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Research Paper

Development and Evaluation of Mild Steel Permanent Mould for Al-Alloys Pulley Production

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ABSTRACT

The development and evaluation of a mild steel permanent mould were conducted with considerations based on materials availability, cost efficiency, and national economic development. The design, material selection, and fabrication strategy were all carefully chosen to meet these objectives. Geometric modelling of the mould design was carried out using Pro/Engineer® software, generating various views and parameters of the mould with and without components. Mild steel was chosen for mould production due to its strength, rigidity, availability, high melting temperature, surface finish, and machinability. Fabrication of the mould utilized basic machine tools such as a lathe machine and drilling machine. To evaluate the performance of the developed mould, an aluminium alloy pulley was produced using the mould and aluminium scraps. Microstructural analysis and hardness tests were performed on mould samples before and after casting. The results indicate that the heated mould sample, after casting, exhibits a fine-induced dendritic structure comprised of smaller grains, whereas the microstructure of the unheated mould displayed larger grain sizes. The maximum hardness number recorded was 204 HV for the mould sample after casting, indicating the ability of the mould material to withstand fatigue stresses and wear generated during casting.

1 Introduction

The performance of a pulley is very critical to the overall power transmission in machinery. Pulleys play an important role in transmitting power from one shaft to another, which is achieved by means of flat belts, V-belts, or ropes [1-4]. The transmission of power between shafts by the help of pulley is done either through gear or belt drives.

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Pulley also serves as automobile component for vibration, noise reduction, weight reduction, damping, and machine durability enhancement. Using a pulley in the engine drive systems of a vehicle makes the overall operation and performance of that vehicle more efficient [3-5]. The majority of pulleys utilized in various vehicles and machinery in Nigeria are imported. The rise in metal costs contributes to an increase in the overall expense of pulleys.

Additionally, the process of machining cast metal blanks to manufacture pulleys further adds to the cost. Hence, Nigeria, being a developing country must strive for self-reliance in various economic activities, encompassing construction and manufacturing engineering components. Foundry technology has contributed immensely to the development and economic growth of nations. Many industries depend, either directly or indirectly, on cast products made from various materials, ranging from metals to non-metals and their productions are carried out through the foundry process [5-7]. Producing a mould locally through our conventional foundry process will have a positive impact on nation's economy development, as many engineering and automobile components can be produced locally using the process.

The design and manufacturing of a pulley with appropriate materials are crucial factors in ensuring the end product and prolonged lifespan of an automobile engine [2, 4]. Pulley can be produced using many operations such as casting, forging of metal blanks, forming of dies and extrusion [1, 8, 9]. Metal casting is a process among the manufacturing process that is the most economical method of producing pulleys [10]. Casting of pulley are done in one piece or from a separate parts [11]. The production of a V-belt pulley with multiple grooves was accomplished using the metal casting process, as described by Dauda and Okechukwu (2014) [1]. The authors used a segmented pattern and a three-flask mould to produce a V-belt pulley. Raharjo et al. [12] produced a multilevel pulley through metal casting method. Casting provides versatility and flexibility that have maintained its position as a primary production method for machine elements. It is a process that involves melting the metal to a molten state, pouring it into a mould, and allowing it to cool and solidify.

Casting processes are divided according to the specific type of moulding method used in casting. These include sand centrifugal, permanent die, plaster mould, and investment casting. With the increasing demand for quality castings in production quantities, the interesting possibilities of metal moulds led to the development of permanent mould processes [11, 13]. A successful casting operation can be assessed through the type of pattern used. Pattern making is the first step towards actualizing quality casting products [5, 14]. The pattern, which is used to create the cavity called the mould, must be made from a suitable material that can withstand the high temperatures of the molten metal. Efficient heat transfers between the solidifying casting and the mould is crucial for ensuring high-quality casting. The heat transferred is controlled by the metal-mould interface condition [15].

According to [16], the type of casting to be produced depends entirely on the mould type used in the metal casting. Two categories of moulds are available for casting process: expendable mould which is temporary mould and permanent mould. Mould used for casting can also classified as an open and closed mould [5]. In an open mould, liquid metal is poured directly until it occupies the cavity. In a closed mould, a gating system is incorporated, providing a passageway for the liquid metal to flow from outside the mould into the cavity. Once the molten metal is in the mould, the process of cooling and gradual solidification begins, requiring time for a complete phase change. After the casting has adequately cooled, it is then extracted from the mould. The choice of permanent mould are on the basis that it can produce large numbers of dimensional intricate parts and it can be made from cast iron or steel. Permanent mould has been used in casting of many engineering components such as combustion engine piston, crucibles, engine connecting rod etc. [9, 17, 18]. The properties of the metal mould, including permeability and hardness, significantly influence the quality of castings [15, 16].

Pulleys can be made from a variety of materials, such as wood, plastic, and metal. Due to environmental and economic requirements, reducing the weight of vehicles or any automobile machine has become increasingly important. Hence, the most commonly used basic material for making pulleys is aluminium alloys [12]. The objective of using this material is to enhance the performance of an automobile engine. It has been noted that selecting suitable materials can significantly impact the overall functionality, durability, aesthetics, and cost-effectiveness of the final product [2, 4]. The material used in the production of pulleys depends on its capacity and engine manufacturer [9]. The usage of aluminium alloys for pulley materials is attributed to their favourable characteristics, including good thermal conductivity, a high strength-to-weight ratio, elevated strength at high temperatures, corrosion resistance, excellent castability, and enhanced wear resistance [17, 19, 20]. The present work aims at creating a conceptual design of a permanent mould using Pro/Engineer® design software and further developing the mould for use in pulley production.

2 Materials and methods

The following experimental techniques and procedures were adopted in carrying out this research:

2.1 Material Selection

When developing the mould for pulley production, the choice of material is fundamental. The selected mould material must withstand the high molten temperature of the aluminium alloy to be used in production. Therefore, a material with a higher melting temperature than aluminium was deemed suitable for designing and fabricating the permanent mould. Mild steel was chosen as the mould material, and its chemical composition is presented in Table 1. The selection of mild steel was based on criteria such as good machinability, dimensional stability, high-temperature strength, thermal shock resistance, fatigue resistance, and good conductivity [5]. Mild steel has a melting temperature range of 1351°C–1531°C and a pouring temperature range of 1566°C–1621°C. For the structural design analysis a Pro-Engineer® software employed as the design tool.

Table 1 – Chemical composition of mild steel

Element	C	Si	Mn	Cr	P	Al	S	Fe
Wt%	0.18	0.52	0.54	0.007	0.04	0.015	0.025	Bal

2.2 Geometric Modelling of the Pulley Mould

The geometric modelling of the pulley mould was carried out using Pro/Engineer® design software. Standard design parameters were employed which was used to compute the conceptual design. Necessary modifications were done and the resulting data was used to obtain the final CAD design, consequently a 3D mould was developed. The designed mould consists of three parts: the cope, the cheek, and the drag. The design was intentionally done without the use of a clamp to reduce the manufacturing cost [21]. Geometric models of the parts of the mould are shown in Figs 1-6.

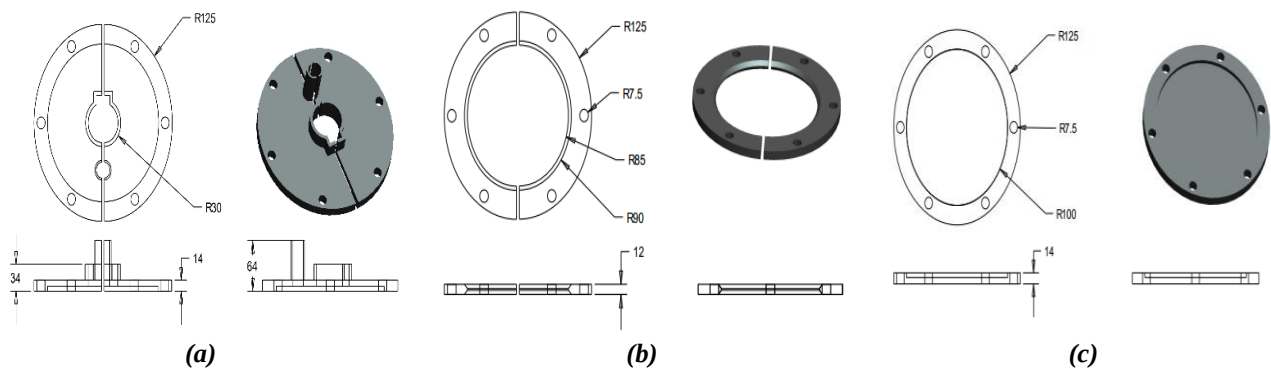


Fig. 1 – Third angle orthographic and isometric projections of the mould (a) Cope (b) cheek (c) Drag

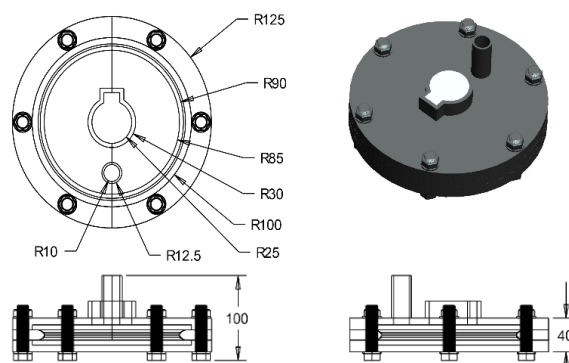


Fig. 2 – Third angle orthographic and isometric projection of the assembled mould

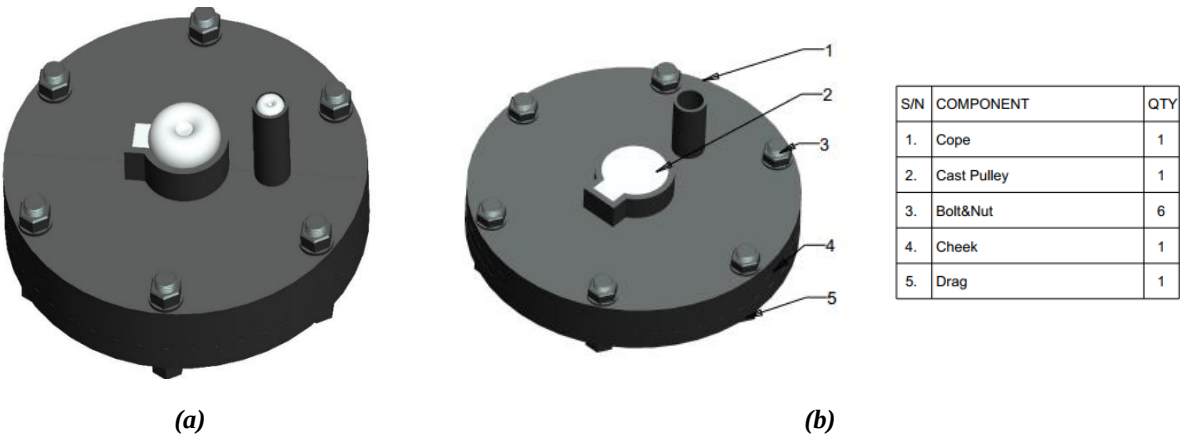


Fig. 3 – (a) Isometric view of the assembled mould and cast pulley (b) Isometric view of the assembled mould and its parts

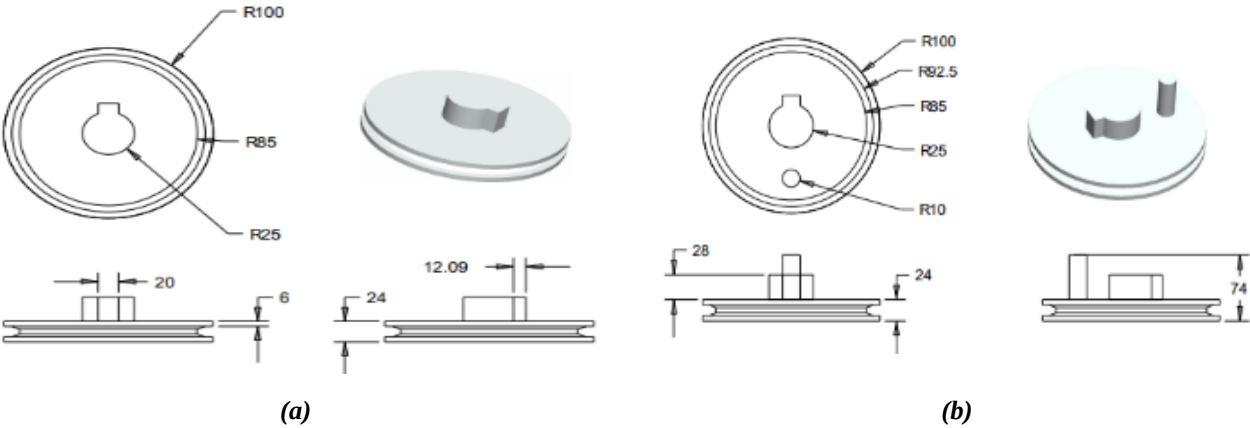


Fig. 4 – Third angle orthographic and isometric projection of the cast pulley (a) without sprue (b) with sprue

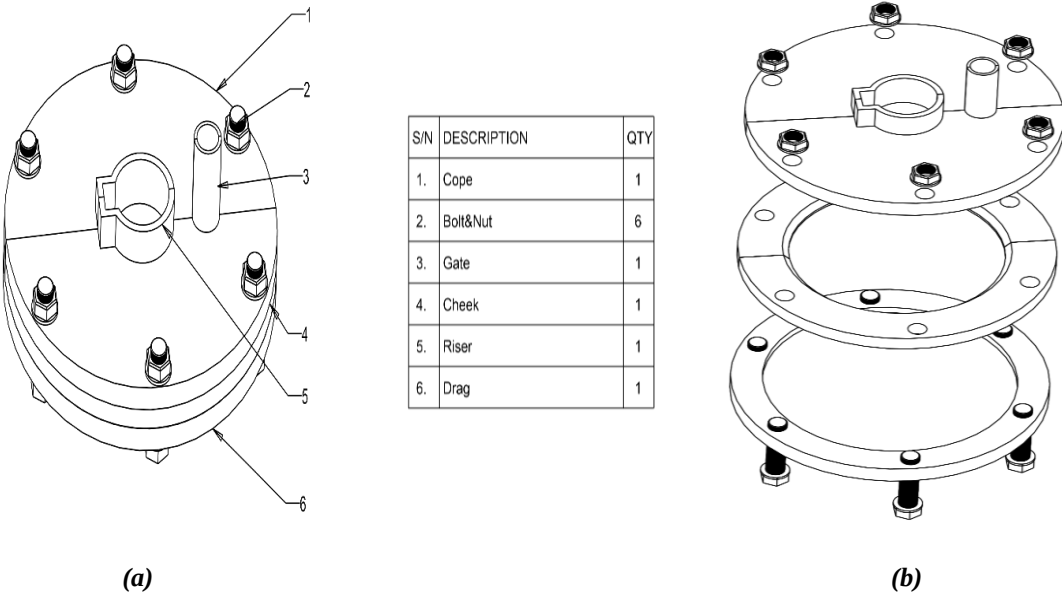


Fig. 5 – (a) Isometric view of the pulley mould assembly-wire frame (b) Exploded view of the mould

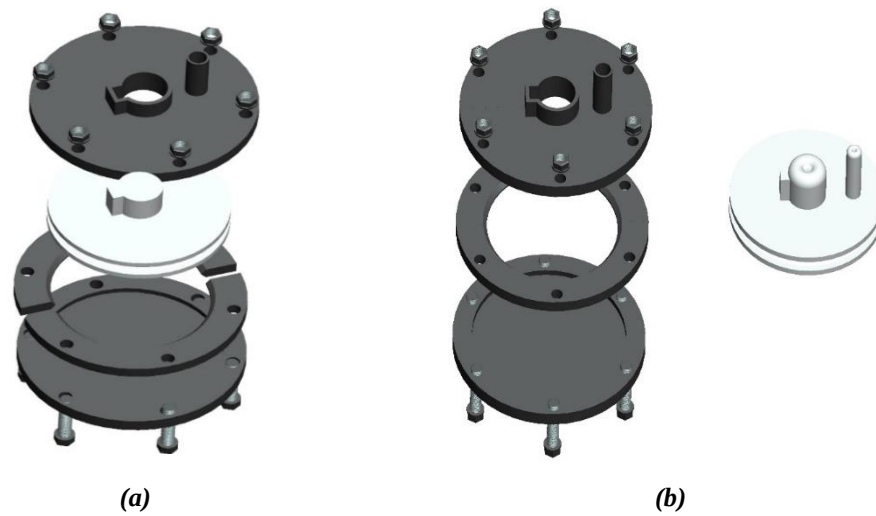


Fig. 6 – 3D Exploded view of the mould (a) attached with the cast pulley (b) without the cast pulley

2.3 Calculation of the Pulley's Mass Properties

Before melting aluminium scraps to assess the performance of the developed mould, the mass properties of the pulley were determined using the Pro/Engineer® software analysis tool, as reported in [1]. The analysis involved several steps in the software, which generated the mass properties. First, the pulley model, as shown in Fig. 7, was drawn. Next, the analysis icon was clicked, and the model was scrolled, followed by clicking on mass properties. The density value was changed to 0.0000000027, and the 'compute current analysis for preview' option was clicked. The volume was then highlighted and copied to mass, and finally, it was pasted in MS Word. Note: The density of aluminium is 2700 kg/m³, which is equal to 0.0000000027 tonne/mm³.

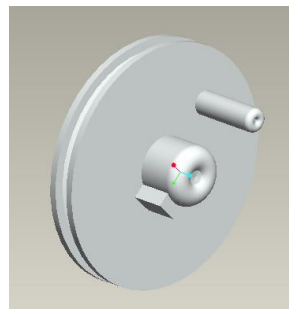


Fig. 7 – Geometric model of the pulley

The results of the mass properties of the pulley model are

$$\text{VOLUME} = 7.5782928e+05 \text{ mm}^3 \quad (1)$$

$$\text{SURFACE AREA} = 1.0131574e+05 \text{ mm}^2 \quad (2)$$

$$\text{DENSITY} = 2.7000000e-09 \text{ Tonne / mm}^3 \quad (3)$$

$$\text{MASS} = 2.0461391e-03 \text{ Tonne} \quad (7)$$

2.4 Development of the Permanent Mould

The procedures for the development of the mild steel permanent mould are summarized in Table 2. The major production processes include cutting, boring, drilling, and turning operations. The mild steel was cut into the desired length and size,

and afterward, it was assembled and mounted on a lathe machine. Cutting with the lathe machine removed unwanted materials by advancing a cutter into the work piece. The work piece was secured in a lathe machine chuck, and selected holes were drilled into the mild steel block to create a cavity for the pulley. Any excess metal was then removed using the turning process of the lathe machine and boring operations

Table 2 – Procedures for mould development

Mould Parts	Production Process
Cope of the mould	Cutting, turning, drilling, boring, welding
Mould cheek	Cutting, drilling, boring, facing, taper turning, welding
Mould drag	Cutting, drilling, boring, welding

2.5 Determination of the microstructure and hardness of the mild steel mould sample

Hardness test was conducted on the mould sample. Additionally, microstructural examinations of the mould before and after casting were performed using a scanning electron microscope equipped with an EDS. The procedures for both tests on the sample were carried out as follows:

For the hardness test, the samples were ground and polished. The Vickers hardness test was conducted using a load of 0.3 kgf. The mould samples were indented, and different hardness values were obtained before and after casting the pulley with the mould. The test was conducted at three different points on each sample to validate the results, and the average value was taken.

Using the scanning electron microscopy (SEM) of Model: JEOL JSM 7600F, the structural characteristics of the mould sample before and after casting were determined, while the elemental distribution was verified using energy dispersive spectrometer (EDS). Prior to the microscopy examination, the samples were thoroughly polished with fine alumina powder after being ground with a series of emery papers of grits 220, 500, 800, and 1200. Nital etchant (ethyl alcohol + 2% HNO₃) was used as an etching Reagent in which the sample surface was dipped before mounting on the microscope for structural inspection and micrographs. Image analysis processing method for the measurement parameters like the grain size, average grain size distribution and the average area was examined using ImageJ software.

3 Results and Discussion

The parts of the developed mould are presented in Fig. 8. The parts consist of mould cheek and mould drag which are assembled together to form a complete mould. The mould consists of three distinct parts: the cope, the cheek, and the drag. The cope serves as the upper part of the mould, while the drag is the lower part of the mould frame. The mould cheek is the central part that separates the cope and the drag. This three-part pulley mould system allows for the casting of larger components.

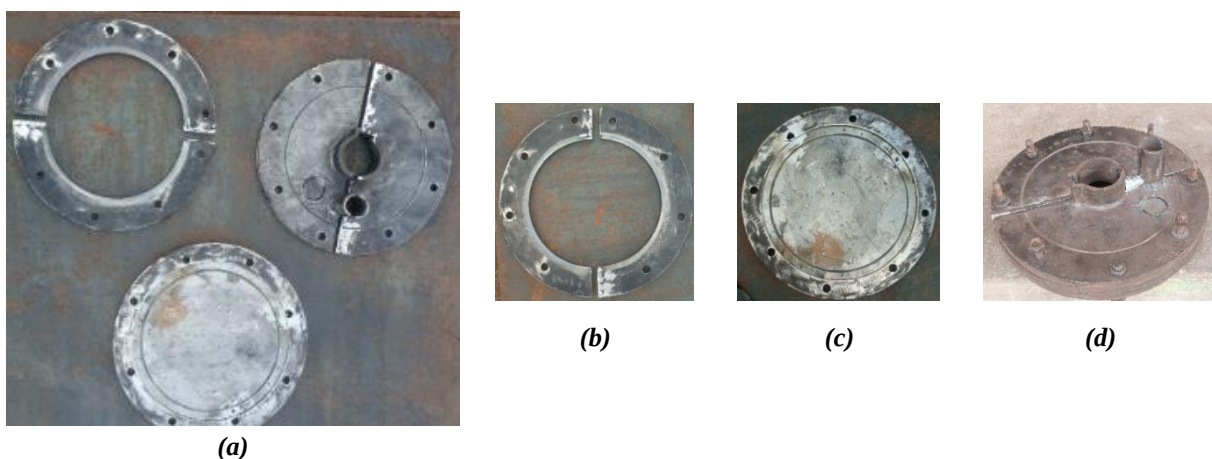


Fig. 8 – Pictorial views of the developed mould (a) mould parts (cope, cheek and drag) (b) mould cheek (c) mould drag (d) assembled mould with the cope

3.1 Microstructure and Grain Features of the Permanent Mould Sample

The microstructural features of the mould before and after casting are shown in Figs 9 and 10, along with their respective EDS. The microstructure of the mould sample before casting (Fig. 9) revealed a large dendritic grain structure and size compared to the mould sample after casting (Fig. 10). It was observed in Fig 10 that the dendritic grains are smaller in size, because of the heat from the molten metal and mould preheating process. The efficient thermal dissipation of the molten metal alloy in the mould resulted in the even dispersal of the grains, contributing to the reduction in dendrite size [17]. The EDS elemental composition results help to authenticate the intensity of the elements that build up the mild steel material both before and after casting.

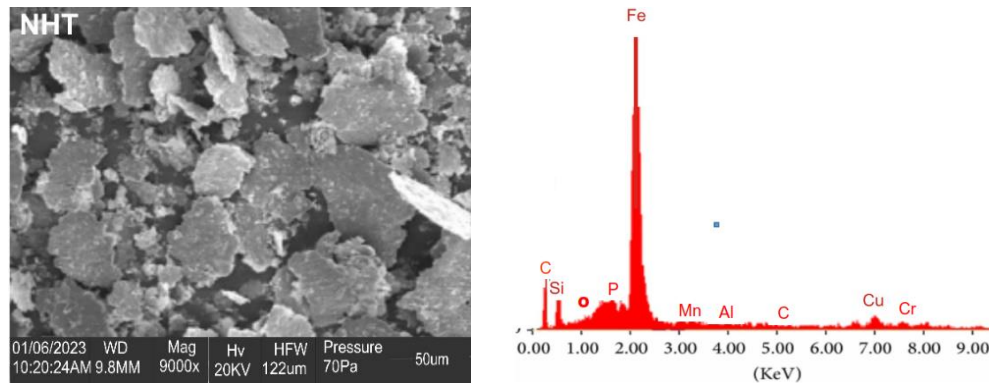


Fig. 9 – SEM image of the mould sample before casting

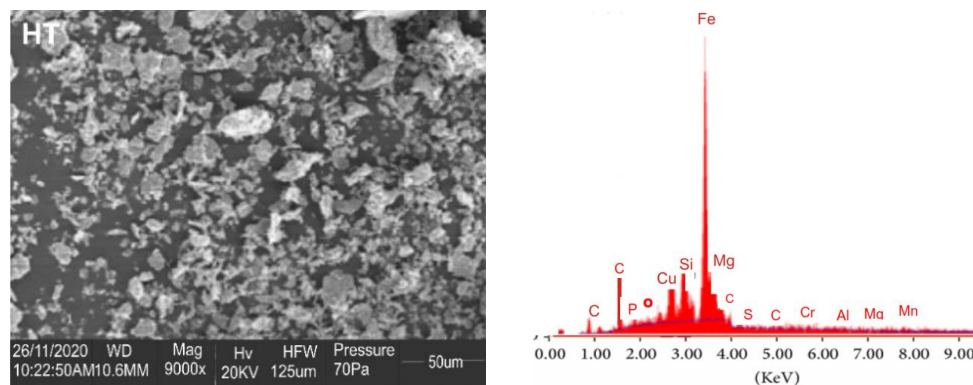


Fig. 10 – SEM image of the mould sample after casting

The grain size distribution in the microstructure was determined by measuring the grains using ImageJ software. The findings in the SEM images could not highlight the differences in the average grain size and distribution of the mould sample; hence, ImageJ software was used. The data obtained after analysing the SEM image of the moulds in ImageJ software are shown in Table 3. From the table, it could be observed that the grain size of the mould samples varies significantly. The mould sample before casting recorded an average grain size distribution of 3.5763 μm and an average particle size of 12.41 μm on 53 grain counts, covering 51.183% area. This indicates that mould grains appear larger and unevenly distributed. At the grain count of 117, the mould sample after casting exhibited a measured average grain size distribution of 14.982 μm , an average particle size of 4.3 μm , and a covered area of 41.592%, indicating the microstructure precipitating smaller grains as a result of the heat from the molten metal on the mould.

The histogram plot shown in Fig. 11 depicts the lognormal fitting function of the measured grain size and size distribution. The grain size distribution was described by the log-normal function on the statistical scale, suggesting that the microstructures were mainly composed of smaller grains, with a few larger grains present in between [22, 23]. From the histogram plot, it is observed that the grain size diameter of the mould sample before casting ranges from 2 to 6 μm , while

that of the mould after casting ranges from 8 to 24 μm . This suggests that the microstructure of the mould sample before casting consists of larger grains with fewer smaller grains filling in the gaps. Conversely, the mould after casting, influenced by heat causing grain dispersion, is composed of smaller grains with very few larger grains in the gaps [22, 24].

Table 3 - Summary of the image analysis results for the microstructural description of the mould samples

Plate Name	HT 9000X.	NHT 9000X
Count	117	53
Average Grain Size Distribution	14.98264	3.5763
Sum	958.889	189.546
Standard Deviation	12.131	51.118
Minimum	3.376	0.283
Maximum	99.361	324.854
Total Area	503.14	620.519
%Area	41.592	51.183
Average Particle Size After	4.3	12.41

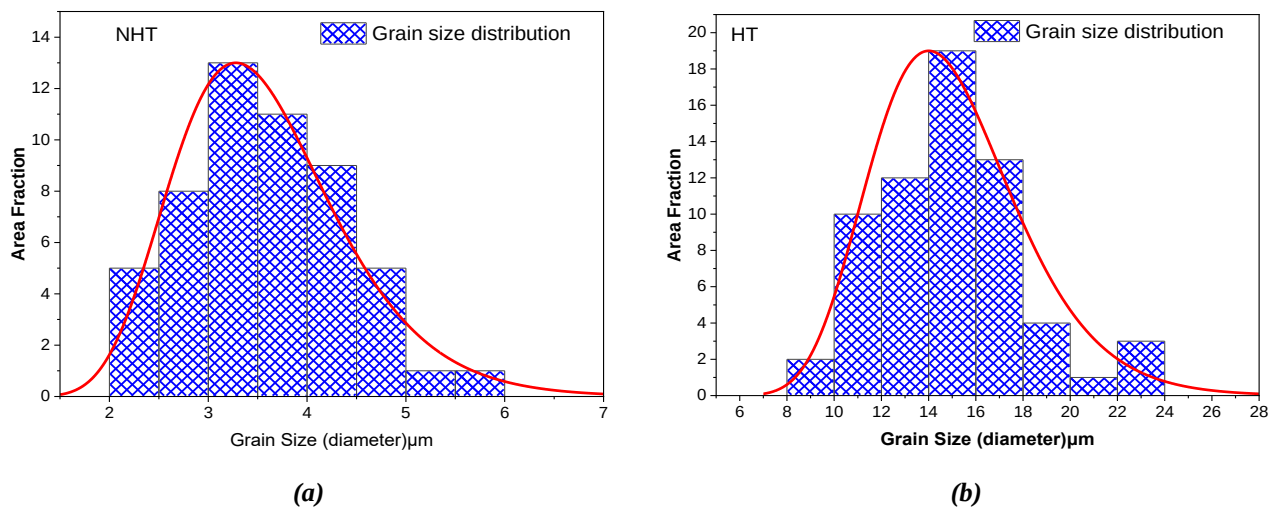


Fig. 11 – Grain size distribution of the mould sample (a) before casting (b) after casting

3.2 Hardness Result

Table 4 shows that the average hardness values of the mild steel mould samples before and after casting are 123 HV and 204 HV, respectively. It is obvious that the hardness value of the sample after casting using the mould is higher than that of the unheated mould. Therefore, it can be concluded that the elevated temperature resulted in an increased hardness value of the mould material. Comparing the average Vickers hardness value of mild steel, which is 174 HV [25], with the obtained average hardness value of the material (204 HV), we can opine that the chosen material possesses favourable properties for the design and can possibly withstand wear.

Correlating the microstructure of the mould (grain size) with the obtained hardness value after casting, it can be stated that finer, smaller grain sizes led to an increase in the hardness value of the mould material, while larger grain sizes lead to a lower hardness value, as observed in the case of the mould material before casting. This observation aligns with the findings of [26], which revealed that indentation hardness increases with increasing indentation depth due to grain boundary effects.

Table 4 – Hardness values of the sample

Mould Sample	Vickers Value (HV)
Before Casting	123
After Casting	204

3.3 Performance Evaluation

After developing the mild steel permanent mould, an aluminium alloy pulley was cast using the mould to assess its functionality. The production process of the aluminium alloy pulley began with preheating the mould to a temperature of 140°C to enhance the fluidity of the molten metal during pouring. Thereafter, aluminium scraps were melted using a local furnace powered by a 20-volt solar panel. When the aluminium scrap had melted, the molten metal was poured into the mould, while ensuring uniform flow. During the casting process, while cooling was taking place, different temperatures of the mould were determined over time. After casting, the mould was dismantled for the removal of the cast pulley once it had solidified. The pictorial view of the melting process and the summary of the casting process are presented in Figs 12 and 13(a-c). Fettling process was carried out on the produced pulley after removal from the mould, to cut off the sprue gate. The cast pulley was then taken to the lathe machine for drilling to ensure that the hole in the pulley hub is concentric.



Fig. 12 – Melting of the aluminium scrap in a bail-out furnace



(a)



(b)



(c)

Fig. 13 – Casting process (a) pouring process (b) molten metal in the mould (c) Cast pulley after dismantling

3.3.1 Thermal behaviour of the mould

The heat flow distribution in the mould during solidification was determined at various times using an industrial thermometer. From the results graphically presented in Fig. 14, a comparison of the solidification temperature and time was made, as it is necessary to facilitate the cooling process during casting. It can be observed that the temperature increases when the molten metal is poured into the mould and decreases with time as it solidifies. The graph shows that the temperature decreases with an increase in time, indicating that the solidification temperature is inversely proportional to the time. The thermal behaviour of the mould corroborates with the conclusions drawn in [12, 17]. Furthermore, it can be inferred that the temperature distribution at the mould cope indicates that opting for mild steel as the mould material facilitates effective dissipation of heat from the mould cavity to the external surface of the mould, owing to the inherent thermal/temperature disparity [17].

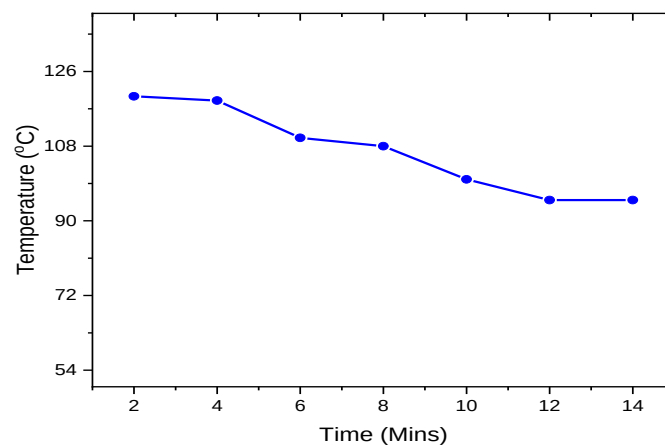


Fig. 14 – Graph of cope temperature and time during solidification process

4 Conclusion

The development and evaluation of the mild steel permanent mould were carried out, and the microstructure characteristics, hardness, and thermal behaviour of the mould material before and after casting were investigated. The use of a Pro/Engineer® software design tool for geometric modelling and orthographic projection, along with the casting of aluminium alloy pulley, facilitated the successful evaluation of the developed mould's performance. The outcome of this work has paved way for local production of pulley components and other engineering parts utilizing our conventional foundry process, as well as enabling efficient management of our scraps for wealth creation and contributing to the nation's economic development. Manufacturers of machine components can explore the permanent mould method of pulley production in mass producing pulleys. Also, local foundries in rural areas where lathe machines are scarce can leverage on the method to produce aluminium alloy pulleys. Based on the analysis results, the major findings are concluded as follows:

- The microstructure and hardness properties of the mould samples are influenced by the heat temperature from the preheating of the mould and molten metal poured into the mould.
- The heated mould sample, post-casting, displays a fine-induced dendritic structure comprised of smaller grains. The application of heat to the mould significantly influences the mould material, as evidenced by the microstructure of the unheated mould, which exhibited larger grain sizes.
- The hardness results of the mould samples (prior to casting: 123HV and post-casting: 204HV) suggest that the mild steel mould is capable of enduring potential wear that may arise during the pulley casting process.
- The thermal temperature results show that the use of mild steel permanent mould in the production of pulleys allows thermal dissipation during the casting process.

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