



ASME Accepted Manuscript Repository

Institutional Repository Cover Sheet

Cranfield Collection of E-Research - CERES

ASME Paper

Title: Thermal history coatings: influence of atmospheric plasma spray parameters on performance

Authors:

Silvia Araguás Rodríguez, Marta Ferran-Marques, Christopher Pilgrim, Spyros Kamnis, Jörg P Feist, J R Nicholls

ASME Journal

Title: Journal of Engineering for Gas Turbines and Power

Volume/Issue: _____

Date of Publication (VOR* Online): 13 September 2024

ASME Digital Collection <https://asmedigitalcollection.asme.org/gasturbinespower/article/doi/10.1115/1.4066533/1206316/Thermal-History-Coatings-Influence-of-Atmospheric>

URL:

DOI: <https://doi.org/10.1115/1.4066533>

*VOR (version of record)

Thermal History Coatings: influence of atmospheric plasma spray parameters on performance

Silvia Araguás-Rodríguez

Sensor Coating Systems

londoneast-uk, Yewtree Avenue, London, RM10 7FN, United Kingdom

s.araguas@sensorcoatings.com

Marta Ferran-Marqués

Sensor Coating Systems & Cranfield University

londoneast-uk, Yewtree Avenue, London, RM10 7FN, United Kingdom

m.ferran@sensorcoatings.com

Christopher C. Pilgrim

Sensor Coating Systems

londoneast-uk, Yewtree Avenue, London, RM10 7FN, United Kingdom

c.pilgrim@sensorcoatings.com

Spyros Kamnis

Monitor Coatings Ltd

2 Elm Rd, North Shields NE29 8SE, United Kingdom

spyros@monitorcoatings.com

Jörg P. Feist

Sensor Coating Systems

londoneast-uk, Yewtree Avenue, London, RM10 7FN, United Kingdom

j.feist@sensorcoatings.com

John R. Nicholls

Cranfield University

College Rd, Cranfield, Bedford MK43 0AL, United Kingdom

J.R.Nicholls@cranfield.ac.uk

ABSTRACT

Thermal History Coatings (THCs) provide a novel method for measuring temperature profiles in the 900-1600°C range. Given the steadily increasing firing temperatures in turbomachinery, it is crucial to understand temperature distribution across the majority of a component surface (>80%) to verify the design and component durability. This new temperature profiling capability records the past maximum exposure temperature in such a way that it can be determined once the component has already cooled down.

THCs are comprised of oxide ceramics deposited via Atmospheric Plasma Spraying (APS) to create a robust coating. APS deposition employs several variable parameters; spray settings such as gun power, gas flow or scan rate can affect the particle exposure and thus, the microstructure of the coating and its temperature sensing performance.

This work shows, for the first time, the influence of APS parameters on luminescent measurements due to changes in the material microstructure. This enabled optimization of the Thermal History Coatings sensing performance. Extensive calibration data was used to develop a new model to relate the APS spray parameters to the luminescent properties in the as-deposited condition and consequent performance as a temperature sensor. The powder composition and the power and gas flow used during deposition were found to be the most influential parameters. The model identified the optimum spray parameters and was used to demonstrate THCs can achieve measurements in excess of 1600 °C.

INTRODUCTION

Operating temperatures in gas turbines have seen a steady increase over the years to allow for higher engine efficiencies and a decrease in hazardous emission levels. However, these harsh conditions severely challenge the component lifetime, requiring a trade-off during the design process. Thus, it is crucial to understand temperature distribution across the majority of a component surface (>80%) to verify the design and component durability. Accurate knowledge of temperatures allows the design engineer to evaluate new component prototypes, validate thermal models and complex cooling designs. While a range of temperature measurement techniques are available, these are primarily focused on lower temperatures, exhibit low durability (thermal paints [1], [2]), require line of sight during measurement acquisition (including pyrometers [3] and phosphor thermometry [4], [5], [6,7]) are destructive (thermal crystals [8]) and only provide point measurements (thermocouples, thermal crystals [1]). More information on the wide range of temperature techniques available can be found in the references provided.

A new temperature measurement technique, Thermal History Coatings, (THCs) [9] has been developed. These luminescent materials

undergo permanent structural changes when thermally exposed, enabling accurate and continuous temperature measurements. The continuous change to the material structure with temperature means that temperature measurements can be recorded at any location on the coated component to generate, through calibration, high-resolution thermal profiles. This project explored the use of $\text{Y}_2\text{SiO}_5:\text{Eu}^{3+}$ (hereon YSO:Eu) as a temperature sensor in a THC at ultra-high temperatures. These coatings are sprayed through Atmospheric Plasma Spraying (APS), a robust technique already employed by the gas turbine sector for other protective coatings, often essential in hot section segments of gas turbine engines. These provide high-performance oxide layers on metals and alloys to increase operational lifetime and performance and lower maintenance expenses.

Yttrium silicate ceramics

Yttrium silicate was selected for study as a thermal history coating (THC) given its high temperature performance. The high melting points of Y-Si-O ceramics (above 1775 °C) enable their use in high-temperature or multifunctional coatings. Their extremely low thermal conductivity ($1.34 \text{ W m}^{-1} \text{ K}^{-1}$) [10], coupled with their excellent resistance to hot corrosion have highlighted Y-Si-O ceramics as functional coatings including thermal barrier coatings [11,12], environmental barrier coatings (EBCs) [11,13–15] and

oxidation resistant coatings [16]. Yttrium disilicate has been identified as a communication window material to be used for re-entry space shuttles [17]. Y_2SiO_5 , particularly the X2 phase, is a popular host for rare earth ions given its wide band gap of 7.4 eV [18], which can accommodate large quantities of substitutional ions. This host has been successfully used with a wide array of dopants for varying applications including cathodoluminescent, photoluminescent or scintillating phosphors given its high thermal and chemical stability. $\text{Y}_2\text{SiO}_5:\text{Ce}^{3+}$ is a strong blue-emitting phosphor used in solid-state lighting and solid-state lasers [19], while $\text{Y}_2\text{SiO}_5:\text{Tb}^{3+}$ is an excellent green emitter with high efficiency under electron beam and UV excitation [20]. $\text{Y}_2\text{SiO}_5:\text{Eu}^{3+}$ is a red emitting phosphor used for red light emission for display devices [21].

A number of phases exist within the Y-Si-O oxide system, shown in Figure 1 [22]. This project employs Y_2SiO_5 , or YSO. YSO is able to crystallize into both X1- and X2-YSO phases, depending on the temperature it is exposed to [23]. The X2 phase can be obtained by heating the X1 phase at high temperatures. The X1 and X2 phases have space groups P21/c and C2/c respectively. The transition temperature between the two polymorphs is seen to vary wildly between authors, ranging from 850°C to 1200°C [24,25]. It appears to vary significantly depending on the impurity level, thermal history

and preparation method. Both phases have two non-equivalent yttrium sites that show different coordination numbers to oxygen and silicon atoms.

Deposition of ceramic coatings

Ceramic coatings can be deposited via thermal spray, atmospheric plasma spray (APS), sputtering, dry-film lubrication and other chemical and electrochemical coating processes. Depending on the application and the coating deposition process, the thickness of ceramic coatings ranges from 50 nm to several millimetres.

APS is one of the most versatile thermal spray processes because there are very few constraints on the materials that can be sprayed or the material, shape and size of the target substrate. APS is extensively used to deposit thick coatings (from tens of micrometres to some millimetres) due to its high deposition rate.

The material precursor of the coating can be in the form of wires, powder, melt materials, suspensions or solutions. The precursor is then heated up above its melting point. The resulting melted particles are accelerated in a plasma jet towards the substrate (Figure 2 (a)). Due to their high velocity, particles impact the substrate, flatten and solidify very quickly, forming anisotropic lamellae with microdefects such as pores, microcracks and unmelted particles (Figure 2 (b)). Some of these defects are connected

and some are isolated. Because of the existence of these microdefects, the microstructure of a plasma sprayed coating is unique.

The microstructure and mechanical properties of APS coatings are influenced by the spray parameters e.g. stand-off distance, argon and hydrogen gas flow, gun power, powder feed rate and precursor state (i.e. solid or liquid) used for coating. These parameters affect the kinetic and thermal energy of the particles. On one hand, if there is too much thermal energy, particles can volatilize in the plasma jet and reach the substrate in a totally molten state. On the other hand, if there is not enough thermal energy, particles will get to the substrate in an unmelted state. Therefore, features of the coatings like atomic structure, porosity, adhesion and roughness are linked to the interaction between the plasma jet and the precursor.

To get operational control of the plasma torch, it is needed to understand the operating range of the input parameters to stabilize the electric arc. Therefore, it is important to be familiar with the current-voltage characteristics (voltage versus current for different flow rates) of the electric arc, which is normally affected by the curve of the power source. Nitrogen, argon, helium and hydrogen are the common gases used in the plasma torch [26]. Gas flow and its chemical composition influence the stability and the kinetic and thermal energies of the plasma jet. The arc voltage, however,

relies on the gas flow rate, plasma torch geometry and mode of arc stabilization. When increasing the arc voltage, the electric power is also increased and therefore, the energy of the plasma is higher [27]. Due to a more energetic plasma, the kinetic and thermal energies of the molten particles increase and therefore, the temperature and velocity of the particles is also increased.

During deposition of the coating, when the molten particles are moving away from the plasma torch, two opposite effects occur in the thermal energy transfer of the particles. On one hand, the hottest point of the plasma is in the exit of the torch gases. So, at longer distances, the plasma becomes cooler. On the other hand, at longer distances, the residence time of the particles inside the plasma is higher, and therefore there is a bigger energy transfer between the plasma and the particles [28]. Due to these two factors, there is a distance at which the temperature of the particles will be at its maximum.

At higher gas flow rates, the kinetic energy transferred to the particles increases and therefore, their velocity is higher [29]. When there are several gases in the plasma (i.e. Ar and H₂), the higher the concentration of the secondary gas, the higher the energy and the thermal conductivity transferred to the particles [30]. The smaller the particles, the higher the

energy transferred between the particles and the plasma, and therefore the faster the velocity [31]. Wang *et al.* [32] stated that the spray parameters affect the velocity and temperature of the melted particles, which in turn affect the coating hardness and porosity. The spraying distance is closely related to the velocity of molten powders when these impact the target substrate. Djendel *et al.* [33] found that the lower the spraying power, the larger the size of the pores and that the bigger the spraying distance, the larger the pores. Zhang *et al.* [34] found that by decreasing the hydrogen gas flow rate, the porosity of the coating increased.

Several studies have reported the influences of spraying parameters on microdefects and therefore, on the mechanical properties and morphology of the coatings. However, there is very little or no information available in the literature related to understanding the APS parameters affecting silicate ceramic coatings luminescent properties. Hence, this article demonstrates the influence of APS parameters on luminescent measurements due to changes in the material microstructure and properties. Extensive calibration data showing the evolution of the luminescent performance over temperature when varying APS settings was studied in order to present, for the first time, the optimal spray settings needed to deposit a THC capable of temperature measurements up to 1600°C. The

optimized coatings are demonstrated in industrial applications with temperatures exceeding 1500 °C in a separate work [35].

THEORY

THCs are composed of a rare-earth doped silicate-based oxide ceramic (YSO:Eu). When irradiated with light, the rare-earth ions are excited, resulting in the promotion of electrons to a high energy state from the ground state. Following the excitation, the electrons relax back to the ground state through two competitive processes: radiative and non-radiative relaxation. Radiative relaxation causes photon emission, while non-radiative relaxation results in phonon emission. The lifetime of the emission is governed by the probability of these two processes occurring (Eq. 1):

$$\tau = \frac{1}{P_R + P_{NR}} \quad (1)$$

Where τ is the lifetime decay (LTD), P_R is the probability of the radiative relaxation and P_{NR} is the probability of non-radiative relaxation. Through deposition via APS, the THC structure is amorphous in the as-deposited condition. Amorphous structures have an irregular arrangement of atoms and matrix defects, increasing the non-radiative probability. By increasing the heat treatment temperature, and thus the crystallinity of the material, the concentration of luminescence quenchers and therefore the PNR decreases,

hence the τ increases. As crystallization is a gradual process, so is the change in the luminescent properties.

These phenomena are used for temperature detection, where the emission decay of the phosphor after irradiation with a short laser pulse is fitted by a single exponential equation (Eq. 2):

$$I(t) = I_0 e^{-t/\tau} \quad (2)$$

Where I_0 is the initial intensity, τ is the LTD and t the time. An example of an experimental decay curve is shown in Figure 3. The dashed line represents the single exponential fit and the signal is a single decay time.

MATERIALS AND METHODS

Owing to the reported SiO_2 volatilization that occurs through the APS deposition process [36], three different yttrium silicate compositions were used to find the optimal composition. These were selected to represent increasing quantities of silicon oxide (SiO_2), with the ratio of SiO_2 ranging between 50% and 80%. The three powders, referred to as 1, 2, 3 show increasing levels of SiO_2 , so that $1 < 2 < 3$. All three powders were manufactured through the co-precipitation method with a maximum synthesis temperature of 1000 °C by an external supplier.

These spray powders were applied on test coupons to understand the effect of critical APS spray parameters on the temperature sensing performance. In order to assess the potential influence of deposition substrate, the coatings were deposited on two different coating architectures. These were selected to represent typical industrial configurations on ceramic-coated and metallic substrates respectively. The metallic configuration was comprised of a nickel-based metallic substrate, with a 50 μm CoNiCrAlY bond coat deposited via APS. The majority of the trials, however, were performed on the ceramic structure given the very high temperatures ($>1600^\circ\text{C}$) intended for the samples which would result in degradation and melting of the metallic substrates. Instead, the coatings were deposited on sacrificial substrates to be removed before the high-temperature exposure. The architecture consisted of a sacrificial substrate (structural steel), a topcoat (8 wt.% Yttria Stabilised Zirconia, 8YSZ) of 500 μm , mimicking a standard TBC often used in such applications, and lastly a THC (YSO:Eu) layer of 30 μm . The THC was applied with different spray parameters to further study the influence of these on the luminescence properties.

The coatings were applied using the 3MB plasma torch by Oerlikon Metco in a dedicated NADCAP certified aerospace booth at Monitor Coatings Ltd in the UK. The torch delivers up to 50KW of power and plasma

temperatures up to 16,000 °C. With plasma gas velocities up to 3,000m/s and particle acceleration up to 600m/s, the torch can produce coatings with tailored properties to the end user specifications. The torch was mounted on a robotic arm and the samples were sprayed using a raster scan program. The torch traverse speed was precisely controlled while several spray passes were required to achieve the desired coating thickness. The torch power level was controlled by altering the inlet gas flow rates and the input current (A). The spray thickness of the THC layer was kept constant for all runs at 30 μm by altering the number of passes required per run. For most runs, 2-4 passes were required. The powder deposition efficiency depended on the parameters used, achieving 10-15 μm per pass. Overall, the coating thickness achieved for all was 30 $\mu\text{m} \pm 10 \mu\text{m}$.

The coatings were sprayed in a total of 12 runs, or combinations of spray parameters. The parameters selected for investigation were the powder composition, gun power, stand-off distance, gas flow and scan rate. The gas flow corresponds to the total plasma gas (H and Ar gases). The experimental table was devised through Design of Experiments to reduce the overall samples required, as is shown in Table 1. The design used was a main effects screening design [37]. The numerical values of the spray parameters have been normalized to their maximum for confidentiality reasons. Analysis

of the as-deposited powders and sprayed coatings were carried out through x-ray diffraction (PANalytical X'Pert diffractometer MRD with Cu α 1,2-radiation and step size of 0.042 $^{\circ}$ 2 θ). The generator settings were 10 mA and 30 kV.

An Elite BRF 17 high-temperature box furnace was used to carry out the heat treatment of samples and subsequent calibration. The box furnace enabled rapid feeding and removal of the samples through the installation of an alumina tube and can reach temperatures up to 1700 $^{\circ}$ C. The temperature distribution along the length of the alumina tube was characterized with the use of an S-type thermocouple and the samples were placed in the isothermal region. To remove the sacrificial substrate and avoid it melting, the samples were heat treated at 800 $^{\circ}$ C for 20 min and quenched to room temperature. By design, due to their differing thermal expansion coefficients, the coating became detached from the sacrificial substrate. The luminescent coatings were not damaged during this process. The YSO:Eu/8YSZ resulting samples were further heat treated for 30 min from 900 $^{\circ}$ C to 1600 $^{\circ}$ C and quenched to room temperature.

Two different luminescent-based measurement were acquired: LTD and emission spectra. The temporal component of the luminescence (lifetime decay, LTD) was measured using SCS's custom built instrumentation. The excitation light source was a pulsed diode pump solid state with a wavelength

of 532 nm and an output of 400 mW. The laser is coupled to an optical fibre that directs the laser beam onto the sample. The emission light is collected by optical fibres, filtered and coupled onto a photodetector. The signal is digitised with data acquisition card and read by a computer. Other descriptions of the setup can be found at [38–40].

To capture the emission spectra, a pulsed Nd:YAG laser (Brilliant B, Quantel) with an excitation wavelength of 532 nm was used. The laser operated at 10 Hz in Q-switched mode with a pulse duration of 8 ns. After excitation with the laser beam, the emission light is collected by an optical fibre probe and focused on the entrance slit of a commercial spectrometer (Avantes AvaSpec). A linear charge-coupled device array was placed to record the relation between light and wavelength and convert the signal to the computer.

High resolution images of the cross-section of the coatings were obtained by using and Field Emission Scanning Electron Microscopy (FE-SEM), (LYRA 3 TESCAN).

RESULTS

Spray powders

The particle size of all powders was studied using FE-SEM pictures and ImageJ Software (sample for Powder 2 shown in Figure 4). When spraying powder, the particle size distribution plays an important role in flowability (i.e. very small particles would not be flowable enough to be sprayed). The same distribution was found for the three powders: D90 of 35 μm , D60 of 22 μm and D10 of 11 μm . All powders were found suitable for APS deposition.

Further, X-ray diffraction patterns for all three powders were taken. The plot revealed clear differences between the powders, exemplified by the detailed section shown in Figure 5. While all powders presented some crystalline reflections, powder 1 showed the highest amorphous character. While all the crystalline reflections for powder 1 matched the $\text{X1-Y}_2\text{SiO}_5$ phase (PDF reference 00-041-0004) [41], powders 2 and 3 also showed peaks corresponding to the higher Si-content yttrium disilicate $\text{Y}_2\text{Si}_2\text{O}_7$ phase (PDF reference 00-048-1623). These observations match well with the intended compositions of the three powders.

As-deposited coatings

The three powders were sprayed through APS by depositing a 30 μm THC coating on top of a sacrificial substrate and a TBC topcoat. During APS, the powders are heated up above their melting temperature and the droplets are then accelerated towards the substrate. Because the particles solidify very quickly, they form a stacking of lamellae with microdefects, such as pores, micro-cracks and un-melted particles. Some of these features can be observed in Figure 6.

The differences between the 12 as-sprayed runs were analyzed to determine the influence of the spray parameters on the as-deposited microstructure. The temporal luminescent properties (LTD) of all coatings were measured using the instrumentation as previously described. Ten repeat samples were produced and measured for each spray run. Each sample was measured on 6 locations, with 3 average repeats on each location. The average LTD of 180 measurements for each spray run on bond coat and TBC (sample architecture described early) are shown in Figure 7. The error bars correspond to the standard deviation of the mean. This was below 10 μs in all cases.

Figure 7 clearly shows a difference in the measured LTD for each run that can be attributed to the changing spray parameters. Furthermore,

luminescent properties in the as-deposited state do not appear strongly affected by the substrate. This finding is of significant benefit for practical applications, when the THC will be applied on a variety of different substrates depending on the application requirements.

The relative importance of each parameter was estimated through the construction of a linear regression model using the software JMP [42]. The quality of the model was assessed by plotting the predicted LTD against the actual measured LTD values in Figure 8. The model showed very good statistical significance with $R^2=0.98$ and $p\text{-Value}<0.0001$. Each data point has been further coloured by the residual (predicted – measured), expressed as a percent. Most points display a low residual below 1%, with the highest residual in the full data set reaching 3%.

The model enables the spray parameters, as well as their interactions, to be ranked in order of significance as shown in Figure 9. For improved graphing quality, the significance is represented by the logarithm of the p -value. The model was designed to include interactions, shown as hashed bars. These indicate that two input parameters are dependent on each other, so that the effect of one depends on the level of the other. The strongest dependency between two continuous variables, distance and gas flow, has been demonstrated graphically in Figure 10.

Figure 10 shows the mean LTD as a function of gas flow and stand-off distance. Blue colour means low LTD values and red colour indicates high LTD values. The graph demonstrates that at lower gas flows, the distance greatly affects the LTD values. However, at higher gas flow values, the distance shows no effect. As mentioned in the introduction section, gas flow affects the kinetic energy of the particles (i.e. the velocity). At high stand-off distances, the plasma forms a temperature gradient. When the gas flow is at its highest, the particles are quickly accelerated towards the substrate and therefore are not heavily impacted by the temperature gradient in the plasma. Conversely, when the gas flow is low, the particles move more slowly while in the plasma, undergoing a temperature gradient. So, these would melt at the beginning but, could start to solidify as they move through the plasma and towards the substrate, resulting in an overall more crystalline structure. Since the luminescence of a material depends on the microstructure of it, the presence of unmelted particles will affect the LTD values.

Figure 10 suggests that under the correct conditions the stand-off distance has limited influence on the coating. For industrial applications, where complex component geometries may be sprayed with such a coating, insusceptibility to stand-off distance will be an important asset to avoid inhomogeneities in coating performance for areas where distance is hard to

control. As a result, provided that other performance parameters are favorable, a high gas flow level is recommended to avoid distance effects.

Heat treated coatings

Following the characterization in the as-deposited condition, the samples were heat treated at temperatures between 900 °C and 1600 °C for 30 minutes. Given the high temperatures, only the architecture with a sacrificial substrate was used to avoid melting of the metallic substrate. The process, described in the previous section, included quenching the samples to room temperature after the heat treatment to more closely mimic the rapid cooldown in the target applications.

The heated coatings for each spray run were compared at 1300 °C by measuring optical emission spectra. A detailed view of the $^5D_0 \rightarrow ^7F_2$ transition of the Eu^{3+} ions [43] is shown in Figure 11.

The optical spectra have been analyzed by using references from the authors' past work, which are in full agreement with the work by [43,44]. In the plot, the peaks arising from the low temperature X1-YSO phase are indicated by a solid blue line. Similarly, the peaks corresponding to the X2-YSO phase are marked with a dotted red line. Lastly, the peaks reported to belong to both phases are shown in a dashed dot line in purple.

While all spray runs show some similarities, including the most intense emission centered around 612 nm, typical of europium doped yttrium silicates, some significant differences are observed. Firstly, the overall structure of some runs (particularly runs 3 and 5) display more amorphous appearance with fewer defined peaks. These also correspond to the runs with the lowest LTD, and their main peak (in dash dot purple) appears shifted to lower wavelengths. Their broad features appear largely centered near the expected X1-YSO emissions.

For the majority of the runs, however, the emission peaks correspond well to the X2-YSO phase (in dotted red line) at 615, 618, 623 and 626 nm, with no obvious emission at the X1-YSO lines. The relative measure of the extent of X2 formation was estimated by calculating the integrated intensity under the peak at 618.7 nm, normalized to the maximum intensity of the main peak at 611.7 nm. Extensive analysis of the magnitude of the X2 peak was carried out, yielding dependencies on the spray parameters. The two most prominent influencing parameters were the gas flow and the gun power. They further showed a strong interaction between them, which has been represented in Figure 12.

X2-YSO arises upon heating of the X1-YSO phase, and therefore its presence is indicative of exposure to higher temperatures. For low gas flows,

exposure to higher APS power results in a lower proportion of X2 phase. A higher gun power leads to increased temperature in the plasma and will therefore more readily melt the spray particles. As a result, the molten particles will be quenched when reaching the substrate, yielding amorphous structures that will require significant heating to form the X1- and then X2-YSO phase. Conversely, when the power levels are lower, the temperature in the plasma is not high enough to fully melt the particles, and therefore they reach the substrate in semi-crystalline state, from which the formation of the X2 phase is easier. This effect will account for the differing degrees of evolution of the X2-YSO phase.

However, at high gas flow levels a different trend is observed. For spray runs deposited with both high power and gas flow levels (runs 4, 9, 11), the proportion of the X2 phase was at its highest. While the high plasma temperature resulting from the high-power levels would be capable of more extensively melting the ceramic particles, the kinetic energy imparted by the high gas flow effectively increases the speed of the particles as they go through the plasma and thereby reducing the time spent under high-temperature exposure. This leads to a significantly reduced degree of melting, and therefore quenching.

LTD measurements were taken on all coatings heat treated between 900 °C and 1600 °C. Using this information, a calibration curve comprising LTD as a function of exposure temperature was constructed for each sprayed coating run. All calibration curves are shown in Figure 13. They have been broadly categorized according to their suitability for thermal history sensing. Most runs presented a two-region calibration curve, which shows monotonically increasing LTD until 1300°C, followed by a gradually decreasing LTD for the remaining range to 1600°C. So long as the LTD is continually changing during the temperature range, it may be employed to deduce past exposure temperatures. However, the fact that it increases and then decreases may present some ambiguity when deciphering the results as two temperature values may be assigned to a single LTD. Nevertheless, the authors have found several strategies to determine what region the measurement is in, by analyzing other characteristics of the signal like the amplitude. Further discussion of these may be provided in a future publication.

From the presented calibrations, the best runs provided a continually dynamic change over the range (runs 1, 2, 7 and 12), some runs showed a similar behaviour but lost resolution at 1500 °C, providing a narrower

temperature measurement range (9, 10, 11). Lastly, four runs proved entirely unsuitable with no discernible trend over the range (3, 5, 6, 8).

The first clear observation from the calibration data is that all the spray runs carried out with powder 1 (with the lowest SiO₂ concentration) showed erratic evolution of LTD with temperature and therefore were deemed unsuitable for the intended temperature sensing. The diffraction patterns showed poor crystalline character, correlating well with the lower LTD values observed for powder 1. While in principle this should be ideal to encourage the amorphous-to-crystalline transition, it is hypothesized that the SiO₂ content for powder 1 is too low, due to volatilization during the deposition process to form the intended yttrium monosilicate phases. This broad difference between powders 1 and 2&3 mimics that observed from the analysis of the raw spray powders.

Powders 2 and 3 showed more consistent behaviour; the coatings yielded a clear trend with increasing temperature. The diffraction data for Run 2, as an example, is shown in Figure 14 at exposure temperatures between 900 °C and 1500 °C. The coatings at low exposure temperatures of 900°C show partial crystalline character, with the observed peaks matching the main reflections of the X1-Y2SiO₅ phase (PDF reference 00-041-0004) [41]. These peaks become more numerous and stronger in intensity as the temperature

increases past 1100 °C, and at 1300 °C, a new phase is visible: X2-Y₂SiO₅ phase (PDF reference 00-036-1476). The results show a transformation of the X1-YSO phase into the X2-YSO phase at 1300 °C. By 1500°C, almost all the peaks present belong to the X2 phase. The main phase transformation occurs at the same temperatures where the LTD changes at 1300 °C.

It is important to note that while Run 2 was sprayed with powder 3 (and had therefore the highest level of Si content), none of the crystalline reflections corresponded to the high-SiO₂ disilicate phase Y₂Si₂O₇, which was identified for both powders 2 and 3 in raw spray powder state. Instead, the phases formed were the lower- SiO₂ monosilicate phase, Y₂SiO₅. This is due to, as previously described by Garcia [36] and others, the volatisation of SiO₂ species during plasma spraying. The higher SiO₂-content powders tested in this investigation were required to offset the loss during deposition.

The suitability of the obtained calibration curves was further quantitatively assessed by calculating a quality factor, or desirability. This was done through four separate parameters, all visualized in Figure 15. Firstly, the calibration curve is separated into two regions: region 1 while the LTD is increasing, and region 2 for decreasing. Each region is described through two parameters, the change in LTD, ΔLTD (with higher changes resulting in increased measurement resolution) and the range in temperatures ΔT over

which the change in LTD is monotonic (with longer ranges improving the measurement capability).

These four quality parameters were combined into one overarching desirability or quality factor (QF) by normalizing each parameter to the maximum of all runs as follows:

$$QF = \frac{\Delta T_1}{\max(\Delta T_1)} + \frac{\Delta LTD_1}{\max(\Delta LTD_1)} + \frac{\Delta T_2}{\max(\Delta T_2)} + \frac{\Delta LTD_2}{\max(\Delta LTD_2)} \quad (Eq. 3)$$

$$QF = Norm \Delta T_1 + Norm \Delta LTD_1 + Norm \Delta T_2 + Norm \Delta LTD_2 \quad (Eq. 4)$$

In this way, the quality factor can have a maximum value of 4, with each individual parameter ranked out of a maximum of 1. Each normalized parameter, as well as the overall factor has been summarized in Table 1.

Undoubtedly the most impactful parameter was the powder selection, as the use of powder 1 renders any calibration impossible, proving unsuitable for thermal history sensing. Upon removal of the coating runs comprised of powder 1, the rest of the quality factors were used for further analysis. A model was generated to evaluate the impact of the spray parameters (excluding powder 1) on the quality factor, or desirability of the produced coatings. The main outcomes are represented in Figure 16, which shows the relative significance of each parameter.

The results provided similar conclusions to those obtained by the model with the LTD in the as-deposited conditions: power, gas flow and powder have the most critical impact on the material structure and temperature sensing performance; these should be optimized and tightly controlled to ensure the desired performance. Using this model, the final preferred spray parameters may be devised to yield the optimum Thermal History Coating for the tested temperature range. Results concluded that powder 3 should be selected and sprayed with minimised gas flow and maximised power within the ranges tested. Distance and scan rate did not appear to provide a significant impact.

The observed changes in the LTD are dependent on the crystallization and phase changes in the coating, which appear to be affected by the microstructure of the coating in the as-deposited state. Crystallization kinetics are complex, particularly for inhomogeneous materials as studied here. Many factors may influence the kinetics, including time and entrained impurities. The JMAK approach is well established for the modelling of transformation kinetics [45–48] and the terms can factor in some of these complex influences [49]. Applying this approach to model the behavior of the THCs is planned in future work.

Despite the complex processes, the THC can be successfully used to measure temperature in challenging industrial applications as demonstrated in accompanying publications [35] with promising results. This is done by accounting for key parameters, such as exposure time during calibration. This may become more challenging for other key exposure parameters including pollutants, water vapour and composition of combustion gases as they are harder to control. While validation against other techniques has shown very promising results (see [35]), the authors have planned further work to understand and quantify these potential effects.

CONCLUSION

Temperature measurements are vital in a range of industries to determine engine efficiency, fuel consumption and level of emissions. Particularly critical are surface measurements to identify hot spots and verify thermal and cooling models. The investigation has focused on the development of Thermal History Coatings (THCs) to measure temperature profiles in the ultra-high 900-1600 °C range. This new temperature profiling capability records the past maximum exposure temperature in such a way that it can be determined once the component has already cooled down.

In this paper, for the very first time, the authors have explored yttrium silicate materials (YSO:Eu) as THC constituents for temperature sensing between 900 °C and 1600 °C. The coatings are very dependent on the deposition, carried out through Atmospheric Plasma Spraying (APS) and its large range of crucial parameters. Three yttrium silicate spray powder compositions with SiO₂ content ranging between 50% and 80% were manufactured and tested.

A series of coatings were deposited via APS using these spray powders, systematically varying critical spray parameters including gun power, stand-off distance, gas flow and scan rate. A model investigating the lifetime decay (LTD) of the coatings in the as-deposited condition was generated, accounting for 98% of the LTD variation. It was found that the LTD of the coatings varied depending on the spray parameters. The model showed that powder, power and gas flow are the most influential parameters on the LTD of the coatings in the as-deposited conditions. It was further demonstrated that gas flow and distance are dependent parameters. At low gas flow values, the distance affects the LTD, however, at high gas flow values, the distance has no effect.

Following heat treatment of all sprayed coatings, optical spectra showed that the runs with lower LTDs had higher amorphous and X1-YSO content at 1300 °C. Gas flow and power showed a dependency on the relative

intensity of the high-temperature X2-YSO phase. At low gas flow levels, exposure to higher powers, resulted in a lower proportion of X2 phase. At high gas flow levels, the proportion of X2 was at its highest.

LTD was measured for all coatings following exposure over the full temperature range 900-1600 °C. Calibration curves, constructed by plotting LTD as a function of heat treatment temperature from powder 1 showed erratic evolution of LTD with temperature and were discarded for the intended temperature sensing. For the other two powders, XRD showed that the coatings were amorphous below 900 °C and crystallised from X1 to X2 phase when going up to 1600 °C. The suitability of the calibration curves was quantified and showed that the optimal spray parameters were powder 3, high power and low gas flow. Distance and scan rate did not seem to affect the results. The authors have identified different strategies to deconvolute the LTD reading, thereby providing measurement capability through the full tested range between 900 °C and 1600 °C, which will be discussed in a future publication. The final coating composition was shown to provide the unique temperature measurement capability for the ultra-high range of 900 – 1600 °C, satisfying a strong industrial need. The coatings were further tested in representative components and conditions to demonstrate their capability shown in the accompanying publication [35].

FUNDING

The authors would like to thank the Royal Commission for the Exhibition of 1851 and the National Aerospace Technology Exploitation Programme (NATEP) for their continued financial support during the project.

NOMENCLATURE

YSO:Eu	Yttrium mono-silicate Y ₂ SiO ₅ :Eu
YPS	Yttrium di-silicate Y ₂ Si ₂ O ₇
EBC	Environmental Barrier Coating
τ	Lifetime decay
SCS	Sensor Coating Systems
THC	Thermal History Coating
APS	Atmospheric Plasma Spray
8YSZ	8 wt.% Yttria Stabilized Zirconia
LTD	Lifetime decay
FE-SEM	Field Emission Scanning Electron Microscopy

REFERENCES

- [1] Lempereur, C., Andral, R., and Prudhomme, J. Y., 2008, "Surface Temperature Measurement on Engine Components by Means of Irreversible Thermal Coatings," *Meas Sci Technol*, 19(10), p. 105501.
- [2] Cowling, J. E., King, P., and Alexander, A. L., 1953, "Temperature-Indicating Paints," *Ind Eng Chem*, 45(10), pp. 2317–2320.
- [3] Magunov, A. N., 2009, "Spectral Pyrometry (Review)," *Instruments and Experimental Techniques*, 52(4), pp. 451–472.
- [4] Feist, J. P., Heyes, A. L., and Nicholls, J. R., 2001, "Phosphor Thermometry in an Electron Beam Physical Vapour Deposition Produced Thermal Barrier Coating Doped with Dysprosium," *Proc Inst Mech Eng G J Aerosp Eng*, 215(6), pp. 333–341.
- [5] Clarke, D. R., and Gentleman, M. M., 2007, "Luminescence Sensing of Temperatures in Thermal Barrier Coatings," *Surf Coat Technol*, 202(4–7), pp. 681–687.
- [6] Feist, J. P., Sollazzo, P. Y., Berthier, S., Charnley, B., and Wells, J., 2012, "Application of an Industrial Sensor Coating System on a Rolls-Royce Jet Engine for Temperature Detection," *J Eng Gas Turbine Power*, 135(1), p. 012101.
- [7] Heyes, A. L., Seefeldt, S., and Feist, J. P., 2006, "Two-Colour Phosphor Thermometry for Surface Temperature Measurement," *Opt Laser Technol*, 38(4–6), pp. 257–265.
- [8] Volinsky, A. A., and Ginzursky, L., 2003, "Irradiated Cubic Single Crystal SiC as a High Temperature Sensor," *MRS Proceedings*, 792, p. R5.3.
- [9] Feist, J. P., Nicholls, J. R., and Heyes, A. L., 2014, "Determining Thermal History of Components."
- [10] Sun, Z., Li, M., Li, Z., and Zhou, Y., 2008, "Hot Corrosion of γ -Y₂Si₂O₇ in Strongly Basic Na₂CO₃ Molten Salt Environment," *J Eur Ceram Soc*, 28(1), pp. 259–265.
- [11] Eaton Jr, H. E., Allen, W. P., Jacobson, N. S., Lee, K. N., Opila, E. J., Smialek, J. L., Wang, H., Meschter, P. J., and Luthra, K. L., 2001, "Silicon Based Substrate with Yttrium Silicate Environmental/Thermal Barrier Layer."
- [12] He, Y., Lee, K. N., Tewari, S., and Miller, R. A., 2000, "Development of Refractory Silicate-Yttria-Stabilized Zirconia Dual-Layer Thermal Barrier Coatings," *Journal of Thermal Spray Technology*, 9(1), pp. 59–67.
- [13] Garcia, E., Miranzo, P., and Osendi, M. I., 2013, "The Prospect of Y₂SiO₅-Based Materials as Protective Layer in Environmental Barrier Coatings," *Journal of thermal spray technology*, 22(5), pp. 680–689.
- [14] Lee, K. N., Fox, D. S., and Bansal, N. P., 2005, "Rare Earth Silicate Environmental Barrier Coatings for SiC/SiC Composites and Si₃N₄ Ceramics," *J Eur Ceram Soc*, 25(10), pp. 1705–1715.
- [15] Xu, Y., Hu, X., Xu, F., and Li, K., 2017, "Rare Earth Silicate Environmental Barrier Coatings: Present Status and Prospective," *Ceram Int*, 43(8), pp. 5847–5855.
- [16] Aparicio, M., and Durán, A., 2000, "Yttrium Silicate Coatings for Oxidation Protection of Carbon-Silicon Carbide Composites," *Journal of the American Ceramic Society*, 83(6), pp. 1351–1355.
- [17] Cao, M.-S., Hou, Z.-L., Yuan, J., Xiong, L.-T., and Shi, X.-L., 2009, "Low Dielectric Loss and Non-Debye Relaxation of Gamma-Y₂Si₂O₇ Ceramic at Elevated Temperature in X-Band."
- [18] Zhang, X., Zhou, L., Pang, Q., Shi, J., and Gong, M., 2014, "Tunable Luminescence and Ce³⁺ → Tb³⁺ → Eu³⁺ Energy Transfer of Broadband-Excited and Narrow Line Red

- Thermal History Coatings: influence of atmospheric plasma spray parameters on performance
- Emitting $\text{Y}_2\text{SiO}_5\text{:Ce}^{3+}, \text{Tb}^{3+}, \text{Eu}^{3+}$ Phosphor," The Journal of Physical Chemistry C, 118(14), pp. 7591–7598.
- [19] Aitasalo, T., Hölsä, J., Lastusaari, M., Legendziewicz, J., Niittykoski, J., and Pellé, F., 2004, "Delayed Luminescence of Ce^{3+} Doped Y_2SiO_5 ," Opt Mater (Amst), 26(2), pp. 107–112.
 - [20] Fan, D., Yang, S., Wang, J., Zheng, A., Song, X., and Yu, D., 2012, "Synthesis and Cathodoluminescent Properties of $\text{Y}_2\text{SiO}_5\text{:Tb}^{3+}$ Phosphors Prepared from Uniform Precursor," J Lumin, 132(5), pp. 1122–1125.
 - [21] Parganiha, Y., Kaur, J., Dubey, V., and Chandrakar, D., 2015, "Synthesis, Characterization, Thermoluminescence and Optical Studies of Eu^{3+} Doped Y_2SiO_5 Phosphor," Superlattices Microstruct, 77, pp. 152–161.
 - [22] Nikl, M., Ruzicka, J., Cannas, C., and Yanagida, T., 2011, "Silicate Glass-Based Nanocomposite Scintillators," Advances in Nanocomposite Technology, InTech.
 - [23] Felsche, J., 1973, "The Crystal Chemistry of the Rare-Earth Silicates," Rare Earths, Springer, pp. 99–197.
 - [24] Nowok, J. W., Kay, J. P., and Kulas, R. J., 2001, "Thermal Expansion and High-Temperature Phase Transformation of the Yttrium Silicate Y_2SiO_5 ," J Mater Res, 16(08), pp. 2251–2255.
 - [25] Fukuda, K., and Matsubara, H., 2003, "Anisotropic Thermal Expansion in Yttrium Silicate," J Mater Res, 18(07), pp. 1715–1722.
 - [26] Heimann, R. B., 2007, Plasma-Spray Coating: Principles and Applications.
 - [27] Carpio, P., Bannier, E., Borrell, A., Salvador, M. D., and Sánchez, E., 2014, "Influencia de Los Parámetros de Proyección Por Plasma Atmosférico En Recubrimientos de YSZ Obtenidos a Partir de Polvos Micro y Nanoestructurados," Boletín de la Sociedad Española de Cerámica y Vidrio.
 - [28] Thirumalaikumarasamy, D., Shanmugam, K., and Balasubramanian, V., 2012, "Influences of Atmospheric Plasma Spraying Parameters on the Porosity Level of Alumina Coating on AZ31B Magnesium Alloy Using Response Surface Methodology," Progress in Natural Science: Materials International.
 - [29] Miranda, F., Caliri, F., Essiptchouk, A., and Pertraconi, G., 2019, "Atmospheric Plasma Spray Processes: From Micro to Nanostructures," Atmospheric Pressure Plasma - from Diagnostics to Applications.
 - [30] Carpio, P., Bannier, E., Borrell, A., Salvador, M. D., and Sánchez, E., 2014, "Influencia de Los Parámetros de Proyección Por Plasma Atmosférico En Recubrimientos de YSZ Obtenidos a Partir de Polvos Micro y Nanoestructurados," Boletín de la Sociedad Española de Cerámica y Vidrio.
 - [31] Miranda, F., Caliri, F., Essiptchouk, A., and Pertraconi, G., 2019, "Atmospheric Plasma Spray Processes: From Micro to Nanostructures," Atmospheric Pressure Plasma - from Diagnostics to Applications.
 - [32] Wang, L., Fang, J. C., Zhao, Z. Y., and Zeng, H. P., 2007, "Application of Backward Propagation Network for Forecasting Hardness and Porosity of Coatings by Plasma Spraying," Surf Coat Technol.
 - [33] Djendel, M., Allaoui, O., and Bouzid, A., 2016, "Effect of Air Plasma Spraying Parameters on the Quality of Coating," International Journal of Computational and Experimental Science and Engineering.

- [34] Zhang, X. C., Xu, B. S., Xuan, F. Z., Wang, H. D., Wu, Y. X., and Tu, S. T., 2009, "Statistical Analyses of Porosity Variations in Plasma-Sprayed Ni-Based Coatings," *J Alloys Compd.*
- [35] Marta Ferran-Marqués, Silvia Araguas-Rodriguez, Christopher C. Pilgrim, Kang Lee, J. L., 2020, "Thermal History Coatings - Part II: Measurement Capability Above 1500 0C," *Proceedings of the ASME Turbo Expo.*
- [36] Garcia, E., Miranzo, P., Osendi, M. I., García, E., Miranzo, P., and Osendi, M. I., 2013, "The Prospect of Y2SiO5-Based Materials as Protective Layer in Environmental Barrier Coatings," *Journal of thermal spray technology*, 22(5), pp. 680–689.
- [37] Lekivetz, R., Sitter, R., Bingham, D., Hamada, M. S., Moore, L. M., and Wendelberger, J. R., 2015, "On Algorithms for Obtaining Orthogonal and Near-Orthogonal Arrays for Main-Effects Screening," *Journal of Quality Technology*, 47(1), pp. 2–13.
- [38] Feist, J. P., Biswas, S. K., Pilgrim, C. C., Sollazzo, P. Y., and Berthier, S., 2015, "Off-Line Temperature Profiling Utilizing Phosphorescent Thermal History Paints and Coatings," *J Turbomach*, 137(10), p. 101003.
- [39] Krewinkel, R., Färber, J., Lauer, M., Frank, D., Orth, U., Gonzalez, A. Y., Pilgrim, C., Feist, J., Saggese, R., Berthier, S., and Araguas, S., 2016, "Validation of Surface Temperature Measurements on a Combustor Liner Under Full-Load Conditions Using a Novel Thermal History Paint," *Volume 5B: Heat Transfer*, ASME, p. V05BT17A010.
- [40] Pilgrim, C., Yañez Gonzalez, A., Saggese, R., Krewinkel, R., Blaswich, M., Feist, J., Orth, U., Rabs, M., Frank, D., and Araguas Rodriguez, S., 2018, "Surface Temperature Measurements in an Industrial Gas Turbine Using Thermal History Paints," *12th European Conference on Turbomachinery Fluid Dynamics and Hermodynamics.*
- [41] Ito, Johnson., "00-041-0004 Y2SiO5 XRD Reference Pattern ."
- [42] Jones, B., and Sall, J., 2011, "JMP Statistical Discovery Software," *Wiley Interdiscip Rev Comput Stat.*
- [43] Yin, M., Zhang, W., Lou, L., Xia, S., and Krupa, J.-C., 1998, "Spectroscopic Properties of Eu 3+ Ions in X 1–Y 2 SiO 5 at Nanometric Scale," *Physica B Condens Matter*, 254(1), pp. 141–147.
- [44] Lin, J., Su, Q., Wang, S., and Zhang, H., 1996, "Influence of Crystal Structure on the Luminescence Properties of Bismuth (III), Europium (III) and Dysprosium (III) in Y 2 SiO 5," *J Mater Chem*, 6(2), pp. 265–269.
- [45] Avrami, M., 1939, "Kinetics of Phase Change. I General Theory," *J Chem Phys*, 7(12), pp. 1103–1112.
- [46] Avrami, M., 1940, "Kinetics of Phase Change. II Transformation-time Relations for Random Distribution of Nuclei," *J Chem Phys*, 8(2), pp. 212–224.
- [47] Avrami, M., 1941, "Granulation, Phase Change, and Microstructure Kinetics of Phase Change. III," *J Chem Phys*, 9(2), pp. 177–184.
- [48] William, J., and Mehl, R., 1939, "Reaction Kinetics in Processes of Nucleation and Growth," *Trans. Metall. Soc. AIME*, 135, pp. 416–442.
- [49] Ranganathan, S., and Von Heimendahl, M., 1981, "The Three Activation Energies with Isothermal Transformations: Applications to Metallic Glasses," *J Mater Sci*, 16(9), pp. 2401–2404.

Figure Captions List

- Fig. 1 Phase diagram of the Y-Si-O oxides, used with permission from [22] via Creative Commons 3.0 license
- Fig. 2 Schematic of Atmospheric Plasma Spray process (a) and the resulting coating structure (b) [26]
- Fig. 3 Single measured luminescence decay time
- Fig. 4 SEM micrograph for Powder 2 as synthesized
- Fig. 5 X-ray diffraction patterns of the three spray powders
- Fig. 6 Top view (left) and cross-section (right) FE-SEM pictures of a THC coating.
- Fig. 7 Mean LTD of each sprayed coating. The error bars correspond to the standard deviation of the mean (based on 180 measurements. Measurements are divided by substrate
- Fig. 8 Model outcome showing the measured LTD vs. predicted LTD using the generated model. The data points are coloured by the residual LTD expressed as a percentage.
- Fig. 9 Relative significance $[-\log_{10}(p\text{-value})]$ of each spray parameter on the LTD of the as-deposited coatings
- Fig. 10 Mean LTD as a function of gas flow and stand-off distance
- Fig. 11 Emission spectra of all spray coating runs, following heat treatment at 1300°C for 30 minutes. Reference lines included are for X1-YSO (solid blue), X2-YSO (dotted red) and mix (dashed)
- Fig. 12 Relative intensity of the X2-YSO phase as estimated by the peak located at 618.7 nm in the coating emission spectra, represented as a function of gas flow and power
- Fig. 13 Measured LTD for increasing heat-treatment temperature for all sprayed coating runs. Error bars are not always visible; they correspond to the standard deviation of the mean. The curves have been broadly categorized in ascending desirability: unsuitable for temperature sensing, narrow sensing range, and most suitable results. Linear interpolation lines have been added to aid visualization of the trends only.
- Fig. 14 X-ray diffraction patterns of the coatings corresponding to Run #2, heat treated for 30 minutes at the denoted temperatures.
- Fig. 15 Schematic showing the four parameters used to assess the calibration's desirability, or quality factor
- Fig. 16 Relative significance $[-\log_{10}(p\text{-value})]$ of each spray parameter on desirability (or quality factor) of each coating run. Model generated excluding powder 1, which provided unsuitable results.

Table Caption List

- Table 1 Spray parameters used for each spray run. The powders used are all yttrium silicates (YSO) with increasing SiO₂ content (1<2<3). The numerical values of the other spray parameters have been normalized to their maximum for confidentiality reasons.
- Table 2 Normalized quality parameters for all calibration runs and the calculated quality factor (QF) calculation as per Eq. 3. Runs corresponding to powder 1 did not provide suitable results and were therefore excluded.

Table 1

Run	Powder	Norm. Power	Norm. Distance	Norm. Gas flow	Norm. Scan rate
1	3	0.4	1	0.8	1
2	3	1	0.7	0.8	0.6
3	1	1	1	0.8	0.6
4	2	1	0.7	1	0.6
5	1	1	0.7	0.8	1
6	1	0.4	1	1	0.6
7	3	0.4	0.7	1	0.6
8	1	0.4	0.7	1	1
9	3	1	1	1	1
10	2	0.4	1	0.8	0.6
11	2	1	1	1	1
12	2	0.4	0.7	0.8	1

Table 2

Run	Norm $\Delta T1$	Norm $\Delta LTD1$	Norm $\Delta T2$	Norm $\Delta LTD2$	QF
1	1.0	0.84	1.00	0.72	3.6
2	1.0	0.94	1.00	0.97	3.9
4	1.0	0.90	1.00	0.65	3.6
7	1.0	0.72	1.00	1.00	3.7
9	1.0	1.00	0.67	0.59	3.3
10	1.0	0.80	0.67	0.75	3.2
11	1.0	0.93	0.67	0.62	3.2
12	1.0	0.73	1.00	0.91	3.6



DSPACE

<https://dspace.org/>

Thermal history coatings: influence of atmospheric plasma spray parameters on performance

Araguás Rodríguez, Silvia; Ferran-Marques, Marta; Pilgrim, Christopher; Kamnis, Spyros; Feist, Jörg P. ...

2024-09-13

American Society of Mechanical Engineers (ASME)

<https://doi.org/10.1115/1.4066533>

Araguás Rodríguez S, Ferran-Marques M, Pilgrim C, et al., (2024) Thermal history coatings: influence of atmospheric plasma spray parameters on performance. Journal of Engineering for Gas Turbines and Power, Volume 147, Issue 1, January 2025, Article number 011024, Paper number GTP-20-1522