Application of Digital Image Correlation (DIC) in resonance machines for measuring fatigue crack growth

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ABSTRACT. This paper presents a simple experimental procedure that greatly facilitates the use of digital image correlation (DIC) techniques in fatigue test conducted in resonant testing machines, without the need of test interruptions. This is possible due to the implementation of USB interface optical microscopes of very small dimensions, so that they can be mounted on the specimen as a contact extensometer. Thus, the microscope-sample assembly oscillates at the resonance frequency of the test. This is how, although the resonant testing machine is in motion, and although the specimen is subjected to fatigue, changing its dimensions according to the applied load, the acquired image is completely static. This allows the evaluation of the plastic deformations generated by the crack growth, avoiding the elastic ones. Preliminary results on monitoring cracks with this technique on flat specimens with cylindrical notches of 1050 aluminium alloy are also presented.

KEYWORDS. Digital Image Correlation; Fatigue test; Resonance Machines; Crack growth.

INTRODUCTION

There is a growing interest in using digital image correlation (DIC) to characterize materials for mechanical properties. DIC techniques allow the strain fields arising from application of a stress to a component to be defined. The procedure involves producing a spot pattern on the surface of the target component and assessing relative motion in the spots between the initial and final states in order to characterize the resulting strain fields. This requires taking photographs of the target element before and after loading (see Fig. 1), and using an appropriate algorithm to assess relative motion between spots to obtain detailed information about the resulting strain fields [1-3].

Successful implementation of DIC entails minimizing any relative motion between the image acquisition system and the testing machine in order to avoid errors in calculating strain fields. This hinders use of the technique with resonance machines because they are mounted on springs and hence in continuous motion.

Notwithstanding this difficulty, DIC has aroused much interest for fatigue mechanics studies as it provide the means for analyzing plastic deformations arising during crack propagation.

In this work, we developed a simple, effective DIC technique for monitoring deformations throughout a fatigue test while avoiding the typical errors due to relative displacements of the image acquisition system from the testing machine - even in resonance machines.

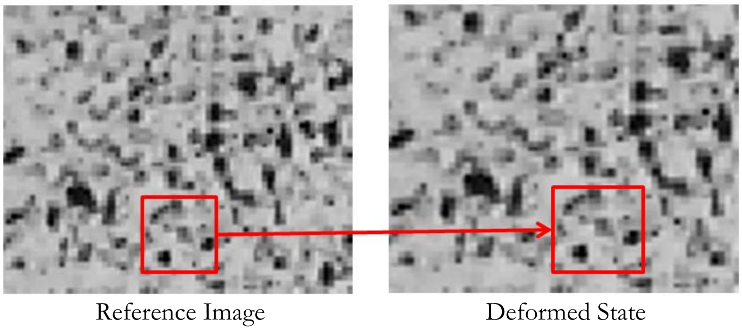

Figure 1: Changes in a spot pattern upon application of a specific strain.

EXPERIMENTAL DIFFICULTIES

Digital images correlation

As noted earlier, successful analysis of experimental deformations entails exercising some cautions. Thus,
- If a single camera is used (i.e., with 2D DIC), specimens should be planar.
- The camera should be positioned normal to the specimen surface.
- Any deformations should be planar (i.e., the distance between the camera and specimen should be constant throughout the acquisition time).
- Even slight motion out of the plane can lead to substantial errors in calculated deformations (see Fig. 2). Such errors can be minimized by maximizing the distance between the camera and specimen (L) or minimizing displacement of the specimen from the plane (w).

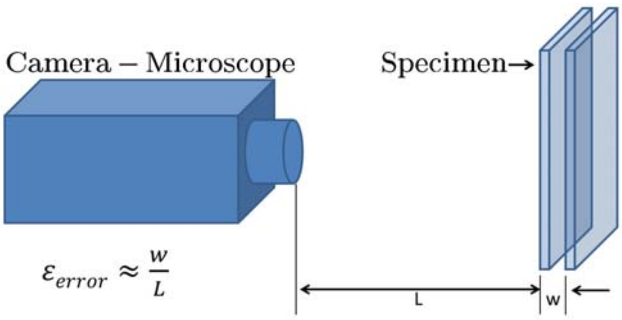

Figure 2: Error resulting from changes in the camera–specimen distance.

- There is the additional experimental difficulty arising from high magnifications. As can be seen from Fig. 3, the translation ΔY resulting from application of a load caused the target zone to fall outside the microscope acquisition field.

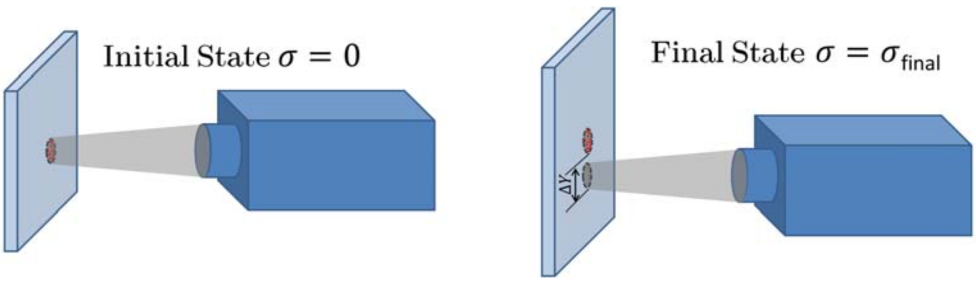

Figure 3: Using a high magnification can displace the target zone outside the microscope observation field.

Resonance machines
Resonance testing machines provide a simple means for tests involving a large number of fields. These machines can operate at much higher frequencies than servohydraulic machines and have other salient advantages including reduced size, servicing requirements and energy consumption (1/100)[4].
However, resonance machines pose some problems in implementing DIC on fatigue loaded specimens. Thus, the resonance frequency cannot be accurately controlled by the user as it depends on the rigidity of the target specimen and changes lengthwise and widthwise in it. Also, the specimen cross-section decreases as cracks grow, which alters its rigidity and hence its resonance frequency.
The inability to accurately set and maintain the resonance frequency throughout a test hinders the use of stroboscopic cameras, which are frequently used on servohydraulic machines. Stroboscopic cameras can take photographs at user-defined frequencies. In fixed-frequency tests, this allows the camera to be set at the test frequency and a static video filmed for subsequent DIC processing with a view to calculating deformations due to crack formation and growth [3].
One other technique used with servohydraulic machines involves periodic halting of the test to photograph the specimen. This technique is difficult to implement with resonance machines because they are mounted on springs and hence in continuous motion. The oscillations are insubstantial to the naked eye but can have a considerable impact on DIC results.
As stated above, in this work we developed a simple solution to the above-described problems.

NEW ACQUISITION SYSTEM

The difficulties encountered in applying DIC to a resonance testing machine were overcome by developing a new method to acquire images involving the use of very small Digimicro microscopic cameras with magnifications of 10–100× and 40–200× (see Fig. 4).

Figure 4: Microscope with a USB interface used for in situ measurements of crack growth.

This type of camera had previously been successfully used to monitor crack growth uninterruptedly in planar specimens [6–8]. With DIC, however, even a very small displacement can lead to error in calculating deformations. This required altering the cameras for sticking to the specimen in roughly the same manner as a contact extensometer in order to prevent relative motion between the specimen and acquisition system. Fig. 5 depicts the camera assembly used, which included two cameras in order to allow both sides of the specimen to be photographed at once. The cameras were mounted by means of elastic bands and fixed by means of two small metal pins along their equator.

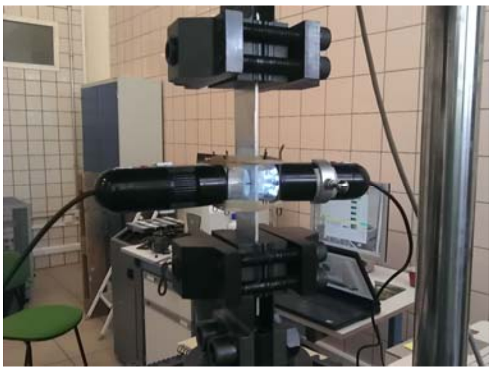

Figure 5: Microscopes attached to the specimen surface.

Fig. 6 shows the target surface (both specimen sides). The inside of the notch was filled with plasticine in order to avoid light from one microscope interfering with the photographs acquired by the other.

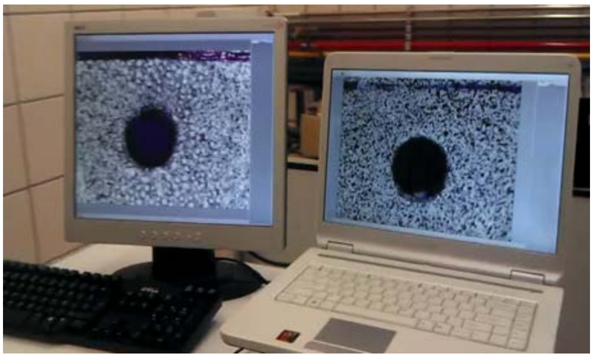

Figure 6: View of the notch during the test as acquired with the microscopes.

TEST

Tests were conducted on a Rumul Testronic 100 KN testing machine using loads of the tensile–tensile type (R = 0.1). The target material was 2 mm thick aluminum alloy 1050 cut into 300×42 mm sheets. Notches were 1, 2 or 4 mm in size. Some specimens were subjected to a thermomechanical treatment described elsewhere [6] to obtain abnormally large grains (8.22 mm) in order to detect microstructural interactions with the plastic zones around the cracks.

RESULTS

Fig. 7 shows an event of crack growth as examined by DIC. The target specimen had a grain size of 0.07 mm and a cylindrical notch 2 mm in diameter. The figure shows 6 photographs taken at different crack growth stages. Propagation of the resulting plastic zone is clearly apparent. These results are quite promising as they confirm that the DIC technique allows the above-described experimental difficulties to be overcome simply by altering the way the cameras are arranged.

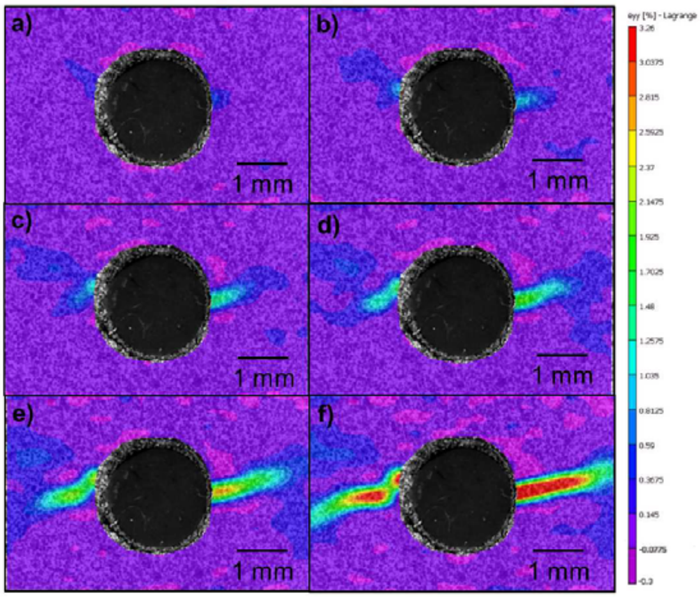

Figure 7: Crack growth as determined by digital image correlation (DIC). Number of cycles (N): (a) 100 000, (b) 130 000, (c) 160 000, (d) 180 000, (e) 210 000, (f) 230 000.

Below are also discussed the results of other studies currently under way at the University of Seville [6–8] on the influence of specimen microstructure on crack propagation. These studies are aimed at confirming the differences in propagation between "short" cracks, which are comparable to the specimen grain size in length, and "long" cracks, which are much longer. Below is commented on the experimental contribution of the proposed technique in this respect.

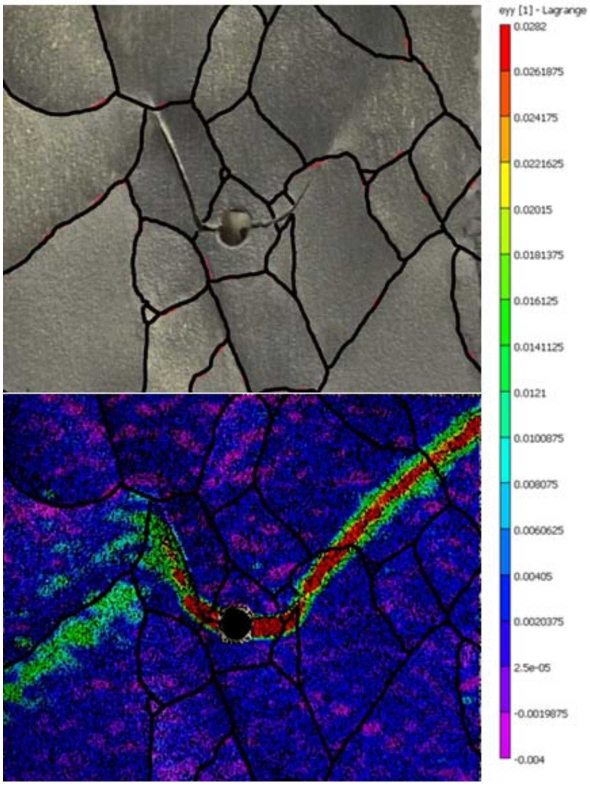

Figure 8: Image of the specimen immediately before plastic collapse. Grain size = 8.22 mm [8].

Fig. 8 shows the situation for a specimen of grain size 8.22 mm. The specimen was 2 mm thick and the grain size across its thickness coincided with the specimen physical thickness. This allowed the microstructure of the material to be assimilated to a two-dimensional arrangement of aluminium single crystals. We used DIC to examine one side only —the other was used to extract microstructural information (viz., the position of grain boundaries). Thus, the notch, the crack and the grain boundaries —which were outlined to facilitate analysis— are shown at the top, and the deformation fields resulting from propagation of the crack at the bottom. Clearly, this example is one case of "short" cracks as the cracks propagated through active sliding of the grains they spanned. In order to propagate from one grain to the next, the crack must switch to a different propagation plane (specifically, to the active sliding plane in the adjacent grain). The active sliding plane is dictated by Schmid's factor. This leads to non-symmetric cracks that propagate at dissimilar rates by effect of successive acceleration and deceleration [6-8].

Fig. 9 provides a detailed depiction of Fig. 7f. The deformation field shown is that occurring immediately before plastic collapse. This example is one of "microstructurally long" cracks, where the specimen microstructure has no influence. Thus, cracks grow symmetrically on both sides of the notch, in a plane at 90º with the loading axis.

Visual comparison of Figs 8 and 9 exposes the influence of microstructure on the way cracks and their associated plastic zones propagate. Thus, the crack of Fig. 9, corresponding to the specimen with the smaller grain size, exhibited a typical propagation pattern (viz., horizontal growth from the notch equator). On the other hand, growth in the crack of Fig. 8 was strongly dependent on microstructure. As can be seen, there was little symmetry. Thus, immediately before plastic collapse, the crack on the left and its plastic zone stopped at the grain boundary. Also, the new plastic zone did not start at the next grain, but rather at one below that was probably more favorably arranged with respect to the loading direction.

Finally, let us highlight the sturdiness of the microscopes, which were used without problem to acquire images over more than 20 tests. Also, they are very inexpensive to replace (less than 50 € each) if they fail.

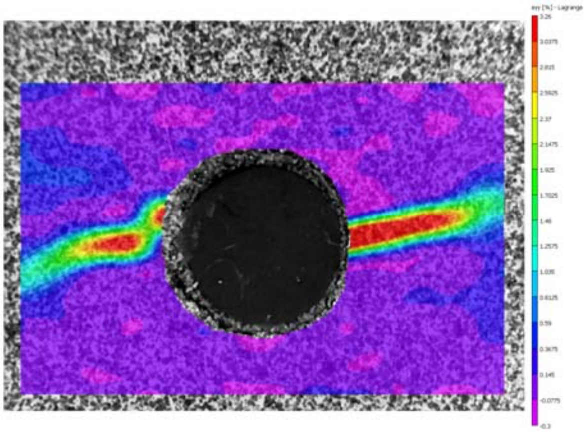

Figure 9: Analysis of the specimen immediately after plastic collapse. Grain size = 0.07 mm.

CONCLUSIONS

In this work, we developed a simple procedure for implementing digital image correlation (DIC) on resonance fatigue testing machines. The experimental difficulties typically encountered with this type of machine were easily circumvented and deformation resulting from crack growth was analyzed without the need to stop the tests in order to acquire images. The DIC technique affords high magnifications with no image displacement errors.

Preliminary results for crack propagation and its plastic zone were obtained. Under special conditions, it is even possible to study crack–microstructure interactions and observe how grain boundaries act as barriers to propagation of the crack and its plastic zone. Our group is currently engaged in refining the surface spot pattern in order to increase the precision of the technique, and in using microscopes of similar size and weight but higher resolution and magnification.

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