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THE USE OF INFRA – RED DETECTORS FOR DETERMINATION OF THE FRACTURE MECHANICS PARAMETERS

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The utilisation of infra – red detectors is presented for determination the mixed mode stress intensity factors. The methodology involves the thermoelastic stress analysis using focal plane array thermal detectors, as DeltaTherm system. The range of the mixed mode stress intensity factors are obtined by fitting the equations describing the stress field around the crack tip, based on Muschelishvili's approach to the thermoelastic data. The thermoelastic data is collected throughout the singular elastic stress field around a sharp notch inclined at 45^0 in a cruciform specimen subjected to biaxial loading.

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1. Introduction

Thermoelastic stress analysis is based on the fact that under adiabatic and reversible conditions, a cyclically loaded structure experiences temperature variations ΔT, that are proportional to the variation of the sum of the principal stresses, $\Delta(\sigma_1+\sigma_2+\sigma_3)$ [1]:

$$\Delta T = -\frac{\alpha T}{\rho C_\varepsilon}\Delta(\sigma_1+\sigma_2+\sigma_3) \tag{1}$$

where α is the thermal expansion coefficient, T is the ambient temperature, ρ is the density and C_ε is the specific heat for constant deformation. These temperature variations may be measured using a sensitive infrared detector and thus the cyclic stress field in terms of the sum of the principal stresses on the surface of the structure may be obtained as:

$$\Delta(\sigma_1+\sigma_2) = A\,S \tag{2}$$

where A is a calibration constant and S is the thermoelastic signal from the detector.

Thermoelastic stress analysis has been developed over the last two decades to be a useful method for studying the stresses around notches and cracks. The first stress field invariant in the region of the crack tip can be derived from the stress field equations using an analytical solution and correlated with the thermoelastic differential signal in order to determine the stress intensity factors.

The stress intensity factor value obtained from thermoelastic analysis is equal to the range of the stress intensity factor, ΔK that occurs at the crack tip due to the applied cyclic load. This allows the actual crack driving force to be experimentally determined rather than being inferred from maximum and minimum stress intensity factors, which is the case with other experimental techniques.

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Although accurate analyses have been performed for opening mode cracks and slots, only limited progress has been made for the determination of stress intensity factors for mixed-mode cracks using thermoelastic techniques, [2], [3], [4], [5]. The most recently published data on the subject, [3] shows good agreement between theory and experiment for both ΔK_I and ΔK_{II} for central slots and cracks, and edge slots. However for mixed-mode edge cracks the differences between theory and experiment were up to 30%. The majority of the published data has been for cracks under predominantly mode I loading and the only data for predominantly mode II loading showed a difference between theory and experiment of up to 40%, [2]. Although it is known that the majority of mixed-mode cracks found in engineering components eventually propagate as mode I cracks, in some cases such as turbine blades and rolling contact fatigue in rails, mixed-mode loading continues to dominate. Therefore this area of research is of importance and further testing is required.

All published experiments generate the mixed-mode conditions at a crack tip with the use of tensile loading of a plate containing a sharp slot or crack at an angle to the direction of loading. However, to the author's knowledge there are no applications of thermoelastic measurements of the stress intensity factors for biaxially loaded specimens.

The paper presents the experimental results obtained by thermoelastic stress analysis for specimens with 45^0 inclined sharp slots subjected to biaxial loading, and study the influence of applied mixed mode load ($\Delta K_{II}/\Delta K_I$).

2. Thermoelastic analysis system

Infra red detectors systems

Thermoelastic analysis systems rely on the detection of photons emitted from a component surface, the wavelengths of which lie in the infrared range. Initial investigations by Belgen [6] employed a single radiometer, which was brought to focus on a distant image plane, enabling the first practical non-contacting thermoelastic studies to be performed. This concept was further developed by Mountain and Webber [6], culminating in the commercial production of the SPATE (Stress Pattern Analysis by Thermal Emission) system, produced by Ometron Ltd., UK, Fig. 1. This system incorporates a single Mercury – Cadmium - Telluride detector cooled by a liquid nitrogen dewar, with a series of optics which allow the point-by point scanning of an image with a pair of moveable mirrors. The detector is sensitive to incident radiation with wavelengths in the 8-14 mm range, in which the thermoelastic effect is readily visible and background ration is comparatively low.

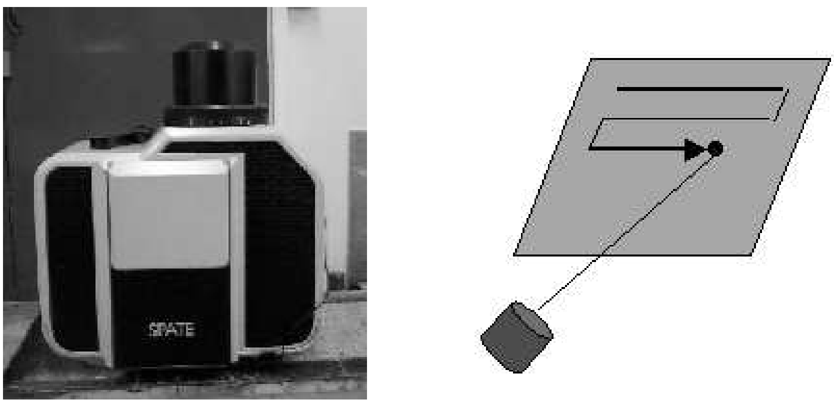


Fig. 1. The SPATE system.

The focal plane array thermal detectors have produced a new family of thermoelastic analysis systems [8] which offer several important improvements over the point-by-point scanning method. Firstly, there is an increase in the maximum spatial resolution attainable, allowing small-scale analyses to be performed and permitting the theoretical maximum spatial resolution associated with the thermoelastic effect to be approached. Secondly, as each detector in the focal plane array is recording information concurrently, many thousands of data points can be recorded concurrently, allowing transient events to be monitored in a full-field manner. And finally, subject to limits in signal processing, a far greater rate of thermoelastic signal recording can be achieved in a given time and thus analysis time is much reduced. An example of such system is DeltaTherm, produced by Stress Photonics Inc., USA, Fig. 2, having Indium – Antimony focal plane array detector with resolutions of 128 × 128 (DeltaTherm 1000) or 256 × 320 (DeltaTherm 1550).

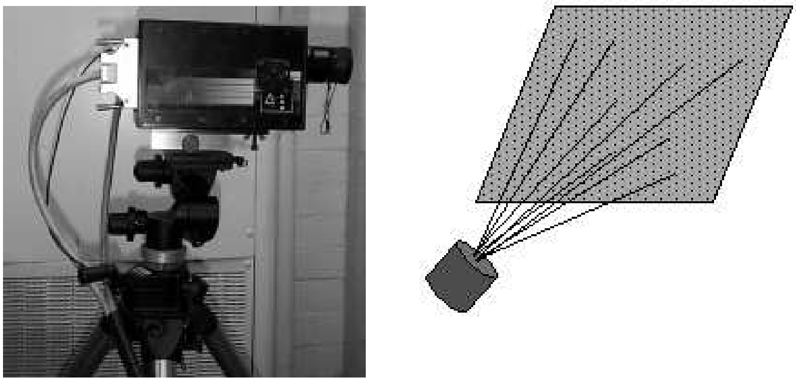


Fig. 2. The DeltaTherm system.

Whilst the qualitative use of data maps to identify critical areas in the stress distribution may be adequate in some situations, the following case studies demonstrate the ability of thermoelastic stress analysis to yield quantitative results in determination the fracture mechanics parameters.

Bloc diagram for thermoelastic stress measurements

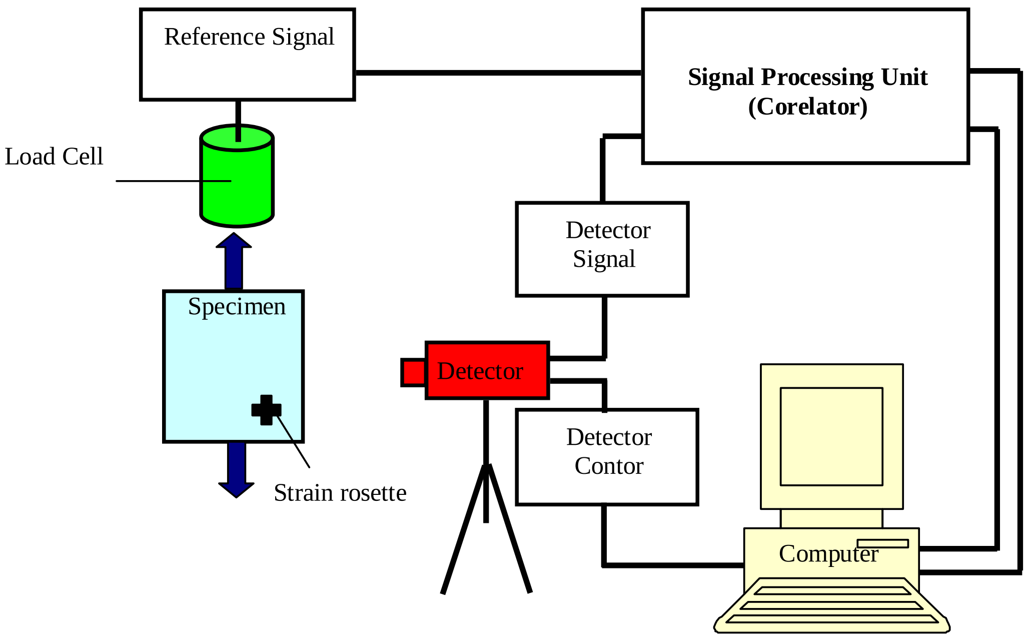


Fig. 3. Bloc diagram for thermoelastic stress analysis.

A bloc diagram for thermoelastic stress analysis is shown in Fig. 3. A test specimen is cyclically loaded usually by servo – hydraulic systems, although it is possible to use service loads. The load frequency needs to be high enough to ensure that the thermodynamic condition in the component material is adiabatic, in which case reversibility is maintained between mechanical and mechanical and thermal forms of energy (for most metallic materials the minimum frequency is 3 Hz).

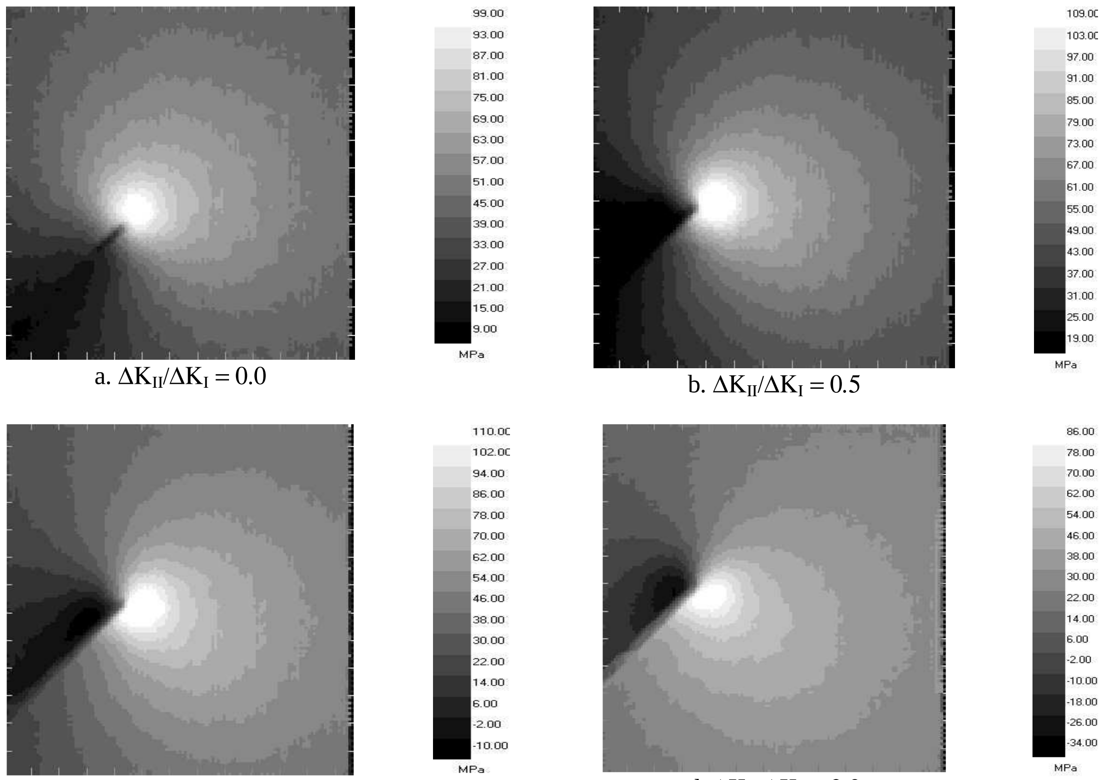
An infra – red detector is placed to view the specimen surface. The detector generates a signal in response to the thermoelastic infra-red flux emitted from the specimen surface. In addition to the infra-red detector signal a clean reference signal taken from a function generator, a load cell or a strain gauge bonded on the specimen surface is used in order to reject the noise from the detector signal, by applying a Fast Fourier Transform (FFT). The infra - red systems operates in a lock – in mode, providing in - phase and out – of – phase images. When properly adjusted, the stress map resides in the in-phase image and the out – of phase image is null. The camera data acquisition (e.g. sample time, scan area, integration time) is controlled using a computer system and DeltaTherm software. The sensivity of infra – red systems is around 0.001^0C, which equates to a stress resolution of 1 MPa for steel and 0.4 MPa for aluminum.

3. Thermoelastic determination of the stress intensity factors from mixed-mode slots

The specimens were made from 150M36 steel and having a cruciform shape with a central spark-eroded notch inclined at 45º, of length 2a = 6 mm initially. One side of the specimen was polished to enable any crack growth to be easily monitored using an optical microscope. The other side of the specimen was sprayed with a thin coat of matt black paint in order to obtain an uniform emissivity on the specimen surface. The load was applied using a 100 kN Denison Mayes Biaxial Testing Machine. The shape of the load waveforms and the response of the load cells were monitored using two oscilloscopes and the reference signal was taken from one of the load cells.

A sinusoidal load was applied at a frequency of 8 Hz and a load ratio, R = 0 along the two axes of the specimen in order to give the ratios of $\Delta K_{II}/\Delta K_I$ approximately equal to 0, 0.5, 1, 1.5, 2, and 2.5. At each load setting thermoelastic data was recorded around the notch tip using a DeltaTherm 1000 system. Each thermoelastic data map was integrated over 3.25 minutes and typical maps for different applied $\Delta K_{II}/\Delta K_I$ ratios are shown in Fig. 4. The thermoelastic signal was calibrated using two orthogonal strain gauge rosettes, located in an area of uniform stress on the polished side of the specimen, using a standard calibration method, [2]. The signal was calibrated at regular intervals throughout the test program since any change in ambient temperature can change the calibration constant. The stress intensity factor ranges, ΔK_I and ΔK_{II}, were determined from each set of data using the CANUTE code based on a method developed by Tomlinson - Nurse - Patterson, and presented in [2]. The CANUTE code use around 100 data points (x, y coordinates related to the crack tip and the thermoelastic signal in this points) to fit the equations describing the stress field around the crack tip, based on Muschelishvili's approach to the thermoelastic data. In this purpose the Canute code used a Newton-Raphson iteration technique with a least squares approach. Statistical calculations are performed and the Mean and Variance of the least-square fit are found. Authors designed an interface between thermoelastic data and CANUTE routine for finding the stress intensity factors, Fig. 5. This interface written in Visual BASIC ensured that the data was collected within the singularity-dominated zone on radial lines. An inner limit of 10 times notch radius is used to mask the non-linear effects at the crack tip caused by plasticity and heat conduction. The outside limit of data collection was considered a fraction of notch length (usually 0.4*notch length). As well the notch edges effect was suppress by using a Mask angle.

The notch was further extended by spark erosion to the lengths 2a = 12, 18, 24 and 30 mm and the same procedure repeated at each of these notch lengths.



a. $\Delta K_{II}/\Delta K_I = 0.0$ b. $\Delta K_{II}/\Delta K_I = 0.5$

c. $\Delta K_{II}/\Delta K_I = 1.0$ d. $\Delta K_{II}/\Delta K_I = 2.0$

Fig. 4. Calibrated thermoelastic data around a sharp slot of 30 mm length under mixed mode load (Image size: 128×128, Integration Time: 3.25 minutes, Resolution: 8.67 pixels/mm).

4. Experimental results and discussion

The values of stress intensity factors ranges (square symbol for the Mode I, and triangle symbol for the Mode II) from thermoelastic measurements (hollow symbols) are shown in Fig.6 and compared with the stress intensity factors ranges determined from theory (filled symbols) developed by Bold *et al* [10], [11].

The results presented in Fig. 6 show good agreement with those from theory. The average difference between experimental and theoretical values for stress intensity factors range was 4.5 % for ΔK_I and 6.5 % for ΔK_{II}. The results are more accurate for longer notches, however for the shortest notch (2a = 6 mm) the singularity dominated zone was relatively small and this was thought to be the reason for the less favorable comparison with theory. The most recently published data for mixed-mode edge notches or cracks monoaxially loaded, the differences between theory and experiment were up to 30% [3] and 40% for predominantly mode II loadings, [2] using SPATE system. The results for mixed mode stress intensity factors, presented in this paper obtained from biaxial loading appear more accurate than those published previously. The increasing in accuracy of the experimentally results could be due to the limitations in data collection of the SPATE system when compared with the higher resolution DeltaTherm system and the improved accuracy of locating the crack tip position using the Phase map of thermoelastic signal.

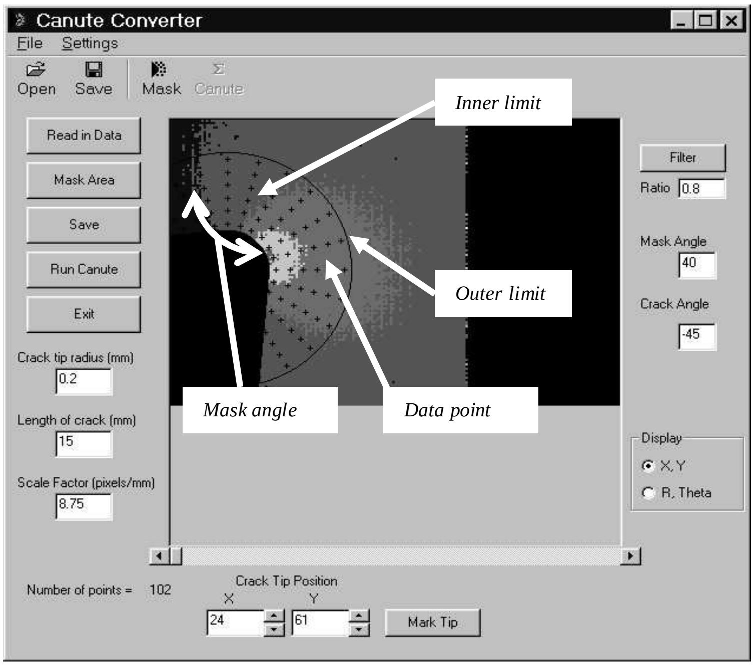
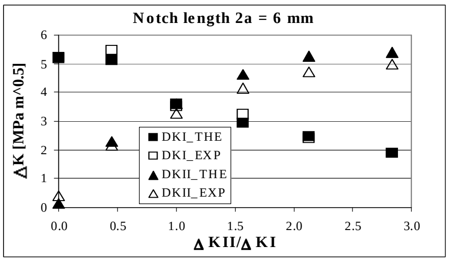
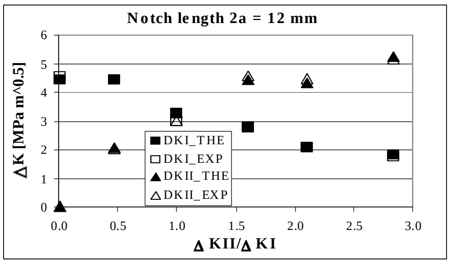


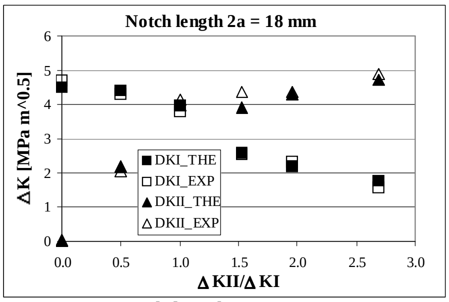
Fig. 5. Pattern of the array of points around the crack tip used for stress intensity factor determination.



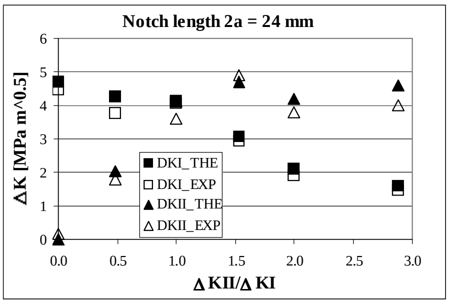
a. Notch length 6 mm



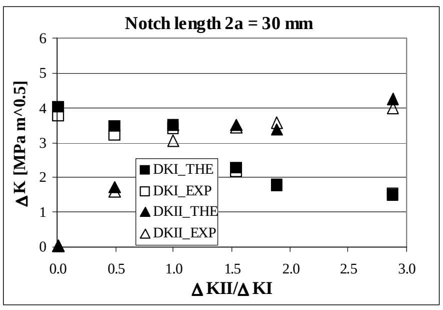
b. Notch length 12 mm



c. Notch length 18 mm



d. Notch length 24 mm



e. Notch length 30 mm

Fig. 6. Comparison between theoretical and experimental values of the stress intensity factors ΔK_I and ΔK_{II} versus applied mixed mode ΔK_{II} / ΔK_I.

5. Conclusions

The determination of mixed mode stress intensity factors using infrared detectors was presented. The influence of mixed mode applied load was studied. The series of thermoelastic investigations showed that accurate stress intensity factor ranges may be obtained under mixed mode loading conditions for both predominantly mode I and mode II. The advantage of the biaxial experiment is that using the same specimen geometry it is possible to model different types of mixed modes only by changing the amplitude of the applied load.

The stress intensity factor value obtained from thermoelastic analysis is equal to the range of the stress intensity factor ΔK that occurs at the crack tip due to the applied cyclic load. This allows the crack driving force to be experimentally determined rather than being inferred from maximum and minimum stress intensity factors, like in other experimental techniques.

The thermoelastic technique has the advantage that it involves no contact with and no complicated preparation of the specimen surface.

Acknowledgements

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