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Design and Analysis of Aluminum Alloy for Gasoline Generator Piston using Aluminum Scrap

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ABSTRACT

The piston is an engine component that converts the heat and pressure energy released by fuel combustion into mechanical work. The primary goal of this study is to create a piston that meets the specific requirements. The piston was created in SOLIDWORKS and examined with ANSYS workstation. Scrap aluminum alloys were used to make the pistons. The working gas pressure, temperature, and material attributes of the piston were employed in the analysis. A permanent mild steel mold was used to manufacture the TG-950 gasoline generator piston. The aluminum fragments were melted in a gas-fired crucible furnace. The developed piston was characterized using XRF and SEM-EDS to ascertain the elemental compositions of the final product, and finally, the piston was put through a thermal and transient study to estimate how well it will perform in service.

KEYWORDS: *Aluminum scrap, pistons, pressure, tem6perature, thermal, mold, generator*

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1. INTRODUCTION

A piston can be found in reciprocating engines, reciprocating pumps, gas compressors, and pneumatic cylinders. In an internal combustion engine, a piston is a sliding plug (cylindrical metal component) that fits securely inside the bore of a cylinder and reciprocates in the cylinder under gas pressure, converting thermal energy into mechanical energy. Its principal function is to transfer force from the cylinder's expanding gas to the crankshaft via the piston connecting rod. The piston also serves as a movable combustion chamber end. The stationary end of the combustion chamber is the cylinder head. One of the most complicated components of an internal combustion engine is the piston, which turns heat energy into mechanical energy. [1].

Pistons are subjected to tremendous mechanical and thermal loads, resulting in massive inertia forces created by fast acceleration during reciprocating motion in the engine cylinder. [2]. The piston component in an internal combustion engine emits combustion products such as carbon monoxide (CO) and carbon, which are frequently deposited on the piston crown, as evidenced by the automotive combustion of fluids. [3]. A good piston material is expected to possess a plethora of mechanical properties.

According to [4] metal casting has many advantages, including refined structure, low porosity, hardness, high tensile strength, high fatigue strength, high strength-to-weight ratio, good wear resistance, weld ability, heat-treatability, near-net shape manufacture, good surface quality, and better dimensional accuracy. There is need to develop local capacity in the production of automotive spare parts in Nigeria. This move will serve both the Nigerian market and her African neighbors.

The TG 950 generator is prevalent in many households in Nigeria as an alternate off-grid electricity source. Because the piston is such an important component of an internal combustion engine, it must be manufactured locally to avoid capital flight caused by product imports. A truly made-in-Nigeria Piston will be a plus to the local content drive of the Federal Government of Nigeria.

2. Literature Review

2.1. Piston

A piston is a reciprocating component in an engine that transfers chemical energy into mechanical energy following fuel combustion. The piston's job is to transfer energy from the connecting rod to the crankshaft. The piston ring is used to seal the cylinder and piston together. It must be able to work in low-friction environments, with high explosive forces, and at temperatures ranging from 2000°C to 2800°C.The piston must be powerful but light in weight to avoid inertia forces caused by reciprocating action.

2.2. Parts of a piston

The piston comprises majorly of two parts which are:

1. Piston crown
2. Piston skirt

2.1.1. Piston crown

The top of the piston is known as the crown or head. During normal engine operation, the upper surface of the piston (closest to the cylinder head) is subjected to pressure fluctuations, temperature stresses, and mechanical load. As has been proved, low-rate, low-performance engines have a flat head. Pistons utilized in some high-powered engines have their crown raised like a dome and is used to expand the compression ratio, as well as manage combustion. Some piston may have their crowns shaped in a dish-like manner to type the desired shape of the combustion chamber, collectively with the cylinder head. There are grooves positioned towards the top of the pistons. They're shaped to fit the piston rings within. Lands are the bands that are left between the grooves. These lands act as a buffer between the rings and the gas pressure, allowing them to flow freely in a circular course [5].

2.1.2. Piston Skirt

The piston's skirt is the area beneath the rings. Its goal is to create a device that is capable of absorbing aspect thrust caused by gas strain [7].

2.2. Functions of Piston

1. To receive and transfer the propulsion force created by the chemical reaction of the fuel in the cylinder.
2. To reciprocate in the cylinder provide seal in suction, compression, expansion and exhaust stroke.

2.3. Piston Materials

Pistons are typically composed of Aluminum and cast iron alloys. However, in comparison to cast iron alloy, the Aluminum alloy is preferred because of its light weight, which is ideal for the reciprocating portion. Aluminum alloys have some disadvantages over cast iron alloys, including lower strength and wear resistance. Aluminum has a heat conductivity that is around three times that of cast iron alloys. The aluminum pistons' thickness has been increased, which is vital for the other strength and proper cooling.

3. Methodology

3.1. Design Consideration for a Piston

The following factors should be considered when developing a piston:

1. To survive the tremendous gas pressure and inertia forces, it must be extremely strong.
2. It should have minimum mass to minimize the inertia force
3. It should seal the cylinder effectively against gas and oil leakages.
4. It should have enough bearing surface to prevent excessive wear.
5. It should immediately disperse combustion heat to the cylinder walls.
6. It should be able to reciprocate at a fast pace while being quiet
7. It should be constructed in such a way that it can tolerate heat and mechanical distortion
8. It should be strong enough to sustain the piston pin.

3.2. The Piston Material:

The materials used to develop the Piston were End-of-life (EOL)/spent aluminum alloy piston scrap of generator, motorcycles, small vehicles and heavy-duty vehicles. These materials were obtained locally from the scrap market at Effurun, Delta State and a Roadside mechanic workshop at Sapele. The melting of aluminum was done using electrically operated crucible furnace.

3.3. CAD Design/Model:

A model of the TG 950 generator piston to be developed was designed using Solidworks with the requisite dimensions measured using appropriate callipers. Figure 3.1 is a depiction of the CAD model generated using SolidWorks.

Figure 1: CAD model of the TG-950 Piston

3.4. Moulding

The Moulding process involves the following steps as previously described in chapter one, which are:

3.4.1. Mould preparation:

Firstly, the mould was oiled and preheated to around 300-500^{0}F (150-260^{0}C) by keeping it very close to the furnace to allow better metal flow and reduce defects. Then, a parting powder/grease is applied to the mould cavity surfaces to facilitate part removal and increase the mould lifetime.

Figure 2: Mould assembly

Figure 3: Mould preparation

Melting and Pouring

The furnace used for the project is electrically controlled gas-fired crucible furnace. The gas used to fire this furnace was propane Gas (C_3H_8).

3.4.2. The melting process

During the melting operation, the following were carried out.

1. The aluminium piston scrap were washed and dried thoroughly
2. The furnace crucible was filled with the scrap of piston and was covered
3. The power cable was connected to a power source and the power button was switched on
4. As the piston melts, more piston scraps were fed into the furnace in order to obtain more volume
5. After the last piece of aluminum alloy piston scrap in the furnace has turned molten the furnace was allowed to run for about forty-five minutes to reach the pouring temperature.

3.4.3. The pouring process

The pouring temperature of aluminum is between 650^{0}C-700^{0}C. before pouring, the mould is properly arranged at the mouth of the furnace. A ladle constructed in the workshop was also used to properly channel the molten aluminum alloy into the rotating moulds. Molten metal found rising in the riser, showed that the molten has filled the required cavity. The molten metal was allowed to solidify and cool. When it was cold enough to handle the permanent mould was taken to the mechanical workshop where it was carefully disassembled in order to remove the Piston from the mould.

3.5. Machining

The cast piston was machined to finish on a lathe machine. The following machining operations were carried out:

1. **Turning:** The cast piston was set-up in a lathe by gripping the crown-end in a 3-jaw chuck. With the first setting, the skirt zone was turned up to thirty-five millimeters (35mm) in length. Then the second setting was made by gripping the skirt zone while the crown was turned.
2. The ring grooves were also with a parting tool on the lathe.

3.6. Design consideration and geometric values of the TG 950 Generator piston

3.6.1. The geometric values of the piston

The geometric values considered for the design of the piston as measured using a vernier caliper is shown Table 1 below.

Table 1: Geometric values considered for the piston

DIMENSION	SIZE (mm)
The diameter of the piston crown (D)	45
The thickness of the piston Head (t_H)	4
The radial thickness of Ring (t_1)	2
Axial thickness of the piston ring (h)	1
Width of ring land (h_2)	1
The thickness of the piston barrel at the open end (t_2)	25
Length of the skirt (l_s)	12
Piston pin diameter (d_0)	2
Piston length (l)	42

The engine specification used is a two-stroke single-cylinder type TG-G950 petrol engine as shown in Table 2.

Table 2: The engine specification for TG 950 Generator

PARAMETERS	VALUES
Engine type	Two-stroke petrol engine
Number of cylinders	Single cylinder
Bore	45mm
Stroke	550V, 600W max.
Power	10.39 Nm, 6500 rpm
Torque	120kmph
Top speed	4.00 L
Fuel capacity	20-25 L
Fuel consumption	0.50 L
Oil capacity	0.50 L
Starting system	Recoil

3.6.2. Design considerations for the piston

The following parameters were considered in the design;

Thickness of Piston head (t_H)

- Heat flows through the Piston head (H)
- Axial thickness of the ring (t_2)
- Radial thickness of the ring (t_1)
- Maximum thickness of the barrel (t_3)
- Piston pin
- Width of the top land (b_1)
- Width of second land (b_2)

A. Thickness of Piston Head (t_H)

The piston head thickness can be calculated using Grashoff's formula

Factor of safety = 2.25

$$t_H = \sqrt{\frac{3PD^2}{16\sigma_t}} \quad (3.1)$$

Where,

P = maximum pressure in N/mm^2 (P = 5N/mm^2)

D = cylinder bore/outside diameter of the material of the piston.

σ_t = permissible tensile stress for the material of the piston

$\sigma_t = \frac{380}{2.8}$ 135.7 Mpa

$t_H = \sqrt{\frac{3\times5\times45^2}{16\times135.7}}$ = 3.7mm

B. Heat Flow through the Piston Head (H):

This can be calculated using the formula

$$H = C \times HCV \times M \times BP \quad (3.2)$$

H = 0.05 × 47000 × 0.069 × 7.5

H = 1216.125

Where;

H = Heat flow through the piston head.

C = Constant heat supplied to engine (C = 0.05)

HCV = Higher calorific value of petrol (HCV=47000 KJ/Kg)

M = Mass of fuel used per cycle (M=0.069 Kw/hr.)

BP = Break power (BP=7.5W)

C. Piston Pin Diameter d0

$$d_0 = 0.28D \text{ to } 0.38D \quad (3.3)$$

where;

D = Piston head diameter (45mm)

$d_0 = 0.28 \times 45$

d_0 = 12mm

D. Shrinkage Allowance

Final shape – Original shape = shrinkage × 0.6 (3.4)

50 – 45 = 5mm

5 × 0.6 = 3mm

E. Theoretical Stress Calculation

The piston crown is designed for bending by maximum gas forces Pz_{max} as uniformly loaded round plate freely supported by a cylinder.

The stress acting in Mpa on piston crown: $\sigma b = \frac{Mb}{Wb}$ or

$$\sigma b = Pz \times \left(\frac{ri}{\delta}\right)^2 \quad (3.5)$$

Where;

Mb = (1/3) Pz_{max} ri^3 is the bending moment, MN m;

Wb = (1/3) $ri\delta^2$ is the moment of resistance to bending of a flat crown, m^3;

δ = Thickness of piston crown

Pz_{max} = is the maximum combustion pressure, MPa = 5Mpa.

This value varies from 2Mpa - %MPa in case of aluminum alloy.

$$ri = \left|\frac{D}{2} - (S + t_1 + dt\right| \quad (3.6)$$

It can also be calculated using; = $[\frac{D_2}{2}]$ (3.7)

Where

ri = The crown inner radius.

s = thickness of the sealing parts

dt = Radial clearance between piston ring and channel

t_1 = Radial thickness of ring

D_1 = external diameter of piston crown

D_2 = internal diameter of piston

But from the analytical design, the thickness of the barrel is 2mm

$\therefore D_2 = D - 2t_2$ (3.8)

$D_2 = 45 - 2(2)$

$D_2 = 41mm$

Therefore, the inner crown radius is, *ri*

$ri = [\frac{41}{2}]$

$ri = 20.5mm$

Hence the force acting on the piston van be calculated using equation (3.5)

$\sigma_b = 5 \times (\frac{0.023}{0.005})^2$

$\sigma_b = 105.8MPa$

Therefore, the required theoretical stress obtained from calculation is 105.8MPa.

For the design to be failsafe, the obtained value of theoretical stress must be less than the permissible stress. The permissible stress calculated previously was 135.7Mpa, which is greater than the obtained stress (105.8Mpa). Hence the design is safe.

3.7. Design calculation on the vertical centrifugal machine

The vertical centrifugal casting machine used in this study was locally fabricated. The following are the major components of the vertical centrifugal machine:

1. Battery
2. DC winch motor
3. Circular steel plate

3.7.1. Determination of power supplied to motor

$P_{in} = IV$ (3.9)

$P_{in} = 12 \times 9 = 108W$

Where P_{in} *is the input power, I* is the current and *V* is the voltage

Determination of angular speed ω

$\omega = \frac{2\pi N}{60}$ (3.10)

$\omega = 31.42rad/sec$

Where ω is the angular speed; rpm is the rotational speed in revolutions per minute; and π is the mathematical constant pi (3.14)

3.7.2 Determination of torque generated

$\tau = (I \times V \times E \times 60) / (rpm \times 2\pi)$ (3.11)

$\tau = 13.57Nm$

Where τ is the torque of motor; E I the 10% efficiency (0.1); and rpm is the rotational speed in revolution per minute

3.7.2. Determination of centrifugal force on machine

$F = m \times r \times \omega^2$ (3.12)

$F = 16,573.041N$

Where m is the mass of the permanent litre; r is the radius of rotating disc; and ω^2 is the angular speed

3.8. Thermal Analysis and Characterization of developed piston

The piston developed was subjected to thermal analysis to predict the performance of the piston during service and characterized by subjecting the samples to XRF and SEM-EDS to ascertain the elemental composition and the morphology of the piston. The material properties of the aluminum 6061 alloy are presented in table 3.

Table 3: Aluminum 6061 Alloy Material property

S/N	Property	Values
1	Mass density	$2700kgm^{-3}$
2	Tensile strength	$124084000Nm^{-2}$
3	Yield strength	$55148500Nm^{-3}$
4	Thermal expansion coefficient	$2.4e^{-05}k$
5	Thermal conductivity	170W/m.K
6	Specific heat	1300J/kg.K
7	Elastic modulus	$6.9e^{+10}$
8	Poisson's ratio	0.33

4. Design Analysis

4.1. Thermal Analysis and Characterization of the developed piston

The piston developed was subjected to Thermal analysis to predict the performance of the piston during service. The piston developed was characterized by subjecting the samples to XRF and SEM-EDS to ascertain the elemental composition and the morphology of the piston.

4.2. Thermal Analysis of the piston developed

A model of the piston was developed using SolidWorks and thermal analysis performed on the piston using SolidWorks. The model of the piston and meshed generated. A total of 65565 tetrahedral elements and 101293 nodes was generated.

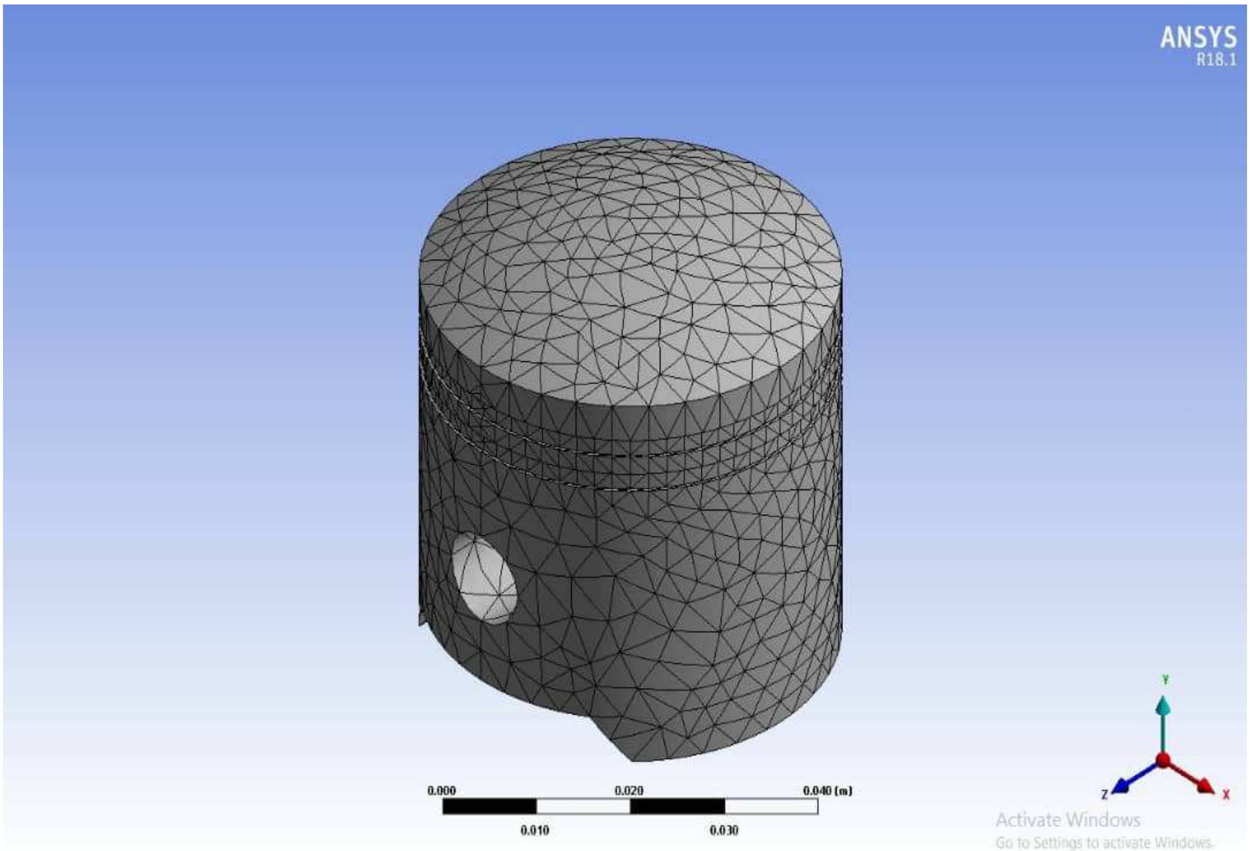

Figure 4: Mesh generated for the Piston developed

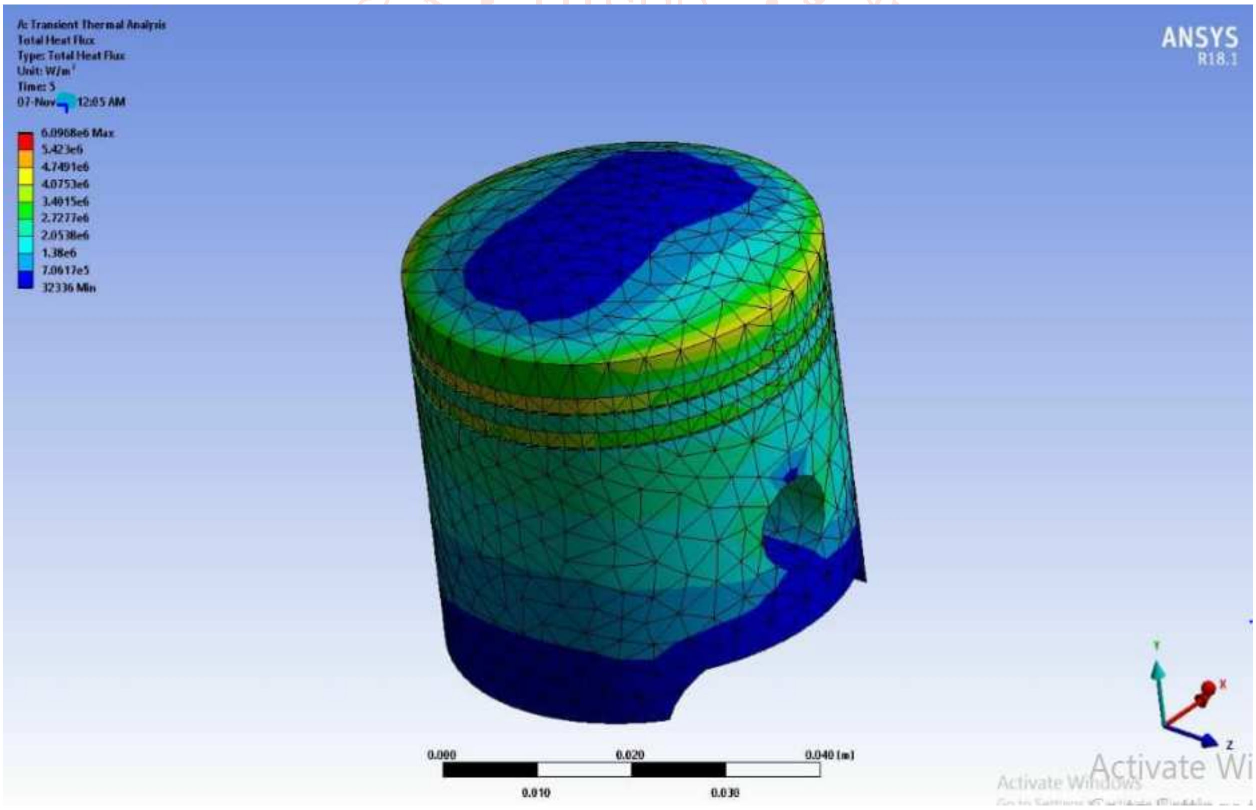

Figure 5: Total Heat Flux in the Piston

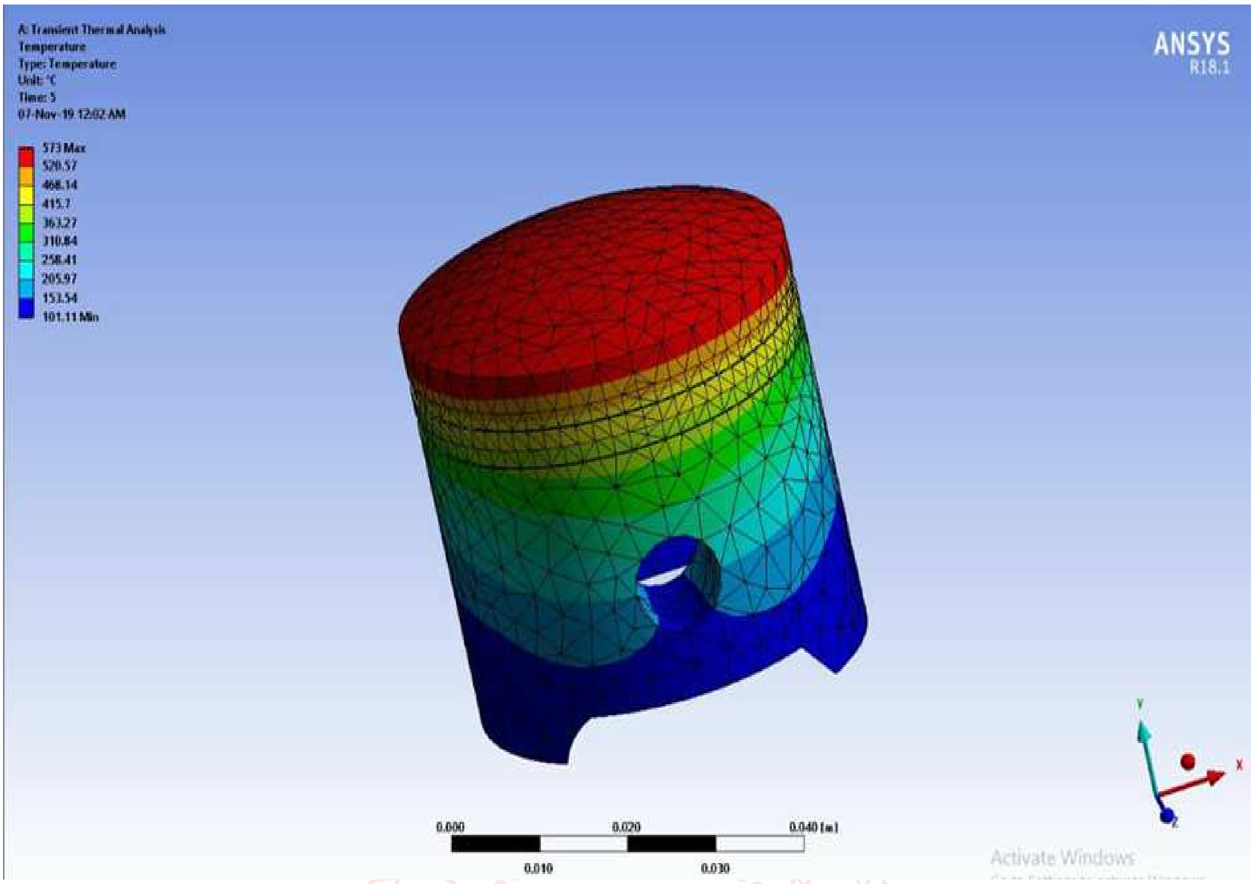

Figure 6: Temperature Distribution of the Piston

5. Results and Discussion

5.1. Characterization of the TG 950 Generator Piston

Table 4: XRF Result of the Piston material

Compound	Al	Ti	V	Cr	Mn	Fe	Ni	Cu	Sb	Ba	Ce	Eu	Os	Pb
Concentrated Unit	95.5 %	0.03 %	0.002 %	0.093 %	0.15 %	1.06 %	0.820 %	1.436 %	0.28 %	0.17 %	0.05 %	0.36 %	0.058 %	0.012 %

The recycled aluminium piston materials used in this study were found to contain the much needed alloying metals such as Iron and manganese, which are beneficial to the aluminium alloy piston.

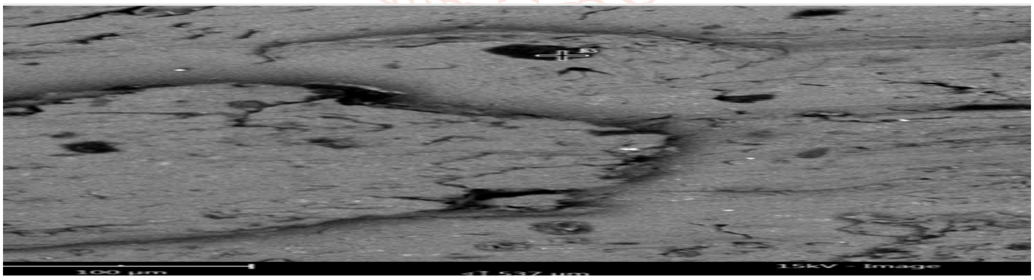

Figure 7: SEM-EDS micrograph of the recycled aluminium for point 3

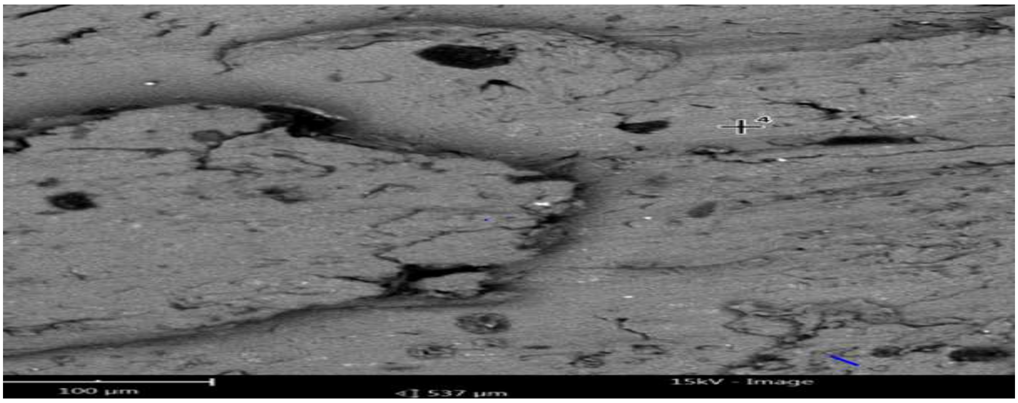

Figure 8: SEM-EDS micrograph of the recycled aluminium for point 4

Table 5: EDS of the points analysed

Element Symbol	Element Name	Point 3	Point 4
Al	Aluminium	3.99	63.43
C	Carbon	73.05	28.24
O	Oxygen	14.37	2.04
Si	Silicon	0.61	1.23
Mg	Magnesium	0.43	0.63
Fe	Iron	0.10	0.25
Na	Sodium	0.78	0.57
N	Nitrogen	6.28	2.17
Zn	Zinc	-	-
Mn	Manganese	-	0.45
S	Sulphur	0.28	0.55
P	Phosphorus	0.11	0.42
Ti	Titanium	-	-

Discussion

The recycled aluminium piston materials used in this study were found from the SEM-EDS to contain the alloying metals such as magnesium and manganese, which are beneficial to the aluminium alloy piston. The XRF and SEM-EDS conducted on the recycled EOL aluminium revealed that aluminium is the most predominant material followed by oxygen as tabulated in the tables.The XRF gave the general elemental composition of the aluminium alloy while the EDS revealed the spot to spot surface composition on the material The presence of C and O indicates the existence of adventitious carbon and oxygen on the surface of the aluminium in all the points. The Centrifugal casting method used in the fabrication of the TG 950 generator piston was found to be cost-effective and flexible. The transient analysis conducted for the developed piston using ANSYS gave good approximations of the Total heat flux and temperature distribution of the piston during service. The presence of iron in the recycled aluminium and the casting process are responsible for the porosity in the cast metal. The TG 950 generator piston was developed using End-of-Life recycled Aluminum scrap. The developed piston was found to contain the needed alloying metals such as Manganese and Magnesium.

Conclusion

It important for engineers in Nigeria to complement the effort of locally based engine spare parts production companies so as to discourage the massive importation of pistons from foreign countries. Building indigenous capacity for the production of aluminum alloys of all types in Nigerian technological sphere may stimulate a very great boost.

Past studies on piston development done by some Nigerian researchers employed reverse engineering in the development of internal combustion engine components rather than detailed design. This study was carried out to fill the gap created by the constant application of Reverse engineering in the manufacture of generator pistons. A piston used in TG 950 generator was successfully designed. The designed values of the piston parameters were in accordance with the recommended range for small internal combustion engines.

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