Experimental Study of Ceramic Coated Piston Crown for Compressed Natural Gas Direct Injection Engines

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Abstract

High temperature produced in a compressed natural gas with direct injection system (CNGDI) engine may contribute to high thermal stresses. Without appropriate heat transfer mechanism, the piston crown would operate ineffectively. In this work, bonding layer NiCrAl and ceramic based yttria partially stabilized zirconia (YPSZ) were plasma sprayed onto AC8A aluminum alloy CNGDI piston crowns and normal CamPro piston crowns in order to minimize thermal stresses. Several samples were deposited with NiCrAl bonding layers prior to coating of YPSZ for comparison purpose with the uncoated piston. The performance of the coating against high temperature was tested using a burner rig. The temperatures on the top of piston crown and piston underside were measured. Finally, the heat fluxes of all conditions of piston crown were calculated. In short, the YPSZ/ NiCrAl coated CNGDI piston crown experienced the least heat fluxes than the uncoated piston crowns and the coated CamPro piston crown, giving extra protection during combustion operation.

Keywords: Compressed natural gas; piston crown; thermal barrier coating; burner rig test; heat flux

Nomenclature

CNGDI compressed natural gas direct injection
TBC thermal barrier coating
YPSZ yttria partially stabilized zirconia
YSZ yttria stabilized zirconia
NiCrAl bentonite
APS air plasma spraying

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1. Introduction

Alternative gaseous fuels like natural gas have higher octane levels than gasoline which allows the engine to operate at higher compression’s levels, and thus at higher efficiency [1]. However, these fuels have very low lubrication, causing increased wear of fuel components such as fuel injectors and valves [2–3]. Due to the exposure of high temperature and pressure in high compression engine, it may affect the durability of parts, mainly the piston crown [4–5]. A research on damage mechanisms of piston showed that different origins might occurred which mainly involved wear, temperature, and fatigue [6–7]. Since internal combustion engine with high efficiency has a tendency to operate at higher temperatures, the heat resisting properties of piston have become an important issue and the demand for a better piston for internal combustion (IC) engine increases particularly in diesel engine pistons for higher heat resistance.

The use of all of available surface modification technologies will be the most crucial method to expand the use of piston especially the aluminum alloy piston for automotive vehicles [8]. However, since the tin coating is mostly useful for corrosion resistance, its characteristic against high temperature should be reconsidered. Therefore, the application of thermal barrier coating (TBC) which was widely investigated during 1980’s is better in order to protect the piston crown from the combustion and capable in reducing an in-cylinder heat loss, thus can increase the thermal efficiency, thermal fatigue protection of underlying metal surfaces, and reduced emission [9–10]. Initially, TBC was used to simulate an adiabatic diesel engine and gas turbine by reducing the heat transfer to the engine parts mainly the piston. Most researchers have analyzed the effect of using TBC coating on piston crown of diesel engine experimentally and/or computationally and found that surface temperature of the coated piston was higher indicating lower thermal conductivity [11–13]. The majority of researchers have chosen the ceramic based yttria partially stabilized zirconia (YPSZ) as the topcoat TBC which can withstand a temperature higher than 1000 °C. With low thermal conductivity, high melting point and good resistance against oxidative and a corrosive environment are the required advantages of ceramic coatings applied in energy applications [14–15]. In a condition without a surface insulation, heat from the combustion was transferred through the piston before going through to the lubricant oil, liner, and water jacket, due to a temperature gradient. The heat transfer by conduction, per unit area per unit time, q, in a steady state is given by Fourier’s law:

$$q = -k \nabla T$$  \hspace{1cm} (1)

where $k$ is the thermal conductivity and $\nabla T$ is the temperature gradient. Nuraini et al. [16] used a thermal boundary condition for finite element model by assuming that the thermal resistance, $R$ of material layer as reversed proportional to the thermal conductivity. This can be shown as,

$$R = \frac{dx}{k}$$  \hspace{1cm} (2)

However, when piston crown surface is insulated by the ceramic coating, the $k$ value of ceramic is lower which makes the conductance became lower leading to a rejection of heat without going through the piston. The TBC is applied to the top land of piston to reflect heat into combustion chamber which would increase the exhaust gas velocity, improving scavenging potential, and extending piston life by decreasing the rate of heat transfer. A research reported that the $Y_2O_3$–$ZrO_2$ based TBC exhibited the highest thermal fatigue resistance which performed by air–plasma spraying compared to the flame sprayed one [17]. In reference [18], the researcher has discovered the delaminating mechanisms in TBC for diesel engine applications through rig tests which resulting in improved TBCs that resist severe cyclic fatigue tests in high output diesel engines and indicated that surface connected porosity and coating surface roughness may influence engine fuel economy. In this research, AC8A type CamPro pistons with uncoated, tin–coated and the YPSZ/NiCrAl–coated piston crown as well as the YPSZ/NiCrAl coated CNGDI piston crown were used for mechanical test. The experimental works are to assess the durability of piston against extreme temperature. Samples of YPSZ/NiCrAl–coated piston crown were prepared using air plasma spraying (APS) to assess its durability by mechanical tests like microstructures, hardness, surface roughness, and mainly the burner rig tests.
2. Methodology

2.1. Sample preparation and deposition works

Table 1. Particle sizes of NiCrAl and YPSZ

<table>
<thead>
<tr>
<th>Bond coat–NiCrAl (67%Ni, 22%Cr, 10%Al, 1%Y)</th>
<th>Top coat–YPSZ (91%Zr, 7.5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size 56 μm – 106 μm</td>
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</table>

Several of uncoated and tin coated JIS AC8A type aluminum alloy CamPro piston with a thickness of approximately 2.5 mm and a diameter of about 75 mm were prepared and the piston crown areas were cut from the first ring groove. A prototype of CNGDI piston with a thickness of approximately 11.7 mm and the diameter was about 75 mm was used where the crown of CNGDI piston were cut. The surfaces of piston crown samples were grit–blasted and followed by ultrasonic cleaning using ethanol. The bond coat and top coat with powder size as in Table 1 were plasma–sprayed with spray parameters as shown in Table 2. Four types of samples that were sprayed based on reference [9] which is:

a) CamPro and CNGDI piston crown surface coated with thicknesses between 100 to 150 μm of bond coat NiCrAl.

b) CamPro and CNGDI piston crown surface coated with thicknesses between 100 to 150 μm of bond coat NiCrAl and 300 to 350 μm of YPSZ topcoat.

Table 2. Spray Settings for bond coating and thermal barrier coating

<table>
<thead>
<tr>
<th>Parameters</th>
<th>YPSZ (91wt%Zr, 7.5wt%Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>700</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>45</td>
</tr>
<tr>
<td>Primary gas pressure: Argon (psi)</td>
<td>40</td>
</tr>
<tr>
<td>Secondary gas pressure: Helium (psi)</td>
<td>120</td>
</tr>
<tr>
<td>Carrier gas pressure: Argon (psi)</td>
<td>30</td>
</tr>
<tr>
<td>Powder federate (g/min)</td>
<td>35</td>
</tr>
<tr>
<td>Gun manipulation speed (mm/s)</td>
<td>200</td>
</tr>
<tr>
<td>Stand of distance (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Number of gun pass</td>
<td>2</td>
</tr>
<tr>
<td>Preheat (time)</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2. Characterization and mechanical tests

Several tests were carried out to determine the performance of the TBC application on the CNGDI piston crowns which are the microstructure of coatings, surface roughness, and hardness as well as the burner rig test. The samples of plasma sprayed YPSZ (7.5Y₂O₃–ZrO₂)/NiCrAl–coated piston crowns were observed for the surface structure by using a scanning electron microscope (SEM). The YPSZ/NiCrAl–coated samples were cut into small pieces for necessary quantities. After that, the samples were washed with acetone and were dried before the cross–section of samples were polished. Then, the pieces of polished sample were hardened and mounted in the mixture of epoxy resin and epoxide hardener for metallographic examination. The microstructure images were taken for surfaces of bond coat NiCrAl and topcoat YPSZ, and its cross–sectional view. Analyses of the images were carried out for
thickness measurement and fracture analysis. Perthometer M1 was used to measure the average surface roughness of the NiCrAl bond coating and the YPSZ topcoat. The hardness of mounted YPSZ/NiCrAl coated piston crown samples was measured.

The samples of piston crown were tested on burner rig test to obtain the function of the coating, and the temperature difference between the top surface of the coating and the backside of the piston could be achieved. The top surface of the uncoated piston crown, tin coated, and YPSZ/NiCrAl coated one were flame–torched at temperature of 300°C to about 900°C for about 10s in every 100°C increment before the samples melt. However, to control the temperature for desire temperature level, the distance of piston crown sample, \( l_p \) was moved accordingly until the desire temperature was reached. The length of the flame torch from the end of nozzle, \( l_f \) was approximately 400 mm while the setting distance of the piston crown sample, \( l_p \) during the direct–burning was in between of 250 mm to 600 mm from the end of nozzle. Referring to Fig. 1(a), the experimental apparatus was set up where the flame source was clamped in front of piston crown sample to have direct heat to the surface of piston crown as the flame power was fixed during the test to get better temperature control. The piston crown sample was clamped in a distance where it just has minimal contact with the flame. To record the surface temperature of the piston crown, the K–type (chromel–alumel) probe of digital thermocouples with a temperature range of from −200°C to +1370°C were installed on the surface of piston crown and the backside of piston crown. The combination of acetylene and oxygen was used as flame source for local heating the piston sample which the nozzle of the flame was clamped in front of a steel cylinder to cover the long flame from wind influence, so that the flame could be in stable position and could directly heat the surface of piston crown. The amount of acetylene and oxygen were standardized after a long blue flame was achieved, so that it could contribute to a high temperature up to 1000°C. Finally, the temperature of top surface and back surface of piston crowns were recorded and the heat fluxes of each sample were calculated. In this research, the target of coating thickness for both top coat of YPSZ and bond coating of NiCrAl were at range of from 300 to 350 μm and from 100 to 150 μm respectively. The obtained results from the plasma sprayed samples showed that the general thickness result for both top coat of YPSZ and bond coating of NiCrAl were at range of from 300 to 340 μm and 100 to 130 μm respectively. The thicknesses were difficult to control because too many parameters such as the feed rate or the gas flow rate, the distance between plasma torch and the piston crown surface, and others must be changed in order to get the thickness in range of tolerance.

![Fig. 1. Image of (a) Experimental apparatus of burner rig test in horizontal view, and (b) Actual plasma sprayed YPSZ coated piston crown.](image)

3. Results and discussion

3.1. Microstructure of TBC

Fig. 1(b) shows the actual plasma-sprayed YPSZ coated piston crown which has surface roughness of about 9.2 μm and micro-hardness of 762.3 HV. The micro-photograph of fracture surface on cross-sectional view of the piston crown samples are shown in Fig. 2(a) and Fig. 2(b) which represents the microstructure of top surface of plasma sprayed NiCrAl bond coating and ceramic based YPSZ coating respectively. The structure exhibited the particles of both material were deformed on impact during plasma spraying process and melted on piston crown surface. The structure of the NiCrAl bond coating had a bigger dense splat–like and a few of big voids which
showed low porosity. Compared to the ceramic based YPSZ coating, the structure of the surface showed fine particles with a lot of small voids which means high porosity and numbers of micro cracks on the surface. The high porosity characteristic of TBC might be the reason of low thermal conductivity which reduced the heat transfer by conduction between engine’s combustion chamber to the piston. However, to alleviate stresses arising from thermal expansion mismatch between the YPSZ coating and the underlying metal, microstructure features such as cracks and porosity might contribute to strain tolerance [19].

Fig. 2. Image of (a) Microstructure of top surface of plasma sprayed NiCrAl, and (b) Microstructure of top surface of plasma sprayed YPSZ.

Fig. 3(a) shows a cross-sectional microphotograph of plasma–sprayed YPSZ–NiCrAl–aluminium alloy. The structure of the top layer of YPSZ ceramic layer exhibited a high porosity and a numbers of small voids and cracks with micro size. High porosity characteristic of YPSZ contributed to brittleness of the structure. This might explain the low thermal conductivity that leads to heat transfer reduction. However, the cracks might be a problem on the lifetime of coating since the materials are low frictional characteristic or low elastic modulus. Meanwhile, the second layer of NiCrAl bond coating showed a splat–like dense structure. Particles of NiCrAl bond coating were deformed on impact during plasma spraying process, and the substrate thereby remains non–melted and the NiCrAl bond coating was observed to form a mechanically bonded or interlock adhesion to the aluminium alloy substrate [20].

Fig. 3. Image of (a) Cross–sectional microphotograph of plasma–sprayed YPSZ–NiCrAl–aluminium alloy, and (b) Temperature difference of piston crowns during elevated temperature

3.2. Burner Rig Test

Figure 3(b) represents the temperature difference during elevated temperature on top of various piston crown surface which were the uncoated, and the YPSZ/NiCrAl–coated piston crowns. The graph showed an increasing pattern started from the lower temperature. However, the pattern was not stable which might due to the thermal expansion of the piston crown. The YPSZ/NiCrAl–coated CNGDI piston crown achieved the highest value of
temperature difference which is 342.5°C at the temperature of 700°C, compared to the uncoated one. The graph pattern of the YPSZ/NiCrAl–coated CNGDI piston crown showed the gradual increment along with increasing temperature of piston crown top surface which might prove that the heat was distributed uniformly on the coating surface and through the piston crown. Considering the coating, the YPSZ/NiCrAl–coated pistons recorded the highest temperature difference compared to others. The function of low thermal conductivity of TBC was clearly proved since the heat from top surface of piston crown having resistance to transfer through piston crown material and the presence of different coating materials results on temperature difference.

The uncoated aluminium alloy piston crown had a trend of the lowest temperature difference value which was 219.4°C at 700°C, and this showed that the increment of temperature difference compared to the YPSZ/NiCrAl–coated CamPro piston crown was about 51%. Since there was no coating on top of the piston crown surface, the heat was allowed to transfer through the aluminium alloy made piston crown. The uncoated piston crown started to melt during at 700°C as the melting point of the material was at approximately 660°C. A problem was occurred during the burner rig test which was the difficulties in measuring temperature since it was troublesome to stabilise the surface temperature [21].

![Fig. 4. Heat flux on piston crowns during elevated temperature](image)

Figure 4 shows the heat fluxes calculated on piston crowns for the uncoated, and the YPSZ/NiCrAl–coated CNGDI piston crown at elevated temperature on top of piston crown surface. Generally, the pattern showed an increment of heat flux value along with elevated temperature on piston crown surface. Uncoated piston crown exhibited the highest value of heat flux which is 16.4 MW/m² at the temperature of 600°C. The YPSZ/NiCrAl–coated CNGDI piston crown exhibited 0.23 MW/m² at temperature of 700°C. In the regions of high heat fluxes, thermal stresses must be less than the levels that would cause fatigue cracks. The average heat flux through the uncoated aluminium alloy piston crown was approximately 12.6 MW/m² and had a reduction of heat flux of the YPSZ/NiCrAl–coated CNGDI piston crown which is about 98%. This was a good sign in order to reduce heat localisation on surface of piston crown and give protection to the piston crown from experiencing thermal stress from combustion would then lead to crack initiation. In comparison, in diesel engine with direct system, the combustion contributed to localisation of heat flux regions on piston which correlated with coating damage was observed during diesel engine evaluation of TBCs [18]. Ref. [7] reported that the bowl rim was the area with higher temperature. The thermal deformations under the temperature at the bowl rim were constrained by surrounding material which causing large compressive stresses and leading to the excess of material yield strength. For this research, further work will be carried out in a real engine operation.

4. Conclusions

From the experiment, the average heat flux of YPSZ/NiCrAl coated piston crown exhibited 98% lower than the uncoated piston crowns. This might be due to the existence of lower conductivity of the ceramic coating. Current result may lead to contribution for the betterment of heat protection to the piston in CNGDI engine.
5. Acknowledgements

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