Heat error reduction in real-time DIC measurements for high temperature biaxial crack growth trials

A. Blug[1a], A. Zaiat[2], G. Laskin[1], A. Bertz[1], C. Kontermann[3], T. Wegener[2], M. Oechsner[2], D. Carl[1,4]

[1]Fraunhofer Institute for Physical Measurement Techniques IPM, Freiburg, Germany;
[2]Department and Institute of Materials Science, Technical University of Darmstadt, Darmstadt, Germany;
[3]Trier University of Applied Sciences, Trier, Germany; [4]Department of Sustainable Systems Engineering (INATECH), Albert Ludwig University of Freiburg, Freiburg, Germany.

[a]andreas.blug@ipm.fraunhofer.de

Abstract. This article quantifies the effect of optical measures to suppress heat effects on a real-time 2D digital image correlation (DIC) system in biaxial crack growth trials at 600 °C. Due to strong temperature gradients in combination with an uneven surface of the biaxial specimen, heat waves driven by convection appear to be the major cause of heat fluctuations. The effect of optical measures on DIC was quantified by zero-strain testing in comparison to a mechanical extensometer. As a result, real-time biaxial strain measurements at 600 °C show a slightly increased repeatability of $2.5 \cdot 10^{-5}$ m/m or 25 $\mu\varepsilon$ in comparison to $1.7 \cdot 10^{-5}$ m/m (17 $\mu\varepsilon$) at room temperature. Thus, real-time DIC provides both, axial strain and full-field evaluation of crack growth parameters. As the DIC system operates without markers, debonding of a speckle pattern is also avoided.

Biaxial crack growth trials are required to determine the remaining service life of technical components under multiaxial far-field loading such as fracture-mechanical behavior related to T-stress or plasticity-induced crack closure [1]. Within these trials, the GPU-based real-time DIC system measures axial strain to control crack growth and full-field DIC for crack flank evaluation [2].

This paper reports the effect of optical measures suppressing convection and heat to enable a GPU-based high-performance DIC system for multiaxial fatigue crack-growth experiments at high temperatures. The DIC system provides comprehensive strain data comprising biaxial integral strain on a measurement rate of 850 Hz, like mechanical extensometers, and fast full-field evaluations in images selected in real-time from the data stream. Fig. 1 shows, on the left, the DIC measurement head in front of a biaxial testing machine equipped with a cruciform specimen. As can be seen in the camera image on the right, the microstructure of the specimen is used as marker-free correlation pattern without need for speckle paint. Axial strain is measured along the axes A, B of the biaxial test rig with a base length of 10 mm (green subsets). Full-field DIC is used to determine crack parameters such as crack path and crack depth. Crack opening/closing forces altered by thermal stress are determined by virtual extensometers placed automatically along the crack path [3].

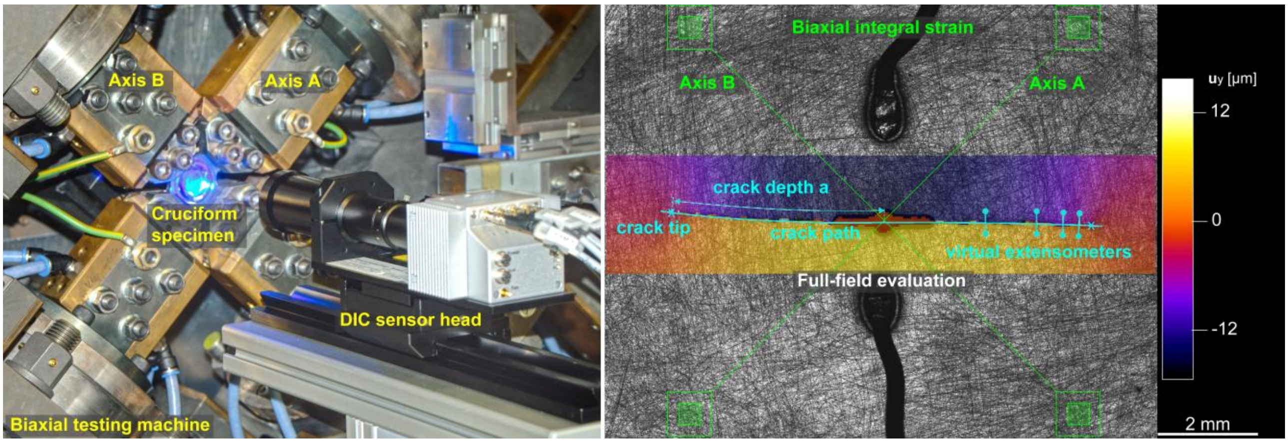

Fig. 1 Left: *DIC sensor head in front of the biaxial testing machine equipped with a cruciform specimen.* ***Right:*** *camera image of specimen surface superimposed by the four subsets for measuring axial strain (green) and by the full-field evaluation area with vertical displacement $\boldsymbol{u_y}$ (color scale), i.e., in force direction. Crack evaluation (cyan): crack opening is measured by virtual extensometers positioned 0.2, 0.5, 1.0, and 2.0 mm behind the crack tip marked by 'x'.*

Material testing at high temperatures affects DIC measurements by a) image saturation caused by intensified thermal radiation of heated sample and surrounding heating elements, b) image contrast reduction due to surface oxidation of the heated sample and speckle pattern debonding, c) image distortion caused by temperature-induced refractive index variations in the air between the sample surface and the camera optics - commonly referred to as heat haze or heat waves [4]. Fig. 2 illustrates the measures to mitigate these effects: a coaxial illumination using a blue LED (465 nm), a ceramic tube to confine the convection volume, mechanical shielding to seal the gap between the tube and the cruciform specimen, and a window to suppress air flow from the hot region to the DIC lens. The window is tilted to avoid reflections of the LED light. In addition, a dielectric coating is applied allowing for transmission of the blue light and reflecting heat radiation described by Planck's law. As drawn on the right side of Fig. 2, the dielectric coating serves as a short pass filter separating DIC illumination from heat radiation, improving the contrast of the surface pattern in the camera image. At 600 °C, oxidation is not an issue for the materials investigated (titanium alloy Ti6246 and tempered steel 26NiCrMoV14-5) and tempering colors do not affect zero normalized cross correlation (ZNCC).

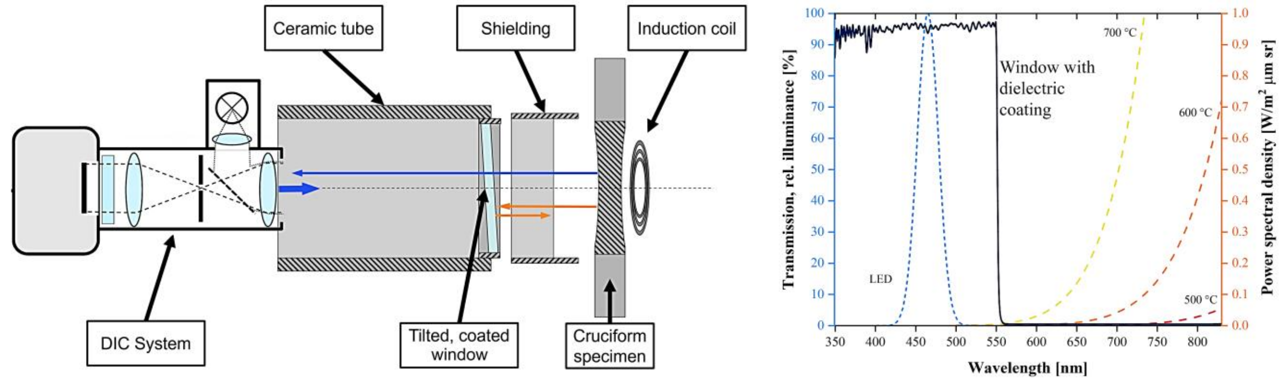

Fig. 2 left: *Overview over all measures to suppress heat effects.* ***Right:*** *spectral confinement. Transmission of the dielectric coating on the window (dark blue curve) together with the relative illuminance of the LED at 465 nm and power spectral density of thermal radiation according to Planck's law at 700°C, 600°C, and 500 °C.*

The effect of these measures was quantified using zero-strain measurements according to VDI/VDE 2626, i.e., strain measurements on the unloaded specimen in force-control mode with F = 0 N. Fig. 3 shows axial elongation Δl and their standard deviations obtained for different temperatures and with different combinations of measures from Fig. 2. As conditions are constant, all fluctuations are measurement errors. The dark blue curve at 20 °C on the left shows the initial conditions at room temperature. The constant noise amplitude is due to the force-control of the biaxial test rig. As the base length is 10 mm, the standard deviation $\sigma_{\Delta l}$ = 0.17 µm corresponds to a strain repeatability of $1.7{\cdot}10^{-5}$ m/m. Without any measures, as shown in Fig. 1, fluctuations with a frequency in the range of 1 Hz occur due to convection between lens and specimen surface, i.e., on the whole working distance of 150 mm, resulting in a standard deviation $\sigma_{\Delta l}$ = 0.71 µm at 600 °C. If this volume is reduced spectrally and spatially by the coated window and the shielding to a height of about 15 mm, the standard deviation drops to 0.25 µm or $2.5{\cdot}10^{-5}$ m/m, similar to that of the mechanical extensometer.

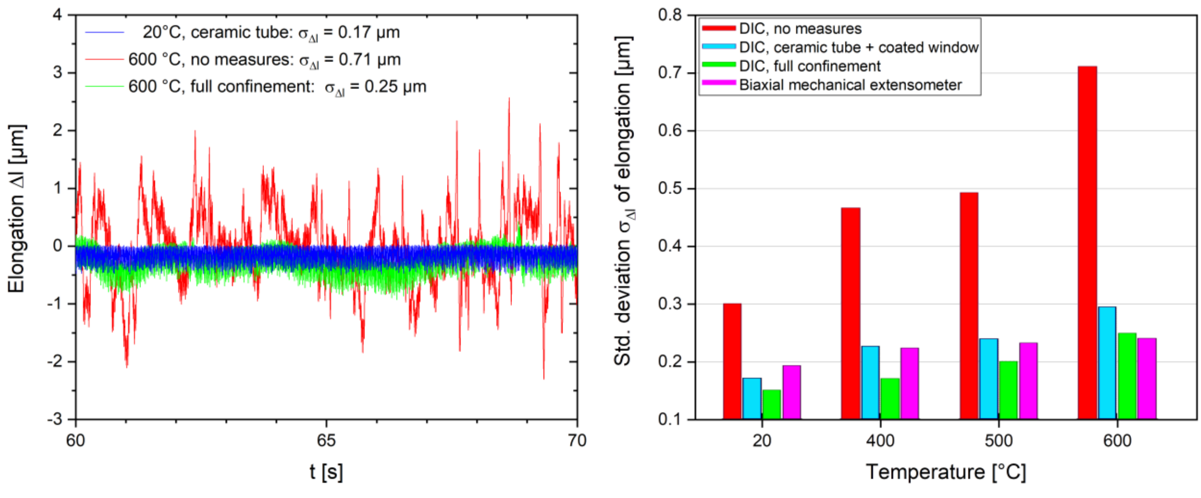

Fig. 3: *Fluctuations of axial elongation Δl (base length 10 mm) under zero-load conditions and with different measures from* ***Fig. 2****. Left: time-based signals. Right: standard deviations over 600 s from DIC and a mechanical extensometer.*

As local full-field evaluations are affected much less by heat waves than axial strain, these results show, that real-time DIC systems provides both, axial strain at a rate of 850 Hz like mechanical extensometers, and crack parameters for a comprehensive evaluation of crack growth – even at high temperatures.

References

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