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Adil Benaarbia, André Chrysochoos, Gilles Robert. Use of IRT and DIC techniques for tracking spatial heterogeneities of thermomechanical responses of SGFR PA6.6 specimens subjected to fatigue loadings. Photomechanics 2015, May 2015, Delft, Netherlands. hal-02057406

HAL Id: hal-02057406

<https://hal.science/hal-02057406>

Submitted on 5 Mar 2019

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USE OF IRT AND DIC TECHNIQUES FOR TRACKING SPATIAL HETEROGENEITIES OF THERMOMECHANICAL RESPONSES OF SGFR PA6.6 SPECIMENS SUBJECTED TO FATIGUE LOADINGS

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1. INTRODUCTION

The purpose of this communication is to shed greater light on the local deformation mechanisms developed within injected-molded 30wt% short E-glass fiber-reinforced polyamide-6.6 (SGFRPA6.6). The study is carried out using full-field measurement techniques: viz. infrared thermography (IRT) and digital image correlation (DIC). The first technique provides heat source fields using the heat diffusion equation, while the second gives access to strain assessments. Several fiber configurations of SGFRPA6.6 are considered in order to track areas susceptible to local failure.

2. EXPERIMENTAL PROCEDURE

2.1 Specimens

The experiments were carried out with injection-molded composite plates of polyamide 6.6 reinforced with E-glass fiber content of 30% by weight. Composite plates were provided by Solvay Engineering Plastics and are commercially available under the trade name A2018V30.

SGFRPA6.6 specimens were loaded at loading frequency of 10Hz using a standard MTS 810 hydraulic testing machine capable of testing specimens at a maximum load cell of 25KN. Specimens with a rectangular active gage section 12mm-in-length by 10mm-in-width and 3.14mm-in-thickness were used. Various fiber configurations were considered: MGF/0°, MGF/45° and MGF/90°.

2.2 Estimate of heat sources and strain fields

The heat produced by deformation is generally obtained from the measured increase (or decrease) in temperature of the specimen, its heat capacity and heat losses. Calorimetric techniques can be used to derive heat sources from thermal data. Infrared thermography is a suitable technique to obtain thermal images, from which the dissipated energy value can be determined using the heat diffusion equation..

By combining both principles of thermodynamics and by assuming that the measured thermal map is very close to the depth-wise averaged temperature field, the following equation can be obtained:

$$\left(\dot{\theta} + \frac{\theta}{\tau_{th}^{2d}} \right) - \frac{k}{\rho C} \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) = \frac{D_1}{\rho C} + \frac{s_{ther}}{\rho C} \quad (1)$$

where θ represents the 2D temperature variations distribution. The terms k, ρ and C denote the heat conduction, the density and the specific heat. The time constant τ_{th}^{2d} characterizes the perpendicular heat exchanges between the outer in-plane surfaces of the specimen and the surroundings.

This expression equates thermal data, which can be experimentally provided by the IR camera, with heat sources that arise during material deformation. The left hand side of Eq. (1) expresses the thermal inertia and the heat exchanges. The right hand side, in turn, includes the intrinsic mechanical dissipation which reflects the irreversible material transformations, and the thermomechanical coupling sources, which are the calorific signatures of possible interactions between the temperature and the other mechanical or microstructural states.

The local deformation energy is mostly determined from local stress-strain data. The digital image correlation gives access to in-plane displacement components. Using spatio-temporal derivatives applied to these in-plane displacement data, strain and strain rate tensors can then be obtained. Both imaging techniques can thus be combined in order to understand the interrelations existing between the local fiber orientation and the thermomechanical properties of SGFR-PA6.6 composites involved during repetitive cyclic loadings.

2.3 IRT and DIC

In this study, infrared data was recorded using a Titanium infrared detector. This detector uses an InSb sensor (middle waves) with 512x640 pixels. It is sensible to radiation with wavelengths from 3 to 5 μ m. In standard operation, the detector has a sensitivity of 25 mK at 25°C with a maximum frame rate of 380 Hz at full frame. It was decided to operate the detector at 100Hz with a window of 160x128 pixels and an integration time of 400 μ s as a compromise between temperature, temporal and spatial resolution. An appropriate calibration protocol was thus conducted to determine the true temperature value. This calibration procedure allows conversion of the thermal radiation digitized by the IR camera

into temperature using pixel calibration functions [1]. The procedure is based on a polynomial fitting of the digital levels delivered by each individual detector element using a black body with a uniform emissivity coating. The measurement accuracy is assessed for each pixel individually in the resulting image.

The kinematic data were recorded using Phantom V12 high speed camera with 20 μ m pixel size. This camera had a 1280x800 pixels resolution, but because higher number of images we needed, 256x256 pixels were used for all tests in order to satisfy hard drive constraints with computing resources available in the lab. This relatively slow resolution limited the spatial precision of the visible measurements, but allowed better temporal resolution. For all tests, we decided to operate with 100Hz acquisition frequency and 1200 μ s integration time. The camera had a high speed internal RAM of 32GB.

A random pattern (local optical signature of a material surface element) was achieved by spraying the specimen surface with a painted speckle pattern (pulverization of black and white paints). A cold light source was used to obtain well illuminated visible high contrast images. The images were thus divided into discrete windows (or cells) and the displacement was obtained by tracking features within each cell. A tailored Kelkins software package, developed by the ThM2 team of LMGC, was used to obtain in-plane displacement fields [2].

Displacement fields were determined with suitable algorithms after digitizing images captured by the visible camera. Since the experimental data were inherently noisy, appropriate spatial smoothing methods, based on least squares methods were applied to reduce the effect of noise on the strain estimate.

The challenge was also to ensure that both cameras were initiated at the same time; this was achieved using specifically designed home-made electronic device (synchrocam). Both systems could then be triggered from a digital pulse used for this purpose [2].

3. RESULTS

The current investigation is intended to establish a correlation between the increase in heat data/strain and the fiber orientation. It focuses essentially on detection of the hottest area that occurs in the dissipation, thermoelastic and longitudinal strain patterns. The challenge is thus to combine thermoelastic source amplitudes, intrinsic dissipation and strain fields in order to detect local degradation in the composite specimens during fatigue testing.

Local assessment of these sources is crucial when establishing local energy balances. The purpose here was to collect more information on the energy behavior of PA6.6. These energy signatures will facilitate the future modelling of this semi-crystalline thermoplastic matrix.

Generally speaking, thermoelastic coupling causes a temporal variation in the temperature field during mechanical loading, i.e. a temperature drop during loading and a temperature rise during unloading. This reversible change in temperature is supposed, in the isotropic case, to be proportional to the change in the first stress invariant, as shown by William Thomson (Lord Kelvin) in 1851 [3], and more recently discussed in Boulanger and al. (2004) [1]. In the following, the large stress concentration areas are quantified via thermoelastic fields while the sensitive zones, where the examined specimen dissipated more, are located by intrinsic dissipation fields.

The selected images in Fig. 1 show patterns of the temperature variations θ , the mean dissipation per cycle \tilde{D}_1 , the thermoelastic source amplitudes ΔS_{ther} , and the longitudinal strain ϵ_{yy} estimated at the last stages in the fatigue life of the composite specimens subjected to tensile-tensile tests with a load ratio of 0.1. The size of the selected heat images is in the average roughly equivalent to a box of 20 to 25 mm in length by 8 to 10 mm in width, covering approximately 42 to 52% of the global specimen surface. The spatial resolution is 0.35 mm/pixel for the thermal data and 0.18 mm/pixel for the kinematic one. All images were obtained after spatiotemporal smoothing of the thermal/kinematic data recorded by the IR/DIC cameras. The computation time required for this smoothing process and heat source/strain assessment was very high, naturally depending on the computational resources.

According to Fig. 1, the spatial heterogeneities were clearly visible throughout all the selected maps. By contrast with the polymer matrix for which it was shown that the localization of dissipative mechanisms took place in an arbitrary direction [4], the propagation of these mechanisms, when the matrix material is reinforced with fibers, seemed to be guided by fibers and travelled along the fiber direction. For instance, the hot spot propagation in MGF/0° was directed along the specimen length, and hence the hottest area propagated freely without deviation (see. Fig. 1, MGF/0°). In this case, the intrinsic dissipation had the lowest maximum value of 0.12 °C.s⁻¹ compared with that of thermoelasticity which was 6.5 °C.s⁻¹. Note also that the location of hot spots in dissipation fields was not necessarily at the place where the thermoelasticity amplitudes (stress) were maximum. This means that the first invariant of the stress tensor was not the only parameter that influenced the dissipative behavior of the material. Fibers could cause shear-stress concentrations at the interfaces (related to the second invariant of the deviatoric stress tensor) where hotspots in thermoelasticity fields were more pronounced, but could not lead to localized sites at the same hottest zones in dissipation fields. This fiber effect changed completely when the fiber orientation took different angles. For instance in MGF/45°, the localized hottest areas were directed along the fibers, i.e. 45°. However, in the case of MGF/90° these hottest areas were diverted along 90°.

The longitudinal strain patterns indicated also a precocious and gradual development of strain localization zones. These mechanisms were clearly visible for composite oriented at 45° and 90°. They were also guided by fiber orientation and took place at the same zone where the dissipation was maximum, especially for MGF/45°.

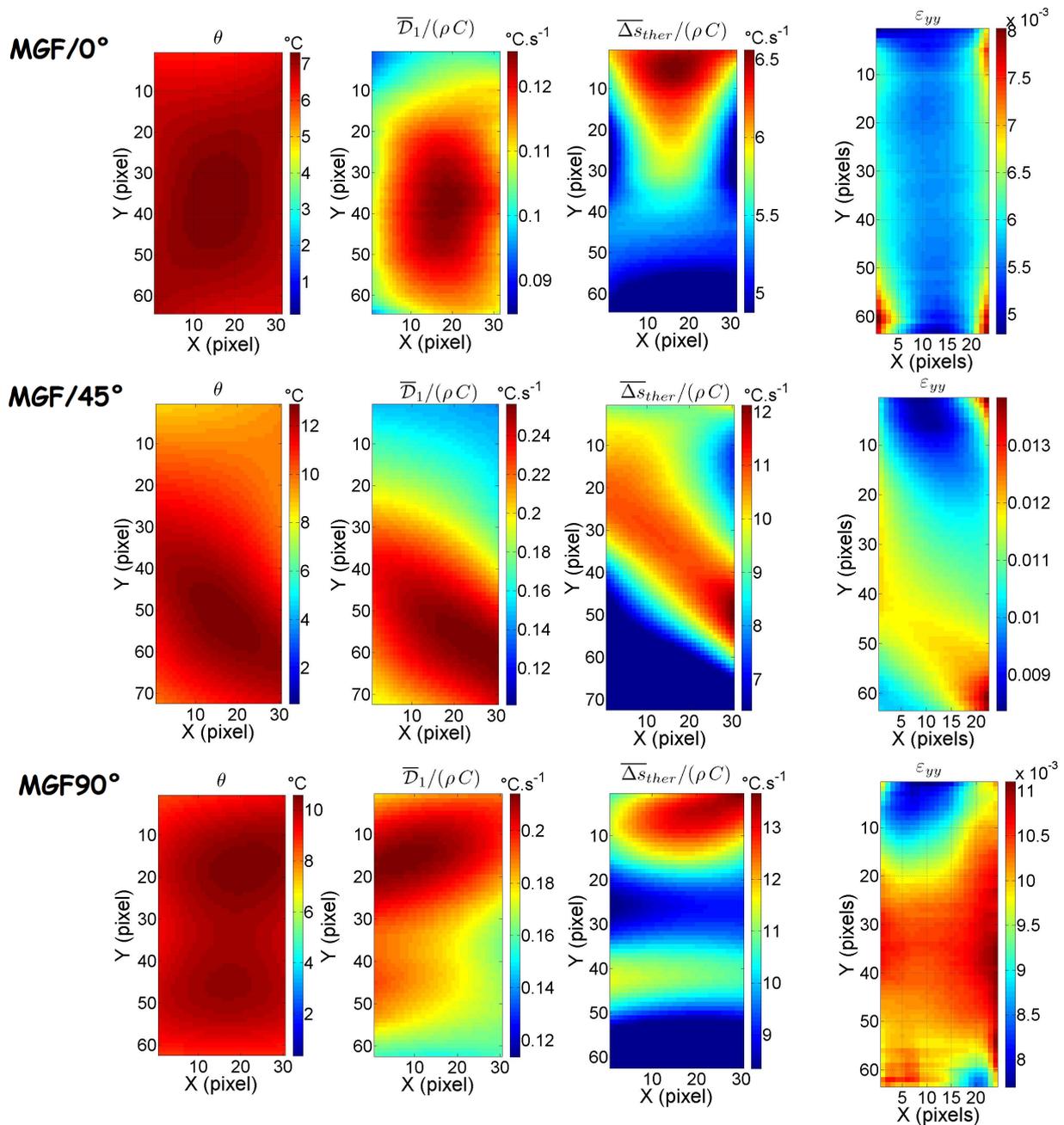


Figure 1- Fields of temperature variations, mean intrinsic dissipation per cycle, thermoelastic source amplitudes and longitudinal strain of RH50-conditioned specimens reinforced with 30% of short glass fibers oriented at 0°, 45° and 90°.

4. CONCLUSION

The above investigation into the progress of spatial heterogeneities demonstrates that calorimetric analysis is a suitable powerful experimental tool that can be used to investigate localized hot spots. It has the potential to provide local information on dissipation and stress fields in an investigated specimen. This thermographic methodology will still be used in subsequent studies which are already under way, especially for investigating the relationships between kinetics of intrinsic dissipation and strain rates in fiber-reinforced polymeric materials.

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