Characterisation of Thermal Barrier Coating on Piston Crown for Compressed Natural Gas Direct Injection (CNGDI) Engines

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Abstract

The high temperature and pressure produced in an engine that uses compressed natural gas with direct injection system (CNGDI) may lead to high thermal stresses. The piston crown fails to operate effectively with insufficient heat transfer. In this study, partially stabilized zirconia (PSZ) ceramic thermal barrier coatings were plasma sprayed on CNGDI piston crowns (AC8A aluminium alloys) to reduce thermal stresses. Several samples were deposited with NiCrAl bonding layers prior to the coating of PSZ for comparison purposes. Detailed analyses of microstructure, hardness, surface roughness, and interface bonding on the deposited coating were conducted to ensure its quality. High stresses were mainly concentrated above the pinhole and edge areas of the piston. In short, the PSZ/ NiCrAl coated alloys demonstrated lesser thermal stresses than the uncoated piston crowns despite a rough surface. Extra protection is thus given during combustion operation.

***Keywords**: compressed natural gas with direct injection system (CNGDI), piston crown, thermal barrier coating, partially stabilized zirconia (PSZ)*

1 Introduction

Alternative fuels such as natural gas possess higher octane levels than ordinary gasoline; therefore, engines fuelled with natural gas can efficiently operate at high compression levels [1]. The durability of parts, especially the piston crown in the compression engine, is highly affected by exposure to high temperature and pressure. Heat concentration or hotspots on any area of piston crown create thermal stresses that may affect the durability of piston material. Furthermore, a piston needs adequate surface coating to be durable. Ceramic coatings [2–5] are potential surface coatings because of their low thermal conductivity, high melting point, and good resistance against oxidative and corrosive environments.

A thermal barrier coating was applied in this paper onto the top part of a compressed natural gas direct injection (CNGDI) engine piston to reflect heat into the combustion chamber. This approach increases exhaust gas velocity and extends piston life by decreasing the rate of heat transfer. The piston was designed for a CNGDI engine with a compression ratio of 14:1; an improvement against high temperature is highly required. To date, most studies [3–5, 6] have only focused on the effects of ceramic surface insulations, which are popularly known as thermal barrier coatings (TBC), on the piston crown of diesel engines. An initiative has thus been taken to investigate the potentials and characteristics of TBC on the piston crown of CNGDI engines.

2 Methodology

2.1 *Starting materials and deposition works*

A set of CNGDI piston prototypes (AC8A aluminium alloys) measuring 11.7 mm in thickness and 75 mm in diameter was selected. Prior to depositing the TBCs, the samples were first grit blasted to 6 µm of surface roughness finish to increase the interlocking and adhesion between the piston crown and the TBCs.

Zirconia-based ceramic coating such as yttria partially stabilised zirconia (YPSZ) with a particle size between 20 µm and 100 µm was selected as the surface thermal insulator; YPSZ possesses low thermal conductivity and a relatively high coefficient thermal expansion that would reduce detrimental interfacial stresses [7]. Plasma spray technique was utilized because of its low thermal stress on substrate parts with high deposition rates. Addition of 150 µm-thick NiCrAl bonding layers was conducted prior to depositing YPSZ. Bond coat was required to improve the top coat adhesion by mechanical interlocking and to prevent or delay the oxidation of the substrate material by forming a dense oxide layer that acts as an oxygen diffusion barrier [8].

Table 1 shows the optimized plasma spray condition for YPSZ deposition. All listed spray conditions were kept constant for all substrates.

2.2 *Characterisation and hardness test*

Microstructural examinations were performed on top of all coated substrates and their cross sectional areas. The cross sectional parts were metallographically polished prior to observation.

Vickers hardness tester was used to measure the hardness of the deposited samples. The tests were conducted at a fixed load of 300 g (2.912 N) for 15 s on both uncoated and coated pistons.

Burner rig tests were also performed to ensure the coating performance in actual engine operations. The specimens were heated for 20 s during thermal shock. The temperature was varied from 300 ^{o}C to 900 ^{o}C to investigate the effect of temperature on the failure mechanism. After the heating period, the specimens were cooled down at room temperature to simulate engine shutdown.

The burner rig tests were stopped if delamination of the top coat occurred in the flame area or in case of severe bond coat and/or substrate degradation. The tests were also stopped if no damage occurred after a large number of cycles.

Table 1: Plasma spray condition for YPSZ deposition on Al alloy substrate

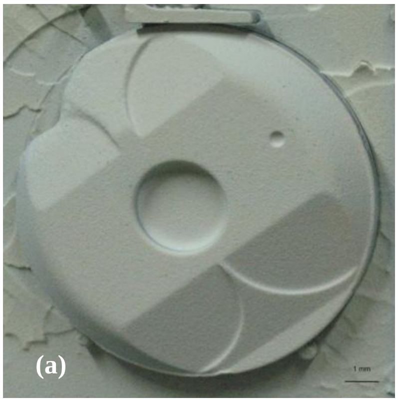
Condition	**YPSZ (91wt%Zr,7.5wt%Y)**
Current (A)	700
Voltage (V)	45
Primary gas pressure: Argon (psi)	40
Secondary gas pressure: Helium (psi)	120
Carrier gas pressure: Argon (psi)	30
Powder feed rate (g/min)	35
Gun manipulation speed (mm/s)	200
Stand of distance (mm)	100
Number of gun pass	2
Preheat (time)	1

3 Results & Discussion

3.1 *Microstructural Investigations*

3.1.1 Top coat surface

Figure 1(a) shows the top coat surface of the YPSZ-coated specimen. Figure 1(b) shows the high magnification of the top coat. The existence of hairline cracks was mainly caused by primary cooling stresses, which develop when deposited particles cool from a temperature above the melting temperature to the substrate contact temperature during the plasma spray process [9–11]. The top coat surfaces were rather generally rough, with an average surface roughness of 9.5 µm.



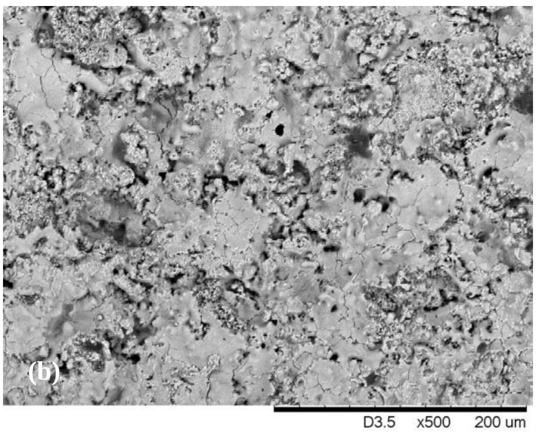


Figure 1: (a) Actual plasma sprayed YPSZ coated piston crown and (b) scanning Electron Microscopy (SEM) photograph of a top coat YPSZ surface

3.1.2 Cross sections

Figure 2 shows the cross-sectional microstructure of the deposited YPSZ aluminium alloy. The top coat of the YPSZ layer with a thickness of approximately 340 µm exhibited large amounts of voids and porosity as well as microcracks throughout the layer. Therefore, the preparation of TBCs for microscopic examinations is a challenging process that should be conducted carefully to avoid further stresses that may be caused by the abrasive cutter. Pull-out particles also easily occur because of the brittle and porous nature of the top coat, which results not only in a damaged surface but also in a false impression of the porosity [12, 13]. Meanwhile, the second layer of the NiCrAl bond with a thickness of approximately 150 µm showed a dense structure. The formed NiCrAl layers were compacted because of the strong effects of plasma spray process; these layers remained partially melted to form a strong mechanically bond or interlocking adhesion to the aluminium alloy substrate [14].

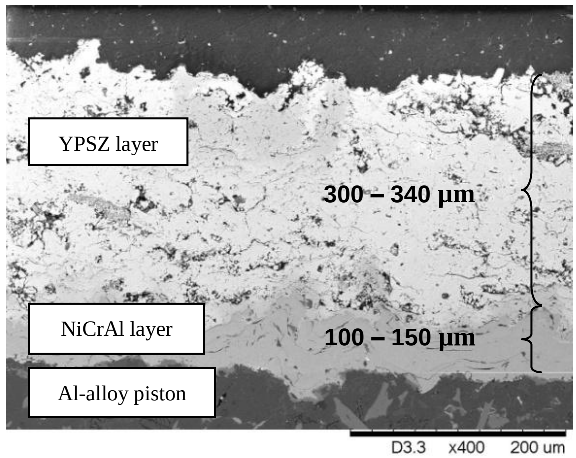


Figure 2: Cross section of YPSZ coated Al-alloy

3.2 *Hardness Profile*

Figure 3 shows the hardness value of the coated and uncoated piston crowns. In the current work, a coated piston crown for commercial petrol engine was selected for comparison purposes. The YPSZ-coated pistons generally possess a hardness almost eightfold greater than that of uncoated pistons. Their harness was also found to be better than that in the work of Chan and Khor [15], who obtained only 417 HV for their YSZ-coated piston crown. The hard characteristic of YPSZ gave extra protection to the piston crown, particularly during engine operation that involves high combustion pressure.

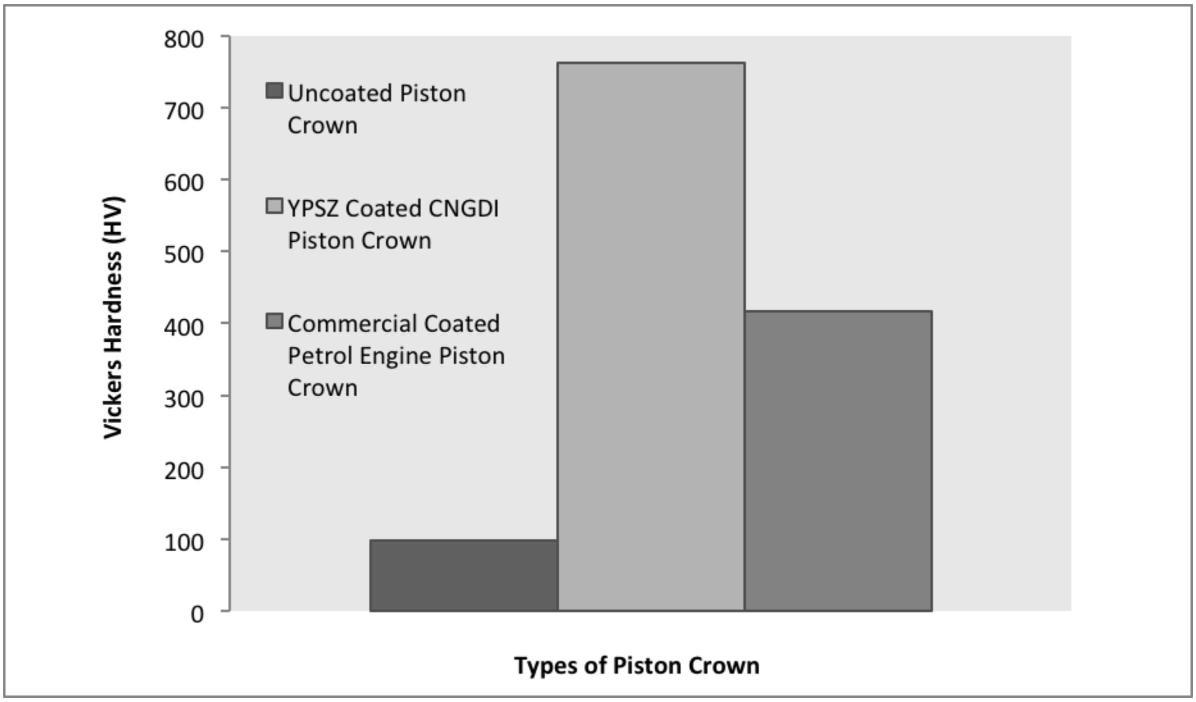


Figure 3: Hardness profile of several types of piston crowns

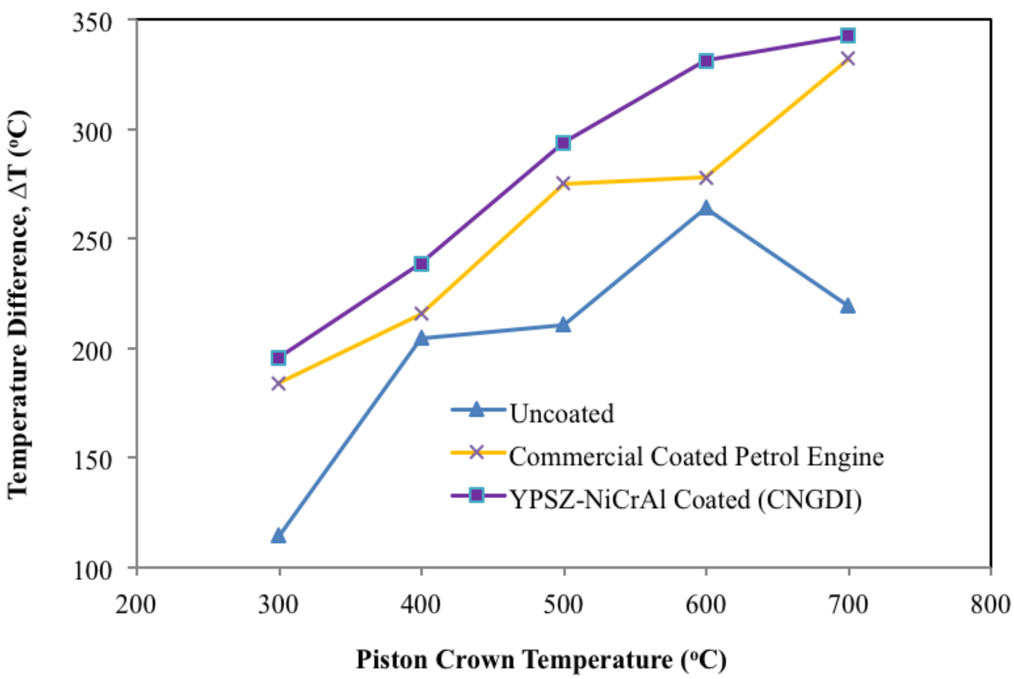


Figure 4: Temperature differences of several types of piston crowns

3.3 *Temperature Profile*

The maximum temperature on the substrate rear side during the burner rig tests (T_{sub}) depends on the coating thickness. The temperature difference between the top coat surface and the substrate rear side is used during the burner rig test. Figure 4 shows the plotted temperature differences of an uncoated piston crown, a coated piston crown for commercial engine (for comparison purposes), and a YPSZ-coated piston crown for CNGDI. All piston crowns showed an increasing temperature trend, except the uncoated piston crown. Both coated pistons crowns showed gradual increments along with the increase in temperature. This result means that the heat spread uniformly on the coating surface and right through the piston crown. An examination of the different types of coating showed that the YPSZ-coated piston crowns exhibited a higher temperature difference than the commercial ones. Therefore, TBCs were proven to possess low thermal conductivity because the heat from the top parts of the piston crown showed great resistance to transfer to rear parts.

Conclusions

A dense deposition of approximately 500 µm in thickness with 760 HV of hardness is one of the important requirements in the production of an efficient coated piston crown, particularly for CNGDI engines. This condition may give extra protection to the piston crown from severe thermal stresses that can lead to crack initiation as a result of high engine combustion. Future studies can focus on real engine tests based on the current values and parameters of deposition.

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