Infrared Thermography:
A Versatile Nondestructive Testing Technique

Starting in the mid-1600s, humans began to create a multitude of temperature measuring devices, culminating with the development of thermal imaging cameras in the 1950s by the U.S. military.

Image 1. Infrared cameras show heat, not visible light. Temperature differences not visible to the eye are easily detected.

All objects radiate infrared energy from their surface. The warmer something is, the more it radiates. An infrared camera detects this radiation and converts it into an infrared image which shows apparent surface temperature differences and thermal patterns across an object (shown in Image 1). Infrared thermography is the technique of using an infrared camera to test these patterns which can then show the current condition of a device or composition of a material.

Long before the advent of this technology, humans learned to visually interpret indications of surface temperature. For example, a piece of iron that is glowing orange is warmer than one that is not glowing. Similarly, water condensing on a surface is an indication that the surface is cooler than the surrounding dry area.

Much of the time, however, surfaces do not visually reveal their temperature and historically there has been a need to rely on other techniques to make these determinations. Starting in the mid-1600s, humans began to create a multitude of temperature measuring devices, culminating with the development of thermal imaging cameras in the 1950s by the U.S. military. Thermal imagers first became commercially available in the 1960s. Since that time, as the cost of cameras have decreased and their capabilities increased, there has been an exponential growth in the use of this technology. Today's modern infrared systems come in a wide variety of resolutions and thermal sensitivities and are available in nearly every price range. However, even with the advancements seen from the lower cost and smaller size of thermal imaging equipment, the reality is that these cameras are still quite dependent upon physical realities when it comes to radiation heat transfer.

Thermal radiation is a form of electromagnetic radiation with wavelengths longer than those of visible light. All objects above absolute zero (0 K, [–459.67°F]) emit infrared radiation as a function of the fourth power of its absolute temperature. In other words, as an object changes temperature, the amount of radiation it emits changes significantly. Of importance is the fact that all objects also have some degree of thermal reflectivity as a characteristic of their surface. What this means to the thermographer is that some of the energy that a thermal imager detects coming from an object has no connection to the actual surface temperature. Understanding this reflective component, as well as learning to evaluate and control it, is one of the primary reasons there is an extensive learning curve for thermographers. A multitude of internal and external factors affecting surface temperature are also of concern, requiring that the thermographer have in-depth knowledge of radiation physics and basic heat transfer, as well as an awareness of environmental influences that affect surface temperature.

Thermography has several advantages relative to other nondestructive testing (NDT) technologies. One advantage is that thermography is very fast. An image or series of images can be captured practically instantaneously. With the appropriate equipment, relatively large areas can also be inspected quickly. Secondly, there is no need to touch the object being inspected, thus allowing for rapid inspection of large areas or many objects. Thermography is also environmentally benign; the thermal imager only receives the radiant energy leaving the surface of the object being inspected.

A condition of thermography is that the inspection must be done when the object is in a thermal situation that will reveal the desired information. A thermal image of an object at the same temperature as its surroundings is barely, if at all, resolvable. The thermographer must either wait for conditions that create thermal contrast or induce a temperature difference in the objects to be imaged. This requires knowledge of the thermal properties of the object and the surrounding environment.

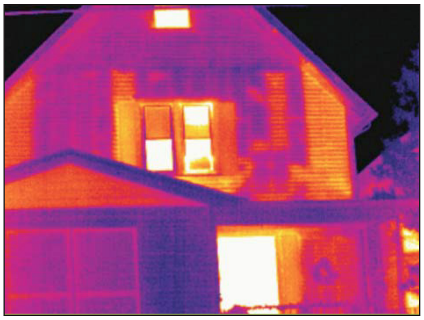

Image 2. The thermal image of this heated building during cold weather conditions clearly shows areas of apparent missing insulation on the second floor.

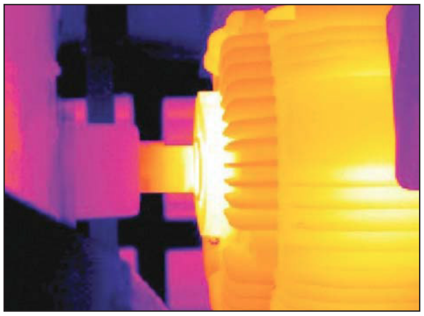

Image 3. Infrared thermography used on a hot motor bearing.

Overview of Thermal Nondestructive Testing

The fact that an infrared camera can detect thermal surface patterns that reveal subsurface anomalies makes infrared thermography the testing technology of choice for a number of applications. As previously mentioned, imaging an object with an infrared camera allows for the immediate evaluation of thermal patterns across its surface. This is valuable information for a wide variety of diagnostic applications. Mainstream infrared and thermal testing (IR) methodologies have been developed in many areas of industry and science, including identifying areas of high resistance in electrical systems, finding areas of excessive friction in rotating equipment, determining fluid levels in vessels, detecting areas of missing insulation or air leakage in buildings (shown in Image 2), identifying thermal asymmetry in natural science applications, and locating subsurface anomalies in metallic and nonmetallic aerospace components.

While infrared thermography can detect hot spots on components such as a motor bearing (shown in Image 3), the reason that the anomaly is present can have several underlying causes. Obviously, if an electrical motor is not energized and has no load, there is little sense in testing the bearing housing for indications of excessive friction. As such, having proper working knowledge of the equipment being inspected is critical. The job of the thermographer is to be present to observe when the object to be tested is going through a thermal transition that will cause a change in the surface's thermal signature.

Infrared thermography works wonderfully on objects that are internally heated or cooled (motors, bearings, buildings, animals and so on), or on those devices that are going through a normal thermal transition. When inspecting these types of equipment, the thermographer must have the proper working knowledge of the object, as well as an understanding of the causes of internal thermal anomalies. One of most egregious errors a thermographer can make is to acquire a thermal image of an object at a time when subsurface anomalies are not revealing themselves on the surface. If the image shows no surface indication, the misinterpretation is often that there is no internal problem. Critical in image analysis is the necessity of acquiring all relevant data for each thermal image captured. Ambient air temperature, wind speed, time of day, operational condition of the object and external thermal influences (such as the sun, or heating and air conditioning equipment) are just some of the data points that should be considered. ASTM International and other professional organizations have provided numerous important published standards that specify thermal conditions for the inspection of electrical and mechanical

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equipment, building envelopes, low slope roofs and concrete bridge decks among others (ASTM 1934-99a, ASTM C1060, 2003; ASTM C1153-97, 1997; ASTMD4788-03).

If the object to be tested is at internal thermal equilibrium, there will be no surface indication of a subsurface anomaly. If, for instance, the intention is to test a composite honeycomb structure for water ingress, the part must be tested when the water in the structure is either warmer or cooler than the adjacent dry cells. This is seldom the case when testing structural components. This type of thermal NDT requires active thermography.

Active thermography involves inducing some type of external or internal thermal stimulus to create a thermal situation that will reveal the subsurface discontinuities, if there are any present. There are a wide variety of techniques for inducing a thermal gradient in a structure. These techniques will be explained later in the paper.

Basic Theory of Thermal Nondestructive Testing

When an object is at internal thermal equilibrium, there is no net heat movement throughout the volume of the material. When an object is subjected to a thermal excitation (heated or cooled), heat begins to move through it by thermal conduction. If a pulse of heat is applied very evenly over the surface, the heat has only one direction in which to move. That direction is perpendicular to the surface and towards the interior and backside of the material. If the item is homogeneous in nature, the material should cool evenly after the pulse of heat is applied to the surface. If, however, there is something internal to the object that disrupts the even conduction of heat through the material, a surface thermal pattern will result over the internal area that is causing the disruption. If the artifact slows heat movement, as would be the case for an insulating anomaly, then the spot over it will appear warmer than the surrounding area. It must be noted that the warm spot is not heating up; it is just cooling down more slowly than the surrounding area. Likewise, if the anomaly is more conductive, or has a higher thermal capacitance, heat will move into the anomaly faster than the surrounding area and create a cooler spot on the surface.

It is the disparity between the thermal properties of the host material and the anomaly that causes the surface indication. All things being equal, the greater this thermal disparity, the greater the difference in surface temperature that will be seen over the area causing the disruption.

A limiting factor in using thermography is that heat conduction is used to probe the structure. Heat conduction is a diffusion process, meaning that the deeper the heat conducts or diffuses into the structure, the weaker it gets. There is a distinct and real limitation to detectability based on the relationship between the depth and diameter of an anomaly. A large anomaly close to the surface will typically create a larger temperature difference than a deeper and smaller anomaly. It is generally agreed that the diameter to depth ratio should be equal to or greater than 1 (Shepard 1999).

Feasibility of Thermal Nondestructive Testing

As with all NDT methodologies, a feasibility evaluation must be performed to determine if a thermal NDT technique will be viable for identifying material discontinuities. When the type, size, depth, orientation, quantity and other aspects of the anomaly are

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established, the responsible Level III thermographer who is overseeing the procedure can begin to determine whether thermal NDT is a possible inspection methodology. Often, all of these data are not available early in the process, but the feasibility research and development work can usually begin with anomaly size and depth information.

There are several approaches in determining the feasibility of thermal NDT. These might include warming the surface with a hot air gun and inspecting the surface to see if any abnormal surface patterns appear, or doing a high definition, high frame rate capture using flash thermography, along with image processing software. The bottom line is that all of the items in the following lists affect the feasibility of thermal NDT (Burleigh, 1996). The thermographer must be aware of these influences to determine the ability of thermal NDT to detect anomalies, as well as the repeatability of the testing process. The following list outlines these important considerations.

Thermal and Physical Properties of the Sample

- Base material(s)
- Manufacturing processes
- Surface spectral emissivity
- Surface optical absorptivity
- Surface thermal transmittance
- Material thermal diffusivity ($\lambda = k/\rho c$, thermal conductivity/thermal capacitance)
- Sample thickness
- Sample geometry
- Access or no access to both sides

Thermal and Physical Properties of the Anomaly

- Diffusivity
- Depth
- Orientation
- Size

Selection of Thermal Imager

- Working distance (distance from imager to object)
- Spatial resolution (detector density relative to distance of imager to object)
- Thermal resolution (minimum resolvable temperature difference)
- Wave band selection (select wave band to coincide with surface opacity)
- Thermal range (imager capable of sensing temperatures of inspected object)
- Image capture rate
- Available optics

Selection of Thermal Excitation

- Hot air gun
- Light (sun, incandescent, quartz or xenon flash)
- Oven, autoclave
- Thermal blankets
- Refrigeration
- Mechanically induced vibrations
- Lasers

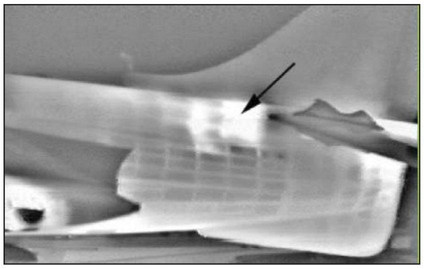

Image 4. An internal exhaust leak in this aircraft is easily seen (indicated by the arrow) using a low-cost infrared thermography system and passive heating of the exhaust gases.

Image Processing Options
- Raw image
- Time/temperature plots, peak contrast evaluation, log/log plots
- Reconstructed thermal data (raw temporal image data converted to mathematical functions)

Environmental Conditions
- Ambient temperature
- Sources of thermal contamination
- Control of spurious convection
- High-temperature background (lights, heaters, coffee makers)

Methodologies of Thermal Nondestructive Testing

There are a variety of techniques used to detect subsurface anomalies in structures with infrared thermography. The differentiation among test techniques is based primarily on the strength and duration of the thermal signature. These techniques can be loosely classified as passive or active, (we say all this later on).

The technique selected depends on several factors, including the thermal characteristics of the part; the types, sizes and orientation of anomaly to be detected; the technique of inducing heat to the component; the sensitivity and spatial resolution of the infrared imager; and the budgetary constraints with respect to the total system cost.

Passive Thermography

In passive thermography, the part or component is inspected during or after a thermal operational cycle. This thermal cycle could be part of the manufacturing process or part of the normal operation of an aerospace component. When using passive thermography, the thermographer must be at the right place at the right time. Figure 4 shows how hot exhaust gases can indicate the location of a leak in a flight system. Another example of this would be inspecting an aircraft for water ingress immediately after it lands from a high altitude. The water, having a high thermal capacitance, would remain cooler than the surrounding material for a period of time, allowing for thermal testing of the component (Vavilov et al., 2003). Another example of passive testing is in the manufacture of components that go through a thermal process such as autoclave curing. If a part is inspected immediately as it emerges from the thermal cycle, it may be possible to observe comparative thermal images. In the automotive industry, glue bonding of laminate and composite materials is commonly tested with thermal imaging systems.

Passive thermography provides unique opportunities to quickly test large areas of a structure without taking the equipment out of service. It is most effective when looking for strong thermal indications that have persistence, such as water or other fluid ingress. Passive thermography does not always require expensive thermal imaging equipment. There are many affordable, handheld systems available today that are capable of resolving strong, persistent thermal signatures.

Active Thermography

Active thermography involves the controlled heating or cooling of the surface of the component to create a thermal gradient in the part. The component is continuously monitored with the infrared camera as it goes through the process of returning to thermal equilibrium (shown in Figure 5). For many types of materials and components, surface indications occur early in this process, which allows for very quick analysis. Active thermography provides the thermographer with more control of the thermal cycle than in the passive technique. This is critical because the thermographer controls when the thermal cycle will begin and matches the intensity and duration of the thermal pulse to the thermal characteristics of the component.

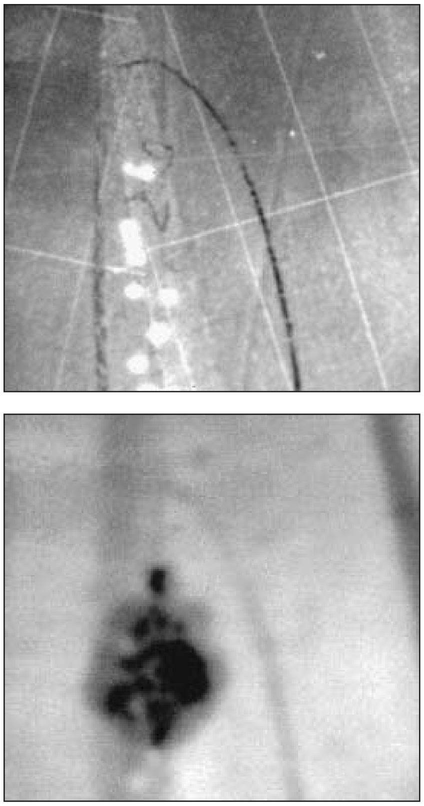

Image 5. Composite radome: (above) surface damage (early image); (below) water incursion (later image).

Testing low diffusivity materials that have significant thermo-physical differences between the host material and the internal anomaly, will often result in a persistent surface indication. There are a variety of ways to induce thermal excitation into these types of materials. Heating sources include hot air guns, quartz lamps, heat blankets and other sources that can be controlled by the thermographer. Even the sun can be used by bringing the component into the sunlight for a prescribed amount of time and then shading it. A strong thermal pulse can be induced into rather large components such as the composite hull of a watercraft to locate water ingress. To be effective, the surface indication must persist long enough for the thermographer to identify it in the camera display. This will allow the thermographer time to optimize and record the thermal image, or even mark the location of the indication on the surface of the component. If repeatable results are required, great care must be taken to input consistent amounts of heat during each test. While these slower excitation techniques work well on materials with thermally persistent anomalies, they may not be effective for identifying anomalies in thin or highly diffusive materials that may present themselves for very short periods of time, sometimes within the thermal excitation period, making identification impossible.

In order to find subtle thermal signatures, more control of the process is required. As the technique of thermal excitation is more precisely controlled and applied (for example, a sub-millisecond flash pulse compared to solar heating), the thermal response of the component becomes more predictable. This makes it possible to develop algorithms that detect deviations from ideal behavior. As a result, modern active NDT systems are capable of detecting anomalies and features that are not visible to the naked eye using passive heating or by simple viewing of the infrared camera output. Flash thermography is one example of active thermography that allows such control.

The following sections discuss a variety of active thermography techniques based principally on thermal excitation, including flash thermography, lock-in thermography and vibrothermography.

Flash Thermography

Today, flash thermography is the most sophisticated and versatile thermal NDT technique. Flash thermography, also called pulsed thermography, has many advantages, including fast uniform heating, variable capture rates to meet the specifics of the material being tested and a variety of software analysis options. Most of today's flash thermography systems are composed of several components, including an infrared camera with high spatial resolution; integrated, high-power xenon flash lamps (to provide heat); and a computer to capture and process the thermal data. This technique is now widely used for both production and repair of a wide variety of commercial and military structural components.

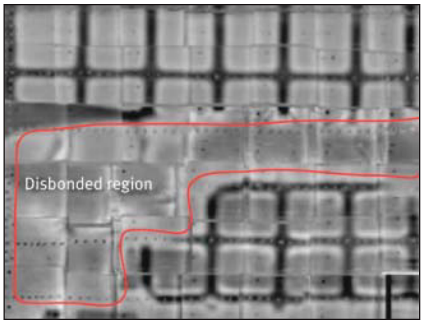

Image 6. Waffle doubler disbonds detected in a jet fuselage using wide-area flash thermography.

When the flash lamps discharge, the pulse of light energy is absorbed by the surface of the component. As the heat conducts and diffuses into the component, numerous images are captured at rates of up to 500 fps. The thermal properties of the material determine the image capture frame rate and duration. The combination of powerful software analysis and trained, qualified operators allows for the detection of anomalies in a wide range of materials, including thin and highly conductive materials, as shown in Figure 6. Transient thermal events, presenting themselves for fractions of a second, can readily be detected. Because the entire process takes only a few seconds, large areas can often be tested faster with flash thermography than with other NDT techniques. The biggest advantage of flash thermography is that it delivers highly repeatable results due to the uniformity of the heat input and the high-speed image capture. The latest advancements concerning flash thermography have come with advanced analysis techniques. Reconstructing the thermal data is a process where the raw temporal response from each pixel is reconstructed into a mathematical function (Shepard et al., 2002). Not only is system noise reduced, but a variety of analysis techniques become possible, improving the ability to resolve deeper and more subtle subsurface features. Images can also be created to show each anomaly at its optimum thermal contrast within the component. Systems can now be fully integrated with robotics to control the movement and placement of the flash head and automatically test an entire component. Post-processing of images allows automated measurement of both anomaly size and depth. It is this type of analysis and automation that has allowed active flash thermography to become a mainstream NDT technique.

Lock-in Thermography

With lock-in thermography, periodic heating is applied to the component surface. The excitation may be optical (light), ultrasound, microwave or any other energy source that results in a temperature change at the surface. In order for subsurface anomalies to be revealed as a surface temperature difference, the excitation frequency must be matched to both the depth of the anomaly and the thermal and physical characteristics of the component. A thermal imager monitors the surface temperature and the resulting signal is processed so that the periodically varying part is retrieved and amplified. Since the excitation is repetitive, it is possible to test thick or thermally slow parts using lock-in thermography. The process is inherently slower than the flash approach, however, and may require multiple passes to test different depth zones (ASNT, 2001).

Vibrothermography

First developed in the late 1970s, vibrothermography has shown positive results in effectively finding cracks in a variety of materials. Also known as sonic thermography, acoustic thermography or thermosonics, vibrothermography injects high-energy acoustic waves, generally in the range of 10 to 40 kHz, into the component using devices such as ultrasonic welders. The acoustic waves do little to heat an anomaly-free part. However, significant heating may occur at the site of an anomaly where frictional heating occurs (for example, a closed crack or tight delamination). Combined with an infrared camera that has an appropriate spatial resolution and capture rate, vibrothermography has shown its ability to detect surface and near surface cracks that conventional thermographic NDT cannot detect. Packaged systems are now available that integrate a high-speed thermal imager, ultrasonic transducer, digital storage and image processing (ASNT, 2001; Henneke et al., 1979).

Today, all major aerospace companies, as well as industries in general, have developed and continue to expand the use of thermography for a wide variety of component tests.

Conclusion

Infrared thermography provides a variety of techniques for testing a wide range of components, machines and structural materials. Infrared cameras record the surfaces of objects and present a thermal image based on the thermal radiation leaving the surface. In controlled situations using a variety of techniques, trained thermographers can interpret these images and locate and identify subsurface anomalies. Over the past 15 years, infrared thermography has become a mainstream NDT technique. After the 2003 Space Shuttle Columbia disaster, NASA chose flash thermography to inspect the reinforced carbon-carbon composite that constituted the leading edge of the orbiter wing (TWI, 2011). Several years ago, astronauts aboard the Discovery orbiter successfully carried out an experiment using a handheld infrared camera adapted for use in space to inspect a sample of a reinforced carbon-carbon composite with known anomalies using the sun as the source of the thermal pulse (Howell et al., 2008). In 2007, ASTM 2582-07 was adopted fully legitimatizing thermal NDT as a consideration for a wide variety of aerospace structures (ASTM, 2007; Shepard, 2007). The growth and significance of thermal NDT was also recently made apparent when the 2010 edition of NAS-410 designated thermal infrared testing as an included technique (AIA, 2008). Today, all major aerospace companies, as well as industries in general, have developed and continue to expand the use of thermography for a wide variety of component tests.

For additional information about thermography, building inspections, and infrared training, visit www.thesnellgroup.com or contact The Snell Group at 1-800-636-9820.

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