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Review

Nondestructive technique of measuring heat conductivity of thermal barrier coatings

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ABSTRACT

A non-destructive technique for measuring **effective** thermal conductivity of thermal barrier coatings (TBCs) was developed. The heat conduction problem in the sample is solved numerically, making this technique applicable to bodies of elements shape covered by TBCs. The principle of the experiment relies on locally heating the sample by a laser flash and recording the time and space variation of the so generated temperature field on the heated surface by an IR camera. Both laser and camera are located on the same side of the heated surface. The thermal conductivity is retrieved by an inverse method where the Finite Element solver is invoked iteratively minimizing the discrepancy between the measured and simulated results. The geometry of the sample is captured by a laser scanner twice: before and after the TBC is deposited. Results are compared with measurements conducted by a commercial Laser Flash Apparatus (LFA) achieving good agreements.

Contents

1. Introduction

Increasingly stringent environmental regulations force the power generation sector to improve the efficiency of fuel-conversion processes and limits emission of harmful pollutants to the atmosphere. Increasing the temperature of combustion enhances the efficiency of power generation, the limits come from the temperature resistance of material of construction. The turbine elements directly exposed to the influence of extremely high temperature are combustion chamber and first stages of turbines. High temperature cause faster degradation, creeping or thermal fatigue of these elements [1,2].

One way to minimize these harmful effects is the application of thermal barrier coatings (TBC). Thin layers of such low conductivity materials protects the substrate from the direct contact with hot gases. *Yttria-stabilized zirconia* e.g., *7YSZ* or *8YSZ* are routinely used to insulate gas turbine components from excessive heat loads.

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Due to the role of TBCs the assessment of their performance is in high demand by industry. One of the crucial parameters characterizing the quality of TBCs condition is thermal conductivity (TC). Due to different modes of heat transferactive within the dense zirconia ceramics, the effective thermal conductivity is measured [3]. Actually, this is the parameter, that is used in standard engineering simulations of heat transfer within the turbine blades. Because, the zirconia ceramic materials at high temperature are partially transparent for radiative transfer the internal radiation effect is increased. In consequences the insulating abilities of the coating material are degrading [4]. All heat transfer modes which can occur within porous zirconia ceramics exposed oto high temperature condition that can occur within advanced turbine engines were widely discussed in [5–7].

Techniques of rapid, non-intrusive and reliable measuring of TC are still not satisfactory developed. The main reason for this is the need of handling arbitrary geometries of the TBC covered parts. The currently used techniques of measuring TC of solids are, as a rule, time consuming, require expensive research infrastructure and qualified staff. Moreover, only very few methods are nondestructive.

Depending on the temporal dependence of the temperature field in the sample during the experiment, the available methods of measuring TC fall into three categories: steady state, periodic and transient. Extensive survey of two first techniques is given in Ref. [8–11]. The main advantage of the transient methods [12–15] is a relatively short time required to run the experiment, insensitivity to boundary conditions and wide range of temperatures the method can be applied. Moreover, as the temperature fields can be acquired at every time instant, transient methods collect more measurement data than their steady state counterparts. The inverse technique where these data are used, produces then more stable results.

One of the most popular transient techniques is the laser flash [16] method, that became an ASTM standard (E1461). The principle is to heat the front surface of the small, regular shape sample by a short laser impulse, while recording the resulting temperature excess of the rear side. Though the technique is destructive (requires extraction of samples from the original part), due to its simplicity and rapidness, it is very frequently used both in research and industry. The literature reports about numerous attempts enhance it [17–19]. The limitation of this approach comes from its destructive character and simple mathematical model not applicable to arbitrary shapes. As the temperature is measured on the rear side of the heated surface, the probes cannot be too thick.

Some other technique which can be applied to measure the thermal conductivity of the TBCs is the photo-acoustic method [20,21]. The technique requires extraction of samples, thus its application to real element is limited.

Another measurement technique which can be used for direct measurement of thermal conductivity of the TBCs is descibed in [22]. This measurement technique is known as photothermal emission analysis (PopTea). It utilizes harmonic laser heating and interrogates the temperature field through the phase of thermal emission from the coating.The method is non-destructive [23] and can be applied to serviceable engine components. The mathematical model used for retrieving TC by fitting the simulated temperature field to experimental data is described in Ref. [24].

The proposed technique belongs to the laser flash methods and is an extension of the earlier works of the team of authors of the present paper [25,26]. The motivation of these works was to develop a non-destructive, rapid and accurate technique to measure the thermal conductivity of samples of arbitrary shape. For that purpose the experimental rig was developed. Although classic Parker's method i.e., short time laser heating is at the root of the proposed technique, there are two important features that distinguish these two approaches.

- the temperature sensor, here an IR camera, has been located on the same side of the probe as the heated surface;
- numerical solver has been applied to retrieve the temperature field in the probe.

Owing to these modifications, the sample may be of arbitrary shape and as such need not be extracted from the original parts. The technique is thus nondestructive. As in the case of the classic Parker method, the experiments take only few seconds.

The geometry, being the input to the numerical solver, is captured by a standard 3D scanner. The TC is then retrieved by Levenberg Marquard inverse method [27]. Within the iterative loop of this technique, a direct numerical solver is invoked, yielding the temperature field in the substrate and TBC. Special definition of variables (nondimensional temperature) makes the inverse technique insensitive to the emissivity of the surface and the laser energy absorbed by the sample. It is worth mentioning here that the method has already been successfully applied to retrieve TC of cuboid anisotropic bodies. It was however not used to retrieve the TBCs thermal conductivity and bodies of arbitrary shapes.

2. Experiment

The developed experimental rig can be used to measure TC of elements of arbitrary shape covered by thermal barrier coating. The apparatus is shown in Fig. 1. As the heat source the IPG Photonics laser is used, which can operate in power range from 20 W to 200 W with adjusted emission time period. Both parameters ensure that the power of the laser pulse can be appropriately adjusted to the expected material properties. The spatial and temporal temperature distribution after laser emission is recorded by the Infrared (IR) camera (FLIR A325, Flir Systems, Inc., USA) working with 60 frames per second frequency. The measurement and data acquisition processes are controlled using an *in-house* PC application written in LabVIEW environment (National Instruments Corp., USA). To reduce the geometrical distortion of both the spot of the laser ray and the image of the temperature field, the optical axis of both devices are orthogonal to the heated spot. To achieve this effect the laser ray impinges the probe in the direction of the local normal surface of the sample. Then the probe is rotated by a small angle so that the optical axis of the camera coincides with the local normal at the impingement point. The rotation is driven by a step motor (see Fig. 1).

The subsequent steps of measurement procedure are:

- scanning the geometry of the sample;
- positioning the sample local normal so that it points to the center of the IR camera lens;
- recording initial temperature field;
- rotating the sample to bring the local normal to a position parallel to the laser optical axis;
- heating the sample by laser pulse;
- moving sample back to previous position with sample normal centered at the camera lens;
- recording spatial and temporal distribution of the temperature on the heated surface.

After all data are collected the recorded thermograms are converted to a format suitable for the inverse procedure. The inverse procedure written as an external code invokes Ansys Thermal package as a heat conduction solver. The computational algorithm used for retrieving the TDs of both materials is described in the next section. To measure the TD of the TBC the measurement