TOWARDS A FLAT-BOTTOM HOLE STANDARD FOR THERMAL IMAGING

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INTRODUCTION

Transient thermal imaging has not as yet found a niche among industrial NDE methodologies even though the field has been active since the mid 1980's. Difficulty with image interpretation is perhaps the primary reason. An ambiguous image leads to false calls and lack of confidence. Ultrasonics, on the other hand appears not to generally suffer from these issues for a simple reason - the term "flat-bottom hole" (FBH) is second nature in the field. Such standards encourage quantitative imaging. The present work provides a deeper insight into certain invariances in 1-D and 2-D heat flow that permit the use of flat-bottom hole standards to quantify thermal imaging yielding reproducible and interpretable images of flaws. The very simple theoretical basis for these effects will be described with emphasis placed on the thermal images obtained and the accuracy of the quantitative results. We describe recent work both at GE-CRD and UTRC in the area of thermal standards evaluation .

SIMPLIFICATION OF FLAWS

In thermal imaging one deals almost exclusively with planar flaws such as delaminations, areas of porosity, lateral cracks, spalled areas of coatings, etc. These planar regions may vary in lateral dimension as compared with the dimension of separation from their substrate. The separation may be slight so contact is intimate or rather large so as to be considered a total disbond. In the former case heat from the transient flash will penetrate the gap as easily as it flows lateraly. In the latter case the thermal resistance will be high so that lateral heat flow will dominate.

We will first be interested only in "thermally thick" gaps. When we have such a situation, for example, a severe delamination, we can approximate the delaminated material as a plate of given thickness. The dimension of the plate will be taken to be large compared with its thickness. We will also assume the gap to be "thermally infinite" for all practical purposes. Then 1-D plate theory heat flow applies. This situation is equivalent to analyzing a "flat-bottom hole" of a given diameter and subsurface depth. We are really approximating such flaws as FBH's. We will find that our analysis applies more generally to an FBH of any diameter over a thermally thick gap.

1-D PLATE HEAT FLOW THEORY

From Carslaw and Jaeger[1], one finds the "back side" solution for a heat flux of duration τ impinging on the front side of a plate of thickness l.

$$U(t) = 1 - 2\frac{T_c}{\tau}\sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-n^2 t/\tau} \left[1 - e^{-n^2\tau/T_c}\right] \tag{1}$$

This solution has been normalized for unit surface temperature and is the infinite series solution. The "characteristic time" of the material is defined from the solution as

$$T_c = \frac{l^2}{\pi^2\alpha} \quad , \tag{2}$$

where α is it's thermal diffusivity.

The graphical solution is shown in Fig.1. As seen from the backside, the temperature rises after the flash to a constant level assuming no sources of loss such as radiation and convection. From this result, one can find the plate thickness , given the diffusivity, or vice versa from the method of Parker[2] which relies on locating, in time, the point of "half maximum" and applying a well known formula to obtain the value. However, with heat losses, this maximum may never be reached and the solution will peak and decay leaving the measurement in doubt.

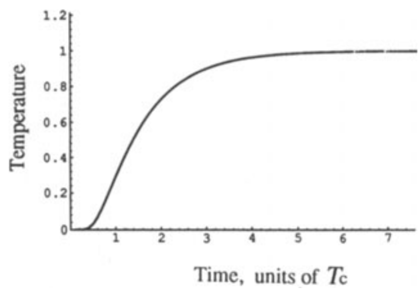

Fig. 1. 1-D heat flow rear-side normalized T-t response to heat impulse on front side. Time is in units of T_C .

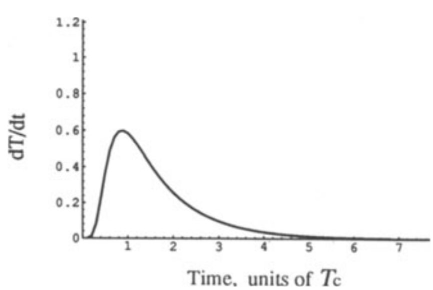

Fig. 2. Time derivative of T-t response of Fig. 1.

There exists, however, another unique point on the temperature-time (T-t) curve, namely its inflection point, which occurs very early in the response and is independent of lateral heat loss mechanisms as will be shown. The inflection point is simply the point of maximum slope of this function . After some algebra, the second derivative of Eq.(1) is set to zero to find the maximum slope and is given by

$$U''(t) = 0 = \sum_{n=1}^{\infty} (-1)^n n^4 p^{n^2-1} \quad , \tag{3}$$

where,

$$p = e^{-t/T_c} \ . \tag{4}$$

We have assumed here that the heat pulse duration is much less than the characteristic time. Eq.(3) is easily solved for the location in time of the inflection point, t_{infl}, in terms of the characteristic time, T_c. This yields

$$t_{inflection} = 0.9055\, T_c \ . \tag{5}$$

From this equation, one can quickly find either the plate thickness or thermal diffusivity by locating the inflection point. In practice, one simply differentiates the T-t curve and finds the time of peaking. This is shown in Fig. 2. Eq.(5) is then applied to find T_c.

Since most thermal imaging is "single-sided", the solution for the front side observation must be used. However, in order to obtain a similar inflection point, the image "contrast" curve is utilized whereby the T-t curve from an "infinitely thick" region the "reference region" is subtracted from the T-t curve over the plate-like flawed region. This will yield a curve very much like that of Fig. 1. But now the thickness, l, is replaced by $2l$, as though the heat returned to the surface. Since the thermal time goes as the square of the depths, the formula for front surface imaging is given by:

$$t_{inflection} = 4(0.9055)\, T_c \tag{6}$$

So this inflection point occurs four times as late as in through transmission imaging.

EXPERIMENTAL RESULTS

The above results have been experimentally verified. We refer to this technique as Thermal Time-of-Flight(TTOF) method because of the similarity of the resultant images to those obtained by the ultrasonic time-of-flight method. Fig.3 shows the TTOF image of a Delrin plate, fabricated at GE, with a number of FBH's drilled in from the backside to different depths. The "plate" thicknesses vary from 0.046 in. to 0.091 in. and hole diameters vary from 0.125 in. to 1.25 in. The Delrin plate is 0.50 in. thick which defines the "infinite" reference region. The center column of holes and bottom left and right holes are all of equal depth (0.046 in.). In the right and left columns depth increases from bottom to top. A stack of frames following the flash was recorded by an Amber "Galileo" focal plane array camera, on the same side, operating at effectively 7.5 frames per second - slow because of the Delrin diffusivity of 0.0018(cgs units). Approximately twenty-five seconds of data was collected. Color is assigned by the location of the frame number corresponding to the inflection point at each pixel of the image down the stack. Depths were determined to accuracies of better than 5% for all the holes. The experimental peak slope curves for a similar plate studied at UTRC are shown in Fig.4. The peaks fall at the same point for the holes of constant depth (here 0.05 in.) but varying radius similar to Fig.3 and are in agreement with single-sided theory showing the peak at 3.4 seconds compared to a 3.3 second prediction.

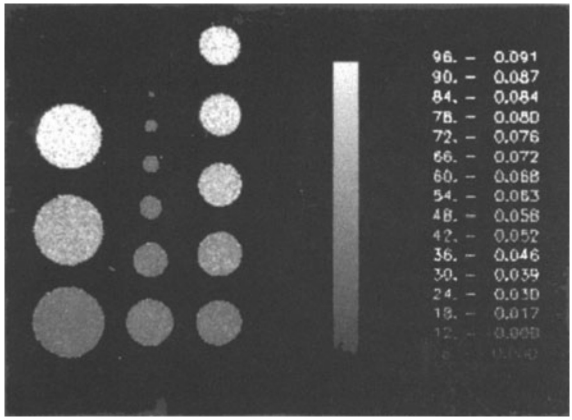

Fig. 3. TTOF image of FBH Delrin plate standard with thickness scale.

We note that the color at equal depth is in fact constant even for the smallest hole which has a depth/radius ratio of 1, a thermally difficult flaw since lateral heat flow is inevitable. Indeed, the color is uniform to the edges of all the FBH's. This suggests a much deeper invariance to lateral heat flow. Indeed this was uncovered from a 2-D finite element heat flow analysis of the same FBH's. The theoretical slope curves for plates of varying radius to depth ratio are shown in Fig.5 . The numerically determined location of the inflection point for this 2-D analysis is in agreement with that found for the 1-D analysis, Eq.(5). Time is normalized to ($4T_c$) of Eq.(2). Thus formulas (5) and (6) are very general and apply to flaws with virtually any lateral heat flow.

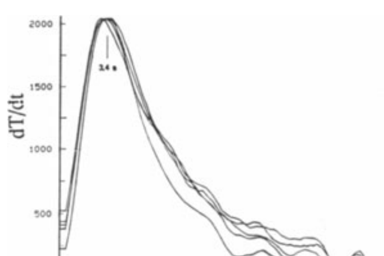

Fig. 4. Experimental T-t slope curves taken at centers of 5 holes in the UTRC Delrin plate for constant depth (0.13cm)but varying radius.

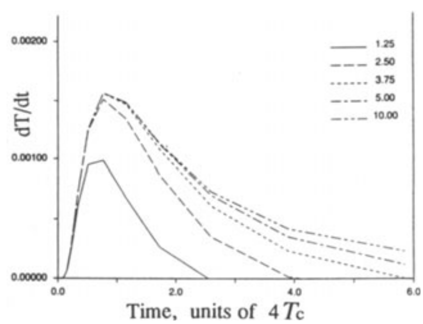

Fig. 5. Finite element calculation of T-t slope curves for plates of varying radius/thickness ratio.

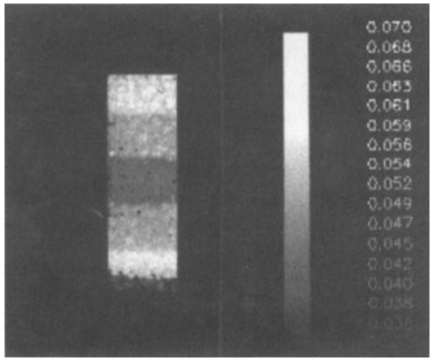

Fig. 6. TTOF image of nickel-alloy step standard with thickness scale.

Figure (6) is a TTOF image of a nickel-based alloy step standard with steps varying symmetrically in 0.005 in. increments from a center step of 0.040 in. Thickness of the steps was determined to better than 3% accuracy. Thickness error is strictly limited by the data signal-to-noise ratio which will place errors on the precise location of the peak slope.

CONCLUSION

"Depth imaging" has been extensively studied and applied by Favro[3], et al and by Vavilov[4], et al , using contrast peaking and T-t slope methods similar to the experimental approaches used here. The present work presents a new result regarding the inflection point, or peak-slope point, of the T-t history that dramatically simplifies the analysis of large stacks of image frames. We have theoretically shown and experimentally verified that there is a simple 2-D heat-flow invariant relationship between the peak-slope time and the material characteristic time as defined above. For the great majority of flaws, one can apply these results very efficiently and thereby circumvent the need for curve fitting or for waiting for thermal responses to even peak, which often may not happen. TTOF imaging results in true depth imaging with high accuracy possible. Either thickness or thermal diffusivity can be evaluated by applying this method.

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