

Frequency Scanning Eddy Current testing (F-SECT) for condition assessment of multiple layers of Coating on Gas Turbine Blades

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Abstract

Gas based power stations are comparatively cleaner mode of thermal power generation and are used to meet base as well as peak load electricity demand. Gas Turbine is the most important component of such power stations. Inlet temperature at turbine is increased to improve the efficiency of the turbine. First stage blades of gas turbine in particular and other stages in general are subjected to very high temperature. To improve the high temperature sustainability of these blades made of nickel based super alloys, a specialized coating is applied on it. The coating generally comprises of a metallic bond coat, known as M-Cr-Al-Y (Metal-Chromium-Aluminium-Yttrium), over which, sometimes, a ceramic coat TBC (Thermal Barrier Coating) is also applied. During operation of these blades, the metallic bond coating degrades with high temperature exposure. The key factors, which influence coating life cycles, are firing temperature and fuel/air contaminants, where corrosion and oxidation are the life limiting factors. Cyclic effects (start ups) that favour the formation of cracks may also reduce coating life. Earlier there were no methods available for evaluating the condition of the coating non-destructively. Only, OEM (Original Equipment Manufacturers) prescribed guidelines, based on Equivalent/Valuated Operating Hours (EOH/VOH), were followed to refurbish these blades, where-in blades are recoated after evaluating condition and profile of base material. At times, like in view of partial loading of gas turbine units, utilities would like to optimize the refurbishment cycle actually required, if they have some tool indicating actual condition of the coating.

Frequency-Scanning Eddy Current Test (F-SECT) technique, characterizes different internal layers of the coating based on difference in electrical conductivity. Concentration of mono- β alumina layer inside the M-Cr-Al-Y coating is directly related to healthiness of coating and its approximate thickness can be estimated using FSECT and inverse modelling software. The paper intends to present fundamental background of FSECT technology with few case studies to show its application for coating assessment of gas turbine blades at NTPC.

[Keywords: FSECT, MCrAlY & TBC Coating, Degradation of Coating, Blade coating]

INTRODUCTION

Gas Turbines operate at high temperature for increase in efficiency and hence the components coming in contact with hot air need protection against the high temperature oxidation and corrosion. Gas turbine blades and vanes are generally provided protective complex multi-layer coatings like MCrAlY and Thermal Barrier Coating to enhance their sustainability to high temperature. MCrAlY coatings, consist of a combination of Cr, Al and Y along with an element (M), which can be Co, Cr or a mix of them. MCrAlY coating is not

only used as stand-alone single layer but also as constituents of more complex multi-layer protecting coatings like thermal barriers, modified MCrAlY and duplex coatings. These coating are subjected to in-service degradation on account of severe operating conditions and need to be reapplied during refurbishment of the concerned components. Refurbishments are generally undertaken after elapse of a certain fixed interval, suggested by the respective OEMs (Original Equipment Manufacturers. Number of refurbishments feasible may be limited and they increase the O&M cost of GT plants^[1,2].

The key factors influencing coating life cycle are firing temperature and fuel/air contaminants where corrosion and oxidation are the life limiting factors. Cyclic effects (start ups) that favour the formation of cracks may also reduce coating life. Contribution of these factors to coating degradation cannot be easily taken in to account. Moreover the reliability of the coating depends on its initial quality, which is usually only statistically accessed through expensive destructive sectioning on a limited number of components. As a result, the preventive maintenance plans currently adopted is conservative enough to compensate also for the lack of information on coating condition^[1,2].

Frequency Scanning Eddy Current Technology utilizes its innovative capability to get information of impedance v/s frequency, i.e. electrical conductivity and magnetic permeability of stratified layers, which is function of health of the coating. It further utilizes a mathematical tool, known as inverse problem solution, to estimate thickness of different layer inside the coating. Details of the technology are discussed later in this paper

COATINGS & ITS DEGRADATION

MCrAlY coatings in “as applied condition” shows a very thin inter-diffusion zone, which provides a sharp contrast in chemical composition & electromagnetic properties between the coating and base material. This coating contains (a) β phase which is reservoir of protective elements like Al, Cr. (b) porosity/roughness in the outer layer, due to over spraying during the deposition (c) residuals of grit blasting during surface preparation before coating. Figure 1 (A) shows a typical New MCrAlY coating.

As mentioned earlier, degradation of coating during service takes place due to high temperature corrosion & oxidation as well as fatigue which may lead to crack formation in the coating due to cyclic effects (start ups). Microstructurally coating degrades due to loss of protective elements (Al, Cr) contained in so called β phase through diffusion. Diffused Aluminium from β phase form an oxide layer on outer side and an inner layer at the interface with substrate due to inward diffusion (Figure 1B). The outer Al/Cr-oxide layer provides shield against high-temperature oxidation and corrosion but has the tendency of spalling off due to thermal cycling. Thus, through diffusion, β phase progressively gets consumed of its protective elements during the service of coating. The full depletion of β phase determines the end-of-life of the coating and necessitates blade refurbishment, which consists of removal of exhausted coating and the application of a new one- to prevent damage to base material. Hence, life or protective capacity of the coating is correlated with the thickness of the effective β layer and it is a parameter to assess the condition of the coating.

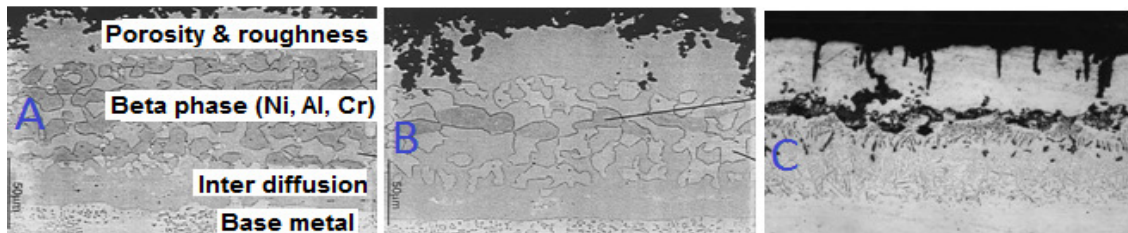


Fig. 1 (A,B,C): Progressive degradation of MCrAlY coatings under service conditions^[1]

Thermal Barrier coating is another type of coating used in Gas turbines which is constituted of a metallic bond-coat made of a standard MCrAlY coating over which a thermal insulating ceramic material is deposited. It reduces the temperature at the metallic bond-coat, thus extends its operation life. The in-service degradation mechanism of TBC is similar to standard MCrAlY coating. Also, thermal barrier coating layer is electrically non-conductive.

FSECT TECHNOLOGY AND PRINCIPLE

There is a very small difference in electromagnetic properties of coating and base material (a few percent) reflecting their quite similar chemical composition and the conventional eddy current method will not be helpful in analysing the different layers inside the coating. Frequency Scanning Eddy Current Technology (FSECT) carries out the measurement in a range of frequency (each having different depth of penetration) to extract information on electromagnetic behaviour (electrical conductivity and magnetic permeability) of different layers of the coating. FSECT uses a high frequency and high stability eddy current module to produce periodic current of increasing frequency in the range of 50kHz-8MHz for typical application of coating assessment of GT blades. The interaction between the electromagnetic field and the test material influences the mutual inductance between the transmitter and receiver coils, and therefore the voltage measured at the receiver coil terminals of the probe. By means of synchronous two-phase demodulation, the real and imaginary components of the receiver signal at each frequency are acquired. This series of complex voltage values constitutes the FSECT raw data^[3]. F-SECT raw data (i.e. complex voltage vs. frequency data) are processed to provide a scalar quantity called Normalized Impedance vs. Frequency, which can be more easily modelled and analyzed.

Figure 2 shows, the conversion of voltage vs. frequency data to Normalized Impedance vs. frequency for three different samples of different conductivity configurations. Qualitative analysis of the coating condition can be carried out based on the behaviour pattern of the normalised impedance v/s frequency curve. Figure 3 shows correlation between normalised impedance v/s frequency curves for nine test locations and corresponding coating condition of MCrAlY coating is shown. The lowering of the curves presents decrease in electrical conductivity of the coating due to loss of protective elements (eg. Al,Cr) in so called β phase showing progressive degradation of the coating.

Curve-1, i.e. top curve represents new coating condition when there is high aluminium content in the β phase. This curve shows low conductivity (normalised impedance) for lower frequency and high conductivity at higher frequency. Curve 2 & 3 represents drop in conductivity at higher frequency meaning the loss of aluminium content in top most layer and

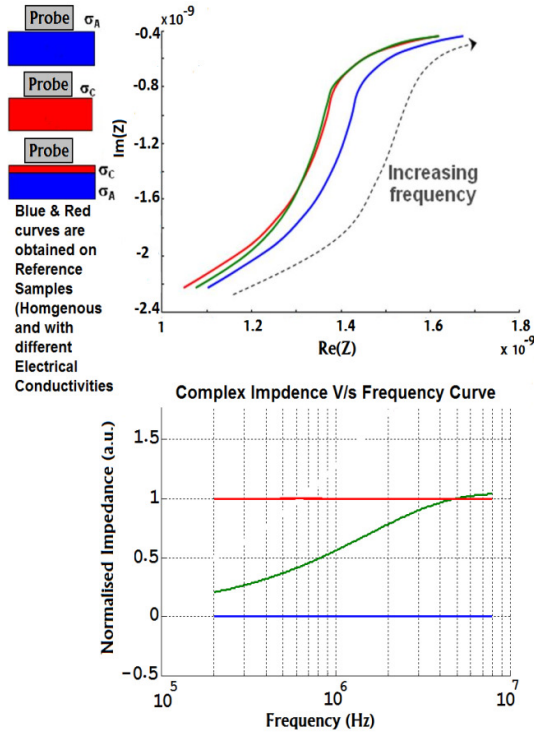


Fig.2:Complex impedance V/s Frequency curve and Conversion from complex to normalised ^[1]

almost no change in conductivity at lower frequency i.e. no corresponding changes in the substrate material. It show that coating is still good but it has started depleting. Curve 4 & 5 shows substantial drop in conductivity at higher frequency and thus represents complete loss of Al in the bond coat. Further Curve 6, 7 & 8 shows decrease in conductivity both at lower and higher frequency. Decrease in conductivity at lower frequency shows growth of cracks in the top coat that penetrated in to the substrate thus reducing the conductivity of the substrate material and decrease in conductivity at higher frequency represents depletion of coating material.

Quantitative information on coating condition can be obtained by model based analysis of the normalized impedance vs. frequency curve.

The model based analysis implemented in the FSECT system is equivalent to solving the so-called “inverse problem”, i.e. quantitatively estimating the test sample parameters from the measured normalized impedance vs. frequency curve. This is accomplished by means of an iterative algorithm that minimizes the error between the measured and calculated normalized impedance curves by adjusting the values of the model parameters at each iteration step. At the end of this minimization process the best estimates of model parameters are obtained, which can then be correlated with the diagnostic quantities of interest, e.g. coating thickness, aluminium depletion, etc. By the model based analysis thickness of bond coat is evaluated and further the effective β thickness (EBT) of service exposed coating is obtained. EBT is equivalent to the thickness of the layer of the coating that still contains protective elements (e.g. β phase for MCrAlY coating). EBT is thus a measure of the residual life of a service run coating , the end of the life is determined by the condition $EBT=0$. ^[4]

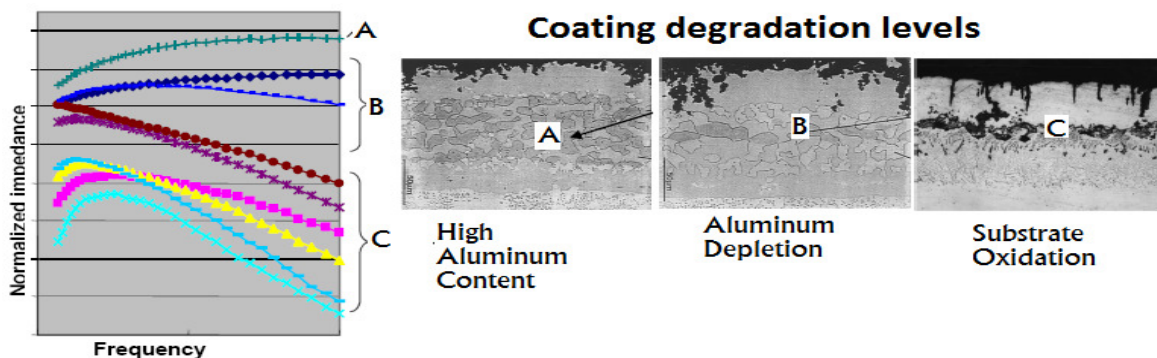


Fig 3: Qualitative analysis of coating condition ^[4]

Similarly Thermal Barrier Coating (TBC) can also be analysed as ceramic thermal barrier is transparent to electromagnetic field generated by an eddy current probe, which means that the bond coat can be inspected through the ceramic layer. In addition, eddy current probe also provide the thickness of this ceramic thermal barrier as it considers it as liftoff for the probe.

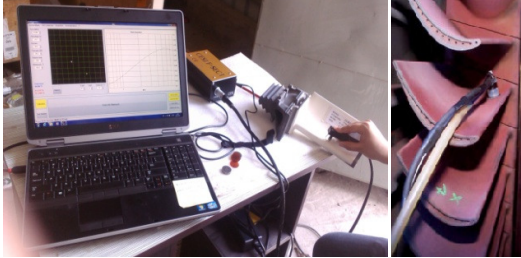


Fig 4: FSECT system

Thus, FSECT system measurement provides-

- (A) Thickness of coatings of new or refurbished coating for quality assessment
- (B) Residual protective thickness of service-run coating
- (C) Thickness of ceramic top-coat in case of TBC.

An FSECT system used for measurement is shown in the Figure 4.

CASE STUDIES

Measurements with FSECT equipment has been carried out for a number of gas turbine units at NTPC during the shutdown of the unit. In many cases, new blades were being put during R&M or otherwise. It was though prudent to have the baseline data of the internal layer for the new blades for any comparison of thickness of different internal layers after certain period of operation. Based on the availability of the gas turbine for inspection, which requires shutdown and access to GT blades, measurements were carried out.

Table 1 shows the details of the unit where FSECT measurements were carried out. Measurements were carried out on units of different makes of gas turbine (denoted as A , B & C here).

Table 1: Details of the GT units for FSECT measurements

Gas Turbines	Type of rotor	Base material of coated blade	Coating type
A	Five stage	IN738	Row#1~MCrAlY
B	Three stage	GTD 111	Row #1GT33-IN+ (Adv. MCrAlY)
C	Five stage	IN738 LC	Row #1 TBC, Row#2 MCrAlY

Measurements were taken at different locations of the blades on both of its pressure side and suction side as variation in thickness layer was expected based on the criticality of different location and the curved profile fo the aerofoil. For each location, qualitative graph on variation of normalised impedance over a frequency range was analysed for assessing general quality of the coating. With the use of the inverse model software, thickness of β layer was estimated. Table 2 summarises the results of the measurements for the different stages of blades of different makes with similar type of coating.

Based on the information on the β layer, studies on trending of its thickness can be done over a time to assess the degradation of coating. It may be prudent to appropriately give the weightage to the partial loading of the gas turbine units prevalent today. This information can

be utilised in optimising the refurbishment interval. Increase in the inspection interval would be economically beneficial to the utilities. Also, in case of shortage of refurbished blades to form a lot of blades for reuse (may be for short interval), this measurement can be utilised for selection of such blades from the old lots.

Table 2: Summary of results with FSECT measurements

GT Manufacturer	Coating thickness Row#1 (in micron)			Coating thickness Row#2 (in micron)		
	Coating type	TBC layer	β layer	Coating type	TBC layer	β layer
A- (new blade)	MCrAlY	-	185-262	MCrAlY	-	165-260
A- (used blade*)	MCrAlY	-	186-260	MCrAlY	-	158-260
B-(new blade)	MCrAlY	-	180-230	No coating	-	-
B-(usedblade**)	MCrAlY	-	70-200	No coating	-	-
C-(new blade)	TBC	250-400	240-340	MCrAlY	-	180-270

*7649 hrs after its refurbishment at 28000 hrs; ** after 24000 hrs

CONCLUSION

Frequency Scanning Eddy Current technology can be used to assess the actual condition of the MCrAlY coating on blades/vanes of a gas turbine. This technology can be a quality control tool for inspection of new/refurbished blades and for optimising the refurbishment interval of the coated blades. The method is more pertinent in view of partial loading of the unit prevalent for gas turbine units, where it may not be necessary to go for refurbishment of the coated blades based on their valuated operating hours. The FSECT technology is expected to minimize the life cycle cost of the coated blades/ vanes.

FUTURE WORK

As mentioned in the paper, trending of the degradation data with proper weightage to different factors is necessary. Hence there is program to gather the data for coated gas turbine blades at intermittent operating interval of their life cycle.

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