3D MODELLING OF A RECONDITIONED PISTON OF A SINGLE-CYLINDER FOUR-STROKE DIESEL ENGINE BY USING SOLID WORKS SOFTWARE

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Article History: Received 11 February 2023; Revised 03 March 2023; Accepted 28 March 2023

ABSTRACT: *This paper gives the possibility of modelling a reconditioned piston of a single-cylinder four-stroke diesel engine using the ZS1115NM diesel engine specifications. Due to the upsurge of counterfeit spare parts in the market, meeting the original equipment manufacturer (OEM) standards requires a reconditioning process. The reconditioned piston is a thermal barrier coated one with a ceramic material that enables it to withstand high gas combustion temperatures without cracking. A piston converts thermal energy to mechanical energy in an internal combustion engine (ICE). The methodology includes sizing and modelling of the conventional piston, topcoat and bond-coat layers and finally assembling them to get a reconditioned piston using SolidWorks Computer-Aided Design (CAD) software. The material chosen for the piston is an aluminum alloy designated as A2618, due majorly to its high coefficient of thermal expansion (CTE) which enables the piston to withstand high thermal stress without cracking or failing. The ceramic material chosen is a 7.5% yttria-stabilized zirconia which is the topcoat with low thermal conductivity and a high coefficient of thermal expansion (CTE) on a bond-coat metallic material called Nickel Chromium Aluminum Cobalt Yttria which are applied by plasma sprayed method on the crown of the substrate. The chosen thickness from the literature of the topcoat layer is 0.35 mm and that of the bond-coat layer is 0.15 mm. Also, from the literature, the major reason for the thermal barrier-coating (TBC) of a diesel engine piston crown using a ceramic material was to improve its performance.*

KEYWORDS: *3D-modelling; Original Equipment Manufacturer; SolidWorks Software; 7.5% Yttria-stabilized Zirconia; Nickel Chromium Aluminum Cobalt Yttria*

1.0 INTRODUCTION

The thermal barrier-coatings (TBCs) are advanced ceramic materials applied on metallic surfaces of aero-engine, turbine and spark and compression-ignition engine parts (cylinder liner, cylinder head, valves, piston crown, etc.), which work at very high temperatures [1]. Coatings help to insulate metallic parts from heavy and excessive heat loads using thermally insulating materials which withstand reasonable temperature difference between the combustion chamber and coating surfaces. This results to high operating temperatures on the metallic or component surfaces. Coatings also reduce the problems of oxidation and thermal fatigue in order to extend the life span of the machine components. Modern coating systems behave as barriers to heat transfer through metallic surfaces so as to protect engine parts from oxidation and hot corrosion [2,3].
The piston in an internal combustion engine (ICE) is a round piece of metal that converts the rotary motion of the crank-shaft into a reciprocating motion in the cylinder and exerts a force on the air-fuel mixture contained in the cylinder [4]. Piston has

compression and oil control rings preventing oil from entering the combustion-chamber including the fuel air from mixing with the oil [5]. Most fitted pistons in engine cylinders have piston rings [6]. Two or more compression rings are acting as seals or barriers between the piston and cylinder-wall. There are also one or two oil control-rings below the compression-rings (Figure 1). The piston head may be flat, bulged or otherwise shaped. Pistons which are either forged or cast have rounded shapes [5]. The preferred common materials for petrol and diesel engine pistons are aluminium alloys because they possess high thermal conductivity, low density, simple machinability, high-reliability, simple fabrication processes and very good recycling-characteristics [7].

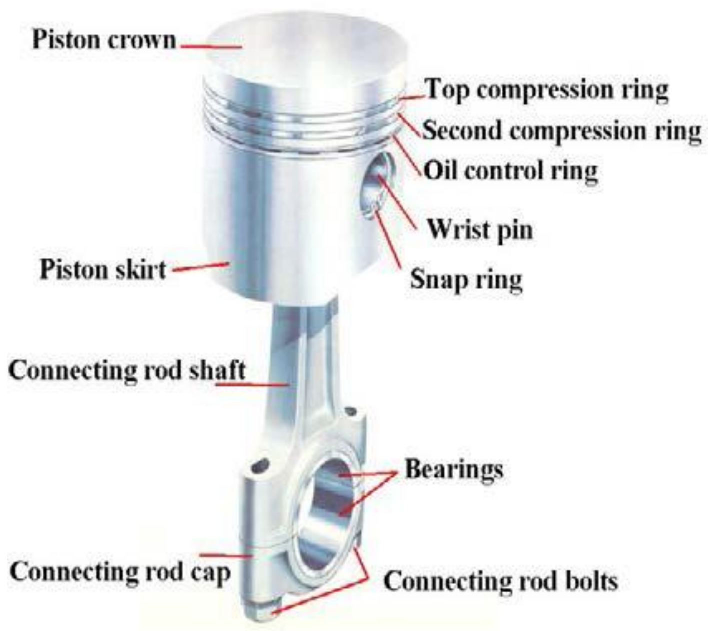

Figure 1: The different parts or elements of the piston

The single-component coating has not satisfied some multifunctional requirements of some engine parts. As a result, a complex thermal-barrier-coating structure was introduced. Research from the 1970s focused on a preferred coating system that comprises three separate layers on the substrate to achieve long-term improvement in the control of oxidation and corrosion at high temperatures [8,9]. Adnan et al. [13] conducted a test on a single-cylinder, indirect injection Ricardo E6-MS/128/76 type diesel engine. They coated the cylinder head, valves and piston with $MgO–ZrO_2$ layer having 0.35 mm thickness on a NiCrAl bond-coat layer also having 0.15 mm thickness. They discovered that in low-heat-rejection (LHR) diesel-engine the NOx emissions were reduced by about 40% and the brake specific fuel consumption (BSFC) also reduced by about 6% compared to the conventional engines when injection timing was retarded to 340^0 crank-angles before top dead centre (TDC) to that of a conventional engine. Ekrem et al. [14] compared a conventional engine with a LHR engine. They used $MgZrO_3$ as a coating material for the diesel piston and $CaZrO_3$ for the cylinder head and valves. The piston was coated with $MgZrO_3$ having a thickness of 350 μm on a NiCrAl bond-coat-layer with 150 μm thickness. The results obtained showed that the combustion gas temperature for the LHR engine was increased by approximately 65 ^{0}C while the BSFC and particulate emissions were reduced by about 6% and 40%, respectively as compared to a conventional engine. Rohini and Prema [11] reviewed thermal barrier-coating (TBC) on the same diesel engine performance to improve thermal efficiency by reducing specific fuel consumption (SFC) and exhaust emissions [15,16]. They were able to make a comparison between a standard diesel engine and a low-heat-rejection (LHR) engine. Experimental results from various researchers show improvement in efficiency and rate of specific fuel consumption. Navin et al. [16] analyzed the performance and emission of a thermal barrier-coated engine by using palm oil biodiesel and diesel as fuels. They prepared TBC using a series of a mixture consisting of different blend ratios of yttria-stabilized zirconia ($Y_2O_3.ZrO_2$) and aluminium oxide-silicon oxide (Al_2O_3-SiO_2) via plasma spray coating method. Their experimental results revealed the mixtures of TBC with 60% $Y_2O_3.ZrO_2$ + 40% Al_2O_3-SiO_2 had excellent nitrogen oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbon (UBHC) reductions when compared with other blend-coated pistons [12,17-18].

Plasma spray-coating system is the process whereby a powder feedstock is injected into a high-temperature plasma-jet where finely divided metallic and non-metallic materials are deposited in a molten or semi-molten state on a prepared substrate [19,20]. It is used as an effective and economical method for producing ceramic-coatings on metallic-substrates and production of bulk-powders from spheroidization [21]. The plasma spray-coating system is shown in Figure 2 while the spraying-gun system is displayed in Figure 3. The system consists of a power unit, gas supply unit, spraying-gun, powder-supply unit, cooling-system and control unit [20,22].

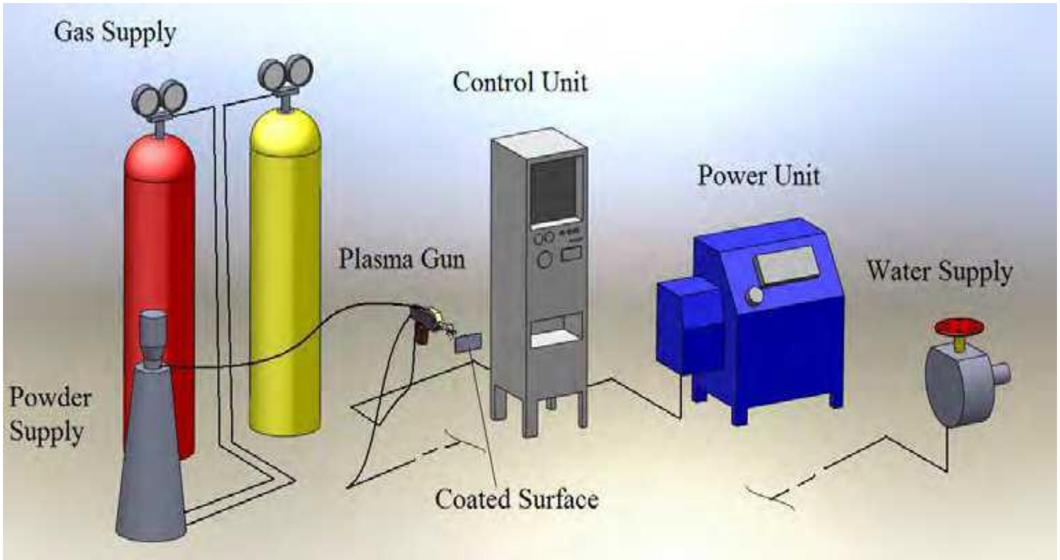

Figure 2: Plasma spray-coating system

The plasma spray-coating is the most widely accepted method of coating [20,23]. Figure 3 shows some coated piston tops.


(a) **(b)**

Figure 3: Ceramic coated piston tops

2.0 METHODOLOGY

2.1 Materials

The three (3) materials used for the 3D modelling were a metal substrate called the aluminium alloy piston A2618, a metallic bond-coat of thickness 0.15 mm called the Nickel Chromium Aluminium Cobalt Yttria (NiCrAlCoY) with a chemical composition of Bal Ni, 17.5% Cr, 5.5% Al, 2.5% Co, 0.5% Y_2O_3; and ceramic topcoat also of thickness 0.35 mm called the Yttria Stabilized Zirconia (7.5% Y_2O_3-ZrO_2) [22]. This paper is part of our PhD work [22].

2.2 Methods

2.2.1 The design of the piston elements

Figure 4 shows the cross-sectional view of conventional or uncoated piston [22].

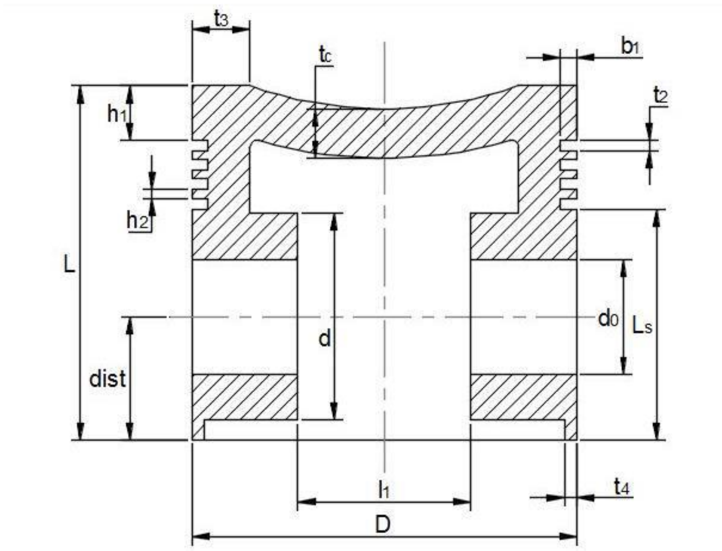

Figure 4: Cross-section of the model conventional piston

2.2.1.1 Design of the thickness of the piston head or crown, t_C

According to Grashoff's formula, the piston head thickness t_C is given by,

$$t_C = \sqrt{\frac{3p_{max}D^2}{16\sigma_y}} \tag{1}$$

where p_{max} is the maximum gas pressure (Pa), D is the cylinder bore or outside diameter of the piston (m), σ_y is the permissible or yield tensile stress (strength) for the piston material (Pa).

2.2.1.2 The number of piston rings

From Figure 2, we have total number of rings = 4 (number of compression rings = 3 and number of oil ring = 1)

2.2.1.3 Design of the radial thickness of the piston ring, t_1

Consider Eq. (2) for the design of piston ring radial thickness.

$$t_1 = D\sqrt{\frac{3p_w}{\sigma_p}} \tag{2}$$

where p_w is an allowable radial pressure of the gas on the cylinder wall taken as 0.025 Mpa, σ_P is permissible bending or tensile stress for cast iron rings which is 84 Mpa.

2.2.1.4 Design of the axial thickness of piston ring, t_2

Also, consider Eq. (3) for the design of piston ring axial thickness.

$$t_2 = \frac{D}{10n_R} \text{ or } = 0.7t_1 \tag{3}$$

where n_R = number of rings taken as 4.

2.2.1.5 Determining the length of the piston pin in the connecting rod bushing, l_1

Eq. (4) gives the length of the piston pin.

$$l_1 = 0.45D \tag{4}$$

2.2.1.6 Design of the width of the piston top land h_1

$$h_1 = 1.2\ t_C \tag{5}$$

2.2.1.7 Design of the width of other piston ring lands h_2

$$h_2 = 0.75t_2 \tag{6}$$

2.2.1.8 Determining the piston barrel

Piston Barrel thickness t_3 at the top end is;

$$t_3 = 0.03D + b_1 + 4.5 \quad (7)$$
$$b_1 = t_1 + 0.4 \quad (8)$$

where b_1 = radial depth of the piston ring groove (mm). The piston barrel thickness t_4 at the open end is:

$$t_4 = 0.25\ t_3 \quad (9)$$

2.2.1.9 Design of the length of the piston and piston skirt

Length of the piston skirt,

$$l_s = 0.6\ D \quad (10)$$

Total Length of Piston L = Length of the piston skirt + Length of the ring section + Top land

$$= l_s + (4\ t_2 + 3\ h_2) + h_1 \quad (11)$$

The length of the piston usually varies from D and 1.5D.

2.2.1.10 Design of the diameter of the piston boss and pin

Outside diameter d_0 of piston pin:

$$d_0 = 0.3D \quad (12)$$

$$\text{Piston Boss diameter } d = 1.5\ d_0 \quad (13)$$

Although, d_0 is given in the owner's manual. The value is 36 mm. The inside diameter d_1 of the piston pin:

$$d_1 = 0.6\ d_0 \quad (14)$$

2.2.1.11 Design of the centre of the pin

The centre of the pin is 0.02D to 0.04D above the centre of the skirt.

$$\text{Centre of pin} = 0.04D + 0.5\ l_s \quad (15)$$

The specifications for designing and modelling the conventional piston of the diesel-engine with the help of SolidWorks software were that of the ZS1115NM single-cylinder, inline and four-stroke direct injection diesel engine manufactured by Changchai Company Ltd, China. The engine specifications are given in Table 1 [24].

Equations (1) through (15) can only be used in designing the piston if the maximum gas pressure p_{max} is known. The maximum gas pressure from our PhD work was 10.2 x 10^6 N/m^2 or 10.2 N/mm^2 [22]. The yield tensile strength of the material used for the piston,

σ_t = 372 N/mm² [22]. Table 2 summarizes the sizes obtained from the design of the piston elements.

Table 1: Engine specification

Item	Specification
Engine model	ZS1115NM
Type	Single cylinder, four stroke, horizontal type, direct injection
Cylinder bore (D) (mm)	115
Piston stroke (L_S) (mm)	115
Piston displacement (V_s) (litre)	1.19
Compression ratio (c.r)	17:1
Rated output/brake power (b.p)(kW)	15.7
Rated speed (N)(Rev/min)	2200
Brake specific fuel consumption (bsfc) (g/kWh)	≤ 244.8
Specific lube oil consumption (g/kWh)	≤ 2.04
Lubricating method	Single circuit
Cooling method	Water cooled, evaporative
Cooling system	Radiator, natural convection
Starting method	Electric starting or hand cranking
Fuel injection pressure (MPa)	18.13 ± 0.49
Net weight (kg)	205
Overall dimension (L x W x H) (mm)	965 x 457 x 713
Mean piston speed (c_m) (m/s)	8.433
Fuel injection timing before TDC	22^0
Fuel type	Diesel
Chemical formula	$C_{14.4}H_{24.9}$
Connecting rod length (L_R) (mm)	258.5
Intake valve closes after TDC	38^0

Table 2: Size of piston parameters

S/N	Piston element	Size obtained (mm)
1	Cylinder bore, D	115
2	Thickness of the piston head, t_C	8.25
3	Radial thickness of the piston ring, t_1	3.436
4	Axial thickness of the piston ring, t_2	2.405
5	No of the piston rings, n_R	4
6	Width of the top land, h_1	9.9
7	Width of the ring land, h_2	1.80375
8	Radial depth of the piston ring groove, b_1	3.836
9	Thickness of the piston barrel at the top end, t_3	11.786
10	Thickness of the piston barrel at the open end, t_4	2.9465
11	Piston pin diameter, d_0	34.5
12	Diameter of the piston boss, d	51.75
13	Length of Skirt, l_s	69
14	Total length of the piston, L	93.93
15	Centre of pin above the centre of the skirt	39.10
16	Inside diameter of the piston pin, d_1	20.7
17	Length of the piston pin in the connecting rod bushing, l_1	51.75

2.3 SolidWorks modelling of the conventional piston

The sizes obtained from the design of the piston elements in Table 4 were used in modelling the conventional piston in SolidWorks CAD Software [23,25]. Figures 5 and 6 show the views of the modelled conventional piston.

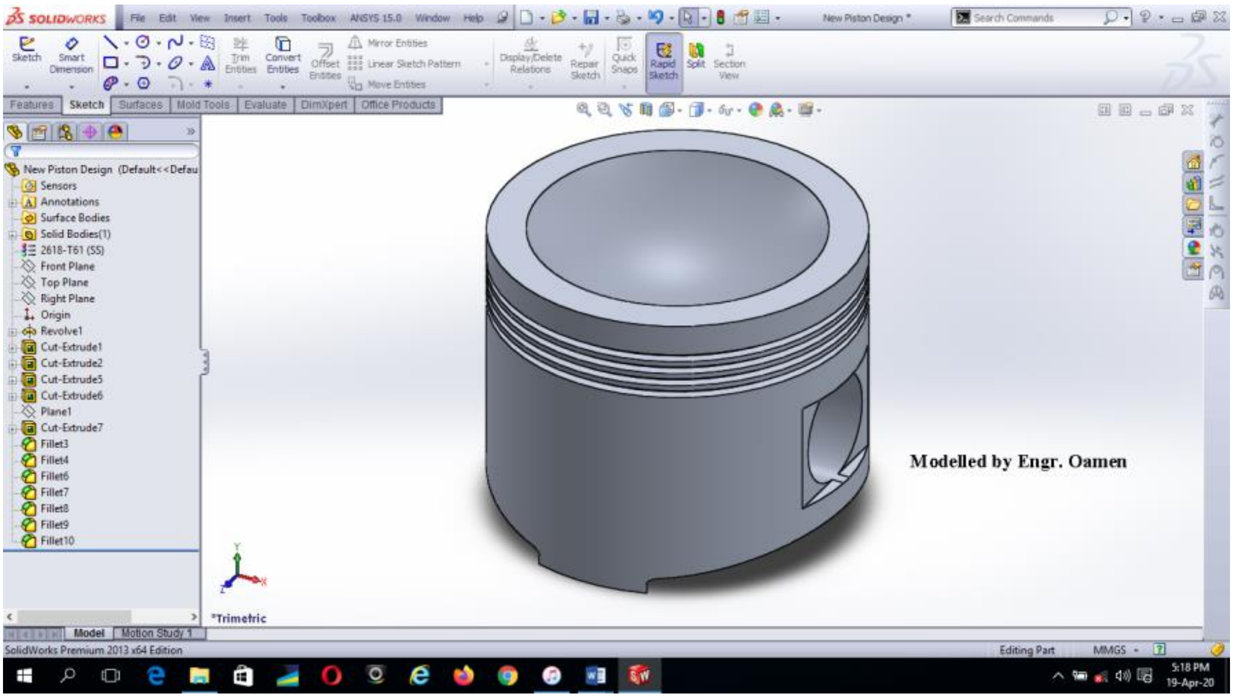

Figure 5: The isometric view of the 3D modelled conventional piston

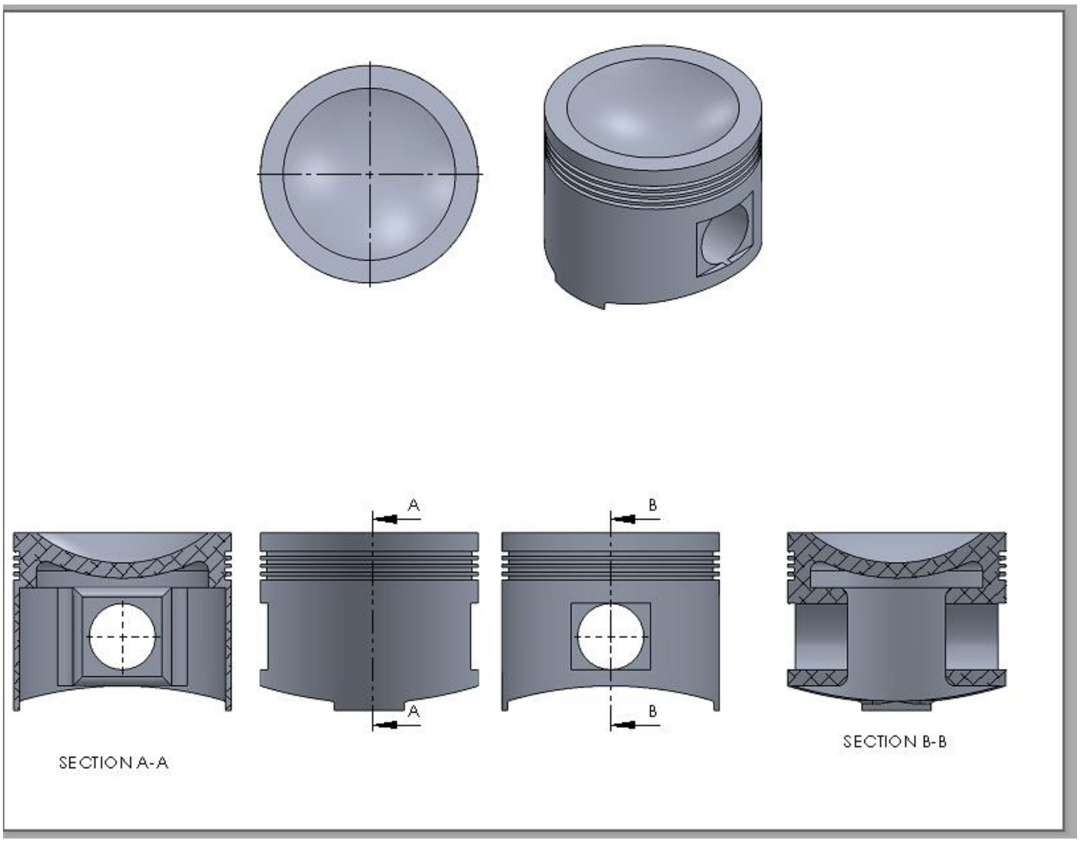

Figure 6: The sectional view of the modelled conventional piston

2.4 SolidWorks modelling of the bond-coat layer

The bond-coat layer of 0.15 mm thick was modelled in SolidWorks software. See Figure 7.

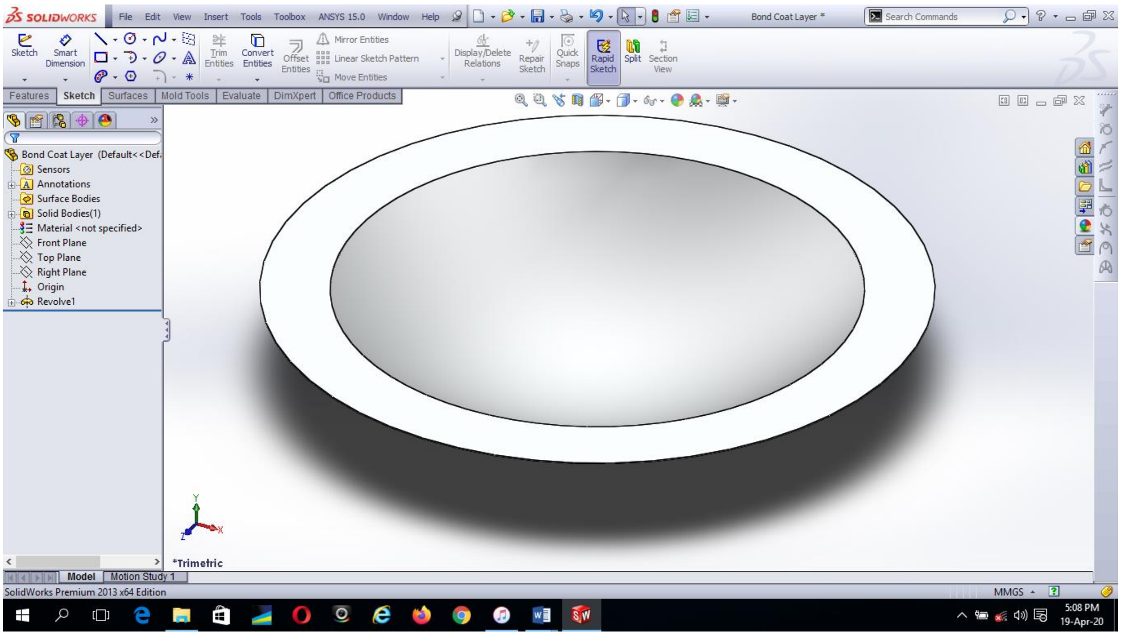

Figure 7: The modelled isometric view of the bond-coat layer of 0.15 thickness

2.5 SolidWorks modelling of the topcoat layer

The topcoat layer of 0.35 mm thick was modelled in SolidWorks software. See Figure 8.

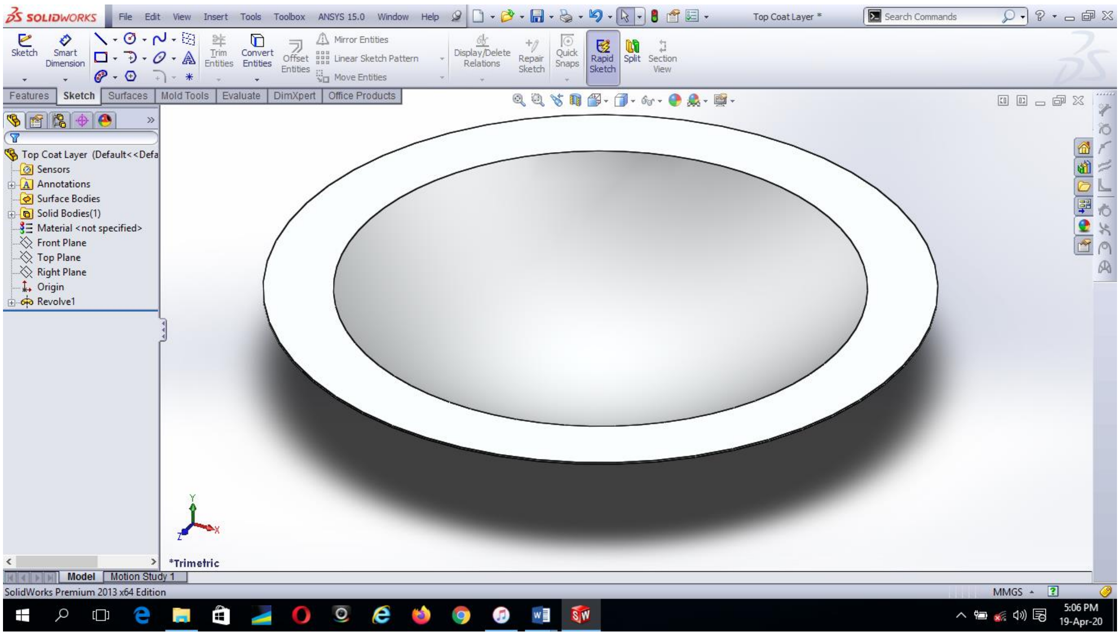

Figure 8: The modelled isometric view of the topcoat layer of 0.35 thickness

2.6 SolidWorks assembling of the conventional piston, bond and topcoats layers

The assembling of the piston, bond-coat and topcoat layers was also carried out using the SolidWorks software. Figures 9 and 10 show the views of the modelled reconditioned piston.

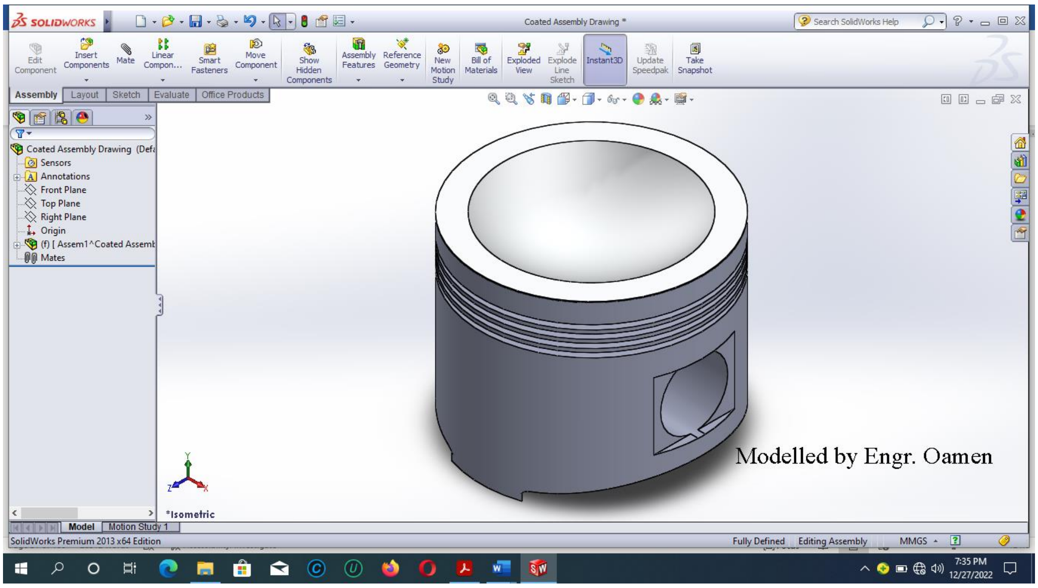

Figure 9: The assembly view of the reconditioned piston with bond and topcoat layers

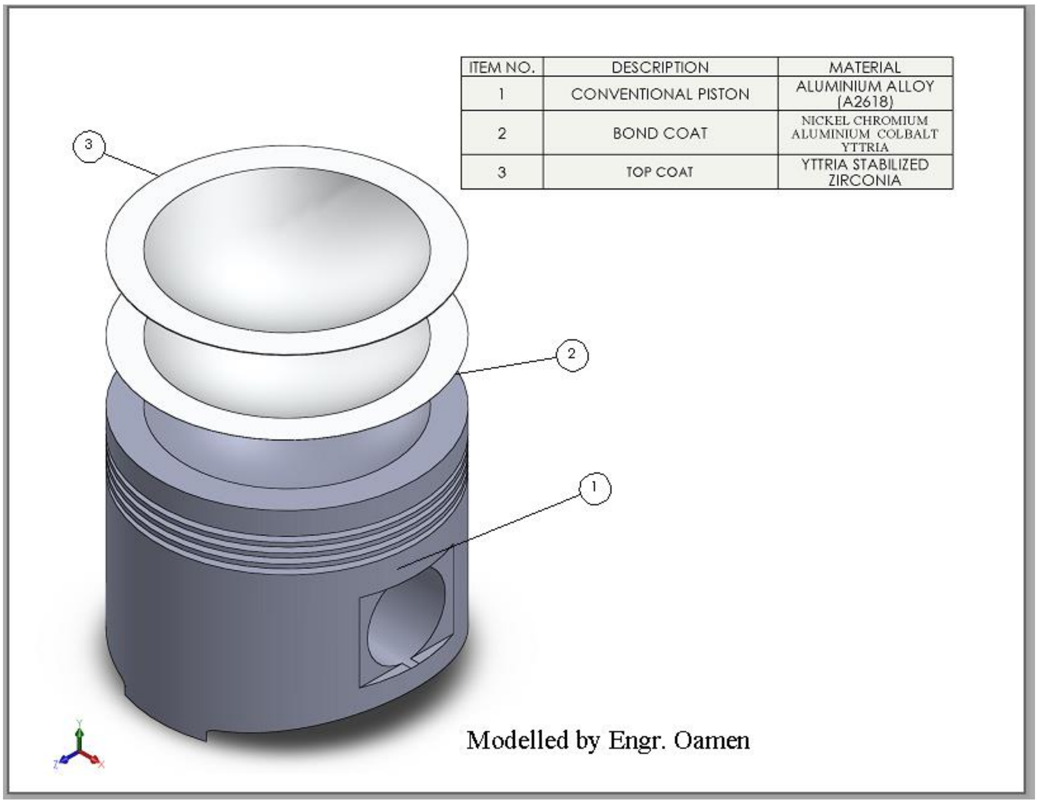

Figure 10: The exploded view of the reconditioned piston with bond and topcoat layers

3.0 RESULTS AND DISCUSSION

Figures 6 to 11 show the results of modelling conventional and reconditioned pistons of the ZS1115NM single-cylinder, inline and four-stroke direct injection diesel engine using SolidWorks 2013 CAD. This modelling provides the next stage involved in the reconditioning or coating of diesel engine pistons for improved performance. Findings from literature have it that reconditioned or thermal barrier coated pistons with a ceramic material that have a very low thermal conductivity give higher piston surface temperature and brake thermal efficiency, reduced brake specific fuel consumption and emissions than the conventional ones.

4.0 CONCLUSIONS

Due to the upsurge of counterfeit spare parts in the market, meeting the original equipment manufacturer (OEM) standards requires a reconditioning process. Having modelled the thermal barrier-coated piston of a single-cylinder, inline and four-stroke direct injection diesel engine using SolidWorks 2013 CAD, it could be concluded that with given engine specification suitable materials for designing and modelling a reconditioned piston of diesel engine are chosen and the model reconditioned.

ACKNOWLEDGEMENTS

We appreciate God almighty and families for supporting us during this work.

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