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MODELING THE HEAT LOSS VIA AN ALUMINA SILICON CARBIDE PARTICULATE REINFORCED ALUMINUM ALLOY COMPOSITE AUTOMOBILE PISTON WALL

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ABSTRACT

Piston as one of the most critical components of an engine must be designed to withstand the damages caused due to extreme heat and pressure of combustion processes resulting to piston side wear, piston head cracks, etc. The temperature of a particular engine determines the performance of the engine. However, the design/analysis of the piston is based on structural and thermal considerations. In this project, we model the heat loss through an Aluminium alloy composite piston wall reinforced with Alumina and Silicon Carbide. The materials (Aluminium ingots, Silicon Carbide and Alumina) were sourced locally and the production of the composites was done by the double stir-casting method and as per ASTM Standards. The conductive and convective steady state thermal behaviour of the individual elements of the piston were modeled using Fourier's Law and Newton's Law of Cooling. Under steady state conditions and assuming an outside and inside engine/piston temperatures of 393K and 363K respectively, the heat loss via the piston wall of the composite was found to be 4.745KW, an information vital in computing the heat load for an automobile engine.

Keywords: Automobile Engine, Piston, Composite, Aluminium, Heat, Transfer.

1.0 INTRODUCTION

Composites are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties that remain separate and distinct within the finished structure (Ram *et al*., 2017). Aluminium matrix composites (AMCs) are the competent material in the industrial world. Due to the excellent mechanical properties, these AMCs are widely used in aerospace, automobiles, marine etc. (Chawla, 1997). The aluminium matrix is getting strengthened when it is reinforced with the hard ceramic particles like SiC (Silicon Carbide), Al_2O_3 (Alumina) and B_4C (Boron Carbide).aluminium alloys are still the subjects of intense studies as their low density gives additional advantages in several applications.

Automobile components are in great demand these days as a result of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components (Olanrewaju *et al*., 2015). R&D and testing engineers should develop critical components in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new products (Velivela and Amar, 2015).

The Internal Combustion (IC) engines had undergone significant advancements since their introduction in the early 16th century, and the latest trend is to make them greener. The latest trend in the IC engine industry is to develop power plants with higher efficiency and to make them running on alternative fuels to meet modern emission norms. There are different IC engine configurations used to generate mechanical output from chemical energy, namely reciprocating engines (single and double piston) and rotary engines. In general, a double piston engine delivers more power than a single piston engine for the same configuration (Abdul Rahman *et al*., 2015). Thus, engine pistons are one of the most complex components among all automotives and other industry field components (Rao *et al*., 2015). A piston as a component of reciprocating IC engines, reciprocating pumps, gas compressors and pneumatic cylinders, is the moving component that is contained by a cylinder. In an Internal Combustion (IC) engine, it is acted upon by the pressure of the expanding combustion gases in the combustion chamber and the motion is transmitted through the piston-connecting rod assembly to the crankshaft (Lavanya and Ahmed, 2015). Piston has to endure the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of the piston such as piston side wear, piston head cracks and so on. Usually the pistons are made of Aluminium for lightweight, thermal conductivity. But it has poor hot strength and high coefficient of expansion makes it less suitable for high temperature applications (John *et al.*, 2015). Aluminium alloys are the preferred material for pistons both in gasoline and diesel engines due to their specific characteristics: low density, high thermal conductivity, simple net-shape fabrication techniques (casting and forging), easy machinability, high reliability and very good recycling characteristics.

The temperature of a particular engine determines the performance of the engine. However, the design/analysis of the piston is based on structural and thermal considerations (Bhattacharya *et al*., 2014). Thus, in order to have full understanding of phenomenon of heat flow through the piston, the temperature distribution within the piston will come handy for designers while calculating the fatigue strength, thermal stresses and achieving higher output (Ramesh et al., 2014). The thermal state of the parts of an internal combustion engine has an effect on the strength characteristics of the material of which the parts are made, on the rate at which deposits appear on the parts, on the lubrication conditions of the parts, on friction, wear and stresses in the parts (Uzuneanu *et al*., 2008). The temperature of the parts has an effect on operating temperature of the lubricating oil and hence, on its viscosity, oil – film thickness which separates of the rubbing pair and the nature of friction. The latter together with wear characteristics of materials, which also depend on the temperature of parts, determine the wear rate. Temperature stresses appear because of uneven distribution of temperature in the parts and also because the majority of parts do not enable the most heated portions to expand freely. By the thermal load we mean the value of specific heat flux transferred from the working fluid to the surface of a part. Transfer of heat from the working fluid to the surface of parts is affected in two ways: by convection and by radiation. Convection has a major importance for engines because combustion is accompanied by formation of soot which burns out subsequently. The soot content in the flame is the cause of its degree of blackness, and therefore, of high emissive power of flame. High flame – temperatures and degrees of blackness of flame are the cause of high fraction of heat transferred by radiation. The thermal stress level of separate portions of parts depends mainly on the disposition of the portion relative to the flame and is therefore not the same.

Invariably, piston as one of the most critical components of an engine must be designed to withstand the damages caused due to extreme heat and pressure of combustion processes. The value of stress that caused the damages can be determined by using Finite Element Analysis (FEA) (Swati and Vinayak, 2013). With advanced computer codes like ANSYS and NISA, attempts on the temperature predictions using finite element analysis increased in the recent past (Kishor, 2016).

A Finite Element Analysis (FEA) is a way of getting numerical solution to a specific problem. It neither produces a formula as a solution, nor does it solve class of problems. Also, the solution is approximate unless the problem is simple that a convenient exact formula is already available. It is used in solving field quantities such as stress analysis (stress field), thermal analysis (Temperature Field/Heat flux), fluid flow (Stream function/velocity potential function) etc. (Stasa, 1986; Reddy, 2006). Finite element procedures are at present very widely used in engineering analysis, and we can expect this use to increase significantly in the years to come (Bathe, 2016). The procedures are employed extensively in the analysis of solids and structures and of heat transfer and fluids, and indeed, finite element methods are useful in virtually every field of engineering analysis. The development of Finite Element Methods for the solution of practical engineering problems began with the advent of the digital computer. That is, the essence of a Finite Element solution of an engineering problem is that a set of governing algebraic equations is established and solved, and it was only through the use of the digital computer that this process could be rendered effective and given general applicability. These two properties effectiveness and general applicability in engineering analysis-are inherent in the theory used and have been developed to a high degree for practical computations, so that Finite Element methods have found wide appeal in engineering practice. The Finite Element Method in engineering was initially developed on a physical basis for the analysis of problems in structural mechanics. However, it was soon recognized that the technique could be applied equally well to the solution of many other classes of problems.

According to Calbureanu *et al*. (2013), Finite Element Methods could be used to model a piston. The methods are commonly used for thermal Analysis. A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component (Reddy *et al*., 2015). Due to the complicated working environment for the piston; on one hand, the FEA for the piston became more difficult; on the other hand, though there have been many methods which are put forward to apply optimal design, the optimal parameters are not easy to determine (Bhagat and Jibhakate, 2012).

Since the main requirement of piston design is to measure the prediction of temperature distribution on the surface of piston which enable us to optimize the thermal aspect for the design at lower cost as reported by Rao *et al* (2015), this present study will focus on heat transfer processes / heat loss which are of much importance especially in automobile engines. This was achieved by formulating a model for analyzing the heat loss in an internal combustion engines piston.

2.0 MATERIALS AND METHODS

2.1 EXPERIMENTAL PROCEDURE

The section describes and discusses the materials, equipment and all the techniques used in this research.

2.2 MATERIALS

Pure aluminium ingots were obtained from Mechanical Engineering Workshop, MOUAU, Nigeria. The Alumina and Silicon carbide particulates were purchased from a chemical shop in Aba, Abia State, Nigeria.

2.3 EQUIPMENT

Equipment used in this research are: Pyrometer, mechanical stirrer, crucible, electrical resistance furnace, etc.

2.4 METHOD

Specimen Preparation

The production of the composites was done by the double stir-casting method (Fig 2.1). Stir casting method is a liquid state method of composite materials fabrication in which a dispersed phase (reinforcement particulates) is mixed with a molten metal by means of stirring. Initially, pure Aluminium ingots were charged into the graphite crucible furnace and heated to about 750 ºC, until the entire Aluminium in the crucible was melted. The reinforcement particles (Al_2O_3 and SiC) were preheated to 800^{o}C for 1 hour before incorporation into the melt. After the molten metal was fully melted, 0.05% by weight degassing tablets (hexachloroethane) were added to reduce the porosity. Simultaneously, 1% by weight magnesium was added to the melt in order to enhance the wettability between reinforcement's particles and the Aluminium melt.

It was noticed that without the addition of magnesium, the reinforcement particles were rejected. The stirrer made of stainless steel was lowered into the melt slowly to stir the molten metal at the speed of the speeds seem too high for stirring (500 -700) rpm. The preheated Al_2O_3 and SiC particles were added into the molten metal during the stirring time. The stirring rate continued for another 5mins, even after the completion of particle feeding. The mixture was poured into the mould which was also preheated for 30 min to obtain uniform solidification. Moulds can be preheated by exposure to direct flame, or in an oven, but preheating in an oven until the molten metal is ready for pouring was chosen and it is much more desirable (Metal Handbook, 1970). It was allows to cool to obtain cast specimens. The specimens were prepared from these castings as per ASTM Standards.

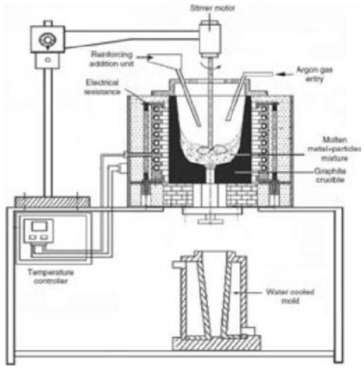


Fig. 2.1: Electrical Furnace Used for the Preparation of the Specimen

Composite Material production

The rule of mixture is applied to the composite material production. The following equations (equations 2.1 and 2.2) relate the Young's Modulus of the composite material (E_c), by knowing the Young's Modulus of the Matrix (E_m), Young's Modulus of the Particulate (E_p), Volume fraction of the matrix (V_m) and the Volume fraction of the particulate (V_p).

$$E_c(u) = E_m V_m + E_p V_p \qquad \text{Equation 2.1}$$

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \qquad \text{Equation 2.2}$$

Where $E_c(u)$ *and* $E_c(l)$ are the upper and lower values of Young's Modulus of the final composite material, E_m and E_p represent the Young's Modulus of the matrix and particulate material, V_m and V_p indicate the Volume fraction of the matrix and particulate material. With decreasing particle size of the particulate material, for a given reinforcement volume fraction, the reinforcement inter particle spacing decreases, resulting in more barriers for the reversible slip motion that takes place during tensile testing of the specimens.

Design of Body:

We created model Piston using Solid Works software. The models are shown in the Engineering drawing of the piston (Figure 2.2) while Figures 2.3 and 2.4 show the 3D Model of the piston and its orthographic views.

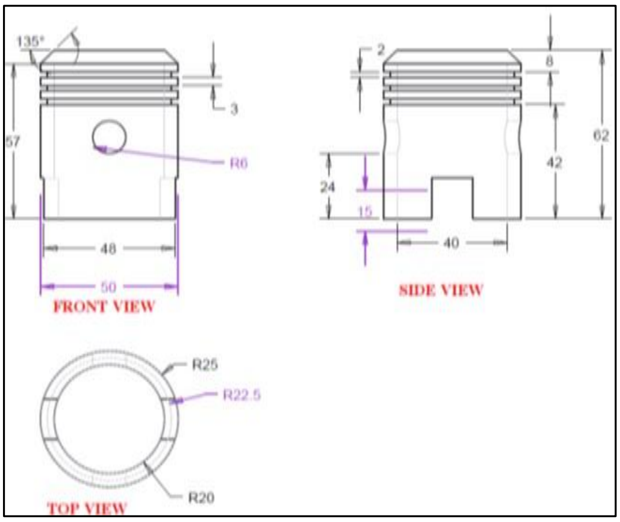


Fig. 2.2: Engineering drawing of a piston

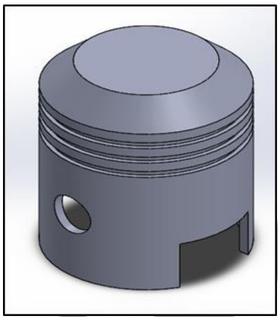


Fig.2.33D end model using solid works

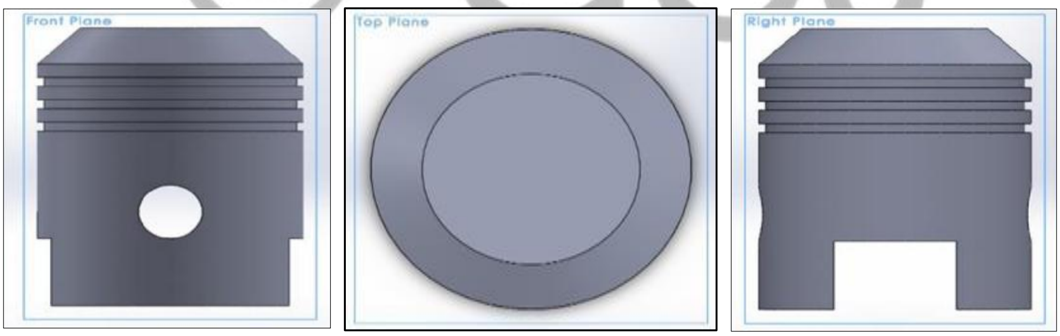


Fig. 2.4: Orthographic view of modelled piston

Incorporation of Reinforcements

Most ceramics are not wetted or are poorly wetted by molten metals, so the intimate contact between reinforcement and aluminium can only be promoted by artificially inducing wettability or by using external forces to overcome the thermodynamic surface energy barrier and viscous drag effects. Mixing techniques generally used for introducing and homogeneously dispersing a discontinuous phase in a melt are: Addition of particles to a vigorously agitated, fully or partially molten melt (Banerjee *et al*., 1983; Rohatgi *et al*., 1979; Surappa and Rohatgi, 1981; Nath *et al*., 1980), Injection of discontinuous phase into the melt with an injection gun (Badia and Rohatgi, 1969), Dispersion of pellets or briquettes into a mildly agitated melt (Pai and Rohatgi, 1978) and long contact times promote wettability due to interfacial reactions, resulting in reduced contact angle between the ceramic phase and the melt. The work of adhesion between a ceramic and a melt decreases with increasing heat of formation of carbides. A high energy of formation for a stable carbide implies strong interatomic bonds and correspondingly weak interaction with melts. This leads to a high interfacial energy and a small work of immersion, resulting in poor wetting. High valence electron concentration generally implies lower stability of carbides and improved wettability of ceramics by metals. Hence, optimization of processing parameters based on thermodynamics and kinetics can result in higher-quality MMCs.

Magnesium/graphite, aluminum/graphite, and several other fiber-reinforced composites are valuable structural materials because they combine high specific strength and stiffness with a near-zero coefficient of thermal expansion and high electrical and thermal conductivities. Wetting and bonding between the fiber and the metal in these systems is induced by the deposition of a thin layer of titanium and boron or SiO_2 onto the fibers (Katzman, 1983).

Solidification Processing of MMC

In solidification processing of composites, liquid metal is combined with the reinforcement phase and solidified in a mold. The solidification processes of composite synthesis can be divided into two main classes: stir mixing and melt infiltration.

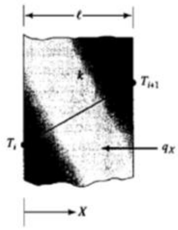
In stir-mixed slurries of melts and reinforcements, it is important to retain adequate enough fluidity in the melts to make sound castings. Generally, the fluidity of alloys decreases with increasing additions of reinforcements, and this can require changes in mold design. Reciprocal relationships between fluidity and the apparent viscosity of melt-particle suspensions have been noted in aluminum-silicon alloys, iron carbon-sulfur alloys, and Al-4.5Cu-1.5Mg alloy/2.5 wt% flaky mica composites. The fluidity values of particle-filled composite melts are generally adequate for making gravity-cast composites at low volume fraction of particles, up to approximately 30 vol%. Additions of silicon carbide, alumina, graphite, mica, and other ceramic particles to aluminum alloys cause a reduction in spiral fluidity. The spiral fluidity of these alloys decreases linearly with increasing particle surface area per unit weight. The fluidity of composite slurries decreases with decreases in the temperature. The fluidity of composite melts also depends on the shape, size, flocculation, and segregation of particles in the melt.

Infiltration Process. In this process, liquid metal is infiltrated through the narrow crevices between the fibers or particulate reinforcements, which are either in a packed bed or arranged in a preform and fixed in space (Fukunaga and Goda, 1985). High pressure or vacuum can be used to assist the infiltration process. As the liquid metal enters between the fibers or particles during infiltration, it cools and then solidifies, producing a composite. In general, the infiltration technique is divided into three distinct operations. The first step is the preform preparation, which involves assembling the reinforcement elements together into a porous body. The second step is the infiltration process during which the liquid metal permeates the preform. The last step is the solidification of liquid metal throughout the preform. Melt infiltration can be achieved with the help of mechanical pressure (Cook and Werner, 1991), inert gas pressure, or vacuum (Kun *et al.*, 1993). The calculations of threshold pressure needed to initiate infiltration (Young's equation) and the kinetics of infiltration (Darcy's law) are in reasonable agreement with the experiments. Recently, techniques of pressure less infiltration of ceramic preforms have been developed (Breval *et al.*, 1993; Aghajanian and Burke, 1989) that allow casting of net-shaped composites. Plate 2.1 below shows some of the processes followed to produce the Piston.

Plate 2.1 Photographic view of some of the processes followed to produce the piston

3.0 HEAT LOSS MODELLING OF THE PISTON

There are two modes of heat transfer (conduction and convection) that we must first understand. The steady state thermal behaviour of the individual elements of the piston may be modeled using Fourier's Law. When there exists a temperature gradient in a medium, conduction heat transfer



occurs as shown in Figure 3.1 below:

Figure 3.1: Heat Transfer in a Medium by Conductions

The energy is transported from the high-temperature region to the low-temperature region by molecular activities. The heat transfer rate is given by Fourier's Law in equation 3.1 as:

$$Q_x = -\kappa A \frac{\delta T}{\delta X} \qquad \text{Equation 3.1}$$

Q_x is the X-component of the heat transfer rate, κ is the thermal conductivity of the medium, A is the area and $\frac{\delta T}{\delta X}$ is the temperature gradient. The minus sign in equation 3.1 above is due to the fact that heat flows in the direction of decreasing temperature. Equation 3.1 above can be written in a different form in terms of the spacing between the nodes (length of the element) l and the respective temperatures of the nodes $_i$ and $_{i+1}$, T_i and T_{i+1} according to the equation 3.2 below:

$$Q = \frac{\kappa A(T_{i+1} - T_i)}{l} \qquad \text{Equation 3.2}$$

In the field of heat transfer, it is also common to write equation 3.2 in terms of the thermal transmittance coefficient *U*, or as it is often called, the *U*-factor ($U = \frac{\kappa}{l}$). The *U*-factor represents thermal transmission via a unit area and it is the reciprocal of thermal resistance. So, equation 3.3 is re-written thus:

$$Q = UA(T_{i+1} - T_i) \qquad \text{Equation 3.3}$$

The steady state thermal behaviour of the individual elements in the piston may be modeled using Newton's Law of Cooling. Convection heat transfer occurs when a fluid in motion comes in contact with a surface whose temperature differs from the moving fluid. The overall heat transfer rate between the fluid and the surface is governed by Newton's Law of Cooling, according to the equation 3.4 below:

$$Q = hA(T_s - T_f) \qquad \text{Equation 3.4}$$

Where h is the heat transfer coefficient, T_s is the surface temperature, and T_f represents the temperature of the moving fluid. Newton's Law of Cooling can also be written in terms of the *U*-factor in equation 3.5, such that:

$$Q = UA(T_s - T_f) \qquad \text{Equation 3.5}$$

Where $U = h$, and it represents the reciprocal of thermal resistance due to convection boundary conditions. Under steady state conduction, the application of energy balance to a surface requires that the energy transferred to this surface via conduction must be equal to the energy transfer by convection. This principle is expressed below in equation 3.6:

$$-\kappa A \frac{\delta T}{\delta X} = hA(T_s - T_f) \qquad \text{Equation 3.6}$$

4.0 RESULTS AND DISCUSSION

4.1 The Thermo-physical Properties of the Composite Piston Materials

S/NO	MATERIALS	DENSITY (Kg/m^3)	VOLUME FRACTION %	SPECIFIC HEAT (J/Kg.K)	THERMAL CONDUCTIVITY (W/m.K)	U-FACTOR ($W/m^2.K$)	MELTING POINT (K)
1.	ALUMINIUM	2707	0.55	921.096	185.5	6870	933
2.	SILICON CARBIDE	4,500	0.15	550	15.0	2055	1800
3.	ALUMINA	3,950	0.35	880	35	2059	2,345

- Exposed Area of the Piston is computed to be $0.0144m^2$ with

Assuming a steady state conditions, inside engine temperature (Summer, Nigeria) of 363K, and an outside piston temperature (Summer, Nigeria) of 393K, the heat loss via the piston wall should be equal to the heat transfer via each individual element of the composite piston material. This value can be determined from the overall *U*-factor equation in the following manner as expressed in equation 4.1:

$$Q = U_{overall} A(T_{outside} - T_{inside}) \qquad \text{Equation 4.1}$$

$$Q = \mathbf{4{,}745W}$$

The heat loss via the piston wall of the composite is computed to be 4.745KW. Such information is vital in computing the heat load for an automobile engine.

5.0 CONCLUSION

Aluminium matrix is strengthened when reinforced with the hard ceramic particles like SiC (Silicon Carbide), Al_2O_3 (Alumina). Usually the pistons are made of Aluminium for lightweight, thermal conductivity. But its poor hot strength and high coefficient of expansion makes it less suitable for high temperature applications. Aluminium alloys are the preferred material for pistons due to their specific characteristics: low density, high thermal conductivity, simple net-shape fabrication techniques (casting and forging), easy machinability, high reliability and very good recycling characteristics.

The thermal state of the parts of an internal combustion engine has an effect on the strength characteristics of the material of which the parts are made, on the rate at which deposits appear on the parts, on the lubrication conditions of the parts, on friction, wear and stresses in the parts

Though a definite permissible level of thermal loads corresponds to specific designs of parts; to the material used and cooling conditions, thermal loads can be reduced further while maintaining the strength of the piston since they are be designed to withstand the damages caused due to extreme heat and pressure of combustion processes. Besides the use of cooled constructions which make possible an appreciable lower temperature of piston, particularly of its critical zones, heat insulating coatings aid in reducing the temperature and temperature gradients of parts. For an Aluminium matrix composite with 55% Volume fraction of Aluminium, 15% Volume fraction of Silicon Carbide and 35% Volume fraction of Alumina, a heat loss through the produced composite piston wall of 4.745KW is expected with high thermal conductivity, low density, low coefficient of expansion, good hot strength suitable for high temperature applications in automobile engines at Summer times in Nigeria. It is expected that the produced piston will practically withstand the fatigue damage such as piston side wear, piston head cracks and so on.

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