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Numerical investigation on laser stripping of thermal barrier coating

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ABSTRACT

Thermal barrier coatings (TBC) are extensively used in turbine blades to improve the energetic efficiency of turbines. For repair and reuse of the TBC aerospace components it is necessary to remove the coatings. Present coating stripping process includes, acid stripping and grit blasting of the components which often cause metallurgical damage and dimensional changes. The laser based coating stripping process has recently gained increasing interest due to its high speed, flexibility and ease of automation, although thermal damage pose the biggest threat to its implementation as a replacement to excising machine process. In order to control the thermal damage and improve quality, it is important to understand the fundamental mechanism involved in the laser stripping process. Based on finite element analysis (FEA), a three-dimensional model for simulating the transient temperature field, residual thermal stress and subsequent material removal has been developed to understand the influence of transient thermal characteristic and thermo-mechanical effects on material removal. In addition to the transient temperature field, the model also predicts the dimensions of the ablated profile and substrate thermal damages that occur during the laser stripping process. Experimental results obtained with same process variables using a nanosecond pulsed laser were used to validate the model. Based on the investigation, the mechanism of the material ablation in the laser stripping of TBC is proposed.

1. Introduction

In the hottest portion of the modern gas turbine engines, metallic materials are used at gas temperatures above their melting points. Current technological advancement for the necessary heat insulation of these engines is the use of ceramic thermal barrier coating (TBC) which protects the metallic substrate materials from direct exposure to high temperatures. Also the TBC increase thermal efficiency, provide increased engine reliability and reduce fabrication cost by eliminating elaborate cooling schemes [1,2]. The TBC system consists of three layer materials made of a TBC top layer, a bond coat (BC) interlayer and the substrate under-layer.

One specific application of TBC is the turbine blades inside the combustion chamber of an aero engine. The temperature inside the combustion chamber is well above the melting temperature of the nickel alloys and the TBC over the surface provides a thermal insulation to the metallic blades. The high temperature gradients, cyclic heating and cooling of the material and the thermal expansion (between the metallic substrate and ceramic coating) results in generation of residual stresses in TBC, which eventually damage the coating with defects, like crack or spall. The general practice is to refurbish these components, subject to check of creep limit of the component and any severe erosion or damages. For repair and reuse of the turbine blades, it is mandatory to completely remove the defective coating so as to recoat with a layer of new coatings before returning to service. Therefore, controlled removal of TBC plays a significant role in reuse of turbine blades in aerospace and power generation sectors. For most applications, it is desirable to remove both TBC and the BC for better adherence of the coatings. There has been an on-going search for a successful, rapid and controlled process to selectively remove the TBC coating layers from the base material.

Presently, the removal of TBC is performed using conventional methods such as grit blasting, high pressure water jet or chemical processes [2–5]. In most cases these conventional processes are inefficient, expensive and labour intensive. In addition, damage to the bond coat/or substrate becomes inevitable due to the poor in-process control [2] associated with the conventional methods. Laser stripping/ablation have attracted much attention in science and engineering [6–8] because of its advantages for high speed processing, selective removal on small areas and elimination of hazardous chemicals. Ultra-fast lasers in ns range are preferred for laser stripping process due to its low interaction time which

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help to remove the material in a well-controlled manner without substantial thermal damage to the substrate [9,10].

Laser stripping of TBC has a good potential of becoming an excellent alternative to the conventional methods. During the laser stripping processing, the thermal effects need to be confined within the TBC layer. Any thermal damage on the base material significantly affects the performance of the component. Simulation of the laser stripping process is therefore required not only to understand and control the stripping process, but also to predict the substrate temperature and to control the laser process parameters. Also, the numerical simulation is expected to provide a better understanding of the embedded phenomena and mechanisms in laser interaction of TBC coating.

Former studies on thermal predictions of laser processing were primarily focused on CW laser macro processing [11–18]. Yung et al. [19] reported theoretical and experimental results on the thermal aspects of Nd:YAG laser ablation of polyimide based on analytical formulations. Though, his model predicts the temperature change with pulse duration, transient thermal effects were not considered in his model. Schäfer et al. [20] developed a hybrid simulation consisting of coupled finite difference and molecular dynamics modelling for picosecond laser ablation of metals. He predicts the ablation threshold and surface temperature of the copper crystallite, but his model is based on one dimensional formulations. Oliveira and Vilar [21] presented a 2D FE model for simulating the pulse laser ablation of titanium carbide. His model predicts the temperature distribution for various pulse durations and wavelength.

Although there were few models on the laser ablation of metals, the investigations into the thermal and ablation phenomena of TBC is still in its early stages. In this paper, a three-dimensional (3D) FE model is developed to predict the transient temperature and subsequent material removal that happens during the laser stripping of TBC material. Two models were considered. The first model is to understand the basic mechanism of the TBC removal and to study the effect of laser parameters on TBC ablation characteristic. The second model analyse the effect of TBC removal on substrate damage (thermal) characteristic. A commercial FEA program (ANSYS) is used for this purpose utilising its parametric design language. The model represents a heterogeneous mesh (TBC, BC and substrate) with anisotropic material properties. The numerical approach used enables efficient prediction of material removal during the process in a pulsed moving laser beam. The ablation depth is predicted by the FEA model at the end of each time step, and is not pre-defined. The experimental results obtained with a diode pumped solid-state (DPSS) laser, was used to validate the FEA results under similar processing parameters.

2. Finite element model

The finite element programming language ANSYS [22] was used to perform the analysis. The target was represented by a mesh of finite elements that changes over time so as to simulate the transient thermal profiles and transient ablation characteristic. The material properties used for the yttria stabilized zirconia top coating, NiCrAlY bond coating and Inconel substrate is adapted from Song et al. [23]. Variable meshes, with very fine mesh at the coating and course mesh expanding gradually away from the top were used to obtain improved accuracy with the limited elements. The use of a thinner mesh in the upper part of the substrate allows a more precise estimation of the material removal. Fig. 1(a) shows the domain used in first part of the simulation. The objective of this simulation is to understand the material removal characteristic of the TBC, hence to moderate the computational time, a reduced domain consisting of only the TBC layer (as shown in Fig. 1(b)) was used for the first part of the analysis. Fig. 1(b) shows the finite element mesh (case-I) with 94,500 quadrilateral elements that was used for the FEM analysis. The latter part of the simulation (case-II) deals with a domain consisting of all three parts (Fig. 1(c)), viz. the bottom Inconel substrate, middle NiCrAlY bond coating and yttria stabilized zirconia top coating.

The transient thermal problem was solved with varying boundary condition and time step in according to the laser pulse shape and number of pulse. The number of pulses incident at each beam spot was calculated according to the scanning speed and pulse length, i.e. 42 ns. Appropriate dwell time has been used between consecutive laser passes to compensate the actual experimental length (50 mm). The time steps are linked to each other by using the output of time step *ts* as the initial conditions for time step (*ts* + 1). The workpiece is initially at a temperature of 298 K.

The governing equations for the three dimensional transient heat conduction can be expressed as [24]:

$$\text{TBC}: \quad (\rho c)_{TBC}\frac{\partial T}{\partial t} = \frac{\partial}{\partial n}\left[k_{TBC}\frac{\partial T}{\partial n}\right] + Q(t)(1 - R_{TBC}) \tag{1}$$

$$\text{BC}: \quad (\rho c)_{BC}\frac{\partial T}{\partial t} = \frac{\partial}{\partial n}\left[k_{BC}\frac{\partial T}{\partial n}\right] + Q(t)(1 - R_{BC}) \tag{2}$$

$$\text{Substrate}: \quad (\rho c)_{S}\frac{\partial T}{\partial t} = \frac{\partial}{\partial n}\left[k_{S}\frac{\partial T}{\partial n}\right] + Q(t)(1 - R_{S}) \tag{3}$$

Subscripts TBC, BC, S represents the thermal barrier coating, bond cote and substrate respectively. T, t, k, ρ, c, Q, R and n denote temperature, time, thermal conductivity, density, specific heat, heat flux from laser, reflectivity and directional vector (x, y, z) respectively. The reflectivity of TBC, BC and substrate used for the simulation has been experimentally measured using Jena Analysis Specord 250 UV Spectrophotometer and found as 88%, 92% and 94% respectively corresponding to 1064 nm wavelength.

During the analysis, if the temperature of an element is higher than the melting temperature (Tm) at the end of a particular step, melting is assumed to have occurred and the latent heat of melting (Lm) is taken into account in the calculation. Similarly, vaporisation/ablation is assumed to occur when the temperature of the elements is higher than the boiling temperature. The 'element death' methodology (available in ANSYS) was used for simulating the material removal by vaporisation. Such an element was considered to be dead, with insignificant effect in subsequent analysis. The heat flux Q is assumed to be a top hat distribution and is applied as a surface heat flux. The applied heat flux surface region was not predetermined and was calculated by the program in a transient manner according to the shape of the ablated profile as elucidated in Fig. 2. During the initial start of the simulation, the heat flux is applied over a flat surface. As the simulation proceeds, due to the material ablation the TBC surface geometry changes, and subsequently, the laser beam heat flux surface also changes as shown in Fig. 2(b). The optical penetration depth of TBC, BC and the substrates were in the rage of 600–800 nm, which is an order of magnitude less than the thickness of the element ($\sim$3 μm) and the assumption of laser energy as a heat flux seems reasonable.

The initial conditions for the thermal analysis were taken as

$$T(n,0) = 298\,^{\circ}\text{K} \quad \text{and} \quad T(\infty,t) = 298\,^{\circ}\text{K} \tag{4}$$

Boundary condition for the laser irradiated surface was

$$k\frac{\partial T}{\partial n} = Q(t)(1 - R) \tag{5}$$

For all other surfaces the boundary condition was

$$k\frac{\partial T}{\partial n} = -h(T - T_{\infty}) \tag{6}$$