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Effects of Thermal Barrier Coatings on Diesel and Gas turbine engines: A review

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Abstract: Future demands for significantly higher engine operating temperature, fuel efficiency and better engine reliability are the driving force behind the development of Thermal barrier coatings (TBCs).Conventional thermal barrier coating (TBC) systems consist of a thermally grown oxide (TGO) sandwiched between topcoat and bond coat. This bond coat is bonded to a metal substrate. Zirconia-yttria based oxides and (Ba,Sr)Al2Si2O8 (BSAS)/mullite based silicates have been used as thermal barrier coating materials. The thermal barrier coating system has effects on the fuel consumption, the power and the combustion efficiency, pollution contents and the fatigue lifetime of engine components. This article describes the effects of thermal barrier coatings on Diesel and gas turbine engines based on the pioneering work of many researchers in this area.

Keywords: Thermal barrier coating, Diesel engine, Gas turbine.

1.0 INTRODUCTION

The thermal barrier coatings found application as protective layers for steel surfaces of pistons and cylinders in Diesel engines and in case of aircraft engines elements of compressors housing, made of titanium alloys, along with working surfaces of exhaust nozzles, made of niobium alloys(Moskal, 2009). Demand of low heat rejection diesel engines, using thermal barrier coatings (TBC's) are increasing due to non-renewable fuel sources, increasing fuel prices and environmental hazards. Normally, in diesel engines about 15-20percent of fuel energy is rejected to coolant fluid.Using thermal barrier coatings to airfoils in research gas turbine engines results in reduction of component temperature about 190°C (Liebert et al).This reduction in temperature results in increase in high temperature capability and improvement in engine efficiency.

J.T. (DeMasi-Marcin et al, 1989) estimated that 10 million gallons of fuel annually can be saved in a 250 aircraft fleet if reduced cooling air supplied to coated engine component is used for propulsion. Although in diesel engine, thermal barrier coatings on piston and cylinder head may yield a 3% fuel savings elaborated by (Yonushonis et al, 1988.) Several generations of super alloys have been developed over thepast 20 years, so that these can with stand the hot gases in harsh environment (Maricocchi et al.,1997.). But the limits of stress rupture, surface protection and melting points creates difficulties ahead of these super alloys. In addition, the amount of air thatcan be used for cooling in high-performance engines is limited. These difficulties divert mind towards use of thermal barrier coatings(TBC's) as a protective and antioxidant layer against hot gases in gas turbine engines.These consequent economics benefits force diesel and aerospace industries to focus on research and development of thermal barrier coatings.But in some instances TBC's fail prematurely, exposing the bare substrate to hot gases. Thus understanding of failure mechanism is key factor for development of TBC's. The failure of plasma-sprayed TBC under thermalcycling is an interplaybetween several general phenomena listed below(i) thermal-expansion mismatch stress, (ii)growth of the TGO (a -Al2 O3) at the undulating interfacebetween the bond-coat and the TBC as result ofoxidation of the bond-coat, (iii) cyclic creep of the bond coat,(iv) depletion of Al in the bond coat leading to theformation of brittle oxides other than a -Al2 O3 , such asspinel, (v) sintering of the porous TBC and the attendantdeterioration of strain tolerance and thermal resistivity,(vi) degradation of the metal ceramic interface toughness ,(vii) delamination and cracking and (viii) crackcoalescence. The TBC failure mechanisms are highly system and application-specific, where one or more of the above phenomena dominate (Schlichting et al 6).

2.0 CONCEPT OF THERMAL BARRIER COATINGS

Thermal barrier coating system are more aggressively designed to protect gas turbine and diesel engine hot- oxidative section components in order to meet future engine higher fuel efficiency andlower emission goals.A schematic drawing of a thermal barrier coating system is shown in fig. 1), where the four layers of the thermal barrier system can be seen: 1)substrate, 2) bond coat (BC), 3) thermally grown oxides (TGOs), and 4) top coat (TC). The topcoat consists of a ceramiclayer, which provides thenecessary insulation, and the metallic bond coat ensures good adhesion of theceramic coating and provides oxidation resistance. The top-coat, which is 'straintolerant'due to the presence of micro structural defects(pores, cracks, splat-boundaries), ranges in thicknessfrom 200 to 500 mm for gas-turbine engines and up to 2mm for diesel engines (Beardsley et al., 1990.).In diesel engine applications wherethe temperatures are usually lower, the ceramic like YSZ coating is generally applied directlyonto the alloy (Clarkeand et al., 2003.).

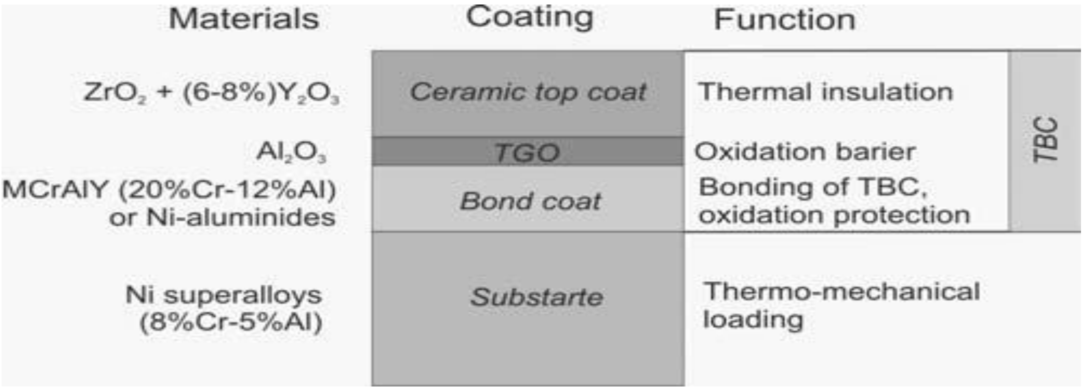

Fig. 1 Scheme of coating construction of barrier layers and a role of individual sub-layers [1]

The properties of thermal barrier coating systems depend strongly on the structure and phaseComposition of the coating layers and the morphology of and the adhesion at the ceramic-metalInterface. They have to be controlled by the process itself, the process parameters and the characteristics of the applied materials (e.g. chemical composition, processing, morphology, particlesize and size distribution(Grunlinget al.,1993.).

Although there are many techniques fordeposition of TBC's such as EB-PVD,PS,flame spray, HVOF, cold spray, Electric arc spray and slurry spray technique (SST). Butfor relatively small components such as blades and vanes in aerospace turbines, the coatings can be appliedby electron-beam physical vapor deposition (EB-PVD). For larger components such as the combustion chambers and the blades and vanes of power generation,stationary turbines, the coatings are usually applied by plasma spraying (PS)(Clarkeet al., 2008).

3.0 EFFECT OF TBC ON DIESEL ENGINES

A major breakthrough in diesel engine technologyhas been achieved by the pioneering work done byKamo and Bryziksince 1978 to 1989 as the firstpersons in introducing TBC system for engines(Azadi et al., 2013).They used thermally insulating material silicon nitride. Recent trend of coating on diesel engine is to providing a thin ceramic (about 2mm top layer) coating on parts like piston and cylinder head resulting in reduction of fuel consumption, emission, oil consumption, engine noise, Components temperature and cost, while increasing engine life, engine power,valves lifetime, reliability.(Gumus andM.Akcay, 2010) describe thatefficiency of most commercially available diesel engine ranges from 38% to 42%. Therefore, between 58% and 62% of the fuel energy content is lost in the form of waste heat. Approximately 30% is retained in the exhaust gas and the remainder is removed by the cooling, etc. More than 55% of the energy, which is produced during the combustion process, is removed by cooling water/air and through the exhaust gas. In order to save energy, it is an advantage to protect the hot parts by a thermally insulating layer. This will reduce the heat transfer through the engine walls, and a greater part of the produced energy can be utilized, involving an increased efficiency [Gumus et al., 2010). (Winkler et al., 1993.) reported effect ofthermal barrier coatings on a diesel engine by ten years of experience on TBC's in table 1.

Table 1: Ten years of the experience for the TBC application [Winkler et al 12-13]

Properties	Variation Type	Maximum variation amount (%)
Fuel consumption	Decrease	11
Engine lifetime	Increase	20
Engine power	Increase	10
Emission	Decrease	20-50
Particle	Increase	52
Oil consumption	Decrease	15

Engine noise	Decrease	3(db)
Reliability	Increase	-
Components temperature	Decrease	100 (°C)
Valves lifetime	Increase	300
Costs	Decrease	20

(M Azadi et al., 2013.) shows increase in diesel engine performance with two layers coating system consist of a layer made of NiCrAlY with 150 microns thickness and another layer made of ZrO2-8%Y2O3 with 300 microns thickness by using the plasma thermal spray method. In this case, fuel consumption and pollution contents decrease with increase in engine power and efficiency. The reduction in surface temperature of about 100 °C is obtained resulting in improvement of fatigue life of engine component like cylinder head and piston. Also reduction in thermal gradient and thermal stresses of substrate(10).

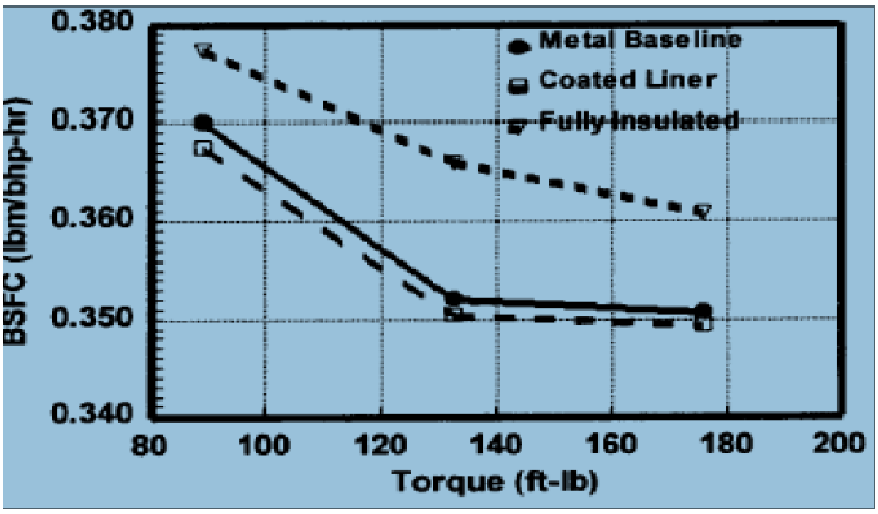

Fig. 2The fuel consumption versus the torque at a constant speed, 1400 rpm [10]

(Hejwowski et al., 2002.) gives that Using TBC can increase engine power by 8%,decrease the specific fuel consumption by 15-20% and increase the exhaust gastemperature 200K. (Buyukkaya et al., 2006.) performed Tests on a six cylinder, direct injection, turbocharged Diesel engine whose pistons were coated with a 350 micrometer thickness of MgZrO3 over a 150 micrometer thickness of NiCrAl bond coat. CaZrO3 was employed as the coating material for the cylinder head and valves. Keeping the working conditions same for the standard engine (uncovered) and low heat rejection (LHR) engine, comparison between these two shows that 1–8% reduction in brake specific fuel consumption could be achieved by the combined effect of the thermal barrier coating (TBC) and injection timing. On the other hand, NOxemissions were obtained below those of the base engine by 11% for 18_ BTDC injection timing.(Sridhar et al., 2013.) made comparison between two-pistonone uncoated aluminum alloy and other ceramic coated. Results shows that 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, simultaneouslyincreasing the thermal efficiency of the engine. (Shrirao and A. N. Pawar, 2011)showed that, using TBC's increases the brake thermal efficiency and decreasing the specific fuel consumption for LHR engine with turbocharger compared to the standard engine. There was increasing the NOx emission and exhaust gas temperature for LHR engine with turbocharger. However there was decreasing the CO and HC emissions for LHR engine with turbocharger compared to the standard engine. A.P. (Sathiyagnanam et al.,2010)finds following results while applying TBC's plus Fuel Additive for Reducing Emission from Di Diesel Engine. (i) The thermal efficiency slightly improve s, however the fuel additive with 1.0% shows better performance than other concentration. (ii) Smoke level is found higher in thermal barrier coated engine. At the maximum brake power, the smoke level was slightly increased in the fuel additive plus thermal barrier coated engine. (iii) Comparing with standard engine the NOx will be reducing about 500 ppm for TBC engine. By introduction of fuel additives to the TBC engine, it was further reduced by 100 ppm of NOx emission. (iv)The heat release rate slightly decreases due to the effect of coating and coating plus fuel additives.

4.0 EFFECT OF TBC ON GAS TURBINE ENGINES

The pioneering work and the majority of TBC research and development have been paced by aerospace applications. According to (L.S. Langston, 2011),gas-turbine engines are a $42 billion industry worldwide, with 65% of the sales accounting for jet engines and the remainder land-based engines for electricity generation (Langston 19).Similarly, airline traffic is expected to double in the next 20 years, whileat the same time, there is a need to reduce high-altitude NOxpollution produced by jet engine exhausts. Together, these developments will require continued innovation in gas turbinetechnology and high-temperature engine materials, including TBCs and associated technologies. The greatest efficiency benefits of TBCs in an aircraft engine come from their use on the stator vanes and the turbine blades -- the hottest components in the engine. Thermal barrier coatings (TBC's) enables in lowering the temperature (at approx. 170°C) of operating elements, exposed to hot section of gas turbine (e.g. combustion chambers and directing and rotating blades) to a range which enables to operate for a long time and prolongs operation of them even three or four times, simultaneously reducing fuel consumption (Meier et al.,1994). (Huda, 2012) has been reviewed that in the modern combined-cycle gas turbines (CCGT) applying single-crystal energy materials (SC super alloys) and thermal barrier coatings (TBC), and – in one design – closed-loop steam cooling, thermal efficiency can reach more than 60%. These technological advancements contribute to profitable and clean power generation with reduced emission. Alternatively, the use of advanced super alloys (e.g. GTD-111 super alloy, Allvac 718Plus super alloy) and advanced thermal barrier coatings (TBC) in modern gas-turbines has been shown to yield higher energy-efficiency in power generation.(Huda et al., 2012).Curt H. Liebert and Stanley R. Levine(1982) performs tests of ceramic thermal barrier coatings on industrial engines and summarizes that various two-layer thermal-barrier coating systems incorporating yttria-stabilized zirconia for thermal protection results, lowered metal temperatures, protected metal parts, increased metal part life, and eliminated metal burning, melting, and warping(Liebert et al 24). (Ahlatci, 1999) describes the various types of protective coatingused in the turbine engines operating are reviewed inhis paper. The factors affecting coating selectionfor turbine applications are discussed, and service conditions are reviewed. Table 2 gives a summary of the coating developments that are related to an interaction between the physical metallurgy of the coating and the processing for turbine components.

Table 2. Coatings For Turbine Components.

Coating Type	Coating Method	Coating Phase	Limitation
Diffusion	Pack aluminizing	NiAl	Hot Corrosion Brittleness Diffusional stability
Overlay	Electron beam Evaporation	MCrAlY	Hot corrosion Thermal Fatigue
Overlay	Low pressure Plasma spraying	MCrAlY	Hot corrosion Thermal Fatigue
Thermal barrier	Air plasma spraying Electron beam processes	Partially stabilized ZrO2	Thermal spalling, oxidation and hot corrosion of bondcoat

(Almeida et al., 2010) reduces the thermal conductivity and improve mechanical properties of gas turbine coating by adding niobia as a co-dopant in the Y_2O_3-ZrO_2 system. The purpose of this work was to evaluate the influence of the addition of niobia on the microstructure and thermal properties of the ceramic coatings. Hence the single-phase tetragonal niobia and yttria co-doped zirconia coatings show a lower thermal conductivity than conventional 6-8 mol% yttria stabilized zirconia coating, the material can conventionally used for thermal barrier coatings for gas turbines.A. (Feuerstein et al., 2007) givestechnical and Economical aspectsof Current Thermal Barrier Coating Systemsfor Gas Turbine Engines by Thermal Sprayand EBPVD. In this article,various coating systems such as Shrouded plasma and HVOF for MCrAlY bond coat,Plasma for low density YSZ and dense verticallycracked Zircoat, Platinum aluminide diffusion coatings and EBPVD TBC are compared. Along with this Lean Manufacturingand Six Sigma programs are used to improve quality and reduce cost.

5.0 CONCLUSIONS

The demand of diesel and aerospace engine industry to increase the performance of engine in hot corrosive environment and increasing air traffic, while at the same time future need to reduce NOxpollution, together led to continues innovation in the field of engine thermal barrier coatings and associated technologies. Thermal barrier coatings(thin layer about 100 microns for gas turbines and thick layer about 1mm for diesel engines) will play a crucial role in advanced gas turbine and diesel enginesbecause of their ability to further increase engine operating temperature and reduce cooling requirements,thus help contributing to achieve significantly reduction in fuel consumption, emission, oil consumption, engine noise, Components temperature and cost, while increasing heat engine efficiency or performance with component reliability and durability.However, TBC durability and insulating ability are highly dependent on thickness,density, microstructure and residual stresses.Future research for engine hot-section metallic and ceramic components is directed towards improved lifetime, reduced thermal conductivity, improved temperature capability, lower manufacturing cost, and ability for repair.

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