iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 10 Issue: III Month of publication: March 2022

DOI: https://doi.org/10.22214/ijraset.2022.40765

FEA Analysis and Experimental Investigation of the Ceramic Coating on Aluminum Piston Material by Plasma Spray Coating Technique

Venkat Karthik N[1], Suresh Kumar V[2], Yuvaraj K[3], Balaji[4], Palani[5]
[1, 2, 3]Final year, [4, 5]Assistant Professor, Department of Mechanical Engineering, Vel tech High tech Dr.Rangarajan Dr. Sakunthala Engineering College

***Abstract:** Functionally graded materials are of widespread interest because of their superior properties such as corrosion, erosion and oxidation resistance, high hardness, chemical and thermal stability at cryogenic and high temperatures. These properties make them useful for many applications, including Thermal Barrier Coating (TBC) on metallic substrates used at high temperatures in the fields of aircraft and aerospace, especially for thermal protection of components in gas turbines and diesel engines. The application of TBC reduces the heat loss to the engine cooling-jacket through the surface exposed to the heat transfer such as the cylinder head, liner, piston crown and piston rings. The insulation of the combustion chamber with ceramic coating affects the combustion process and, hence, the performance and exhaust emissions characteristics of the engines improve. In this project, the main emphasis is placed on the study of thermal behavior of functionally graded coatings obtained by means of using a commercial code, ANSYS on aluminum and steel piston surfaces and the results are verified with numerical and experimental works.*
***Keywords:** Thermal Barrier Coating, Piston, Insulation, Corrosion, ANSYS, engine cooling-jacket.*

I. INTRODUCTION

Functionally graded materials are of widespread interest because of their superior properties such as corrosion, erosion and oxidation resistance, high hardness, chemical and thermal stability at cryogenic and high temperatures. These properties make them useful for many applications, including Thermal Barrier Coating (TBC) on metallic substrates used at high temperatures in the fields of aircraft and aerospace, especially for thermal protection of components in gas turbines and diesel engines. Thermal barrier coatings have been successfully applied to the internal combustion engine, in particular the combustion chamber in order to simulate adiabatic changes. The objectives are not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction of engine emissions and brake specific fuel consumption. The application of TBC reduces the heat loss to the engine cooling-jacket through the surface exposed to the heat transfer such as the cylinder head, liner, piston crown and piston rings. The insulation of the combustion chamber with ceramic coating affects the combustion process and, hence, the performance and exhaust emissions characteristics of the engines improve.

On the other hand, the desire of increasing the thermal efficiency or reduce fuel consumption of engines lead to the adoption of higher compression ratios, in particular for diesel engines, and reduced in-cylinder heat rejection. Both of these factors cause increased mechanical and thermal stresses of materials used in combustion chamber. In this project, the main emphasis is placed on the study of thermal behavior of functionally graded coatings obtained by means of using a commercial code, ANSYS on aluminum and steel piston surfaces and the results are verified with numerical and experimental works. The following is the major forces acting over piston,

1) Due to explosion of fuel gases
2) Due to compression of fuel gases
3) Side wall friction and forces
4) Thermal load
5) Inertia force due to high frequency of reciprocation of piston
6) Friction and forces at crank pin hole

The following are the functions of piston, to reciprocate in the cylinder as a gas tight plug causing suction, compression, expansion, and exhaust strokes, to receive the thrust generated by the explosion of the gas in the cylinder and transmit it to the connecting rod and to form a guide and bearing to the small end of the connecting rod and to take the side thrust due to obliquity of the rod. The application of TBC to the surfaces of these components enhances high temperature durability by reducing the heat transfer and lowering temperature of the underlying metal. Typical TBCs failure is by spalling of the ceramic top coat from the bond coat. There are many factors that influence the overall performance of coatings and cause spalling of the coating. However, oxidation and thermal mismatch are identified as two major factors influencing the life of the coating system. The coatings are permeable to the atmospheric gases and liquids resulting in the oxidation of the bond coat and spalling of the coating. The functionally graded coatings were used to reduce the mismatch effect. Therefore, the thermal expansion and interfacial stresses are an alternative approach to conventional thermal barrier coatings.

Energy conservation and efficiency have always been the quest of engineers concerned with internal combustion engines. The diesel engine generally offers better fuel economy than its counterpart petrol engine. Even the diesel engine rejects about two thirds of the heat energy of the fuel, one-third to the coolant, and one third to the exhaust, leaving only about one- third as useful power output. Theoretically if the heat rejected could be reduced, then the thermal efficiency would be improved, at least up to the limit set by the second law of thermodynamics. Low Heat Rejection engines aim to do this by reducing the heat lost to the coolant.

Thermal Barrier Coatings (TBCs) in diesel engines lead to advantages including higher power density, fuel efficiency, and multifuel capacity due to higher combustion chamber temperature Using TBC can increase engine power by 8%, decrease the specific fuel consumption by 15-20% and increase the exhaust gas temperature 200K.

Although several systems have been used as TBC for different purposes, yttria stabilized zirconia with 7-8 wt. % yttria has received the most attention. Several important factors playing important roles in TBC lifetimes including thermal conductivity, thermal, chemical stability at the service temperature, high thermo mechanical stability to the maximum service temperature and at last but not least the thermal expansion coefficient (TEC).

The diesel engine with its combustion chamber walls insulated by ceramics is referred to as Low Heat-Rejection (LHR) engine. The LHR engine has been conceived basically to improve fuel economy by eliminating the conventional cooling system and converting part of the increased exhaust energy into shaft work using the turbocharged system.

A large number of studies on performance, structure and durability of the LHR engine have been carried out since Kamo and Bryzik presented a new concept of the LHR engine 041 combined with the turbo compound system. Although promising the results of the investigations have been somewhat mixed.

Most have concluded that insulation reduces heat transfer, improves thermal efficiency, and increases energy availability in the exhaust.

However contrary to the above expectations some experimental studies have indicated almost no improvement in thermal efficiency and claim that exhaust emissions deteriorated as compared to those of the conventional water- cooled engines. Plasma spray is the most common method of depositing TBCs for diesel applications. It creates a splat structure with 10- 20 % volume fraction of voids and cracks. High porosity of this structure makes it an ideal choice for TBC. Widespread application has been limited by insufficient lifetimes and the cost.

TBCs for diesel engines have generally been accepted to improve engine thermal efficiency and reduce emissions as well as specific fuel consumption because of their ability to provide thermal insulation to the engine components. The generally known principle that increased operation temperatures in energy conversion systems lead to an increase in efficiency, fuel savings and reduced emissions as particles, carbon monoxides (CO), hydrocarbons (HC) and limited reductions of NOx emissions have, over many decades, promoted R&D activities in the field of TBCs development.

II. RESEARCH BACKGROUND

J Bobzin et al(2008) [1], Engine blocks of passenger cars made of hypoeutectic AlSialloys are generally equipped with cast iron liners in order to provide cylinder running surfaces that meet the tribological requirements. Thermally sprayed cylinder running surfaces are a promising alternative to cast iron liners. APS sprayed cylinder running surfaces made from low alloyed C steel have already proven their ability to reduce friction losses within the engine. Additional potential to reduce friction losses is offered by novel, and highly alloyed iron based surface building materials. This work describes the development of such materials and their application by the Plasma Transferred Wire Arc internal diameter coating process. The feedstocks lead to partially amorphous coatings with embedded boridicnanoscale precipitations if processed by thermal spraying. The coatings were applied onto the inner diameters of test liners made of aluminium EN AW 6060 and onto cylinder bore walls of an inline 4 cylinder engine.

Prior to coating, all surfaces to be coated were pre-treated by a novel fine boring process in order to create a surface topography which enables the adherence of the coatings. The coatings microstructures were analysed by light optical microscopy, hardness measuring and transmission electron microscopy. Furthermore the oil storage capacities of the honed surfaces were determined. © 2008 Elsevier B.V. All rights reserved.

Ulrike Schulz et al (2006), Vacuum technologies for the deposition of optical interference coatings on polymer substrates, based on long-term experience in glass coating, have been under development for about 20 years. A growing market for precision optical elements and consumer optics molded from thermoplastic polymers requires antireflective properties and hard coatings. Owing to the manifold chemical and physical properties of optical polymers, special efforts are essential for each type of plastic to find polymer-capable coating conditions. The main focus of this article is on evaluating the state of the art in vacuum-coating processes applied to plastics today, and on discussing specific coating techniques and evaluation procedures. A better understanding of the complex interactions between low pressure plasmas and the various polymer materials will be a key factor in making durable plastic optics for future applications; achieving this will be a challenge to surface scientists. 2006 Elsevier Ltd. All rights reserved. Giovanni Bolelli et al(2006) [2], The wear resistance of plasma-sprayed ceramic coatings (Al2O3, Al2O3–13%TiO2, Cr2O3) has been investigated through pin-ondisk and dry sand-steel wheel tests, has been correlated to microstructural and micromechanical characteristics (microhardness, fracture toughness) and has been compared to well- known platings (such as Cr electroplating and electroless Ni) and HVOF-sprayed cermets (WC–17%Co, WC–10%Co–4%Cr). Plasma-sprayed ceramics are hard but brittle: dry particles abrasion occurs through splats detachment. The toughest coating (Al2O3) displays the highest wear resistance, which in fact overcomes HVOF-sprayed cermets and Cr electroplating, when a low number of wheel revolutions are considered. In pin-on-disk tests, no coating undergoes wear loss against the 100Cr6 ball, that possess lower hardness. Against the alumina ball, Al2O3 and Al2O3– TiO2 coatings show high wear rates and friction coefficients (due to chemical affinity), while Cr2O3 possesses better wear resistance, lower friction coefficient and inflicts less wear on the counterpart. Cr2O3 wear scar consists in plastically deformed splats and debris forming a quite adherent protective tribofilm. Rajesh Ranganathan et al (2005) [3],The purpose of this paper is to introduce the fabrication of metal-matrix composite (MMC) coatings with welding processes, such as plasma arc welding, using tailored MMC precursor materials such as particulatecored wires. The methods in this study are designed to obtain specific structures and properties in the coatings. Because the features of the MMC coatings depend on the dynamic temperature field generated by the welding process, thermal modeling and feedback control are implemented to ensure the required thermal field conditions; for example, infrared pyrometry sensing is used in robotic plasma arc welding deposition. The control method used in the thermal process is explained, and the resulting microstructures and hardness properties of the produced fabricated coatings are assessed and evaluated.

III. OVERVIEW OF PISTON, COATING AND ITS METHODS

A. Piston

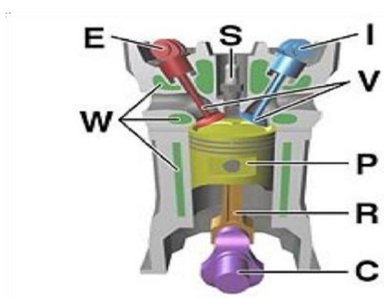


Fig 1. Components of Diesel Engine

The figure 1 portrays the components of the diesel engine having a piston. The following is the definition of the components, (E) Exhaust camshaft, (C) Crankshaft, (W) Water jacket for coolant flow, (I) Intake camshaft, (S) Fuel Injector ,(V) Valves, (P) Piston, (R) Connecting rod, (W) Water jacket for coolant flow. A piston is a component of reciprocating engines, pumps and gas compressors. It is located in a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. In a pump, the function is reversed and force is transferred from the crankshaft to the piston for the purpose of compressing or ejecting the fluid in the cylinder. In some engines, the piston also acts as a valve by covering and uncovering ports in the cylinder wall.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue III Mar 2022- Available at www.ijraset.com

B. Coating

Coating is a covering that is applied to an object. The aim of applying coatings is to improve surface properties of a bulk material usually referred to as a substrate. One can improve appearance, adhesion, wetability, corrosion resistance, wear resistance, scratch resistance, etc.. They may be applied as liquids, gases or solids. Coatings can be measured and tested for proper opacity and film thickness by using a Drawdown card.

1) Nano Coating: Nano-coating is a recently developed technology used for coating any kind of material in hard coating and low friction coating both in which coating is done at nano scale that is of the order of 10^{-9}

The two major types of nano-coating are

a) Physical vapour deposition (PVD)
b) Chemical vapour deposition (CVD)

2) *Physical Vapour Deposition (PVD):* Thin film deposition is a process applied in the semiconductor industry to grow electronic materials and in the aerospace industry to form thermal and chemical barrier coatings to protect surfaces against corrosive environments and to modify surfaces to have the desired properties. The deposition process can be broadly classified into physical vapor deposition (PVD) and chemical vapour deposition (CVD). In CVD, the film growth takes place at high temperatures, leading to the formation of corrosive gaseous products, and it may leave impurities in the film. The PVD process can be carried out at lower deposition temperatures and without corrosive products, but deposition rates are lower and it leaves residual compressive stress in the film. Electron beam physical vapor deposition, however, yields a high deposition rate from 0.1 µm / min to 100 µm / min at relatively low substrate temperatures, with very high material utilization efficiency.

Parameters of PVD is given by

Deposition chamber vacuum pressure: 10^{-4} torr No. of electron guns: 6

Accelerating voltage: 20kv-25kv

Evaporation rate: 10^{-2} g/cm^{2}sec

3) *Electron Beam Physical Vapour Deposition (Thin Film Deposition Process):* In an EBPVD system, the deposition chamber is evacuated to a pressure of 10^{-4} Torr. The material to be evaporated is in the form of ingots. There are as many as six electron guns, each having a power from few tens to hundreds of kW. Electron beams can be generated by thermionic emission, field emission or the anodic arc method. The generated electron beam is accelerated to a high kinetic energy and focused towards the ingot. When the accelerating voltage is between 20 kV – 25 kV and the beam current is a few amperes, 85% of the kinetic energy of the electrons is converted into thermal energy as the beam bombards the surface of the ingot. The surface temperature of the ingot increases resulting in the formation of a liquid melt. Although some of incident electron energy is lost in the excitation of X-rays and secondary emission, the liquid ingot material evaporates under vacuum. The ingot itself is enclosed in a copper crucible, which is cooled by water circulation. The level of molten liquid pool on the surface of the ingot is kept constant by vertical displacement of the ingot. The number of ingot feeders depends upon the material to be deposited. The evaporation rate may be of the order of 10^{-2} g/cmsec .

4) *Material Evaporation Method:* Refractory carbides like titanium carbide and borides like titanium boride and zirconium boride can evaporate without undergoing decomposition in the vapour phase. These compounds are deposited by direct evaporation. In this process these compounds, compacted in the form of an ingot, are evaporated in vacuum by the focused high energy electron beam and the vapours are directly condensed over the substrate. Certain refractory oxides and carbides undergo fragmentation during their evaporation by the electron beam, resulting in a stoichiometry that is different from the initial material. For example, alumina, when evaporated by electron beam, dissociates into aluminium, AlO_3 and Al_2O. Some refractory carbide like silicon carbide and tungsten carbide decompose upon heating and the dissociated elements have different volatilities.These compounds can be deposited on the substrate either by reactive evaporation or by co-evaporation. In the reactive evaporation process, the metal is evaporated from the ingot by the electron beam. The vapours are carried by the reactive gas, which is oxygen in case of metal oxides or acetylene in case of metal carbides. When the thermodynamic conditions are met, the vapours react with the gas in the vicinity of the substrate to form films. Metal carbide films can also be deposited by co- evaporation. In this process, two ingots are used, one for metal and the other for carbon. Each ingot is heated with different beam energy so that their evaporation rate can be controlled. As the vapours arrive at the surface, they chemically combine under proper thermodynamic conditions to form a metal carbide film.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue III Mar 2022- Available at www.ijraset.com

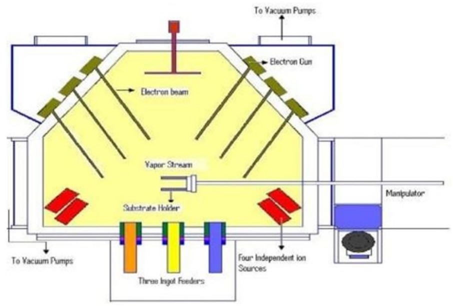


Fig 2. Electron beam deposition physical vapour deposition

IV. DESIGN AND ANALYSIS

Generally, for modeling, packages like Pro- Engineer, IDEAS will be used. In this analysis the model is created in the ANSYS itself to eliminate the data losses that will occur if standard data exchange formats like IGES, STEPS are used. To create the model the details about the key point locations are taken as the inputs. The following is the example of design and modelling procedure in ANSYS,

Cylinder bore diameter = 4.000" , Stroke length = 3.480" , Number of cylinders = 8

Engine displacement = bore X bore X 0.7854 X number of cylinders

Engine displacement = 4.000 X 4.000 X 3.480 X
0.7854 X 8

Engine displacement = 349.8586 cubic inches (round up to 350 cubic inches)

A. Stroke Length

Stroke Length = engine displacement / (bore X bore X 0.7854 X number of cylinders)

Stroke Length = 349.8486 / (4.000 X 4.000 X
0.7854 X 8)

Stroke Length = 3.480"

B. Cylinder Bore Diameter

Cylinder bore diameter = square root of [engine displacement / (stroke X 0.7854 X number of cylinders)]

Cylinder bore diameter = √[349.8486 / (3.480 X 0.7854 X 8)]

Cylinder bore diameter = 4.000"

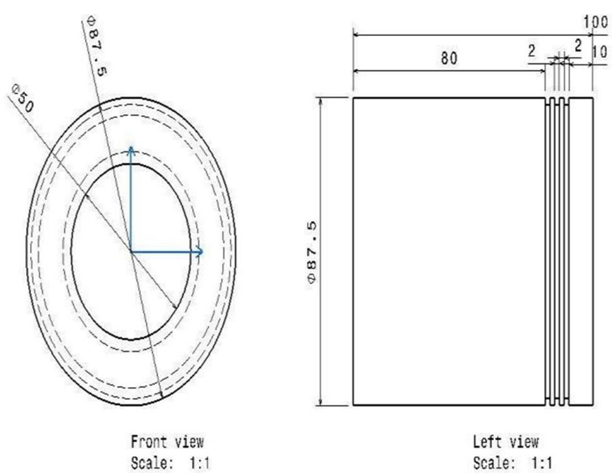


Fig 3. Sketch of the piston

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue III Mar 2022- Available at www.ijraset.com

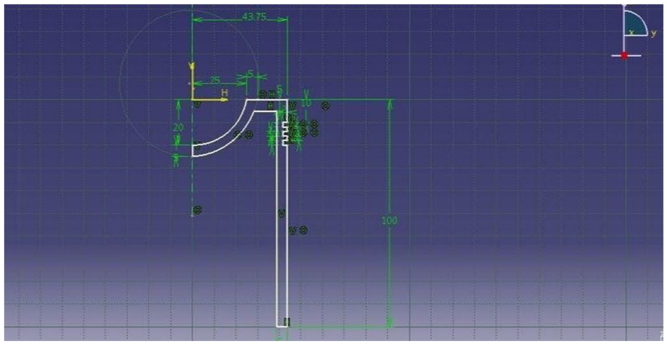


Fig 4. 2D sketch of the piston

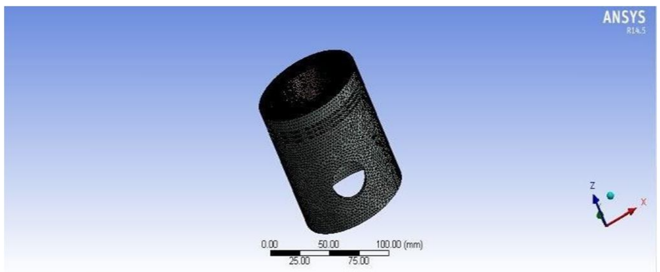


Fig 5. 3D sketch of the piston

Category	Element Name(s)
Spars	LINK1, LINK8, LINK10, LINK180
Beams	BEAM3, BEAM4, BEAM23, BEAM24, BEAM44, BEAM54, BEAM188, BEAM189
Pipes	PIPE16, PIPE17, PIPE18, PIPE20, PIPE59, PIPE60
2-D Solids	PLANE2, PLANE25, PLANE42, HYPER56, HYPER74, PLANE82, PLANE83, HYPER84, VISCO88, VISCO106, VISCO108, PLANE145, PLANE146, PLANE182, PLANE183
3-D Solids	SOLID45, SOLID46, HYPER58, SOLID64, SOLID65, HYPER86, VISCO89, SOLID92, SOLID95, VISCO107, SOLID147, SOLID148, HYPER158, SOLID185, SOLID186, SOLID187, SOLID191
Shells	SHELL28, SHELL41, SHELL43, SHELL51, SHELL61, SHELL63, SHELL91, SHELL93, SHELL99, SHELL150, SHELL181
Interface	INTER192, INTER193, INTER194, INTER195
Contact	CONTAC12, CONTAC52, TARGE169, TARGE170, CONTA171, CONTA172, CONTA173, CON-TA174, CONTA175
Coupled-Field	SOLID5, PLANE13, FLUID29, FLUID30, FLUID38, SOLID62, FLUID79, FLUID80, FLUID81, SOLID98, FLUID129, INFIN110, INFIN111, FLUID116, FLUID130
Specialty	COMBIN7, LINK11, COMBIN14, MASS21, MATRIX27, COMBIN37, COMBIN39, COMBIN40, MATRIX50, SURF153, SURF154
Explicit Dynamics	LINK160, BEAM161, PLANE162, SHELL163, SOLID164, COMBI165, MASS166, LINK167, SOLID168

Fig 6. Elements used in Structural Analysis

C. SOLID45 Element Description

SOLID45 is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions.The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

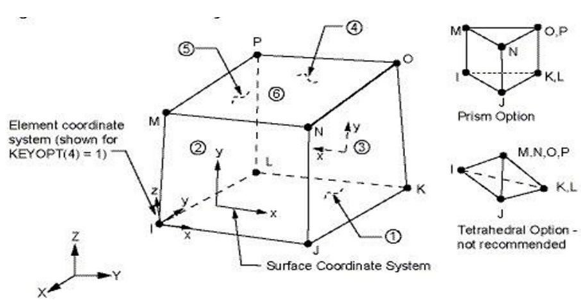


Fig 7. Solid 45 geometry

D. TARGE170 Element Description

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements (CONTA173, CONTA174, CONTA175, CONTA176 & CONTA177). The contact elements themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface is discretized by a set of target segment elements (TARGE170) and is paired with its associated contact surface via a shared real constant set. We can impose any translational or rotational displacement, temperature, voltage, and magnetic potential on the target segment element. we can also impose forces and moments on target elements.

For rigid target surfaces, these elements can easily model complex target shapes. For flexible targets, these elements will overlay the solid, shell, or line elements describing the boundary of the deformable target body.

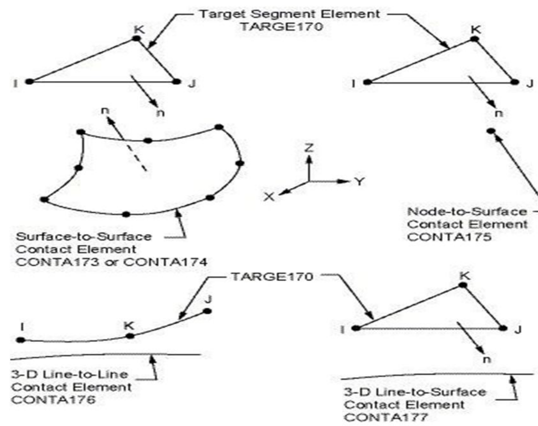


Fig 8. Target170 geometry

V. RESULTS

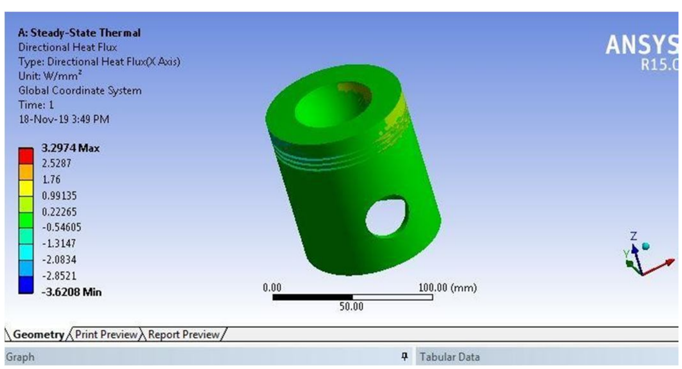


Fig 9. Uncoated Zirconia(Zro2)

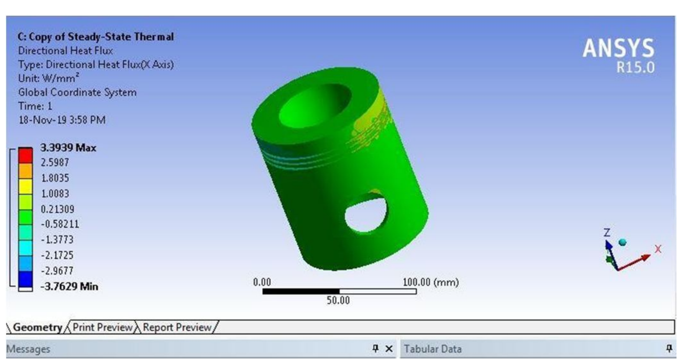


Fig 10. Zirconia coated (Zro2)

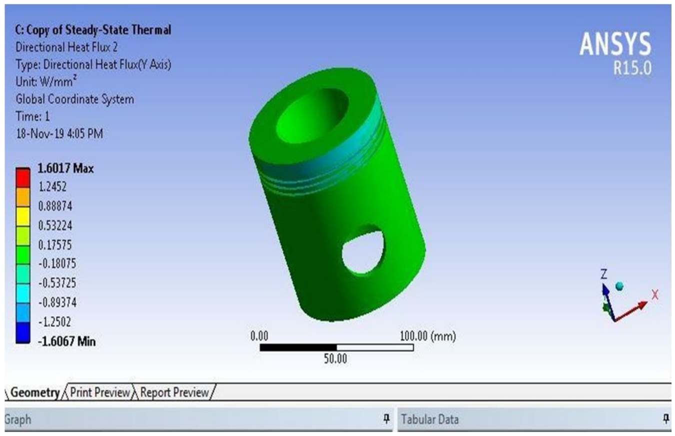


Fig 11. Titania (Alo2) Uncoated

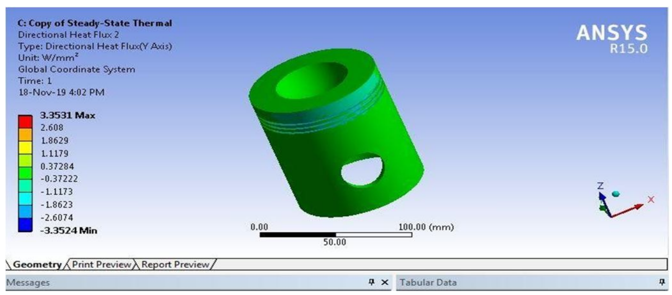
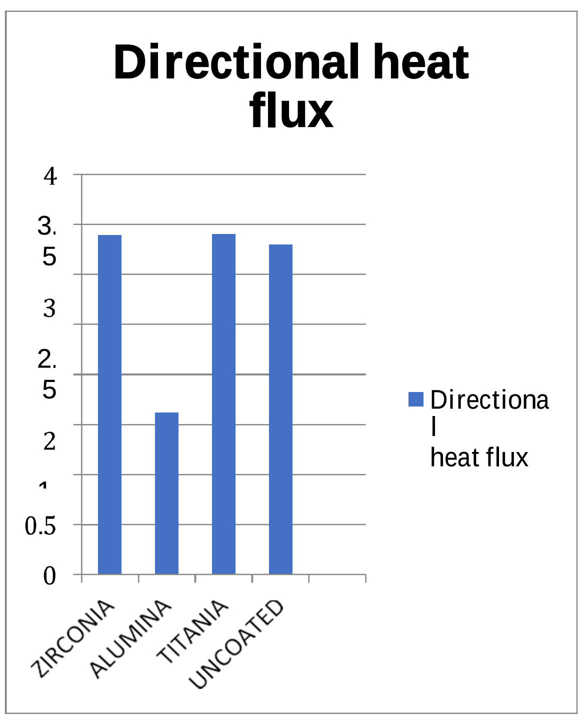


Fig 12. Titania(Tio2) coated



Total heat flux

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue III Mar 2022- Available at www.ijraset.com

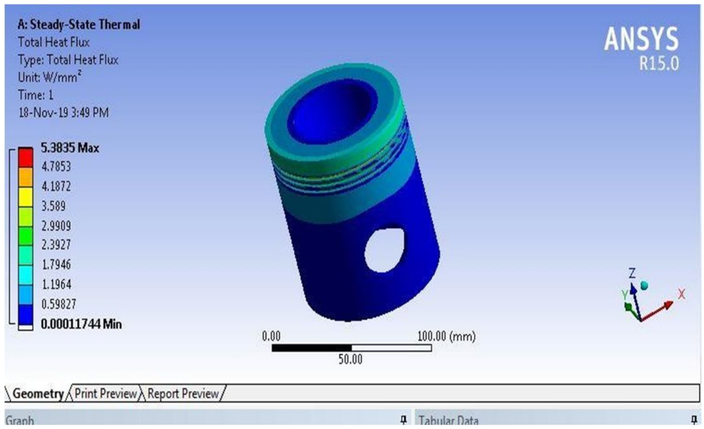


Fig 13. Aluminia (Alo2) Uncoated

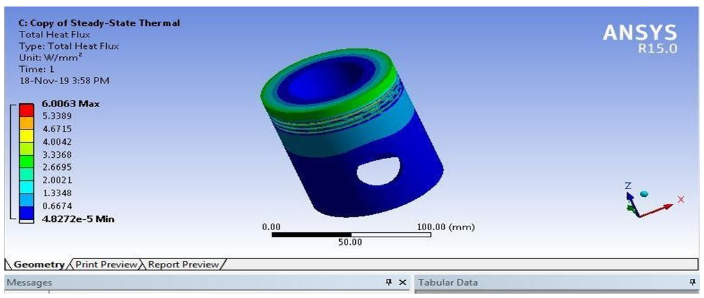


Fig 14. Aluminia (Alo2) coated

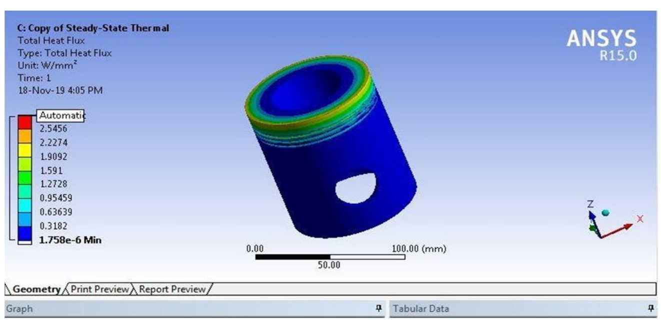


Fig 15. Titania (Alo2) Uncoated

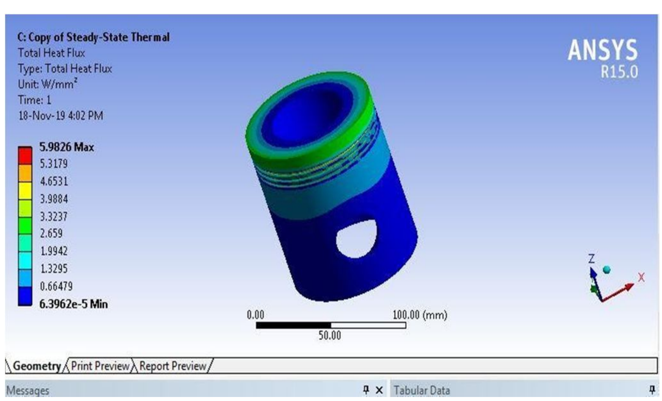
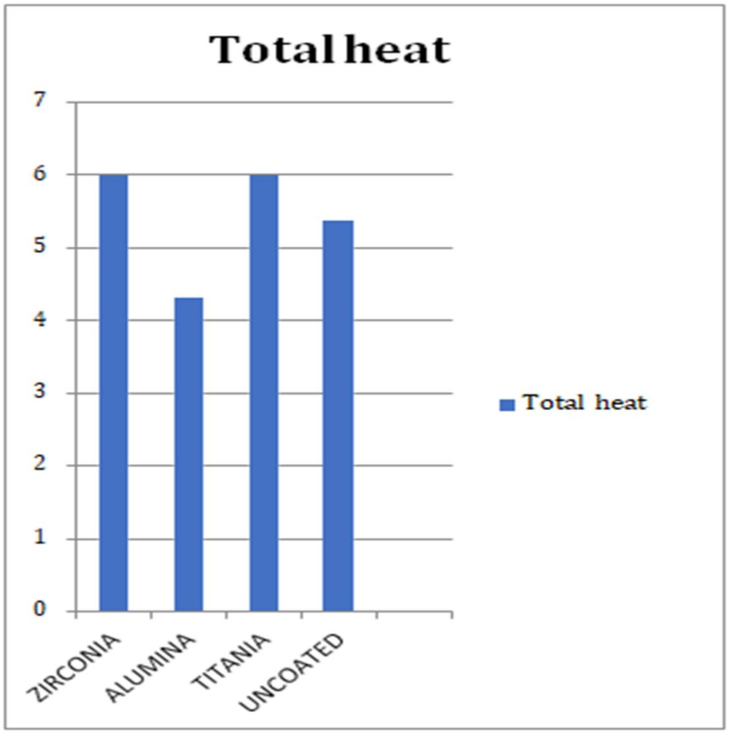


Fig 16. Titania(Tio2) coated



Temperature

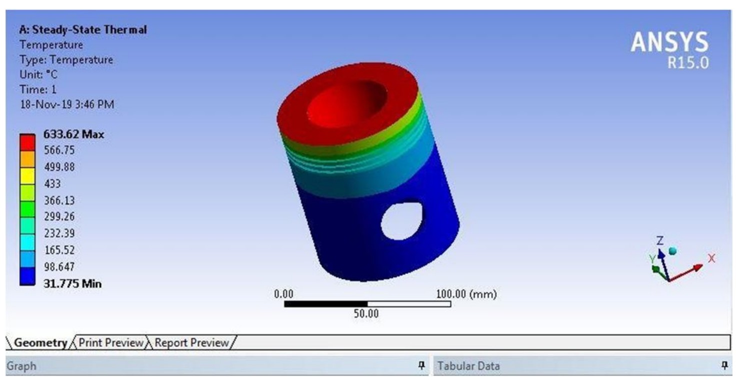


Fig 18. Uncoated Zirconia(Zro2)

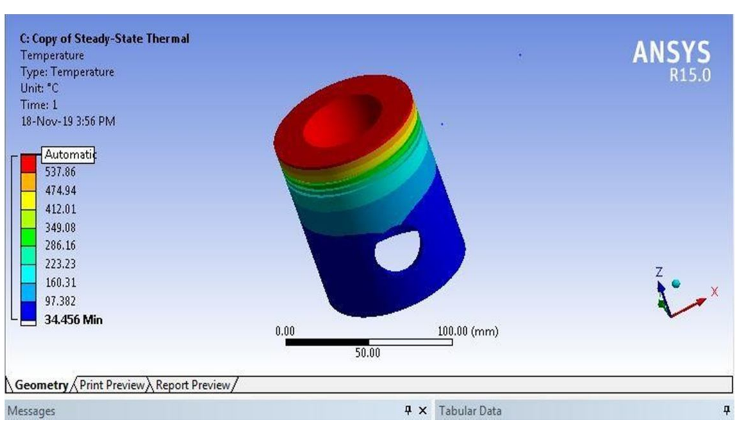


Fig 19. Coated Zirconia(Zro2)

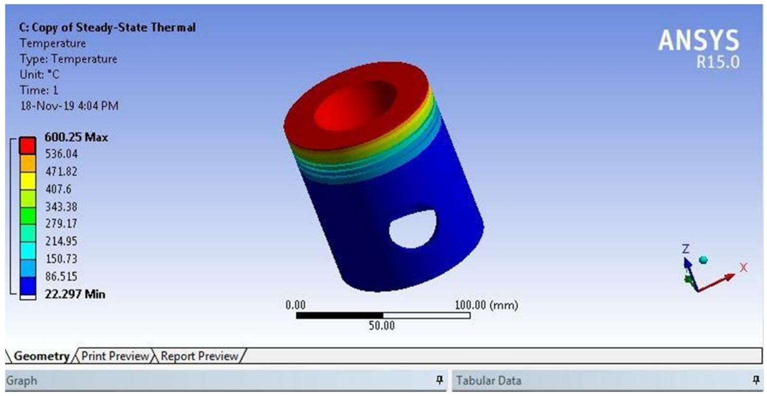


Fig 20. Aluminia (Alo2) Coated

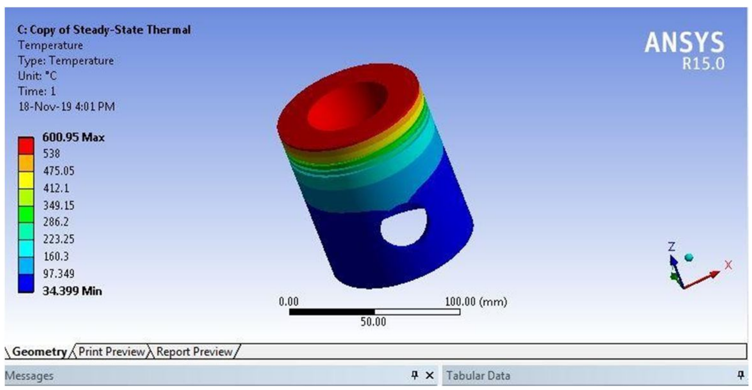
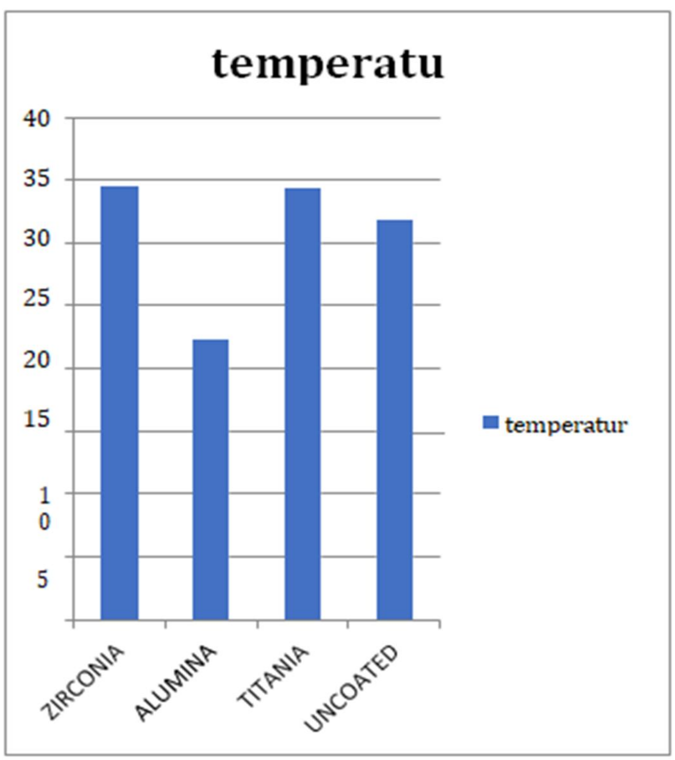


Fig 21. Titania (Tio2) Coated



Temperature analysis of Materials

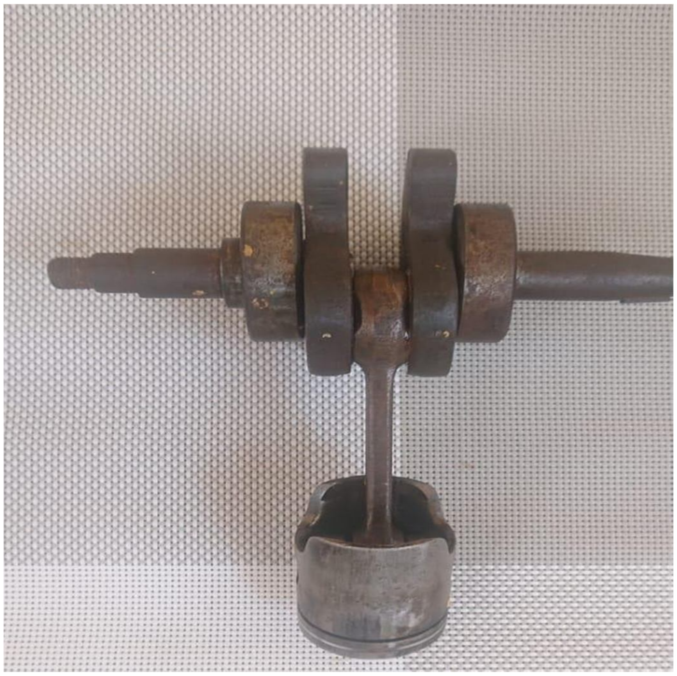


Fig 22. Hardware Implementation

VI. CONCLUSION

From the obtained literature survey the strengthening point of view the Zirconia coated piston strength will be higher than the all other coated piston. So that the tribological property will be increased in terms of wear and thermal barrier also, this will improve the further overall engine efficiency due to the good combustion takes place. Due to more strengthening of the Zirconia coated piston surface, the corrosion and wear properties also improved. This will further helpful for the incomplete combustion. Then the temperature is lower for the zirconia coated piston than the other pistons, so that the heat loss was lesser for the zirconia coated piston. This will improve the combustion properties and reduces the emissions.

REFERENCES

[1] Ekrem Buyukkaya, “Thermal Analysis of functionally graded coating AlSi alloy and steel pistons”, Surface and coatings technology (2007)
[2] Reinhold H. Dauskardt, “THERMAL BARRIER COATINGS” (1999).
[3] M. Foy, M. Marchese, G. Jacucci, Engineering plasma spray films by knowledge based simulations proceedings of IFIP conference on, in: Arthur B. Baskin, et al., (Eds.), Cooperative Knowledge Processing for Engineering Design, Kluwer Academic Publishers, The Netherlands, 1999, p. 289.
[4] J.S. Lee, T. Matsubara, T. Sei, T. Tsuchiya,
[5] J. Mater, Preparation and properties of Y2O3-doped ZrO2 thin films by the sol–gel process, Surface Coating Technology (1997).
[6] J.N.Reddy, “An introduction to finite element analysis”.
[7] Zhang T, Xu L, Xiong W, et al. Experimental research on the thermal contact resistance between Cu-Cu in vacuum and low temperature. Cryogenics, 1999.
[8] ANSYS manual guide.
[9] www.azom.com - “Functionally Graded Materials (FGM) and Their Production Methods.
[10] D.Robinson,R.Palaninathan.Thermal analysis of piston using 3D finite element method.2001Elsevier B.V
[11] A. R. Bhagat, Y.M. Jibhakate. Thermal Analysis of I.C Engine Piston Using Finite element method(IJMER)Vol.2,Issue4,July- Aug 2012.