# <u>Theoretical estimation of thickness variation in thermal barrier coatings by using</u> <u>Pulse Phase Thermography</u>

M Mahesh Kumar\*, K S Vikrant\*, M Swamy\*, M.S.Rawat\* and R Markandeya\*\* \* Metallurgy Department, Bharat Heavy Electricals Limited (Corp.R & D), Hyderabad, India \*\* JNTUH College of Engineering, Kukatpally, Hyderabad, India

### ABSTRACT

Materials used in power generation units and aerospace industries experience excessive temperature, pressure and demands for use of expensive materials for their extremely high specific strength. To prolong the life, ceramic materials as coatings are applied on gas turbine blades. A newer coatings material needs to be designed for specific applications. The basic parameters like thermal diffusivity, thermal conductivity, and thickness of material are involved for estimation and are not readily available in literature and the data may not match for specific application. A practical method of use of Pulse Thermography (PPT) can be utilised for approximation of theoretical generated equations. The diffusivity of the material can be fed in the generated equation to get the desired results. Also the method promises for quick estimation of thickness of material to be required to use for specific application. Metals like steel, aluminium are coated with ceramic coatings for insulation against sudden impact of heat to increase the life.

Ceramic Coatings of a few microns to hundred microns thickness are applied over materials exposed to high temperatures and pressures. New variant materials are required for specific application and needs to be validated. Computer Modelling, use of ANSYS can be worked based on known values of diffusivity, coating thickness in understanding the behaviour of materials. The derivation of mathematical equations to find the basic variables is a straight forward and more conclusive results can be established. An approach of mathematical equations for determining the thickness of coatings to be applied coupled with active thermography data is useful. This work generates mathematical equation which can be used for any engineering material to be coated on substrates.

Keywords: Pulse Thermography, Composite Materials, Diffusivity, Thermal Conductivity, Phase, Thermal Images

#### INTRODUCTION

Excessive temperature and abrasive nature of flue gases needs expensive material for use. Application of ceramic coating on engineering material is essential to prolong the life of components. Several qualitative and quantitative methods are available for assessing the ceramic coatings integrity to metal. To measure thickness eddycurrent technique is used directly on components [1-3]. The method needs manual scanning of entire material which is difficult to do so. An alternative method of ultrasonic scanning is reliable but cumbersome in practice as the size and shape may hinder the use of technique[4-6]. Thermography inspection is fast and simple in operation and size, shape is not a resitriction. The technique reveals thermal difference in materials based on the properties of materials like thermal conductivity, thermal diffusivity etc. Evaluation of material thermal properties is a field of great intereset for two reasons first in order to predict the behaviour of a given component or solver the inverse problem, it is necessary to model the actual experiments. Such modelling requires knowledge of the thermal properties of the material being inspected. In-situ estimation of thermophysical material properties is thus advantageous to simulate the thermal behaviour of components. Values given tables and handbooks give only an estimation of such values, Since material properties may change due to the variability of the fabrication processes. Disrect evaluation is a straight forward approach.

Measurement of thermal diffusivity is of paramount interest for understanding the heat flow in a material assisted by thermography. There are several techniques available to measure diffusivity of material by the evolution of temperature on either front or back face of material. As suggested by W.J.Parker et.al(1961),the time t1/2 is workable for material with thickness 1cm or above for high diffusive material like aluminium or copper. The heat propagation by flash is so fast in case of smaller thickness of high conductive material that measuring t1/2 is difficult and front face temperature evolution as suggested by W.N.Reynolds and Wells (1984) and Hobbs (1991) for t1/2 is tricky under In-situ condition. Of the available active thermography techniques, long pulse lock-in thermography is best suited to measure temperature peak on the back side of flat component [1,7].

Thermal barrier coating depending on the coating thickness restricts heat flow on the other side. Heat transfer in the material is governed by fick's law of diffusion. The rate of heat transfer is measured by using boundary conditions. A classical approach of measuring diffusivity or coating thickness is used in present study. The conjugate heat transfer problem is solved using heat diffusion equations. These equations are further used with experimental results to estimate either thickness of coating/thermal diffusivity value. For experimental purpose a thermal barrier coating material is applied over aluminium plate using plasma spray arc. In order to adhere the coating on aluminium substrate a bond coating (known as primer) is also applied on the aluminium substrate. High power constant heat injection source were used on the above sample to determine the coating thickness.

#### THEORY

Heat transfer in a coating material is a typical conjugate slab diffusion problem. The heat flux is injected on metal substrate as shown in Fig.1. The heat transfer problem is solved using following equations (1-16). Radiation losses are not considered in solving the problem and were controlled during experimentation to reduce losses by radiation to minimum by subjecting heat injection very near to surface of metal.



Fig.1. Schematic diagram of heat transfer across the metal substrate and coating

The governing equations for metal substrate and coating are given in equation 1 and 2, respectively.

# **Governing Equations:**

The four boundary conditions at metal outer surface, coating outer surface and metal/coating interface are shown in equation 3-6.
Boundary Conditions

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$\frac{\partial T_1(L_1,t)}{\partial t} = -\frac{Q}{Q} at X = L t > 0$	(3)
$\partial X = K_1  \text{if } X > 0$	(3)
$K_{1} \frac{\partial T_{1}(0,t)}{\partial t} = K_{2} \frac{\partial T_{2}(0,t)}{\partial t}$	(4)
$\frac{\pi_1}{\partial X} \frac{\partial X}{\partial X} = \frac{\pi_2}{\partial X} \frac{\partial X}{\partial X}$	(1)
$I_1(0,t) = I_2(0,t)$	(5)
$\frac{\partial I_2(-L_2,t)}{\partial Y} = 0 \text{ at } X = -L_2, t > 0 \dots \dots$	(6)

#### Solution for above equations:

$$T_2(X,t) = \left\{ \sum_{n=0}^{\infty} [a_2 \cos \lambda_n \sqrt{\frac{\alpha_1}{\alpha_2}} X + b_1 \sin \lambda_n \sqrt{\frac{\alpha_1}{\alpha_2}} X] e^{-\lambda_n^2 \alpha_1 t} \right\} + C_2 X^2 + D_2 X + E_2 t \cdots \cdots$$
(8)

$$T_1(X,t) = \left\{ \sum_{n=0}^{\infty} [a_1 \cos \lambda_n X + b_1 \sin \lambda_n X] (1 - \lambda_n^2 \propto_1 t) \right\} + C_1 X^2 + D_1 X + E_1 t \cdots \cdots \cdots \cdots$$
(9)

$$T_2(X,t) = \left\{ \sum_{n=0}^{\infty} \left[ a_2 \cos \lambda_n \sqrt{\frac{\alpha_1}{\alpha_2}} X + b_1 \sin \lambda_n \sqrt{\frac{\alpha_1}{\alpha_2}} X \right] (1 - \lambda_n^2 \alpha_2 t) \right\} + C_2 X^2 + D_2 X + E_2 t (10)$$

$$T_{2}(-L_{2},t) = \left\{ \sum_{n=0}^{\infty} [a_{2}\cos\lambda_{n}\sqrt{\frac{\alpha_{1}}{\alpha_{2}}}(-L_{2}) + b_{1}\sin\lambda_{n}\sqrt{\frac{\alpha_{1}}{\alpha_{2}}}(-L_{2})](1-\lambda_{n}^{2}\alpha_{2}t) \right\} + C_{2}L_{2}^{2} - D_{2}L_{2} + E_{2}t \cdots$$
(11)

#### Final Solution for analysis

 $t = time(\mathbf{S})$ 

 $K_1, K_2 = Thermal Conductivity values of Metal and Coating respectively($ **W**/**mK**)<math>Q = Constant Heat - flux given to Metal(**W**/**m**<sup>2</sup>) $<math>\lambda_n = Eigen values obtained from initial conditions, b_2, C_1, C_2, D_1, D_2, E_1, E_2 = Constants$ 

The equations 1-6 are solved to obtain final solution for analysis as shown in equation 13. The equation 13 is combined with experimental results to obtain the thickness of the coating  $(L_2)$ .

#### Experiment

In-Situ examination of high temperature resin coating having different diffusivity and conductivity material will be characteristed for estimating the thickness of the material. A constant heat flux from high powered lamps is applied on metal substrate. Study made on three samples with different coating thickness to validate experiments. Experimental setup consists of High speed Cedip 5500M camera, IRNDT software for acquiring and post analysis of signals and dedicated PC. Camera was calibrated using Altair software and camera Integration time was adjusted for specific application and frequency of 50Hz used. During experimentation constant heat flux was applied on sample for 110 seconds acquiring 5500 frames. Temperatures on sample were recorded at different locations using mid wave Cedip5500M camera. The experimental set up is shown in Fig.2.The temperature profiles with respect to frames are shown in Fig.3-5. For verification of coating thickness, eddy current testing is carried out on the 3 coated samples for thickness measurements. The values from both the methods are compared and shown in §Results and Discussion.





Fig2: Experimental set up and data logger for injection of heat on metal substrate and receiving of heat on coating substrate

Three aluminium substrates coated with a heat resistant coating of different thickness were exposed to constant heat fluxes of value 0.2KW, 0.3KW, 0.4KW and 0.5KW power rating. Each metal substrate sample is of dimensions 75mm\*75mm\*2mm was taken. The samples were designated as sample1, sample2, sample3. The constant rises in temperature on individual samples were studied using two heat fluxes of 0.4KW&0.5KW, 0.2KW&0.3KW and 0.25KW&0.3KW, respectively. The delta 't' temperature difference in respective power rating were ploted and shown in Fig6-8. The thermal profile of the outer surfaces of coating for different heat fluxes are shown in Fig3-5.

#### **Results&Discussion**

The two thermal profiles of a sample for two different heat fluxes were taken. As shown in equation 13, the first term  $f(\alpha_1, \alpha_2, K_1, K_2, L_1, L_2, t)$  of is independent of heat flux. Therefore, the difference of two thermal profiles of different heat fluxes of same sample can give the relation between the thermal diffusivity, thickness, heat flux and time. The temperature differences ( $\Delta$ T) against number of frames (N) exhibit a linear relationship and falls in line with derived equation 17.

 $\mathbf{Slope} = \frac{(Q_1 - Q_2) \propto_1 \propto_2}{(K_2 L_2 \propto_1 + K_1 L_1 \propto_2) * frequency};$ 

 $Intercept = \frac{(Q_1 - Q_2) \alpha_1 L_2^2}{2(K_2 L_2 \alpha_1 + K_1 L_1 \alpha_2)}$ 

 $\frac{Slope}{Intercept} = \frac{2*\alpha_2}{L_2^2*frequency}$ 

.....(18)

The temperature difference Vs. number of frames graph is plotted for three samples are shown Fig.9-11.

The thermal diffusivity value of the coating was found to be  $2.5*10^{-9}$  m<sup>2</sup>/s. Several experimentation values were evaluated for validation and found to be constant throughout the test sample. The thickness values obtained from the experiment & mathematical model are compared with eddy current thickness and as shown in Table1.

Table1:					
Sample No	Slope(°C)	Intercept	Thickness(micro m)	Eddy current	
•	/	•	· · · ·	thickness (micro m)	
1	0.0004	0.1821	213	225	
2	0.0001	0.3787	615	625	
3	0.00007	0.7843	1058	1010	

The thickness values of three samples obtained from experiment and analytical values are matching the thickness values from the eddy current values. The small error also can be quantified taking radiation losses into consideration. Further, this experimental procedure is applicable to conductive and non-conductive types, as the technique uses thermal properties of material. The technique is simple and fast as it takes few seconds for experiments..

# Conclusion

The technique helps in knowing facts:

- 1. The technique is unique in its approach for finding diffusivity of known and unknown materials In-situ.
- 2. Arriving theoretical values with the technique is fast
- 3. Method of finding theoretical values is easy
- 4. With the help of this technique diffusivity values of defects can also be found, which will help in characterising the defects like crack,gas, air inclusion
- 5. This technique is unique in approach and can be utilised for design and assessment of the component for use in high temperature applications.
- 6. The technique can be conviently applied over conductive and non-conductive coating without worrying for nature of substrate material used.

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Fig 3: Temperature on coating surface with respect to frames on sample 1 with heat fluxes of 0.4 and 0.5KW



Fig 4: Temperature on coating surface with respect to frames on sample 2 with heat fluxes of 0.2 and 0.3KW



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Fig 5: Temperature on coating surface with respect to frames on sample 1 with heat fluxes of 0.4 and 0.5KW





Fig 6:  $\Delta T$  Vs no of frames for sample 1 for two different heat fluxes



Fig 7:  $\Delta T$  Vs no of frames for sample 2 for two different heat fluxes



Fig 8:  $\Delta T$  Vs no of frames for sample 1 for two different heat fluxes