Effect of Copper Chill and Al5Ti1B Grain Refiner on Mechanical Characteristics of LM6 alloy Casting

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Abstract

Aluminum-silicon alloys, particularly LM6, are widely used in the automobile industry due to their excellent casting and machining properties. The mechanical behavior of LM6 largely depends on solidification and casting conditions. This study examines the influence of copper chill thickness and Al5Ti1B grain refiner on its mechanical properties. Grain refiner was added at three levels (0.25, 0.50, and 1 wt%), while copper chill thicknesses of 10, 20, and 40 mm were applied. Casting simulation with AutoCast-X1 optimized parameters, and sand casting experiments were conducted. A full factorial orthogonal array was employed, considering tensile strength and hardness as responses. Mathematical models were developed from test data. Results indicate that grain refiner and external chill significantly enhance casting quality. The optimum combination of 40 mm copper chill and 1 wt% Al5Ti1B produced maximum improvement, with tensile strength increasing by 30.05% and hardness by 4.76%.

Keywords: LM6 alloy, metal chills, grain refiner, mechanical properties.

1. Introduction

Casting makes it possible to produce components with intricate geometries at a reasonable cost, frequently resulting in near-net forms [1]. The formation of almost all metals and alloys is based on solidifying them from a liquid condition. The effects of a few casting factors, such as chill thickness and grain refiner, have been researched to improve the mechanical properties of castings. The mechanical properties of cast aluminum-silicon alloys are heavily influenced by defects that occur during mold filling and solidification, composition, metallurgical quality, heat treatment, and the casting process itself. [2]. Additional feed aids such as padding, fins, exothermic sleeves, and metallic chills are employed in aluminum-silicon alloy casting to encourage directed solidification when feeders alone are insufficient. Metallic chills can be constructed of steel, aluminum, iron, and copper. External copper chills enhance the cooling rate of LM6 alloy castings, improving mechanical characteristics and refining microstructure [3]. An excellent equiaxed grain structure increases casting uniformity by adjusting secondary phase distribution and microporosity levels [4]. Grain refinement in aluminum alloys gives both technical and economic benefits, such as reduced ingot cracking and enhanced uniformity [5]. Grain refining is a significant melt treatment in aluminum-silicon alloy casting that is commonly employed in the aluminum manufacturing sector to improve the mechanical qualities of castings Al-Ti-B alloys have been extensively employed as grain refiners for most aluminum alloys [6]. Despite decades of investigation, the method of grain refinement and material characteristics of LM6 alloys containing Al-Ti-B master alloys and copper chill elements is uncertain.

Liu [7] et al. examined chemical grain refinement methods that is the main approach used in aluminum alloys, commonly involving refining agents like Al–Ti–C , Al–Ti–B and advanced multi-element alloys such as Al–Ti–B/C -RE. The author found that the refinement procedure is vital for boosting the alloys strength, toughness, and overall mechanical properties. Xia [8] et al. studied the effectiveness of incorporating a small amount of La in improving the performance of the Al–5Ti–1B master alloy, with significant implications for enhancing the durability of vehicle wheels made from A356.2 aluminum alloy. Prema [9] et al. investigated the effects of addition of grain refiners and modifiers to the eutectic LM6 alloys. The author concluded that the mechanical properties of aluminum alloys are mostly affected by key microstructural features, with a fine grain size being especially beneficial for enhancing these properties. Choudhary [10] et al. concluded that inclusion of Al-5Ti-1B to Al-7Si melt transforms primary α-Al grains from dendrites to rosettes. The irregular shape of eutectic Si is similarly turned into a regular shape. The microstructure of the produced alloy is formed of α-Al, eutectic Si, β-Al5FeSi, TiAl3, and Ti7Al5Si14 particles. Ait El Haj [11] et al. concluded that grain refining not only creates fine grain size but also improves material mechanical characteristics. The efficacy of grain refiners in aluminum is heavily impacted by the alloying elements used.

Janardhan [12] et al. examined the effectiveness of chill in sand casting of aluminium alloy and sample with copper chill has the highest mechanical properties. Dehnavi [13] et al. examined the effect of the cooling rate and as the cooling rate increases, grain size and secondary dendritic arm spacing decrease. Nafisi [14] et al. studied that adding a small quantity of boron increases the cooling curve and causes recalescence to disappear completely. Shabani [15] et al. concluded that tensile characteristics of grain refined and base alloys showed no significant variations in thinner sections. Pongen [16] et al. demonstrated an increase in the case of A713 alloy when grain refiners such as Al-3.5Ti-1.5C and Al-3Cobalt are applied, as compared to that without grain refining. Sharma [17] et al. suggested that the addition of grain particles to the AA 6082 metal matrix is not useful due to non-uniform microstructure and decreased mechanical characteristics at all Grain weight proportions. Leela [18] et al. investigated the influence of chill materials on the solidification of an Al-B4c composite. The copper chill produced fine grain structures, whereas the stainless steel and cast iron chills produced coarse grain structures.

Meneghini [19] et al. discovered that copper chills have a better cooling effect than aluminium chills and gray cast iron. Copper chill size has a direct effect on heat transfer coefficient value however aluminum and cast iron chills have an inverse relationship. Ramesh [20] et al. observed that using copper chill resulted in faster cooling rates during the solidification of the produced composite. The author concluded that the experimental and predicted cooling rates derived using FEA software for the created composites are not in good agreement. Gafur [21] et al. concluded that chill thickness and superheat has a substantial effect on the rate of temperature increase of chill in contact with the solidifying casting. Goto [22] et al. investigated the mechanism of the wrinkle found on the casting produced by a directed solidification method using a chill and a high temperature mold. Szeliga [23] et al. has concluded that, there is no change in the chemical composition of IN-713C alloy on the surface of a cast equipped with silicon carbide chill, and there is no reaction between the ceramic shell mould and the chill material. Kanthavel [24] et al. author observed that the chill thicknesses play a key role in solidification and reducing shrinkage defects. Hemanth [25] author determined that the cooling curves and temperature distribution produced from FE analysis do not converge as closely with the experimental data. Ahmed [26] et al. discovered that the melt temperature has a considerable influence on the quality of green sand casting of LM6 alloy. The lower pouring temperature produces a fine microstructure with fewer faults like porosity.

Seah [27] discussed on the application of sand molds with external chills such as cast iron, copper, steel, and silicon carbide for production and testing on aluminum cast composites. This work highlighted that castings mechanical characteristics can be improved by employing inoculants to increase qualities like hardness and ultimate tensile strength and by adding chilling to improve local heat transmission. LM13 alloy stir-cast hybrid composites enriched with garnet and carbon particles were developed by Prasad [28] et al. Several external chill materials, such as steel, iron, copper, and silicon carbide are used to improve solidification. The mechanical characteristics of the reinforced composites, including their ultimate tensile strength and hardness, are assessed. Dobrzański [29] et al. studied the effects of cooling rate are investigated on secondary dendrite arm spacing, grain size, precipitation size, and thermal characteristics of AlSi7Cu2 cast alloy. The study discovered that the thermal properties of the cooling curve can be used to assess the chemical and thermal change of eutectic silicon.

However, no studies have been reported so far on the result of grain refiner Al5Ti1B and its impact on mechanical characteristics with the addition of an external copper chill to LM6 aluminum alloys. In this study, the influence of two control factors, chill thickness and weight % of Al5Ti1B grain refiner, is investigated. Design of experiment technique is used to optimize these casting parameters. This experiment shows important findings for LM6 casting and the impact of copper chill and grain refiner on mechanical properties.

2. Experimental methodology

2.1 Simulation Work

The complete casting arrangement is simulated in AutoCast-X1[30] to ensure a defect-free solidification process, determine precise design parameters, and identify the exact location of the feeder [31].The primary objective is to accomplish sound casting, followed by trials to improve the mechanical characteristics. The design calculations for gating mechanism are completed by using design data book [32]. Solidification of molten metal is vital stage in the metal casting and significantly influences product quality and yield. Casting simulation software offers a detailed insight into casting processes, enabling the identification of hotspot and severity of internal defects to ensuring defect free casting. The best possible location of a feeder is decided based on the identified hot spot area and the feeder dimensions is subsequently modelled within software.

A simulated casting process produced a rectangular plate of solid model size 150 × 100 × 25 mm is created in CAD software in .stl format file for importing in AutoCAST X1 is shown in Fig. 1. The parting line is decided on the volumetric mesh elements. Simulation of LM6 alloy rectangular plate is done to identify the region of hot spot in the casting and proper location of feeder which is shown in Fig. 2. . Based on the software result for feeder location first attempt is completed feeder without exothermic sleeve; however it has not shown any significant improvement in casting. For better result, second attempt has been made by providing the exothermic sleeve on the feeder which is shown in Fig. 3. It is clear that all hot spot region is transferred to feeder and the casting is defect free.

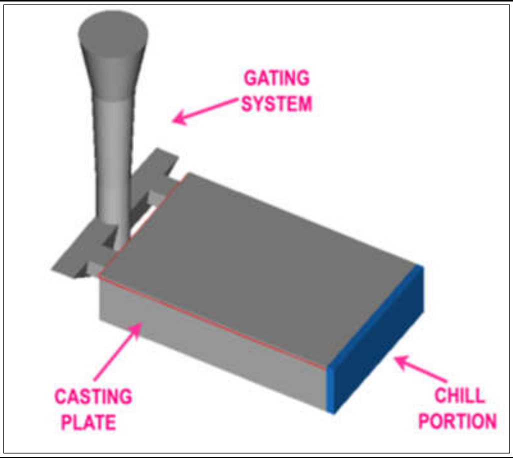


Fig. 1 Casting with copper chill in AutoCAST X1

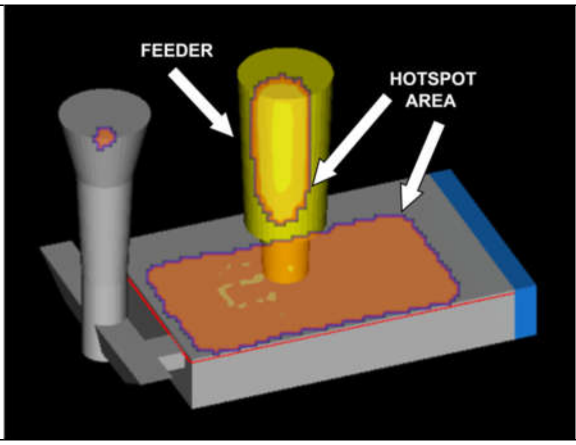


Fig. 2 Hotspot area in casting

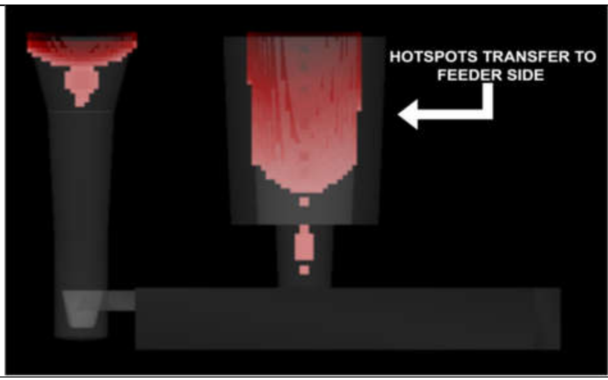


Fig. 3 Transfer of hotspots to feeder side to elimination the shrinkage defects

2.2 Experimental Work

The sand casting technique is used in the foundry to carry out the experimental work. Composition of molding sand consist of 60% lake sand, 40% reclaim sand as per American Foundry Society (AFS 100). Moisture content is 3% and Bentonite binder is 5 %. The LM6 alloy employed in this study is made by melting an LM6 alloy ingot in an electrical resistance furnace. LM6 castings are cast at 700°C. The chemical composition of the alloy as tested by BMT Laboratories LLP, NABL Accredited Lab (TC-6546) is shown in Table 1.

Table 1 Chemical composition of LM 6 alloy

Elements	Al	Mg	Si	Mn	Fe	Zn	Ni	Ti	Sn	Pb	Cu
(%)	89	0.013	10.5	0.004	0.214	0.008	0.0017	0.010	0.020	0.0006	0.0758

The experimental trials are carried out at the foundry, where the casting processes and conditions are precisely controlled and monitored. The rectangular plate is measuring 150 × 100 × 25 mm considered for study. A wooden pattern is created by considering pattern allowances, and casting mold boxes are prepared incorporating copper chill. The experimental trials are carried out on LM6 alloy, with copper chill and addition of grain refiner. The mold cavity is created in mold box and copper chill is incorporated by one end of the mold cavity is as shown in Fig. 4. The gating arrangement of the component as per casting design standard is shown in Fig.5. The chill encourages directional solidification; the molten metal solidifies gradually from the chilled end to the opposite side. The regulated solidification technique reduces flaws such as porosity and shrinkage, hence improving the cast components mechanical qualities. The final component after cast is shown in Fig. 6.

A total of nine castings are made, each with varying grain refiner content and chill thickness is shown in Fig. 7. These modifications are introduced to investigate the influence on mechanical qualities and microstructure. The experiments goal is to determine ideal conditions for increasing the quality and performance of the cast components by systematically changing these variables. An experiment is performed with copper chill of different thicknesses, specifically 10 mm, 20 mm, and 40 mm and Al5Ti1B grain refiner such as 0.25 weight %, 0.50 weight %, 1 weight %. These variant are designed to explore the cause of chill thickness and grain refiner on solidification performance.

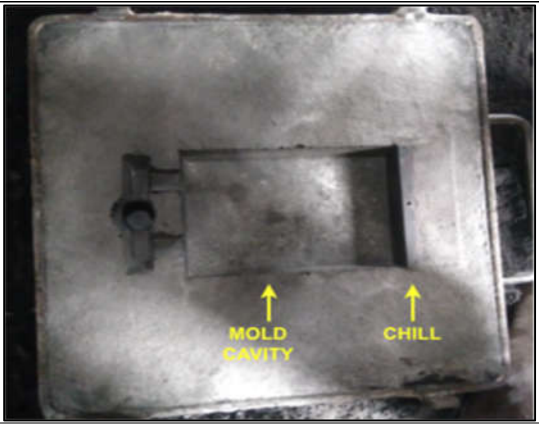


Fig. 4 Mold cavity with copper chill

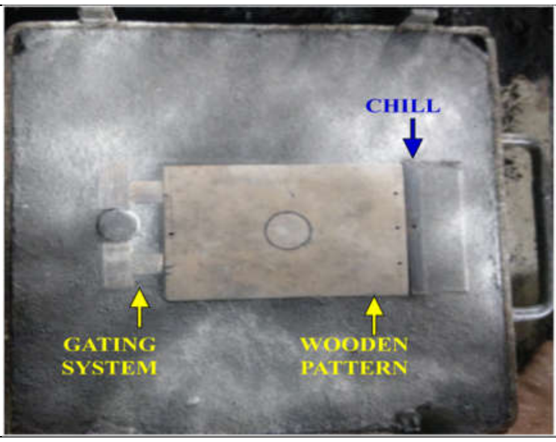


Fig. 5 Pattern and gating system

Fig. 6 Final component after cast

Fig. 7 Nine test components with varying grain refiner content and chill thickness

The experimental work is done on a rectangular plate constructed of LM6 alloy. The ultimate tensile strength is determined using a universal testing machine. The hardness is measured using the Vickers hardness test method which is as shown in Fig. 8. This standard specifies the dimensions and methods for preparing tensile test specimens ensuring that mechanical parameters like ultimate tensile strength are measured accurately and consistently which is as shown in Fig. 9. The hardness test is performed on cast components in accordance with the ASTM E10:2015 standard [33].

Fig. 8 Test casting samples for hardness test

Fig. 9 Test casting samples as per ASTM-B557 for ultimate tensile test

3. Optimization methodology

Process parameter optimization is widely used in metal casting industry. The Taguchi method is a greatly useful experimental design technique that enhances process performance while requiring a minimum number, of trials. It minimizes production expenses, cycle time costs, rework costs. The Taguchi design attempts to discover optimal values for the desired function in industrial processes. The experimental data obtained using the orthogonal array are then converted into S/N ratios to assess performance characteristics [34]. Taguchi defines product quality as the entire loss transmitted to society from the time the product is shipped to the client.

The parameter design of Taguchi method by [24] has includes following steps which are shown in Fig. 10.

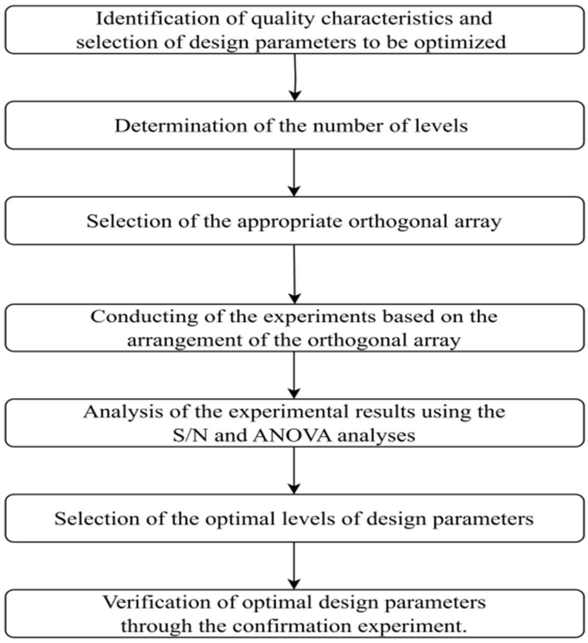


Fig. 10 Steps of taguchi method

In this study, the Larger-the-better is used for good tensile strength and the Smaller-the-better is used for hardness. Different types of S/N Ratio are mentioned below along with equation (1), (2) & (3). The design of experiment has been set up by using Minitab 22 software. The most suitable array L_9 orthogonal array is used to check the experimental design. Nine castings are casted as per L_9 orthogonal array technique with consideration of varying chill thickness and grain refiner in terms of weight percentage. The design of experiment is created with three separate levels and two factors as shown in Table 2. This method allows for the systematic adjustment of input parameters or factors in order to determine their impact on output or response variables. The number of levels given to each factor controlled the orthogonal array selection. The experimental results for mechanical properties, including hardness and ultimate tensile strength is achieved using the sand casting procedure and are shown in Table 3. The response table for signal to noise ratios (Larger is better) is shown in Table 4. The response table for signal to noise ratios (Smaller is better) is shown in Table 5. It is clear that the rank for grain refiner is at first and for chill thickness second.

Smaller-the-better: $$\left(\frac{S}{N}\right) = -10\text{Log}_{10}\left\{\frac{1}{n}\sum_{i=1}^{n} y_i^2\right\} \text{-------(1)}$$

Larger-the-better: $$\left(\frac{S}{N}\right) = -10\text{Log}_{10}\left\{\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right\} \text{-------(2)}$$

Nominal-the-best: $\left(\frac{S}{N}\right) = 10 \operatorname{Log}_{10}\left\{ \frac{y^2}{\sigma^2} \right\}$ -----------(3)

Table 2 Casting input factors and their levels

Input factors	Code	First level	Second level	Third level
Chill thickness (in mm)	X1	10	20	40
Grain refiner (weight %)	X2	0.25	0.50	1

Table 3 Ultimate tensile strength and hardness values

Case No.	Chill thickness (mm)	Grain refiner (weight %)	Ultimate tensile strength (N/mm2)	Hardness (HV)
Case 1	10	0.25	103.74	66
Case 2	20	0.25	101.35	64
Case 3	40	0.25	107.46	65
Case 4	10	0.5	107.17	64
Case 5	20	0.5	107.46	63
Case 6	40	0.5	116.67	63
Case 7	10	1	116.62	66
Case 8	20	1	114.08	64
Case 9	40	1	117.42	66

The research indicates a linear relationship between ultimate tensile strength and hardness as a function of chill size and grain refiner. This connection quantifies the changes in chill size and grain refiner effect casting mechanical qualities, allowing for more accurate process control and optimization. The equation 4 and equation 5 provide the models of regression for ultimate tensile strength and hardness with respect to the input parameters. These equations are mathematically define the relationship between input parameters such as chill size and grain refiner and output mechanical qualities, making it possible to forecast and optimize the casting process. Fig.11 (a-b) shows the major effect plots for individual parameters, such as ultimate tensile strength, however Fig. 12 (a-b) shows the plots for hardness as the second output parameter. These graphs show the influence of each parameter on the mechanical properties.

The regression equation of tensile strength is,

$$\text{Ultimate tensile strength} = 97.23 + 0.1780\ X1 + 15.15\ X2 \qquad (4)$$

The regression equation of hardness is,

$$\text{Hardness} = 64.28 - 0.0119\ X1 + 0.95\ X2 \qquad (5)$$

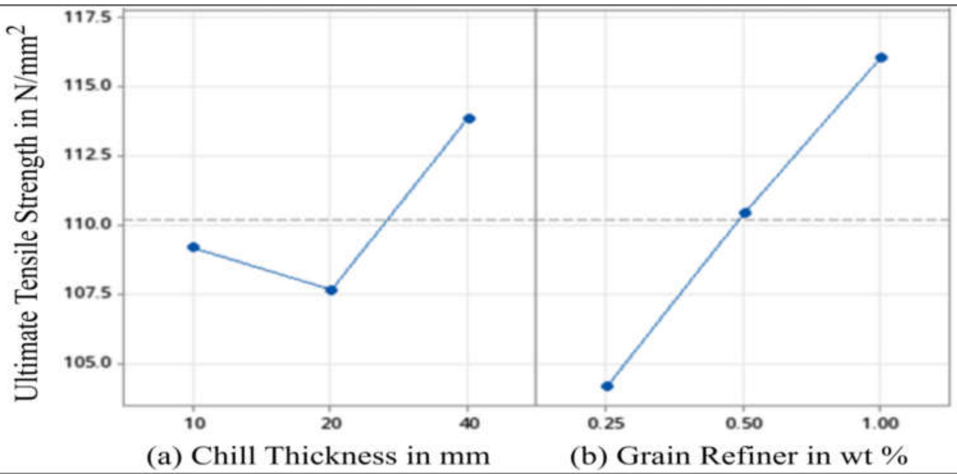


Fig. 11 (a) Main effect plot of chill thickness versus ultimate tensile strength, (b) Main effect plot of grain refiner versus ultimate tensile strength

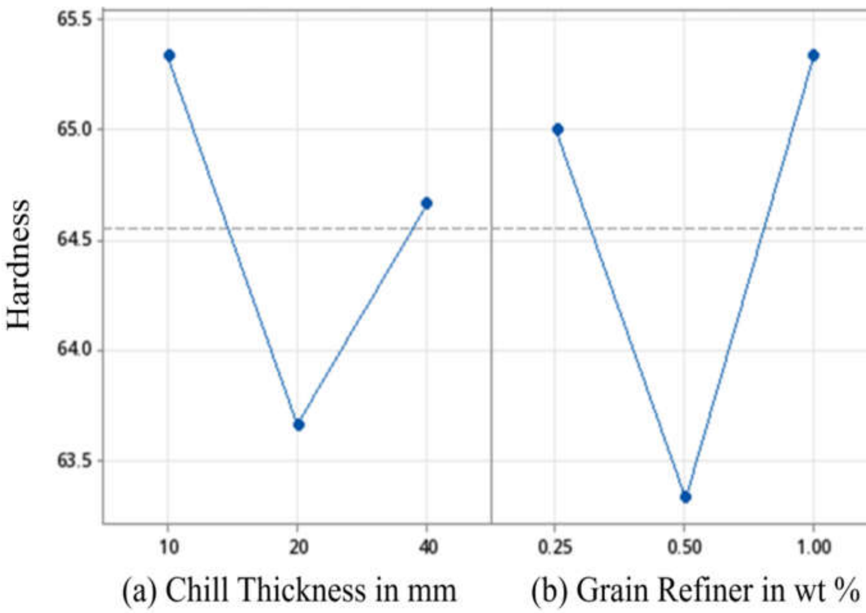


Fig. 12 (a) Main effect plot of chill thickness versus hardness, (b) Main effect plot of grain refiner versus hardness

Table 4 Response table for signal to noise ratios (Larger is better)

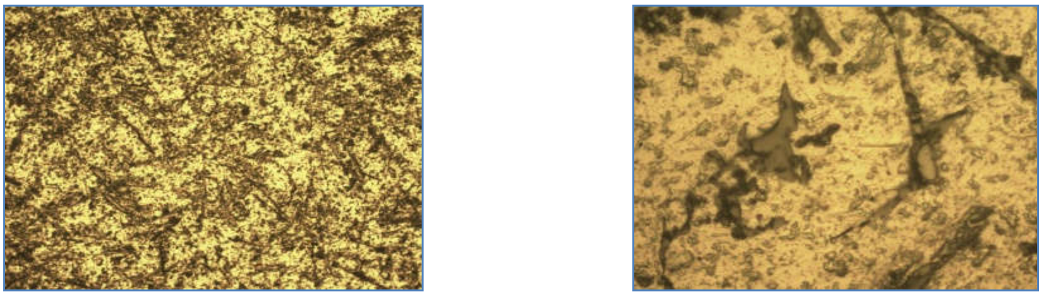
Level	Chill thickness	Grain refiner
1	40.75	40.35
2	40.63	40.86
3	41.12	41.29
Delta	0.49	0.94
Rank	2	1

Table 5 Response table for signal to noise ratios (Smaller is better)

Level	Chill thickness	Grain refiner
1	-36.30	-36.26
2	-36.08	-36.03
3	-36.21	-36.30
Delta	0.22	0.27
Rank	2	1

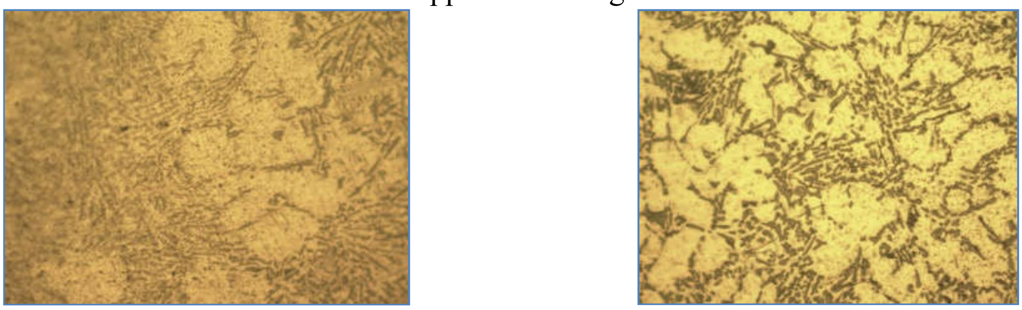
4. Microstructure study

Microstructure investigation is carried out on sand-cast LM6 alloy samples poured at a temperature of 700°C. This examination sought to investigate the grain structure, phase distribution, and other micro-structural aspects that are important for understanding the materials mechanical characteristics. Standard metallographic procedures are used to produce the specimens. This entailed polishing the samples using emery paper to obtain a clean and shiny surface, which is required for precise microstructural analysis under a microscope. The polished samples are treated with Keller's reagent, and micrographs are obtained with an optical microscope. The micrograph is captured with an optical microscope.



(a) (b)

Fig. 13 (a) Microstructure without copper chill and grain refiner 100X etched, (b) Microstructure without copper chill and grain refiner 500X etched



(a) (b)

Fig. 14 (a) Microstructure with 40 mm thickness copper chill and grain refiner 1 wt % 100X etched, (b) Microstructure with 40 mm thickness copper chill and grain refiner 1 wt % 500X etched

The casting specimens are prepared for microscopic examination, both without and with the addition of copper chilling and grain refiner. Fig 13 a-b shows micrographs 100X etched and micrographs 500X etched of the casting samples without copper chill and grain refiner. The casting indicated dendric network of silicon particles which are observed. The micrograph shows that network of silicon particles in alpha phase matrix.

Fig. 14 a-b shows micrographs 100X etched and micrographs 500X etched of the casting samples with copper chill and grain refiner. After applying 40 mm copper chill and 1 wt % Al5Ti1B grain refiner, it is observed that the casting indicated no dendric network of silicon particles. The spherical silicon particles are observed. The micrograph shows network of silicon particles in alpha phase matrix. The micrograph shows a finer grain structure. The grain pattern shown in the micrograph clearly indicates that a well developed microstructure improves mechanical characteristics.

5. Experiment without external chills and grain refiner

In addition, an experimental trial without copper chill and grain refiners is carried out on a foundry. The temperature of the molten metal pouring and casting is measured using a data recorder. The mechanical parameters, such as ultimate tensile strength and hardness, is tested using the sand casting process and is shown in Table 6.

Table 6 Ultimate tensile strength and hardness values for experiment without external chills and grain refiners

Case No.	Chill thickness (mm)	Grain refiner (weight %)	Ultimate tensile strength (N/mm^2)	Hardness (HV)
Case 10	NO	NO	90.29	63

6. Results and Discussion

A total of 10 trials are carried out in the foundry to investigate the influence of grain refiner and external copper chill on the mechanical characteristics of LM6 alloy castings. The goal of these experiments is to figure out the way variations in these factors affect the castings strength, hardness, and overall characteristics. The Fig.11 a-b shows that the ultimate tensile strength achieves its minimum value at 20 mm beyond this limit, the ultimate tensile strength rapidly increases as the chill thickness increases however increases in percentage of grain refiner, the ultimate tensile strength continuously increases. The ultimate tensile strength increased with chill thickness, with the maximum ultimate tensile strength value found at 40 mm.

The Fig. 12 a-b shows that the hardness achieved with a minimum value at 20 mm beyond this degree, the hardness rapidly increases as the chill thickness increases however increases in percentage of grain refiner, the hardness continuously increases. The hardness increased with chill thickness, with the maximum hardness value found at 40 mm. The microscopic examination of the LM6 alloy after copper chill and grain refiner shows improved grain structure. There is no dendric network of silicon particles becomes visible with the application of external copper chill with 40 mm thickness. The combined effect of adjusted input parameters produced higher ultimate tensile strength values at 40 mm chill thickness and 1 weight % Al5Ti1B grain refiner. Similarly, the hardness value was found to be higher at copper chill with 40 mm thickness and 1 weight % Al5Ti1B grain refiner. The use of external copper chillers significantly raised the cooling rate.

7. Conclusion

This study investigates the influence of external copper chilling and grain refiner content on the mechanical properties of LM 6 alloy castings. The findings reveal that controlling the chill size and integrating a 1 weight % Al5Ti1B grain refiner significantly enhances the mechanical characteristics. Specifically, external copper chilling facilitates directed solidification, resulting in a finer grain structure and improved ultimate tensile strength and hardness. Castings incorporating a 40 mm thick copper chill exhibit superior mechanical properties compared to those without external chilling. Regression analysis confirms a strong correlation between ultimate tensile strength, hardness, grain refiner content, and chill thickness. Overall, the application of external copper chills proves instrumental in enhancing microstructural integrity, with observed increases of 30.05% in ultimate tensile strength and 4.76% in hardness.

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