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Simultaneous Surface Deformation and Temperature Measurements using Digital Image Correlation and Thermographic Phosphors

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INTRODUCTION

Combined strain and temperature measurements are critical for many applications, such as material characterization, where specimen temperature rises due to the conversion of plastic work into heat, or combined thermo-mechanical testing, where specimens are subjected to mechanical loads at elevated or depressed temperatures. Traditional instrumentation such as strain gauges and thermocouples provide limited information and can be intrusive in some situations. Digital image correlation (DIC) is a well-established optical technique providing full-field shape, displacement and strains on the surface of a test piece [1], a vast improvement over strain gauges alone. Full-field temperature measurements can be accessed through infrared (IR) thermography, but these measurements require a thorough characterization of the emissivity of the specimen, which may evolve in unknown ways during the course of a test.

As an alternative to IR thermography, thermographic phosphors – rare earth or transition metals doped into ceramic materials – also provide temperature information. The chemical physics of the phosphors is a two-part mechanism; initial absorption of incident photons excites electrons from the luminescent atoms into higher energetic states, followed by the subsequent relaxation back to the lowest energetic state (the ground state) through spontaneous emission or internal energy transfer. The latter is a temperature dependent process, known as thermal quenching. This process can be described mathematically as a single-exponential decay [2], where $I(t)$ is the intensity measured at any time, t, after the excitation, I_0 is the initial intensity immediately after the excitation, τ is the characteristic lifetime of the luminescence, and T is the phosphor temperature. Thus, with proper calibration curves, the time constant of the phosphorescence lifetime can be related to the temperature of the phosphor.

$$I(t) = I_0 \exp\left(-\frac{t}{\tau(T)}\right) \quad \text{(Eqn. 1)}$$

In this work, we combine thermographic phosphors with DIC to develop a diagnostic that provides simultaneous measurements of full-field strains and surface temperatures of a test piece in combined thermo-mechanical testing.

EXPERIMENTAL METHODS

Test pieces were comprised of 304L stainless steel sheets, 1/16 inch (1.6 mm) thick, cut into 3.5 x 3.5 inch (89 x 89 mm) squares (Fig. 1a). A DIC pattern was created by suspending Mg_4FGeO_6:Mn phosphor in methanol, and applying the mixture directly to the surface of the test piece in isolated droplets. When the methanol evaporated, the phosphor powder remained on the surface as individual speckles used as DIC pattern features. Black high-temperature paint was also applied in a speckle pattern with a paintbrush for simultaneous IR thermography measurements. The back sides of the test pieces were painted with a solid coat of high-temperature black paint to aid in absorption of radiation from the heater. Finally, a K-type thermocouple was welded to the to front surface of the specimen.

Two Shimadzu HPV-X2 cameras (250 x 400 pixel resolution) with Nikon 24-85 mm macro zoom lenses were arranged as a stereo-pair for stereo-DIC measurements. The focal lengths of the lenses were set to 85 mm and the stand-off distance was

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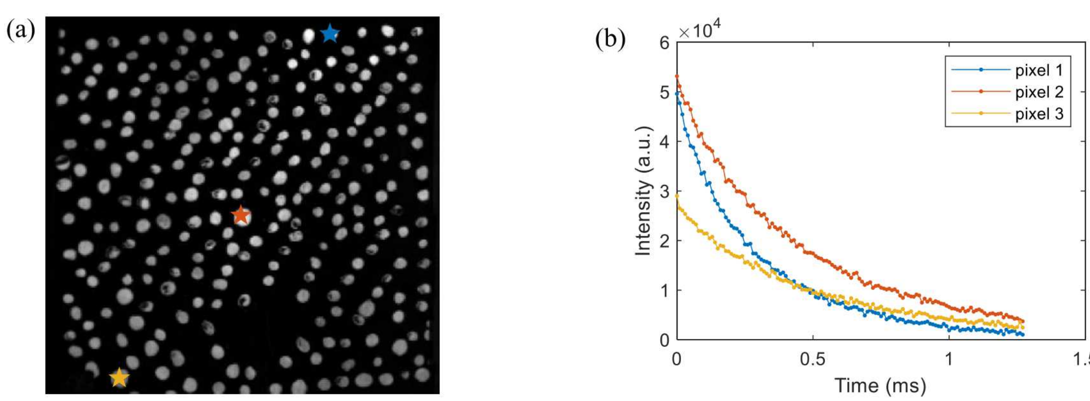
approximately 2 feet (610 mm), leading to an image scale of 110 px/inch (4.3 px/mm) and a field of view of 3.6 inch (91 mm) horizontally. The stereo system was calibrated using a standard DIC calibration target and bundle adjustment algorithm. Additionally, IR images were taken with a FLIR S8300 mid-wave infrared camera placed between the two Shimadzu cameras. The setup is shown in Fig. 1b.

Test pieces were placed in front of a radiant heater, and the temperature was ramped from room temperature up to 550°C at different rates and with different maximum dwell temperatures and times; a select thermal history is show in Fig. 1c. The phosphors were excited by a 355 nm laser, and a narrow bandpass filter centered on the phosphor emission wavelength (MidOpt Bi660, with a 650-665 nm bandpass) was mounted onto each lens. The laser repetition rate was 10 Hz to maintain thermal equilibrium of the laser. Once every 15 seconds, a burst of 128 images were acquired with the Shimadzu cameras immediately following a laser pulse, at an acquisition rate ranging from 10 kHz to 3 MHz depending on the current specimen temperature; simultaneously, a single IR image was captured with the FLIR camera.

Figure 1: (a) Stainless steel test specimen, 3.5 x 3.5 inches (89 x 89 mm), with phosphor and black high-temperature paint features and a welded K-type thermocouple, after heating to approximately 400°C for 2 hours. (b) Overview of the test setup, showing two Shimadzu HPV-X2 ultra high-speed visible-light cameras, one FLIR S8300 mid-wave IR camera, and the test piece mounted in a vertically-oriented radiant heater. (c) Thermal history of one test, as measured by the specimen thermocouple. The black circle indicates one time step that is explored in later figures and analysis.

ANALYSIS

A representative image of the phosphor pattern captured by the Shimadzu cameras is shown in Fig. 2a, with three representative pixels highlighted by star markers. The image intensity as a function of time for each pixel is shown in Fig. 2b, at the burst time indicated by the black circle in Fig. 1c and Fig. 2d. An exponential (Eqn. 1) was fit to the intensity-versus-time curves for each pixel containing phosphor. The inferred lifetimes from these fits are presented in Fig. 2c across the entire sample. Shorter decay times indicate higher temperatures on the top portion of the sample. An *in situ* calibration curve was created by averaging the decay constants for the phosphors immediately adjacent to the thermocouple (Fig. 2d). For a given temperature, the decay constants were the same for the ramp up, dwell, and cool down portions of the test, indicating that the phosphor response was not altered by the thermal cycle.



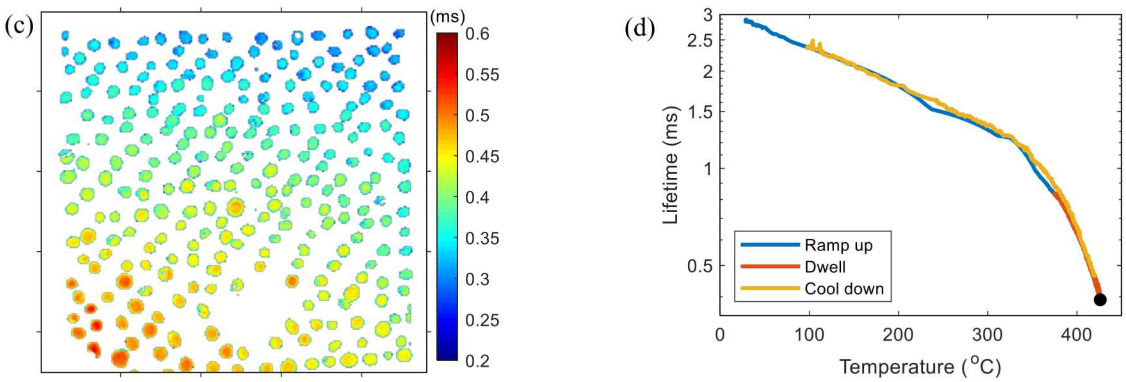


Figure 2: (a) Representative image of the phosphor pattern captured by the Shimadzu cameras. (b) Intensity versus time for one burst during the test (indicated by the black circle in Fig. 1c and Fig. 2d), for three representative pixels (indicated by the stars in Fig. 2a). (c) Full-field lifetime constants for the same burst. (d) Mean lifetime constants for phosphors near the thermocouple plotted with respect to the thermocouple temperature.

The first image of each burst was used for DIC measurements, and images were correlated using Correlated Solutions Vic3D, with a subset size of 25 px, step size of 1 px, and strain window of 15 px, leading to a virtual strain gauge size of 39 px or approximately 0.35 inch (8.9 mm). The equivalent strain was computed according to Eqn. 2, and a contour of the strain field at one point in time is shown in Fig. 3a.

$$Eeqv \ = \ \sqrt{\frac{2}{3}\left(\varepsilon_{xx}^2 + \varepsilon_{yy}^2 + 2\varepsilon_{xy}^2\right)} \qquad \text{(Eqn. 2)}$$

Though the strains are expected to be nearly uniform, resulting from thermal expansion of the test piece, the field data is severely corrupted by heat waves [3], which is a common deficit of optical DIC in thermal testing. However, when the strains are averaged over the entire region of interest (Fig. 3b), the coefficient of thermal expansion is computed as 19.9 µm/m/°C, which agrees favorably with the known value of 16-18 µm/m/°C [4].

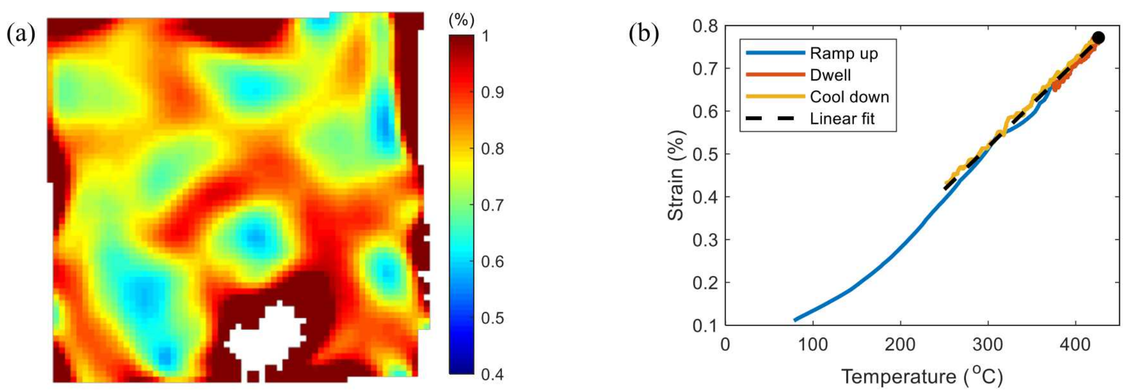


Figure 3: (a) Equivalent strain for one time step during the test (indicated by the black circle in Fig. 1c, Fig. 2d, and Fig. 3b). (c) Mean equivalent strain of the entire region of interest with respect to the thermocouple temperature. The black dashed line represents a linear fit to data above 250°C to compute the mean coefficient of thermal expansion.

CONCLUSION

Simultaneous, full-field temperature and strain measurements were realized by creating a DIC pattern from thermographic phosphors. To demonstrate the combined diagnostics, stainless steel specimens were subjected to radiant heating, and both the surface temperatures and strains from thermal expansion were measured. While initial results are promising, several details must be addressed before the diagnostics can be deployed, including correction of the nonlinearity and inhomogeneity of CMOS camera detectors, employing a more rigorous curve fitting process to account for the multi-exponential nature of the phosphor decay [2], and effective filtering of DIC data to remove distortions caused by heat waves.

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