

Thermal Analysis of Crack Tearing*

A T Zehnder[†]

K S Bawa-Bhalla[†]

R Thomas[‡]

L D Favro[‡]

Much of the plastic work done ahead of a moving crack tip is dissipated as thermal energy. The solution of the resulting thermo-mechanical problem is of interest, since for high enough crack speeds, the temperatures generated can lead to thermal softening of the material. However, even at low crack speeds, the temperature fields carry quantitative information about the energy flowing to the crack. In this study, energy flux to the crack tip is computed from infrared images and the results are validated by a finite element analysis of the process.

Single edge notched specimens (Figure 1) of vacuum annealed, 302 Stainless Steel were mounted in a tabletop Minimat tester and loaded in displacement control at a constant pulling rate of 1.33 mm/sec. An Amber/Raytheon Proview infrared imaging system was used to acquire thermal images of the specimen at a rate of 38 frames/sec. The imaging system consisted of a focal plane array of 256x256 InSb detectors focussed on a region of size 24mm x 24mm. The schematic of the experimental set up is shown in Figure 2. Crack position and velocity were extracted from the thermal images by using edge detection. Typically, tests lasted about 2.5 sec with peak crack velocities of about 16 mm/sec.

The temperature field, T , is governed by the 2D heat equation:

$$\beta\sigma_{ij}\epsilon_{ij}^p + k\nabla^2 T - \alpha(3\lambda + 2\mu)T_0\dot{\epsilon}_{kk} = \rho c\dot{T} \quad (1)$$

where, λ and μ are Lamé's constants, σ_{ij} and ϵ_{ij} are the components of the stress and strain tensors, respectively, and k , ρ , c and α are the conductivity, density, specific heat and the coefficient of thermal expansion of the material. It is assumed that a fraction, β , of the plastic work done is converted to heat and provides the heat source (first term in [1]). The second term accounts for the heat conduction and the third term represents cooling due to the thermoelastic effect which is negligible and is ignored. Thus, the rate of energy flux to the crack tip, can be written in terms of the temperature field as:

$$G = \frac{1}{v} \int_R \sigma_{ij}\epsilon_{ij}^p dR = \frac{1}{v\beta} \int_{A_p} \rho c\dot{T} dA_p - \frac{k}{v\beta} \int_{A_p} \nabla^2 T dA_p \quad (2)$$

where, v is the crack speed and A_p is the plastic zone. The last term in [2] requires computation of the second spatial derivative of the temperature field. This is circumvented by using the divergence theorem to convert the area integral into a contour integral. Thus, [2] becomes,

$$G = \frac{1}{v\beta} \left[\int_{A_p} \rho c\dot{T} dA_p - k \oint_C (T_x dy - T_y dx) \right]. \quad (3)$$

A 2D, coupled temperature-displacement, large deformation, plane stress analysis was performed using the FEA code, ABAQUS. The experimentally measured crack length history was prescribed and the crack was propagated by node release. The material was assumed to be elastic-plastic with isotropic hardening. At each increment of the nonlinear analysis, the plastic work field was extracted and a fraction, β , of this was supplied back to the analysis as a distributed heat source for the thermal analysis.

Figure 3 shows that the experimentally measured temperature fields compare well with those predicted by the mathematical analysis both in magnitude and trend. Energy flux to the crack extracted from the thermal images using [3] is plotted in Figure 4, along with values computed directly from the stress and strain fields predicted by the FEA. The results match well, confirming our hypothesis that IR imaging can be used to compute the energy flux to the crack. Thus the ability to systematically combine thermal imaging and stress analysis to validate the consistency and accuracy of IR imaging techniques in the study of crack growth is demonstrated for the first time.

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[†]Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, NY 14853, atz2@cornell.edu, (607)255-9181

[‡]Department of Physics, Wayne State University, Detroit, MI 48201

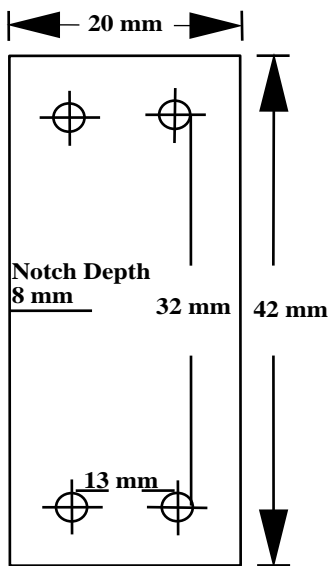


Figure 1: 302 Stainless steel specimens (0.1 mm thick)

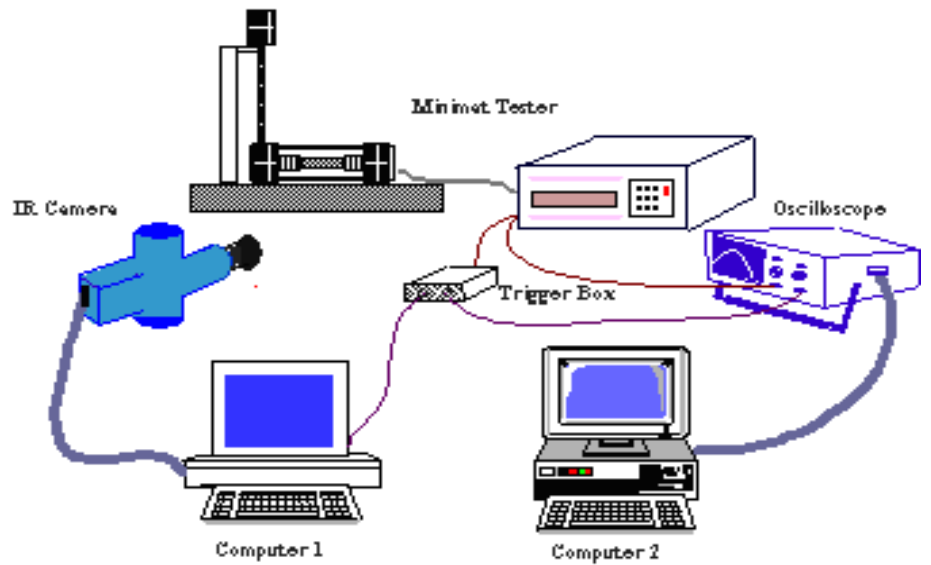
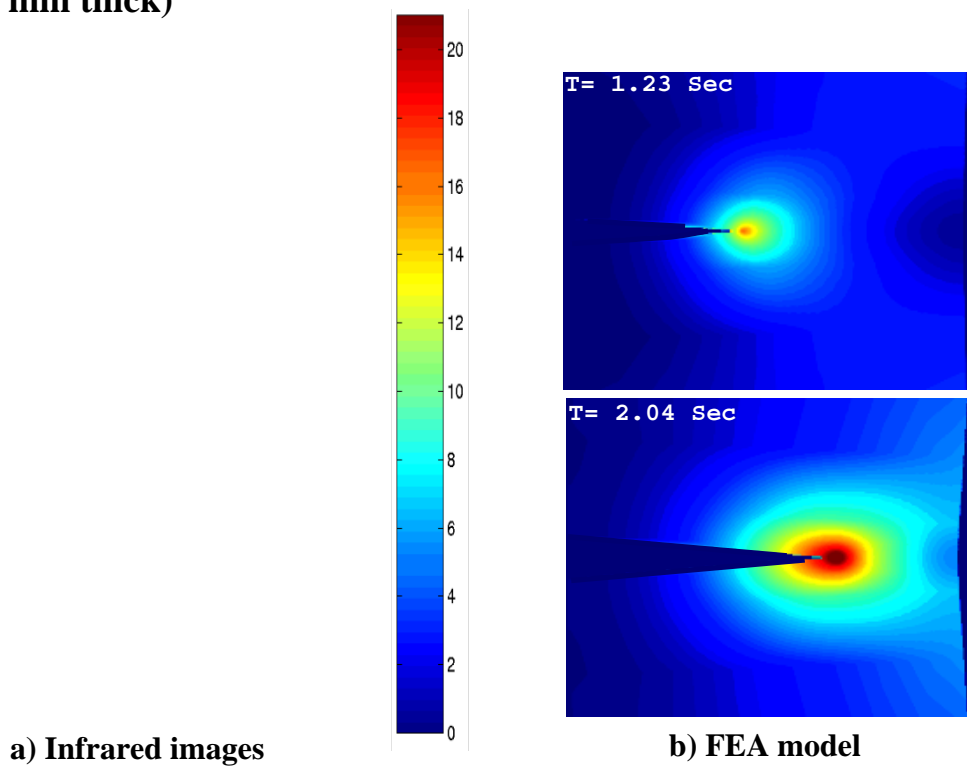


Figure 2: Schematic of the experimental setup



a) Infrared images
b) FEA model
Figure 3: Temperature (deg C) field ahead of the crack tip.

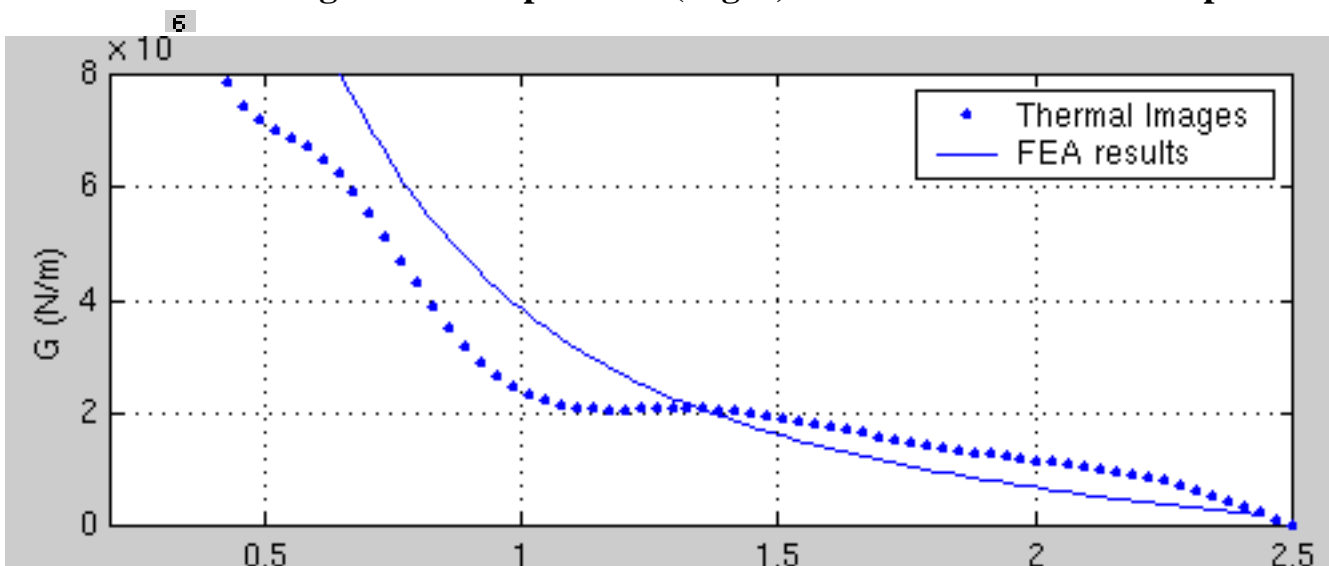


Figure 4: Energy flux to the crack tip