Infrared Imaging for Material Characterization in Fracture Mechanics Experiments

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Abstract. 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 order to illustrate this concept, tensile and shear tests were carried out on steel, aluminium and carbon fibre composite materials and monitored using high-speed and high-definition infrared imaging. 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. One of the most common way of characterizing materials consist in establishing a stress-strain curve. The stress-strain curve reflects the behaviour 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. 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. Therefore, measurement techniques with high temporal and/or spatial resolution are usually required for proper investigation. In this work, high-speed infrared imaging was carried out during tensile and shear stress tests on steel and aluminium respectively. High-definition infrared imaging was carried out during a tensile stress test on a woven carbon fibre epoxy-polymer matrix composite material. The results illustrate how infrared imaging can bring some additional insights for material characterization in fracture mechanics experiments.

Experimental

All samples were coated using a high-emissivity paint prior to testing. Consequently, the temperature values measured by infrared thermography are considered close to their actual surface thermodynamic temperature. 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 aluminium sample was pulled under adiabatic shear conditions. The woven carbon fibre epoxy-polymer matrix sample was pulled at 2 mm/min. The Telops FAST-IR 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 aluminium sample, a 192×192-pixel sub-portion of the FPA detector was used for imaging at 3350 frames per second. The Telops HD-IR 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 fibre 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. Selected images recorded during the experiment, corresponding to different stages of a typical stress-strain curve are shown in Fig.1. In the first three frames (Fig. 1a-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 (Fig. 1d-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 Fig. 1. 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 also 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.

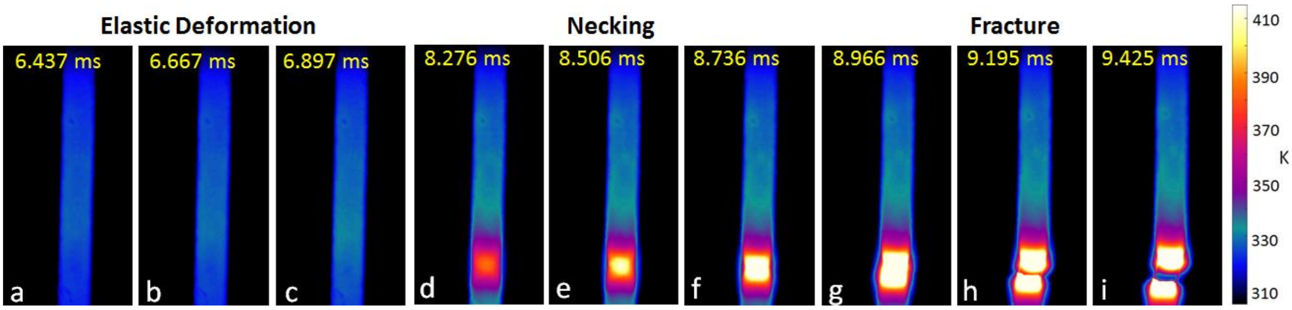

Figure 1. Selected infrared images recorded during a tensile stress test carried out on a steel sample.

Shear Stress Test on Aluminium. In order to demonstrate the versatility of high-speed infrared imaging, a shear test was carried out on an aluminium sample. 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 favours stress release as the sample is being pulled. Therefore, moderate heat release occurs in the course of the fracture (approximately +30 °C). 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.

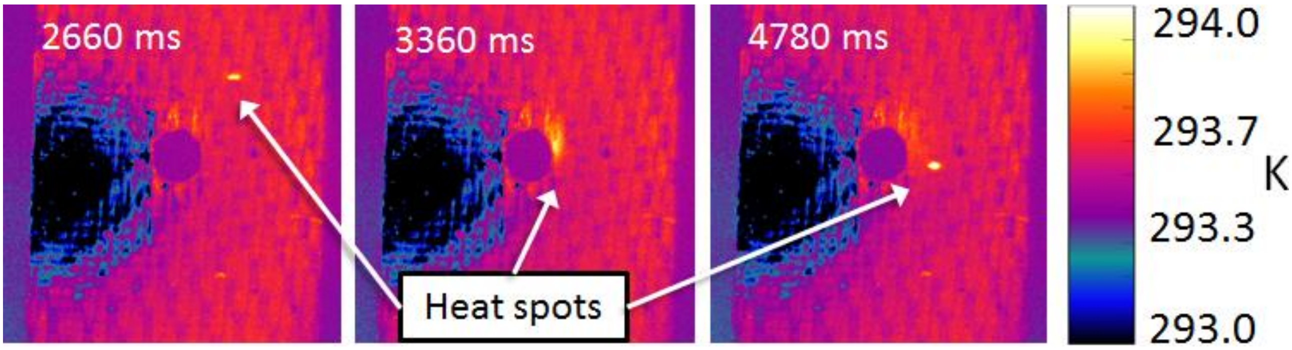

Figure 2. Selected frames recorded during a tensile test carried out on a carbon fiber composite material highlighting the presence of cracks within the epoxy-polymer matrix.

Tensile Test on Composite Material. Tensile test was finally carried out on a composite sample made of woven carbon fibre embedded in an epoxy-polymer matrix (see Fig.2). Carbon fibre 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 Fig.2. 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, i.e. near the fracture area. A few hot spots can also be seen apart from this stress-concentrated zone.

Conclusion

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.

References

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