unsteady inDuction heating in Two-layered slabs: an analytical solution for thermal resistance measurement in tbc-coated turbine blades

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| Shani Eitan, Technion - Israel Institute of Technology | Beni Cukurel, Technion - Israel Institute of Technology |

Abstract

This research introduces an exact analytical solution for the unsteady induction heating of a two layered slab representing a thin coating problem. The known heat transfer equation is solved for the nonhomogeneous case with oscillating heat generation term representing electrical power produced by induction heating. Current solutions of induction heating treat steady state cases only, with one layer of metal. This unique case of boundary conditions can serve as a new methodology for measuring thermal properties of TBCs, however other applications are of necessity for internal heating. Analytical solution results revealed the relations between electrical parameters such as frequency and amperage, coating thermal properties such as thickness and thermal diffusivity, and surface temperature signal amplitude and phase, thus enabled defining optimal methodology configuration. Suitable coil geometry parameters were defined by the number of turns and by overall dimensions. Additionally, a numerical solution was conducted to evaluate the validity of the analytical solution, together with further enhancement of the desired induction heating system characteristics, by estimating heat losses represented by system efficiency factors. Optimal coil geometry was optimized to produce sensible temperature fluctuations response, as well as modulated frequencies range for a typical specimen size representing an engine turbine rotor blade coated by a TBC. The numerical solution was found with a good fit to the analytical model, allowing the authors to safely rely on it for the experimental setup stage of the research.

introduction

In applications containing hot parts such as gas-turbine engines, ceramic coating layers are applied to metals to provide thermal protection achieved due to its low conduction and diffusivity coefficients. There is a high demand for acquiring thermal properties data in both production and service phases. In the realm of coating thermal properties measurements, this kind of application require multi-layer thermal analysis involving parent material internal excitation for measurement as well as for design purposes. While there are several other ways to do this, all contemporary methods found in the literature propose applying the boundary conditions such as heating through the outer surface either by laser irradiation or by applying waves in by other medium propagation methods such as sound waves. These methods necessitate passing through the outer layer of the material, although this is not desirable. In this study we aim to propose a different and unique method for internal activation of boundary conditions inside the parent material by means of time-dependent oscillatory electromagnetic induction heating. This way, accuracy is expected to increase as we avoid inherent error resulting from excitation source wave passing through the TBC. Additionally, this methodology can potentially be applied in-situ, as it requires less support equipment compared to other methods.

RESULTS and DISCUSSION

Repeating the solution for several different diffusivities, and TBC thicknesses showed the effect of diffusivity over phase. As most would expect the phase decreases when increasing diffusivity and increases when increasing thickness. The analytical solution also allows assessing the required frequency limit to use for typical hot engine parts materials, i.e., Inconel parent material, and YSZ TBC. It was found that for those materials, heat source modulated frequencies above 1[Hz] will not yield measurable surface temperature oscillations response. The analytical solution is then further expanded with a more complex heat generation term including modulation of the heat source. The use of modulated signal is required for use of two frequencies, as there are two important frequencies in the measuring process: modulated signal (0-1[Hz]) for the methodology sweeping, and carrier signal (~140[kHz]) for Inconel induction heating. We found that the response is not affected by the level of the high carrier frequency. Numerical solution was conducted using COMSOL for several models: steady and unsteady loading, 2D and 3D geometry, evaluating the sensitivity of the response to different induction coil shapes, electrical loading and specimen thermal properties. Optimal coil 'pancake' shape was found for the process, and loading for typical engine hardware was defined. It allows to apply a novel internal boundary condition which can serve for a variety of applications such as measurement of thermal properties via induction phase radiometry.

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| **Figure 1. Left: Example of temporal Evolution of Energy Signal Input and Thermal Response Output and the time phase between them for SET#1 and fm=0.2 Hz. Right: Comparison between analytical solution and numerical solution for different efficiency factor** |