

Heat Transfer Coefficient Experimental Modelling of Aluminium 6061 Shape Casting in Green-Sand Mould

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ABSTRACT

This study investigates the casting of aluminum alloy 6061 using green sand molds to evaluate the heat transfer coefficient (HTC) and solidification behaviour for different cast shapes. The shapes employed for the study includes rectangular plate, square bar and cylindrical bar. Aluminum alloy 6061 ingots were melted and poured at 700°C into the moulds of rectangular plate, square bar, and cylindrical bar configurations. Experimental results revealed that the HTC varies across different shapes, with the rectangular plate exhibiting the highest average HTC of 131.6 W/m²K, followed by the cylindrical bar (98 W/m²K) and square bar (73.7 W/m²K). The study demonstrated that shapes with lower casting modulus exhibit faster solidification due to enhanced heat dissipation. The casting of shapes that involves using aluminium alloy 6061 solidified within 105 seconds after pouring of the molten metal into mould cavity and also plate was the first to solidify. The thermal conductivity of the alloy was consistent with ASTM standards, confirming the material's suitability for casting applications. The experimental result shows that thermal conductivity of the alloy was 102.3 W/mK and the value was within range of stated value (85 - 173 W/mK) by ASTM. Heat transfer coefficient (HTC) in the cast objects was 101.1 W/m²K. These findings highlight the influence of casting geometry on heat transfer and solidification characteristics, providing valuable insights for optimizing casting processes.

Keywords: Aluminum alloy 6061, Heat transfer coefficient, Solidification time, Casting modulus, Green sand mold, Thermal conductivity, Casting geometry.

INTRODUCTION

The casting process is an essential manufacturing technique widely used in various industries, including automotive, aerospace, and industrial machinery. Shape casting is a process by which metal is transformed from ingot or scrap to a final form required by a designer (Jolly & Katgerman, 2022, Olofsson *et al.*, 2020). The shape can be in plate and bar form all depends on design requirement and investigating interfacial heat transfer coefficient is necessary for minimising design requirement and cost. Aluminium 6061 alloy has gained significant attention due to its desirable properties, including light weight, high strength, and excellent corrosion resistance (Chikhale *et al.*, 2016; Samuel *et al.*, 2021). In casting Al 6061 in a green-sand mould, understanding the heat transfer characteristics is crucial for optimizing the casting process, improving product quality, and reducing energy consumption. Understanding heat transfer characteristics is crucial for optimizing the casting process of Al 6061 in green-sand moulds. The effective heat transfer coefficient at the mould/metal interface plays a significant role in this process (Aroge *et al.*, 2021, Sun & Chao, 2009). Factors such as pouring temperature and the presence of inclusions affect the cooling rate and quality of the casting (Rendi *et al.*, 2021). The interfacial heat transfer coefficient (IHTC) varies with time during solidification and is essential for accurate

simulation of the casting process (Gowsalya *et al.*, 2019). Thermal resistance within the casting, at the metal-mould interface, and within the mould itself significantly impacts the heat transfer process (Shukla *et al.*, 2020). Different mould materials, such as green sand and mullite, affect heat distribution during solidification (Shukla *et al.*, 2020). Accurate modelling and simulation of these heat transfer characteristics, considering temperature-dependent properties of materials, can lead to improved casting quality and process optimization (Shukla *et al.*, 2020; Sun & Chao, 2009). This research paper aims to investigate the heat transfer coefficient during the casting of Al 6061 in a green-sand mould and develop a predictive model for the process. The study will involve experimental analysis, data collection, and numerical modelling to provide a comprehensive understanding of the heat transfer mechanisms involved.

Green sand casting is a complex process influenced by numerous factors affecting casting quality. Optimization of process parameters is crucial for efficient and economical production (Banchhor & Ganguly, 2014). The process involves pouring molten metal into a sand mould, where solidification occurs through nucleation and grain growth (Kumar *et al.*, 2019). Mould variability plays a significant role in defect generation, with time-temperature behaviour of process parameters being essential for understanding and predicting defects (Pandit & Deshpande, 2023). Key parameters such as moisture content, green compressive strength, permeability, and mould hardness exhibit systematic, time-dependent behaviour. The metal/sand mould interface phenomena significantly impact the surface quality, microstructure, and mechanical properties of castings (Holtzer *et al.*, 2015). To improve casting quality and reduce defects, it is necessary to move beyond traditional trial-and-error methods and employ statistical and artificial intelligence tools for process optimization (Banchhor & Ganguly, 2014). The heat transfer coefficient (HTC) during the casting of Aluminium 6061, particularly in green-sand moulds, is critical for understanding the solidification process and optimizing casting quality. The study intends to encompass experimental approaches for modelling Aluminium 6061 Shape Casting in Green-Sand Mould

Experimental Analysis

An experimental investigation was conducted to determine the effective heat transfer coefficient at the metal-mould interface during the casting of Al 6061 in a green-sand mould. Experimental methods using thermocouples to measure temperature distributions in casting systems are commonly employed (Sun & Chao, 2007; Sun *et al.*, 2019). Inverse modelling techniques are utilized to calculate HTCs based on measured temperatures (Meneghini *et al.*, 2007; Sun & Chao, 2007; Sun *et al.*, 2019). HTCs vary depending on mould materials, with inorganic sand moulds exhibiting higher values ($1000\text{--}1800\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) compared to organic sand moulds ($300\text{--}700\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) (Sun *et al.*, 2019). The lump capacitance method is proposed as an alternative approach for calculating HTCs in green sand mould casting (Sun & Chao, 2007). Factors influencing HTCs include metal head pressure (Meneghini *et al.*, 2007), solidification phase changes, and mould moisture content (Sun & Chao, 2007). Numerical simulations using calculated HTCs show good agreement with experimental results, validating these methods for predicting temperature distributions and solidification times in casting processes (Sun & Chao, 2009; Sun *et al.*, 2019).

Experimental analysis has utilized diverse measurement techniques to evaluate the interfacial heat transfer coefficient (IHTC) during the solidification of aluminium alloys (Belsare *et al.*, 2017). One widely applied method is the Inverse Control Volume Technique, which estimates heat flux and temperature at the mould surface by measuring temperatures at various points within the mould. This approach has been effectively employed for spherical aluminium alloy (Al 6061) castings, validating IHTC values against experimental data (Gowsalya *et al.*, 2019). Another study adopted two different inverse methods—control volume and Beck's approach—to estimate IHTC during the solidification of rectangular aluminium alloy castings. The findings demonstrated good agreement with existing literature, highlighting the reliability of these methodologies (Rajaraman *et al.*, 2018).

Modelling Approaches

Mathematical modelling techniques have significantly advanced the simulation of solidification processes by incorporating critical parameters. For instance, the convective heat transfer coefficient has been effectively modelled in vertical twin roll casting processes, alongside factors like roll speed and melt superheat, to achieve

accurate predictions (Dhindaw *et al.*, 2020). Similarly, studies on low-pressure die casting have demonstrated how interface pressure and water flow rates impact the interfacial heat transfer coefficient (IHTC), providing valuable insights for optimizing casting conditions (Zeng *et al.*, 2019). Additionally, simulation tools such as COMSOL Multiphysics are widely utilized to model heat transfer and fluid dynamics in casting processes, enabling a comprehensive analysis of the interactions between various factors during solidification (Dhindaw *et al.*, 2020).

MATERIALS AND METHODS

The primary material used in this study was aluminum alloy 6061, prepared in ingot form. The chemical composition of the alloy is shown in Table 1, and its physical and thermal specifications, as per ASTM standards, are detailed in Table 2. Additional materials included green sand for mold preparation and standard casting equipment, including a mold box, patterns, pliers, scissors, and a pouring cup. The electronic temperature recorder and thermocouples were used to measure temperature variations during the solidification process.

Table 1: Composition of Aluminium 6061

Aluminium 6061 Component	Weight %
Aluminium	96.20
Magnesium	1.20
Silicon	0.75
Iron	0.70
Copper	0.40
Zinc	0.25
Titanium	0.15
Manganese	0.15
Chromium	0.20

Table 2: Specification of Al6061 (ASTM)

Specification	Unit
Liquid Density (kg/m ³)	2400
Solid Density (kg/m ³)	2700
Solid Thermal conductivity (W/mK)	173
Liquid Thermal conductivity (W/mK)	85
Fusion Temperature (°C)	585

Solid Specific Heat (J/kgK)	1050
Liquid Specific Heat (J/kgK)	1090
Latent Heat of Fusion (J/kg)	381900

Experimental methods and Set Up

Preparation of Mould and Patterns

Three casting patterns were prepared to produce a rectangular plate, a square bar, and a cylindrical bar. The dimensions were as follows:

1. Rectangular plate: 250 mm × 60 mm × 10 mm
2. Square bar: 250 mm × 24.5 mm × 24.5 mm
3. Cylindrical bar: 250 mm length, 27.6 mm diameter

The patterns were used to create cavities in green sand molds. Molding and core-making were carried out to ensure dimensional accuracy and stability.

Melting and Pouring

Aluminum alloy ingots (10 kg) were melted in a gas furnace and heated to a pouring temperature of 700°C. The molten metal was poured into the pre-prepared mold cavities.

Temperature Measurement

Thermocouples connected to an electronic paperless recorder were used to monitor temperature variations at critical points within the molds and the castings.

Four thermocouples were placed within the casting to measure the temperature gradient:

$$T_{if}, T_{lc}, T_{uf}, \text{ and } T_{uc}$$

Another thermocouple was positioned 50 mm from the mold wall to measure the sand mould temperature T_s .

Figure 1 shows the positioning of thermocouple in cast plate. The blue pigment in Figure 1 was one-quarter of the plate pattern in which thermocouple mounted onto for measuring the readings of temperature points. The measuring points of temperature in the cast include $T_{if}, T_{lc}, T_{uf}, \text{ and } T_{uc}$ and these measured using thermocouple through electronic paperless recorder.

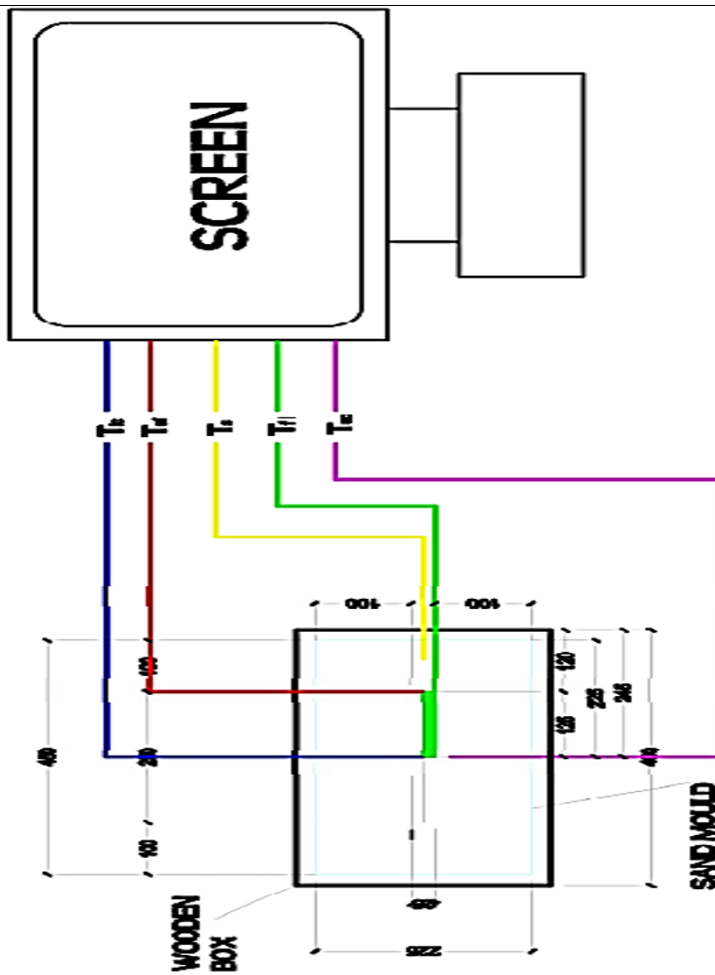


Figure 1: Casting temperature measuring point Using Thermocouple Paperless Recorder

The sand mould temperature (T_s) measuring point was located 50 mm from the wooden or mould box. Four points were used for positioning the thermocouple within the one quarter of the cast. The thermocouple used for measuring the temperature within the cast was positioned at 30mm ($h/2$) from the edge of both width faces (60mm) of the cast in Figure 1. The thermocouple helps to measure temperature at four different points within cast. The thermocouple that measured sand mould temperature was positioned at centre point between pattern and core box within the mould.

Determination of casting modulus

The temperature per unit time or cooling of the casting depends on modulus of the casting and it is defined as ratio of volume to effective cooling surface area. The casting modulus, M , was calculated using (Bala and Khan, 2013):

$$M = \frac{V_m}{A_m} \quad (2.1)$$

Where V_m is the casting volume and A_m is the effective cooling surface area.

$$M_p = \frac{t}{2} \quad (2.2)$$

$$M_s = \frac{w}{2} \quad (2.3)$$

Casting Shape	Modulus (M, mm)	Solidification Time (ts, sec)
Rectangular Plate	4.0	320
Square Bar	8.2	620
Cylindrical Bar	10.0	720

$$M_c = \frac{d}{4} \quad (2.4)$$

Condition I (equation 2.1) holds if $L > 5t$

Condition II (equation 2.2) holds if $L > 5w$

Condition III (equation 2.3) holds if $L > 5d$

Determination of solidification time

The solidification time (t_s) is the time required to complete solidification process in casting and depends on heat transfer across the casting surface and mould of the casting and given by Solidification time (t_s) was determined using the Stefanescu equation (Stefanescu, 2008):

$$t_s = B \left(\frac{V_m}{A_m} \right)^n \quad (2.5)$$

where, B is a constant incorporating material properties and n is the cooling rate exponent

$$t_s = \frac{\rho_m(Q_f + c_m(T_p - T_m))}{HTC_v(T_m - T_o)} \left(\frac{V_m}{A_m} \right) \quad (2.6)$$

$$B = \left[\frac{\rho_m L}{(T_m - T_o)} \right]^2 \left[\frac{\pi}{4k\rho c} \right] \left[1 + \left(\frac{c_m(T_p - T_m)}{L} \right)^2 \right] \quad (2.7)$$

RESULTS AND DISCUSSION

Solidification Time Analysis

The solidification times for the rectangular plate, square bar, and cylindrical bar castings were determined experimentally using thermocouple data. The results, presented in Table 3, indicate a direct relationship between casting modulus (M) and solidification time (t_s) and the study boundary condition is in Table 3.

Table 3: Solidification Time for Different Casting Shapes

The cylindrical bar, having the highest modulus, exhibited the longest solidification time, while the rectangular plate solidified fastest. This outcome aligns with Chvorinov's rule, which states that larger moduli correspond to longer solidification times due to slower heat dissipation.

Table 4: Boundary condition of aluminium 6061

Parameter	Quantity
Volume per workpiece	0.00015m ³

Length of Cast Alloy	0.25m
Pouring Temperature	700 °C
Time interval	10 seconds

The cooling of the casting depends on modulus of the casting (M) and it was calculated for different cast shapes based on same length (L) 125mm (Sun, *et al.*, 2019).

$$\text{Plate modulus, } M_p = \frac{t}{2} = \frac{10\text{mm}}{2} = 5\text{mm}$$

$$L > 5t = 5(10) = 50\text{mm}$$

$$A_m = \frac{V_m}{M} = \frac{150,000}{5} = 30,000 \text{ mm}^2$$

$$\text{Square bar modulus, } M_s = \frac{\text{width}}{4} = \frac{24.5}{4} = 6.1 \text{ mm}$$

$$L > 5w = 5(24.5) = 122.5\text{mm}$$

$$A_m = \frac{V_m}{M} = \frac{150,000}{6.1} = 24,590 \text{ mm}^2$$

$$\text{Cylindrical bar, } M_c = \frac{\text{diameter (d)}}{4} = \frac{27.6}{4} = 6.9\text{mm}$$

$$L > 5(d) = 5(27.6) = 138\text{mm}$$

$$A_m = \frac{V_m}{M} = \frac{150,000}{6.9} = 21,739 \text{ mm}^2$$

The plate has lowest casting modulus of 5mm and this mean it has high cooling surface area of 30,000 mm² in comparing to other shapes used for the experiment. The heat transfer coefficient (HTC) of aluminium alloy was determined using experimental records of temperature distribution in the cast. Figure 2 shows the temperature gradient in plate cast and the pouring of molten metal was at 700°C.

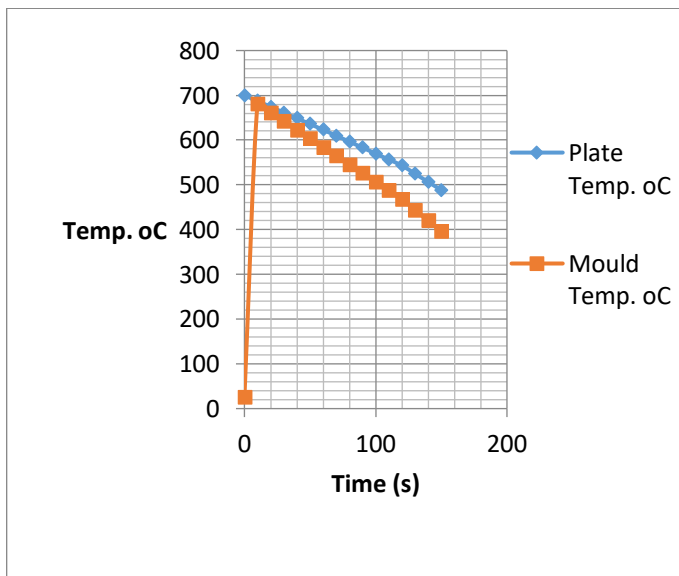


Figure 2: Temperature profile of rectangular plate

Heat Transfer Coefficient (HTC) Analysis

The heat transfer coefficient was calculated for each casting shape based on thermocouple readings. The rectangular plate exhibited the highest value, decreasing rapidly during solidification due to its higher surface area-to-volume ratio, which facilitated faster cooling. The cylindrical bar showed the lowest value throughout solidification, attributable to its smaller surface area relative to its volume, resulting in slower heat dissipation. This variation highlights the importance of HTC in determining the cooling rate and solidification behavior of castings. Table 4 presents heat transfer coefficient (HTC) of the alloy determined from the experimental result obtained for rectangular plate.

The room/fluid temperature (T_f) used for the study was at 25.3 °C during the experiment. The length of cast plate was 0.125m (half of the cast length) and heat energy was expected to transfer across the cast for solidification to complete. The expected HTC of the cast rectangular plate after 90 seconds was 48.4 W/m²K. It implies 48.4 W/m²K was the HTC of molten stage of the plate. The liquid thermal conductivity of the plate was at 111.8 W/mK. The ASTM-liquid thermal conductivity of the alloy in Table 3.2 was at 85 W/mK therefore efficiency of obtained HTC was at 68.5 % in plate.

Table 5: HTC of Rectangular Plate

Time (s)	T (°C)	T _s (°C)	T-T _s (°C)	T _s - T _f (°C)	HTC (W/m ² K)
10	687.2	680.7	6.00	655.4	6.2
20	674.3	661.4	12.9	636.1	13.8
30	661.4	642.1	19.3	616.8	21.3
40	648.6	622.8	25.8	597.5	29.4
50	635.7	603.5	32.2	578.2	37.9
60	622.9	584.1	38.8	558.8	47.2
70	609.6	564.8	44.8	539.5	56.5
80	596.3	545.5	50.8	520.2	66.4
90	583.0	526.2	56.8	500.9	156.9
100	569.7	506.9	62.8	481.6	180.9
110	556.4	487.6	68.8	462.3	206.0
120	543.0	468.2	74.8	442.9	233.7
130	524.7	444.0	80.7	418.7	266.8
140	506.4	419.7	86.7	394.4	304.2
150	488.2	395.5	92.7	370.2	346.6

Table 5 presents summary of HTC in aluminium alloy cast and therefore it was observed that plate has high value of HTC in the casting with $131.6 \text{ W/m}^2\text{K}$ for the experiment. The HTC of cast square bar was at $73.6 \text{ W/m}^2\text{K}$ and HTC of cast cylindrical bar was at $98 \text{ W/m}^2\text{K}$ after 150 seconds

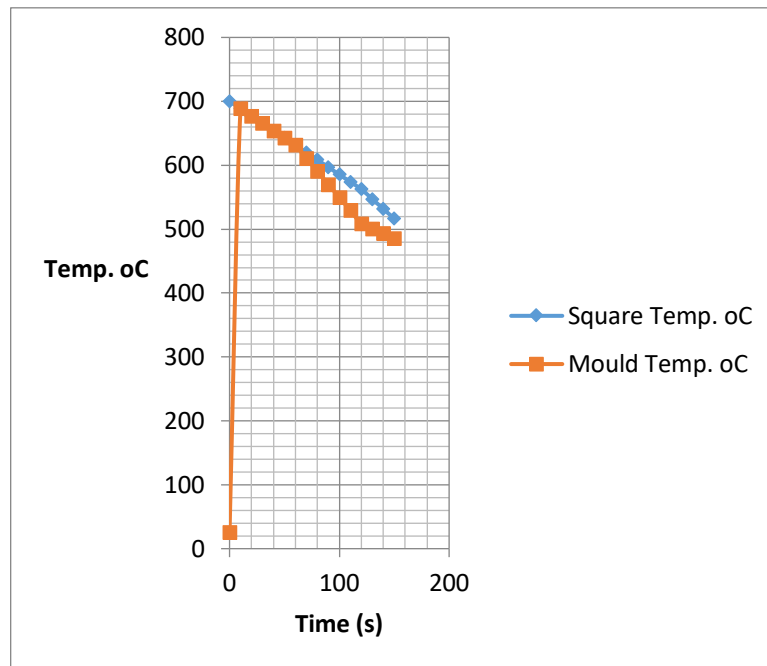


Figure 3: Temperature-profile of square bar

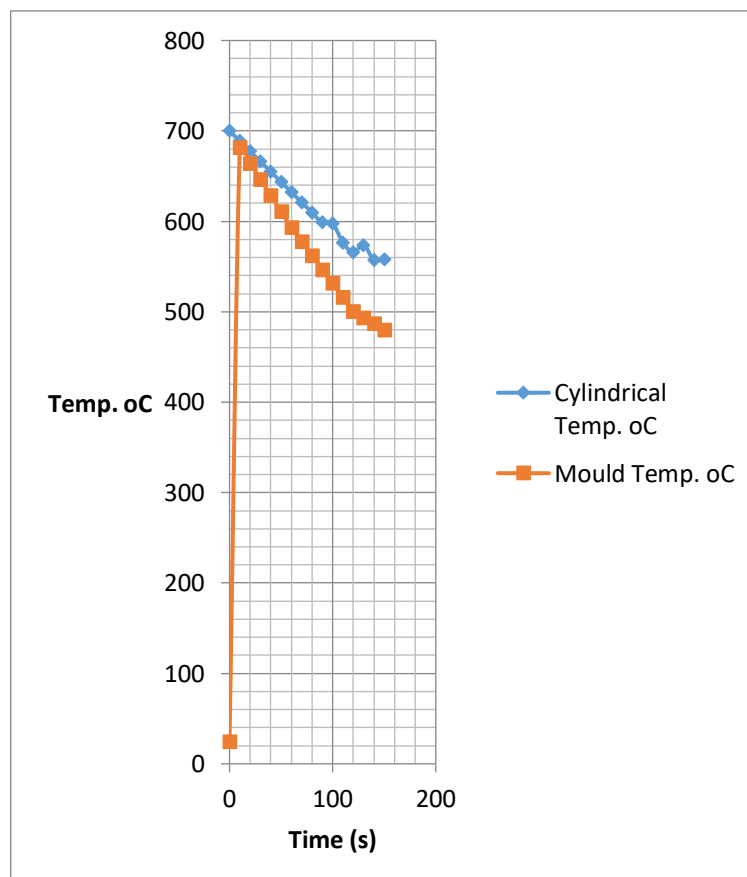


Figure 4: Temperature profile of cylindrical bar

Rectangular plate solidified faster than other cast object due high HTC across its surface

Table 6: HTC Average of the Aluminium Alloy

Time (s)	HTC-plate (W/m ² K)	HTC-square (W/m ² K)	HTC-cylindrical (axial) (W/m ² K)
10	6.2	6.9	6.7
20	13.8	13.3	13.9
30	21.3	18.3	21.4
40	29.4	44.5	29.4
50	37.9	31.3	37.9
60	47.2	49.2	46.9
70	56.5	91.0	53.3
80	66.4	76.2	60.2
90	156.9	91.4	67.5
100	180.9	75.8	88.8
110	206.0	22.8	169.9
120	233.7	153.2	188.4
130	266.8	134.2	236.1
140	304.2	113.9	211.2
150	346.6	183.6	238.8
ave	131.6	73.7	98

Considering the average of HTC presented in Table 6, HTC required for casting of aluminium alloy was at 131.6, 73.7 and 98 W/m²K after 150 seconds in rectangular plate, square and cylindrical shapes. However, the liquid thermal conductivity (k) obtained of the material used was at 111.8, 90.1 and 105 W/mK for plate, square and cylindrical bar respectively. The average of liquid thermal conductivity was at 102.3 W/mK within the range of 85 to 173 W/mK of ASTM Table. The following Figures 6-8 were the cast of rectangular plate, square bar and cylindrical bar obtained during the experiment.



Figure 6: Cast Rectangular Plate



Figure 7: Cast Square Bar



Figure 8: Cast Cylindrical Bar

DISCUSSION

The study demonstrated that the shape and size of castings significantly influence solidification behavior, thermal gradients, and resultant microstructures. These findings align with established principles of heat transfer and solidification theory, validating the experimental methodology. However, limitations such as uniformity in mold preparation and potential thermal conductivity variations in the green sand may introduce minor inconsistencies.

CONCLUSIONS

This study investigates the solidification behaviour and heat transfer characteristics of aluminium alloy 6061 castings using green sand moulds. Various casting shapes, including rectangular plates, square bars, and cylindrical bars, were evaluated to determine the impact of geometry on solidification time, heat transfer coefficient (HTC), and the resulting microstructure. The aluminium alloys 6061 are cast-able using green sand mould with Heat transfer coefficient (HTC) in the cast objects obtained as $101.1 \text{ W/m}^2\text{K}$. The findings reveal that lower modulus shapes, such as the rectangular plate, solidified faster due to a higher surface area-to-volume ratio, leading to a higher HTC and finer microstructure. Conversely, shapes like the cylindrical bar, with lower HTC and slower solidification, exhibited coarser microstructures. The results emphasize the needs of heat transfer coefficient for understanding solidification and cooling process in Al6061 casting adoptable in industrial application.

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