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Insulated Piston Heads for Diesel Engines

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Widely studied in the 1980s, the insulation of pistons in engines aimed at reducing the heat losses and thus increasing the indicated efficiency. However, those studies stopped in the beginning of the 1990s because of NO_x emission legislation and also because of lower oil prices. Currently, with the improvement of exhaust after treatment systems (diesel particulate filter, selective catalytic reduction, and diesel oxidation catalyst) and engine technologies (exhaust gas recirculation), there are more trade-offs for NO_x reduction. In addition, the fast rise of the oil prices tends to lead back to insulation technologies in order to save fuel. A 1 mm thick plasma sprayed thermal barrier coating with a graded transition between the topcoat and the bondcoat was deposited on top of a serial piston for heavy-duty truck engines. The effects of the insulated pistons on the engine performance are also discussed, and the coating microstructure is analyzed after engine test.

Keywords air plasma, diesel, graded transition, TBC

1. Introduction

Thermal barrier coatings (TBC) have been widely used in aero engines for many years. Applying a TBC on a component allows a higher combustion gas temperature and/or a reduction of the cooling of the part, and this leads to a better efficiency of the engine. Aeronautic application was the first to be developed because of very high combustion temperatures in the engine (Ref 1).

Volvo Aero has extensive experience in thermal barrier coatings and thermal spraying in general. The current strategic development is to establish Volvo Aero as the center of excellence for thermal spray technology for the Volvo group. As a consequence, several projects have been or are being conducted at the moment to establish the feasibility of applying thermal sprayed coatings in a nonaeronautic environment. Volvo Powertrain is one of the current partners interested in the technology as well as Volvo Construction Equipment, for example.

Attempts to implement the thermal spray technology in nonaeronautic applications were done early in the 1980s and 1990s, first in combustion chambers of marine engines (Ref 2), then in truck engines (Ref 3). These attempts were stopped because of the important increase in NO_x emission resulting from the increase in combustion temperature. Moreover, the relatively low fuel price at that time made this solution not profitable.

Several tests were carried out in the past with various coating materials or thicknesses, and the results were somehow contradictory. Some authors did find a fuel consumption reduction, whereas other found an increase (Ref 4-6). The main problems were coming from the drastically modified fuel injection, since the insulating coatings affected the boundary conditions (higher wall temperature, altered combustion, etc.).

Currently, with the new improved technology of the exhaust treatment systems (diesel particulate filter, selective catalytic reduction, and diesel oxidation catalyst) and engine technologies (exhaust gas recirculation), NO_x emissions can be controlled and maintained to low levels. Besides, the fast rise of the oil prices tends to again attract insulation technologies to reduce fuel consumption for heavy-duty trucks.

Ideally, the combustion chamber has to be fully insulated to bring the best efficiency and keep the process closer to adiabatic. This work, however, was focused on the piston only, since it has one of the main contributions to heat losses (with cylinder head and liner) and is the hottest part.

2. Experimental Procedure

2.1 Spraying

Standard powders were used to make the thermal barrier coatings on the pistons. They are a regular $7Y_2O_3$-ZrO_2 (Volvo PM 819-84, agglomerated-sintered, H.C. Starck Amperit 827.873, H.C. Starck Gmbh, Goslar, Germany, and Volvo PM 819-55, hollow oxide spherical powder, or HOSP, Sulzer Metco 204 B-NS, Sulzer Metco Inc., Westbury, NY, USA) and NiCrAl (Volvo PM 819-47, Sulzer Metco 443 NS) for the topcoat and bondcoat, respectively. The powders used for the graded transition were blends of these two powders (NiCrAl and A&S YSZ), with three different mixtures: 75-25, 50-50, and 25-75 wt.%. Two topcoat powder morphologies were investigated, one agglomerated-sintered (A&S) and one HOSPed, as well as the finishing of the topcoat surface; in

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these cases, only nongraded coatings were investigated. The spray experiments were carried out using a F4-MB plasma gun mounted on a six-axis robot (ABB IRB 2400, ABB, Västerås, Sweden) and controlled through a Multicoat system (Sulzer Metco AG, Wohlen, Switzerland).

Topcoat and bondcoat were sprayed with the standard spray parameters used in production at Volvo Aero. Parameters in between those were developed and used for the graded transition. The nominal thickness of the whole coating was 1 mm.

To improve the homogeneity of the coating thickness, the coatings were made on steel plates (8 mm wide, 1 mm thick) having the same shape as the piston head (Fig. 1) using a specially developed fixture. This configuration allowed an easy development of the robot program that was used for the final coating, since there was no need to cut a piston after each trial, and the shape of the sample was representative of the real piston; thickness was measured directly on the plates.

The pistons were from serial production and made of phosphatized age hardening ferritic-pearlitic steel (38MnVS6). Before spraying the prototypes, the pistons were ground to compensate the coating thickness to get the same bowl volume as the standard ones, thus limit the effects of the coating on the combustion. The phosphate layer was thus removed on top of the piston, but was preserved on its sides.

The preparation of the piston was:

- Degreasing with acetone
- Masking the sides with tape and grit blasting the surface
- Mounting the piston in the special fixture avoiding the presence of coating anywhere else than on the top
- Application of the bondcoat, the three mixed layers and the topcoat
- Removal of the piston, grinding the edge for a better finish

A total of nine pistons were sprayed; one of them was used for destructive analysis.

2.2 Coating Characterization

Mounts were prepared through a combined cold and hot procedure according to Volvo Aero patented method (Ref 7).

Image analysis was carried out using an optical microscope, using Picsara image analysis software (Euromed Networks AB, Stockholm, Sweden) for thickness measurement. The thickness of the graded transition was measured between the first occurrence of the zirconia and the last of the NiCrAl bondcoat and therefore includes the three mixed layers.

A thermal shock rig was used to choose the best topcoat material (see Fig. 2). It consists of a rotating wheel with eight positions: four are heated with a burner flame and the other four cooled with compressed air on the back side. The wheel is indexed to achieve 75 s on the hot station and 75 s on the cold position. Within time combined with proper burner gas flow adjustments, approximately 1100 °C surface temperature on the hot side is

Fig. 1 Example of test plate used for coating thickness measurement

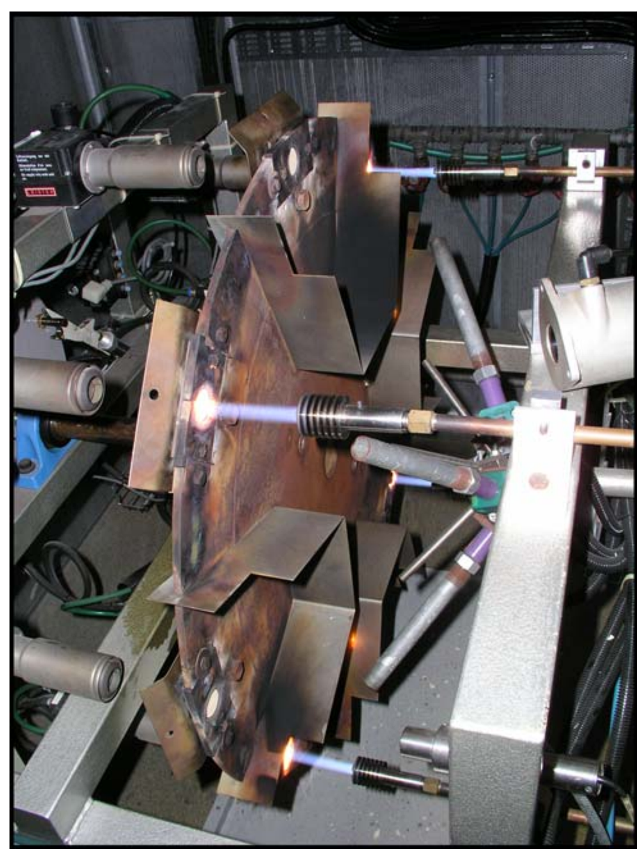

Fig. 2 Thermal shock test rig

achieved. The sample backside was kept at 450 °C by cold air coolers. Because of the rather high temperature during the test, Hastelloy X coupons were used as substrate material, since they have a coefficient of thermal expansion rather similar to steel. The coating is considered to have failed when 10% of the sample surface have spalled off. This temperature is high compared to the combustion chamber of a diesel engine, but allows a much faster test.

2.3 Robot Programming

The spray program was first developed using an off-line robot programming software (Robcad OLP, Siemens PLM Softwares, Plano, TX, USA) at University West (Trollhättan, Sweden). The spray booth was already modeled and using the computer-aided design (CAD) file of the piston and spray properties of the bondcoat and topcoat, such as deviation and width of the particle jet, allowed the calculation of the spray gun position and its speed as well as the turntable speed. Rotating the part makes spraying easier because of its symmetrical geometry and allows a more homogeneous thickness distribution. The use of this program entailed a drastic reduction of the amount of spray trials. However, since this program was at first developed for painting, the precision was not absolutely perfect, and the program had to be adjusted through spray experiments. The rotational speed of the part was increased while maintaining a constant gun to part speed in order to achieve constant coating thicknesses, as done and recommended by Novak et al. (Ref 8).

2.4 Engine Test

The engine test was carried out at the CMT—Motores Térmicos (Universidad Politécnica de Valencia) in Valencia (Spain). The fully instrumented test bed is a standard MD-11 US04 turbocharged direct injection diesel engine, with a variable geometry turbocharger and an exhaust gas recirculation system (type "short route," water cooled). Other main instrumentation used is related to the exhaust emissions analysis including HC, CO, CO_2, NO_x, and smoke. The tests were divided into two parts: a first one ("back to back") where the standard pistons are in the engine to establish reference measurements and followed by the substitution with the insulated ones. No adjustments were made in that part of the test, only the measurements were recorded to visualize the effect of piston head insulation on the engine performance. In the second part of the test, the injection parameters (start of injection, needle opening pressure, etc.) were adjusted to bring the engine performance back to the reference. At this point, fuel consumption, power, emissions were measured.

3. Results and Discussion

3.1 Topcoat Material Selection with Thermal Shock Test

Two coatings of standard thickness, that is, approximately 150 μm bondcoat and 350 μm topcoat, were tested, with different powder morphologies: A&S and HOSP. The coatings experienced different failure modes: while the A&S topcoat failed at the bondcoat/topcoat interface, the HOSP topcoats started early to show pitting in front of the flame that led to spallation of some small pieces of the coating, followed by failure at the bondcoat/topcoat interface in the upper part of the graded transition.

The final lifetime was 593 ± 104 cycles to failure for the A&S topcoat, and 178 ± 75 when using the HOSP material. This results from the HOSP coating morphology; the lamellar pores that are present in that kind of coatings lead to a very low thermal conductivity leading to a higher coating surface temperature, but also entail a lower adhesion when compared to A&S coating. This phenomenon is even worse when there is a hot gas stream normal to the coating surface, such as on the piston rim in front of the fuel injection flames. Conclusively, the A&S topcoat was chosen for coating the piston head.

A second investigation was then made on the surface state of the coating. Using A&S topcoat, four normal samples and four polished (Ra < 0.5 μm) were also tried in the thermal shock rig. The four polished samples were sprayed approximately 30 μm thicker than the standard ones, and then ground, to get a similar coating thickness. The idea was to improve the flow of the hot gases on the coating. However, the result was not positive, and polishing the coating surface led to early failure after only 291 ± 140 cycles, whereas standard coating failed after 578 ± 36. It seems like polishing may be a good idea if the flame leads to a hot gas flow sliding on the coating surface, but not when the coating is directly facing the flame. One explanation could be that the reduced heat exchange surface leads to locally higher heat flux densities, and thus to locally higher stresses, entailing the failure of the coating. Another possible reason could be the presence of defects coming from the polishing step since it was only controlled through surface roughness measurement (no specific inspection of the coating surface was carried out).

3.2 Coating Microstructure and Thickness

Coatings were nominally structured as follows (by wt.%), see also Fig. 3:

- Bondcoat 150 μm
- 75 bondcoat—25 topcoat 150 μm
- 50 bondcoat—50 topcoat 150 μm
- 25 bondcoat—75 topcoat 150 μm
- Topcoat 400 μm

The choice of the graded transition was motivated by the thickness of the coating. With this range of thickness it has been demonstrated that a graded transition is beneficial to the lifetime of the coating, particularly when thermal shocks occur. The graded transition allows the progressive change in the mechanical properties by progressively accommodating the difference in the coefficient of thermal expansion. It has been reported that a graded transition improves both the coating bond strength and its life regarding thermal cycling (Ref 9, 10).

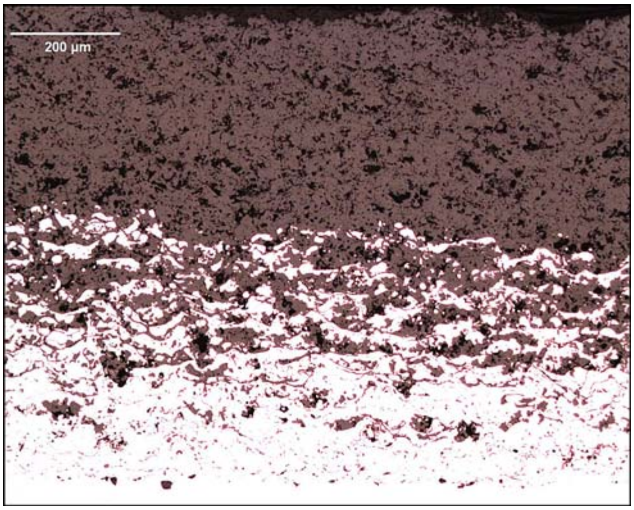

Fig. 3 Coating microstructure

Two sets of 1 mm thick coatings were investigated to check these results, one with and one without the graded transition. Without graded transition, the coatings failed after 107 ± 37 cycles, whereas the coatings with a graded transition failed after 1142 ± 7 cycles. Bond pull tests (ASTM C 633) were also carried out and showed a slight increase in adhesion for the coating from an average of 12.7 ± 1.5 MPa without to 14.2 ± 1.1 MPa with a graded transition. The failure location was also moved from the bondcoat/topcoat interface for a duplex coating into the graded transition for the graded one.

The graded transition can, however, exhibit some limitations in the oxidation properties of the coating (Ref 11), by bringing bondcoat material closer to the hot surface and increasing the bondcoat surface. Concerning diesel engines, the oxidation/corrosion is not highly important at the relatively low operating temperatures (compared to aero engines). Moreover, in the past years, the quality of fuels have been significantly improved by better refining, thus reducing sodium or vanadium compounds that are detrimental to zirconia.

The coating thickness varies slightly from the targets, especially in the lower radius (area 7 in Fig. 4) of the piston because of rebounds of the particles on the upper radius (area 4 in Fig. 4). This results in a nonoptimized coating structure at that location.

A coated piston as used in the engine test is shown in Fig. 5.

3.3 Engine Test Results

Measurements from back-to-back engine tests showed that using insulated pistons lead to a lower engine torque with the same quantity of injected fuel, higher turbo speed, higher compressor discharge temperature, and higher intake manifold and turbine pressures, as well as higher inlet turbine temperature due to higher exhaust gas recirculation (EGR) levels. Exhaust gas recirculation is an engine technology that recirculates exhaust gases, mixes them with cold air, and reintroduces them through the inlet manifold into the combustion chamber, permitting a reduction of NO_x emissions. The calculations from these data gave higher break specific fuel consumption (BSFC) by 2.3%, a drop-in volumetric efficiency, an increase of NO_x emissions, and some mixed results for smokes. The insulation of the piston head is effective since a high

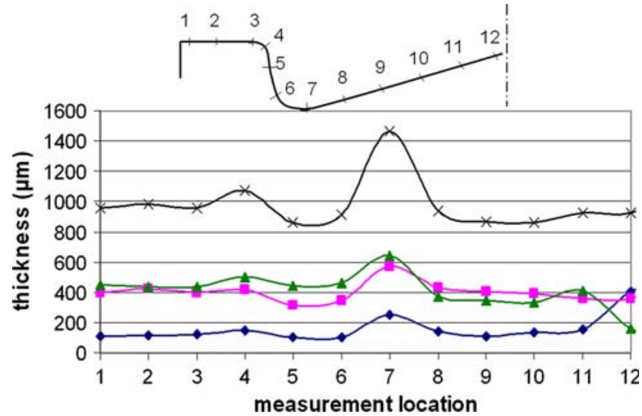

Fig. 4 Thickness distribution of the coating along the piston profile. Note that ''graded transition: includes the three mixed layers

Fig. 5 Piston after coating

diminution of the heat flux transferred to the coolant has been observed, as well as a slight increase of heat flux transferred to the EGR; globally the heat flux transferred to the engine block is also lower, even if it is slightly higher through the cylinder liner. These results are in good agreement with the literature that reports same trends as well as a drop in volumetric efficiency. For instance, Tree et al. reported a BSFC increase, more smoke and NO_x, as well as a 2% drop in volumetric efficiency (Ref 12). Taymaz et al. explained this drop by the higher combustion chamber wall temperature due to insulation and reported that this problem could be overcome with the resulting boost pressure increase from the turbocharger (Ref 13).

The analysis of the combustion reveals that the combustion process is slower with insulated pistons, but the main difference appears in the combustion diffusion, principally at high loads. Small changes in *P-V* diagram indicate a modified efficiency depending on the load. Insulated pistons delay the combustion start and extend the combustion duration, creating an increment of pressure at the exhaust valve opening. By reoptimizing engine parameters (such as EGR rate, variable geometry turbine position, or injection parameter), it is possible to compensate the piston effect and to come back to initial results. The pressure peak is roughly the same, but the temperature peak is slightly higher. The net mechanical efficiency, which is defined as the ratio between the mechanical energy available at the crankshaft to the energy contained in the injected fuel, remains lower with insulated pistons. One possible reason could be that the engine water pump is consuming more energy, because the thermostat is locked closed for a longer time with the insulated pistons, and therefore the coolant circuit has higher permeability for the same speed of the water pump. Charge exchange efficiency that can be defined as the amount of energy saved in the charge process is lower with insulated piston, meaning higher pumping losses. The trapped mass is also lower with insulated pistons: this means that the air density in the cylinder is lower, resulting in a slower mixture that increases smoke emission by 4.2%. Moreover, higher temperature at the intake valve closing, in combination with a high oxygen concentration leads to an increment in NO_x emissions by 7.5 %.

This is in agreement with Schihl et al., who reported a 10 to 90% longer fuel combustion duration with zirconia coating compared to the baseline pistons, as well as a delay in fuel ignition (Ref 14).

During the engine test, the effect of the cleanliness of the exhaust gas recirculation (EGR) system was investigated. The differences between the engine working with dirty EGR cooler and clean EGR cooler were negligible.

The second step of the engine test consisted in getting back to the "standard" engine by adjusting engine/combustion parameters, while using insulated pistons. In general, insulated pistons damaged the final results. Optimizing one parameter (NO_x or BSFC) provoked a dramatic increase of soot emission, which is not acceptable. On the contrary, optimizing soot emissions led to an increase of fuel consumption (BSFC), which is also unlikely.

The bad results observed have been questioned in the case of yttria-stabilized zirconia coating. In Ref 15, Mendera stated that in a diesel engine, radiation represents 20 to 35% of the total heat transfer, with a wavelength between 0.5 and 5 μm (both visible and infrared). The problem is the semitransparency of zirconia ceramic below 6 μm. This paper said that in a diesel combustion environment, if YSZ coatings are thicker than 1.5 mm; they are opaque, whereas below they are optically translucent. Transmittance has been reported to be 30% and 40%, respectively for a 1 mm thick coating and for a 0.5 mm thick one, facing a 2.5 μm wavelength. The presence of soot on top of the pistons heads, coming from the fuel combustion can also make this phenomenon worse, because soot acts as heat accumulator and retransfer the accumulated heat by radiation to the coating. Thus the effective thermal insulation of the coating decreases, since there is a "deep heating of the coating." The optimal thickness of the coating was said to be 200 μm; above this thickness, the temperature swing was stabilized, meaning that the surface temperature of the TBC increases without any increase in fluctuation amplitude, leading to a drop in volumetric efficiency, entailing a reduction of the thermal efficiency. Following the results of Ref 15, a material other than zirconia has to be used for pistons.

3.4 Piston Expertise after Engine Test

After engine test, one piston was visually and destructively analyzed, after degreasing and cleaning the surface.

It revealed a coating surface covered with soot especially on the rim in front of the burner flames. Some cracks caused by piston expansion and bending in the engine were observed, but did not affect the coating properties (no spalling) (see Fig. 6).

The coating microstructure did not exhibit any modification compared to the microstructure before coating. Even in the warmest zone, on the rim in front of the flames (marked 4-5 in Fig. 4), no alteration of the coating microstructure could be observed.

The fear of galvanic corrosion that was observed on the small test plates shown in Fig. 1 was not justified. Because of the too-high nobility of the bondcoat (high chromium content) compared to the steel-based piston, some rust problems had been noticed. This was overcome by giving special care to the packaging of the piston for storage before engine test. The atmosphere in the combustion chamber, during testing, did not allow the formation of water vapor that could condensate on the coating during engine stops.

4. Conclusion

A robot program was developed to spray a homogeneous (thickness and structure) TBC on a piston head. It can be concluded that this was achieved, but improvements can still be implemented.

Fig. 6 Piston head after engine test with TBC coating showing soot and cracks

If considering large series production, improvements can also be done by reducing coating cost by changing topcoat material to, for example, less expensive zirconia (CaO- or MgO-stabilized), silicates or zirconates (such as $ZrSiO_4$, $CaZrO_3$, or mullite) are commonly referred to in the literature. The bondcoat can also be change to Ni-5Al for instance, since the rather low temperature in the engine does not require chromium.

The engine tests showed results in agreement with the literature. Replacing standard pistons with insulated pistons leads to an increase of NO_x, soot, and BSFC. The principal reasons were the differences in the combustion process and the reduction in volumetric efficiency. As expected, it also reduces the heat losses.

When optimizing the engine settings to same performance as a standard engine considering NO_x, or BSFC, the soot residues are drastically increased.

The use of the current coating is actually not beneficial for the engine since it entails very minor gain in engine performance, but may be considered for alternative fuel use since it entails higher combustion temperature. However, even if it reduces the heat losses through the piston head, allowing a longer life of the piston, and if reasonable coating price can be found in the context of large volume production, no economic advantage is foreseen because of the increase in fuel consumption or pollutant emissions.

The coating survived the test without showing any damage, more than 500 h at various loads, without showing any alteration.

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