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TEMPERATURE MEMORY COATINGS FOR SHORT AND LONG TERM APPLICATIONS IN GAS TURBINES

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ABSTRACT

Temperature profiling of components in gas turbines is of increasing importance as engineers drive to increase firing temperatures and optimize component cooling requirements in order to increase efficiency and lower CO2 emissions. However, on-line temperature measurements and, particularly, temperature profiling are difficult, sometimes impossible, to perform due to inaccessibility of the components. A desirable alternative is to record the exposure temperature in such a way that it can be determined later, off-line when the engine is at room temperature.

The existing method using colour changing Thermal Paints comes with a range of technical disadvantages such as subjective readout and some of the paint constituents are highly toxic. This paper describes a novel alternative measurement technique which the authors call Thermal History Paints and Thermal History Coatings. These can be particularly useful in the design process, where hotspots can occur during operation.

This paper reviews results from temperature measurements made with a water based non-toxic paint for the temperature range 100˚C to 900˚C in controlled conditions. Repeatability of the tests and errors are discussed. The precision of the technique is shown to be ±3°C, comparable to commercial thermocouples. Tests to estimate the accuracy of the technique indicate that ±10°C can be achieved with different substrate compositions. Measurements were conducted using an electronic hand-held interrogation device which can scan a component surface. The instrument enables mobile measurements outside of laboratory conditions.

Further, a comparison between a commercial thermal paint and the new technique is presented demonstrating the durability of the new system.

Finally, results are briefly presented from engine tests with Thermal History Coatings. These results demonstrate the capability of the technique for long term applications up to thousands of hours.

INTRODUCTION

Temperature is a critical parameter in many engineering applications but it can be challenging to measure, particularly in situations where access is limited or the measurement is required on moving components. A pertinent example of this is gas turbines. The operating temperature of a gas turbine is fundamental to its performance. The drive for improvements in thrust and efficiency have led to higher operating temperatures which have been made possible through the incorporation of cooling channels and Thermal Barrier Coatings (TBCs) on the critical components in the hot gas stream. The operating temperature of components is directly linked to the service life of the component. Accurate temperature information is required over a range of components to ensure maximum operating efficiency while retaining economic component life and avoiding catastrophic failures. In many cases the maximum operating temperature is the most critical parameter because it causes changes to material properties and the greatest stress on components. The location of the hot spots may not be known therefore a measurement technique which allows temperature profiling of components is vital.

The conventional thermometry techniques including pyrometry and thermocouples have fundamental limitations for application in gas turbine engines. Extraneous radiation from reflections or particles in the gas stream cause significant errors in pyrometry (Douglas, et al. 1999, Kerr and Ivey 2002). Thermocouples are inherently intrusive because they require contact with the measured component. Installing thermocouples can be extremely difficult, particularly on rotating components. It has been shown that accurate temperature measurements can be achieved on an operating gas turbine using phosphor thermometry (Feist, et al. 2013, Feist, et al. 2012) however the optical access required during engine operation is not always feasible.

Several techniques have been developed which determine the operating temperature of the component after service due to a thermal history effect. The most prominent of these techniques is known as temperature indicating paint or thermal paint. This paint is applied to the components of interest which are then installed and run in the engine. Chemical reactions between the metal elements and other molecules in the paint or surrounding environment cause colour changes, due to permanent changes in the reflection spectra (Lempereur, et al. 2008). The colour changes are then interpreted by a trained technician under controlled lighting in a laboratory and compared to calibration tables to determine the temperature. The disadvantage with this technique is the subjective detection method, the requirement to disassemble parts of the engine, and the durability of the paints. The longevity of the paints usually limits their application to dedicated short engine tests to avoid removal of the paint (Bird, et al. 1998). Furthermore some thermal paints rely on materials which are restricted under the EU REACH legislation (Regulation 2006), for example chromium, mercury and lead.

Other techniques have been developed for thermal history sensing which have greater durability and do not require restricted materials. These include metallurgical and crystal temperature sensors. Both rely on permanent changes to the material structure caused by temperature exposure. In both cases, however, the sensor material is inserted into drilled holes in the test component, hence it can only provide point measurements and, due to their destructive nature, can only be applied on development engines (Annerfeldt, et al. 2004, Lo, et al. 2008). The analysis of the thermally grown oxide by microscopy of sectioned samples is also used to infer the thermal impact but this is also an inherently destructive technique (Kumar, et al. 2009).

A non-destructive technique is required which provides accurate temperature measurements which could be preferably be applied in-situ to avoid the high costs associated with disassembly of the engine. A novel technique was proposed by Feist, et al. (2007) which introduces optically active material into ceramics which make them luminescent. During thermal exposure the ceramics undergo permanent physical change which can be non-destructively detected and quantified by analysis of the luminescence. Recent research has demonstrated that the technique can be applied using materials which are well established phosphors to provide temperature measurements over a large dynamic range, 100 to 1000ºC and potentially 1400ºC (Feist, et al. 2014a, Pilgrim, et al. 2013, Rabhiou, et al. 2011b). These phosphor materials can be applied to the surface in two ways depending on the severity of the application environment. The phosphor powder can be mixed with a liquid paint to produce a paint. This embodiment provides a low cost route of application which can be applied simply using a gravity fed air spray gun. Alternatively the powder can be used as feedstock for an atmospheric plasma spray (APS) gun to achieve an architecture similar to TBCs. This robust architecture is better suited to longer duration and higher temperature applications, such as in the hot section of gas turbines.

In both embodiments, the sensor material is spread over the surface of the measurement area to record a two-dimensional temperature profile across the surface of the component. Hence, combined with the automated, non-destructive read-out, it has important advantages over the previously mentioned thermal history sensor techniques.

The current contribution describes recent results with Thermal History Paints which cover 100-900°C for short term exposures of 30 minutes. The precision, accuracy and durability of the paints are investigated and a demonstration of the thermal profiling capability is provided. A brief description of result Thermal History Coatings is provided to highlight the capability of the technique for long term applications.

NOMENCLATURE

TBC – Thermal Barrier Coating
APS – Atmospheric Plasma Spray
YAG – Yttrium aluminium garnet
RPM – Revolutions per minute

THEORETICAL ASPECTS

The thermal history sensors described in this paper rely on the fundamental relationship between the phosphorescence and physical properties of a material. The phosphorescence is introduced by the addition of optically active ions into the host ceramic. The optical features of the dopant ions are dependent on the ion itself as well as the surrounding host. As such, they act as atomic level sensors whereby the information is transferred in the properties of the phosphorescence for example the duration of the decay or the intensity of different emission lines.

The degree of crystallinity of the host material is an irreversible property which is known to affect the phosphorescence. After a pulse of excitation light the phosphorescence decay exponentially as described by:

$$I(t) = I_0 \exp\left(-t/_\tau\right) \quad \textbf{(1)}$$

Where I_0 is the initial intensity, τ is the lifetime decay and t is time. The lifetime decay, τ, is dependent on the radiative, P_R, and non-radiative decay rate, P_{NR}, as given by:

$$\tau = \frac{1}{P_\mathrm{R} + P_\mathrm{NR}} \quad \textbf{(2)}$$

Crystal defects increase the non-radiative decay rate, hence decreases the lifetime decay. High purity crystals have a limited number of defects hence exhibit long decay times and efficient phosphorescence. The random structure in amorphous materials introduces a large number of defects which decrease the lifetime decay. As such, the lifetime decay is related to the crystallinity of the material.

The phosphor material can be deposited with a high amorphous fraction. On subsequent heating the thermal energy allows crystallization of the material. The degree of crystallization depends on the temperature of exposure and also affects the phosphorescence. Therefore, through calibration, the temperature of exposure can be determined by analyzing the phosphorescence.

EXPERIMENTAL ASPECTS

Sensor powder production

Thermal History Paints are composed of two materials, a phosphor powder and a high temperature binder. The europium doped phosphor powder was synthesized in its amorphous state using a standard sol-gel preparation route (Heyes, et al. 2012, Rabhiou, et al. 2011a). After production, the quality of the phosphor product is checked using x-ray diffraction and Fourier transform infrared spectroscopy.

Paint production

To form a smooth paint, the phosphor powder needs to be homogenously mixed with a binder. The binder must provide good adherence with the substrate so that the paint can survive at elevated operating temperatures. In addition the binder should not react with the phosphor powder to impede its sensing capability. There is a range of commercially available non-toxic silicate and silica based binders specifically designed for the preparation of paints intended to survive at high temperatures. A typical water based alkali silicate binder was found to be most compatible with the phosphors in terms of high temperature durability and surface adherence. The phosphor powder was mixed into the binder using an overhead stirrer. Two different compositions of paint will be described here named Thermal History Paint A and B.

The results from a variety of investigations on different substrates are presented in the next section. The preparation of the substrate and application of the paint is common to all substrates. A SRi Pro gravity fed spray gun was used for applying the thermal history paint to the substrates. Spraying paint requires careful preparations and some experience in order to produce a smooth and uniform surface. First, the substrate surface was roughened by grit blasting followed by cleaning with acetone. The paint is applying in a series of thin layers and allowed to air dry before curing. The paint is typically cured at 150°C for 1 hour to evaporate the water in the binder.

The calibration of the paint is typically conducted using 20mm × 20mm stainless steel substrates. After application and curing of the paint on one side of the substrates, the samples are heat treated in a tube furnace for 30 minutes. The samples are placed on a sample holder which is connected to a thermocouple. The temperature of the furnace is confirmed using a calibrated thermocouple which is at the same location as the sample during heating. Once the specified time has elapsed the samples are quenched to room temperature in air. The samples are then measured using the measurement equipment described in the following sub-section.

Measurement equipment

The measurement equipment excites the phosphorescence, records the subsequent emission and analyses the result providing a lifetime decay value or temperature if the required calibration data is stored. The equipment is contained in a portable box with a fibre guided probe, as shown in Figure 1.

Figure 1. An operator using the measurement equipment is contained within a box with a fibre guided probe and a touchscreen for control.

A pulsed diode pumped solid state laser, operating at a wavelength of 532nm, is directed into one end of an optical fibre. The other end of the fibre is directed at the coating. The laser light excites the phosphorescence and the emission is collected by the optical fibre which directs it to an optical detector via a band pass filter. The light is converted to an electrical signal which is then digitized by an acquisition card.

The decay data is fit to Eq. (1) using a Levenberg-Marquardt algorithm. Figure 2 shows a typical decay signal indicating when the laser is operating and the vertical dotted line shows when it is switched off. The phosphorescence decays exponentially and the result of the fit gives the lifetime decay value. The duration of this decay changes with heat treatment temperature. The data plotted in Figure 2 is from a single laser pulse and indicates the signal-to-noise ratio of the measurement.

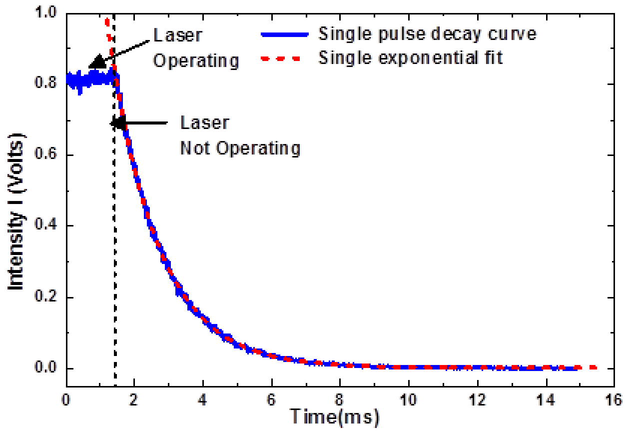

Figure 2. A typical phosphorescence decay signal with an exponential fit.

RESULTS AND DISCUSSION

A photograph of calibration samples of Thermal History Paint A after heat treatment is shown in Figure 3. The paint remained adherent on all samples up to 900°C. Furthermore, the appearance of the paint changes with temperature. They became increasing white at approximately 600°C then turning a dark green/grey at higher temperatures. This feature could be used to visually identify hot spots to focus the temperature profiling using the measurement equipment on critical areas.

The phosphorescence from the samples was analyzed using the measurement system described in the previous section. The results are collated to generate a calibration curve, as shown in Figure 5 for Thermal History Paint A. This relates the measured lifetime decay to the heat treatment temperature and is the basis of the technique. The calibration data is used to convert the lifetime decay recorded on a component into the exposure temperature at the measurement location, typically using linear interpolation.

Figure 4 shows that the lifetime decay monotonically increases with heat treatment temperature from 240°C to 910°C. Over this range there is over a two-fold increase in the lifetime decay. The plot also shows the standard deviation on 30 repeat measurements as an error bar on each marker. At all temperatures the standard deviation is less than 0.5% of the lifetime decay. Therefore, the variation on the measurement of lifetime decay is very low compared to the dynamic range of the decay values over the temperature range.

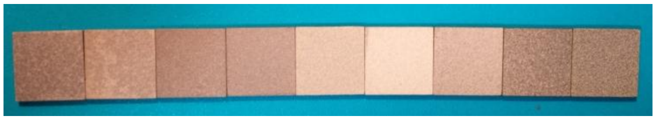

Figure 3. A photograph of samples of Thermal History Paint A after heat treatment for 30 minutes at 150°C (left) to 900°C (right)

The calibration curve for Thermal History Paint B is shown in Figure 5. Comparing this calibration curve to that shown in Figure 4, shows that the change in the lifetime decay with heat treatment temperature is dependent on the paint type. This behaviour can be used to optimize the paint selection for a particular application. The steeper the gradient of the calibration curve, the greater the precision of the measurement because for a given uncertainty in the lifetime decay there is less uncertainty in the temperature. The plot for paint B shows a steeper gradient at lower temperatures, up to approximately 500°C, as the lifetime decay increases by over 60% compared to approximately 50% for paint A. However, above 500°C the calibration curve flattens out, reaching a maximum at 800°C where the normalized lifetime decay is 1.75. Therefore, paint B is better suited to temperature measurements below 500°C compared to paint A but the overall change in lifetime decay and temperature range is lower.

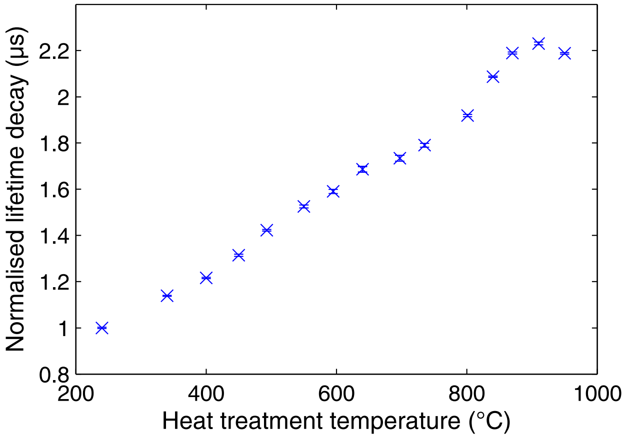

Figure 4. The calibration data for thermal history paint A for 30 minutes exposure time. The error bars show the standard deviation on 30 repeat measurements.

The plot in Figure 5 includes measurements by three different operators, shown as different shaped and coloured markers. The different operators were free to choose the measurement location on the sample. The results show there was no difference observed for different operators as the repeat measurements are within the error bars of an individual measurement.

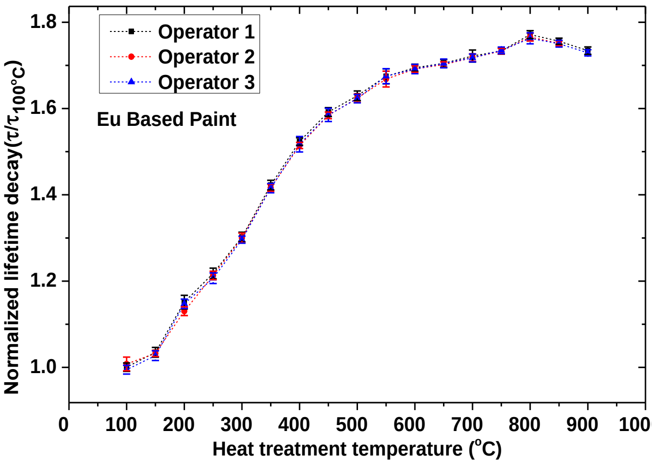

Figure 5. The calibration data for the thermal history paint B for 30 minutes exposure time. The error bars show the standard deviation on 30 repeat measurements and the different markers represent measurements by different operators.

Precision

In order to assess the precision of the technique the variation on the measurement is recorded across a sample. Since each sample was heated to the same temperature for the same duration it should provide the same temperature value across the surface. Variation in the value gives an indication of the precision of the measurement.

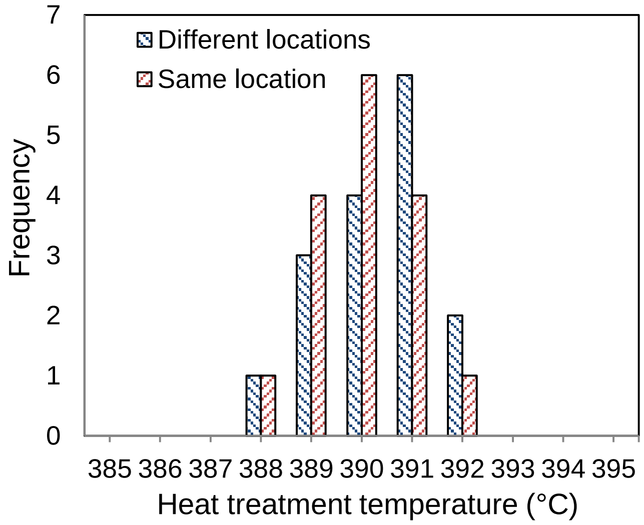

Figure 6. Histogram of the variation in 16 temperature measurements at a single location and different locations measured on a sample heat treated to 390°C for 30 minutes.

The precision analysis was conducted on three samples. A single location on the sample was measured 16 times. Then 16 repeat measurements were conducted at 16 different locations. The results for one sample, provided in Figure 6, show that the variation at a single location or different locations is similar indicating high uniformity in the sample.

The results for all three samples are collated in Table 1. The standard deviation of 16 measurements at a single location is below 1°C. The results show that the variability due to the measurement equipment is not the limiting factor on the precision because in all cases the standard deviation at different locations is slightly higher than at a single location. The standard deviation of temperature due to non-uniformity in the paint is below 1.8°C. This is comparable to the commercial thermocouples used for the calibration for which the standard deviation is approximately 1.6°C.

Table 1. A comparison of the standard deviation on 16 repeat measurements at either the same or different locations on 3 different samples heat treated at the denoted temperatures for 30 minutes.

Heat treatment temperature (°C)	Standard deviation (°C)	
	Single location	Different locations
390	0.90	1.20
400	0.87	1.77
840	0.57	1.55

Accuracy

Thermal History Paint A was applied to two different sets of substrates composed of different steel compositions, referred to as steel A and B. This was done at a later date than the application on the stainless steel calibration samples. The samples were heat treated in the same way as described for the stainless steel calibration samples between 300°C and 810°C. After heat treatment, the measurement equipment was used to record the lifetime decay from the samples. The lifetime decay was converted to temperature using the calibration curve shown in Figure 4. The difference between the recorded temperature and the heat treatment temperature of the new steel substrate samples was calculated. The result is plotted against the heat treatment temperature in Figure 7.

For both sets of steel samples the temperature difference is less than ±10°C over the full temperature range. The result demonstrates the repeatability of the technique. The combination of different application and heat treatment times and different substrates results in an error of within ±10°C. This provides an indication of the accuracy of the technique.

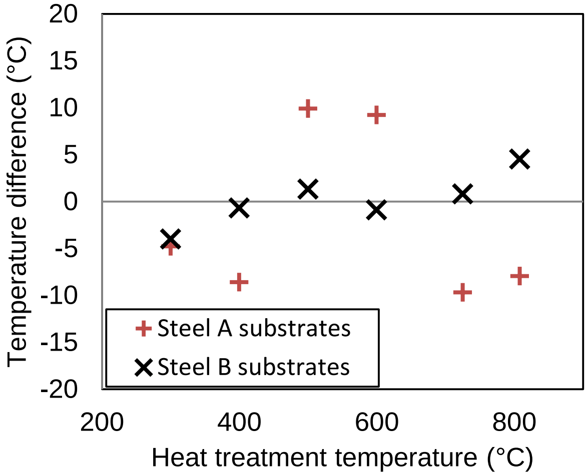

Figure 7. The temperature difference recorded on paint samples applied on different composition steel substrates to the calibration samples.

Durability of paint coatings

To assess the durability of the Thermal History Paint, samples were tested in a burner rig against reference samples of commercially available Thermal Paint. A more detailed description of the rig is given elsewhere (Feist, et al. 2014b).

Thermal History Paint and the commercial Thermal Paint was applied to different Nimonic 90 alloy button samples. The button samples were tested in the gradient test rig for 2.5 hours with cycling periods of 7 minutes; 5 minutes heating to 900°C and 2 minutes cooling reaching room temperature. Figure 8 shows three typical cycles recorded with the surface temperature recorded by a pyrometer and the substrate temperature recorded using an embedded thermocouple. A thermal gradient was generated by heating the front and actively cooling the back of the substrate. Such a test is considered to be representative of operating conditions in harsh environments in gas turbines or in similar applications with cooled components.

The photographs in Figure 9 show the paint samples before and after testing. The Thermal History Paint remained adherent to the surface with a dark mottled appearance after testing. No flaking or loss was observed. Despite the dark appearance it was possible to measure the lifetime decay on the coating surface. Conversely, the commercial Thermal Paint became brittle with delaminations and cracks observed at the edge of the sample. Furthermore, the colour of the paint was compared to the calibration colour chart and no match was found, therefore, it could not be used to determine the exposure temperature.

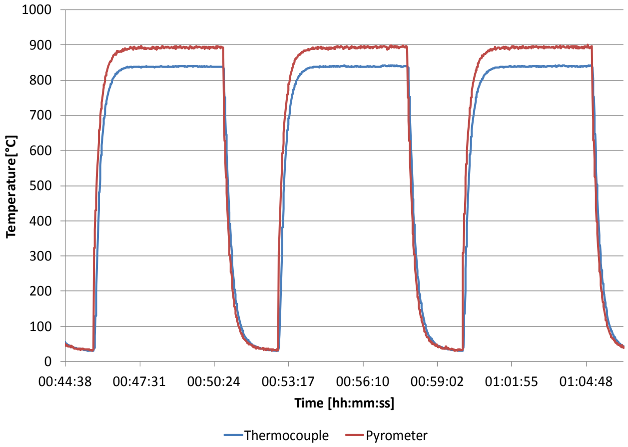

Figure 8. Temperature trace of 3 cycles on the thermal gradient testing rig. The blue line is the thermocouple data and the red line is the pyrometer data.

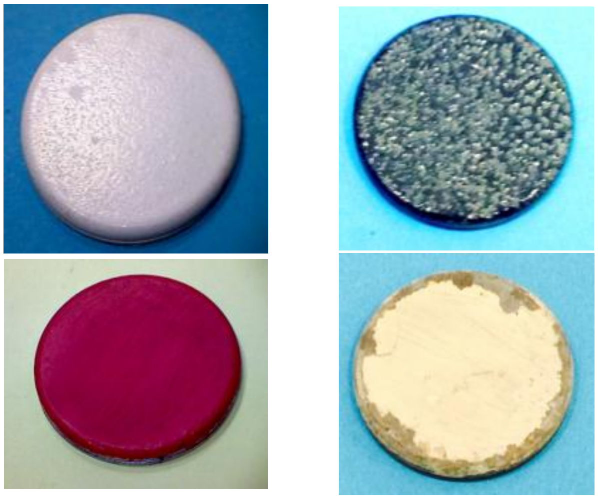

Figure 9. Photographs of the Thermal History Paint before testing (top left) and after testing (top right) alongside the Thermal Paint before testing (bottom left) and after (bottom right).

As a further test of the paint durability, samples were heat treated under isothermal conditions. Thermal History Paint was applied on Inconel substrates which are often used in high temperature applications due to its oxidation and creep resistance. The samples were exposed at 800°C, 900°C and 990°C for 30 minutes in a tube furnace. A photograph, in Figure 10, shows that the paint was adherent on all the samples after heating and the decay time could be measured on all samples. This result gives further evidence of the durability of the paint at high temperatures.

Figure 10. Samples of paint applied to Inconel substrates then heated at 800°C (left), 900°C (middle) and 990°C (right) for 30 minutes.

Demonstration

Thermal History Paint A was applied to the surface of a 200mm diameter stainless steel disc to provide a demonstration of how the Thermal History Paint can be used to record two-dimensional temperature profiles. The disc was heated in the centre using a propane-oxygen flame to reach a stable temperature for 30 minutes. As shown in Figure 11, five thermocouples were placed into 1mm deep indentations in the disc. The first indentation was in the centre of the disc and the rest were spaced 20mm apart towards the edge of the disc.

Figure 11. A photograph of the painted disc during heating showing the five thermocouples on the surface and the red hot centre of the disc.

After heating, measurements were taken from the paint along two parallel lines either side of the diametric line on which the thermocouples were placed. The recorded lifetime decay was converted into temperature using the calibration curve presented in Figure 4. The data are plotted in Figure 12 along with the thermocouple readings.

There is very good agreement between the temperature measurements recorded with the Thermal History Paint along the two parallel adjacent lines. The temperature profile across these lines are expected to be very similar due to their proximity. The consistency in the results provides further evidence of the repeatability of the measurement system.

There are two notable differences between the results recorded using the thermocouples and that recorded with the paint. Firstly, the central thermocouple shows a lower temperature than the thermocouple at 80mm. This does not correlate to the expected temperature profile and the observed colour of the plate during heating, as shown in Figure 11. Secondly, there is a consistent offset between the outer four thermocouple readings and the temperature recorded with the paint. The lower temperature provided by the thermocouple is thought to be caused by poor thermal contact of the thermocouple with the disc surface. During testing it was observed that while the disc was glowing red hot the thermocouples did not. Furthermore, the maximum temperature recorded by the thermocouples is 660°C was is not consistent with the glowing colour of the disc during heating.

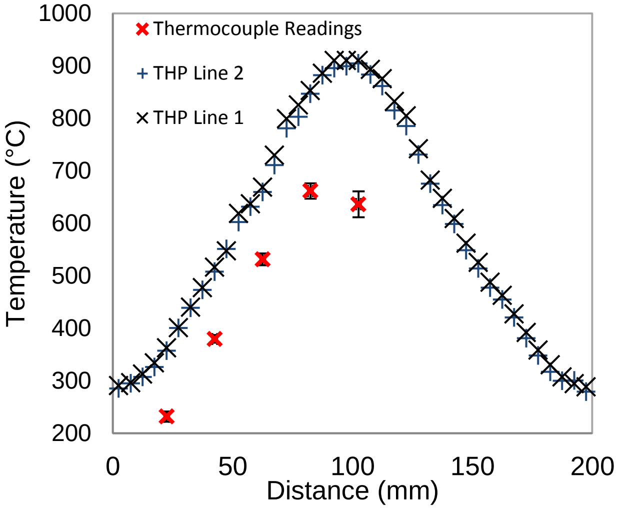

Figure 12. The results taken from the thermocouples and Thermal History Paint (THP) along two parallel diametric lines. The thermocouple data is averaged over the 30 minute heating period and the error bar indicate the standard deviation.

To generate a two-dimensional temperature profile the disc was measured at 360 locations which took approximately 1.5 hours. The probe of the measurement equipment was aligned at the edge of the disc, a measurement was recorded then the probe was translated 20mm along a diametric line. The disc was then rotated 10° and the process was repeated. The results are shown as a contour plot in Figure 13.

The plot shows the hot spot in the centre of the disc with concentric rings indicating the temperature drop to the outer edge. The heat was expected to dissipate evenly over the disc resulting in circular contours. However, the contours are not circles but exhibit wavy profiles. This is due to slight misalignments which occurred between rotations of the disc during the measurement procedure. The thermal gradient along the radii of the disc was calculated to be 7.3°C/mm, therefore, slight misalignments of several millimetres cause a significant change in the measured temperature. As a result, in some locations the recorded temperature is higher or lower than expected causing deviations from the expected circular contours. The effect can be observed along the 20° diametric line. Above the centre, the contours along this line show a slightly lower value while below the centre they show a slightly higher value. This indicates that the measurement location was closer to the top edge than thought.

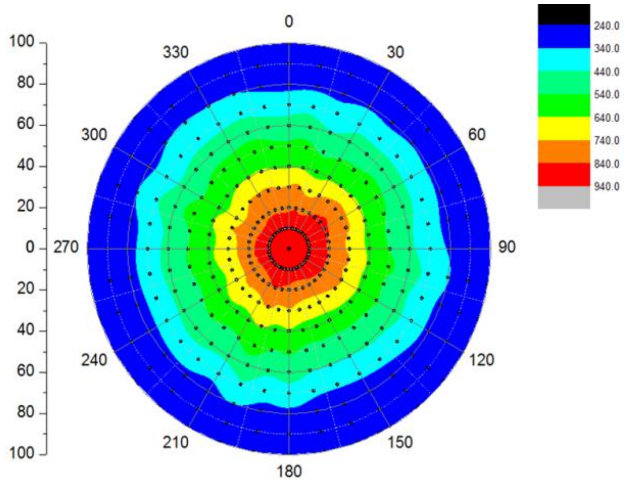

Figure 13. A contour plot of the temperature measurements recorded on the disc. The black dots represent measurement locations.

Thermal History Coatings

When the phosphor powder is applied by APS the coatings are very robust and durable so can be used for long term exposures. They can be applied as a sole layer or embedded within a TBC. This sub-section provides an example of each to give a brief demonstration of the capability of the coatings.

A yttrium aluminium garnet (YAG) based Thermal History Coating was applied to a turbine blade of a Rolls-Royce Viper engine owned by Sensor Coating Systems and operated at Cranfield University. This was done using production line facilities as part of a larger programme which is described in detail elsewhere (Feist, et al. 2013, Feist, et al. 2012). The coated turbine blade was installed and the engine was operated over the full working range from 5,000 to 13,500 RPM. The cumulative operating time was approximately 70 hours. A photograph of the suction face of the blade after testing is shown in Figure 14. There is some slight damage to the leading edge of the blade however the entire coated surface remains intact.

The blade was scanned along the four lines shown in the figure to record the lifetime decay, measurements were taken every 5mm. The results are plotted as a contour plot in Figure 15. No samples were available to perform the calibration therefore the results are presented as lifetime decay rather than temperature. The low decay times at either end of the blade indicate that the coating was cooler in these regions. This is because the turbine blade is cooled at the ends during operation by a flow of air from the compressor. The tip of the blade has a higher decay time compared to the root because the flow of cooling air was less at the tip.

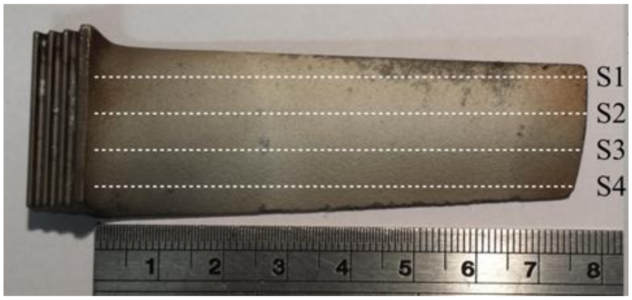

Figure 14. The suction face of the coated turbine blade after testing with the four scan lines shown.

This result shows that the Thermal History Coatings can be used on rotating components in operating gas turbines. The coating can be used to gather information about the operating temperature of the component.

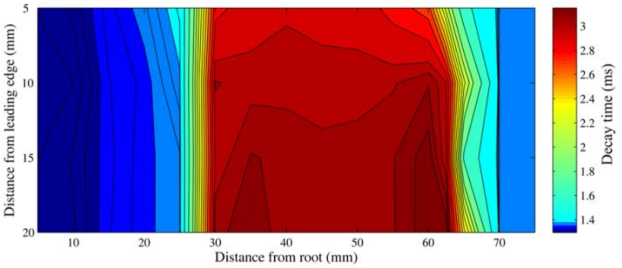

Figure 15. The contour plot showing the result of the lifetime decay measurements on the suction face of the turbine blade.

A similar YAG based Thermal History Coating material has been embedded into TBC by mixing it with 90 wt.% YSZ (Feist, et al. 2006). Composite coatings have been produced which comprised a base layer of YSZ and a top layer of the YSZ/YAG:Dy mixture. These coatings have shown the same or increased durability compared to reference YSZ samples during thermal cycling testing (Feist and Nicholls 2008, Feist, et al. 2014b). Furthermore, this coating construction was applied to a combustor tile which was subsequently operated in Didcot powder station in the UK for 4,500 effective operating hours. Reference YSZ coatings were applied to adjacently installed tiles. The composite coating exhibited less degradation compared to the reference coatings. In addition, the decay time was recorded across the surface of the coating. The profile, shown in the right of Figure 16, indicates that the thermal history effect can be observed after operation. The higher decay times, depicted in red are thought to indicate higher temperatures. This observation corroborates with micrograph analysis of the thermally growth oxide layer beneath the ceramic coating which suggested a higher operating temperature by ~15°C at the top of the tile compared to the bottom. The profile also matches the expected cooling air flow over the tile.

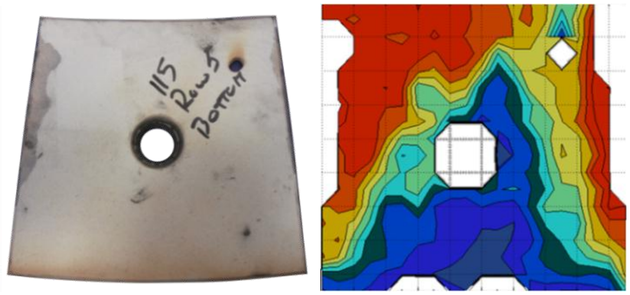

Figure 16. (Left) A photograph of the combustor tile with the composite coating after operation for 4,500 hours. (Right) The profile of the luminescence decay time where red represents higher values and blue lower values.

The coating can survive for thousands of hours in an industrial engine and indicates the thermal profile of the component. This demonstrates the capability of the Thermal History Coating for long term applications, possibly to monitor the operating temperature of components throughout life at maintenance schedules.

CONCLUSIONS

The capability of Thermal History Paint and Coatings has been outlined. Results on the paint have shown that different compositions can be used to cover the temperature range from 100-900°C for short term exposure of 30 minutes. The paint remains adherent under isothermal and cyclic testing at or above 900°C and shows greater durability than commercial Thermal Paint.

The precision of the measurement was indicated to be ±3°C which was the same as the commercial thermocouples used for the heat treatment procedure. Repeat tests have shown that results can be achieved within ±10°C using different substrate compositions.

A laboratory based demonstration was used to demonstrate the two-dimensional thermal profiling capability. The measurements were highly repeatable and a detailed temperature profile was achieved with 360 measurement locations recorded in 1.5 hours. The test also highlighted the difficulty of recording reliable results with thermocouples.

An outline of results gained from engine tests with Thermal History Coatings has demonstrated the durability of the coatings and their capability for long term applications. When embedded in a TBC, the coating remained intact after 4,500 effective operating hours in a power station gas turbine.

ACKNOWLEDGEMENTS

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