Infrared Imaging for Material Characterization in Fracture Mechanics 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 is the need for both 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 materials 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 the 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, shear strain, viscosity and fracture toughness is very important in the development process 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 dictates the parameters that need to be determined and to which extent. Metal alloys are typically ductile, while fiberglass materials are not. Consequently, laboratories are typically equipped with a great variety of instruments in order to face all of 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 of the most common way of characterizing materials consist in establishing a stress-strain curve (see Figure 2). The strain corresponds to the force applied on the material while the stress is associated with how the material reacts to the applied constraint. In the early stage, 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 elastic modulus that is also known as 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](image1.png) 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).

The stress-strain curve reflects the behavior of the overall sample at the macroscopic level. It does not contain any information at the microscopic level on how the sample deforms or breaks locally during testing. For example, materials typically release heat as they undergo...
alterations because of elastic or plastic deformations (i.e., work). It is well known that thermal energy is released during the breaking of chemical bounds. In addition, 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](image)

**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-polymer matrix composite material. The results illustrate how infrared imaging can bring some additional insights for material characterization in fracture mechanics experiments.

### Experimental Information

#### Sample Preparation

Since smooth metals and polymer materials typically exhibit low-emissivity behaviors (because they are highly reflective materials), all samples were coated using a high-emissivity paint prior to testing. This helps to minimize infrared reflections. Consequently, the temperature values measured by infrared thermography are considered close to their actual 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-polymer matrix sample was pulled at 2 mm/min.

![Figure 3](image)

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

**Telops FAST-IR 2K**

The Telops FAST-IR 2K (see Figure 3) is a cooled high-performance infrared camera featuring a 320x256-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 128x256-pixel subportion 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 192x192-pixel subportion of the FPA detector was used for imaging at 3350 frames per second.
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.

Results and Discussion

Tensile Stress Test on Steel

A tensile test was first carried out on a steel sample (Figure 1). Selected images recorded during the experiment, corresponding to different stages of a typical stress-strain curve, as 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 temperature increases are homogeneously distributed all across the sample. The infrared frames collected at a later stage (Figure 4d-f) correspond to the necking stage, where localized deformations and important temperature increases occur. In the plastic deformation regime, the temperature rises locally and more rapidly than thermal exchanges (adiabatic conditions). Temperature rises on the order of +115 °C were measured, which is in good agreement with prior work on similar samples [1]. 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 illustrate how fast the sample switches from one regime to another and highlight the need for high temporal resolution in this kind of experimental testing.

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

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 6. 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 6. This special shape also strongly dictates where the fracture will likely happen.
Figure 5  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).

Figure 6  Shear stress test carried out on an aluminum sample (top). A typical sample (before being painted) used for this test (bottom left) as well as a representative infrared image of the shear area (bottom right).

For this reason, this area was targeted for infrared imaging, as shown in Figure 6. Selected frames recorded during the shear stress experiment are presented in Figure 5A. In the early stage, the temperature rises rapidly within the area of the (eventual) fracture. 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 heat release occurs in the course of the fracture (approximately +30 °C). Successive frames recorded during the material’s rupture are shown in Figure 5B. Once again, it can be seen that high-speed infrared imaging is needed to provide enough information in order to characterize the fracture’s onset.

Tensile Test on Composite Material

Tensile test was finally carried out on a composite sample made of woven carbon fiber embedded in an epoxy-polymer matrix. Investigation was carried out using high-definition infrared imaging. As shown in Figure 7, 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. 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 for being brittle, which means that they do not undergo significant elastic deformation under tensile constraints. Nevertheless, some cracks within the epoxy-polymer matrix can be seen prior to the material’s rupture, as shown in Figure 8.

It can be seen from the images that these defects are relatively small. They show up as few-micron wide hot spots and only during a few milliseconds at the time (a few frames in the present acquisition conditions). The temperature rises associated with these defects are of only a few tenths of a degree, which is in good agreement with prior work on similar samples [2]. As expected, heat spots can be seen near the hole (see Figure 8C), i.e. near the fracture area. A few hot spots can also be seen apart from this stress-concentrated zone. At the rupture point, the cracks multiply rapidly. The amount of stress resulting from the coalescence of all defects within the material is then transferred to the carbon fibers, which eventually leads to the material’s rupture, as shown in Figure 9. For this specific sample, fracture occurred at about 45 000 N and was followed by temperature rises on the order of +10 degrees.

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

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**References**


**Telops Inc.**
100-2600 St-Jean Baptiste Ave +1-418-864-7808
Québec, QC, Canada G2E 6J5 www.telops.com