Designation: E2582 – 07 (Reapproved 2014)

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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
D3878 Terminology for Composite Materials
E1316 Terminology for Nondestructive Examinations

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*—the diameter to depth ratio of a 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*—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*—a thermal discontinuity whose projection onto the inspection surface completely fills the field of view of the inspection apparatus.

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[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.

3.2.4 *first logarithmic derivative*—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*—the surface of the specimen that is exposed to the FT apparatus.

3.2.6 *logarithmic temperature-time plot*—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 temperature or radiance may be used to create the plot.

3.2.7 *log plot*—see *logarithmic temperature-time plot*.

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

3.2.9 *thermal diffusivity*—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*—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. The surface temperature falls predictably as heat from the surface diffuses into the sample bulk. However, 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.

4.2 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.

4.3 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.

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

4.5 In common practice, signal processing algorithms 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. Flaws detected with FT include delamination, disbonds, voids, inclusions, foreign object debris, porosity or the presence of water that is in contact with the back 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 ideal blackbody behavior (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.

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

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 to be disabled during the data acquisition period. The camera should provide real-time digital output of the acquired signal. The camera output signal should be approximately linear over the (post-flash) temperature range of the sample. The camera wavelength should be in either the 2-5 micron range or the 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 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 *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.

6.4 *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 image subtraction, noise-reduction, calculation of first or second time 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.

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 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.

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 Standard*—Uniformity of the distribution of light from the flash lamp array may be determined with aluminum plate reference standard.

7.2.1 Aluminum plate thickness should be 3 mm.

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

7.2.3 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 *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 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.

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

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).

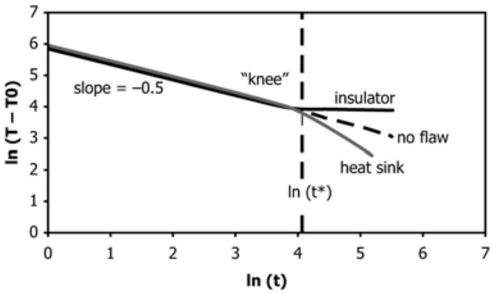

FIG. 1 Logarithmic Temperature-time Plot

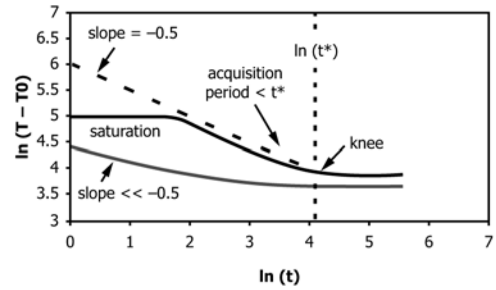

FIG. 2 Typical Acquisition Problems

8.6 Incorrect acquisition parameters or procedures may be diagnosed by viewing the log plot. Common acquisition errors are illustrated in Fig. 2.

8.7 If the knee does not appear in the log plot, the duration of the acquisition should be increased and the examination and analysis should be repeated until the knee appears. The acquisition period may be increased by either increasing the number of frames acquired, or by decreasing the rate at which frames are acquired (that is, by acquiring every nth frame).

8.8 The amplitude of the log curve at the time that the knee occurs should be sufficient to allow it to be discriminated from the background. If the value of the log amplitude in the vicinity of the knee intersects becomes excessively noisy, or is less than one, the flash amplitude should be increased.

8.9 The initial post-flash frames in the data sequence may be saturated due to excessive IR radiation input to the camera detector, as a result of reflection of the flash signal from the inspection surface or background.

8.9.1 Saturation should be minimized, and should not mask the knee associated with the back wall in the logarithmic temperature-time curve.

8.9.2 Saturation may be minimized by reducing the flash amplitude or duration, reducing the camera integration period, or by adjusting the onset of the flash relative to the integration period of the IR camera.

8.10 The initial portion of the logarithmic temperature-time plot should have a slope approximately equal to -0.5. However, different slope values may occur due to the influence of time-varying IR sources in the background. In general, slope values should be in the range -0.55 to -0.35.

8.10.1 Early slope values outside the prescribed range may be improved by isolating the system from IR radiation sources such as space heaters, incandescent lamps, direct sunlight or other hot objects. Isolation should block sight lines from the source to the camera.

8.10.2 If the initial slope value is not in the range - 0.55 to -0.35 after the previous steps have been taken, the following steps may be performed to improve performance:

8.10.2.1 The sample surface may be coated with a water washable black paint to increase the optical absorption and emissivity of the sample.

8.10.2.2 The sample may be IR translucent in the spectral range of the camera, and a camera that operates in a different spectral range may be required.

8.10.2.3 The sample may be too thin or heat transfer through the sample may be too fast to be detected at the IR camera frame rate. An IR camera capable of operation at a higher frame rate may be required.

8.10.3 If the knee associated with the back wall does not appear after the previous steps have been taken to optimize slope performance and acquisition period, the material or structure under consideration may not be appropriate for FT.

8.10.4 The log plots for a flaw-free multilayer or coated structure may be more complex than the simple straight line. However, a distinct knee associated with the back wall interface should be readily discernible.

8.11 View the raw or derivative image sequence and identify each indication that corresponds to a programmed flaw in the detectability reference standard. The smallest detected aspect ratio should be noted as the minimum detectable flaw aspect ratio for the material and flaw type represented by the test standard. The method used to detect the minimum detectable flaw (for example, raw, first or second derivative; contrast or numerical analysis) should also be noted.

8.12 Verify flash lamp array uniformity using the uniformity reference standard (see 7.2) and the analysis software.

8.12.1 Acquire a one second data sequence for the uniformity reference standard using the normal FT examination procedure (see Section 9).

8.12.2 Using the analysis software, plot the temperature (or radiance) along horizontal and vertical lines on the inspection surface at 50 milliseconds after flash heating. The variation of the signal should be less than 15 % of the mean value.

8.12.3 Adjust the individual flash lamp amplitudes to correct excessive non-uniformity.

9. Procedure

9.1 Position the apparatus so that the inspection surface is in the field of view of the IR camera and flash array. The sample should be mounted to minimize thermal conduction to the mounting apparatus.

9.2 Focus the IR camera by placing a thermally reflective object (for example, foil marker) on the sample surface and adjusting the camera lens until the edges of the object appear distinctly.

9.3 The inspection surface should be clean and free of dirt or grease. Obvious visual indications or features should be noted.

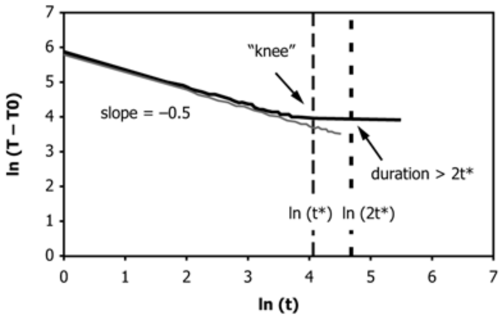

FIG. 3 Acquisition Duration

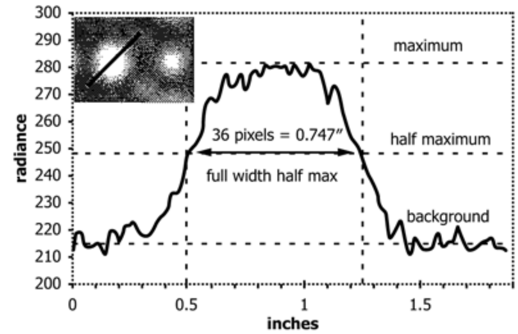

FIG. 4 Radiance Profile of a 0.75 in. Diameter

9.4 Begin data acquisition and recording with the IR camera.

9.4.1 The data sequence should contain at least one frame acquired prior to the flash event, and 100 frames acquired after the flash event.

9.4.2 If the thermal diffusivity and thickness of the test panel are known, the acquisition period should be estimated to be at least

$$\tau_{acq} = \frac{2L^2}{\pi\alpha}$$

where L is the thickness of the panel and α is its thermal diffusivity. This value is two times greater than the time required for heat from the inspection surface to reach the back surface, as shown in Fig. 3.

9.5 Activate the flash lamp array.

9.6 Terminate IR camera data acquisition after a sequence of appropriate duration has been acquired.

10. Interpretation of Results

10.1 The raw captured data sequence, or its first or second logarithmic derivatives, may be viewed as a sequence of images so that the entire volume of interest of the test material is interrogated.

10.2 *Raw Sequence Analysis*—Analysis of the raw captured sequence is based on visual identification of contrast between flaw indications and intact areas in the field of view. Raw sequence analysis is appropriate for detection of discrete flaws that are smaller than the inspection field of view, but larger than the minimum detectable flaw size.

10.2.1 In the raw data sequence, subsurface flaws that obstruct the flow of heat (for example, voids or delaminations) will have higher temperature (or radiance) values than nearby intact areas. Conversely, flaws that act as heat sinks (for example, water or metal inclusions) will appear to be cooler than surrounding intact areas.

10.3 *Derivative Sequence Analysis*—Sequences showing the first or second logarithmic derivative of the raw data may be viewed to identify either discrete or extended subsurface flaws. Contrast or numerical analysis may be used to identify flaws.

10.3.1 *Contrast Analysis*—Discrete flaws will appear during the sequence, and have higher, and then lower amplitudes (or vice versa) than flaw-free regions in the field of view.

10.3.2 *Numerical Analysis*—Both discrete and extended flaws will have numerical derivative values that are substantially different than the derivative values obtained for flaw-free areas in the reference standard.

10.4 *Log Plot Analysis*—Indications may be evaluated by viewing the logarithmic temperature-time plot for points that are representative of the indication. A flaw is indicated if the log plot is substantially different than that of a flaw-free point on the reference standard.

10.5 *Flaw Sizing*—The lateral dimensions of a discrete flaw may be determined by measuring the raw or derivative full-width at half maximum amplitude, along a line segment that bisects the flaw (or traces the major and minor axes of an equivalent rectangle), as shown in Fig. 4. The pixel field of view size, (see 8.2) may be used to convert the defect dimensions measured in pixels, to appropriate physical units.

10.6 The location, size and nature of indications detected in either the raw or derivative data sequences should be recorded.

10.7 In the event that an indication is detected, the inspection surface (or a photograph of the surface) should be visually examined to determine whether the indication is superficial, for example, due to dirt or markings on the surface.

11. Hazards

11.1 Thermographic test methods involve the use of heated or electrically energized equipment.

11.2 Personnel in the test area should not be exposed to the direct flash.

11.3 Operation of flash lamps may not be permitted in fuel-rich environments.

12. Report

12.1 To ensure test validity, including reproducibility and repeatability, essential information about test method, specimen geometry, condition and preparation, test equipment, optics, camera frame rate and integration period, flash lamp energy, working distance between apparatus and specimen, and data processing methods shall be recorded.

13. Keywords

13.1 composite; flash; IR; nondestructive; thermography