Publishable Summary for 15SIP05 TBCUnc
Advanced uncertainty evaluation: example and software for industrial uptake

Overview

Dissemination of measurement results and reliable decision-making require harmonised treatment of uncertainty. The current state of the art for uncertainty evaluation in metrology is provided by the Joint Committee for Guides in Metrology (JCGM) Guide to the expression of uncertainty in measurement and its Supplements, which are currently successfully applied in many but not all areas of metrology. EMRP project NEW04 developed new approaches to address uncertainty evaluation for inverse problems and for computationally expensive problems. Many industries incorporate finite element analysis in their design processes, a prime example of a computationally expensive model solved using “black box” software, and one whose results are commonly used for decision making without an associated uncertainty evaluation to support those decisions. This project aimed at facilitating the uptake of the outputs of EMRP project NEW04 by industry by providing a case study and associated freely available software.

Need

Thermal barrier coatings (TBCs) are used to protect expensive components, such as turbine blades and car engine parts that operate in high-temperature environments from thermal load and chemical damage. Thermal conductivity is a measure of how rapidly a material transports heat and is a key property affecting TBC performance. TBCs have a layered structure and thermal conductivity values of individual layers are challenging to measure.

Thermal conductivity is often derived from measurements of thermal diffusivity, which for homogeneous materials at high temperature is commonly measured using the laser flash technique. A method exists in the literature to derive the properties of individual materials of a layered sample from laser flash measurements. However, the uncertainties associated with these values are typically estimated using approximate methods and in practice are often overestimated to produce a “safe” uncertainty for decision-making purposes. The primary supporter of this project has stated a need to:

- improve the process of specification of TBCs and assessment of nonconforming coatings, thus reducing waste during manufacture and supporting the development of improved measurement methods for TBCs in future,
- increase the confidence in decisions made at the design stage, such as choice of thicknesses, thus reducing design time and hence cost, and
- plan their TBC development programmes and testing campaigns more efficiently, thus reducing time to market for products.

The work in EMRP project NEW04 has provided a more rigorous calculation method for uncertainties associated with thermal diffusivities and conductivities of the components of TBCs and has demonstrated this method for a simple layered system. However, it has not applied the method to a real industrial problem. Provision of software and a worked example of the method were needed to enable industrial users to apply the algorithms generated in EMRP project NEW04 to their problems without needing expert mathematical knowledge, maximising the ease of take-up.

Objectives

The objectives of the SIP were to:

1. Encourage the take-up of the outputs of EMRP NEW04 by publishing a trade journal article describing a clear, well-defined method for users to evaluate thermal conductivity and associated uncertainties of the components of a TBC system from laser flash measurements. The method should be applicable to any layered material that can be measured using the laser flash technique.

2. Remove a key barrier to uptake of the first objective by creating freely available software that automates the mathematically challenging aspects of the calculations, the software being promoted via the trade journal article and through other appropriate channels.

Results

Objective 1: impact through a trade journal article

The first objective was to be achieved by applying the methodology addressed in project NEW04 to historical data measured on a typical TBC system during EMRP project ENG06 and reporting the results and subsequent benefits to the primary supporter in a trade journal article.

The initial work has assessed the available historical data to ensure its fitness for use. The measurements of thermal diffusivity made during EMRP project ENG06 have been shown to be suitable for the techniques used in the project, and estimates for the thermal conductivities of individual layers of the TBC system have been obtained.

Statistical characterisation of the relevant uncertain input quantities has led to a suitable set of input distributions for the quantities of interest. The characterisation has followed the recommendations in Guide to the Expression of Uncertainty in Measurement (GUM) Supplement 1, and has incorporated image analysis techniques for determination of layer thicknesses, expert advice from metrologists on experimental uncertainty, and an analysis of literature data for the yttria stabilized zirconia coating. The procedure followed and the distributions obtained were presented to an audience interested in simulation for engineering at the NAFEMS World Congress 2017, and an associated paper appeared in the proceedings.

A sensitivity analysis has been carried out to identify the most important input quantities. The results of this work are consistent with the previous work on this experiment, in as much as they indicate that sample radius has little effect on the parameter estimates, but the results have also identified some interesting links between the inputs and the outputs that should be further explored.

The uncertainty evaluation method was then applied to the historical data to obtain uncertainty estimates using the input uncertainty estimates described above. The resulting best estimate of the thermal conductivity of the top coat was much higher than was expected from expert opinion and literature values. This disparity made publication of the intended journal article inappropriate.

Objective 2: impact through freely available software

The second objective was achieved by creating software to automate the mathematically challenging steps of the uncertainty evaluation methodology. Existing routines were linked and suitable input and output routines were prepared, based on guidance from the primary supporter. The improved software has been made freely available for download on this project's website. The software was promoted to several different audiences with potential interest in thermal simulation via presentations, including a webinar for users of the COMSOL finite element package and a UK industrial advisory group. The uptake of the software has been somewhat limited to date and so little useful feedback is available to improve the software.

Impact

The early outcomes of this project were disseminated to an audience from a range of industry sectors at the NAFEMS World Congress held in Stockholm in June 2017. The presentation described the project and explained how the challenges of going from information to an input distribution have been addressed for the quantities of key importance to the model. NAFEMS is an international organisation promoting good practice in use of finite element and similar modelling techniques for engineering simulation, and has a membership drawn from most sectors of industry, international academia, and software vendors.

The software has also been promoted to users of the FE package COMSOL Multiphysics via a webinar "Simulating Heat Transfer: Knowing Your Material Properties", to attendees of a meeting of the Foundations Of Measurement working group of the German Society for Measurement and Automatic Control, and to a UK industrial advisory group on Thermophysical Properties. Key stakeholders interested in thermal barrier coating characterisation were contacted by email directly to promote the software.

The core routines in the software will be extended and reused within the EMPIR project 17IND11 Hi-TRACE, which started in July 2018. The key extension to the code will enable layered material systems with debonds and poor thermal bonds to be simulated.

Project start date and duration	01 June 2016, 24 months	
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