Surface & Coatings Technology 350 (2018) 1–11

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Influence of microstructure on thermal cycling lifetime and thermal insulation properties of yttria-stabilized zirconia thermal barrier coatings for diesel engine applications

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ARTICLE INFO

Keywords:
Thermal barrier coatings
Thermal cycling lifetime
Hemispherical reflectance
Thermal conductivity
Diesel engine
Yttria-stabilized zirconia

ABSTRACT

Thermal barrier coatings (TBCs) may improve the fuel efficiency of heavy-duty diesel engines by reducing heat losses. A combination of durability, low thermal conductivity, and high directional hemispherical reflectance is required for a TBC in the combustion chamber. These properties are evaluated for yttria-stabilized zirconia coatings, produced using atmospheric plasma spraying (APS) and plasma spray–physical vapour deposition (PS-PVD). The influences of different types of microstructure and metallic coatings on the surface are studied. APS coatings with segmentation cracks and PS-PVD coatings with columnar microstructure have the best thermal cycling lifetime, while nanostructured and conventional APS coatings have the lowest thermal conductivities. The nanostructured APS coating has the highest reflectance at low temperatures, while the columnar PS-PVD coating has the highest reflectance at elevated temperatures. It is further demonstrated that a thin silver layer improves the reflectance of a dense, segmented APS YSZ coating.

1. Introduction

In modern heavy-duty diesel engines, approximately 45% of the energy in the fuel can be converted into useful mechanical work. The rest of the fuel energy is lost, mainly as heat to the coolant or the exhaust. For heavy-duty trucks and buses, approximately 30% of the fuel energy is lost to the exhaust and 20% to the coolant [1]. Thermal barrier coatings (TBCs) may be used on exhaust components to keep more heat in the exhaust gas, from which is can be recovered by, for example, turbochargers or waste heat recovery systems. TBCs can also be used on combustion chamber components to reduce the heat losses from the hot gases to the surrounding walls. This may lead to more work on the piston and, consequently, higher fuel efficiency. TBCs for this latter application will be studied in this paper.

Durability is a key factor, since spallation of the TBC will not only result in increased heat losses but may also damage components such as the turbocharger. In applications such as gas turbines, TBCs often fail due to stresses within the thermally grown oxide (TGO) during thermal cycling [2,3]. Since the coatings experience lower temperatures in diesel engines than in gas turbines, the bond coats will not be as oxidized in these applications [4]. The highest coating temperature will be seen in exhaust manifolds, since these, in opposite to the piston, have no active cooling, where the coating can reach 760° [5], while the maximum surface temperature of TBCs on combustion chamber components such as the piston will be approximately 550 °C [6]. Mechanisms other than TGO growth may thus cause TBC failures in diesel engines.

For pistons, having a large temperature gradient through the TBC due to internal oil cooling of the substrate, compressive in plane stresses form at the surface during heating [7,8]. Creep and sintering during high temperature exposure, that cause tensile stresses and surface cracking in the coating after cooling, have been suggested to cause TBC failures for pistons in diesel engines [4,9]. For components such as exhaust valves or exhaust manifolds, which have no active cooling of the substrate, the temperature gradient will be smaller, and the stress state different. Another type of thermal cyclic fatigue (TCF) test is required for evaluating lifetime of TBCs for these components.

Thermo-cyclic fatigue testing of coated test specimens is commonly

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Abbreviations: APS, atmospheric plasma spraying; EB-PVD, electron beam/physical vapour deposition; DHR, directional hemispherical reflectance; EDS, energy dispersive X–ray spectroscopy; HCF, high cycle fatigue; LCF, low cycle fatigue; LOM, light optical microscope; LPPS, low-pressure plasma spray; PS-PVD, plasma spray–physical vapour deposition; SEM, scanning electron microscope; SPS, suspension plasma spray; TBC, thermal barrier coating; TCF, thermal cyclic fatigue; TGO, thermally grown oxide; YSZ, yttria-stabilized zirconia

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https://doi.org/10.1016/j.surfcoat.2018.07.005
Received 18 August 2017; Received in revised form 12 April 2018; Accepted 2 July 2018

used in testing TBC lifetime in gas turbines and aero-engines. In these tests, the TBCs are often exposed to temperatures up to 1100–1200 °C [10–13]. The high temperatures in this type of test often cause failures driven by the growth of TGO in the bond coat/top coat interface [10]. Consequently, thermal cyclic tests of TBCs for diesel engines should be performed at temperatures with lower oxidation rates. There is a rapid increase in bond coat oxidation above 1075 °C [14], so this temperature should not be exceeded in the thermal cycling of TBCs for diesel engine applications. Lower temperatures may also enable the use of bond coats other than the often-used NiCoCrAlY alloys.

Few thermal cycling tests of this type TBCs for diesel engines have been published. In one study, TBC specimens were positioned in the exhaust manifold of a diesel engine to test the coatings under realistic conditions, as well as in a chamber furnace to expose the specimens to thermal cycling similar to the exhaust manifold conditions [5]. In both of these tests the maximum temperature was kept below 800 °C. The combined effect of HCF and LCF in diesel engines has been studied by heating the TBC with a laser [9]. In those tests the combined effect of HCF and LCF accelerated the crack growth rate as compared with only LCF exposure.

To reduce the heat losses in a diesel engine, a low thermal conductivity is required. Under conditions with significant amounts of thermal radiation, a high directional hemispherical reflectance and low transmittance is also required, to reduce the heat transfer through the top coating.

Thermal radiation of 1.5–6-μm wavelength is generated by the hot gases in the combustion chamber while incandescent soot emits radiation of 0.77–1.5-μm wavelength [15]. Some measurements indicate that thermal radiation may account for up to 20–40% of the total heat flux in the combustion chamber of a diesel engine [16], while other measurements have indicated that the energy in thermal radiation coming from soot is $< 0.5\%$ of the fuel energy [17].

Many TBC materials, including YSZ, are partially transparent to thermal radiation [18,19], which makes the optical properties of TBCs an important factor to consider at high temperatures, especially for coatings inside the combustion chamber, where the highest gas temperatures are found. It has been shown that plasma-sprayed YSZ absorbs almost no IR radiation at wavelengths below 5 μm, so thermal radiation that is not reflected by the coating will heat up the substrate and contribute to the heat losses [20].

It has been suggested that the influence of thermal radiation can be reduced by using a highly reflective TBC. High hemispherical reflectance can be reached by either using a top coat material with a high scattering and low absorption coefficient, or by adding an extra layer of opaque, high-reflectance material [21]. Tests with a heat flux probe in a diesel engine combustion chamber, and experiments with convective/radiative heating, have shown that zirconia coatings were effective as thermal barriers only when the surface was covered by a metal film that could reflect thermal radiation [18].

Multilayer ceramic coatings may be used to increase the hemispherical reflectance, as has been shown in simulations and experiments [22,23]. For APS coatings, it has been shown that an increase in reflectance and in scattering coefficient can be obtained by either increasing the porosity or adding a nanostructured suspension-plasma-sprayed (SPS) coating on top of the APS coating [24]. It has also been demonstrated that reflectance increases with greater thicknesses of APS YSZ coatings, due to increased volume scattering [20].

The usual coating process for applying TBC to components such as pistons and valves is atmospheric plasma spraying (APS). A conventional APS microstructure consists of disc-shaped splats with microcracks and pores between them. Improved strain tolerance and lifetime can be obtained in thermal cycling tests by adjusting the spray parameters to create a denser structure with vertical segmentation cracks [25,26]. A bimodal microstructure with nanozones embedded in a conventional microstructure can be obtained by using agglomerated nanosized particles as feedstock in an APS coating process [27]. Such nanostructured microstructures have been demonstrated to have longer thermal cyclic lives than those of conventional microstructures [27,28]. Nanostructured TBCs have also been found to have lower thermal conductivity than conventional TBCs [29,30], which can be attributed to more grain boundaries [31] and more pores [32]. Thermal conductivity between room temperature (RT) and 1300 °C for nanostructured plasma-sprayed YSZ has been reported to be $0.71–0.79\ \mathrm{Wm^{-1}K^{-1}}$ and $0.88–1.1\ \mathrm{Wm^{-1}K^{-1}}$ for conventional plasma-sprayed YSZ [33]. The thermal conductivity of segmented plasma-sprayed YSZ is higher due to its lower porosity, and is reportedly $1.1–1.8\ \mathrm{Wm^{-1}K^{-1}}$ at 1000 °C [34].

Another coating process that can be used to produce TBCs is plasma spray–physical vapour deposition (PS-PVD), which can produce columnar microstructures with good strain tolerance [35,36]. The thermal conductivity of YSZ PS-PVD coatings has been reported to be $1.15\ \mathrm{Wm^{-1}K^{-1}}$ at 1200 °C [36].

As TBCs are usually evaluated at high temperatures and using substrate materials not relevant to diesel engines, the results found in the literature regarding, for example, thermal cycling lifetime might not be directly applicable to diesel engines. It is important to investigate TBC properties for different coating processes and coating microstructures under conditions found in heavy-duty diesel engines.

The aim of this study is to investigate how different YSZ microstructures, produced using APS and PS-PVD, influence the thermal conductivity and thermal cycling lifetime of TBCs to be used in heavy-duty diesel engines. Furthermore, it is also studied how optical reflectance is influenced by these different microstructures or by adding an extra metallic coating on top of the YSZ coating. This will give a better understanding of how to design a TBC that can combine properties such as long thermal cycling lifetime and good thermal insulation properties.

2. Materials and methods

2.1. Substrate materials

The investigated TBCs were deposited onto substrate materials typical of components used in heavy-duty diesel engines. The substrate materials were 38MnSiVS5, a micro-alloyed steel typically used for pistons, and SiMo51, a nodular cast iron often used for exhaust manifolds. Disc-shaped test samples 25 mm in diameter and 15 mm thick were used for adhesion testing and thermal cycling tests. Disc-shaped test samples 12 mm in diameter and 4 mm thick were used for most other tests.

2.2. Coatings

The coating processes used to produce the TBC test samples were APS and PS-PVD, see details in Tables 1-2. The APS coatings were sprayed by Oerlikon Metco (Wohlen, Switzerland) using a TriplexPro-210 spray gun with standard spray parameters. As a bond coat, Fe24-Cr8Al0.5Y (Amdry 9700) was used for all APS coatings. Three different 8YSZ powders were used in producing top coats with varying properties: agglomerated and hollow spherical powder (HOSP) (Amdry 204NS-1) for a conventional top coat with normal porosity, agglomerated and HOSP (Metco 204F) for a dense and segmented top coat, and agglomerated and sintered (Metco 222A) for a nanostructured top coat.

The PS-PVD coating was supplied by the University of Rzeszow, Poland, using a Metco O3CP spray gun. The low-pressure plasma spraying (LPPS) process was used for the NiCoCrAlY (Amdry 365-1) bond coat followed by agglomerated 7.5YSZ (Metco 6700) powder for the top coat in a PS-PVD process.

Amdry 204NS-1 samples with conventional top coat were coated with different metal films on top of the ceramic. Thin layers of silver or chromium were deposited using a sputter coater (Q150T ES; Quorum Technologies, Lewes, UK) and APS was used for spraying