NON DESTRUCTIVE EVALUATION OF COATINGS FOR LAND BASED GAS TURBINES USING A MULTI-FREQUENCY EDDY CURRENT TECHNIQUE

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Abstract: To provide a commercial return from Combined Cycle Gas Turbine (CCGT) technology for power generation, a balance has to be struck between efficiency, maintenance costs and component life. The parts that significantly influence this are collectively known as Hot Gas Path (HGP) components and generally consist of blades, vanes and heat shields. To achieve high thermal efficiencies, these components are subject to high temperatures, centripetal forces and erosive/corrosive atmospheres and therefore need to be protected by complex coatings and through internal cooling. The drive for higher efficiencies however often means that the protection put in place is only a partial solution and experience shows that these components have a relatively short lifespan and require regular inspection. Inspections to date have consisted of visual examination and fluorescent penetrant inspections and therefore limited to the detection of surface damage usually associated with 'teething' problems during early years of operation and are often inadequate for detecting in-service degradation or for coating qualification. Furthermore, as CCGT technology is becoming more established, there is a requirement to assess the remnant life of components of which there is currently no suitable technique.

This presentation describes the inspection technique developed using a multi-frequency eddy current instrument capable of distinguishing between coatings and substrates for the thickness gauging of TBC's to help qualify coatings prior to engine runs. This is a crucial inspection as poor control during coating application can lead to premature failure of the component by thermo-mechanical fatigue as was the case at a UK CCGT power station. Here several blades in one particular row which were coated by two different vendors exhibiting TMF cracking, however through a thorough investigation with a multi-frequency instrument, it was possible to identify the poorly coated blades and establish that they were all from the single vendor.

Introduction: Some of the most stressed components of land based gas turbines for electricity generation are the power turbine blades and vanes. Their performance significantly contributes to the thermal efficiency of the plant whilst their degradation rate determines the operating period between overhauls. The components are manufactured from nickel based superalloys and contain complex cooling passages. They are coated with a corrosion and oxidation resistant layer and often finished with a thermal barrier coating to insulate them against high temperatures. Each process of their manufacture requires several variables to be set using strict tolerances to ensure the end product is capable of lasting the required period between overhauls. Control of these processes is difficult and a range of defects can occur during manufacture. This paper describes an eddy current technique that can accurately measure the thickness of the thermal barrier coating to within a few microns to ensure the components are coated to the correct tolerance prior to fitting them in the gas turbine. The equipment has been proven on site to be a reliable instrument for the in-situ inspection of gas turbine blades.

Background: Thermal barrier coatings (TBC’s) are ceramic coatings applied over the corrosion/oxidation metallic coating to insulate the blade substrate from the high temperature fuel mixture. They consist of zirconium oxide (ZrO_2) which is stabilised by yttria (Y_2O_3). They are applied by vacuum (VPS) or air (APS) plasma spray or more recently by electron beam vapour phase deposition (EBPVD). The TBC layer is 200-500µm thick for APS coatings and 50-200µm for EBPVD coatings. The TBC has a thermal and electrical conductivity much lower than that of the metal substrate and coating and a higher reflectivity. Zirconium oxide is very brittle however, as it has a relatively high coefficient of thermal expansion; this reduces the stresses between the adjacent metallic layer and itself. This enables the TBC to adhere well to the blade and withstand the thermal gradients caused by operating the plant in two-shift operation to maximise its commercial return. If the correct thickness of TBC is not applied then the stresses due to the thermal gradients cannot be withstood and cracks form in the TBC which grow until a region of the coating spalls off leaving the underlying metallic coating exposed to the high temperatures of the gas flow. The longevity of the blade is then dramatically reduced and if the spallation goes undetected, the continued use of the unprotected blade can lead to rapid failure. The development of this technique was a result of detecting a damaged blade during a routine overhaul that could have led to an engine failure at one of our power plants in the UK, which was later found to be as a consequence of poor control of the TBC coating process. Cracks were appearing early in the life of the blades at the trailing edge of nearly all the 1st stage blades apart from a few odd blades (see figure 1).

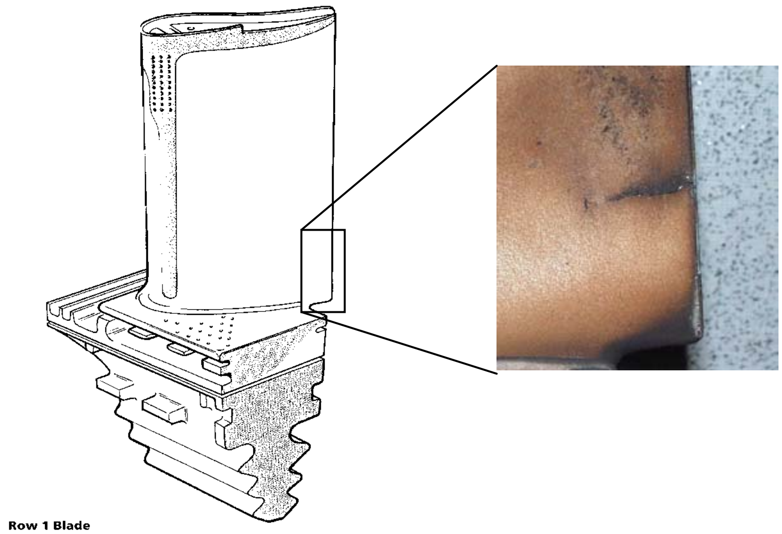

Figure 1: Blade cracking contributed to by poor coating application

QA records showed that the blades were coated by two different vendors and that at that stage it was not clear whether all the cracked blades came from the same vendor whilst the non cracked blades came from a different vendor or whether there were a mixture of failed blades from both. Our task was to develop a technique that could measure the TBC thickness accurately enough to determine the thickness profiles of the blades which would enable us to identify the two different coating systems. If it was found to be that one of the vendors had produced satisfactory blades and other didn't it would be possible to identify the poor vendor and allow us to put in place controls to ensure that all future blades are acceptable.

Method: The thickness of the TBC coating may be measured using many NDE methods[1] including ultrasonics (bulk wave and rayleigh wave), thermal techniques (thermal wave, lock-in and transient thermography), electromagnetic techniques (eddy current, alternating current field measurements and interdigital electrode dielectrometry) and radiographic techniques (film radiography and computerised X-ray tomography etc), however all of them have their individual drawbacks when applied to gas turbine parts which centre around the complex geometry or the materials used. Consideration also needs to be given to the speed of the inspection and the ability to inspect the parts in-situ when choosing a suitable technique.

Having evaluated several techniques, the eddy current method seemed to be the best compromise between speed, accuracy and the ability to use the technique in-situ. There are several eddy current instruments on the market, however, most of them rely on eliminating lift-off to enable an accurate reading of the coating thickness. This is because the TBC being an insulator, gives a similar effect to that of lift-off. Lift-off is caused by any movement of the eddy current probe including slight removal of the probe from the part surface or through probe 'wobble' associated with performing the inspection without the use of automated jigs to hold the probe perpendicular to the surface. One instrument which enables lift-off to be controlled through the unique design of the probe is the Meandering Winding Magnetometer (MWM). This is a sophisticated multi-frequency instrument capable of determining the level of degradation of the oxidation/corrosion resistant coating beneath the TBC[(2)] and many more complex structures, however, used in its simplest form is an ideal instrument for measuring TBC coating thickness. By using measurement grids to model the eddy current response from a material (see figure 2), a trained operator can measure TBC thicknesses on a variety of non-magnetic substrates with a high degree of accuracy by quickly scanning the part using line scans (see figure 3).

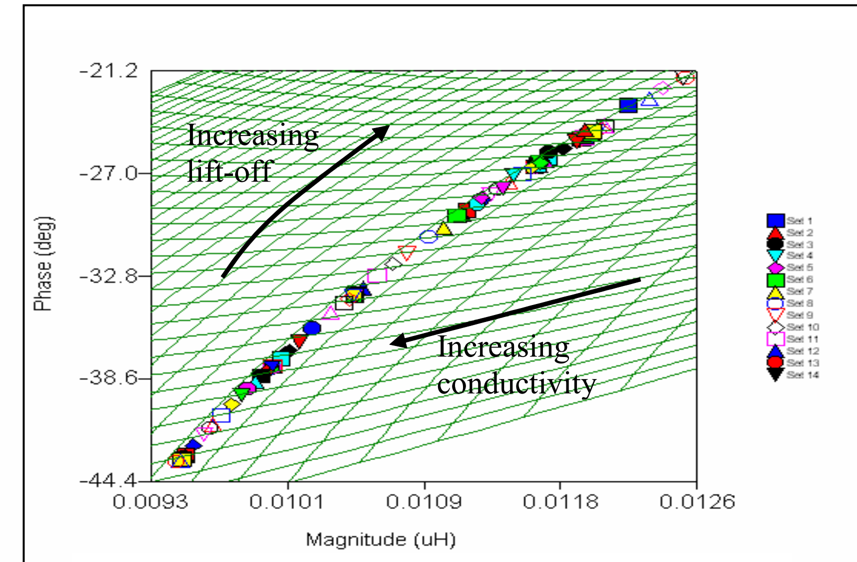

Figure 2: Measurement grid showing results typical results from a scanned blade

The unit requires just one operator, however, for in-situ inspections two operators are generally required. One operator controls the data acquisition software and monitors the computer display assessing the signal responses and the second operator manually scans the component, either making "pick and place" (single spot) measurements or through continuously scanning. The analysis of the saved raw data requires the operator to use calibration data, obtained prior to the component inspection to compensate for noise originating from parasitics in the probe cable, modelling discontinuities etc. that can produce small, but significant errors. The operators are then able to produce an on site report for the client using real data exported from the instrument.
To validate the inspection procedure and technique, the equipment set-up criteria was chosen to represent the mode whereby data can be collected at the fastest rate and therefore at the lowest resolution; typical of that required to perform a quick examination of several parts during a short overhaul. The accuracy and resolution of the data collected therefore represents the worst case scenario possible using this equipment.
The specimen used was a 30mm x 30mm by 6mm thick uncoated IN738LC sample taken from a gas turbine heatshield. Multiple shims of thickness 0.001" (25.4 μm) were used to simulate various thicknesses of TBC. Lift-off ranged from 0μm to 558.8μm, simulating the total range of TBC thicknesses found on current service parts.

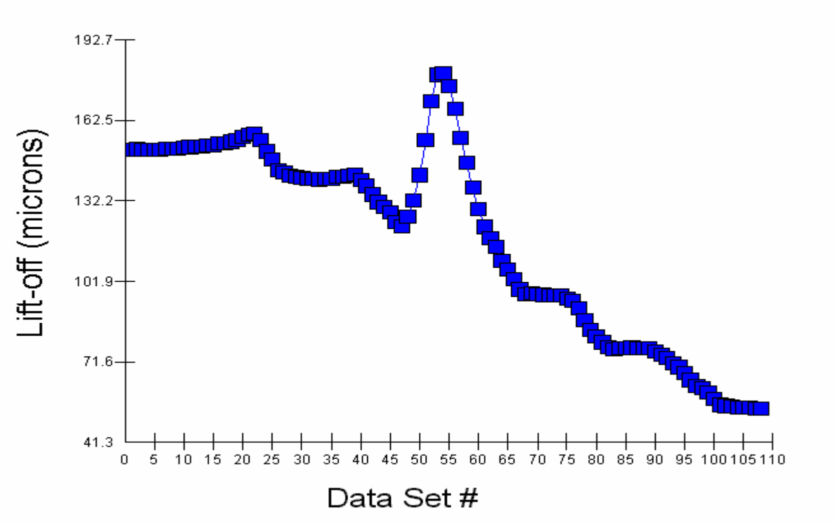

Figure 3: Data set showing typical TBC thickness profile across blade airfoil

Results: Twenty three measurements were taken on the IN738LC sample with increasing lift-off in steps of 25.4µm up to 558.8µm. The results are as shown in the graph below (figure 4). For a system setup that is claimed to be accurate up to 25µm, the results showed excellent agreement with the actual lift-off up to 300µm [3]. Above 300µm the errors were up to 16µm but after applying a simple curve fit, the measured readings were within 5µm of the actual lift-off for all readings.

Discussion: The results of the trial demonstrate that even with the equipment optimised to perform the inspection at speed rather than accuracy, it has proved to be an accurate method of measuring lift-off and hence TBC thickness on turbine blades. The uncertainty on lift-off readings is within 16µm for the raw data and is reduced to 5µm when a simple polynomial curve fit is introduced. The equipment is capable of far greater accuracies when used to measure lift-off, however, for TBC thickness gauging, it is not worth improving the accuracy and resolution of measurements at the expense of inspection speed as the TBC surface roughness is of a similar order to the uncertainty. Further work using shims has shown that by optimising the equipment for accuracy, lift-off can be measured within less than one micron uncertainty.

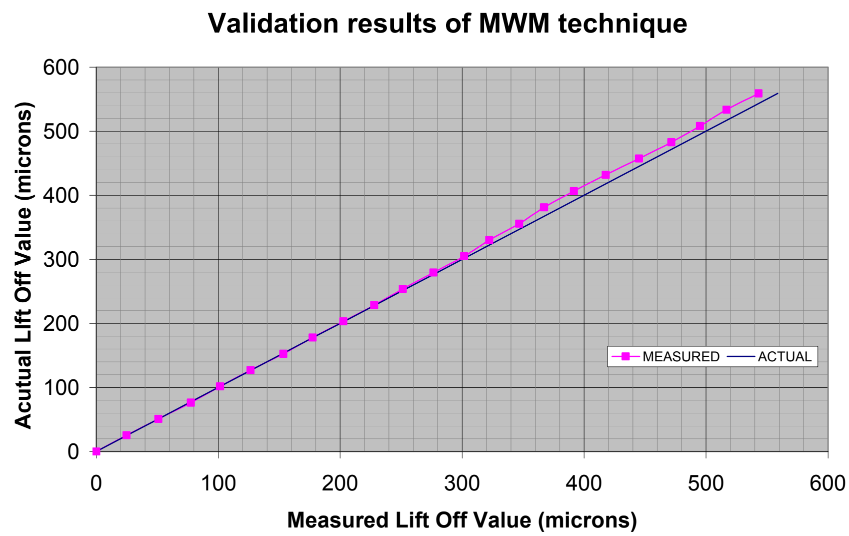

Figure 4: Validation results showing excellent correlation

When applying the technique to real blades, there are limitations due to the curvature of the blade airfoil (see figure 5), but with careful manipulation of the probe it is possible to inspect this area. The technique has been successfully employed to the row one blades that exhibited cracking in the trailing edge and to all subsequent rows of blades ordered. Figure 6 shows that it is possible with the MWM technique to distinguish between the two coating systems employed by using a simple line scan up the trailing edge of the blade. This led to us being able to establish that in fact the cracking in the blades was confined to one type of coating, coating 2. The cracking occurred approximately where the coating thickness dropped quickly from ~600μm to ~400μm.

Figure 5: Probe has good conformity to tight radii's such as the leading edge

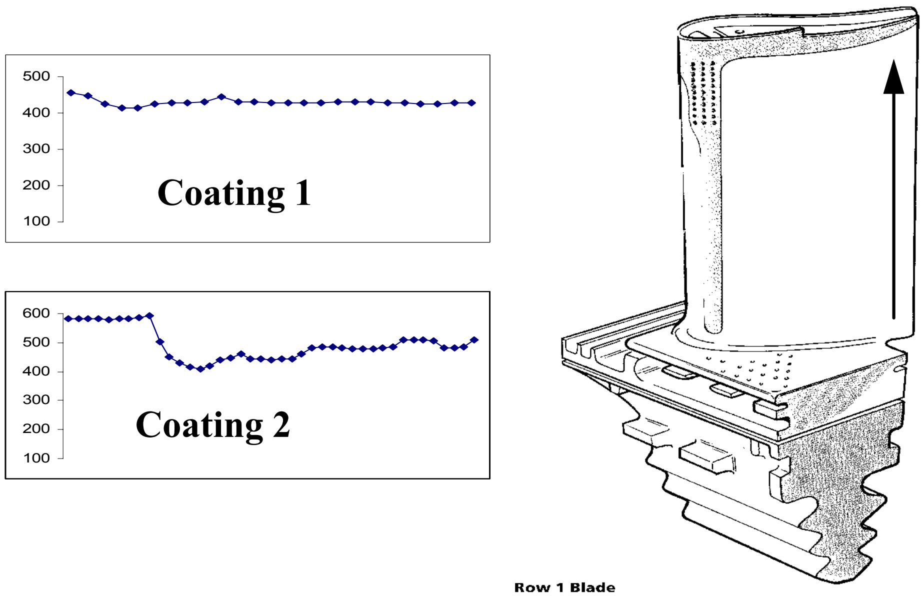

Figure 6: Coating thickness variations on identical blades due to differences in vendor spraying techniques (in microns)

Conclusions: An accurate technique to evaluate the thickness of thermal barrier coatings has been developed and demonstrated. It uses an eddy current based technique with a conformable sensor to enable parts with complex geometry to be tested. The technique is non destructive and can be used for inspections with the blades on the rotor and in-situ with the use of different sensor configurations.

The use of the equipment for thickness gauging of non conductive coatings has shown that it is a valuable tool for verifying the actual coating thickness which as the paper has detailed, can aid in the quality assurance of blades and vanes prior to fitting them to the engine.

Coating thickness gauging can be used for several applications on gas turbine parts including:

- Quality assurance of TBC coating thickness during manufacture instead of using inaccurate indirect methods such as weight gain and the use of sacrificial tabs for later destructive analysis
- Quality assurance of corrosion/oxidiation resistant coating thickness during manufacture
- Establish refurbishment potential of components i.e., remaining wall thickness in critical areas such as leading edge once exhausted coating is stripped prior to recoating

Further work has been undertaken on metallic coatings and the assessment of the remaining life of oxidation/corrosion resistant MCrAlY gas turbine coatings using the MWM system, the results of which are encouraging.

References: 1. H.Harper, 'Evaluation of NDT techniques for gas turbine blades and vanes,' August 1998, Internal Report.
2. N.J.Goldfine., P.Zombo., R.Miller.,'Conformable eddy current sensors and methods for gas turbine inspection and health monitoring,'ASM International Gas Turbine Technology Conference, Materials Solutions '98, Rosemont, IL, October 12-15, 1998.
3. P. Crowther, 'Validation Of Thermal Barrier Coating Thickness Gauging Using An Advanced Electro-Magnetic Technique (MWM)' January 2000, Internal Report.