JJMIE

Volume 14, Number 4, December. 2020
ISSN 1995-6665
Pages 401 - 411

Jordan Journal of Mechanical and Industrial Engineering

Design and Analysis of Permanent Mould for Small Internal Combustion Engine Piston

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Received June 5 2020 *Accepted November 7 2020*

Abstract

The lack of electrical power supply in African homes has led to a quantum proliferation and usage of portable backup power alternatives like generators. The ceaseless running of generators makes most homes to overshoot the recommended service life (approximately 150 hours) and maximum continuous runtime (4 - 6 hours) of generators in the earliest possible time. Burnout of piston and its eventual impairment consequently ensue, and this gives room for endless replacements of piston and incessant piston wastes. To manage piston waste, and to create a sustainable piston market, the outlook of reproducing piston from its wastes is engineered. As a result, this work examines the conceptual permanent mould design, thermal analysis and fabrication of the designed mould, and casting of 950 Watts generator's piston. The mechanical and microstructural properties of the as-cast pistons were correlated with the properties of LM13. Defect-free pistons were produced while the re-melting process slightly altered the composition of the as-cast alloy as compared to that of LM13.

Keywords: Permanent Mould, Mould Design, Piston, Casting, Mechanical properties; Aluminum alloy;

1. Introduction

The performance of pistons is critical to the overall output of internal combustion (I.C.) engines. Therefore, pistons must possess good strength and heat resistance properties [1]. The continuous operation of pistons beyond the recommended service life impairs their thermal bearing capacity and degrades their wear resistance capabilities. This situation is prevalent in the under-developed nations where electricity generation by state or public companies is poor, thereby, causing the citizens to run personal generating units for long time. The accumulation of extracted pistons from these units produces a disturbing pile of scrap pistons and creates a good opportunity for recycling.

Pistons receive an impulse from expanding gas and transmits the established energy to the crankshaft via the connecting rod. Pistons run at high speeds and work under high temperature, pressure, and fatigue stresses [2]. A piston's work environment is also corrosive which predisposes it to wear. The heat generated during the reciprocating action of the piston in the combustion chamber is dispersed through the piston to the cylinder walls [3]. Consequently, the continuous reciprocating motion of the piston generates severe stresses on the piston crown, sidewall, and the piston's ring. Therefore, there is a need for the piston construction and material to guarantee good strength, toughness, corrosion resistance, resistance to abrasive wear, and less fracture susceptibility [4]. The piston must also be light while presenting a good ratio of tensile strength to mass density [5]. Rao et al. [6] reported that the introduction of Al-1Ti-3B and P (as grain refiners), and Sr (as modifier) to the hyper-eutectic Al-15Si-4Cu alloy promotes the formation of CuAl2 particles (at the interdendritic regions) and this attribute improves the wear resistance of the cast alloy. The studies of Reghu et al. [7] revealed that the application of thermal barrier coating on the Al-Si piston alloy enhances combustion (within the combustion chamber of diesel engines), and improves performance and piston life.

The most commonly used materials for piston production are cast iron, cast aluminum, forged aluminum, cast steel, and forged steel. The wide usage of Al-Si alloys as piston materials has been attributed to their desirable characteristics such as good thermal conductivity, high strength over weight ratio, high strength at elevated temperatures, excellent castability, and improved wear resistance [8]. The pistons for high-speed engines are primarily made of aluminum alloys which contain about 11–13% silicon and approximately 1% each of copper, nickel, and magnesium. As a result, typical pistons of automobiles and generators are cast from near eutectic Al-Si alloys or LM13 Al alloys [9] [10]. This class of aluminum alloy exhibits complex multi-phase microstructures which usually comprise of primary and eutectic Si, Al, and several intermetallic particles [11]. Chemical composition and microstructural features, such as eutectic Si particles,

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intermetallic compounds, and morphologies of dendritic α-Al (or secondary dendritic arm spacing) are factors that influence the mechanical properties of Al-Si cast alloys. However, casting technology remains the commonest means of improving the mechanical properties of these (aluminum-silicon) alloys [12].

Zhang et al. [13] compared the high pressure die casting and permanent mold casting of the Al-Si-Cu-Ni-Mg alloy. It was revealed that the cast from the high-pressure die casting process produced a higher tensile strength after thermal exposure. El-Labban et al. [14] employed a squeeze casting procedure to produce cast Al-Si piston alloy reinforced with Ni and nano-Al2O3 particles. The addition of Ni and nano-Al2O3 to the constituent of the alloy improved the resultant ultimate tensile strength of the cast piston. Ni particles were affirmed to be responsible for the improved ductility. Characterization undertaken by Zhang et al. [15] showed a fractographic appearance of automotive piston material (heavily alloyed Al−Si alloy) after tensile rupture. Cleavage or brittle fracture being reported as the failure mode of the piston under tension loading condition. Fracture of Si particle within the piston matrix was observed to have promoted the formation of cleavage facets and several secondary cracks. Meanwhile, the studies of Divya and Gopal [16] revealed that Al-Si pistons produced low deformation and equivalent strain values as compared to aluminum pistons.

Recent studies show an increasing interest in the reproduction of Al-Si pistons from scraps [17] [18]. Defected pistons and undesirable results have been attributed to the casting processes such as sand casting. There is a need to investigate the self-support casting process which can achieve reproducibility of pistons without the need for the preparation of mould at each casting time. This work presents a permanent piston mould design with a non-destructive core for 950 Watts generators and examines the thermal analysis of the designed mould. The development of the designed mould and casting of pistons were carried out to evaluate the effectiveness of the designed mould.

2. Methods

2.1. Permanent Mould Design

Fig. 1 shows the normal dimensions of a typical 950W generator. The mould material, requisite allowances, in-gate system design (dimensions), and morphology of riser are identified as the most central factors in the piston mould design. Equally, the hollow profile of the interior section or core of the piston requires careful consideration and design.

Based on manufacturers' specifications, pistons are made from Al-Si alloys and the liquidus temperature or the melting point of Al-Si alloys is usually about 530-660 oC. Thus, the appropriate melting and pouring temperature for the Al-Si alloy cast is adjudged to be greater than its liquidus temperature to ensure homogeneous melting, non-slurry molten metal, and cold shut defect-free cast. A pouring temperature range of 700 - 750 oC is chosen because this is the optimized temperature for Al-Si cast [19] and above this temperature, the vaporization of alloying constituents has a chance of occurring.

The choice of material for the casting process is vital because the chosen mould material is expected to withstand the high molten temperature of Al-Si alloy (700-750 oC). Materials with melting temperatures twice that of pure aluminum were considered to be suitable for the casting process. Mild steel was selected as the mould material (having a melting range of 1350oC-1530oC). The thermal/temperature simulation of the mould is investigated in Section 2.2. Based on the availability of the required thermomechanical properties of AISI 1065 carbon steel (with a melting point of 1460°C), the AISI 1065 carbon steel was employed for the mould simulation in this paper. The melting points of these steel alloys (AISI 1065 and mild steel) are relatively similar.

2.1.1. Mould Geometry (Piston Cavity)

The mould geometry is designed to take the form shown in Fig. 1 which is without the ring grooves because the grooves are expected to be machined afterward, to produce the standard piston dimensions. However, other allowances are built into the standard piston specification to avoid the production of undersized piston cast. The requisite allowances needed for the mould design include shrinkage, machining, and draft allowances. The allowances employed based on Narayanan [20] are given in Table 1.

Machining allowance (Ma) for non-ferrous metals with dimensions up to 203.2 mm is given as 2.29 mm. The diameter (D) and length (H) of the piston to be produced are 45 and 50 mm respectively. Likewise, to facilitate easy removal of the solid core from the cast piston, draft allowance (Da) is incorporated into the core length of the piston. The diameter of the piston core is 40.0 mm and its depth is 47.0 mm. The draft angle for metal with a height between 25.4 - 50.8 mm is 1o; thus, this angle (Da) is employed for the piston core.

The molten metal or cast is expected to undergo the following contractions or shrinkages: liquid shrinkage (a contraction of the liquid metal before solidification), liquid-to-solid/solidification shrinkage (shrinkage that occurs as crystals begin to form in the molten cast), and solid shrinkage (the final contraction that emerges as the solid metal casting cools to ambient temperature). For the permanent mould design, liquid shrinkage is considered to be negligible due to its minimal effect on volumetric cast while solidification (liquid-to-solid) and solid shrinkages are adjudged to be extremely important and must thus be considered in the casting design. Metals have different percentages of solidification and solid shrinkages. As a result, the shrinkage percentage (Sp) of non-ferrous alloys is adopted as the shrinkage allowance (Sa) for the Al-Si alloy (piston). According to Narayanan [20], the shrinkage allowance (Sa) in percentage for Al-Si alloy is provided as 1.29 %. Thus, the shrinkage allowances (Sa) for the piston's diameter (D) and length (H) are estimated using Eq. 1 and Eq. 2 respectively. The estimated diameter and length allowances are 0.37 and 0.68 mm respectively.

$$S_{a-W} = \frac{1.29}{100}(D + M_a) \quad (1)$$

$$S_{a-L} = \frac{1.29}{100}(H + M_a) \quad (2)$$

Where S_{a-W} and S_{a-L} are the designations for shrinkage allowances for the diameter and length of the piston. Also, the designed mould diameter (Dm) and mould length (H_m)

for the piston are estimated via Eq. 3 and Eq. 4 respectively. The computed mould diameter and length are 48.0 and 53.0 mm respectively.

$$D_M = D + M_a + S_{a-W} \quad (3)$$

$$H_M = H + M_a + S_{a-L} \quad (4)$$

The mould is designed to be of two symmetrical halves (split mould) with one half fixed and the other movable to facilitate easy removal of the cast piston. Representations of the designed split-half (mould) are shown in Fig. 2. Machining of a block of mild steel is employed for the fabrication of the mould. The thickness of the mould is continuous/kept constant throughout the mould's geometry to aid even heat suction or sink. Likewise, the mould is designed to be supported by other features such as mould base, clamping bolts, lock nuts, and turn-handle to aid easy assembly and disassembly of the two halves of the mould.

Table 1. Allowances built into the piston mould design

Allowance	Value
Machining allowance (M_a)	2.29 mm
Draft allowance (D_a)	1°
Shrinkage allowance for diameter (S_{a-w})	0.37 mm
Shrinkage allowance for length (S_{a-w})	0.68 mm

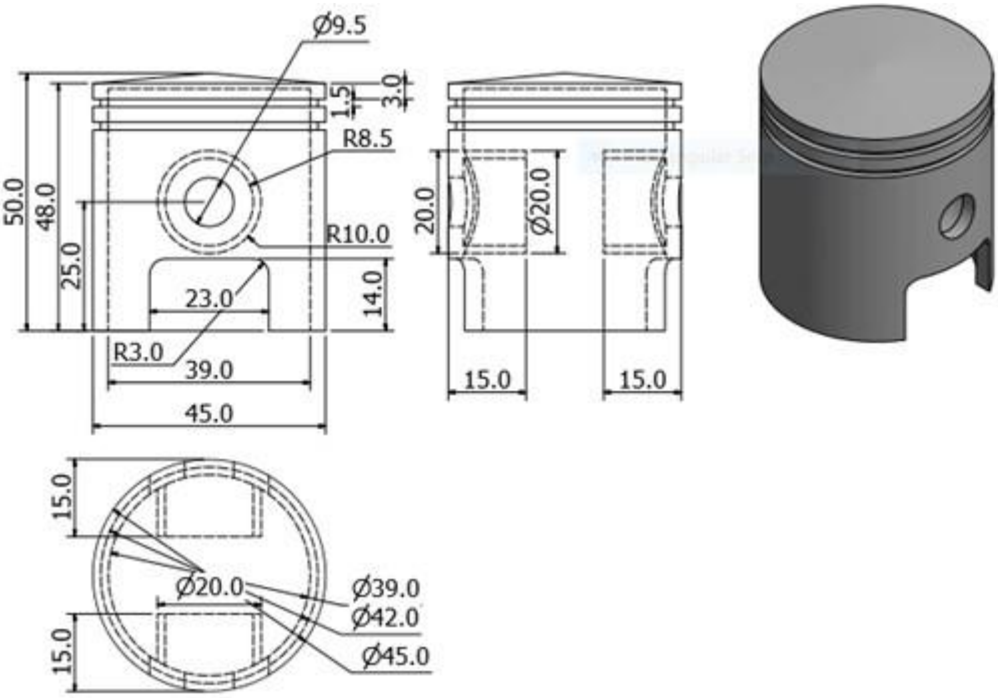


Figure 1. Standard dimensions (mm) of a 950 W electric power generator piston

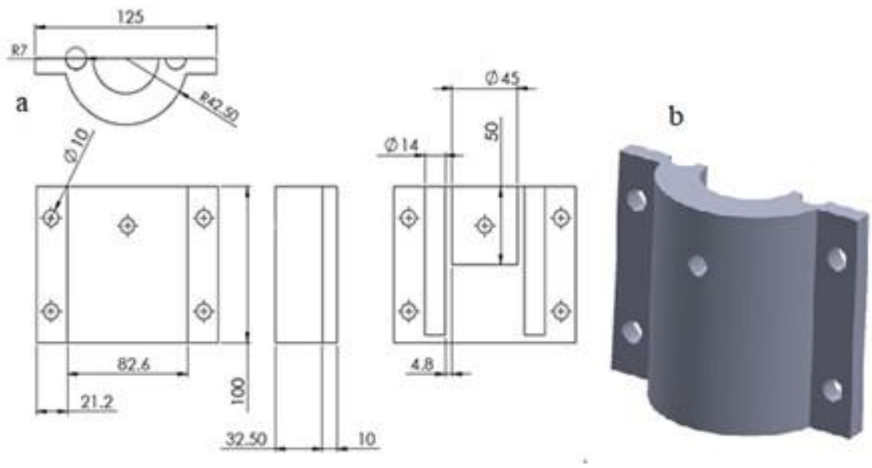


Figure 2. Mould half (split mould) (a) projection views; (b) isometric drawing

2.1.2. In-gate system design

The main purpose of the gating system is to direct the flow of the molten metal into the mould cavity. The gating system for the piston mould comprises of the following components: pouring basin; sprue; runner; and in-gate.

The pouring basin is otherwise known as the funnel-top and it is the point of entry where molten metal is first received in a designed mould before the entry of the molten metal into the sprue. The sprue is the tapered cylindrical section of the molten metal entry gate which controls the rate of the entry (of molten metal) into the mould (runner, in-gate, and cavity). The channel designed for the distribution of molten metal from the sprue to different regions in the casting is referred to as the runner. The runner also controls the velocity or flow rate of the molten metal into the mould. The point of metal entry into the actual casting or mould cavity is referred to as in-gate. Good quality of a cast or homogeneous mould filling has been adjudged to be dependent on a proper gating system design [21] and the gating system design needs to follow an iterative process [22]

The sequential steps employed in designing the gating system for the piston cast involve:

1. Estimation of optimum pouring time of casting,
2. Calculation of sprue choke area
3. Selection of gating ratio
4. Selection of the type of gating/location
5. Calculation of runner and in-gate sizes

The pouring time (t) is considered to be dependent on fluidity and dross-forming characteristics of the Al-Si alloy. The total weight of the casting or the casting geometry can as well influence the pouring time required for the piston casting. Based on this understanding, the pouring time is estimated from Eq. 5. Increasing casting speed or reduced pouring time has been adjudged to be an effective way to eliminate shrinkage porosity defect as revealed in the works of Jie et al. [23].

$$t = \frac{W_m}{M_{fr}} \quad (5)$$

Where t is the pouring time, W_m is the total weight of the casting or weight of the metal to be poured and M_{fr} is the metal flow rate of Al-Si alloy at 700-750oC. The sprue choke area of the ingate system is estimated by using Eq. 6 [24].

$$A = \frac{G}{c*\rho*t\sqrt{2gh}} = 29.59mm^2 \quad (6)$$

Where A is the sprue choke area (sprue exit area), G is the casting gross weight (cavity, piston, and runner) = 0.1738 Kg, c is the discharged coefficient which is 0.4 for thin-wall casting, ρ is the density of the Al-Si base alloy (2500 kg/m3), t is the pouring time (4.07 s), h is the metallostatic height from the ladle to the choke area (104 mm) and g is the acceleration due to gravity (9.81 m/s2). The in-gate area was estimated as 49.22 mm2 via Eq. 7 while the in-gate diameter was approximately 8 mm. The transition between the sprue exist area and the in-gate (that is the runner) must be designed to reduce metal velocity. Thus, the runner of a 10 mm diameter was chosen for the design because the cross-section of the runner should be greater than that of the sprue exit area.

$$A_{sprue-exit} = \frac{A_{spue-inlet}\sqrt{H_{sprue-exit}}}{\sqrt{H_{spue-inlet}}} \quad (7)$$

Where A_{sprue_inlet} is the sprue inlet cross-sectional area, A_{sprue_exit} is the sprue exit cross-sectional area, H_{sprue_inlet} is the distance between the ladle and sprue top and H_{sprue_exit} is the distance between ladle and sprue exit. A side gating type/location was chosen for this design due to the mould type, casting wall thickness, and weight of metal required to enter the mould.

2.1.3. Riser design

A riser is needed to accommodate the liquid shrinkage and to supply feed metal to compensate for the solidification shrinkage during the casting process. The volume of the riser should be greater than that of the in-gate to ensure that casting solidifies before the riser [25]. According to Chvorinov's Rule, the mathematical relationship between the solidification time for a simple casting, the volume, and surface area of the casting is provided as shown in Eq. 8 [25] [26].

$$T_{TS} = C_m\left(\frac{V}{A}\right)^n \quad (8)$$

Where T_{TS} is the total solidification time in min, V is the volume of the casting, A is the surface area of the casting, n is an exponent usually taken to be 2 in value, C_m is the mould constant which is dependent on the mould material, thermal properties of the cast metal and pouring temperature.

The mould constant (C_m) is determined from the piston's mould cavity. The T_{TS} is expected to be less than 1.5 minutes. The volume and the surface area of the piston are estimated according to Eq. 9 and Eq. 10 respectively. The mould constant is thus estimated by employing Eq. 8. This mould constant is also applicable to that of the riser. The volume and surface area of the riser (it is assumed to be cylindrical) are determined via Eq. 11 and Eq.12 respectively.

$$V_c = V_{mc} - V_{cc} + V_I + V_r \quad (9)$$

$$A_c = A_{mc} - A_{cc} + A_I + A_r \quad (10)$$

$$V_r = \frac{\pi d^2 h}{4} \quad (11)$$

$$A_r = \pi dh + \frac{2\pi d^2}{4} \quad (12)$$

Where Vc is the total cast volume, Vmc is the volume of the mould cavity, Vcc is the volume of the core, V_I is the volume of the sprue/in-gate, and Vr is the volume of the riser (in Eq. 9 and Eq. 10). Also, V_r is the volume of a cylindrical riser, A_r is the surface area of a cylindrical riser, d is the diameter of the riser, h is the height of the riser (see Eq. 11 and Eq.12). The height of the riser is twice the diameter of the riser (h = 2d). Therefore, the modulus of the riser is given as Eq. 13. The diameter of the riser is thus estimated as the product of the modulus of the riser and five (5) units. Based on the condition of freezing, the ratio of the inverse modulus of the casting to the inverse modulus of the riser should be greater than unity or $M_r : M_c > 1$ (where, M_c is the modulus of the casting). The $M_r : M_c$ is taken to be 1.2 ($M_r = 1.2M_c$) to satisfy the condition of freezing (freezing ratio) in this design. Thus, the diameter of the riser (d) is estimated as 10 mm using Eq. 13 when M_c is 1.6.

$$M_r = \frac{V_r}{A_r} = \frac{d(2d)}{4(2d)+2d} = \frac{d}{5} \quad (13)$$

The designed permanent mould with its support structures is shown in Fig. 3. The supports provided are integrated into the permanent mould to aid handling and easy removal of cast piston via the turning handle after solidification.

2.2. Thermal simulation of the designed mould

Based on the designed mould in Section 2, the thermal gradient of the mould around the piston core is simulated. The modeled geometries of the mould and its core were drafted using 3D CAD Design Software (Solidworks) for analysis in COMSOL Multiphysics Software (simulation package). The meshing of geometries and boundary condition assignments were carried out before the post-processing (simulation) of the mould. The triangular tetrahedral element was selected as the element type for the halves of the mould and the piston core as indicated in Figs. 4 and 5 respectively.

The components were discretized and the numbers of elements of the movable mould half and piston core were 32050 and 8460 respectively. Since the mould is asymmetrical, the movable half of the mould is considered and simulated to save time. The employed mould material is AISI 1065 carbon steel (UNS G10650) which has a density of 7.85 g/cm3; the chemical composition and mechanical properties of the alloy are shown in Tables 2 and 3 respectively.

The reference temperature for the study was pre-set at 273.15 K while the entire body of the mould was insulated to ensure the visibility of temperature distribution across the bulk matrix of the mould and piston core upon subjection to high-temperature molten metal. The temperature of the molten metal for the casting was set as 800 oC. Basic governing laws of thermodynamics apply to the simulation process. The generalized governing differential equation for heat conduction in the permanent mould can be represented as given in Eq. 14 [28-30]

$$K\nabla^2 T + q_E - \rho C \frac{\delta T}{\delta t} = 0 \qquad (14)$$

Where K is the thermal conductivity in the radial and axial direction of the mould, q_E is the heat conduction per unit volume, ρ is the density of the mould material, C is the heat capacity of the mould material, T is temperature and t is time.

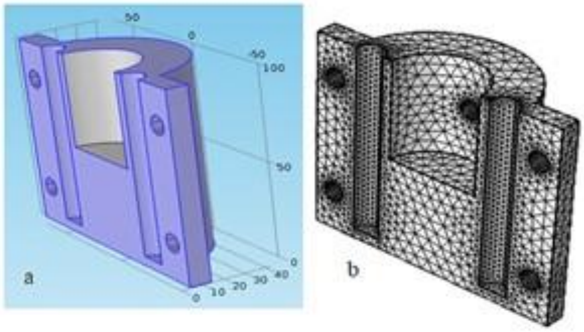


Figure 4. Cast piston permanent mould on (a) Movable half of mould; (b) discretized mould

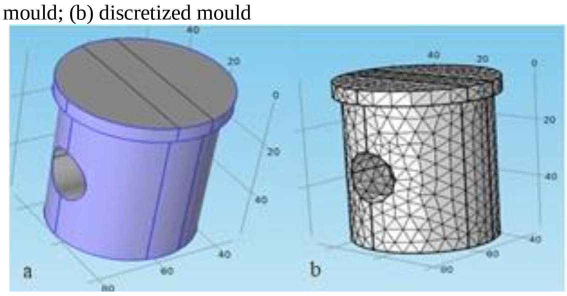
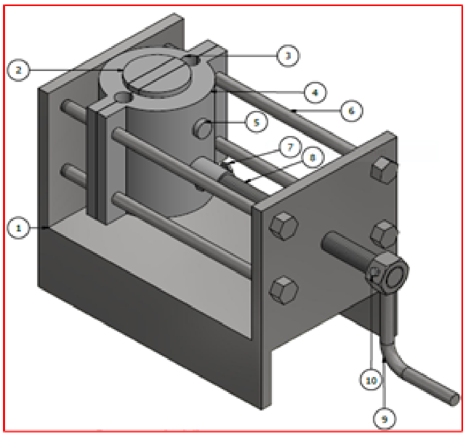
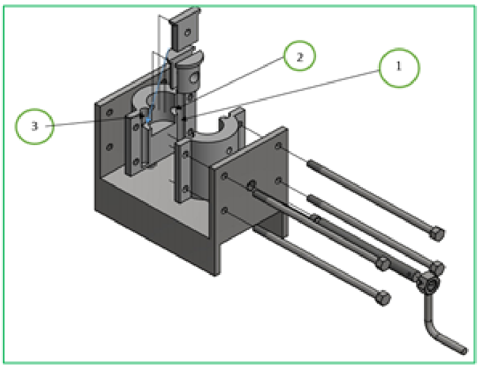


Figure 5. Geometry of the piston core (a) unmeshed core; (b) discretized/meshed core



Parts list		
Part number	Qty	Item
11	1	Lock nut
10	1	Lock bolt
9	1	Turning handle
8	1	Clamping bolt
7	2	Locating bolt
6	4	Guide bolt
5	1	Gudgeon pin
4	2	Side mould
3	2	Inlet hole for molten metal
2	3	Core components
1	1	Mould base



Part list		
Part number	Qty	Item
3	1	runner
2	1	Ingate
1	1	riser

Figure 3. An assembled model of the permanent mould

Table 2. Chemical composition of AISI 1065 steel [27]

Element	Fe	Mn	C	S	P
Content	98.31 - 98.8	0.60 - 0.90	0.60 - 0.70	0.05	0.04

Table 3. Mechanical properties of AISI 1065 steel [27]

Tensile strength (MPa)	Yield strength (MPa)	Elongation	Hardness (Brinell)
635	490	10%	187

3. Results and discussion

3.1. Thermal analysis of mould and core

Heat flows or temperature distributions in the mould and the piston core are examined at various times or durations as indicated in Figs. 6, 7, and 8. The results show that heat transfer increases with time from the mould cavity to the external surface of the mould due to the inherent thermal/temperature disparity (between the core and the surface of the mould). A progressive heat transfer from the mould cavity/core ensues in the mould to attain thermal equilibrium. This occurrence is expected to facilitate the cooling process during the casting process.

Figs. 6 and 7 describe the thermal response of the mould when molten material is introduced into it. The assessment of the volume and surface temperature distributions across the mould shows a relatively similar pattern. As a result, the surface temperature distribution was used in the description of results in this study. The progress and pattern of the heat flow or temperature distribution from inside the mould are studied. The surface temperature distribution shows that the choice of the mould material (steel) permits satisfactory thermal dissipation as the external surface temperature of the mould rises from room temperature to about 640 K after the post-pouring time of 60 s. This observation corroborates the higher thermal conductivity of the AISI 1065 mould material (49.8 W/mK) [27] as compared to that of a sand mould. The highest temperature appears at the mould interior/cavity at the beginning of the casting process and it progressively rises towards the mould's exterior/external surface via a conductive heat transfer mode. Although there is a big range of temperature distribution between the interior and external surfaces of the mould at the beginning of casting, the temperature gap closes down as the post-pouring time increases to establish thermal equilibrium. The rate of conductive heat transfer in the mould is influenced by the temperature difference between the interior part and the external surface of the mould.

The thermal transfer distances across the mould at different post-pouring times are revealed in the contour thermal plots (sectional views) of the mould provided in Fig.7. Fig. 7 shows that thermal dissipation through the sharp edges (corners) of the mould is not as pronounced as the body of the mould without geometrical changes as the post-pouring time increases. The width of the yellow coloration (590 - 680 K) is narrower at the corner of the mould after the post-pouring time of 60 s. This occurrence may be likely attributed to geometrical variations which could bring about constriction of contour lines and an eventual narrow temperature range of 590 - 680 K in the mould. The obtained result corroborates the findings of Rafique and Iqbal [31] as heat transfer patterns were reported to be strongly dependent upon the mould geometry and wall thickness.

On the other hand, the thermal dissipation in the core of the mould is revealed in Fig. 8. This shows that the core acted as a form of the heat sink on receiving the molten metal of the Al-Si alloy. The bulk of the heat/temperature of the molten metal is transferred to the mould as the post-pouring time increases. Evidence of this occurrence is revealed on the external surface of the core as rapid cooling appears on the core as the post-pouring time increases. The lower surface area of the core as compared to that of the mould cavity may be responsible for the faster cooling of the piston's core due to a direct relationship exists between the rate of heat transfer and surface area.

3.2. Casting result

The designed mould was fabricated via various machining processes and the produced mould was employed for casting 950 Watts pistons. The Al-Si alloy scraps were melted in an open-hearth furnace set at a temperature of 720 ^oC. The molten alloy was stirred to ensure a homogeneous mixture and degassing of the melt was carried out by using the powder of CCl4. The melt was poured into the mould after preheating the mould to a temperature of about 200 ^oC.

Twelve metal pours were carried out and four of them had misruns (incompletely filled mould cavity), which could have been caused by the backpressure effect of the mould cavity. However, the as-cast pistons had a slightly rough surface appearance owing to the machining-induced roughness within the mould cavity. Samples of the as-cast pistons showing the attached risers and in-gate profiles are shown in Fig. 9. These attachments (riser and in-gates) were knocked off via the use of a hammer to commence the fettling process on the as-cast piston. The machining of the as-cast pistons to standard sizes and the cutting of oil grooves and pin diameter were carried out on the lathe and drilling machines respectively. The machining process was carried out at high spindle speeds and low feed rates to improve the surface appearance of the as-cast piston. This combination of machining parameters has been reported by Gharaibeh et al. [32] to promote a better surface finish. No palpable solidification-induced defect was found on the surfaces of the machined samples as smooth surface appearances were obtained. Samples of the machined pistons are provided in Fig. 10.

The microstructure of the as-cast piston was prepared according to metallurgical standards, etched with Keller's reagent, and viewed under an optical microscope. The microstructure of the as-cast piston shows no visible proof of micro- and macro-pores as revealed in Fig. 11. The designed in-gate system of the permanent mould could be adjudged to have accommodated adequate venting and consequently produced defect-free as-cast pistons. However, the magnifications of the notable areas on the microstructure (see Fig. 11) show evidence of dendritic solidification as dendrites are formed within the fine grains of the alloy. The adequate thermal dissipation attribute of the mould facilitates a rapid cooling cycle which reduces the size of dendrites and dendritic arm spacing in the solidified as-cast pistons. The high solidification/cooling rate of the Al melt has been reported to aid the reduction of dendritic arm spacing (SDAS), the modification of eutectic Si, and the refinement of solidification-induced intermetallic phases [33]. These are desirable attributes that influence the mechanical properties of as-cast Al alloy. Thus, it can be concluded that the permanent mould was able to satisfactorily produce as-cast pistons. The suitability of the produced pistons for the harsh service conditions was not covered in the scope of this work but the elemental compositions of the as-cast piston showed a very close comparison with that of LM13 as revealed in Table 4.

Based on LM Chart 2017, LM13 is the major ASTM classification of aluminum alloy used for internal combustion engines' pistons. The little variation in the composition of the as-cast alloy with LM13 (see Table 4) may be because of the re-melting/recycling process or the influence of the as-manufactured compositional variation of the individual scrap piston. Thus, the introduction of little percentage weight of the deficient alloying elements (such as Mn, Ni, Zn, and Ti) into the re-melted Al-Si piston scrap is recommended to bring the composition of the as-cast piston into par with that of LM13. Besides, Table 5 shows the appraisal of the mechanical properties of the as-cast pistons and the LM13. The average tensile strength and hardness of the as-cast piston are 15% and 9% lesser than those of the LM13 respectively. The slight deficit in the weight percentages (wt%) of Mn, Ni, Zn, and Ti) in the as-cast piston (see Table 4) could be responsible for the observed results (tensile strength and hardness) in Table 5. Shehadeh and Jalham [34] revealed that the addition of Mn (< 0.6 wt%) to Al alloy increases the tensile properties and hardness of the as-cast Al alloy. Thus, the addition of about 0.29 wt% Mn with other elements (such as Ni, and Ti) to the as-cast piston alloy is adjudged to be capable of improving the tensile and hardness values of the as-cast piston. On the other hand, the as-cast sample exhibited significant improvement in elongation under monotonic axial loading as compared to that of LM13. This occurrence may be attributed to the reduced dendrite sizes in the structure of the as-cast samples owing to the significant thermal dissipation away from the cast into the mould after a few seconds of pouring. Smaller dendrites are notable for producing higher ductility in metals.

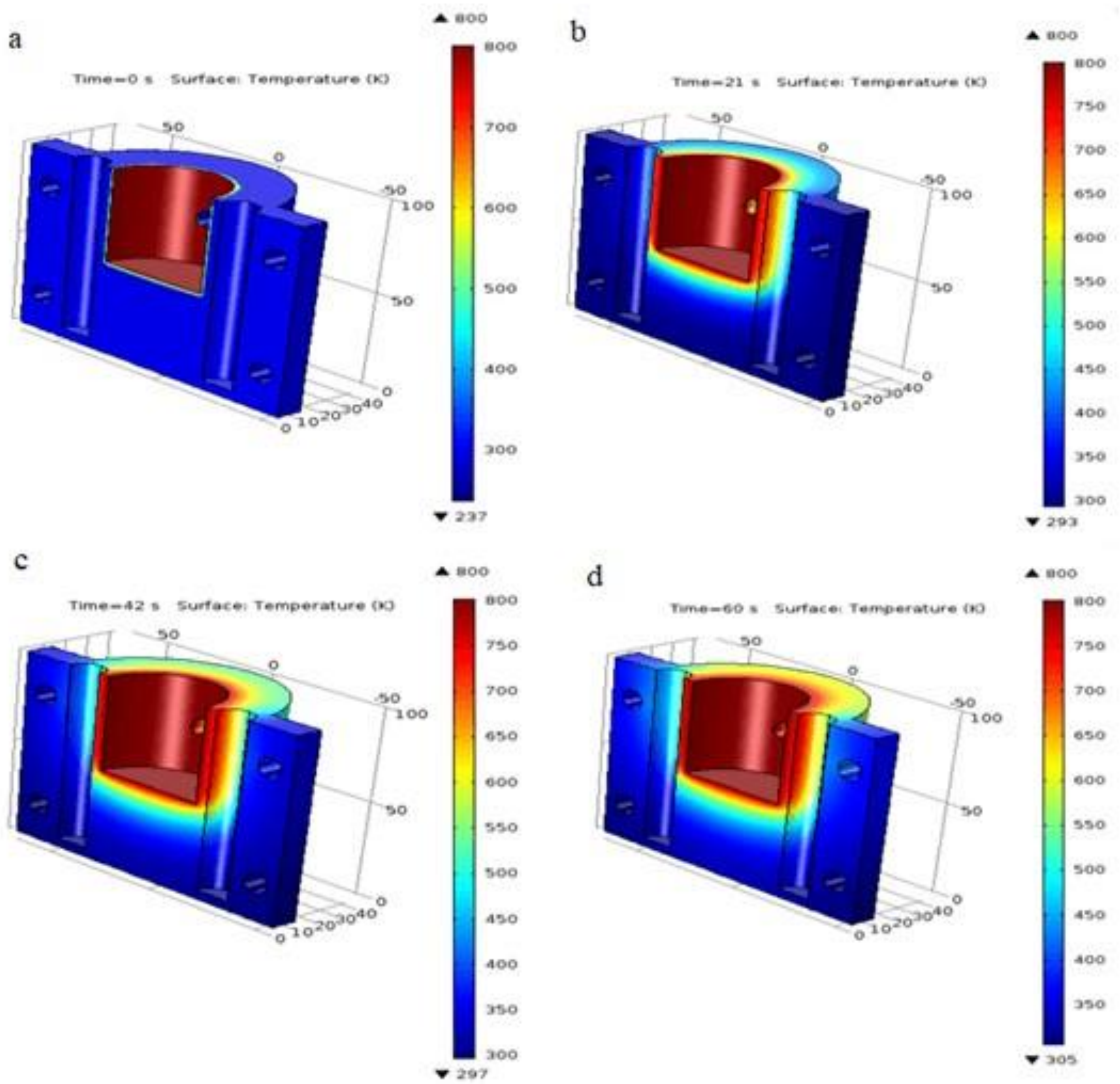


Figure 6. Surface temperature distribution in the movable mould at different times (a) 0 s time; (b) 21 s time; (c) 42 s time and (d) 60 s time

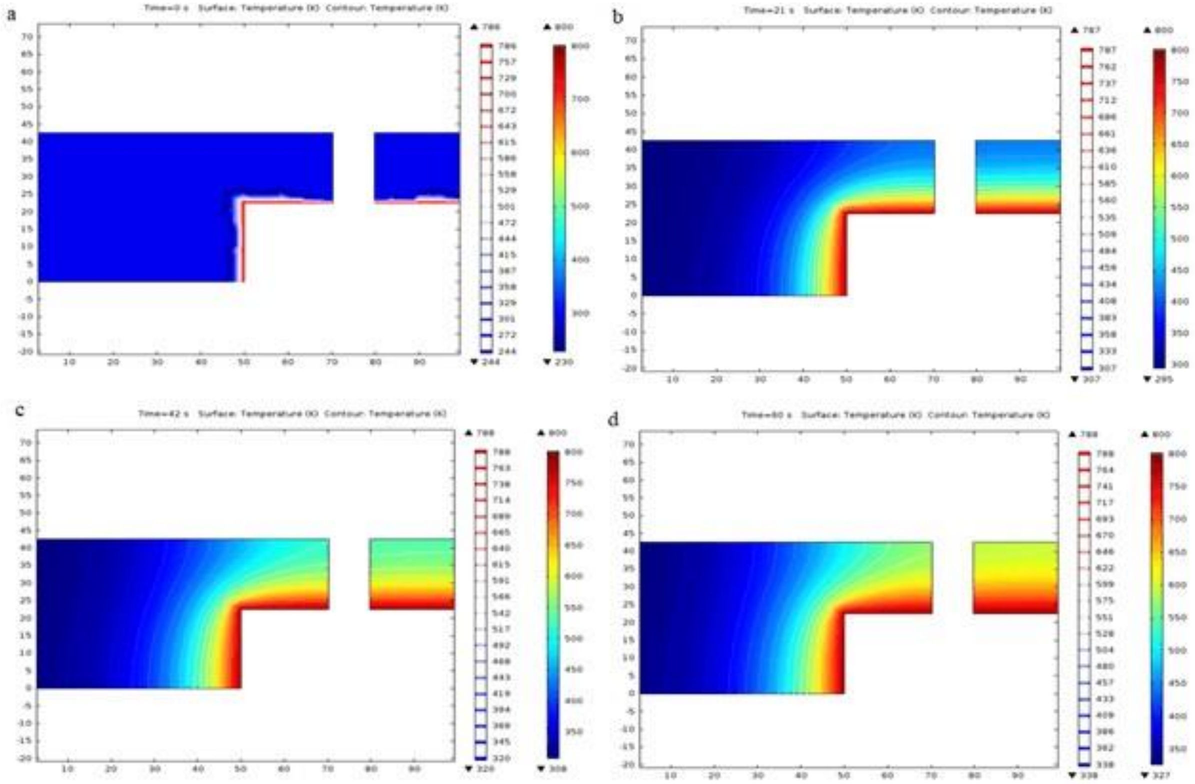


Figure 7. Thermal plot through the central section of the mould at different times (a) 0 s time; (b) 21 s time, (c) 42 s time, and (d) 60s time

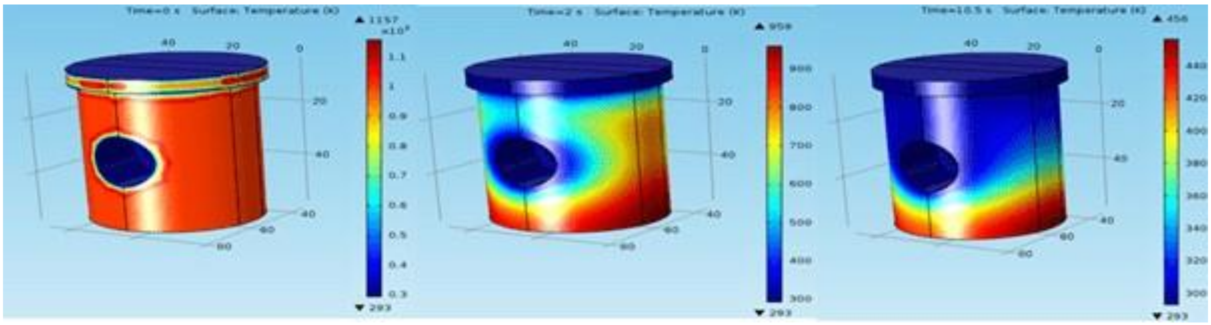


Figure 8. Surface temperature distribution around the piston core at different times (a) 0 s time; (b) 2 s time and (c) 10.5 s time

Figure 9. Unmachined cast pistons

Figure 10. Machined cast pistons

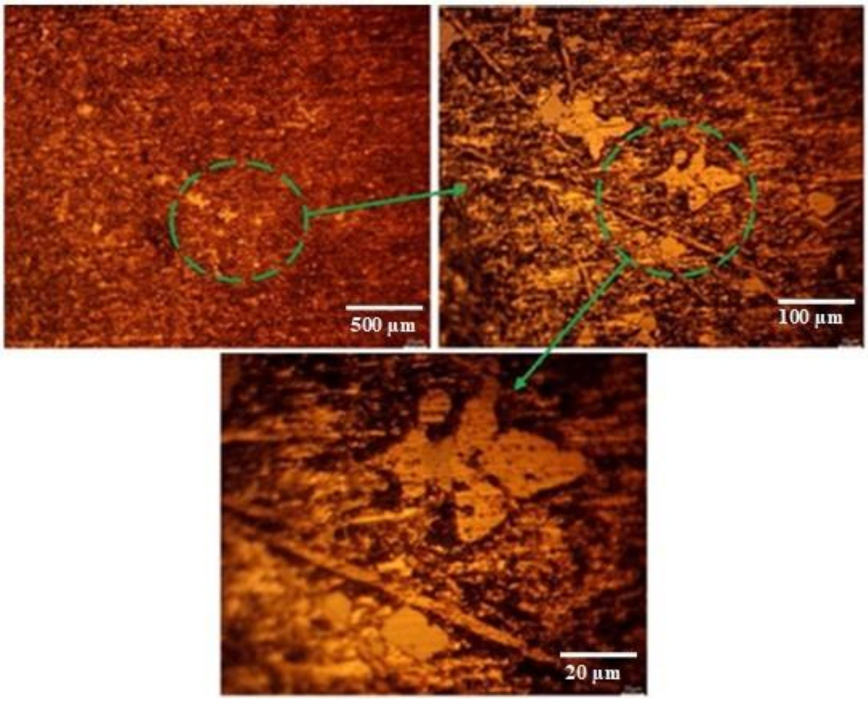


Figure 11. Microstructure of the as-cast piston

Table 4. Chemical compositions of as-cast piston and LM13 (wt%)

Elements	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al	Sr	Cr
As-cast 1	1.94	2.20	14.35	2.28	0.22	0.86	0.22	0.03	0.10	0.05	77.62	0.02	0.02
As-cast 2	1.77	1.93	13.49	2.45	0.21	0.86	0.23	0.05	0.08	0.04	78.75	0.01	0.06
As-cast 3	1.52	2.22	13.06	1.49	0.17	0.85	0.22	0.02	0.05	0.04	80.26	0.01	0.01
LM13	1.40	1.50	13.00	1.00	0.50	1.50	0.50	0.50	0.10	0.20	79.80	-	-
Recom.			***		Add	Add	Add		***	Add	***		

Note: "Recom." means recommendation; "Add" means elemental addition; "***" implies relatively close wt%

Table 5. Comparative mechanical properties of the as-cast sample and LM13 alloy

Mechanical Properties	Values of the LM13 Alloy [35]	Values of the AS-Cast Piston Alloy
Tensile Strength (MPa)	200	170
Elongation %	0.5	1.417
Hardness (VHN)	130	118

4. Conclusions

The detailed design of a permanent mould for casting 950 Watts pistons was carefully carried out and the thermal analysis of the mould was investigated by using COMSOL Multiphysics Software. The development of the mould was carried out and the casting of 950 Watts pistons from the Al-Si piston scraps was successfully carried out. The success of this research work has opened up a window for the recycling of aluminum scraps as a means of managing piston scraps, and an avenue for wealth creation. The major findings of this work are as highlighted below:

1. The temperature simulation results show that the use of steel mould allows satisfactory thermal dissipation during the casting process.
2. The appearance of the as-cast piston is slightly rough due to the machining-induced roughness on the mould cavity. However, no inherent matrix defect is found in the microstructure of the as-cast piston at a pouring temperature of 720ºC.
3. The microstructure of the as-cast piston predominantly consists of solidification-induced dendrites and fine grain structures. The re-melting of the Al-Si piston scraps slightly alters the composition of the as-cast alloy when compared with that of LM13
4. The average tensile strength and hardness of the as-cast piston are 15 and 9% lesser than the properties of the LM13 respectively due to the slight composition variation between the as-cast and the LM13 alloys.

Further studies on the improvement of the properties of the as-cast piston (from piston scraps) via elemental additions are part of the authors' future research plans.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this work.

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