PARALLEL IMAGING OF THICKNESS VARIATIONS AND DISBONDING OF THERMAL BARRIER COATINGS BY TIME-RESOLVED INFRARED RADIOMETRY (TRIR)

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INTRODUCTION

Pulsed photothermal radiometry has been shown to be a useful thermally-based nondestructive evaluation technique for various thin films and layered specimens [1,2]. In this method the time development of the surface temperature is studied for both heating and cooling, during and after the application of a step heating pulse of duration, t. In this paper, we show that the method gives quantitative information about layered materials including measurement of coating thickness and the detection and characterization of disbonding between layers. Since all times are monitored, it is not necessary to know the thickness of the coating provided the heating pulse is set longer than the thermal transit time of the coating. As a result, both coating thickness and the integrity of the coating-substrate bond can be determined simultaneously.

These techniques have particular application for thermally-thick structures such as zirconia thermal barrier coatings which typically have thicknesses near 250 microns and thermal diffusivities near 2 x 10^-3 cm²/sec. Previous CW-modulated thermal wave studies employed modulation frequencies near 5 Hz to study these coatings [3]. Acquisition of full-field images is not feasible at these low frequencies due to the long dwell times required for each point in the image. The time-resolved infrared radiometric (TRIR) technique implemented with an infrared scanner allows full-field images to be obtained much more rapidly than is possible with CW-modulated thermal wave techniques.

EXPERIMENTAL TECHNIQUE

A schematic diagram of the system used for time-resolved infrared radiometry (TRIR) measurements is given in Fig. 1. An argon ion laser is used as the heating source and is temporally-gated to provide a range of pulse lengths using an acousto-optic modulator. Two heating beam profiles can be selected, either a Gaussian-profile having a selected beam diameter or a line-profile obtained by using a cylindrical lens or an acousto-optic deflector. An infrared scanner (Mikron 6T61) is used to monitor the time development of the surface temperature of the specimen. Synchronizing electronics are used to turn on the laser heating source at a fixed time with respect to the frame rate of the scanner. This data is
transferred to a microcomputer (Macintosh II) over the IEEE-488 bus for analysis.

Three types of TRIR measurements are typically made: temperature-time linescans, X-time temperature images and X-Y temperature images. The temperature-time linescans follow the development of the surface temperature at a particular point on the specimen and analysis of these curves and comparison with theoretical calculations allow measurements of coating thickness and identification of coating disbond to be made. This type of data is shown in Figs. 2(b), 4(c) and 8. TRIR X-time images show the time development of the surface temperature along a line in one direction (X-direction) on the sample with time as the vertical axis in the image [4]. Temperature is displayed in either pseudo-color, greyscale or contour representations. Examples of TRIR X-time images are shown in Fig. 4(a) and (b). The final data presentation type involves placing the sample on a positioning system stage and collecting a series of X-time images as a function of vertical position on the sample. A particular time slice from each the X-time images is used to construct full-field TRIR X-Y images of the sample at any desired time interval. Figures 6 and 7(b) and (c) show typical TRIR X-Y images.

MEASUREMENT OF COATING THICKNESS VARIATIONS

A one-dimensional model which describes the temperature versus time response for step heating of a three-layer system consisting of substrate, coating and gas layer above the coating has been presented previously [5, 6]. This model has been used to compute the temperature-time curves shown in Figure 2(a) for 3 zirconia coatings of thicknesses 165, 250 and 375 microns on a superalloy substrate and for a semi-infinite zirconia specimen. Note that temperature is plotted versus the square root of time from the onset of the heating pulse since this presentation linearizes the result for the semi-infinite response. The calculated
Fig. 2 Temperature versus square-root-time curves for zirconia coatings of thicknesses 165, 250 and 375 microns (a) Theoretical results calculated using a one-dimensional, three layer model. (b) TRIR experimental results.

temperature vs root-time curves for the coatings show the same behavior at early times as the semi-infinite zirconia but deviate from the semi-infinite response at different characteristic times which are determined by the thickness of the coating. The characteristic thermal transit time \( t_c \) is found to be \( 0.36 L^2/\alpha \) where \( L \) is the coating thickness and \( \alpha \) is the thermal diffusivity. For times \( t > t_c \) the presence of the substrate, which here is more thermally conducting than the coating, causes a decrease in the slope of temperature versus time.

Experimental TRIR results showing the temperature vs root-time curves for three zirconia coatings of thicknesses 165, 250 and 375 microns are given in Fig. 2(b). These results agree well with the theoretical calculations. The curves follow the semi-infinite response until the characteristic thermal transit time is reached at which point the slope decreases. In the experimental results, the slope decrease is greater than in the theoretical results because of the effects of three-dimensional heat flow which will be discussed in the next section. The result for the 165 micron coating also shows a slight slope increase at about 0.73 sec. We have previously shown that this is due to the presence of another ceramic layer behind the superalloy substrate [7].

IMAGING OF COATING DISBONDING

The results of the one-dimensional, three layer theory for a disbonded coating is shown in the dashed curves of Fig. 3 along with the semi-infinite response. The disbond result follows the semi-infinite response until the characteristic thermal transit time is reached. At this point, however, the slope of the temperature vs root-time curve increases instead of decreases as occurred for the bonded coating. The slope increase is due to the fact that the disbond is thermally insulating. The effect of finite beam diameter must be taken into consideration in any experimental measurement and we have developed a three-dimensional model which examines these effects [8]. The results of this three-dimensional theory are shown in Fig. 3 as the solid curves for the case of a heating beam of diameter 4 times the coating thickness. These curves follow the one-dimensional model until a particular time which is determined by the thermal diffusivity of the coating and the diameter of
Test Specimen with Artificial Disbands

A test specimen was developed to test the ability of the TRIR technique to detect, size, and quantify a coating disbond. A 775 micron thick layer of a machinable ceramic (Macor) was bonded to an aluminum substrate in which two holes of diameters 2 mm and 5 mm had been drilled. The theoretical characteristic thermal transit time for such a coating is 0.31 sec (0.56 sec^2). TRIR X-time images for a well-bonded location and for a disbonded region are shown in Figs. 4(a) and (b) respectively. In these images the horizontal axis is the horizontal position on the specimen and the vertical axis represents time with the pulse turned on at t=0 at the top of the image and then turned off at t=3 sec. Contour lines have been superimposed over the grey-scale image to aid in visualizing the temperature variation. The X-time images for these two locations show different temporal developments of surface temperature both during the heating pulse and after the heating pulse was turned off, as well as a different total temperature excursion. A quantitative analysis of the development of temperature versus time for a line down the center of the X-time images for these two locations is given in Fig. 4(c). Note that the thermal transit time is identical for both the bonded and disbonded regions and after this time the slope decreases for the bonded location and increases for the disbond. The effects of three-dimensional heat flow can be clearly seen in the disbonded result as the slope of the curve begins to decrease near 1.0 sec^2. Use of a line source in other measurements enabled both defects to be imaged simultaneously although the X-time images showed an intensity variation in the X direction which is due to the spatial non-uniformity of the line heating source. The effect of beam profile can be removed and the detectability of the defects increased by dividing an image acquired in the defect region by an image acquired over well-bonded material [9].
TRIR X-Y images were produced for this specimen as described in the experimental section and the orientation of the TRIR X-Y images is shown in Fig. 5. The line heating source was successively positioned along the surface of the test specimen with the 5 mm defect at the top and the 2 mm defect at the bottom. The 3 images shown in Fig. 6 were produced from time slices of the X-time images at (a) \( t=0.22 \) sec which is less than the thermal transit time for the coating, at (b) \( t=1.0 \) sec which is greater than the thermal transit time and at (c) \( 0.05 \) sec after end of heating pulse. Three features are observed in Images (b) and (c). The middle feature is the 5 mm defect and the bottom feature is the 2 mm defect. The top feature is an unintentional disbond between the coating and substrate due to poor bonding when the test specimen was made. These features are not found in Image (a) since the time of this image was less than the thermal transit time of the coating. The temperature variation in the X direction is due to the spatial non-uniformity of the line heating source. It is possible to use the early-time behavior to correct for the non-uniformity and also to calibrate for spatial variations in sample reflectivity and emissivity before features due to disbonding appear in the image.
Fig. 6 TRIR X-Y images of test specimen at times (a) 0.22 sec and (b) 1.0 sec after the start of the heating pulse and (c) 0.05 sec after end of heating pulse.

Spalled Thermal Barrier Coating Specimen

TRIR temperature-time linescans, X-time images and X-Y images were also performed for a zirconia thermal barrier coating specimen on a superalloy substrate which had been run in a burner rig to produce coating spallation. Figure 7(a) shows a diagram of the rod specimen and the location of the spalled portion of coating where the substrate is bare is indicated by the dark, downward-pointing arrowhead feature. The figure also shows an "unwrapped" representation of the coating to show the locations of two TRIR X-Y images shown in Fig. 7(b) and (c). The image in Fig. 7(b) shows the spalled area on the coating and indicates that there is an extensive region of disbanded coating surrounding the bare substrate. Fig. 7(c) shows an area on the sample which is not near the spalled region and again localized disbanded regions can be seen. Both of these images are after 1.0 sec of heating. Analysis of the temperature-time linescans for different locations around these images showed variations in the disband response, indicating that the TRIR technique is sensitive to the degree of disband. This is shown in Fig. 8 which gives the temperature vs root-time linescans for three different locations on Fig. 7(a) showing temperature-time responses for well-bonded coating and for two different locations in the region of disbanded coating.

Fig. 7 (a) Diagram of thermal barrier coating specimen showing location of TRIR X-Y images with respect to the area of spalled coating. TRIR X-Y images at t=1.0 sec of a thermal barrier coating specimen showing (b) disbanded coating surrounding the spalled region, (c) another disbanded region well-removed from the spalled area.
CONCLUSIONS

The TRIR technique has been shown to provide both thickness measurement and disbond detection within the same measurement. There is also the capability for quantitative measurements on multilayer systems with demonstrated sensitivity to the degree of disbond. A key requirement in obtaining quantitative information from TRIR measurements is the analysis of temperature-time linescans and comparison of this data with one-dimensional and three-dimensional models.

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