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Crack closure under plane strain and plane stress

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Aims of the experiment and scientific background

In general the rate of crack growth under fatigue is traditionally either related to the stress intensity range applied (ΔK) or equivalently to the change in crack opening displacement (ΔCTOD). Unexpected changes in crack growth rate are commonly ascribed to crack closure. Closure over part of the fatigue sample reduces the range of stress intensity experienced at the crack tip so that the effective crack-tip stress intensity range is less than that nominally applied (ΔK^{nom}). Plasticity induced crack closure is one of the most important mechanisms of crack closure, but is still the target of heated debate [*1*]. Some say that closure does not occur at all [*2*], others say that it can only occur under plane stress[†] [*3*]. To date, experimental measurements of crack closure have been inconclusive and have relied on either (i) measuring some secondary property of the cracked body such as compliance or electrical resistance or (ii) measurement of crack-opening displacements on the surface of the cracked body. There are significant difficulties interpreting secondary data in terms of crack-tip stresses, whilst the surface of a cracked body experiences conditions of plane stress in contrast to the bulk which experiences conditions more akin to plane strain. Until the advent of high spatial resolution synchrotron diffraction it has not been possible to probe this region experimentally.

It is the aim of this experiment to correlate measurements at the surface of specimens measured by image correlation with those in the bulk measured by synchrotron diffraction to determine unambiguously if closure can occur in thick (plane strain) samples or not.

Current approach

We have developed software which can infer CTOD and effective stress intensity factor (K^{eff}) directly from measurements of crack tip displacement or elastic strain field [*4*, *5*]. We are able to assess the crack-tip stress field at the surface (which must necessarily be under plane stress) using image correlation , whereby successive images of the finely abraded surface (Fig 1a) are compared. By correlating the images it is possible to deduce the crack tip displacement field (Fig 1b) at the surface and thereby K^{eff} (Fig 1c).

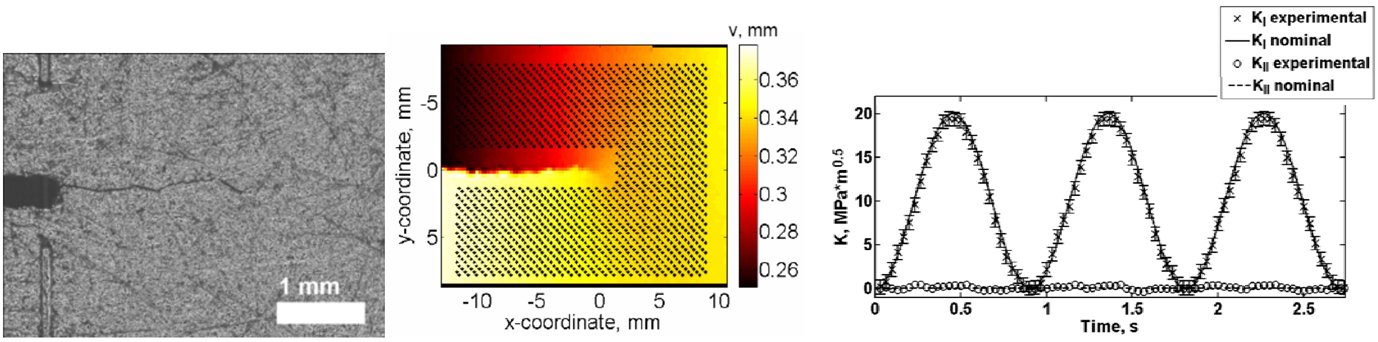

Fig 1: a) Micrograph of a fatigue crack together with the finely abraded surface employed in image correlation b) Crack tip displacement field measured by image correlation and full-field array of data points used for evaluating K^{eff} c) Result of monitoring K^{eff} together with the nominally applied K.

The methodology is also able to measure crack closure effects and the plasticity developed at the crack tip (Fig 2) [*6*]. In addition we have used the software to infer the stress intensity for crack-tip strain fields determined by synchrotron diffraction (Fig 3). Here we will determine the extent of crack-tip closure at

† Plane stress conditions are those where the stress field is biaxial, such as must occur at the surface of a sample as the stress normal to the surface must be zero. Plane strain conditions are found in the centre of thick cracked test pieces, where constraint effects mean that the strain through thickness is zero.

the surface and at the centre of thin and thick samples in order to determine whether crack tip plasticity induced closure can occur under conditions of plain strain.

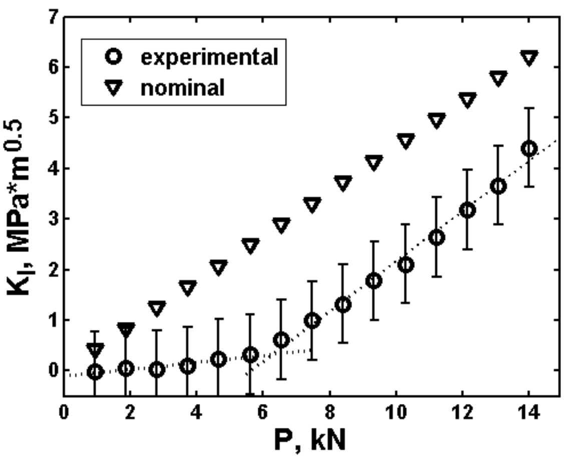

Fig 2. Comparison of experimental (K^{eff}) and nominal K during the loading portion of the cycle. The clearly visible deviation of K^{eff} and the knee observed are due to crack closure [*6*].

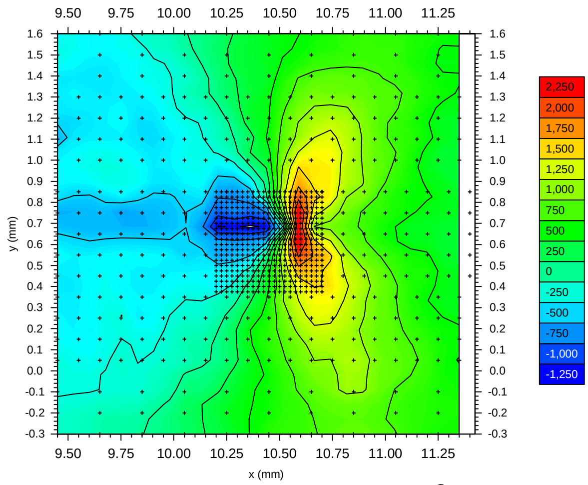

Fig 3: Crack tip strain field ($x10^{-6}$) as determined at the specimen centre by synchrotron diffraction [*7*].

Experimental method

We will measure the strain fields at the surface and the interior using simultaneous image correlation by video camera (Fig 1a) and synchrotron diffraction for the first time for a crack as it is cycled from maximum to minimum fatigue load. We will examine the loading sequence for two AISI 316L steel fatigue crack samples each having a sufficiently small grain size that we can image the crack with 20μm spatial resolution. One of the samples will be thin relative to the size of the plastic zone (2mm) and thus in a state of plane stress throughout; the other will be thick (~10mm) so that the centre will be in a state of plane strain. The fatigue load amplitude will be sufficient for a fatigue crack plastic zone of around 2mm. In each case a complete load – unload cycle will be monitored in order to determine the load at which the crack tip begins to open and the load and location at which it begins to close. This will require approximately 6 maps for loading and 6 maps for unloading determined from experiments in the lab. beforehand. Previous experience has shown that we can acquire a grid of measurements (Fig.3) in around 4 hours. As a result each experiment will take around 36 hours. The overall time for the experiment will thus be 5 days including setting up. By using two detectors, one oriented for vertical scattering and the other for horizontal scattering, we will measure both the crack opening (vertical) and transverse (horizontal) strains simultaneously.

Results expected

In theory the image correlation and the synchrotron data should agree for the thin sample but differ for the thick sample. Recent results have shown that we can extract values of CTOD and K from synchrotron data to high accuracy. This will be the first time crack closure measurements have ever been made at the centre of a test-piece. The experiment will immediately help to resolve the controversy existing since Elber's original discovery of plasticity-induced crack closure in 1971, about its existence and importance for retarding crack growth in thick components.

References

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