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ON THICK THERMAL BARRIERS FOR COMBUSTOR APPLICATION

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SUMMARY

Basic features for future advanced gas turbines will be low emission rates and increased efficiency. To fulfil these requirements a reduction of cooling air in the combustor chamber demanding more efficient cooling technology and/or an increasing inner wall temperature is needed. The development of thicker thermal barrier coatings for combustor tile applications is one concept followed to enable a reduction in cooling air.

Thermal barrier coatings with a thickness up to 2mm and improved thermal cycling life have been developed as well as mechanical and thermophysical data determined.

Combustor segment rig testing demonstrated a potential of 25% cooling air reduction by the use of thick thermal barriers for the tile design investigated.

1. INTRODUCTION

A basic feature for the development of advanced gas turbines will be low emission rates of Nitrogen Oxides (NOx), Carbon monoxides (CO) and Hydrocarbons (HC) to suit expected lower limits for pollution in the future. One way to fulfil these requirements is a reduction of cooling air in the combustor chamber demanding more efficient cooling technology and/or increasing inner wall temperatures.

Beside the development of more efficient cooling technologies there are several materials technology concepts that are followed at BMW Rolls-Royce to reduce cooling air requirements in the combustor:

i) a development of improved superalloys for combustor application with higher temperature capability,
ii) investigation of the potential of ceramic matrix composite materials for combustor tiles and
iii) development of thicker thermal barrier coatings (TBCs) for combustor tile applications.

This paper will focus on the latter.

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Typical current applications of TBCs are thin coatings on guide vanes, blades and combustors of gas turbines often introduced during overhaul in order to extend lifetime of parts. Current technology is the use of plasma sprayed bond coat (BC) such as CoNiCrAlY mainly for adhesion and oxidation protection and partially stabilised ZrO_2 (about 8wt%Y_2O_3) with a thickness below 0.5mm. The benefit is a component temperature reduction up to 150°C resulting in reduced cooling airflow requirements and/or component durability improvement (1, 2, 3). Thickness and lifetime of the barriers are limited by mechanical and thermal stresses in the coatings due to the mismatch of thermal expansion coefficients of the ceramic and the metals and/or oxidation of the bond coat.

In a current Brite Euram project (BE7287)[1] plasma sprayed thermal barrier coatings up to 2mm in thickness have been developed to meet the requirements of improved thermal insulation (4). Different microstructures of coatings has been addressed from different partners. Volvo Aero Corporation has investigated segmented TBCs (4), BMW Rolls-Royce 'conventional' highly porous TBCs and ANSALDO Richerce has developed a process route to spray highly porous TBCs using a mixed ceramic-polymer powder (5).

This paper will report on the development of the highly porous coatings, the investigation of thermophysical and mechanical properties and thermal cycling experiments as well as combustor sector rig tests performed to determine the potential for cooling air reduction of thicker TBCs applied on combustor tiles. The sector rig test has been performed in the course of a national research programme.

2. EXPERIMENTAL

Spraying

In general TBC development within the above mentioned Brite Euram Project has had the objective to reduce Youngs modulus as one method to reduce thermal mismatch stress. Mechanisms chosen have been segmentation (vertical cracking) or production of highly porous coatings.

Spraying of porous 7%Y_2O_3 stabilised ZrO_2 TBCs has been performed at the BMW Rolls-Royce APS spray facility (Sulzer Metco A3000S, 9MB gun) using different spray parameters. During spraying temperature has been measured by means of a pyrometer at the coating surface and by means of thermocouples at the backside of the substrate. Substrates have been 2mm thick flat plates of Hastalloy X.

Microstructural investigations are performed at BRR to determine typical coating features such as thickness, porosity and crack density.

Thermophysical and mechanical Properties

Four point bend testing has been performed at UMIST at room temperature and elevated temperature to determine the nominal strength, the failure strain and Young's modulus. For testing free standing TBCs have been used by dissolving away the substrate. This has been possible due to the thickness of the coating.

For the measurement at elevated temperatures, a high temperature rig has been designed in accordance with European standards. All parts of the rig within the hot zone of the furnace are made out of Alsint 99,7 which can theoretically withstand a temperature of 1700 ºC. The capacity of the furnace enables temperatures up to 1500 ºC. Figure 1 shows the design of the apparatus. The sample is supported by two rollers 20 mm apart. In order to minimise the torsional loading, one of these rollers can also rotate about an axis parallel to the length of the sample. The specimen is loaded by a second set of rollers which are isocentric to the first ones. They are 10 mm apart and both of them allow a rotation about their own axis as well as about the axis of the sample.

The Young's modulus is strongly affected by the ratio of the sample length l and its thickness h and turns out to be too low in comparison with results from adequate tensile tests. In order to come to an understanding of the influence of the l/h ratio of the samples on the calculation of the Young's modulus, a coating was measured by an ultrasonic pulse method at 'Fraunhofer Institut Werkstoffphysik und Schichttechnologie' in Dresden resulting in a compensation factor for the l/h ratio of the 4 point bend test specimen.

[1]Partners of the Brite Euram Project BE7287 are: BMW Rolls-Royce GmbH, Volvo Aero Corporation , ANSALDO Richerce, CTAS Air Liquide, Fraunhofer Gesellschaft Institut für Betriebsfestigkeit, University of Lund, UMIST, Kvernes Technology, IceTec, RWTH Aachen, Rolls-Royce plc.

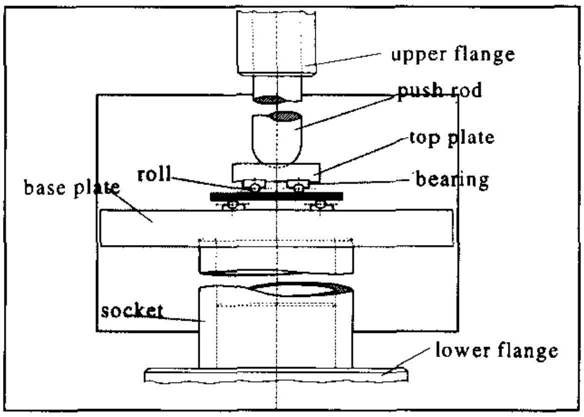


Fig. 1: design of the four-point bending rig, the hot furnace area is marked by the grey background

For the measurement of the thermal diffusivity α, the laser flash method was used. The samples examined had a dimension of 10 mm * 10 mm with a thickness of about 2 mm. In this experiment, a heat flux through the sample is caused by an energy pulse from a Nd glass laser which is incident on the front face of the specimen. The heat flux causes a temperature rise at the sample rear side, which is monitored as a function of time using an InSb detector. From this trace, the thermal diffusivity can be calculated. For the samples investigated, the measurements of the thermal diffusivity were performed under vacuum. The experiments were done in a temperature range from 80 ºC to 1200 ºC(6).

Thermal expansion measurements were performed in a conventional Al_2O_3 pushrod dilatometer, over a temperature range from 30 ºC to 1000 ºC. The heating rate was 60° h^{-1}. After reaching the maximum temperature, the sample was cooled at -250 ºC h^{-1}. Since the push rod and the guiding tube it is surrounded by also expand, this effect had to be compensated mathematically. The temperature gradient across the pushrod-guiding tube arrangement is taken into account by a compensation measurement. The latter one was performed following the same heating and cooling programme as for the actual measurement (6). The samples tested were about 15 mm long and 4 mm wide. Their thickness was about 2 mm, but varied slightly due to the sprayed coating thickness not being constant.

Thermal Cycling

Thermal cycling experiments are one typical test performed to rank TBCs for gas turbine applications. Tests should simulate heating up and cooling down of the specimen to create failure such as spallation by thermal mismatch stresses resulting from cycling.

Thermal cycling tests have been performed at the University Karlsruhe (IKM). The cycling time is about 60 sec for heating up (T_{TBC} = 1250°C, $T_{substrate}$ = 800°C) and cooling down to 60°C. Temperature measurements are performed using a pyrometer at the TBC surface and thermocouples on the substrate. Specimen geometry is a flat plate of 10x50mm, substrate thickness has been 2mm. Cycles are controlled by temperatures of the substrate, i.e. heating is restarted at a substrate temperature below 60°C. Maximum temperature at the TBC of 1250°C is settled for different specimens by varying distance from torch to specimen. By this the same temperature gradient of TBC surface to substrate back side is guaranteed and temperatures at the interface bond coat to TBC will be comparable. Additionally bending of the specimen can be measured using an inductive measurement device from the backside of the specimen. Fig. 2 exhibit an example of the temperature cycle obtained and the bending of the specimen measured.

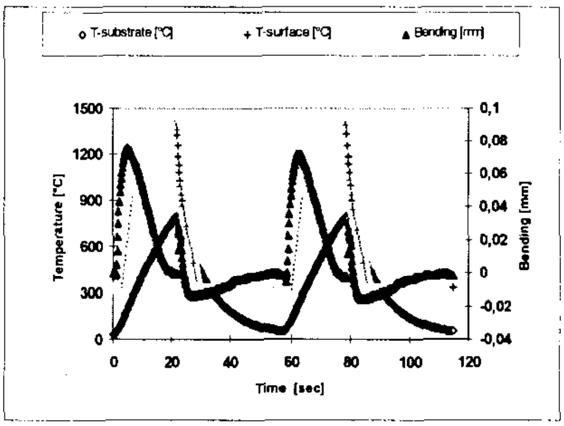


Fig. 2: Thermal cycles performed at IKM

Combustor Sector Rig Test

In the course of a German national research programme combustion liner tiles with 7%Y_2O_3 stabilised ZrO_2 were tested in the BR700 High Pressure 90°-sector rig. For the investigations on liner cooling a rig combustor was made and segments of outer and inner liner were cut out. The free space allows mounting of liner panels with various cooling designs. Hence, it is possible to test new cooling concepts using relative cheap panel specimen in a representative annular combustor. The objective of a test run is to demonstrate the thermal integrity and the temperature distribution of specimen close to engine take off conditions as well as to evaluate the potential for cooling air reduction. After ignition the conditions are raised to take off rating with an inlet air pressure of 20 bar and inlet temperature of 885K. The facility limits the inlet pressure to 20 bar.

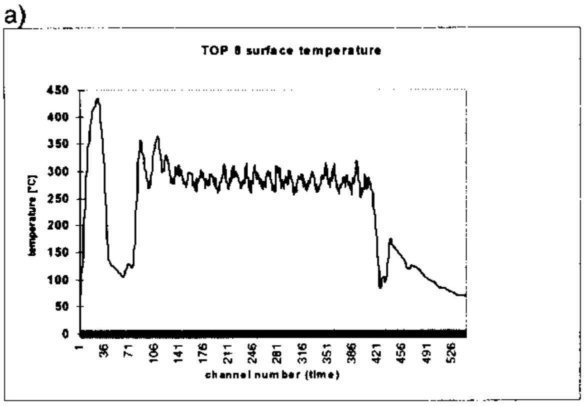
3. RESULTS

Spraying

Several parameter settings have been investigated to spray highly porous coatings. Typical temperature spectra measured during spraying are shown in Fig. 3 a and b.

Porosity values obtained for the different specimen are in the range of 8.5 to 20% (see fig. 4). For a number of specimen segmentation cracking has been found , which has been related to porosity values in the range of 8.5 - 12.5%.

a)



b)

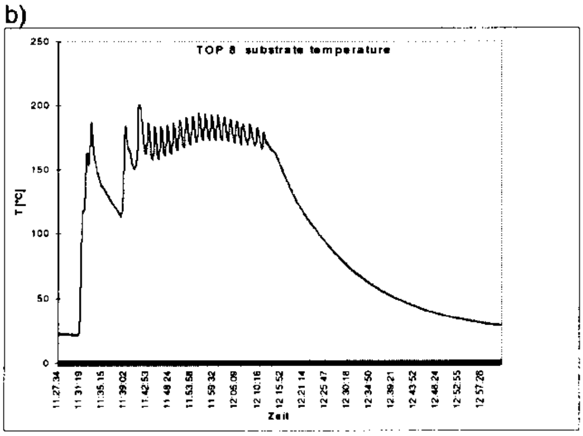


Fig. 3: Temperature readings during spraying from the coating surface (a) and substrate backside (b).

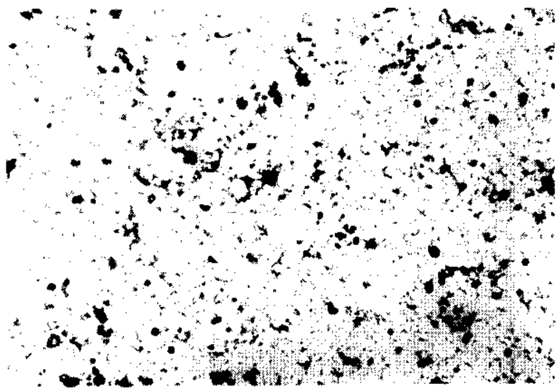


Fig. 4: micrograph of TOP 7, 15%porosity, x 150

Thermophysical and mechanical properties

Since the structure of the coatings is expected to vary through thickness two different loading types have been considered; where the top is either in the state of compression or of tension.

Mechanical properties determined are listed in table 1. Numbers given there are mean values out of the two loading types. Values from the experiments, where the surface of the TBC is under compression were found to be slightly higher in most cases. Youngs moduli found are lower than typical values reported on plasma sprayed TBCs, which lies in the range of 10 - 50 GPa (see for example ref. 8, 9, 10) .

Specimen	Youngs modulus [GPa]	failure strength [MPa]	failure strain [%]
Top 7	5.7	15.9	0.29
Top 8	6.9	13.6	0.22
Top 11	3.3	7.4	0.26
Top 12	8.8	30.4	0.37
Top 13	7.8	25.1	0.35

Table 1: Mechanical properties of thick TBCs

No significant change in these properties was observed in the experiments carried out up to 1000°C.

The failure strength and stress is found to be correlated to the Youngs Modulus determined (Fig. 5).

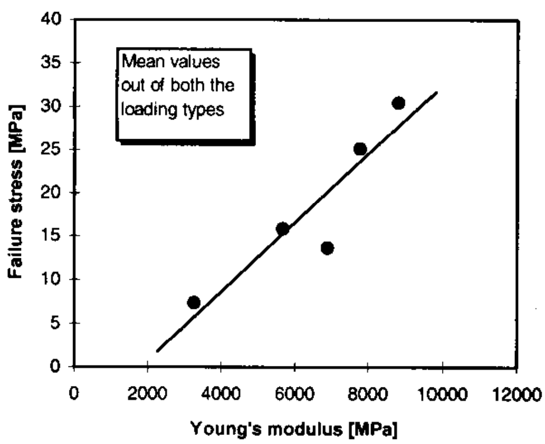
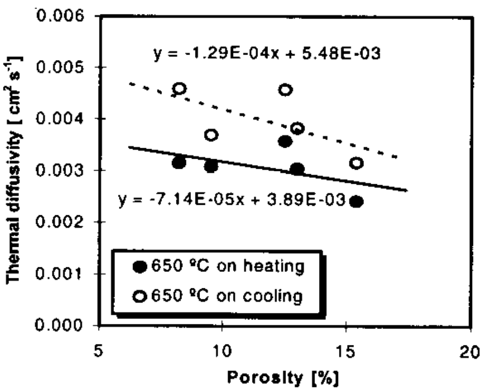


Fig. 5: Failure stress versus Youngs modulus

The expansion coefficient of the samples tested seems to have a rather constant value of $10.7 \cdot 10^{-6} K^{-1}$, which is typically for plasma sprayed 7%Y_2O_3 stabilised ZrO_2 (8, 11). Obviously, the porosity has rather little influence. Over the whole temperature range, the thermal expansion coefficient is almost constant and differences during heating and cooling, a typical indicator of phase changes, cannot be determined.

a)



b)

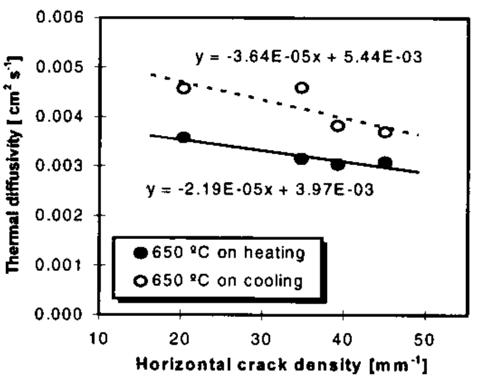


Fig. 6: thermal diffusivity versus porosity (a) and horizontal crack density (b)

For all specimen measured the thermal diffusivity obtained on cooling was higher than that observed during heating, showing that some irreversible change had occurred during first cycle only. The values obtained ranged from 0.0029 cm^2s^{-1}(Top 7) up to 0.0057 cm^2s^{-1} (Top 8). There is a general trend for the diffusivity to decrease with increasing porosity (Fig. 6a), but the effect is more pronounced when diffusivity is plotted against horizontal crack density (Fig. 6b).

From the diffusivity α, the thermal conductivity λ can be calculated as:

$$\lambda = \alpha \bullet \rho \bullet c_p$$

with ρ and c_p being the density and the specific heat capacity respectively (6). Values ranged from 0.8 W/mK to 1.5 W/mK for the TBCs investigated here.

Thermal cycling

Thermalshock test at BRR (perrformed at University Karlsruhe, IKM) used a cycling time of 60 sec for heating up (T_{TBC} = 1250°C, $T_{substrate}$ = 800°C) and cooling down to room temperature and has been performed for several specimen up to 2000 cycles yet in comparison to a cycling life below 10 cycles for the first tests. Some specimen tested to 2000 cycles did not fail at all. Fig 7 was an overview about number of cycles obtained.

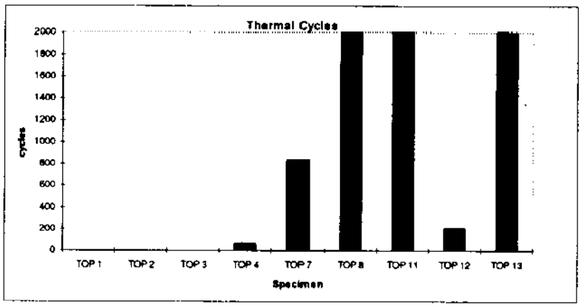


Fig 7: mean number of cycles reached for several specimen

The main influence on thermal cycling life is determined to be the temperature during spraying. A correlation from porosity to thermal cycling life could not be found (Fig. 8 an 9). Specimens exhibiting segmentation cracks instead of high porosity tend to show higher life times in the tests performed.

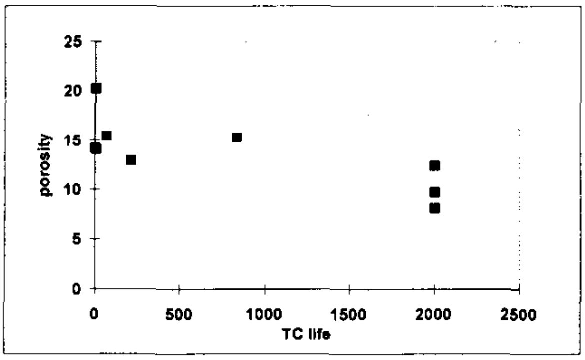


Fig. 8: porosity versus thermal cycling life

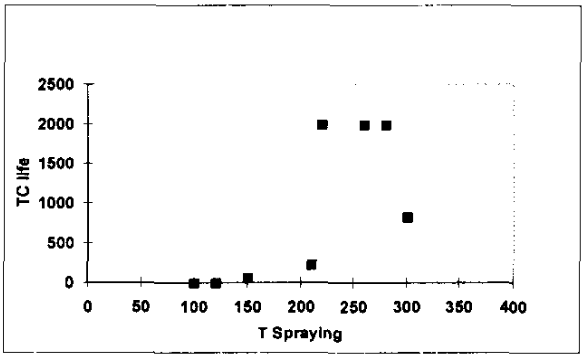


Fig. 9: Spray temperature versus thermal cycling life

FEM simulations have been performed using thermophysical and mechanical data described above to compare calculated and measured bending of the specimen during cycling. The bending behaviour (see Fig. 2) could be described qualitatively, quantitative deviations are expected to be related mainly to the quality of temperature data recorded during cycling.

Combustor Sector Rig Test

Two panels with different coating thicknesses (0.40 mm and 1.35 mm TBC thickness) were tested. The panel have been cooled by an array of impingement holes on the carrier. At the end of each tile the cooling air is used as a film for the hot side of the following tile. The tiles has been painted with thermal paint to investigate temperatures and temperature distributions. For the tiles with thick TBCs on the amount of cooling air used was reduced compared to the thin TBC tiles.

The specimens were not tested under identical conditions. The fuel to air ratio of the test with thin TBCs was approx. 5% lower than for the test with the thick coated specimen. This means that the specimen with a thick TBC was exposed to slightly more severe conditions.

The coating surface of the specimen with the 0.4mm TBC thickness shows only small spots with temperatures above the 1160°C limit of the thermal paint, whereas the 1,35mm thick TBC specimen has approximately 50% of the surface hotter than 1160°C. It should be noted however that the amount of cooling air has been reduced for the thick TBC specimen.

The metal temperature on the cold side of the 0,4mm coated tile was around 830°C with peaks at approximately 900°C. The thick insulated tile had approx. 50°C lower temperatures on the inner side.

A cooling film on the hot side is still necessary for thick coated tiles to keep the maximum temperature of the top coating below 1250°C. With the current design temperatures of top - and bond coating a thickness of the ceramic layer of approx. 1,3 mm should provide the desired temperature drop of 350 to 400°C between the hot surface and the critical layer where the ceramic adheres to the bond coating.

With a thick coated tile approximately 25% of the cooling air required for a standard coated tile could be saved.

4. CONCLUSIONS

TBCs with a thickness up to 2mm and improved thermal cycling life have been developed as well as mechanical and thermophysical data determined.

Thermal cycling life is mainly influenced by spray temperature. Porosity has not found to be of high importance, but segmentation seems to be beneficial in the test performed.

Youngs Moduli in the range of 3 - 9 GPA has been determined. Failure strengths range from 7 to 30 MPA, failure strains from 0.2 - 0.4%.

Successful simulation of the bending of the specimen during cycling indicates that the materials data obtained are of reasonable quality.

Combustor segment rig testing demonstrated a potential of 25% cooling air reduction for the tile design investigated.

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