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Standard Practice for Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

This standard is issued under the fixed designation E2582; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope

1.1 This practice describes a procedure for detecting subsurface flaws in composite panels and repair patches using Flash Thermography (FT), in which an infrared (IR) camera is used to detect anomalous cooling behavior of a sample surface after it has been heated with a spatially uniform light pulse from a flash lamp array.

1.2 This practice describes established FT test methods that are currently used by industry, and have demonstrated utility in quality assurance of composite structures during post-manufacturing and in-service examinations.

1.3 This practice has utility for testing of polymer composite panels and repair patches containing, but not limited to, bismaleimide, epoxy, phenolic, poly(amide imide), polybenzimidazole, polyester (thermosetting and thermoplastic), poly(ether ether ketone), poly(ether imide), polyimide (thermosetting and thermoplastic), poly(phenylene sulfide), or polysulfone matrices; and alumina, aramid, boron, carbon, glass, quartz, or silicon carbide fibers. Typical as-fabricated geometries include uniaxial, cross ply, and angle ply laminates; as well as honeycomb core sandwich core materials.

1.4 This practice has utility for testing of ceramic matrix composite panels containing, but not limited to, silicon carbide, silicon nitride, and carbon matrix and fibers.

1.5 This practice applies to polymer or ceramic matrix composite structures with inspection surfaces that are sufficiently optically opaque to absorb incident light, and that have sufficient emissivity to allow monitoring of the surface temperature with an IR camera. Excessively thick samples, or samples with low thermal diffusivities, require long acquisition periods and yield weak signals approaching background and noise levels, and may be impractical for this technique.

1.6 This practice applies to detection of flaws in a composite panel or repair patch, or at the bonded interface between the panel and a supporting sandwich core or solid substrate. It does not apply to discontinuities in the sandwich core, or at the interface between the sandwich core and a second panel on the far side of the core (with respect to the inspection apparatus).

1.7 This practice does not specify accept-reject criteria and is not intended to be used as a basis for approving composite structures for service.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate ~~safety~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D3878 Terminology for Composite Materials

E1316 Terminology for Nondestructive Examinations

[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.10 on Specialized NDT Methods.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3. Terminology

3.1 *Definitions*—Terminology in accordance with Terminologies D3878 and E1316 and shall be used where applicable.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aspect ~~ratio—~~ratio, n—*the diameter to depth ratio of a ~~flaw. For~~flaw; for irregularly shaped flaws, diameter refers to the minor axis of an equivalent rectangle that approximates the flaw shape and area.

3.2.2 *discrete ~~discontinuity—~~discontinuity, n—*a thermal discontinuity whose projection onto the inspection surface is smaller than the field of view of the inspection apparatus.

3.2.3 *extended ~~discontinuity—~~discontinuity, n—*a thermal discontinuity whose projection onto the inspection surface completely fills the field of view of the inspection apparatus.

3.2.4 *first logarithmic ~~derivative—~~derivative, n—*the rate of change of the natural logarithm of temperature (with preflash temperature subtracted) with respect to the natural logarithm of time.

3.2.5 *inspection ~~surface—~~surface, n—*the surface of the specimen that is exposed to the FT apparatus.

3.2.6 *logarithmic temperature-time ~~plot—~~plot, n—*a plot of the natural logarithm of the surface temperature with preflash temperature subtracted on the y-axis versus the natural logarithm of time on the x-axis, where time t=0 is taken to be the midpoint of the flash ~~event. Either~~event; either temperature or radiance may be used to create the plot.

3.2.7 *log ~~plot—~~plot, n—*see *logarithmic temperature-time plot*.

3.2.8 *second logarithmic ~~derivative—~~derivative, n—*the rate of change of the first logarithmic derivative with respect to the natural logarithm of time.

3.2.9 *thermal ~~diffusivity—~~diffusivity, n—*the ratio of thermal conductivity to the product of density and specific heat; a measure of the rate at which heat propagates in a material; units [length^2/time].

3.2.10 *thermal ~~discontinuity—~~discontinuity, n—*a change in the thermophysical properties of a specimen that disrupts the diffusion of heat.

4. Summary of Practice

4.1 In FT, a brief pulse of light energy from a flash lamp array heats the inspection surface of a composite specimen, and an IR camera monitors the surface temperature (or radiance) as the sample cools.

4.2 The surface temperature falls predictably as heat from the surface diffuses into the sample bulk over a period t* (Eq 1).

$$t^* = \frac{L^2}{\pi\alpha} \quad (1)$$

where:

L = the specimen thickness, and
α = the thermal diffusivity.

4.3 ~~In FT, a brief pulse of light energy from a flash lamp array heats the inspection surface of a composite specimen, and an IR camera monitors the surface temperature (or radiance) as the sample cools. The surface temperature falls predictably as heat from the surface diffuses into the sample bulk. However, internal~~ Internal thermal discontinuities (for example, voids, delaminations, or a wall or interface between the host material and a void or inclusion) modify the local cooling of the surface, and the corresponding radiation flux from the surface that is detected by the IR camera.

4.4 Fundamental detectability of a flaw will depend on its size, depth, and the degree to which its thermal properties differ from those of the surrounding host material. For a given flaw-host combination, detectability is a function of the aspect ratio of the flaw. The minimum detectable flaw size increases with the depth of the flaw. Detectability is highest for larger flaws that are closer to the sample surface and have thermal properties that are significantly different from the host matrix material.

4.5 Operational parameters affecting detectability include component surface emissivity and optical reflectivity, data acquisition period, flash lamp energy, and camera wavelength, frame rate, sensitivity, optics, and spatial resolution.

4.6 This practice describes a single-side access examination, in which the flash lamp or heat lamp array (excitation source) and IR camera (temperature sensor) are both located on the same (inspection) side of the component or material under examination.

4.7 In common practice, signal processing algorithms (for example, Thermographic Signal Reconstruction, Principal Component Analysis) are used to enhance detectability of flaws that are not detectable in the raw IR camera signal, and to assist in evaluation and characterization of indications.

5. Significance and Use

5.1 FT is typically used to identify flaws that occur in the manufacture of composite structures, or to ~~track flaw development during service.~~ identify and track flaws that develop during the service lifetime of the structure. Flaws detected with FT include delamination, disbonds, voids, inclusions, foreign object debris, porosity, or the presence of ~~water~~fluid that is in contact with the back side of the inspection surface. With dedicated signal processing and the use of representative test samples, characterization of flaw depth and size, or measurement of component thickness and thermal diffusivity may be performed.

5.2 Since FT is based on the diffusion of thermal energy from the inspection surface of the specimen to the opposing surface (or the depth plane of interest), the practice requires that data acquisition allows sufficient time for this process to occur, and that at the completion of the acquisition process, the radiated surface temperature signal collected by the IR camera is strong enough to be distinguished from spurious IR contributions from background sources or system noise.

5.3 This method is based on accurate detection of changes in the emitted IR energy emanating from the inspection surface during the cooling process. As the emissivity of the inspection surface ~~deviates from~~ falls below that of an ideal blackbody ~~behavior (emissivity~~(blackbody emissivity = 1), the signal detected by the IR camera may include components that are reflected from the inspection surface. Most composite materials can be examined without special surface preparation. However, it may be necessary to coat low-emissivity, optically translucent inspection surfaces with an optically opaque, high-emissivity water-washable paint.

5.4 This practice applies to the detection of flaws with aspect ratio greater than one.

5.5 This practice is based on the thermal response of a specimen to a light pulse that is uniformly distributed over the plane of the inspection surface. To ensure that 1- dimensional heat flow from the surface into the sample is the primary cooling mechanism during the data acquisition period, the height and width dimensions of the heated area should be significantly greater than the thickness of the specimen, or the depth plane of interest. To minimize edge effects, the height and width dimensions of the heated area should be at least 5 % greater than the height and width dimensions of the inspection area.

5.6 This practice applies to flat panels, or to curved panels where the local surface normal is less than 30 degrees from the IR camera optical ~~axis~~axis.

6. Equipment and Materials

6.1 *IR Camera*—The camera should be capable of uninterrupted monitoring of the sample surface for the entire duration of the acquisition. ~~Cameras with automatic internal shuttering mechanisms should allow the shuttering~~ The camera should allow automatic recalibration, non-uniformity correction or other operations that interrupt the continuous data stream to be disabled during the data acquisition period. The camera should provide real-time digital output of the acquired signal. The camera output signal response should be approximately linear over the (post-flash) temperature range of the sample. The camera wavelength should be in either the ~~2-5~~2–5 micron range or the ~~8-14~~8–14 micron range, selected such that the test material is not IR translucent in the spectral range of the camera. The optics and focal plane should be sufficient so that the projection of ~~nine~~15 contiguous pixels onto the sample plane is less than or equal to the minimum flaw area that is to be detected.

6.2 *Flash Lamp Array*—At least one flash lamp should be employed to provide uniform illumination to the sample surface. The full width at half maximum duration of the flash pulse should be less than ~~or approximately~~ five milliseconds. The array should be placed to avoid a direct path of the flash energy into the IR camera lens opening. The ~~lamps should be enclosed in a reflector and covered by an optically transparent window that suppresses IR radiation in the camera wavelength range (for example, borosilicate glass). The~~ flash lamp array should be enclosed in a protective hood to prevent workers in the inspection area from direct exposure to the flash, or alternately, the apparatus should be operated in a partitioned area with appropriate safety warnings to prevent inadvertent exposure.

6.3 *Heat Lamp Array*—A heat lamp array may be used as an alternative to a flash lamp array for the purposes of illuminating the sample surface. At least one heat lamp (for example, 500W linear halogen bulb in a parabolic reflector) should be employed to provide uniform illumination. The lamps should be enclosed in a reflector and covered by an optically transparent window that suppresses IR radiation in the camera wavelength range (for example, borosilicate glass). The duration of the heating pulse should be less than 25 % of t* (see Eq 1). The array should be placed to avoid a direct path of the reflected energy into the IR camera lens opening.

6.4 *Acquisition System*—The acquisition system includes the IR camera, flash lamps, and a dedicated computer that is interfaced to both the camera and flash lamps. The acquisition system should be capable of synchronizing the triggering of the flash lamps and IR camera data acquisition. The system should allow data to be acquired before, during, and after the flash occurs.

6.5 *Analysis Software*—The computer software should allow acquired sequences to be archived and retrieved for evaluation, and allow real time display of the IR camera signal, as well as frame-by-frame display of previously acquired flash sequences which have been archived. The software should allow viewing of the logarithmic temperature-time for specified pixels. Additional processing operations on each raw image sequence (for example, averaging, ~~preflash~~pre-flash image subtraction, noise-reduction, calculation of first or second ~~time~~logarithmic derivatives) may be performed to improve detectability of subsurface features.

7. Reference Standards

7.1 *Detectability Standard*—A reference standard with known thermal discontinuities is used to establish operating parameters of the apparatus and limits of detectability for a particular application, and to periodically verify proper performance of the ~~apparatus.~~ apparatus for that application.

7.1.1 Known discontinuities may be actual flaws, or artificial features that simulate the thermophysical behavior of typical flaws that are known to occur in the structure of interest.

7.1.2 At least five known flaws of a particular type should be included in the reference standard. The known flaws should represent the range of aspect ~~ratios~~ ratios, diameters, and depths for anticipated flaws, and should include the minimum required detectable flaw size for a given application, as determined by the cognizant engineering organization.

7.1.3 If the minimum detectable flaw size requirement is not known, the reference standard should include at least five known flaws of a given type, spanning the range of aspect ratios from ~~0.5 to 10.~~1 to 10 or higher.

7.1.4 If different types of known flaws are to be used, at least five instances of each type should be included.

7.1.5 Known flaws should be arranged so that edge-to-edge separation of adjacent flaws is at least one diameter of the larger neighboring flaw.

7.1.6 Known flaws should be arranged so that the edges of each flaw are at least one diameter from the edge of the test sample.

7.1.7 If a test standard containing actual or simulated flaws is not available, one may be constructed using flat bottom holes machined into the back side of the panel. It should be recognized that flat bottom holes represent a best case scenario for detectability, where no heat transfer through the flaw occurs. Actual flaws are likely to be less detectable.

7.2 ~~*Uniformity*~~ *System Performance Standard*—~~Uniformity of the distribution of light from the flash lamp array may be determined with aluminum plate reference standard.~~A reference standard with specific programmed thermal features and discontinuities is used to validate the operating performance characteristics, and the consistency and repeatability of the FT system.

7.2.1 ~~Aluminum plate thickness should be 3~~ The standard should be a plate of a homogeneous material (for example, aluminum, steel, carbon fiber) with thickness ≥3 mm.

7.2.2 The plate may be free standing or attached to a core material (for example, aluminum or fiberglass honeycomb, foam).

7.2.3 The plate surface should fully cover the field of view of the apparatus.

7.2.4 The examination surface of the plate should have a uniform high emissivity finish (for example, flat black paint). Under static conditions, the paint coating should appear uniform when viewed with an IR camera.

8. Calibration and Standardization of Apparatus

8.1 *IR Camera Calibration*—The IR camera should be calibrated and maintained at regular intervals, following the procedure recommended by the manufacturer. Non-uniformity or flat field correction should be performed according to the manufacturer's instructions, or more frequently, if required to achieve optimum ~~camera~~ performance.

8.2 *System Check Procedure*—~~Measure the dimensions of a single pixel field of view at the sample plane by placing an object with known dimensions in the field of view at the sample plane, and determining the number of pixels that span the object in either the horizontal or vertical direction.~~A comprehensive system check may be used to verify the acceptable operational performance characteristics, at the beginning and conclusion of each work cycle, such as a standard 8 h work day. Tested characteristics may include Camera Alignment and Focus, Lamp Array Alignment, Excitation Uniformity, Excitation Levels, Response Linearity, Linear Measurement Calibration, Flaw Size Measurement,

$$\text{Pixel field of view size} = \frac{\text{object length}}{\text{number of pixels}}$$

and Signal/Noise Measurement.

8.2.1 The system check shall utilize the System Performance Standard.

8.2.2 The system check shall be performed at the beginning of each operating shift prior to performing the standardization and prior to inspecting any specimens.

8.2.3 The system check shall be performed at the conclusion of each operating shift (maximum 12 h). If the result of the system check reveals a discrepancy in the acceptability of the operational performance characteristics, all of the inspection results since the last acceptable system check shall be deemed invalid.

8.2.4 The results of each system check shall be recorded and archived as part of the inspection record for the specimens.

~~8.3 *Standardization*—Operating parameters for FT inspection will vary with the thickness, surface characteristics and composition of the component under test, as well as the geometry and thermophysical characteristics of a rejectable flaw, as determined by the cognizant engineering organization. Standardization should be performed prior to examination of a component or material, on a detectability reference standard (see 7.1) that is representative of the structure to be examined, to establish appropriate operating parameters.~~

~~8.3.1 Acquire a data sequence for the reference standard using the normal FT examination procedure.~~

~~8.4 Using the analysis software, view the logarithmic temperature-time plot for a point on the surface that corresponds to the deepest feature or interface that must be detected.~~

~~8.5 The log plot should be a monotonically decreasing straight line with slope approximately equal to -0.5, and a pronounced "knee" in the curve at a later time (t*), indicating the presence of a back wall or flaw interface, as shown in Fig. 1. The knee may bend either higher or lower than the straight line, according to whether the backing layer acts as a thermal insulator (for example, air, vacuum) or a heat sink (for example, metal).~~