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Temperature and Thermal Stress Analyses of a Ceramic-Coated Aluminum Alloy Piston Used In a Diesel Engine

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Abstract:

The thermal stress distributions of the conventional and ceramic-coated diesel engine pistons were obtained, respectively. The calculated results obtained by wavelet finite-element method were compared with test results and the simulation results gained by Catia &ANSYS software. Through analyzing the calculation results, the wavelet finite-element method was convergent and had higher analysis precision than the traditional finite-element method. The wavelet finite-element method avoids the numerical oscillation during analysis of the transient-state thermal stress fields of the piston. The wavelet finite-element method showed advantages for analyzing the high gradient problems. The wavelet finite-element method provides a preferable theoretical basis for optimizing the design of the ceramic-coated diesel piston.

Introduction:

Increasing competition and innovations in automobile sector tends to modify the existing products or replacing old products by new and advanced material products. A suspension system of vehicle is also an area where these innovations are carried out regularly. More efforts are taken in order to increase the comfort of user. Appropriate balance of comfort riding qualities and economy in manufacturing of leaf spring becomes an obvious Necessity. To improve the suspension system many modification have taken place over the time. Inventions of parabolic leaf spring, use of composite materials for these springs are some of these latest modifications in suspension systems.

This paper is mainly focused on the implementation of composite materials by replacing steel in conventional leaf springs of a suspension system. Automobile-sector is showing an increased interest in the area of composite material-leaf springs due to their high strength to weight ratio. Therefore analysis of composite material leaf springs has become essential in showing the comparative results with conventional leaf springs. Advantages of leaf spring over helical spring are that the ends of the springs are guided along a definite path so as to act as a structural member in addition to shock absorbing device. This is the reason why leaf springs are still used widely in a variety of automobiles to carry axial loads, lateral loads and brake-torque in the suspension system.In this analysis the conventional steel leaf spring is tested for static load condition and results are compared with a virtual model of composite material leaf spring. Leaf spring is modeled in Pro-E 5.0 CAD software and it is imported and simulated in ANSYS 10.0 for better understanding. Results of Composite Leaf Spring are compared on the basis of analysis reports produced by ANSYS software. The material used for conventional steel leaf spring is 60Si7 (BIS) and for composite leaf spring E- Glass/Epoxy material is used.

II. Literature review:

Ekrem Buyukkaya and Muhammed Cerit investigated the effects of ceramic coating over diesel engine piston using 3D finite element method; they found that maximum surface temperature of the coated piston with material which has low thermal conductivity is improved approximately 48% for the AlSi alloy and

35% for the steel.[1]. EkremBuyukkaya, Department of Mechanical Engineering, Esentepe Campus, Turkey.. Thermal analysis of functionally graded coating AlSi alloy and steel pistons... Thermal analyses were employed to deposit metallic, cermet and ceramic powders such as NiCrAl, NiCrAl+MgZrO3 and MgZrO3 on the substrate. The numerical results of AlSi and steel pistons are compared with each other. It was shown that the maximum surface temperature of the functional graded coating AlSi alloy and steel pistons was increased by 28% and 17%, respectively. [2]. Imdat Taymaz investigated the effect of thermal barrier coatings on diesel engine performance his results indicate a reduction in fuel consumption and an improvement in the efficiency of the diesel engine.[3].

P. M. Pierz investigated the thermal barrier coating development for diesel engine aluminum piston he found that the resulting predicted temperatures and stresses on the piston, together with material strength information, the primary cause of coating failure is proposed to be low cycle fatigue resulting from localized yielding when the coating is hot and in compression.[4]. O. Altun ,Mechanical Engineering Department , Turkey., Investigated in Problems for determining the thermal conductivity of TBCs by laser-flash method., Laser-flash method is the most widely used experimental technique to determine the thermal conductivity of APS TBCs at high temperatures. The research contributes to better understanding and recognition the importance of sample preparation in laser-flash method.

S. C. Mishra., Laser and Plasma Technology Department, Mumbai, India. Investigated in Microstructure, Adhesion, and Erosion Wear of Plasma Sprayed Alumina–Titanium Composite Coatings.. Adhesion strength value of the coating varies with operating power. The trend of erosion of the coatings seems to follow the mechanism predicted for brittle materials. Coating deposited at 18kW power level shows a higher erosion rate than that of the sample deposited at 11kW power level [6].

H.W. Grunling and W. Mannsmann, ABB Kraftwerrke AG, KallstadterStz 1, 6800 Mannheim 31, Germany., investigated in Plasma sprayed thermal barrier coatings for industrial gas turbines: morphology, processing and properties. The properties of thermal barrier coating systems depend strongly on the structure and phase composition of the coating layers and the morphology of and the adhesion at the ceramic-metal interface. They have to be controlled by the process itself, the process parameters and the characteristics of the applied materials. [7]. A. J. Slifka, National Institute of Standards and Technology, Boulder. Thermal-Conductivity Apparatus for Steady-State, Comparative Measurement of Ceramic Coatings, and an apparatus has been developed to measure the thermal conductivity of ceramic coatings. Since the method uses an infrared microscope for temperature measurement, coatings as thin as 20 _m can, in principle, be measured using this technique. This steady-state, comparative measurement method uses the known thermal conductivity of the substrate material as the reference material for heat-flow measurement.[8].

Dongming Zhu Ohio Aerospace Institute, Cleveland, Ohio. Effect of Layer-Graded Bond Coats on Edge Stress Concentration and Oxidation Behavior of Thermal Barrier Coatings.. A low thermal expansion and layer-graded bond coat system, that consists of plasma-sprayed FeCoNiCrAI and FeCrA1Y coatings and a high velocity oxy fuel (HVOF) sprayed FeCrAIY coating, was developed for minimizing the thermal stresses and providing excellent oxidation resistance.[9]. S. Alphine’, M. Derrien, Thermal Barrier Coatings: the Thermal Conductivity challenge. In this paper, the importance of the challenge associated with the control of the thermal conduct why of thermal barrier coatings for turbine engines hot stages is being reviewed. It is firstly illustrated by the description of a practical aeronautic coated and uncoated turbine blade design exercise. The various contributions to TBC thermal conductivity are then reviewed.

III. Thermal Barrier Coating:

Thermal barrier coatings are highly advanced material systems applied to metallic surfaces, such as gas turbine aero-engine and diesel engine parts, operating at elevated temperatures. These coatings serve to insulate metallic components from large and prolonged heat loads by utilizing thermally insulating materials which can sustain an appreciable temperature difference between the load bearing alloys and the coating surface. In doing so, these coatings can allow for higher operating temperatures while limiting the thermal exposure of structural components, extending part life by reducing oxidation and thermal fatigue. In fact, in conjunction with active film cooling, Thermal barrier coatings permit flame temperatures higher than the melting point of the metal airfoil in some turbine applications. Modern Thermal barrier coatings are required to not only limit heat transfer through the coating but to also protect engine components from oxidation and hot corrosion. No single coating composition appears able to satisfy these multifunctional requirements.

As a result, a “coating system” has evolved. Research in the last 20 years has led to a preferred coating system consisting of three separate layers such as metal substrate, bond coat and ceramic coating to achieve long term effectiveness in the high temperature, oxidative and corrosive use environment for which they are intended to function. The application of Thermal barrier coatings on the diesel engine piston head reduces the heat loss to the engine cooling-jacket through the surfaces exposed to the heat transfer such as cylinder head, liner, piston crown and piston rings. It is important to calculate the piston temperature distribution in order to control the thermal stresses and deformations within acceptable levels. The temperature distribution enables the designer to optimize the thermal aspects of the piston design at lower cost, before the first prototype is constructed. As much as 60% of the total engine mechanical power lost is generated by piston ring assembly.

Most of the internal combustion (IC) engine pistons are made of aluminum alloy which has a thermal expansion coefficient 80% higher than the cylinder bore material made of cast iron. This leads to some differences between running and the design clearances. Therefore, analysis of the piston thermal behavior is extremely crucial in designing more efficient engines. The thermal analysis of piston is important from different point of views. First, the highest temperature of any point on piston should not exceed 66% of the melting point temperature of the alloy. This limiting temperature for the current engine piston alloy is about 370°C. This temperature level can be increased in ceramic coating diesel engines. Thermal barrier coatings consist of three layers. They are the metal substrate, metallic bond coat and ceramic topcoat. The metal substrate and metallic bond coat are metal layers and the topcoat is the ceramic layer. The metal substrate is typically a high temperature aluminum alloy that is either in single crystal or polycrystalline form. The metallic bond coat is an alloy typically with the composition of Nickel, Cobalt, Chromium, and Aluminum.

The bond coat creates a bond between the ceramic coat and substrate. The third coat is the ceramic topcoat, Zirconia (ZrO_3), Mullite($3Al_2O_3$-$2SiO_2$), Alumina (Al_2O_3) which is desirable for having very low conductivity while remaining stable at nominal operating temperatures typically seen in applications. This layer creates the largest thermal gradient of the thermal barrier coating. In industry, thermal barrier coatings are produced in a number of ways:

- Electron Beam Physical Vapor Deposition (EBPVD)

- Air Plasma Spray (APS)

- Electrostatic Spray Assisted Vapour Deposition (ESAVD)

- Direct Vapor Deposition

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Diesel engine piston made of Aluminum Alloy is taken for this study and ceramic material having low thermal conductivity is preferred as the coating material on the piston head or crown.

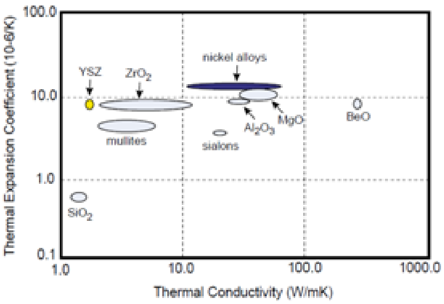


Fig.1. Materials for thermal barrier coating

The ceramic material chosen for this study should have low thermal conductivity and thermal expansion as shown in the above graph. The selected materials are as follows,

☐ Zirconia (ZrO2)

☐ Mullite (3Al2O3-2SiO2)

☐ Alumina (Al2O3)

IV. Electron Beam Physical Vapor Deposition:

EB-PVD is an evaporation process for applying ceramic thermal barrier coatings to gas turbine engine parts .It has been the favored deposition process technique for TBCs because of the increased durability of coating that is produced when compared to other deposition processes. EB-PVD TB exhibits a columnar microstructure that provides outstanding resistance against thermal shocks and mechanical strains. Figure presents a diagram of the coating chamber where the EB-PVD process takes place. The EB-PVD process takes place in a vacuum chamber consisting of a vacuum-pumping system, horizontal manipulator, a water-cooled crucible containing a ceramic ingot to be evaporated, an electron-beam gun, and the work piece being coated.

The electron beam gun produces electrons, which directly impinge on the top surface on the ceramic coating, located in the crucible, and bring the surface to a temperature high enough that vapor steam is produced. The vapor steam produces a vapor cloud, which condenses on the substrate and thus forms a coating. The substrate is held in the middle of vapor cloud by a horizontal manipulator that allows for height variation in the chamber. During the coating process, oxygen or other gases may be bled into the vapor cloud in order to promote a stoichiometric reaction of ceramic material. An over source. Heater or an electron beam gun may be used for substrate heating, which keeps the substrate at a desired temperature.

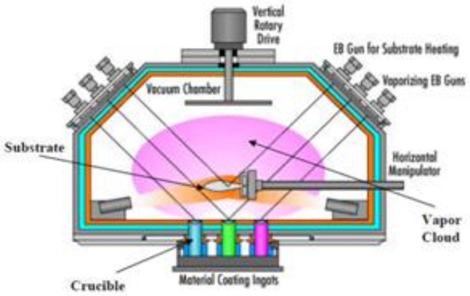


Figure 2. EB-PVD Coating Chamber

In our six stroke engine we are placing thermal barrier component in between the cylinder block and cylinder liner. The heat is transferred from the combustion chamber to the cylinder block through the cylinder liner and thermal barrier. The heat flow rate through the thermal barrier is low. Materials of thermal barrier are discussed in the forthcoming chapters.

V. Simulation:

In this project work, ANSYS workbench 10 software has been used to investigate the temperature distribution in the ceramic coated Aluminum alloy piston and to compare the maximum surface temperature of the uncoated Aluminum alloy piston with ceramic coated Aluminum alloy piston, ceramic materials such as Zirconia stabilized with magnesium oxide, Mullite and Alumina were used for this study

In the numerical simulation performed, a diesel engine piston, made of Al alloy is analyzed. 3-D finite element thermal analyses are carried out on both uncoated and ceramic coated pistons. In the model, surface-to-surface contact elements are defined between piston ring and ring grove. Piston thermal boundary conditions consist of the ring land and skirt thermal boundary condition, underside thermal boundary condition, combustion side thermal boundary condition. Convective heat transfer coefficients and ambience temperatures were specified as the thermal boundary conditions.

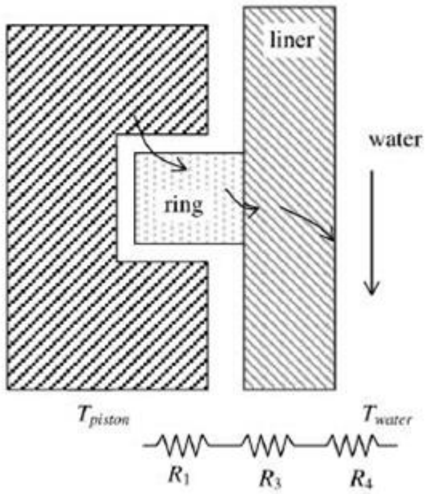


Fig 3. Thermal circuit of heat transfer resistances in the region of the rings.

R1: Conductive resistance of the ring,
R2: Conductive resistance of the oil film is negligible,
R3: Conductive resistance of the liner,
R4: Convective resistance between the liner and the cooling water.

Thermal circuit of heat transfer resistances in the ring land is to be set with the following assumptions.

1) The effect of piston motion on the heat transfer is neglected.
2) The rings and skirt are fully engulfed in oil and there are no cavitations.
3) The rings do not twist.
4) The heat transfer mode in the oil film is neglected.

Table .1.Thermal properties of parts

Material	Thermal conductivity W/m0C
Piston (Al-Si)	155
Oil Ring	33
Compression Ring	52
Liner	55

The resistances are:

Conductive resistance of the ring, R1= (ln(r1/r2)/2πL1Kring) = 0.085048 m2k/kw

Conductive resistance of the film, R2= (ln(r3/r2)/2πL2Koil) = 8x10-5 m2k/kw

Conductive resistance of the liner, R3= (ln(r4/r3)/2πL3Kblock) = 0.06417 m2k/kw

Conductive resistance between the liner and cooling water, R4 = 1/ (hwaterAs) =0.171 m2k/kw

Total resistance Rtot=0.32 m2k/kw

The effective heat transfer is obtained from, heff=1/RtotxAeff = 617.68 w/m2k

The value of convective heat transfer coefficient of crown underside is, hun1=900(N/4600)0.35 =672.415 w/m2k

The value of convective heat transfer coefficient of piston skirt underside, hun2=240(N/4600)0.35 =179.31 w/m2k

The Crevice heat transfer coefficient, h=k/S =230 w/m2k

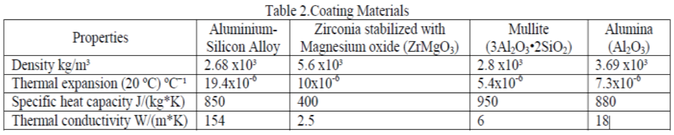


Table 2.Coating Materials

Properties	Aluminium-Silicon Alloy	Zirconia stabilized with Magnesium oxide ($ZrMgO_3$)	Mullite ($3Al_2O_3$•$2SiO_2$)	Alumina (Al_2O_3)
Density kg/m³	2.68 x10³	5.6 x10³	2.8 x10³	3.69 x10³
Thermal expansion (20 °C) °C⁻¹	19.4x10⁻⁶	10x10⁻⁶	5.4x10⁻⁶	7.3x10⁻⁶
Specific heat capacity J/(kg*K)	850	400	950	880
Thermal conductivity W/(m*K)	154	2.5	6	18

Initial Conditions:

Piston top surface temperature: 4000C

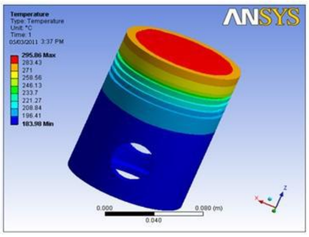
Piston skirt temperature: 1100C

Boundary Conditions

The Crevice convective heat transfer coefficient, h = 230 w/m2k

The piston crown or head underside convective heat transfer coefficient, hun1 = 672.415 w/m2k

The piston skirt underside convective heat transfer coefficient, hun2 = 179.31 w/m2k



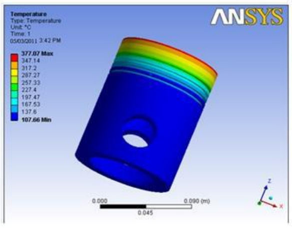
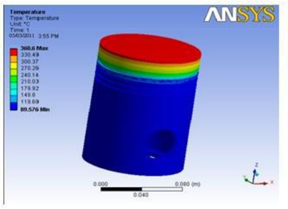


Fig .4 Uncoated Aluminum alloy piston Fig 5.Ceramic material Zirconia coated piston



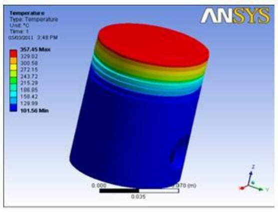


Fig .6 Ceramic materialMullite coated piston Fig 7. Ceramic material Alumina coated piston

VI. Results and Discussion:

Finite element analysis were performed to evaluate temperature gradients of the uncoated Aluminum alloy piston and ceramic materials such as partially stabilised zirconia with magnesium oxide (ZrMgO3), Mullite and Alumina (Al2O3) coated Aluminum alloy piston. The temperature distributions of an uncoated aluminum alloy piston are shown in the figure 4. The maximum surface temperature on the piston crown of the Aluminum alloy piston is determined as 295.860C.The temperature distributions of the ceramic materials such as partially stabilized zirconia with magnesium oxide (ZrMgO3), Mullite and Alumina (Al2O3) coated Aluminum alloy piston is shown in the figure 5, figure 6, figure7, respectively.

The maximum surface temperature on the piston crown for Ziconia coated Aluminum alloy piston is determined as 377.070C, For Mullite Coating it is 360.60C and for Alumina coating it is 357.450C. Fig.8 represents the temperature distribution comparison curve of uncoated Aluminum alloy piston with zirconia, Mullite and Alumina coated piston. It is clear that the maximum surface temperature of Zirconia coated piston (377.070C) is more than the conventional Aluminum alloy piston (295.860C).and the maximum surface temperature of Mullite coated piston (360.60C) is more than the conventional Aluminum alloy piston (295.860C) and the maximum surface temperature of Alumina coated piston (377.070C) is more than the conventional Aluminum alloy piston (295.860C).From the graphical representation the ceramic material partially stabilized Zirconia gives more performance to the diesel engine taken for this study.

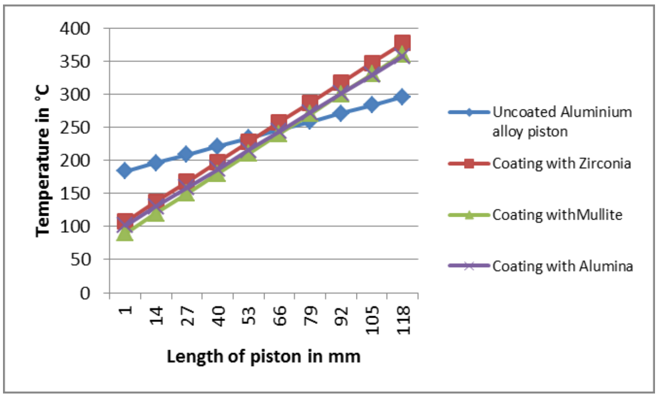


Fig. 8.Comparisons of coated Aluminum alloy piston with uncoated Aluminum alloy piston

VII. Conclusion

A comparative evaluation was made between the temperature distributions of the uncoated aluminum alloy piston and the ceramic coated piston. The maximum surface temperature of the ceramic coated piston is improved approximately 28% for Zirconia stabilized with magnesium oxide (ZrMgO3) coating, 22% for Mullite coating (3Al2O3-2SiO2) and 21% for Alumina (Al2O3) than the uncoated piston by means of ceramic coating.

According to the software simulations conducted in this project, it has been concluded that the using of ceramic coating for Aluminum alloy piston increases the temperature of the combustion chamber of the engine and the thermal strength of the base metal. Finally the combustion chamber temperature increases the thermal efficiency of the engine also increases.

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