to fully oxidize carbon residues within the ceramic mold. Comparable findings were reported by [5], who emphasized that low burnout temperatures contribute to surface porosity due to incomplete gas evacuation.

A substantial improvement in surface quality was achieved at a mold preheating temperature of 710 °C, as clearly shown in Fig. 7. Compared to Fig. 6 (660 °C), the intensity and distribution of penetrant indications are significantly reduced, indicating fewer surface defects. This improvement is attributed to more complete wax burnout and improved mold permeability, which facilitate gas escape during pouring, particularly with holding times of 120–130 minutes. Under these conditions, surface defects were significantly suppressed, and the propeller surfaces became more uniform and smoother. This improvement is associated with more complete wax elimination and increased mold permeability, facilitating the release of gases during pouring, as noted by [3]. However, excessive holding at 180–190 minutes resulted in minor surface roughness, which is likely related to the gradual degradation of the gypsum-based mold material.

At the highest preheating temperature of 760 °C, minimal surface defects were observed at shorter holding times. In contrast, prolonged exposure at this temperature caused mold erosion and increased surface roughness on the cast propellers. Excessive thermal exposure can reduce mold strength, intensifying mold–metal interactions and ultimately degrading surface quality, in line with the observations of [4].



(a) (b) (c)

Fig. 6. Dye penetrant test results of aluminum castings at a mold heating temperature of 660 °C. Sub-figures (a), (b), and (c) correspond to holding times of 60–70 minutes, 120–130 minutes, and 180–190 minutes, respectively, illustrating the variation in surface defects indicated by penetrant intensity.



(a) (b) (c)

Fig. 7. Dye penetrant test results of aluminum castings at a mold heating temperature of 710 °C. Sub-figures (a), (b), and (c) represent holding times of 60–70 minutes, 120–130 minutes, and 180–190 minutes, respectively, showing the reduction in surface defects with increasing holding time.



(a) (b) (c)

Fig. 8. Dye penetrant test results of aluminum castings at a mold heating temperature of 760 °C. Sub-figures (a), (b), and (c) correspond to holding times of 60–70 minutes, 120–130 minutes, and 180–190 minutes, respectively, highlighting changes in surface quality and potential mold degradation at higher thermal exposure

Evaluation of casting defects across different mold preheating temperatures shows a strong correlation between temperature, holding time, and surface quality. At 660 °C, dye penetrant testing revealed numerous defects—including pinholes, open pores, and missruns—even when holding time was extended from 60–70 to 180–190 minutes, indicating that this temperature was insufficient for complete burnout.

Raising the temperature to 710 °C reduced defect frequency. Short holding times (60–70 minutes) still produced minor pinholes and open pores, intermediate durations (120–130 minutes) limited defects mainly to small open pores, and prolonged heating (180–190 minutes) yielded minimal surface flaws, reflecting effective burnout and improved casting quality.

At 760 °C, surface quality improved markedly with longer holding times. While brief heating (60–70 minutes showed minor defects, 120–130 minutes nearly eliminated surface flaws, and 180–190 minutes produced virtually defect-free castings. These results demonstrate that higher mold temperatures combined with sufficient holding times optimize burnout, reduce gas-related defects, and achieve consistent, high-quality casting surfaces.

3.2 Density measurement

Density measurements based on the Archimedes principle demonstrated a clear relationship between mold preheating parameters and the internal quality of the cast propellers. Specimens produced at 660 °C with short holding times exhibited the lowest density values, indicating significant internal porosity. This aligns with the surface defect observations, confirming that insufficient burnout leads to gas entrapment within the solidifying aluminum [11].

At 710 °C, density increased notably, as presented in Table 1 and Fig. 9. The highest average density was observed at a holding time of 120–130 minutes, indicating reduced internal porosity and improved metal feeding during solidification. This condition suggests more stable solidification behavior and fewer internal voids. Higher density values are commonly associated with better internal soundness and reduced casting defects in aluminum alloys [11].

At 760 °C, however, density values showed a slight decrease with extended holding times. This trend is likely caused by mold degradation at elevated temperatures, which can induce micro-defects and internal voids during solidification. [13] reported similar findings, showing that excessive mold temperatures adversely affect the internal quality of aluminum castings.

Table 1. The minimum shrinkage occurred at 710 °C with a holding time of 120–130 minutes. Under these conditions, more uniform heat distribution within the mold promoted controlled solidification, reducing volumetric contraction. As highlighted by [6]. Density measurements assessed casting integrity, where higher density indicates lower porosity and better quality, while lower density signifies increased internal defects.

Temperature (°C)	**Time**		
	60-70 minute	**120-130 minute**	**180-190 minute**
660	2,27 gr/cm^3	2,36 gr/cm^3	2,29 gr/cm^3
	2,27 gr/cm^3	2,29 gr/cm^3	2,22 gr/cm^3
	2,17 gr/cm^3	1,92 gr/cm^3	2,07 gr/cm^3
Average	**2,23 gr/cm^3**	**2,19 gr/cm^3**	**2,19 gr/cm^3**
710	2,11 gr/cm^3	2,14 gr/cm^3	2,22 gr/cm^3
	2,12 gr/cm^3	2,14 gr/cm^3	2,24 gr/cm^3
	2,18 gr/cm^3	2,14 gr /cm^3	2,26 gr/cm^3
Average	**2,13 gr/cm^3**	**2,14 gr/cm^3**	**2,24 gr/cm^3**
760	2,40 gr/cm^3	2,32 gr/cm^3	2,36 gr/cm^3
	2,05 gr/cm^3	2,14 gr/cm^3	2,18 gr/cm^3
	2,08 gr/cm^3	2,20 gr/cm^3	2,26 gr/cm^3
Average	**2,17 gr/cm^3**	**2,22 gr/cm^3**	**2,26 gr/cm^3**

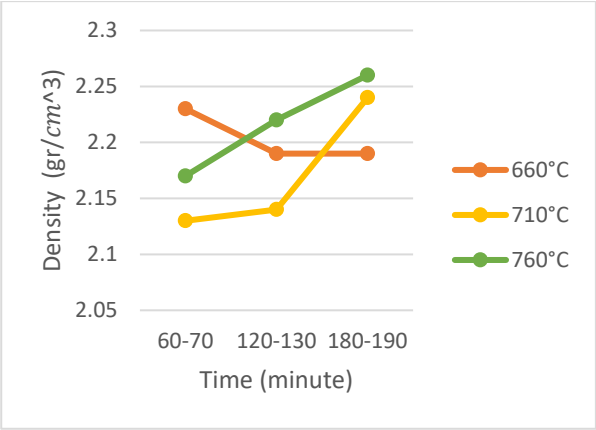


Fig. 9. Density results of the casting specimens. Density measurements were carried out to assess the quality and soundness of the castings, where variations in density values indicate differences in internal porosity levels. Higher density values are associate.

The density graph data indicate that increasing mold preheating temperature has a pronounced effect on propeller quality. At 660 °C, the density values remain relatively low and fluctuate, reflecting incomplete burnout conditions in which residual wax and carbon persist within the mold, thereby promoting porosity formation.

At a preheating temperature of 710 °C, a noticeable improvement in density is observed, particularly with longer heating durations. This trend suggests that residual combustion becomes more effective, leading to a reduction in internal voids.

The most favorable results were obtained at 760 °C, where density consistently increased from the first to the third hour of heating. The elevated density at this temperature indicates a significant decrease in internal porosity as a result of a more thorough burnout process. Although mold preheating at 760 °C with a holding time of 180–190 minutes produces high density and reduced internal defects (Table 1 and Fig. 9), this condition is not considered optimal due to the observed deterioration in surface quality and potential mold degradation (Fig. 8), which can negatively affect overall casting performance.

3.3 Shrinkage measurement

Shrinkage analysis indicates that both mold preheating temperature and holding time significantly influence the dimensional accuracy of the cast propellers. At lower preheating temperatures, particularly 660 °C, higher shrinkage was observed, caused by uneven solidification and inadequate feeding during cooling—conditions commonly seen in aluminum castings under suboptimal thermal management [2].

The minimum shrinkage occurred at 710 °C with a holding time of 120–130 minutes, as shown in Table 2 and Fig. 10. This condition promotes a more uniform temperature distribution within the mold, resulting in controlled solidification and reduced volumetric contraction. Proper thermal balance during burnout is essential to minimize shrinkage defects in aluminum casting [6], maintaining balanced thermal conditions during burnout is crucial for minimizing shrinkage defects.

At 760 °C with prolonged holding times, shrinkage increased slightly, likely due to premature solidification near the mold surface and insufficient feeding of molten metal during the final stages of solidification.

Table 2. Results of the specimen shrinkage calculations, indicating dimensional changes during solidification and cooling that affect casting accuracy and quality.

Temperature (°C)	Time		
	60-70 minute	120-130 minute	180-190 minute
660	14 %	11 %	6 %
710	9 %	6 %	3 %
760	3 %	2 %	2 %

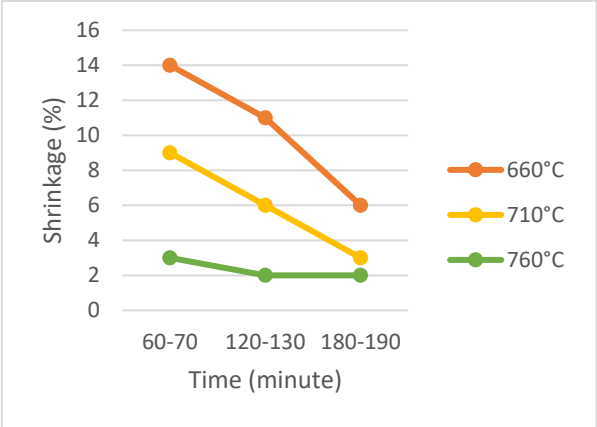


Fig. 10. Shrinkage results of the casting specimens. Shrinkage analysis was conducted to evaluate dimensional changes during the solidification and cooling stages of the casting process, where variations in shrinkage values reflect the influence of processing parameters on dimensional accuracy and overall casting quality.

The shrinkage graph shows a general decreasing trend in shrinkage values as the mold preheating temperature increases. At 660 °C, the highest shrinkage was recorded, reaching approximately 14% at a holding time of 60–70 minutes, and subsequently decreasing to about 11% and 6% at longer durations. These relatively high values indicate incomplete burnout, where residual wax and trapped gases remain inside the mold. Such conditions disturb melt flow stability and lead to greater volumetric changes during solidification.

At a preheating temperature of 710 °C, shrinkage was significantly reduced, falling within a range of approximately 9% to 3%. This reduction suggests more effective residue combustion, resulting in improved dimensional stability of the cast product. The lowest and most consistent shrinkage values were achieved at 760 °C, with shrinkage levels of around 3% and 2%. This behavior indicates that the mold cavity was substantially cleaner, allowing the molten metal to fill the mold more

uniformly and produce a casting volume closer to that of the original pattern.

Based on this trend, mold preheating at 760 °C with holding times of 120–130 minutes and 180–190 minutes produces the lowest shrinkage values (Table 2 and Fig. 10), indicating improved dimensional accuracy. However, this condition cannot be considered fully optimal when evaluated alongside surface quality and mold integrity, as higher temperatures may lead to mold degradation and surface roughness (Fig. 8). In comparison, a temperature of 710 °C with a holding time of 120–130 minutes provides a more balanced performance across shrinkage, density, and surface defects.

These results demonstrate that optimal casting quality cannot be determined solely based on a single parameter such as density or shrinkage. Instead, a comprehensive evaluation considering surface defects, internal integrity, and dimensional accuracy is required. This explains why the condition of 710 °C with 120–130 minutes is identified as the most balanced and optimal parameter combination in this study.

4 Conclusion

This research confirms that mold preheating temperature and holding time are key factors governing the quality of Aluminum 6061 propellers manufactured by the lost wax casting process. Adjustments to these parameters were shown to have a substantial impact on surface condition, internal integrity, and dimensional precision of the cast components.

The results demonstrate that inadequate preheating leads to incomplete wax burnout and gas retention within the mold, which subsequently causes surface porosity, lower density, and higher shrinkage. In contrast, overly high preheating temperatures combined with excessive holding durations tend to compromise mold strength, giving rise to surface roughness and internal micro-defects. These observations indicate that optimal casting performance depends on achieving an appropriate balance between effective burnout and the mechanical stability of the mold.

Among all experimental conditions, a mold preheating temperature of 710 °C with a holding time of 120–130 minutes yielded the most satisfactory results. Under this condition, the propellers exhibited minimal surface defects, relatively high density, and reduced shrinkage, reflecting improved internal soundness and dimensional stability.

In summary, this study provides useful technical insight for optimizing mold preheating parameters in the lost wax casting of Aluminum 6061 propellers. The findings are particularly relevant for the production of propulsion components for unmanned surface vehicles and may serve as a reference for future investigations involving alternative alloys or mold systems

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