

Thermal and Structural Analysis of Functionally Graded NiCrAlY/YSZ/Al₂O₃ Coated Piston

Sakthinathan Ganapathy Pandian
Education Center

Srivathsan Puzhuthivakkam Rengarajan

Terrin P Babu
College Of Engineering Chennai

Vignesh Natarajan and Harikrishnan Kanagasabesan

ABSTRACT

Functionally Graded Thermal Barrier Coatings (FG-TBC) increases the performance of high temperature components in gasoline engines by decreasing the thermal conductivity and increasing the unburned charge oxidation in the flame quenching area with the increase in temperature near the entrance of the crevice volume between the piston and the liner during the compression and the early part of the expansion strokes.

In this study, a 3-D finite element steady state thermal and structural analysis are carried out on both uncoated and functionally graded NiCrAlY/YSZ/Al₂O₃ coated gasoline engine piston using a commercial code, namely ANSYS. The effects of coating on the thermo mechanical behaviours of the piston are investigated. It has been shown that the maximum surface temperature of the ceramic coated piston is improved approximately by 7% for the Al-Si alloy. The application of TBC enhances the Von Mises stress withstanding capacity approximately by 15% than the uncoated piston due to maximum temperature difference and difference in thermal expansion coefficients within the ceramic layers.

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INTRODUCTION

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 [1]¹. 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 at 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 640 K [2].

Ceramic thermal barrier coatings (TBCs) have been successfully applied to the internal combustion engine, in particular the combustion chamber, to simulate adiabatic engines [3, 4, 5, 6, 7, 8]. A typical two-layer TBC system consists of a ZrO₂-Y₂O₃ ceramic top coating and an oxidation-resistant metallic bond coat. These TBC systems can be applied to the metal substrate either plasma spray or by electron beam physical-vapor-deposition (EB-PVD) techniques [9]. The zirconia-based ceramic coatings are used as TBCs owing to their low conductivity, high thermal expansion coefficients, oxidation resistance, chemical and thermal stability at cryogenic and high temperatures [10]. TBCs have a limited life due to crack nucleation and propagation in a direction parallel to the ceramic-bond coat interface (horizontal cracks), which leads to coating delamination [11, 12]. In general, typical TBCs failure is by spalling of the ceramic top coat from the bond coat. Oxidation and thermal mismatch are identified as two major factors influencing the life of the coating system. The highly porous and micro-cracked structure of the coatings imparts strain entrance to the ceramic and decreases its

1. Numbers in brackets refer to references at the end of this paper

thermal conductivity. However, the coatings are permeable to the atmospheric gases and liquids resulting in oxidation of the bond coat and spalling of the coating [13, 14, 15].

The application of TBC 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. The insulation of the combustion chamber with ceramic coating affects the combustion process causing an increase in available energy that would increase the in-cylinder work and utilizes the energy carried by the exhaust gases, thereby improving the performance and exhaust emissions characteristics of the engines [16, 17, 18, 19]. In general, thermal efficiency can be improved by the adoption of higher compression ratios, in particular for diesel engines and also by reduced in-cylinder heat rejection. Both of these factors cause increased mechanical and thermal stresses of materials used in the combustion chamber. The adoption of TBC over the pistons, rings, liners and the cylinder heads in engine cylinders overcomes the durability concerns of the materials which limit the maximum in-cylinder temperature by reducing the heat transfer and lowering temperature of the underlying metal [20]. The application of ceramic coating over the piston enhances the Von Mises stress withstanding capacity [21]. It is important to calculate the piston temperature distribution in order to control the thermal stresses and deformations within acceptable levels. Computer simulations of thermo mechanical analyses can significantly reduce the time and cost in designing of a piston in SI engines before the first prototype is constructed [22].

Mesut Durat et al. [23] investigated the effects of two different partially stabilized thermal barrier coatings on the temperature gradient on the piston surface near the crevice volume of spark ignition engine by using the finite element method (FEM). A thermal circuit model of heat transfer resistances in the region of the rings to study the thermal behavior of functionally graded coatings on an Al-Si alloy and steel diesel pistons is reported in [24]. The effects on the cold start HC emissions at idle and performance characteristics at the wide open throttle (WOT) conditions are examined with the deposition of thermal barrier layer (TBL) on the top surface of a piston near the crevice [25].

In the literature, although there are a lot of experimental studies on thermal barrier coatings in the internal combustion engines, there are only a few numerical studies focused on 3-D structural and thermal analyses on a gasoline piston model. This paper presents a 3-D finite element modelling of Al-Si alloy and a ceramic coated gasoline engine piston. Thermal analyses are employed to deposit NiCrAlY, NiCrAlY + YSZ, YSZ on the piston material.

FUNCTIONALLY GRADED COATED PISTON

Based on the phase considerations in zirconia and the thermal/mechanical compatibility between the coating and the coated materials of the piston, a functionally graded thermal barrier coating is considered.

The functionally graded material (FGM) consists of ceramic material zirconia and bondcoat (NiCrAlY) varying in proportions along its doping. This gradual transition of thermo-mechanical properties

between the ceramic and the bondcoat reduces the detrimental interfacial stresses which generally arise due to thermal expansion mismatch [10]. In general, partially stabilized zirconia is used as a top coat owing to their low thermal conductivity and their relatively high coefficients of thermal expansion and bond coat as MCrAlY ($M = \text{Ni}$ or/and Co). Al_2O_3 is deposited over the YSZ (Yttrium Stabilized Zirconia) to reduce the thermally grown oxide (TGO) layer growth [26, 27]. The presence of fine alumina particles over the YSZ coating can decrease the oxygen diffusivity through this layer resulting in lower formation of detrimental oxides such as NiCr_2O_4 , NiCrO_3 and NiCrO_4 [28]. Another factor that favours the presence of Al_2O_3 over the ceramic YSZ is that full coating on the gasoline piston is possible due to the higher thermal conductivity of alumina as compared to YSZ and the deposition of YSZ alone over the entire gasoline piston top could lead to auto-ignition [23].

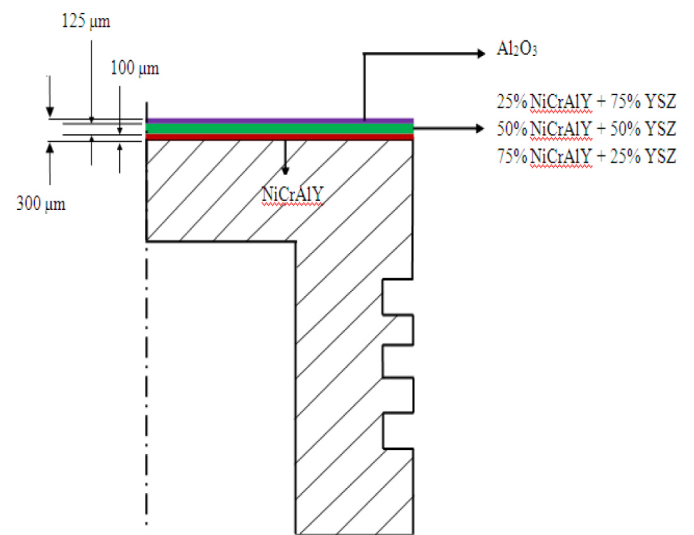


Fig. 1. Functionally Graded Material (FGM) coating thickness.

Material properties of the NiCrAlY, YSZ, Al_2O_3 , interlayers (75% NiCrAlY + 25% YSZ, 50% NiCrAlY + 50% YSZ, 25% NiCrAlY + 75% YSZ), piston ring and the piston material made of Al-Si alloy are listed in Table 1. Piston is coated with a 100 μm thickness of bondcoat NiCrAlY, a 125 μm thickness of functionally graded coated NiCrAlY/YSZ and a 75 μm thickness of Al_2O_3 as shown in Fig. 1. The interlayers and the bondcoat between the substrates (Al-Si piston) and the top coat play an important role in reducing the internal stresses. Thermal shock resistance of a ceramic coating depends on the thermal expansion coefficient, elastic modulus and thermal conductivity coefficient [29].

The solid model of the piston under study is generated by SolidWorks. Three dimensional piston solid models are meshed in HyperMesh before being imported into ANSYS for analysis. The finite element mesh of the piston model using ANSYS code is shown in the Fig. 2. Thermal and structural analyses with and without TBC are investigated with numerical simulation models using ANSYS FE software. A total number of finite elements including the coating layer are 2,17,756 and uses 3,48,291 nodes. The coated layers are meshed with 13,968 prismatic elements (pyramid 13) and 1,05,144 tetrahedral elements (tet 10) are used for the piston model.

Table 1. Material properties of the piston, ring and coating

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Material	Thermal conductivity [W/m K]	CTE $\times 10^{-6}$ [K ⁻¹]	Density [Kg/m ³]	Specific heat [J/Kg K]	Poisson ratio	Young's modulus [GPa]
Al-12% Si	155	21.06	2768	960	0.33	73.14
100% N	6.4	24	7320	592	0.3	186
75% N + 25% Y	3.5	19.1	6960	672	0.2875	193
50% N + 50% Y	3.8	19	6626	621	0.275	146
25% N + 75% Y	3	15.1	6208	629	0.2625	119
100% Y	1.2	9.4	6037	576	0.25	52
Al ₂ O ₃	10	0.06	3978	942	0.24	377.7
Oil ring	25-42	10	7200	-	0.29	160

N: NiCrAlY, Y: YSZ

CTE: Co-efficient of thermal expansion

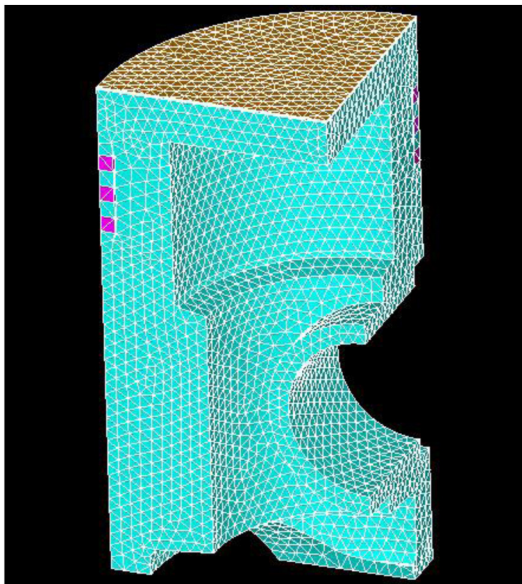


Fig. 2. The finite elements mesh of the piston.

NUMERICAL ASSESSMENT OF THERMAL AND STRUCTURAL ANALYSIS

The simulation model includes the piston and the coating parts as continuous structures and a seven-layer FE mesh is employed for thermal calculations.

Fig. 3 shows the thermal boundary conditions applied in the FE simulations respectively. A 3-D finite element thermal analysis is carried out on both conventional and ceramic-coated engine piston.

Prior to thermal analyses, the following thermal boundary conditions are considered. They are as follows

1. Ring land and the skirt thermal boundary condition,
2. Underside thermal boundary condition,

3. Piston pin thermal boundary condition,
4. Combustion side thermal boundary condition.

Thermal circuit method is used to model the heat transfer in the ring land and the skirt region (Fig. 4) with the following assumptions:

- the effect of piston motion on the heat transfer is neglected,
- the rings and the skirt are fully engulfed in oil and there are no cavitations,
- the rings do not twist,
- the conductive heat transfer in the oil film is neglected [30].

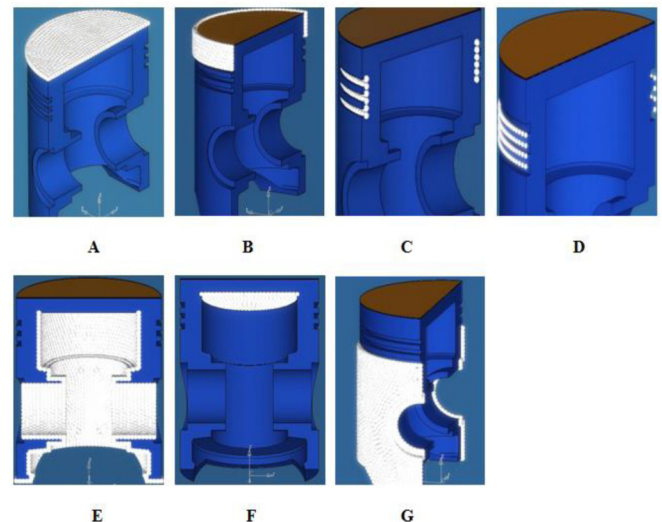


Fig. 3. Piston thermal boundary conditions

In this research, thermal boundary conditions are determined by examining similar works in literature. It is assumed that the inside ambient temperature could be estimated as the average of temperature values of intake, compression, combustion, expansion and exhaust temperatures during an engine cycle.