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A dedicated illumination system for fatigue crack-growth measurement

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A B S T R A C T

This letter describes the design and development of a dedicated lighting system for the automation of fatigue crack-growth measurements. Crack growth testing is important to the characterization of the expected behaviour during service. Characteristic da/dN vs. ΔK enables the Mechanical Engineer's understanding of the material state in the presence of stress, and assists in the calculation of the remaining fatigue life expected behaviour. Similar to the darkfield illumination principle, the developed system uses a grazing incidence angle to enhance even the smallest crack detail, a necessary feature to enable the successful application of image processing methodologies for crack-growth monitoring. A poor or wrong illumination fails to reveal the true extent of hairline cracks, greatly influencing calculations that depend on large stress gradients. The device is being used in combination with a vision system for continuous monitoring of crack-growth in metallic specimens with great success. The results obtained to date are in full agreement with the expected data for the utilized specimens, which increases the confidence in the use of the device and the continuous work towards automation of fatigue experimental procedures.

1. Introduction

Measurement of fatigue crack-growth is a fastidious but necessary activity for the Fatigue and Fracture Mechanics experimentalist. The traditional method for crack propagation measurement involves continuous observation and measurement of the crack-tip growth with a travelling microscope and a reticule, whereby measurements are taken at regular time or test cycle periods, and crack-growth rate is calculated [1]. The experimentalist's experience and sensitivity on fatigue testing is therefore critical to ensure both correct readings and optimal estimation of the reading time intervals, in particular towards the end of the experiment when crack-growth rate increases and failure to perform the necessary readings may irrevocably jeopardize the test. An important source of measurement variability is, reportedly, the human evaluation of the crack length readings [2].

Automatic measurement of physical phenomena, such as crack-growth, based on image data is therefore both a convenient and expedite method to tackle fastidious time-consuming experiments. While effectively reducing human observation errors that may arise from tiresome measurements, it frees the experimentalist from the time wasted in performing repetitive tasks. Still, the automation of some metrological tasks based on image data, has yet to prove reliable, in order to gain widespread acceptance by the experimentalist.

Such an automated system has been under development at the Optics and Experimental Mechanics Laboratory (LOME) of INEGI, the Institute of Science and Innovation in Mechanical and Industrial Engineering, in Porto University. Recently, the first measurements and results assessment in Mode I fatigue testing of an aluminium alloy AA6082-T6 specimen have been accomplished, which are very encouraging and in good agreement with data measured with a traditional device [3].

Up until recently, image acquisition equipment with satisfactory quality for detecting thin cracks in metallic coupons subjected to fatigue testing was either too complex or too expensive to be contemplated as an attractive alternative for the traditional travelling microscope and reticule based measurements. The introduction of fast, small and inexpensive CMOS cameras that can be operated without resourcing to frame grabbers changed this paradigm significantly, as well as many others in image-based metrology, and is now promoting its widespread use in measurement automation. LOME is currently using USB 3.0 CMOS cameras with 1 inch sensors at frame rates of 75 frames per second, which cover the vast majority of the traditional fatigue tests. These cameras use high quality Schneider-Kreuznach optics and the required extension tubes for the work at hand.

An additional impediment to the use of image-based measurements is the degradation of data that arises from poorly controlled

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lighting environments. The sheer fact that lighting conditions change throughout the day, even inside laboratory premises, hinder the required image quality and the necessary image processing operations, let alone the lighting degradation due to other reasons such as the continuous movement of the test coupon or the specular reflections on random artefacts on the metallic surface.

In order to address the issues described above, a special lighting device was developed and optimized in INEGI which is presented herein. The device uses light-emitting diodes (LED) lighting at a grazing incidence to the observed metallic coupon in order to reveal even the smallest changes to its surface in a dark-field approach.

In the following, the foremost currently available methods for fatigue crack detection will be reviewed, prior to a thorough description of the proposed method and the developed illumination device in Sections 3 and 4. The obtained results will be presented in Section 5 and a discussion of the method will follow in Section 6 that points to further expected developments towards a standardization for global acceptance of the work proposal.

2. Crack detection and measurement techniques

According to the ASTM standard E647-08, a precision of 0.1 mm is mandatory when testing specimens of width smaller than 127 mm [4]. To illustrate the size of the involved dimensions, if the captured images were recorded such that at least 2 pixel covered 0.1 mm, cracked areas up to 123 mm $\times$ 82 mm could be monitored with a conventional 4MPixel (2464 $\times$ 1632) camera. This valid measurement area can be considered more than satisfactory for most laboratory tests and can easily be enlarged by increasing the monitoring camera resolution.

2.1. Potential Drop technique

The Potential Drop or electric potential difference (EPD) technique for crack size determination is applicable to virtually any electrically conducting material [4]. The technique is based on the changes of the electric properties of a monitored specimen when it is subjected to discontinuities such as cracks. By measuring the electric potential, and its changes, between two different zones separated by a crack, it is possible to infer about its length if a proper calibration is made. In some cases, for non-conducting materials a conducting foil or film can be firmly attached to its surface enabling test with this technique, as long as the conducting film does not change the fatigue crack growth rate properties of the test specimen [4].

Due to eccentric/asymmetrical crack propagation, more than one potential measuring probe is often used in order to correct and compensate possible errors derived by the crack symmetry assumption [5]. This technique has been a standard methodology for measuring 'open' cracks, such as the ones propagating predominantly in Mode I [6], but can also be used to detect crack opening with both DC and AC current [7]. While optical methods rely on direct access to the crack and can become unreliable when the observable crack front tends to bend in thicker test pieces, the electrical methods rely on the fact that a crack disrupts an electric potential field in a way that relates to the crack's length and shape. Important drawbacks to this technique include the requirement of specific calibration curves for each tested specimen geometry, possible underestimation of crack depth and the introduction of undesirable electric effects if heat induction is used [8]. According to the ASTM E647 standard, this method may not be suitable for tests with constant stress intensity control, since for these tests crack size measurement errors may cause unacceptable differences between envisaged and applied control forces. Changes in specimen or instrumentation can also result in proportional changes in the measured voltage, adding noise to the final result [4] and elastic as well as plastic deformation can affect the material resistivity and magnetic permeability when AC current is used [9]. Some material can also exhibit time dependent conductivity changes when submitted to high temperatures [10] and the DC method has been found to be susceptible to thermoelectric effects that, not taken into account, can introduce significant errors in the crack size measurement [11].

Other possible noise sources added to the measured signal may be caused by the equipment used, such as signal amplifiers, the presence of "skin effects" when high AC frequencies are used, the induction of electric magnetic fields from other equipment and the absence of electrical grounding, among others [4].

2.2. Compliance technique

One of the indirect methods of measuring crack length that is popularly used is the compliance technique. Compliance is the reciprocal of the force-displacement slope normalized for elastic modulus and specimen thickness [4]. Under cyclic loading in fatigue experiments, the crack will grow a small amount in each load cycle. If the compliance has been predetermined for that test specimen, its measurement can be used to determine crack length [12,13]. This technique is therefore based on the increase of elastic compliance, with crack length, by simply measuring those two quantities and comparing them to calibrated data [12,14] or [15]. Although the method requires specific calibration for each test specimen geometry, it is considered a very mature technique that does not need special and expensive equipment.

2.3. Crack propagation gauge

In order to measure a crack length or its propagation rate, propagation gauges or fracture sensors can also be used, by measuring the changes of an electric signal caused by the crack expansion. In order to do this, conducting strips are bonded to the test specimen along the predicted crack path, acting as a resistance within an electric circuit. When the crack advances, the sensor wires rupture changes the overall resistance of the sensor, enabling some degree of assessment about the crack propagation rate with common resolution of the order of 0.25 mm [16]. One of the shortcomings of this method of crack length propagation rate measurement is the time discrepancy between the moment of rupture of the gauge wires and the moment when the crack passes underneath them [17].

2.4. Optical observation

Optical observation methods rely on the use of a travelling microscope or a scale assisted by a camera that records the crack evolution over time [1,18]. However, either of these solutions requires long observation times and have not been proposed to successful automation [5]. Although microscopes can provide high resolution measurements, accuracy is also subjected to human errors since for different observers, different crack measurement lengths can be registered [2].

2.5. Thermoelastic stress analysis

Thermoelastic Stress Analysis (TSA) is a method based on the thermoelastic effect, whereby the stress imposed to an elastic material produces a small but detectable temperature change. Under compression, a material experiences an increase in temperature whereas under tension its temperature decreases. This conversion of mechanical energy to thermal energy can be reversible