FABRICATION AND CALIBRATION TECHNIQUES FOR TURBINE ROTOR TIP HEAT TRANSFER GAUGES

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ABSTRACT

This paper describes fabrication techniques that have been developed specifically for instrumenting an unshrouded turbine blade tip and the associated over-tip casing with high-bandwidth heat transfer gauges. The primary aim of the work has been to enable the deployment of high-density instrumentation on a part of the blade that is both remote from the traditional connecting wire locations, and of relatively small physical dimensions. For both the casing and blade-tip instrumentation, platinum thin-film resistance thermometers have been adopted. A new laser etching technique is described that is capable of producing these gauges rapidly, to high dimensional tolerance and at precisely known locations. Typically the gauges are 1 mm in length and 0.08 mm in width. The blade mounted heat transfer gauges are formed on an electrically insulating enamel coating while the casing gauges are mounted on a Macor (machineable glass ceramic) substrate. A calibration technique for the two-layer blade mounted instrumentation is also described.

INTRODUCTION AND BACKGROUND

A significant body of work has been reported in the last three decades that relates to the measurement of time-resolved heat flux levels on both rotating and stationary turbine components. For example, the work of Ainsworth et al (1989), Dunn (1990). This work has traditionally relied on the thin-film resistance thermometer as a means of establishing the surface temperature history of the component under test; from this parameter the surface heat flux can be determined by assuming one-dimensional heat conduction into a semi-infinite substrate. The emphasis in the literature is clearly on the measurement of heat flux to the aerodynamic surfaces of vanes and blades, and only a small number of reported works cover the increasingly important area of heat transfer to the blade tips and casing over-tip regions (for example, Dunn, 1990 provides a limited data set). This situation coincides with the accumulation of a large amount of computational data for which there is little or no corroborating experimental data (for example, Ameri and Steinthorsson, 1995).

NOMENCLATURE

a	thickness of enamel coating
c	specific heat capacity
k	thermal conductivity
$\dot{q}$	heat transfer rate
s	Laplace operator
T	temperature
α	thermal diffusivity
ρ	density

Subscripts

1	relating to enamel coating
2	relating to metal substrate
s	relating to properties at the surface of a gauge

The Oxford Rotor Facility has for a number of years been used to investigate the aerodynamic and heat transfer performance of a turbine stage under appropriate engine operating conditions (Ainsworth et al, 1988). This facility operates on the transient principle, wherein the correct non-dimensional flow conditions are produced by an isentropic light piston tube for a period of approximately 100 ms. In this test facility transducer signals from rotating sensors are conditioned in the rotating frame of reference and passed to the stationary frame through slip-rings. Various rotating signal conditioning modules are available for use with pressure, heat transfer and hot-wire instrumentation.

The current programme of investigation is centred on a detailed investigation of the time-resolved heat-transfer levels to the turbine blade tip and over-tip casing. It is the development of appropriate instrumentation for this work that forms the central theme of this article. However, it is worth noting that the techniques currently being employed are based upon previous work in Oxford (Allen, 1990) that proved the concept of using enamel coated turbine blades for tip heat transfer measurements. A photograph of an instrumented blade used by Allen is shown in Figure 1a, and originally had 5

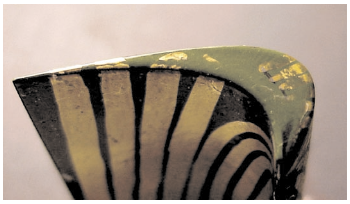

Figure 1a: A photograph of a turbine blade instrumented with 5 thin-film heat transfer gauges that was used by Allen (1990)

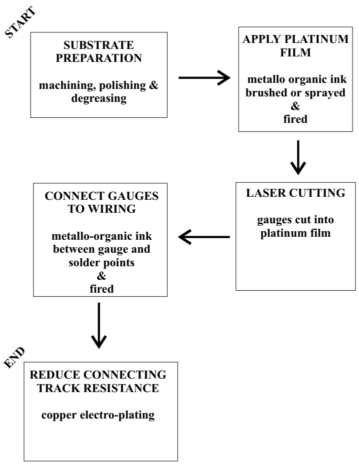

Figure 2: A flow-chart indicating the steps involved in fabricating miniature, high-density thin-film heat transfer gauges.

hand-painted platinum resistance gauges arranged over the tip. Typical data obtained with this instrumentation is shown in Figure 1b.

THIN-FILM GAUGE FABRICATION

Introduction

The approach previously employed in Oxford for conducting heat transfer measurements on rotating metal turbine blades has been to apply a thin, robust, electrically insulating coating to the surface of the blade and then to use fired metallo-organic inks to generate the thin-film thermometers and electrical connections (Ainsworth et al, 1989). A detailed discussion of the procedures involved in using metallo-organic products is provided by Ligrani et al (1982). The painting of the inks onto test models has traditionally been carried out by hand using fine brushes, a difficult and time-consuming process that produces gauges of approximately 0.5 mm width. The relatively small size of the blade tip (30 mm axial chord),

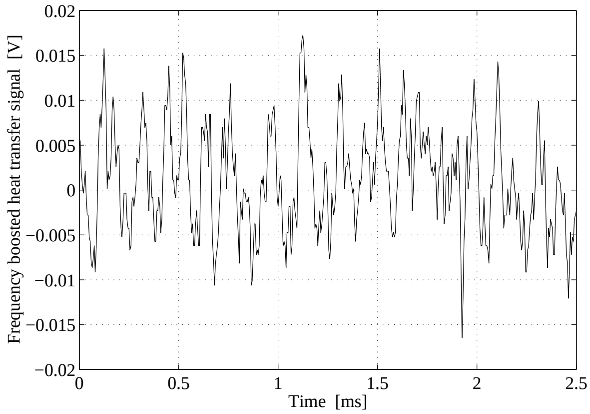

Figure 1b: A graph showing the measured heat transfer signal from a tip mounted thin-film gauge (after the work of Allen, 1990)

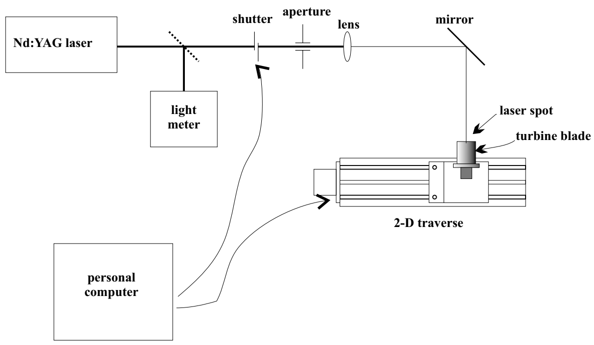

Figure 3: A schematic diagram of the apparatus used for laser cutting thin-film resistance thermometers.

coupled with the desire to deploy a large number of thin-film gauges (thereby maximising the information generated in each experiment) and the requirement of using miniature instrumentation to improve spatial resolution have rendered this approach redundant; consequently an alternative methodology has been sought.

The new technique for producing miniature, high spatial density thin-film gauges again relies on the use of enamel coated blades and fired metallo-organic inks, but exploits a laser ablation process to define the individual gauges and connecting tracks. This computerised system enables precise tolerance to be placed on both the gauge dimensions and position. For the over-tip casing, Macor machineable glass ceramic has been selected as the substrate, but again laser ablation is used to define the gauges in high-density arrays.

The Fabrication Technique

Shown in Figure 2 is a flow chart that describes the 5 basic steps involved in making miniature thin-film gauges with this new technique. The fabrication processes for both the blade-tip and casing heat transfer gauges are fundamentally the same; in the following description, any differences for the two cases will be highlighted as necessary.

Substrate Preparation

The electrically insulating substrate needs to be polished (Ligrani et al, 1982) and degreased prior to the application of metallo-organic inks. In the case of enamel coated blades, this is trivial owing to the excellent surface finish that is automatically produced in the fired ceramic. For machined components (such as those made from Macor) however significant effort needs to be expended using various abrasive compounds that remove any residual machining marks and then produce a high polish.

Application of Platinum Metallo-Organic Ink

The use of laser ablation to define the gauge and track locations means that the platinum ink can be applied as an extensive, uniform region, either by brushing or spraying (as opposed to hand painting individual gauges as has traditionally been conducted). Experience has shown that good uniformity can be achieved in the thickness of the platinum layer (and thereby final gauge resistance) by both of these methods. The ink employed is 05X, manufactured by Engelhard-CLAL. The firing profile for this material is well reported (for example, Ligrani et al, 1982). Successive layers of platinum ink are applied and fired until the appropriate film thickness (and thereby elecetrical resistance) is achieved.

Laser Cutting of the Gauge Outline

At this stage of the gauge fabrication process the model (blade or casing) is coated with an appropriate thickness of platinum over an area that covers the intended locations of thin-film gauges. It is now necessary to cut or etch the gauges out from this continuous film. This has been done by utilising the focused light beam from a pulse laser and arranging for the model to be moved relative to this cutting spot by a two-dimensional computer controlled traverse. The output energy from the laser can be adjusted such that ablation of the platinum layer is achieved without damaging the underlying substrate. A schematic diagram of the laser ablation apparatus is shown in Figure 3.

The laser system employed is a Q-switched neodymium YAG device that is capable of producing radiation at 532 nm with peak output pulse energy of approximately 200 mJ at 15 Hz repetition rate. The beam diameter at exit from the laser resonator is nominally 9 mm. This laser is perhaps not ideal for thin-film cutting due to its relatively low pulse rate, but it is however very reliable and a useful means of verifying the fabrication technique. Control of the laser ablation process is effected through two primary routes: firstly, by adjusting the energy in the laser output pulse (either by controlling the flash-lamp energy or use of absorbing filters), and secondly by using an aperture (Figure 3) to narrow the effective diameter of the beam. In this way the diameter of the focused cutting spot and the light energy incident upon that spot can be independently controlled. The spot diameter is typically 50 microns, although values as low as 25 microns have been shown to give acceptable results.

As indicated in Figure 3, the beam can be interrupted and prevented from reaching the model by a computer controlled shutter—this means that the laser can be run in a continuous and stable manner while gauge cutting can be independently turned on or off. Focusing of the beam is achieved using a simple symmetric singlet lens with a focal length of approximately 250 mm, the location of this item being shown in Figure 3.

The model onto which thin-film gauges are to be cut is held on a two-dimensional traverse that is actuated by stepper motors and a precision lead screw. The traverse motors are controlled by a personal computer that is also responsible for opening and closing the shutter. The step size of the traverse is nominally 5 microns in both horizontal and vertical directions, and a measured positioning repeatability better than 10 microns is typically achieved.

Connecting Tracks between the Gauge and Solder Points

Having formed the platinum gauges by laser cutting, it is necessary to complete the electrically conductive tracks between the gauge and solder points where wiring connections are established. This procedure is slightly different for the blade-tip and casing gauges. For the blade-tip, gold metallo-organic thin-films are fired onto the enamel surface between the tip-gauges and blade platform. Subsequently, individual tracks are formed from this film, again by using laser cutting. In the case of the casing, which is a large area with small degrees of curvature, the tracks are made at the same time as the gauges, and are initially cut from the platinum (see later). This approach to track layout means that virtually the entire surface of the blade or casing model is employed in connecting the gauges, and means that track resistances can be kept to the minimum value possible.

Reducing the electrical resistance of the Connecting Tracks

The electrical resistance of the connecting tracks between the thin-film gauges and solder points needs to be kept to a sufficiently low value, so that the sensitivity of the thermometer is restricted to the desired area. For both the blade and casing mounted instrumentation the method for achieving this is to use a copper electroplating process such that the resistance of the tracks is reduced to below 1% of the resistance of the gauge itself. Finally, an immersion gold plating process is employed that deposits a thin layer of gold onto the copper. This is done purely to stop oxidation and degradation of the low resistance copper layer.

BLADE-TIP HEAT TRANSFER INSTRUMENTATION

Introduction

Although the design of the layout of the gauge locations is currently ongoing, a prototype arrangement has been produced that employs 15 gauges along the mean camber line of the blade tip. These sensors are 0.8 mm long and 0.08 mm wide. The following section provides a detailed description of the stages in the fabrication process..

An overview of the fabrication

Shown in Figure 4a is a photograph of the bare metal Inconel blade prior to being instrumented. The surface of the blade is

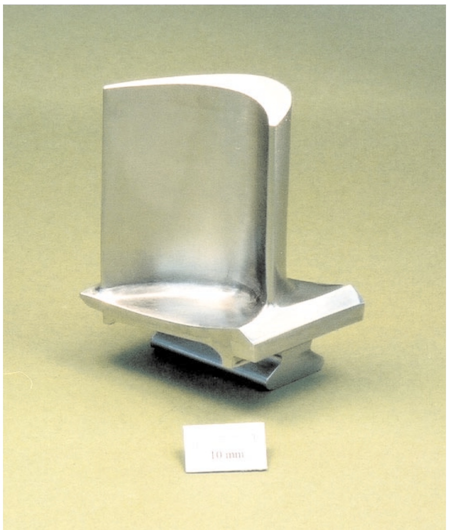

Figure 4a: A photograph of the Inconel 718 turbine blade prior to instrumenting

Figure 4b: A photograph of the turbine blade after application of the enamel coating

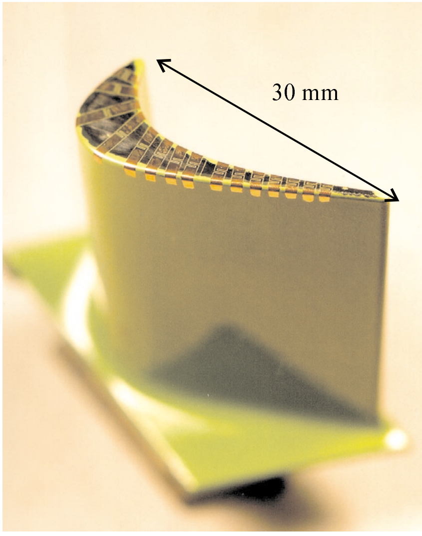

Figure 4c: A photograph of the tip gauges after laser cutting and application of gold tracks around the tip corner (15 thin-film gauges arranged along the tip mean camber-line.)

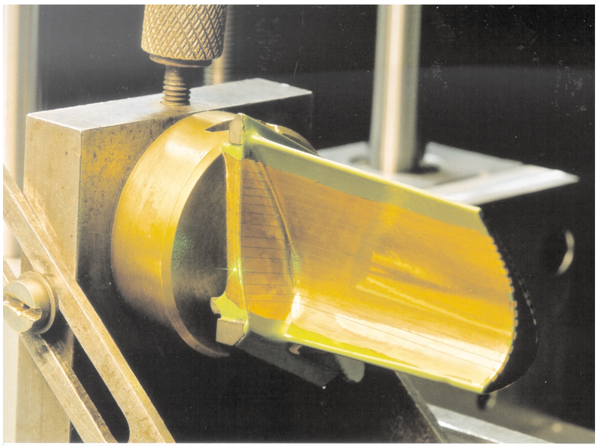

Figure 4d: A photograph showing the laser cutting of gold connecting tracks between tip thin-film gauges and blade platform. (The cutting spot is visible on the platform edge).

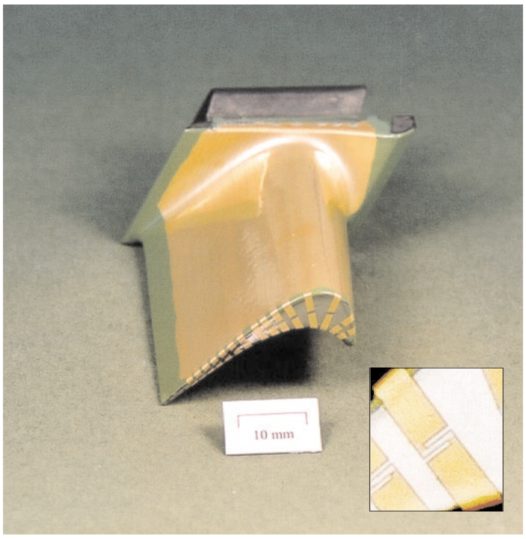

Figure 4e: A photograph showing the finished blade tip instrumentation and suction surface connecting tracks. Also shown is a close-up photograph of a thin-film gauge.

subsequently coated with vitreous enamel and fired (Ainsworth et al, 1989) which results in the electrical insulation of the blade surface (Figure 4b). The thickness of the enamel layer is typically 100 microns (Ainsworth et al, 1989). At this stage, the blade has an electrically insulating coating over the entire aerodynamic surface, including the tip itself. The enamel coating is also applied in a continuous fashion between the aerodynamic surfaces and the under side of the blade platform. In this way, electrical connections between the blade mounted gauges and external wiring looms can be made at solder points on the platform.

The next stage in the fabrication process is to apply the metallo-organic platinum ink to the tip surface and fire the blade; this process is repeated as necessary until the platinum layer has the appropriate thickness (this being determined from the film resistance). Experience has indicated the thickness of platinum required to give particular gauge resistances, and the amount of ink and number of layers that give rise to this thickness. The gauges on the tip can then be

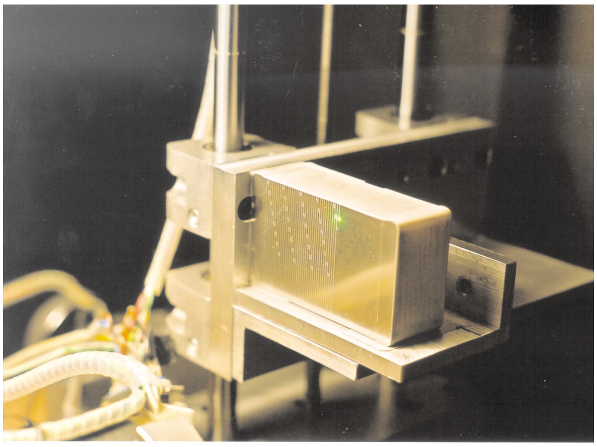

Figure 5a: A photograph showing the laser cutting of 56 thin-film gauges (8×7 array) on a Macor substrate.

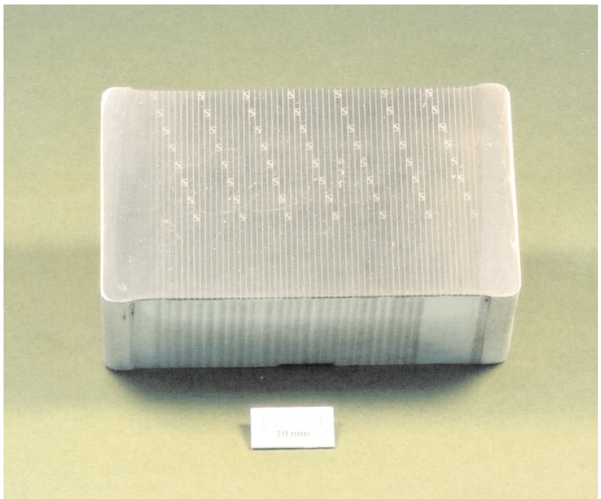

Figure 5b: A photograph showing the Macor block after laser cutting of the thin-film gauges into the platinum layer. Notice also that the connecting tracks are cut into the platinum layer.

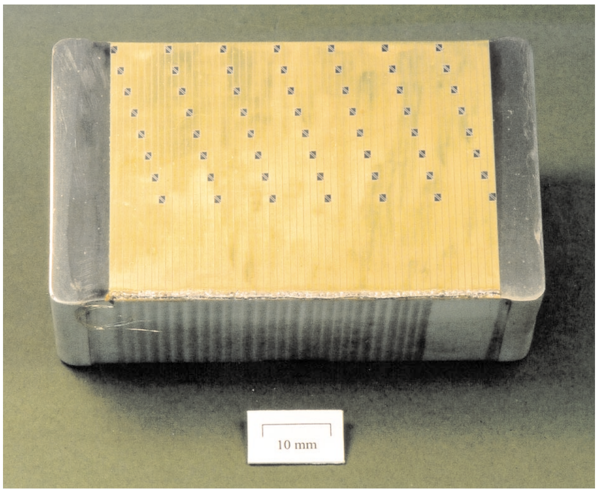

Figure 5c: A photograph showing the completed array of 56 gauges on a Macor substrate.

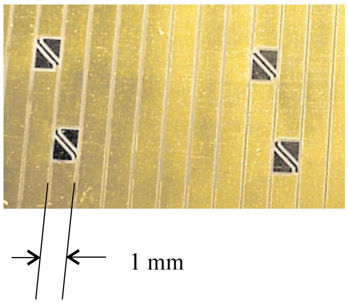

Figure 5d: A photograph showing a close-up view of 4 completed thin-film gauges on a Macor substrate.

laser cut using the apparatus described previously. A photograph of the blade at this point is shown in Figure 4c. In this photograph, 15 gauges are visible and are arranged along the mean camber line of the blade tip. The gauges are cut parallel to the local camber line direction. For each gauge, two electrical connecting tracks are required; one track is taken along the suction surface of the blade while the second is provided on the pressure surface. Also apparent in Figure 4c are gold connection tracks that have been applied to make electrical connection from the tip gauges, around the suction surface tip corner,and onto the suction surface of the blade (these being hand painted). Equivalent gold tip corner tracking is used on the pressure surface, but this is not visible in Figure 4c.

The connecting tracks between the tip gauges and the blade platform are made by firing gold metallo-organic ink onto the aerodynamic surfaces and then laser cutting individual tracks from this layer. A photograph of this laser cutting process is shown in Figure 4d. The cutting spot of the laser is visible on the edge of the blade platform. After this process has been completed, the electrical definition of each tip gauge is complete. Also, of course, the gauges are all electrically isolated from each other. Solder pads are applied to the termination of these tracks on the underside of the platform.

The purpose of the remaining processes in the manufacture of the blade tip instrumentation is to reduce the electrical resistance of the connecting tracks to an appropriate level such that the temperature sensitive region of each gauge is restricted to the small platinum area on the tip. A deposit of copper is electroplated onto the connecting tracks for this purpose. The final operation is to use a gold immersion plating process to produce a thin oxidation resisting layer on the surface of the copper. The finished blade is shown in Figure 4e. Clearly visible in this figure are the 15 gauges on the tip, and the 30 connecting tracks on the tip surrounded by the unused areas of the original mirror-like platinum layer. Also shown is a close-up photograph of one of the tip gauges that illustrates the

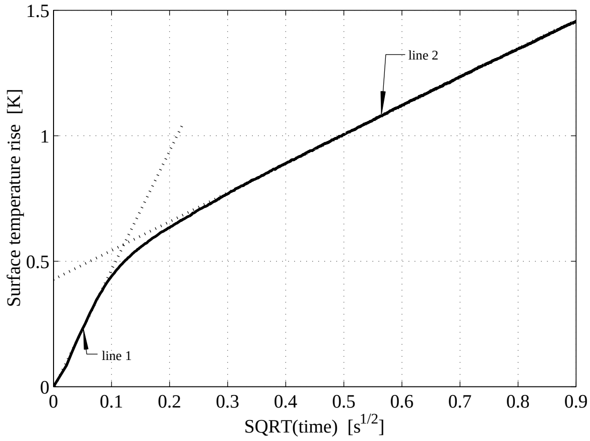

Figure 6a: A graph showing the measured rise in two-layer gauge temperature after a step change in heat transfer (radiant heating by fast-switched laser). The dotted lines indicate straight line fits to the two characteristic regions of the data.

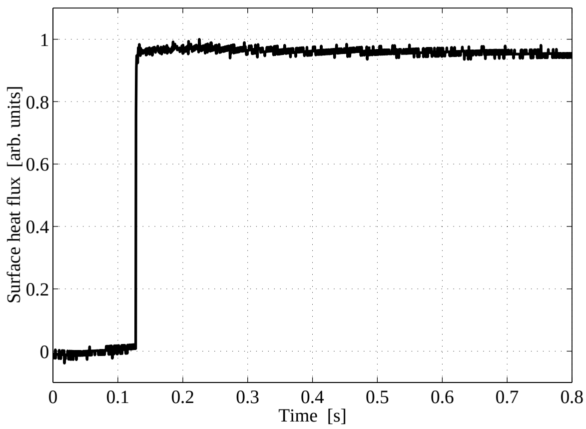

Figure 6b: A graph of the reconstructed heat transfer rate from the surface temperature rise data of Figure 6a.

way in which the platinum sensor is connected to the connecting tracks.

OVER-TIP CASING HEAT TRANSFER INSTRUMENTATION

Introduction

The design and fabrication of the over-tip casing thin-film gauges is currently continuing, but a complete prototype design (similar to the expected final instrumentation) has been constructed. Only a sector of the over-tip casing ring will be made from Macor and this will be mounted in NGV cassettes that can be removed from the test facility. The current intention is that the Macor blocks will be approximately 70×45 mm, this allowing instrumentation to be placed over 1.5 NGV pitches and the full axial chord of the turbine blades. The following section provides a detailed description of the fabrication stages involved in producing this prototype.

An overview of the fabrication

Shown in Figure 5a is a photograph of the casing gauges being laser cut. The photograph shows the Macor block (complete with a uniform platinum thin-film on its polished surface) positioned on the two-dimensional traverse. Clearly visible is the laser cutting spot and the lines that have been cut into the platinum. Just over half of the gauges have been cut in this figure. A photograph of the block after laser cutting has been completed is shown in Figure 5b. The locations of the gauges (which appear as small rectangles with a diagonal line) are evident in this figure, as are the completed connecting tracks that extend to the edge of the block. The pitch of the gauges is 1 mm.

Having cut the individual gauges on the Macor model, it is necessary to reduce the resistance of the connecting tracks by electroplating a copper layer onto the platinum. Once this is achieved, a final immersion process is employed that puts a thin gold coating onto the copper. A photograph of the finished prototype casing block is shown in Figure 5c. A close-up photograph of 4 gauges is shown in Figure 5d wherein the laser cut areas, platinum gauge and plated connecting tracks can be seen.

TWO-LAYER HEAT TRANSFER GAUGE CALIBRATION

Introduction

The use of thin-film gauges to measure surface heat transfer rates is dependent upon the theory of one-dimensional heat conduction into a semi-infinite substrate. This well known theory is described in excellent detail by Schultz and Jones (1973). In order to apply the resulting transfer function (equation 1) between surface temperature and surface heat flux, the thermal product ($\sqrt{\rho c k}$) of the substrate material must be known. In the case of two-layer gauges, such as those on enamel coated turbine blades, the thermal product of both the enamel and metal substrate need to be known (Ainsworth et al, 1989). Additionally, the ratio of thickness to thermal conductivity (a/k_1) of the enamel needs to be established for each gauge location. Although the enamel thickness is small, inevitably there are slight variations in this parameter over the blade profile. Consequently, all of the blade mounted gauges require the calibration of the local value of a/k_1.

$$\dot{q}_s(s) = \sqrt{\rho_1 c_1 k_1 s}\,\frac{\left(1 - A\exp\left\{-2\,\dfrac{a}{k_1}\sqrt{\rho_1 c_1 k_1 s}\right\}\right)}{\left(1 + A\exp\left\{-2\,\dfrac{a}{k_1}\sqrt{\rho_1 c_1 k_1 s}\right\}\right)}\,T_s(s) \qquad \textbf{(1)}$$

where,

$$A = \frac{\sqrt{\rho_1 c_1 k_1} - \sqrt{\rho_2 c_2 k_2}}{\sqrt{\rho_1 c_1 k_1} + \sqrt{\rho_2 c_2 k_2}}$$

Additionally, calibration is also required for the variation in gauge resistance with temperature. This is obtained for every gauge by immersing the completed instrumentation in a temperature controlled water bath and monitoring the resistance variation.

Calibration of thermal properties

The technique developed for calibrating the thermal properties of the two-layer gauges utilises a step change in surface heat flux. A continuous wave argon ion laser is employed that acts as a source of radiant heat that is directed to a region that encompasses the gauge under test and its immediate surrounding substrate. The laser beam is chopped rapidly by a Pockels cell/polariser arrangement (a fast optical switch) before being expanded to a size that is appropriate for the gauge under test. This is typically 10 mm in diameter and yields a uniform heat flux at the gauge. The gauge temperature (resistance) is continuously monitored during this step change. A typical temperature history for this test is shown in Figure 6a in which two distinct response regions can be identified. The first region is a straight line from $\sqrt{t}$ equal to zero to ≈ 0.1 while the second is from $\sqrt{t}$ equal to ≈ 0.3 to 0.9. Considering the theoretical transfer function, it is possible to relate the first straight line region (line 1 in Figure 6a) to the thermal properties of the enamel surface coating. The gradient of this line is proportional to the thermal product of the enamel. The second straight line (line 2 in Figure 6a) is associated with the thermal product of the metal base material. Again, the gradient is proportional to the thermal product of the material. Consequently, the ratio of the gradients of these two lines is identical to the ratio of the thermal products of the two materials (equation 2). Additionally, the time at which the two straight lines intersect is directly related to the other unknown parameter a/k_1.

$$\frac{gradient(1)}{gradient(2)} = \frac{\sqrt{\rho_1 c_1 k_1}}{\sqrt{\rho_2 c_2 k_2}} \qquad \mathbf{(2)}$$

Consequently, the data produced by this test contains all the information required to find the unknown thermal properties in the gauge transfer function (equation 1). The thermal product of the Inconel blade material is widely reported in the literature, and consequently this test enables the value of the thermal product for the enamel to be established. The calibration error is considered to be better than ±5 % for both $\sqrt{\rho_1 c_1 k_1}$ and a/k_1.

Once the characteristics of the two-layer gauge are determined, a check can be made on the quality of the calibration by introducing the transfer function between $\dot{q}_s$ and the surface temperature history in the frequency domain. The resulting reconstructed surface heat flux is shown in Figure 6b. As can be seen, the surface heat flux determined from the measured surface temperature history is a step function, and correctly reflects the step change in radiant heat transfer during the laser calibration.

Ongoing work in this area seeks to isolate the best data processing strategy and to establish a quantitative assessment of the calibration accuracy. Incorporated in this work is an effort to allow the determination of the thermal product of the metal base material, as this currently relies on book values for the bulk material, and probably represents the single largest error in determining the properties of the enamel layer. It is worth noting that the nature of the two-layer gauge system is such that interpretation of the high frequency components in the heat transfer signal depends upon the thermal product of the enamel, while low frequency components depend upon the thermal product of the metal substrate.

SUMMARY AND CONCLUSIONS

This article has considered the application of constant current thin-film thermometers to the measurement of heat transfer rates to shroudless blade tips and over-tip casing of a transonic axial turbine. The small size of the tip and the desire to resolve high spatial frequencies over the tip surface have promoted the development of a new fabrication strategy for these gauges. This technique relies upon the use of metallo-organic inks to establish the thin platinum film on the test model and the use of computer controlled laser cutting to define individual miniature gauges within that film. The system has been shown to be capable of producing gauges that are less than 1 mm in length and less than 0.1 mm in width. The benefit of using this system is that gauges can be designed on a computer, thereby allowing accurate gauge dimensions to be achieved and precise location of the gauges to be guaranteed to close tolerance. Traditional techniques for creating conducting paths between the gauges and wiring points are also employed, along with improvements such as the using of electroplating to reduce connecting track resistance.

Two prototype cases have been presented that illustrate the capability of this new approach to fabrication of heat transfer gauges on complex model shapes. Firstly, the case of creating 15 gauges along the mean camber line of the tip of a shroudless blade. Secondly, the case of fabricating an array of 56 thin film gauges on a Macor substrate for over-tip casing measurements. Excellent repeatability in the gauge resistance and dimensions has been seen throughout.

Finally, calibration issues for two-layer gauges have been presented and a strategy for determining the appropriate parameters has been described. This technique employs a step change in radiant heat flux to the gauge under test, this being produced by an argon ion laser and a fast optical switch (Pockels cell). This test has been seen to deliver the necessary thermal and physical properties of the two-layer substrate employed in blade mounted sensors.

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