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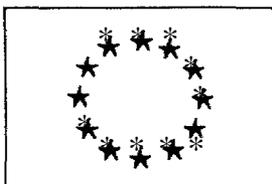
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ATTAIN: Application of Transient Thermography to Advance Industrial NDT

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summary
ATTAIN was concerned with the development of transient thermography for material characterisation and the detection of surface defects in coatings and bulk materials. Three different transient thermography techniques were addressed:

Three variations of transient illumination thermographic techniques have been further developed in ATTAIN:

Scanning Laser Irradiation Transient Thermography (scanning LITT)
Scanning LITT has been successfully applied for the detection of defects in organic coatings, plasma sprayed coatings on turbine blades and other components. It is particularly useful for very thin coatings (less than 10 pm), for which at present no other non–contacting imaging technique exists.

Static pulsed LITT
Static pulsed LITT records the whole of the thermal transient, and has been applied to materials characterisation applications such as the qualification of electronic packaging ceramics and microstructural analysis of iron-zinc alloy coatings on steel. The instrument is also capable of standard laser flash diffusivity measurements on bulk solid.

Flash lamp thermography
This technique benefits the inspection of thermally slow materials such as composites and thick organic coatings. A new flash lamp thermography system has been built featuring adjustable pulse duration and good pulse definition. The equipment has been successful y used on coated steel strip, and composite components such as bridge hinge bearings.

Introduction
ATTAIN deals with the development of a non–invasive inspection technique, *transient thermography*. The concept of passive thermography is not new; indeed infrared cameras and sensors have long been used to monitor equipment in operation for incipient failure, to measure the temperature of components in general, to inspect factory buildings for insulation faults and so on. Transient thermography, for surface inspection, was first used in the late 70's and early 80's, but has since then remained very much a laboratory technique without significant use in industry.

' Project Coordinator

The innovation in ATTAIN is the development of transient thermography for industrial applications. With the technique, the surface of the object under investigation is briefly and gently heated and subsequently observed with an infrared detector. The rate of penetration of the heat into the object is a measure of the heat conduction of the surface and can be interpreted in a number of useful ways. For example, it can show underlying defects in a coating, or can be used to measure thermal and electronic properties in thin films.

ATTAIN focuses on two distinct application areas of transient thermography, each of which has its own specific technical requirement. The first area, Laser Irradiation Transient Thermography (LITT), uses a laser which is used to heat the surface rapidly, followed by the observation of the decaying surface temperature with an infrared detector. This technique can used in a number of ways; for example, scanning LITT uses a scanned laser and a scanned detector, where the time lag between the laser and the detector is fixed so that differences in the observed temperature must be due to sub-surface defects or changing surface conditions. Scanning LITT is especially useful for the inspection of very thin or very 'fast' coatings (i.e. with a very high thermal diffusivity), and curved objects. In static pulsed LITT, the laser and detector are not scanned over the surface under inspection. In this way, the whole of the surface temperature decay curve is recorded, rather than a single temperature measurement at a fixed time after heating, as in scanning LITT. The temperature curve can then be used to calculate thermodynamic properties of the material under inspection. This is highly relevant for the quantitative characterisation of substrates and thin films for the microelectronics industry.

Static pulsed LITT

Description
A static pulsed LITT system with a nanosecond timescale speed has been developed within the ATTAIN project. Figure 1 shows a schematic of the pulsed LITT system.

A Q-switched pulsed Nd:YAG laser with frequency doubler and Gaussian optics is used as the optical excitation source. Pulses of 7 ns duration with energies of 1-20 mJ at wavelengths of 1064 nm or 532 nm are typically employed, in a Gaussian beam profile of 6-8 mm beam waist. A pair of rhodium coated off-axis paraboloidal reflectors, optically flat for 8-12 μm radiation are employed to collect black body radiation from the central region of the laser beam spot on the sample and to focus it through a Germanium filter antireflection coated for 8-12 μm radiation onto a SAT A4 class HgCdTe detector of active area 1mm diameter. The detector has an upper cutoff frequency 52 MHz at the 3dB level, a spectral defectivity (D*) of 6.7 x 10^{10} cm.$Hz^{-0.5}$.W^{-1} and a quantum efficiency of 77%. A matched SAT IR 150 preamplifier/low-pass filter combination of bandwidth 700 Hz -60 MHz is employed. A noise level for preampflifier/detector combination of 2.73 μV.$Hz^{-0.5}$ has been determined by the manufacturers. A 0.1 Hz - 1 MHz bandwidth preamplifier is used for rear surface transient measurements. Transients are acquired using a Tektronix TDS 540 digitizing storage oscilloscope of 500 MHz maximum analog bandwidth, with 1 Gigasample/second maximum digitizing rate, acquiring data at 2 ns intervals. Instrument control is by PC via IEEE488 and RS232 interfaces controlled by the system's graphical user interface.

The response of the HgCdTe detector has been measured using a chopped black body radiation source as 9.2 mV per Kelvin temperature rise above ambient. Linearity of the detector has been verified from 25°C to 110°C. The low frequency cut-off of the SAT detector/pre-amplifier combination has been determined as 700 Hz using the chopped calibration source. The pulsed LITT system has been applied to record thermal transients from materials with thermal diffusivities in the range 10^{-4} - 10^{-7} $m^2.s^{-1}$. The signal to noise ratio is a function of the signal amplitude immediately after the laser pulse, which is dependent on material parameters including optical absorption, thermal diffusivity and emissivity. The minimum detectable signal level is 0.5 mV, corresponding to approximately 0.05 K for a sample of emissivity 1 (a true black body).

The pulsed LITT instrument is controlled via the graphical user interface control program 'PANEL', in National Instruments LabView graphical programming language, developed within the project (Figure 2).

Laser Flash Diffusivity Method

Sample

Infrared
(blackbody)
radiation

Ge filter

HgCdTe
detector

Off Axis Paraboloidal Reflectors

LITT

1064/.532 nm laser pulses

Pre-amp

Digitizing
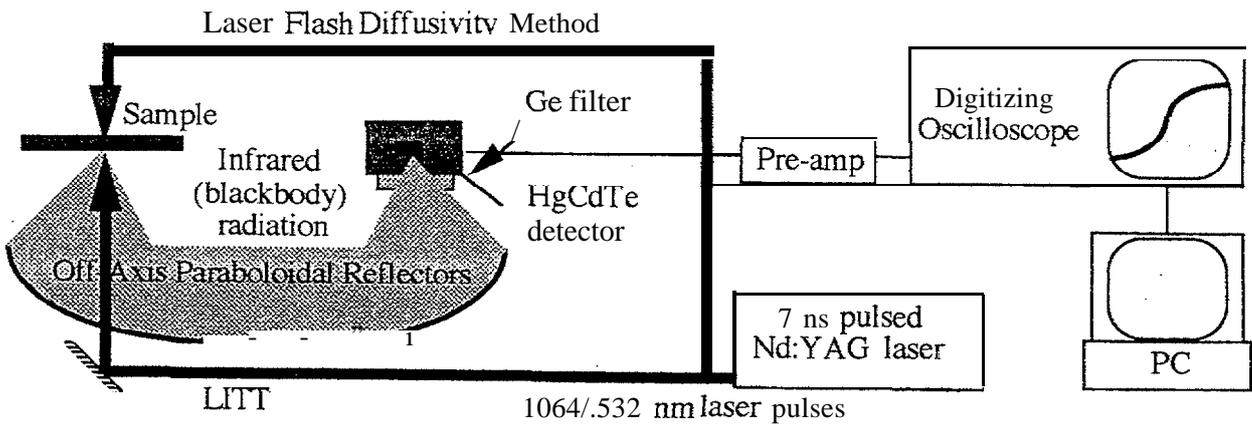Oscilloscope

7 ns pulsed
Nd:YAG laser

PC

Figure 1. Schematic diagram of the static pulsed LITT/laser flash system

An algorithm using the parameters pre-set on the main and sub-panels activates the aser and synchronously triggers the digitizing oscilloscope to acquire and electronically average a fixed number of transients, and then performs a background noise and interference acquisition. Background subtraction is carried out within the oscilloscope functions, and the transient is exported to the controlling computer where it is stored in a standard two-column format. Related programs have been written in LabView to read and display combinations of thermal signatures and provide hard-copy printouts of displayed thermal signatures.
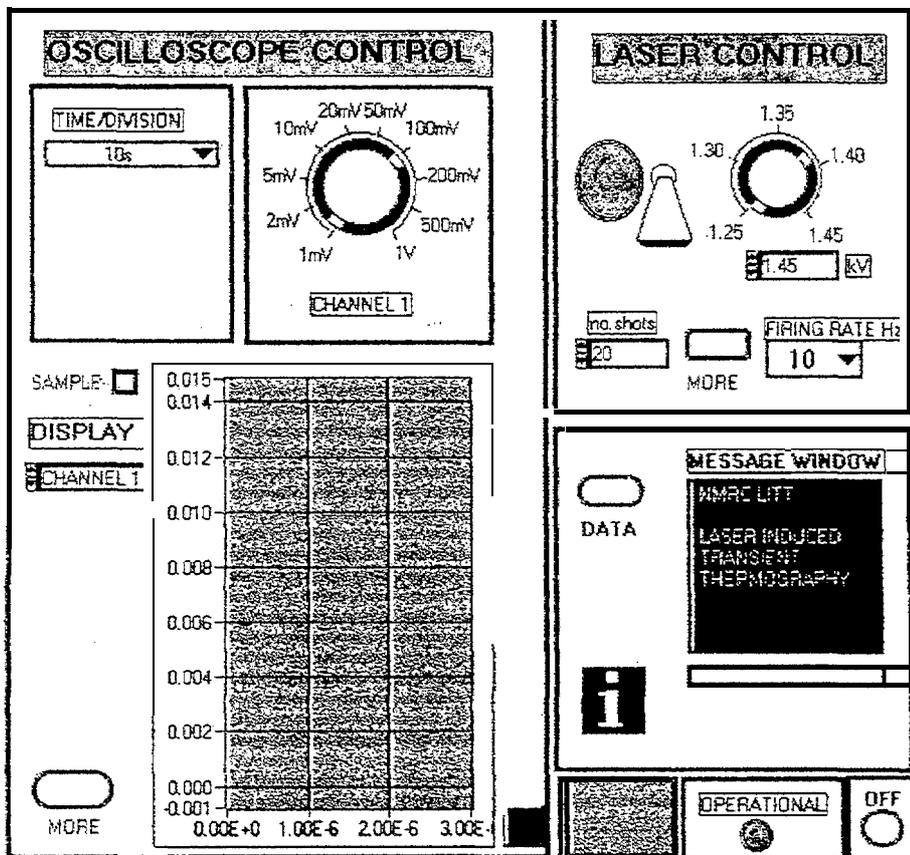

Figure 2. The front panel of the Graphical User Interface PANEL for control of the static pulsed LITT instrument

Heat flow studies have been performed using finite element models developed within the ANSYS 5.0 program (Swanson Analysis Systems). A 2-D axisymmetric model has been used to verify that heat flow under pulsed LITT conditions may be well approximated as 1-D heat flow. A 1-D heat flow model has been applied to investigate the effect of thin film thickness, laser pulse duration, and thermal property variation on the transient in the nanosecond to microsecond time regime for pulsed LITT.

The pulsed LITT system has been applied to the thermal characterisation of alumina and glass ceramics for electronic packaging, and as a method of process control of the microstructure and thickness of iron-zinc alloy coatings on steel.

Results

Negligible lateral heat diffusion (of order 0.01 mm) compared to the laser spot dimensions (typically 6 mm) occurs during a the first 300 ns of a pulsed LITT transient induced by a 7 ns laser pulse on a silicon nitride ceramic sample. The instrument is designed only to detect black body radiation emanating from the centre of the heated surface spot, so that the area within the measurement spot (of 1 mm diameter) is effective y free from lateral heat diffusion.

1-D heat flow models using a 7 ns constant intensity pulse of 1 mJ in an area of 1 mm^2 incident on a copper coated alumina slab have revealed that the pulsed LITT transient amplitude is in copper for the pulse duration, and that the cooling transient shape (i.e. time-dependence) is dependent on coating thickness at thicknesses up to ten times the thickness limit for the amplitude dependence (Figure 3). At thicknesses beyond this higher limit, no difference is observed between the copper on alumina and bulk copper transients, i.e. the surface transient decays before the heat pulse diffuses to the coating-substrate interface.

Variation of the laser pulse length in modelling the pulsed LITT transient from an aluminium slab revealed that the shape of the pulsed LITT transient is a function of laser pulse duration in the case of a thermally fast material with a strong optical absorption. (Figure 4). This has been ascribed to significant thermal diffusion beyond the optical absorption depth of the laser pulse in the metal during the finite pulse duration.
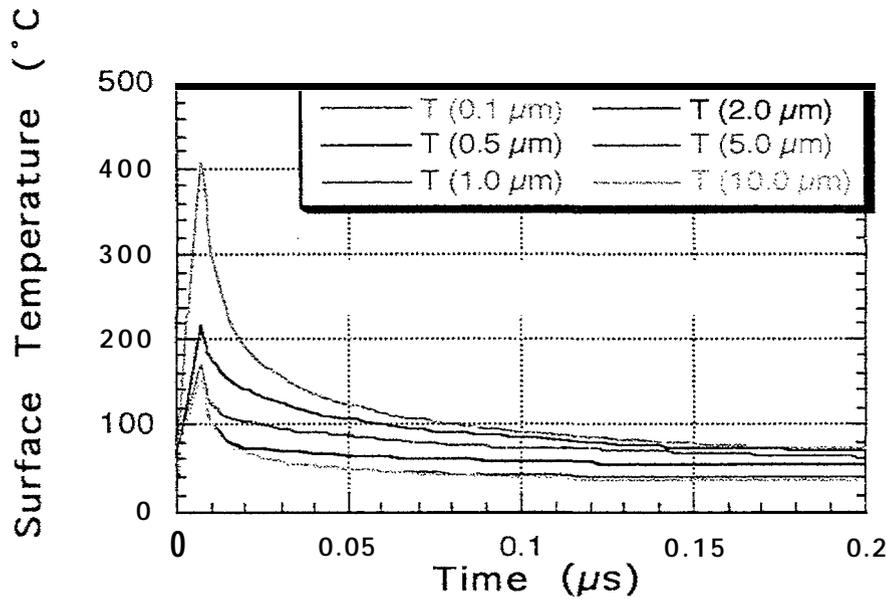

Figure 3. Thermal transients at the surface of the copper film on alumina system as a function of copper film thickness in the range 0.1 μm to 10 #m, for the same laser irradiation conditions, numerical y calculated "by a 1-D finite element model running under ANSYS 5.0.
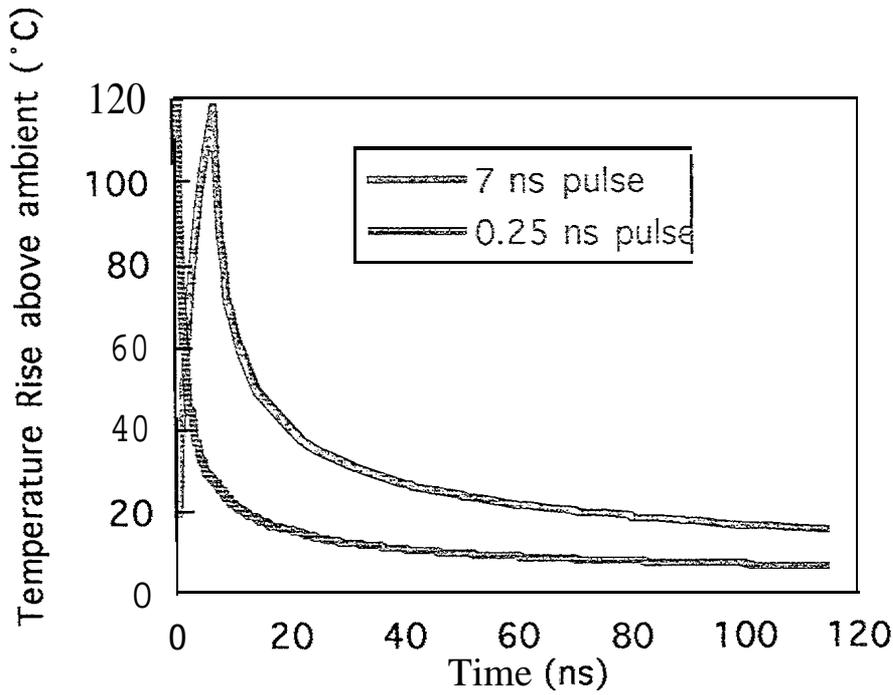
Figure 4. Static pulsed LITT thermal transients calculated using a 1-D finite element model for bulk aluminium, with pulse durations of 250 ps and 7 ns, and the same pulse intensity during the pulse in each case

Planar ceramic substrates of nominal thickness 1 mm polished on one side to a roughness average $R_a < 100$ nm were characterised by pulsed LITT. The materials were derivatives of 92% alumina with glass-frit inclusions, and Low-Temperature Co-fired Ceramic (LTCC) borosilicate and silicate glass ceramics, for electronic packaging applications. Pulsed LITT measurements of the front surface radiometric transient were analysed with the aid of thermal diffusivity measurements made according to ASTM standard 1461-92 using the rear surface radiometric transient for the same materials [1]. For a semi-infinite bulk solid, heated uniformly across its front face by a laser pulse of negligible duration, the front surface radiometry transient $S_B(t)$ is given by [2]:

$$S_B(t) = \frac{AC\alpha\alpha'}{\alpha'^2 - \alpha^2}\left[\alpha' \exp(\alpha^2 \mathbf{D}t)\mathrm{erfc}\sqrt{(\alpha^2 \mathbf{D}t)} - \alpha\exp(\alpha'^2 \mathbf{D}t)\mathrm{erfc}\sqrt{(\alpha'^2 \mathbf{D}t)}\right] \qquad (1)$$

where α and α' are the optical absorption coefficients at the laser and black body infrared wavelengths, $\mathbf{D}$ is the thermal diffusivity of the material, and A and C are instrument constants. Graphical fitting software incorporating a Levenberg-Marquardt algorithm was used to fit this expression to the pulsed LITT transients. Figure 5 shows a transient with the fit obtained. It is evident from equation (1) that a strong parameter correlation exists between thermal diffusivity and optical absorption, and also that the optical absorption coefficient α' is defined as constant over the wavelength sensitivity y range of the black body detector. Detailed optical analysis of the ceramics has revealed the difficulties in measuring the optical absorption properties of these materials by reflectance techniques, and the inadequacy of the definition of α' [3]. A methodology which eliminates the optical absorption dependence of the LITT transient shape, has been developed and reported [3].
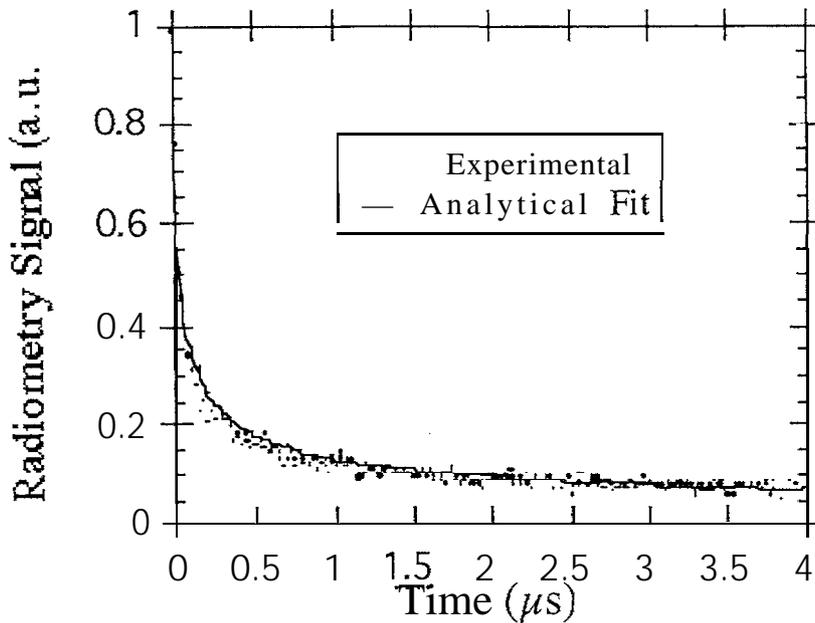
Figure 5. LITT transient of borosilicate ceramic wafer with fit to analytical expression for the LITT transient of a thick bulk solid (equation (1))

In a second study, the use of pulsed LITT for control of thin iron-zinc coatings on steel was investigated. Pulsed LITT transients were recorded from each sample surface of set of iron-zinc coated steel plates previously analysed by coulometry, metallography, X-ray diffraction and scanning electron microscopy. Figure 6 shows the transients recorded from a series of three coatings of increasing %Fe content. The %Fe content differences are sufficient to significantly influence the microstructural phase of the coating. The lower %Fe content coatings have a shiny appearance and consequently a low emissivity, but even when normalised, the cooling transients in Figure 6 exhibit a trend of slower cooling for higher iron content. This is consistent with the known thermal diffusivity of iron, which is lower than that of zinc. Analysis of a larger sample set has revealed that a continuous trend of transient shape corresponding to %Fe content in the alloy does not exist. Instead, LITT appears to be sensitive to microstructural phases, and in particular, to the phase at the surface.
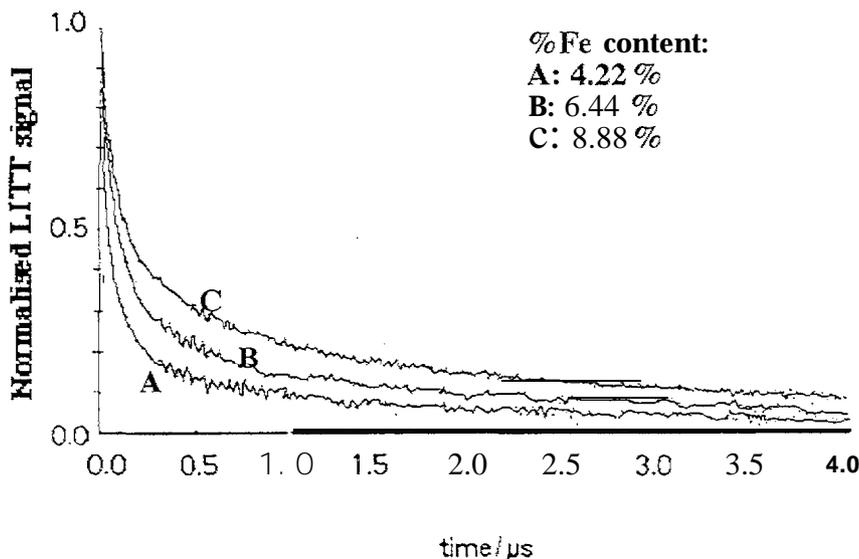

Figure 6. Normalised **pulsed LITT** transients for iron-zinc alloy coatings of different alloy compositions on steel

Flashlamp thermography

Description

The AIN work within the ATTAIN framework can be synthetised in:

– Development of a Finite Element Modelling tool, based on ANSYS 4.4, able to simulate the PVT testing.

  The modelling has made it possible to define the optimum parameter values for the. flash lamp thermography inspection of known materials, and indications for the limits of detection of thickness variations and various types of defects.

  Development of a flash lamp thermography test-rig and development of instrument control and data analysis software. The main result is a fast, non-contact method for measurement of coating and paint thickness.

The materials best suited to AIN's flash lamp thermography technique are organic coatings on metal or composite substrates.

The range of thickness measurement is $10\,\mu m$ to 10 mm for these coatings. the detection accuracy is of the order of a 1% of total thickness. The system is highly suitable for on–line use on a continuous production line (the most typical example would be a steel strip coating line).

All the components used in the flash lamp thermography system are standard commercial products and as such easily available. The system is therefore inexpensive and easily maintained.
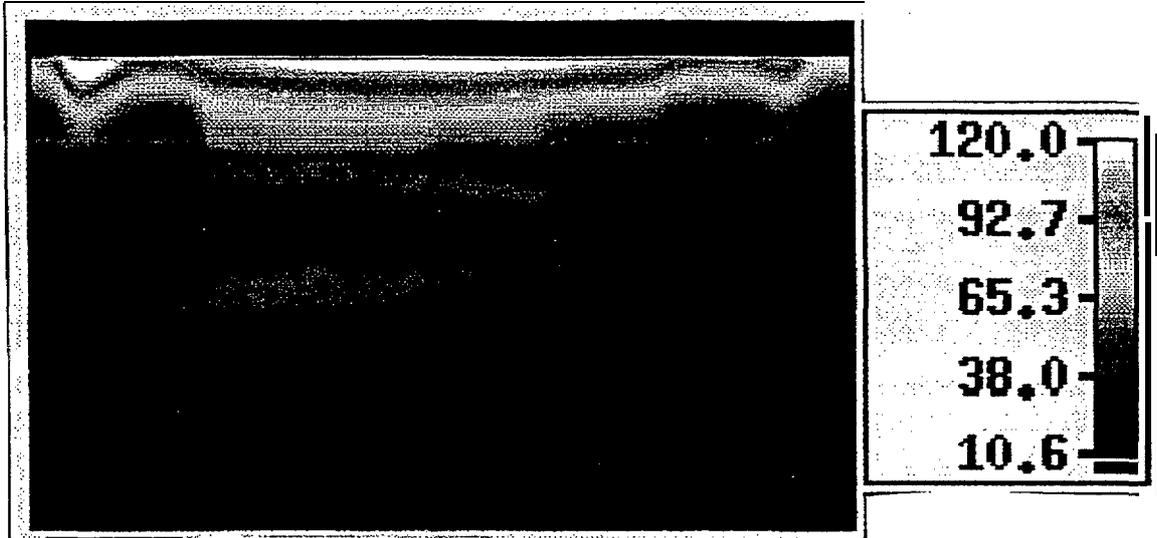
Figure 7 on the next page shows a typical result from the new flash lamp thermography system. A steel strip sample, coated with with various thicknesses of organic coating was subjected to inspection. The top image shows a single line scan from the infrared imager in 'waterfall' mode. The temperature scale is indicated to the right. The graph below shows qualitatively the remaining temperature rise after a given time interval, as a function of the coating thickness.
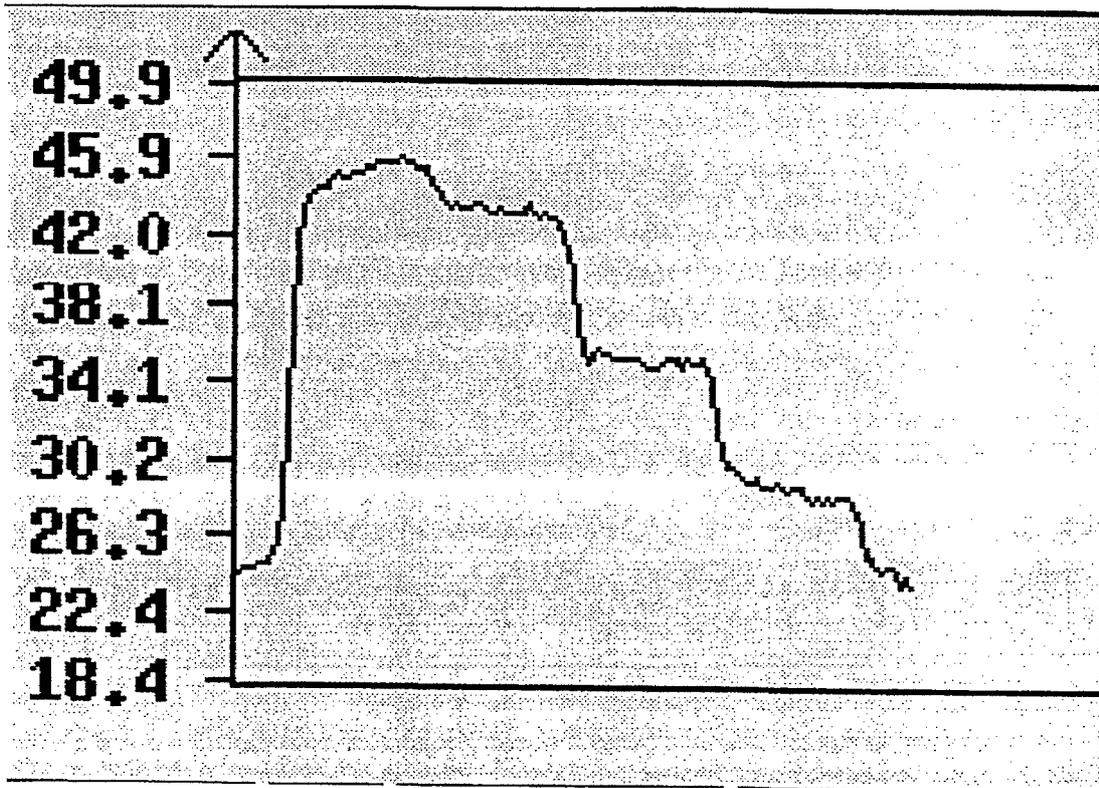

Scanning LITT

Description

Scanning LITT uses a laser beam to heat up the surface of a sample, and observes the surface temperature while the heat wave it travels into the material. The use of a laser, the wavelength of which can be chosen to match the optimum absorption into the surface, offers the advantages of enabling very fast transients to be generated so that very thin surface layers can be inspected, and flexibility for the inspection of complex shaped components. Scanning LITT is an imaging technique: it produces an infrared recording of the whole of the surface when it is at an elevated temperature shortly after it has been heated by the laser. This helps locating a defect once it has been detected. Scanning LITT is also very fast: typically 2 to 3 orders of magnitudes faster than imaging ultrasound when used on the same surface.

Figure 8 shows the principle of operation of the scanning LITT device developed by AEA Technology. The field of view of the detector, focused by means of a lens, is scanned with a plane mirror mounted directly on the shaft of a brushless motor. The laser beam, also focused, is scanned with the same speed along the same line as, but a short distance ahead of the detector. The laser beam is scanned with a second mirror, mounted on a second brushless motor. The short time difference between laser irradiation and observation is determined by the distance between the laser spot and the detector observed area, and the scan speed. Hence, the continuous signal from the detector conveys the temperature of the scanned line at a time delay between irradiation and observation.

PVT Image (°C)

THICKNESS Image (μm)

Figure 7. Flash lamp thermography thickness measurement of organic coating, See text on previous page.
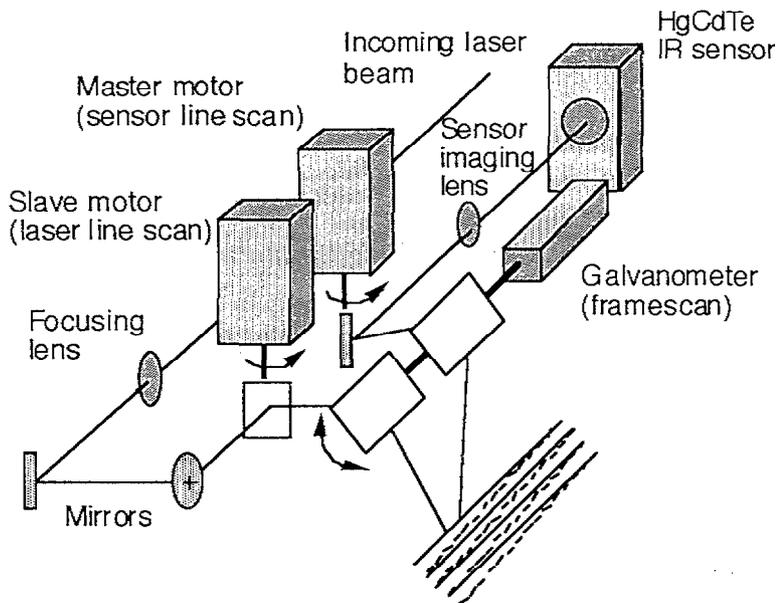
Figure 8. Scanning LITT system outline

Further line scans are made through the slow step-wise movement of a rectangular mirror, mounted on a galvanometers. Longer time delays between laser irradiation and observation by the detector are available from a split line drive optical system which allows the detector to lag the laser for a number of optical line scans. The line scanning speed can be set from 2 to 70 ins-1, while the maximum frame scan frequency is approximately 20 Hz.

The motors are identical servo motors, each controlled by its own matched servo drive, Each motor is fitted with a resolver, the signal of which is emulated by the servo controller into an encoder signal with high resolution. The servo motors are locked together by means of a separate device, an 'electronic gearbox' that uses the emulated encoder pulses. The gear ratio is user selectable but is unity for scanning LITT. At the highest encoder resolution, there are approximately 8 pulses per mm scanned over on the surface of the test piece. The (emulated) marker pulse from the encoders is used to control the framescan. The detector signal is captured and digitised with a fast data acquisition board. The board is triggered to read the detector output signal each time an encoder pulse from the servo motor that drives the detector is encountered on its external trigger port.

The rotating mirrors make it necessary that the laser beam be chopped, which is achieved by switching the laser power supply by means of the marker pulse from the encoder of the rotating laser mirror.

The spatial resolution of the scanning LITT system is approximate y O. 13mm over a square area of approximate] y 75 by 75 mm. Typical acquisition time for a complete image depends on the Scanning speed but is of the order of half a minute.

The temporal resolution of the data acquisition is closely related to the accuracy with which the temperature can be measured, since the temperature on the sample surface is not constant but decreasing rapidly. The LITT system is designed such that the accuracy of the detector and timing accuracy are similar, enabling temperature measurements with an accuracy of better than 0.1 degree Kelvin to be made. From Figure 8 follows that, since both the detector field of view and the laser beam are scanned with rotating mirrors, there will be additional inaccuracies, both spatial and in temperature measurement. These errors are however small, and the system is tolerant to several mm height variation of the sample surface.

Results

Figure 9 shows the thermal decay curves from a WCCo coating (0.1 mm thick) on a mild steel substrate, recorded at a well bonded position, and at a position where all of the substrate has been carefully removed from under the coating by machining and etching without causing damage to the W CCo layer ('flat bottomed hole'). The differences between the two curves are obvious, the well bonded location returning to ambient temperature at a faster rate that the unbended region. Figure 9 was obtained with the scanning LITT system, by fixing the detector field of view onto a point on the surface, and scanning the laser beam across it.
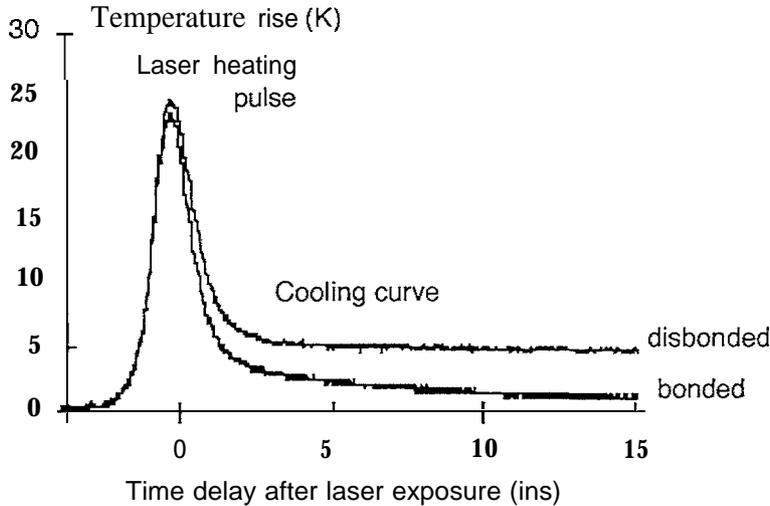

Figure 9. Thermal decay curve recorded from a well bonded WCCo coating and a disbonded coating

As can be seen in Figure 9, the influence of the substrate on the temperature decay profile becomes noticeable only after a certain time interval following exposure to the laser heating pulse. The length of this time interval is characteristic of the coating thickness and coating thermal diffusivity. For shorter time durations, the coatings behave essentially as a semi–infinite wall and the heat penetration causes the surface temperature to decay proportional to $t^{-1/2}$. After longer durations, the heat input pulse has penetrated down to the substrate, the effect of which is that the temperature no longer follows the $t^{-1/2}$ law. Figure 10 shows the thickness of a selection of the British Steel organic PvF_2 coatings as a function of the ratio

$$\frac{\tau_{1/4}}{\tau_{1/2}}$$

where $\tau_{1/2}$ and $\tau_{1/4}$ are the times taken for the coating to cool down to one half and one quarter of the initial heat pulse temperature rise.
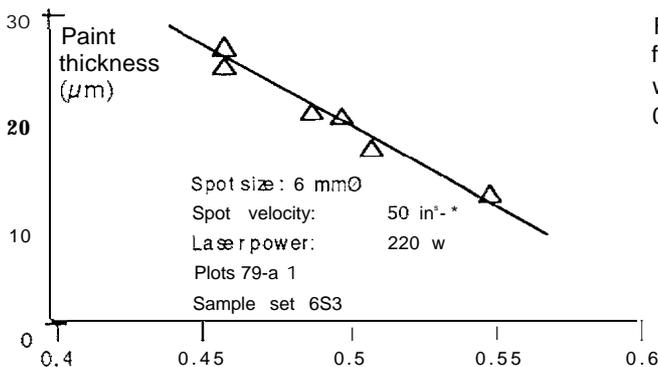

Figure 10. Paint thickness of pvf_2 coatings, as a function of the ratio of the decay times after which the surface has cooled down to 0,25 and 0.5 times the original temperature rise.
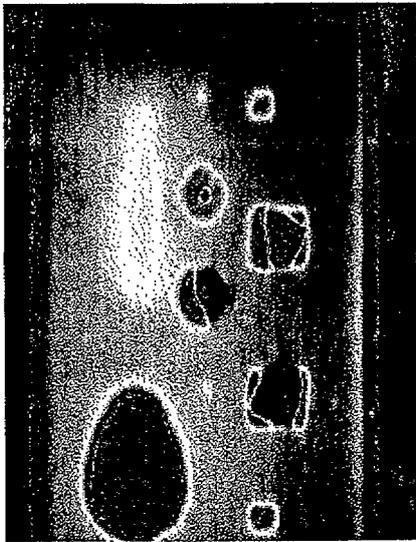
Figure 11. Left: a scanning LITT image of alumina coating on mild steel substrate with various artificial disbonds and substrate thickness; right: ultrasonic comparison of the same sample.

Figure 11 shows a direct comparison of scanning LITT with ultrasound. The LITT image is not only capable of detecting all defects that ultrasound can – it shows also less noise and clearly shows substrate thickness variations (the yellow area) that ultrasound does not. The disbonded areas show partly in blue because the temperature difference is too high for the dynamic range of the data acquisition hardware).

Figures 12 to 14 show three more examples of the capabilities of scanning LITT. Figure 12 shows a LITT image of three turbine blades, the centre blade having a coating defect. Figure 13 shows very clearly the underlying aluminium honeycomb structure that is sandwiched between two carbon fibre reinforced composite sheets of an aircraft wing. Scanning LITT can therefore be used to inspect for the bonding integrity. The surface has a white coating of paint; contrary to other transient thermography techniques that do not use a laser, scanning LITT does not require the surface to be painted black with a temporary coating for improved heat absorption. Figure 14 shows an application of scanning LITT on an organic coating on steel strip.

Figure 12. Scanning LITT image of coated turbine blades. The blade in the middle has a coating defect, clearly indicated by the red area.
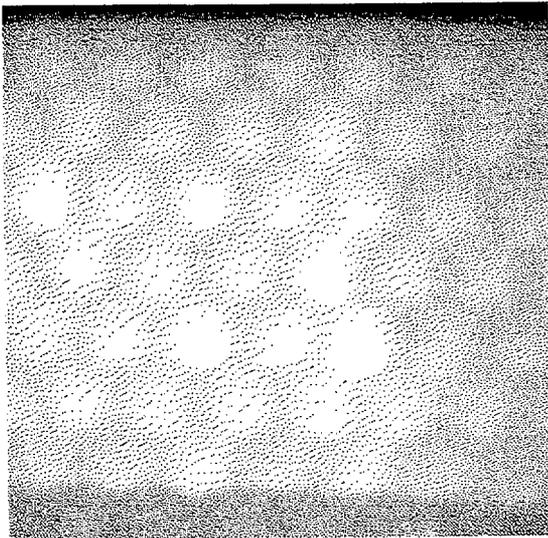

Figure 13. Scanning LITT image of a piece of aircraft wing panel, consisting of an aluminium honeycomb that is boded between two sheets of CFRC.
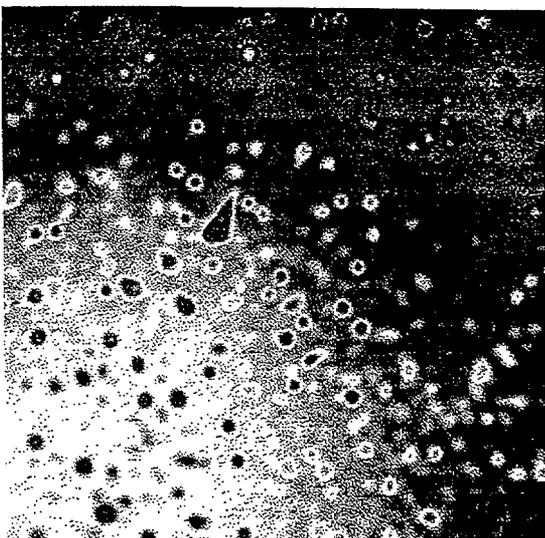

Figure 14. Scanning LITT image of coated steel strip with point–like defects, artificially caused by water vapour during the coating process,

LITT control and data acquisition software – Graphical User Interface
The scanning LITT hardware control software is incorporated into a Graphical User Interface (GUI). This interface is predominantly mouse-driven, and makes extensive use of 'point-and-click' operations.

The drop-down menus are arranged in a Windows-like format, but the system does not run under Windows. Tests with the hardware control components of the scanning LITT system had shown an incompatibility with Windows 3.1 of the software drivers supplied with the components. It was evident that from time to time the operatings ystem interrupted the data acquisition. It is clear that there are potential problems in running real-time control applications under Windows 3.1.

The top level screen is shown in Figure 15. The row of buttons along the top of the screen can be selected with the mouse, by typing the key letter which is highlighted in red, or by use of the function keys. The options include Files, for saving and recalling images from disc and exporting images in .PCX format; Setup for storing hardware settings including the scan speed and resolution and the delay between the detector and the laser; Live for repetitive update of the screen for adjustments; Measure for image-based measurements including grey - level cross sections etc.; Scan for initiating a 2-D scan of the sample; Image for control of false colour, 3-D plots and contouring; Proc (Process) for image smoothing, contrast enhancement etc; Prog (Programme) for geometrical transformations, convolution filtering (see Section 3-3 below), and real-time dynamic background thresholding. On-line, context sensitive Help is available at all levels in the programme.

A low resolution representation of the scanned image is presented in the large square area to the right of the screen; the full resolution 8 bit scanned image is displayed on a second SVGA monitor. The large square area to the left of the screen is used to display thermal response graphs when the system is used in single point, non-scanning mode.
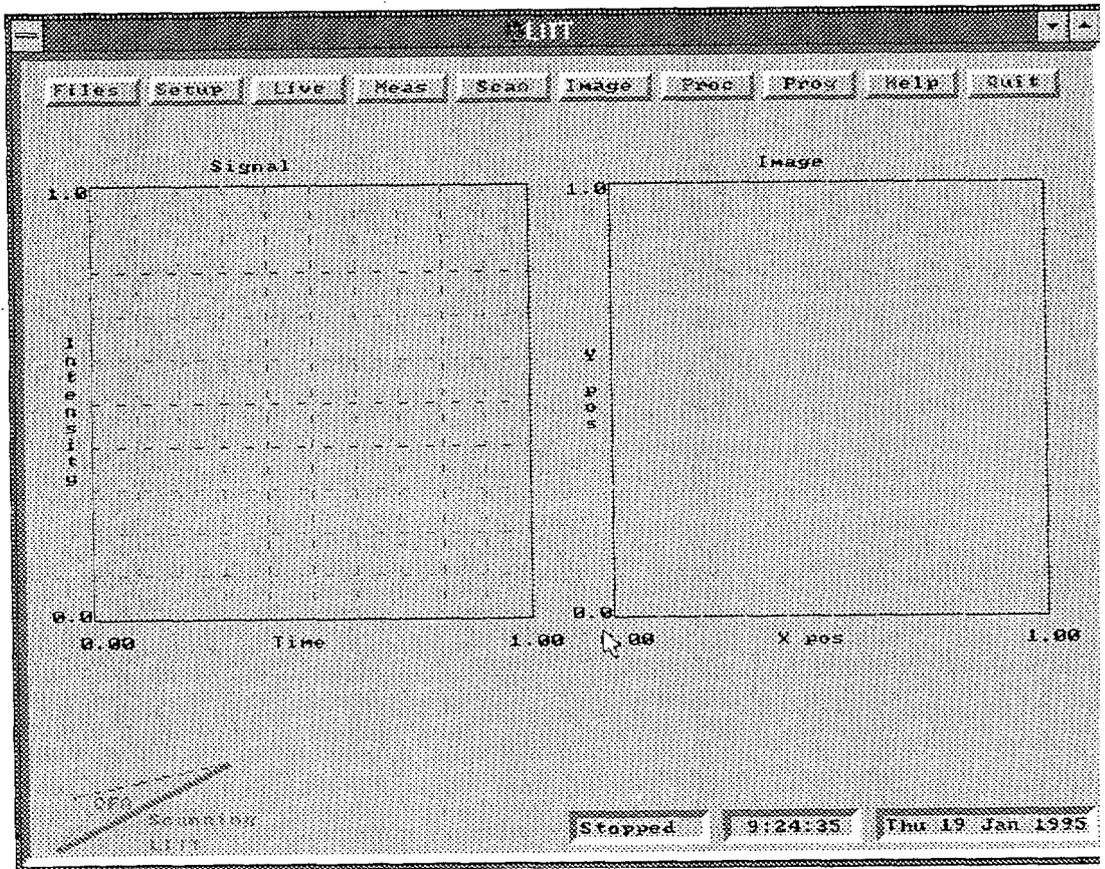

Figure 15. Top–level screen of the scanning LITT Graphical User Interface

Conclusions

Static pulsed LITT

Static pulsed LITT in the nanosecond time resolution regime has been shown by both heat flow studies and experimental measurements on iron-zinc coated steels to have a sensitivity to coating thicknesses in the range 1-10pm and to the microstructure of alloy coatings in the near surface region of coatings in this thickness range. Heat flow studies have shown that the laser pulse duration needs to be reduced to the hundred picosecond timescale in order to neglect thermal diffusion effects in metals during the finite pulse duration. The finite pulse duration, and a strong parameter correlation between the optical absorption coefficient and the thermal diffusivity in the analytical expressions for the LITT transient are the major obstacles to a simple analysis of the pulsed LITT transient for the extraction of the thermal diffusivities of materials. A methodology to overcome these effects, based upon the application of an ultrathin (O. 1 μm) metal overlayer to ceramics, has been demonstrated to result in a thermal transient whose shape is independent of the influence of optical absorption. Further work on the analytical theories of heat flow, and technological developments to produce picosecond timescale LITT, are recommended. Nanosecond pulsed LITT has clearly demonstrated potential as a laboratory based analysis tool for thin coatings, in terms of controlling drift in both microstructure and in thickness as a function of process parameter drift. Standard laser flash diffusivity measurement of bulk thermal diffusivities has been demonstrated using nanosecond scale laser pulses, demonstrating the feasibility of combining this technique with pulsed LITT in a single instrument.

Flashlamp thermography

A new thickness measuring device for organic coatings on steel strip and other substrates has been developed, using standard, inexpensive components. The technique has shown promise to, and interest from, Spanish steel industry.

Scanning LITT

A novel, imaging transient thermography technique has been developed, using a scanned laser beam and a single infrared detector. The technique is applicable to a wide range of coating materials, and the wavelength of the laser can be chosen for optimum absorption by the surface. In most cases, a low power sealed CO_2 laser is the best choice (CW power 20-50 W typically). Scanning LITT has been shown to be applicable to ceramic, metallic and organic coatings of thickness in the range of 10 μm to several mm, although the technique's particular strength is its applicability to coatings at the thin end of the range. For these coatings, there is at present no other imaging transient thermography instrumentation available that has the speed to detect the fast transients induced in such thin coatings. The scanning LITT instrument is controlled by software that was developed for the purpose and offers data – and image analysis options.

Scanning LITT is of special interest to the turbine manufacturing industry, since many blades are coated with thin plasma sprayed or electrodeposit thermal barrier coatings. However, there are also several other areas of industry, such as coated steel strip production and aerospace, which too have shown strong interest in scanning LITT.

Acknowledgements

References

1. W.J. Parker, R.J. Jenkins, C.P. Butler and G.L. Abbott, J. Appl. Phys. 32 (1961) 1679
2. W.P. Leung and A.C. Tam, J. Appl. Phys. 56 (1984) 153
3. L. Kehoe, P.V. Kelly, G.M. O'Connor, M. O'Reilly and G.M. Crean, Proc. Eleventh Annual IEEE Semiconductor Thermal Measurement and Management Symposium, p 92-101, 1995.