Infrared Imaging for Material Characterization in Fracture Mechanic Experiments

Heat transfers are involved in many phenomena such as friction, tensile stress, shear stress and material rupture. Among the challenges encountered during the characterization of such thermal patterns are the simultaneous need for high spatial and temporal resolution. Infrared imaging provides information about surface temperature that can be ascribed to the stress-response of the material and breaking of chemical bounds. In this work, tensile and shear tests on steel, aluminum and carbon fiber composite material were carried out at the *University of Waterloo*, in Canada. High-speed and high-definition infrared imaging was performed using the Telops FAST-IR 2K and Telops HD-IR cameras respectively. The results illustrate how high-speed and high-definition infrared imaging in the midwave infrared (MWIR, 3 – 5 µm) spectral range can provide detailed information about the thermal properties of materials undergoing mechanical testing.

Introduction

Characterization of mechanical properties such as Young's modulus, elasticity, shear strain, viscosity and fracture toughness is a critical stage in the development of new materials. Researchers must typically carry out many different measurements like tensile displacement tests, compression tests and fatigue tests in order to determine these parameters. The nature of the material to be characterized also affects the mechanical properties to be determined. Metal alloys are typically ductile, while fiberglass materials are not. Consequently, a great variety of experimental techniques is required in order to face all these very different situations. Among the common instruments used by material engineers are high-elongation extensometers (see Figure 1), split-Hopkinson's bars and high-speed visible imaging.

One way of characterizing a material is to draw a stress-strain curve (see Figure 2). In such graph, the strain corresponds to the force applied on the material while the stress corresponds to the way in which the material reacts to the constraint. In the early stage of the curve, stress varies linearly as a function of strain and refer to the elastic region. Material deformations are reversible and the slope of the curve corresponds to the Young's modulus. The stress level at which the material begins to deform plastically is called the yield strength. Beyond this point, deformations are permanent and the relationship between stress and strain becomes non-linear. Once the maximum strength is reached, the material deforms locally and the cross-section of the material changes (necking). Ultimately, the fracture point is reached and the material breaks. The area under a stress-strain curve corresponds to the work.

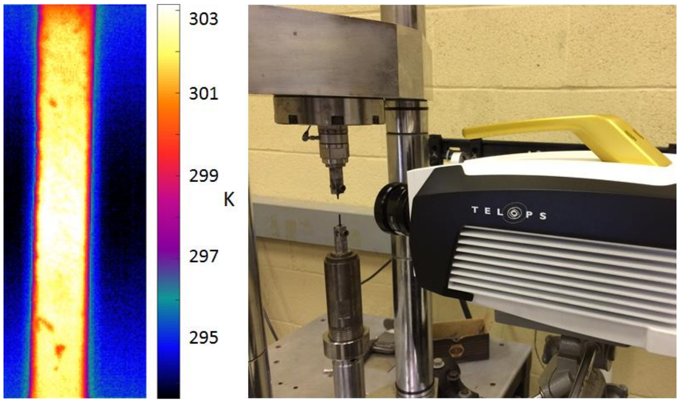

Figure 1 Tensile stress test carried out on a steel sample using high-speed infrared imaging (right). A representative infrared image recorded during the test is also shown (left).

In any case, a global answer, i.e. stress-strain curve, is obtained for a macroscopic sample. While the material undergoes alterations, it releases heat because of elastic or plastic deformation (i.e., work), and thermal energy due to the breaking of chemical bounds. It is well-known that the material properties (e.g. Young's modulus) change as a function of temperature. Therefore, being able to monitor heat profiles across the sample during testing may provide complementary information about its mechanical properties. Depending on the extent of the applied constrains and the sample's properties, the material can switch from one regime to another (e.g., from elastic to plastic) very quickly. In addition, when the rupture point is reached, defects usually tend to propagate quite rapidly through the material. Moreover, the cracks arising just before the fracture's onset can be quite challenging to locate due to their small size. Therefore, measurement techniques with high temporal and/or spatial resolution are usually required for proper investigation.

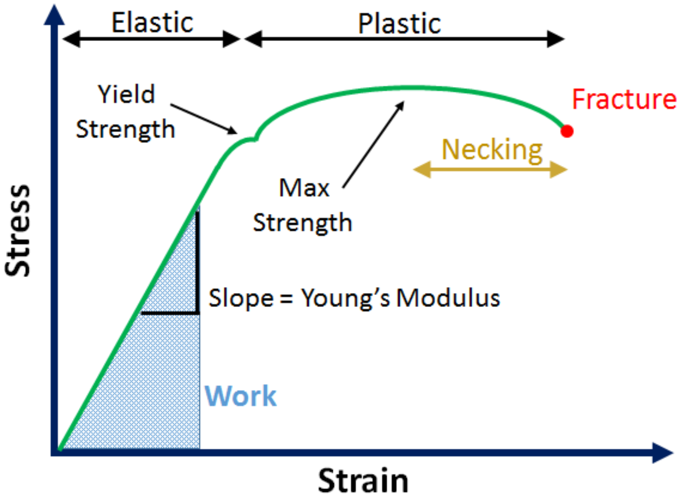

Figure 2 **Typical stress-strain curve for metallic materials.**

In this work, high-speed infrared imaging was carried out during tensile and shear stress tests on steel and aluminum respectively. High-definition infrared imaging was carried out during a tensile stress test on a woven carbon fiber epoxy matrix composite material. The results illustrate how infrared imaging can bring some additional insights for material characterization in fracture mechanic experiments.

Experimental Information

Sample Preparation

Since, smooth metals and polymer materials typically exhibit low-emissivity behaviors (highly reflective material), all samples were painted using a high-emissivity paint prior to testing. The use of a thin paint coating helps to minimize infrared reflections and obtain infrared temperature readings that are as close as possible to the surface thermodynamic temperature.

Tensile and Shear Stress

A high-elongation extensometer from MTS was used for all experiments. A 12.5 mm gauge steel sample was pulled at 10 strain/s (125 mm/s). The aluminum sample was pulled under adiabatic shear conditions. The woven carbon fiber epoxy matrix sample was pulled at 2 mm/min.

Telops FAST-IR 2K

The Telops FAST-IR 2K (see Figure 3) is a cooled high-performance infrared camera featuring a 320×256-pixel indium antimonide (InSb) focal plane array (FPA) detector covering the 3 – 5.5 µm spectral range. A 50-mm Janos lens was used for all experiments along with a ¼-inch extender ring. For the tensile stress test carried out on the steel sample, a 128×256-pixel sub-portion of the FPA detector was used for imaging at 4350 frames per second. For the shear stress test carried out on the aluminum sample, a 192×192-pixel sub-portion of the FPA detector was used for imaging at 3350 frames per second.

Figure 3 **Telops high-performance infrared camera.**

Telops HD-IR

The Telops HD-IR (see Figure 3) is a cooled high-performance infrared camera featuring a 1280×1024-pixel InSb FPA detector covering the 3 – 5 µm spectral range. A 50-mm Janos lens was used along with a ¼-inch extender ring. Imaging of the carbon fiber composite sample was carried out at 50 frames per second.

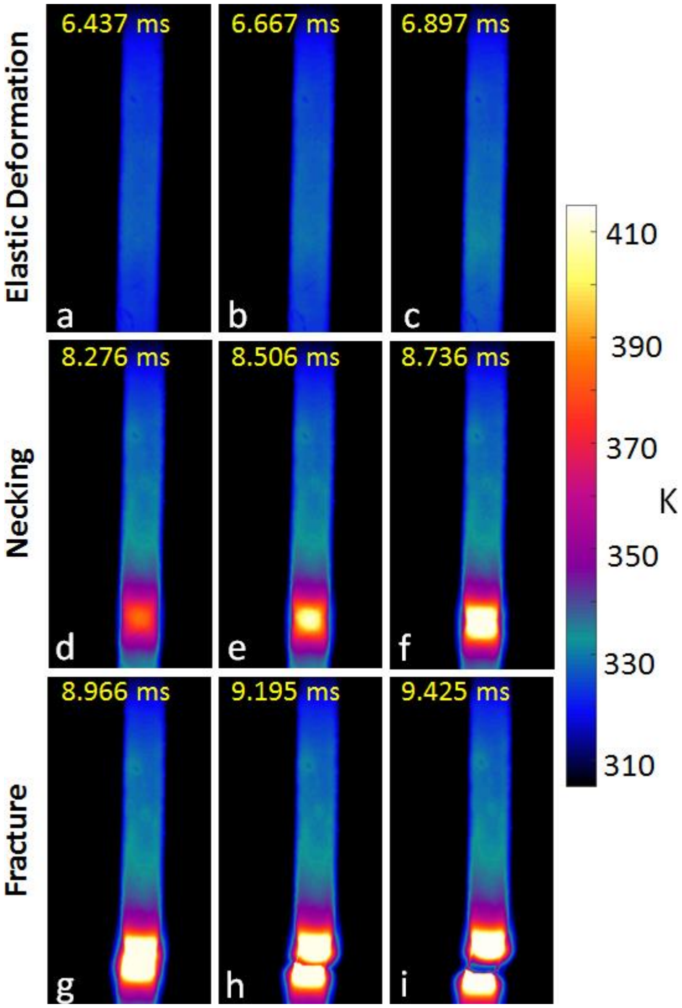

Figure 4 **Selected infrared images recorded during a tensile stress test carried out on a steel sample.**

Results and Discussion

Tensile Stress Test on Steel

A tensile test was first carried out on a steel (Figure 1). Selected images recorded during the experiment, corresponding to different stages of the stress-strain curve previously discussed (see Figure 2), are shown in Figure 4. In the first three frames (Figure 4a-c), the sample is still in the elastic deformation regime. The measured temperatures are slightly higher than room temperature (initial temperature of the sample prior to testing) and increase in a homogeneous fashion across the sample. Frames collected in a later stage of the tensile stress experiment (Figure 4d-f) correspond to the necking stage, where localized deformations and important temperature increases occur. The temperature rises locally since the heat release rate is much greater than thermal exchanges (adiabatic conditions). Temperature rises on the order of +115 °C were measured which are in good agreement with prior work on similar samples. Finally, frames collected just before (g), during (h) and after (i) the fracture point are shown in Figure 4. Beyond the fracture point, heat conduction through the sample and rapid cooling near the fracture area can be monitored (data not shown). The time labels in Figure 4 illustrates how fast the sample switches from one regime to another highlights the need for high temporal resolution in this kind of experiment.

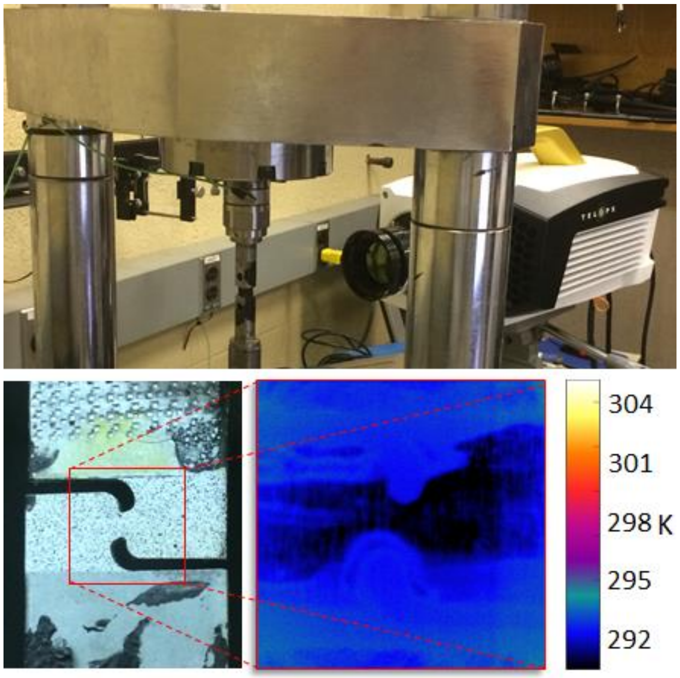

Figure 5 **Shear stress test carried out on an aluminum sample using high-speed infrared imaging (top). A typical sample (before being painted) used for this test is shown (bottom left) as well as a representative infrared image of the shear area (bottom right).**

Shear Stress Test on Aluminum

In order to demonstrate the versatility of high-speed infrared imaging, a shear test was carried out on an aluminum sample, as shown in Figure 5. In shear conditions, the constraint must be applied in a perpendicular plane. In order to perform such measurements with a high-elongation extensometer a special cut-out was made in the sample, as shown in Figure 5. This special shape also strongly dictates where the fracture will likely happen.

This area was targeted for infrared imaging, as shown in Figure 5. Selected frames recorded during the shear stress experiment are presented in Figure 7A. In the early stage, the temperature rises rapidly within the area of the (eventual) fracture location. Once again, the experimental conditions ensure that adiabatic shear conditions prevail and that thermal equilibrium is not reached. Under such conditions, the sample mostly undergoes localized heating and softening. This favors stress release as the sample is being pulled. Therefore, moderate stress increase as a function of strain occurs leading to much lower heat release (approximately +30 °C).

Successive frames recorded during material’s rupture are shown in Figure 7B. Once again, it can be seen that high-speed infrared imaging can provides enough details for characterizing the fracture’s onset.

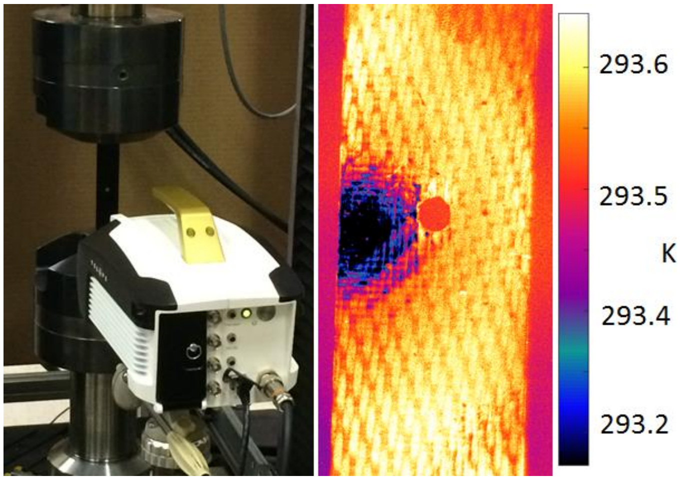

Figure 6 Tensile test carried out on a carbon fiber composite sample using high-definition infrared imaging (left) and an infrared image of the sample (right).

Tensile Test on Composite Material

Tensile test was finally carried out on a composite sample made of woven carbon fiber embedded in an epoxy matrix. Investigation was carried out using high-definition infrared imaging. A representation of the experimental setup is shown in Figure 6 as well as an infrared image of the sample. As shown in Figure 6, a hole was introduced in the center of the sample in order to specifically increase stress concentration at this location and initiate fracture at this point.

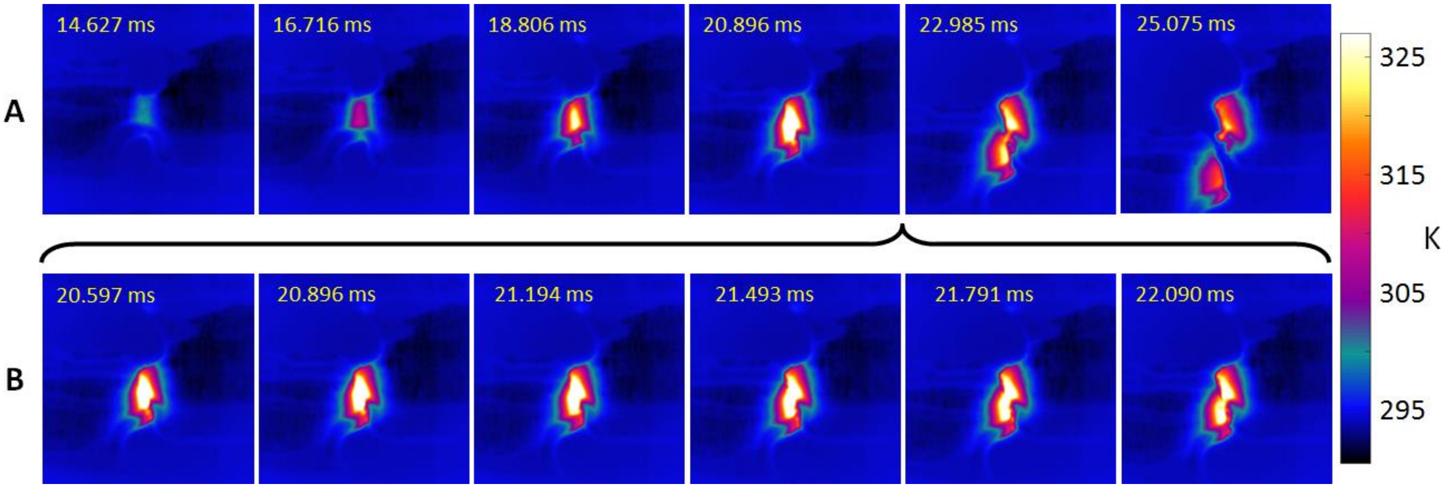

Figure 7 Selected infrared images representing different stages of the shear experiment on aluminum (A). Successive frames recorded during the short fracture phenomena are also shown (B).

The area left of the hole appears somewhat cooler than the rest of the sample by a few tenths of a degree. This results from uneven paint drying during sample preparation (emissivity contrast) and should have very little effect on the measurements. Carbon fiber materials are known to be brittle, which means that they do not undergo significant elastic deformation under tensile stress. Nevertheless, some cracks within the epoxy matrix can be seen prior to the material's rupture, as shown in Figure 8.

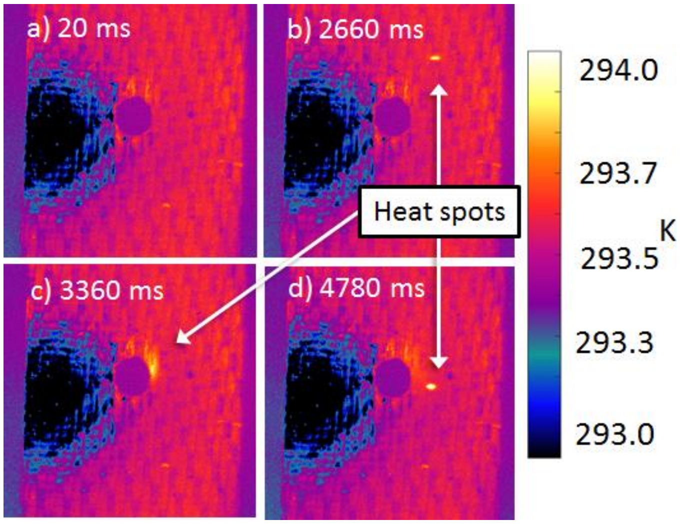

Figure 8 Selected frames recorded during a tensile test carried out on a carbon fiber composite material highlighting the presence of cracks within the epoxy matrix.

These defects are expected to be relatively small. They show up as few-micron wide hot spots during a few milliseconds at the time. The temperature rise associated with these defects is only a few tenths of a degree, which is in good agreement with prior work on similar samples. As expected, heat spots can be seen near the hole (see Figure 8C), but also apart from the fracture location. At the rupture point, the number of cracks multiply rapidly. The amount of stress resulting from the coalescence of all defects within the material is then transferred to the carbon fibers and eventually leads to the material's fracture, as shown in Figure 9. In this case, fracture occurs at about 45 000 N followed by temperature rises on the order of +10 degrees, in good agreement with prior work on similar material.

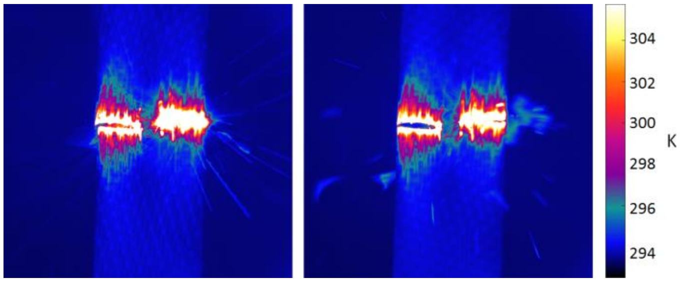

Figure 9 Frames recorded during fracture upon tensile testing of a carbon fiber composite material.

Conclusion

Heat release associated with tensile and shear testing could be successfully monitored using high-speed infrared imaging. Heat spots resulting from energy release upon breaking of chemical bounds can be monitored with high-resolution infrared imaging. Infrared imaging was shown to be a useful tool for monitoring temperature profiles and represents an important asset for obtaining the most out of each experiment, especially in the case of destructive testing experiments.

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