INTRODUCTION

The General Electric IR system, as developed at the Research Center, is shown in Fig. 1. It consists of four to eight frame-mounted Speedotron Model 105 flash units with 4.8 kJ supplies, an Indigo, Phoenix, IR camera, flashquenchers and an image acquisition system. Image analysis was developed at GE and is based on the “Time-of-flight” method [1,2].

Flash quenching is described in detail elsewhere [3]. Its essential function is to cut off the exponentially decaying tail of the optical flash thereby closely simulating an ideal “delta function” impulse. This has been shown to increase accuracy in depth resolution and near surface feature analysis in a variety of materials [4] such as metals, ceramic matrix composites (CMC) and carbon/carbon materials. In the present paper we will describe these methods as they apply to different materials being addressed at GE.

SYNTHETIC THERMAL TIME-OF-FLIGHT IMAGING (STTOF)

TTOF imaging of flaws or for thickness evaluation makes use of the assumption that a defect, such as a delamination, behaves like a thin plate partly or totally separated from the substrate which could be a “half-space” of significantly greater thickness. The TTOF approach first derives the contrast curve, defined simply as the difference between the plate and the half-space responses, at each pixel of an image [1].

The contrast curve is then differentiated to extract the “slope curve”. The peak of the slope curve occurs at the inflection point. The inflection point for single-side imaging is located in time at precisely

\[ t_{inf} = 3.622 \tau_c \]  

\( \tau_c \) is the “characteristic time” for the specific material given by

\[ \tau_c = \frac{l^2}{\pi^2 \alpha} \]

where \( l \) is the plate thickness, and \( \alpha \) is the thermal diffusivity. Thus we need only seek this point on each temperature-time curve of the image stack permitting rapid image analysis. In STTOF imaging, the half-space reference curve is synthesized and normalized at the initial flash temperature of the surface following the optical pulse. This procedure effectively removes the effects of temperature from the image, leaving a temporal analysis of the propagating heat pulse. Thus, this method is essentially impervious to surface problems such as discoloration, texture and shape. Due to the method’s insensitivity to lateral heat flow effects [1] and heat loss mechanisms, accuracy can be maintained very close to thermal boundaries. A Delrin plastic flat-bottomed hole (FBH) standard is shown in Fig. 2. Holes of the same color indicate the
same depth. It is noteworthy that the image color of each hole top, indicating depth of material below the surface, is uniform right up to the edge of the hole. A hollow aircraft engine blade wall (Fig. 3) indicates uniform wall thickness between narrowly spaced ribs. This is a difficult inspection for ultrasound, especially in single crystal materials where corrections must be considered. Thermal imaging is insensitive to crystal orientation. Note the wall thickness is (accurately) indicated even around the leading edge of the airfoil to the right. Ribs are green. Hollow channels with “turbulators” can be seen between.

Figure 2: Flat-bottom hole Delrin plate standard depth image. Color bar indicates thickness in inches.

Figure 3: Aircraft engine blade wall thickness image. Color bar indicates thickness in inches.

STANDARDS DEVELOPMENT: CMC, Carbons

In order to quantify imaging results, an effort is made to develop standards for thickness and flaw evaluation. Typical standards include “step-standards” for depth imaging [3], FBH standards, such as shown above, and simulated defect standards. We have developed standards to accommodate each new material as needed. Standards not only allow correct calibration of a technique throughout GE but also enable proper development of new techniques under ideal flaw imaging conditions. For example, when developing “CMC imaging”, it is extremely useful to have realistic flaws embedded in the Si/SiC material. Figure 4a shows such a standard approximately 0.200 inches thick with non-wetting, high temperature, material inserts at varying depths and diameters. The rough edges of the circular flaw IR images result from edge cracking. The “flaw thickness” is approximately 0.010 in. Overall, the IR image is reasonably good and the standard is reproducible [6]. Figure 4b shows a flat-bottom hole carbon/SiC material standard. The intrinsic material variation is evident in that it masks the deeper, smaller holes near the top of the image. The “depth steps” on the left show this masking particularly well as the deepest (lowest) step blends into the background. Such features are important since they determine the ultimate depth and spatial resolution in any given material.
FLAW DISCRIMINATION

Having developed the capability to image ceramics, the next issue became the ability to discriminate flaws. This work was based on prior research into the nature of porosity time-temperature curve signatures [7]. Then it was shown that layered porosity contrast responses always show an early peaking behavior arising from entrapment of heat above the layer, delaying its dissipation. The depth of the layer can be determined from the TTOF method and is accurate. This allows us to discriminate delamination signals from porosity signals. An example is shown in Fig. 5. This is a CMC test part viewed and flashed single-sided on its inside, at an angle as seen below. The STTOF image on the right shows flaws at varying depths indicated by the different colors - red meaning shallow to blue which indicates the correct full thickness with no flaws. The image on the left discriminates delaminated areas (red) from porous areas (yellow), green indicating flawless regions.

Figure 4: a) Flat-bottom hole CMC plate standard depth image; b) carbon/SiC FBH standard

APPLICATION TO LARGE-SCALE COMPOSITES

We have developed high power very large scale flash systems capable of handling complex-shaped polymer components with as large as 10 ft. dimensions. These can be processed either in a single flash (with a high resolution 1000x1000 array camera) or in 4 or more segments depending on extremity of curvature. Curvatures with as much as 60 degrees slope are easily imaged. Polymers (e.g. gr/ep) as thick as 1/8 inch are feasible. This is ideal for structural, aircraft components. Shown in Fig. 6 is a large-scale system installed recently in a GE business. It is shown imaging a 10-foot polymer engine nacelle.
component. Imaging is done in 4 shots – each covering 5’x5’ areas. The inspection takes approximately ½ hour, replacing an ultrasonic inspection normally taking 8 hours.

Figure 6: Robotic IR transient flash system with large aircraft composite component.

CONCLUSIONS

We have described recent developments in infrared imaging at GE for nondestructive testing. These include flash quenching with transient thermography applied to a variety of materials ranging from metals to ceramics and the development of flaw standards and flaw discrimination, essential for calibration as well as technique development. This technique is now in practice or production at several GE businesses.

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REFERENCES