

APPLICATIONS OF IR THERMOGRAPHY IN CAPTURING THERMAL TRANSIENTS AND OTHER HIGH-SPEED THERMAL EVENTS

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ABSTRACT

The high-speed, snap-shot mode, and the external triggering capability of an IR camera allows thermal transients to be captured. These advanced features were used to capture thermal transients during electrical breakdown of ZnO varistors and to freeze the rotation of an automobile disk brake in order to study thermoelastic instability in the braking system. The IR camera also showed the thermoelastic effect during cyclic fatigue testing of a glass matrix composite.

1 INTRODUCTION

Infrared thermography is widely used as a process monitoring or non-destructive inspection (NDI) technique in scientific research and industry. Obtaining a surface temperature map with high spatial and temperature resolutions is the key in IR thermography. Non-uniformity in a temperature map often signals defects or potential of failure. Defects in a material or imperfections in a system usually show up as hot spots in IR images. Some defects such as bad electrical contacts in an electrical system are easier to identify because the hot spots do not change over time. On the other hand, many thermal events only last a very short period of time. These so-called thermal transients are usually related to electrical or optical transients.

Since excessive heat generated by the thermal transient must be transferred to the surrounding environment, the lifetime of a thermal transient depends not only on the transient duration and energy, but also on the thermophysical properties of surrounding materials. Capture of thermal transients requires the IR camera to have external triggering capability and also to operate at a speed higher than the thermal transients. An example of an active application of thermal transient is to heat up a surface with a flash lamp and watch the temperature change after the heat pulse. Thermal diffusivity maps of the target can be generated from the infrared images⁽¹⁻³⁾. In this paper, we present IR images of ZnO varistors during electrical breakdown, hot spots on a rotating brake disk, and heating-cooling of a glass-matrix composite specimen during cyclic fatigue tests.

2 THERMAL TRANSIENTS IN ZnO VARISTORS

ZnO varistors are used as surge protection devices⁽⁴⁻⁶⁾. The most important electrical property of ZnO varistors is that each grain boundary behaves as a double Schottky barrier. Below the breakdown voltage, i.e. 3.2 V per grain boundary, the device acts as an insulator. Above the breakdown voltage, the device acts as a perfect conductor providing current paths to the electrical transients. During electrical breakdown, a large current passes through the device in a fraction of a second. During this switching process the current in a varistor can increase as much as 8 orders of magnitude. A large amount of heat is associated with the breakdown process. The localized heat sometimes can cause thermal runaway and puncture failure⁴ in the varistor. The heat generated at the grain boundaries is rapidly transferred to the adjacent grains. Normal IR cameras operated at video frequency of 30 Hz can only capture the overall temperature increase after the transient.

We used a Raytheon-Amber Focal Plane Array (FPA) IR imaging system to capture the thermal transients during electrical breakdown of ZnO varistors⁽⁴⁾. An electrical circuit was built to trigger the IR camera during the electrical pulse (usually 1 ms long). Figure 1 is the thermal image of a varistor block 1 ms after a 1000 V electrical

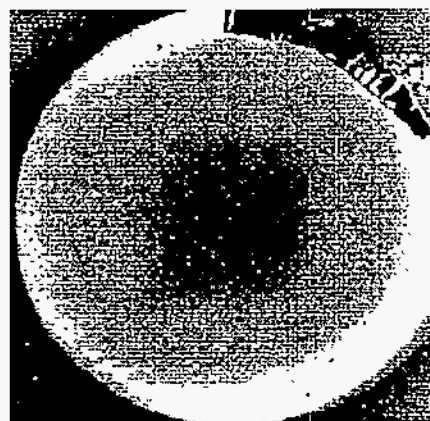


Figure 1. Temperature map of a large varistor block.

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pulse. Aluminum was evaporated on both sides of the block as electrodes. Electrical contacts were made through copper tapes, i.e. the dark strip in Figure 1. The temperature profile showed a variation of about 1.5°C between the dark and bright areas. The large varistor block was about 5 cm in diameter and 1 cm thick. There are hundreds of grain boundaries in each current path during breakdown. No hot spots or paths were found in the large-scale varistors. This result is consistent with the grain size distribution of the large varistor block. A temperature gradient during sintering caused excessive grain growth at the periphery of the block. More electrical current goes through the area with fewer grain boundaries during the breakdown. Thus, the outside of the block appears to be warmer.

The GE V27 varistor is a low-voltage varistor with an average grain size about 100 μm . A specimen was ground to about 100 μm thick and mounted on a glass slide. The electrodes were thermally evaporated aluminum. An 80V pulse was applied across the 4 mm wide specimen between the electrodes. Using an extension tube to the 25 mm lens, we obtained IR images with spatial resolutions of 15 μm . The IR camera was triggered to take a sequence of images 1 ms after the pulse. Unlike the large varistor block, many distinct conducting paths were observed in the very first image, Figure 2. The electrical current went through the paths that contained fewer numbers of grain boundaries. The bright spots in the conducting paths are grain boundaries. The grain boundary temperatures were 15°C to 20°C higher than the grains during the transient. Heat transfer in ZnO was so fast that the second image taken 8 ms later only showed a blurred high temperature area, and neither grain boundaries nor conducting paths could be seen. The combination of external triggering and high-speed of the FPA camera allowed us to observe the first IR image of varistor breakdown. IR images of varistor breakdown such as shown in Figure 2 confirm the grain-boundary-barrier theory of varistors.



Figure 2. Temperature map of a 27V varistor

3 AUTOMOBILE BRAKE SYSTEM

Automobile brake systems convert kinetic energy into heat in order to stop the vehicle. The friction at the interface between the brake pads and the disk rotor generates heat. The temperature of a brake rotor during braking can reach nearly 500°C under some conditions. Thermoelastic instability of the brake system can result in brake judder, a combination of torque and vibration changes. This effect has been known for many years^[6-7]. Severe brake judder causes the vibration of the steering wheel. In most cases, both the brake pads and the rotor have to be replaced. Using IR thermography to monitor hot spots has long been desired as an important need to understand brake judder. However, early made IR cameras could not provide the fast imaging needed to capture the high-speed rotation of the rotor. Only a blurred image with a hot band at the contact area could be observed.

Working with FORD and GM, Dinwiddie^[8] designed a circuit to trigger the IR camera with the RPM signal from the dynamometer. The divided-by-n and phase-delay functions of the circuit allowed images to be taken every n'th rotation at exactly the same location. The trigger circuit and high-speed imaging capabilities were sufficient to "freeze" the action. Using this circuit, hot spots on the brake rotor were observed soon after the brake was applied. Figure 3 is an IR image of a brake rotor at 60 MPH dragging speed. Five distinct hot spots (areas) were observed. A gold-mirror also showed hot spots on the other side of the disk. The formation, movement, and disappearance of the hot spots were recorded. Temperature profiles across the hot spots and time profiles showing the temperature history of an area of interest provided important information to FORD and GM. Parameters such as speed, brake pad material, rotor material, and surface roughness were used to systematically study the origin of brake judder^[8-9].

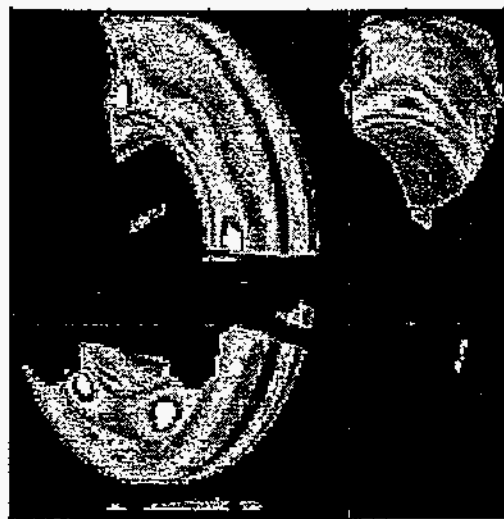


Figure 3. Hot spots on a brake rotor spinning at 60 mph

4 THERMOELASTIC EFFECT DURING CYCLIC FATIGUE TESTS

The thermoelastic effect is known to be the reason for temperature oscillation of the test specimen during cyclic fatigue tests⁽¹⁰⁻¹¹⁾. The temperature oscillation depends on the thermal and mechanical properties of the material. We have employed the high-speed IR camera to monitor temperature changes during cyclic fatigue tests. The specimens were Nicalon-LAS glass matrix composites. Cyclic fatigue tests cause damage at the interface between the fiber and the matrix, and significant changes in mechanical properties were observed in the composite. The debonding and oxidation of the interface greatly decreased the thermal diffusivity and thermal conductivity of the material. Internal friction caused by fiber-matrix sliding is believed to cause a temperature increase. Since the thermal diffusivity of the composite was about $0.008 \text{ cm}^2/\text{sec}$, significant heating should be achieved in a short time during a cyclic fatigue test. The fatigue tests were performed at 350 MPa and 30 Hz. Figure 4 is the temperature vs. fatigue cycle plot. The IR camera was set to take one image every 100 cycles. A total of 20,000 cycles were recorded. The specimen temperature increased from 25°C to just below 45°C after 5000 cycles, and was then approximately constant until the test was stopped at 20,000 cycles.

The 20°C increase shown in Figure 4 was very significant. Figure 4 also shows that the steepest temperature change happens before the first 1000 cycles. On a similar specimen, we used the IR camera to take 120 images per second while keeping the fatigue test running at 30 Hz. The IR camera was triggered to take 200 images starting from the 950th cycle. Four images were taken within a cycle. Figure 5 shows the temperature oscillation caused by the thermoelastic effect during loading and unloading. The temperature oscillation was about 0.06 °C. The temperature of the specimen increased about 1.35 °C

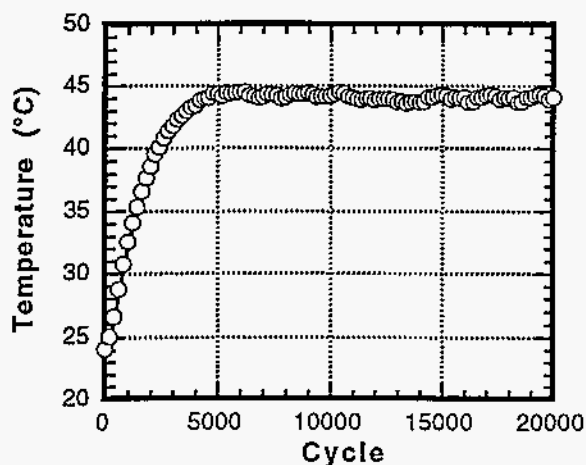


Figure 4. Temperature increase of a glass matrix composite specimen during cyclic fatigue test (30Hz)

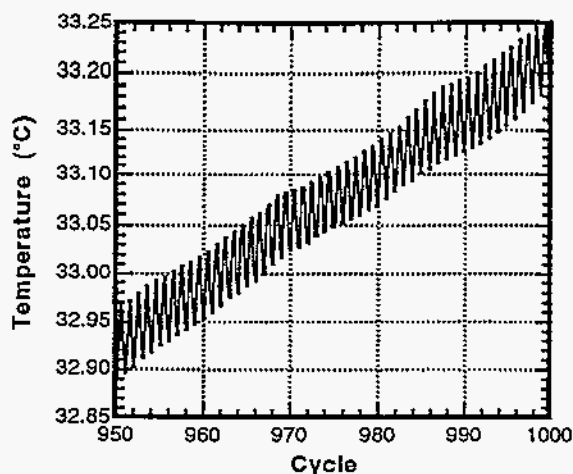


Figure 5. Heating and cooling effect during a cyclic fatigue test at 30 Hz. Images taken at 120 Hz

within the 50 cycles. Further analysis is underway at ORNL and Georgia Tech to identify the heat source and hopefully to locate crack initiation and propagation in the composite material.

5 CONCLUSIONS

IR imaging has been used to successfully capture thermal transients. By designing special triggering circuits, we obtained IR images of ZnO varistors during breakdown. The high-speed rotation of a brake rotor was frozen, and the hot spots caused by thermoelastic instability of the brake system were studied. Thermoelastic effect was observed during cyclic fatigue tests of glass-matrix composites. The high-speed imaging captured detailed heating and cooling of the specimen within a loading cycle.

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