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Thermomechanical aspects of dynamic crack initiation

D. RITTEL
Faculty of Mechanical Engineering, Technion, Haifa 32000, Israel. e-mail: merittel@tx.technion.ac.il

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Abstract. Dynamic fracture is generally addressed as an isothermal phenomenon. When specific phenomena such as shear band formation and propagation are involved, the analyses include thermomechanical conversion of strain and/or fracture energy into heat (*thermoplasticity*). In this case, it has been shown that very significant temperature rises can develop which cause softening of the crack-tip material. In these works, *thermoelastic* temperature changes at the tip of the crack are implicitly neglected. In a recent work, we have questioned this issue and shown that for a stationary crack subjected to transient loading, adiabatic thermoelastic effects were noticeable, thus causing a large temperature drop in the elastic zone surrounding the crack-tip (Rittel, 1998).

In the present work, we pursue this line of investigation by presenting additional experimental results about temperature changes ahead of a dynamically loaded crack in commercial polymethylmethacrylate. We investigate mode I and mode II loading configurations.

We observe, *as expected*, that the temperature drops for mode I loading while it rises for the mode II case. In each case, the crack initiates during the phase where the temperature changes (drop or rise).

While showing that thermoelastic aspects of fracture should certainly be taken into account, the present results indicate that thermomechanical aspects in general should not be overlooked when addressing dynamic crack initiation.

Key words: Polymer, dynamic fracture, thermoelastic, thermoplastic.

1. Introduction

Dynamic crack initiation is generally treated both theoretically and experimentally as an isothermal phenomenon. While the introduction of the inertial term in the equation of motion complicates both the theoretical (Freund, 1990) and experimental (Kobayashi, 1987) aspects of the problem, it seems that thermomechanical aspects of dynamic fracture should also be taken into account to reach a viable criterion for dynamic crack initiation. Consider, for example, the recently reported failure mode transition in which dynamic crack initiation under mode II loading proceeds *either* by an opening *or* by a shear mechanism including (adiabatic) shear band formation at different impact velocities. This phenomenon was first reported for maraging steel by Kalthoff (1988), then by Zhou et al. (1996) who compared the same steel and a titanium alloy. Finally the failure mode transition was also observed in polycarbonate by Ravi-Chandar (1995). These authors investigated the transition under *dominant mode II loading*. More recently, Rittel et al. (1997a,b) investigated the operation of a shear failure mechanism in polycarbonate under general *mixed-mode loading* conditions. Their conclusion was that at the higher impact velocities, specimens which normally fail by an opening mechanism can exhibit a noticeable amount of shear failure, as long as the mode II component of the mixed-mode is not negligible. Indeed, the operation of a shear failure mechanism, which has been related to material softening, requires that the crack-tip material be heated significantly.

The conversion of plastic work (thermoplastic effect) into heat has been reported many years ago by Taylor and Quinney (1934). Consequently, a large body of experimental and theoretical work has been dedicated to this subject, often in relation with the problem of adiabatic shear banding. Experimental evidence of very large temperature rises has been brought, e.g. by Marchand and Duffy (1988) and Zhou et al. (1996).

Another important effect is the reversible thermoelastic effect which correlates temperature changes to volume changes of the elastic material. A thorough characterization of these effects can be found in Dillon (1963) and Dillon and Tauchert (1967).

However, this latter effect is most often neglected in dynamic fracture studies due to the overwhelming evidence of crack-tip heating, and in fact, most of the work to date has concentrated on the assessment of *temperature rises* at the crack-tip. The underlying assumption is that thermoelastic effects are necessarily of limited extent so that they can be neglected.

The purpose of this paper is to report experimental results on thermal (thermoelastic and thermoplastic) phenomena which accompany dynamic crack initiation in mode I and mode II. It will be shown that under *transient conditions* thermoelastic effects are not negligible and should therefore be taken into account.

The paper is organized as follows: the second section is a brief theoretical review of transient thermoelastic and thermoplastic effects. Next we present and discuss results for dynamic mode I and dynamic mode II experiments during which the transient crack-tip tempertature is measured. The last section summarizes and concludes the essential points of this work.

2. Theoretical considerations

The transient heat equation is given by (Boley and Weiner, 1960):

$$k\nabla^2 T - \alpha(3\lambda + 2\mu)T_0\dot{\varepsilon}^e_{kk} + \beta\sigma_{ij}\dot{\varepsilon}^p_{ij} = \rho c\dot{T}, \tag{1}$$

where k is the heat conductance and α is the thermal expansion coefficient. ρ, c, λ and μ stand for the material's density, heat capacity and Lamé constants respectively. T is the temperature and the strains ε are divided into elastic and plastic (the superposed dot indicates time derivative). Finally the factor β expresses the fraction of plastic work rate converted into heat (typically 0.6 for polymers and 0.9 for metals).

This equation comprises two heat sources: the first which relates to the elastic properties of the material (compressibility) and the second related to the conversion of plastic work into heat.

When the rate of deformation is high, as in dynamic fracture or impact related phenomena, the heat conduction term is customarily neglected ($k\nabla^2 T = 0$) to express adiabatic conditions. For this case, the thermoelastic term will contribute to a temperature drop when the material expands and a temperature rise when it is compressed. This effect is reversible. By contrast, the plastic work term is irreversible and contributes only to a temperature rise.

A very common assumption is that thermoelastic effects are negligible when compared with thermoplastic ones and the temperature rise is calculated by converting the plastic work into heat according to: (see e.g. Mason et al., 1993):

$$\beta\sigma_{ij}\dot{\varepsilon}^p_{ij} = \rho c\dot{T}. \tag{2}$$

Consider now the elastic response of a *thermoelastic* material subjected to transient loading. Assuming adiabatic conditions 1 is rewritten as:

$$\frac{-\alpha E}{1-2\nu} T_0 \dot{\varepsilon}^e_{kk} = \rho c \dot{T} \tag{3}$$

which can also be formulated in terms of the hydrostatic pressure p using $\varepsilon_{kk} = -p/\kappa + 3\alpha(T - T_0)$, where κ is the bulk modulus and T_0 a reference temperature. The resulting temperature change is given by:

$$T(t) = T_0 \left(1 + \frac{3\alpha}{\rho c} p(t)\right). \tag{4}$$

Equation (4) will now be applied to the crack-tip material subjected to transient loading (Rittel, 1998). In the framework of linear elastic fracture mechanics, the crack-tip stress fields have been solved for the three basic crack loading modes. For the sake of simplicity, we will consider here the mode I (opening) only, keeping in mind that the very same way of reasoning can be applied to mixed mode as well using the superposition principle. It should be noted that, in the following treatment, the problem is approximated and simplified by using the solution of the elastic crack problem together with a coupled heat equation and thermoelastic constitutive law as an alternative to solving the fully coupled problem.

For the stationary crack subjected to transient loading, the stress intensity factor K is a function of time only and the stresses and strains vary accordingly (Freund, 1990). The components of the stress tensor can therefore be substituted into (4).

Consequently, for plane strain mode I loading, the temperature ahead of the crack-tip is expected to vary according to:

$$T(r, \theta = 0, t) = T_0 \left(1 - \frac{2\alpha(1+\nu)}{\rho c} \frac{K_{\mathrm{I}}(t)}{\sqrt{2\Pi r}}\right). \tag{5}$$

Equation (5) shows that the material situated in the elastic region ahead of the crack-tip cools down as the stress intensity increases. The amplitude of the cooling effect bears a $r^{-1/2}$ singularity as dictated by the framework of linear elastic fracture mechanics (LEFM). By analogy with LEFM, one must assume the existence of a small plastic zone or a process zone, isolated from the elastic surroundings, in which the temperature remains *finite*. The size of the plastic zone will be dictated by the yield strength of the material. The latter can vary for strain-rate sensitive materials (Meyers, 1994) so that the higher the strain rate, the smaller the plastic zone and the crack-tip material gets *colder closer* to the crack-tip.

To assess the extent of the cooling effect, one must first calculate a plastic radius corresponding to the loading conditions, *outside of which* the temperature will be calculated. The plastic zone radius ahead of the crack ($\theta = 0°$) is calculated according to:

$$r_p = \frac{K_{\mathrm{I}}^2}{2\Pi} \left(\frac{1-2\nu}{\sigma_y}\right)^2. \tag{6}$$

The following representative values can be assumed: $\nu = 0.37$, the *dynamic* (rate sensitive) yield strength of PMMA $\sigma_{yd} = 200\,\mathrm{MPa}$ (twice the static value). For an applied stress intensity factor $K_{\mathrm{I}} = 3\,\mathrm{MPa.m}^{1/2}$, Equation (6) yields a plastic radius $r_p = 2.5 \times 10^{-6}\mathrm{m}$.

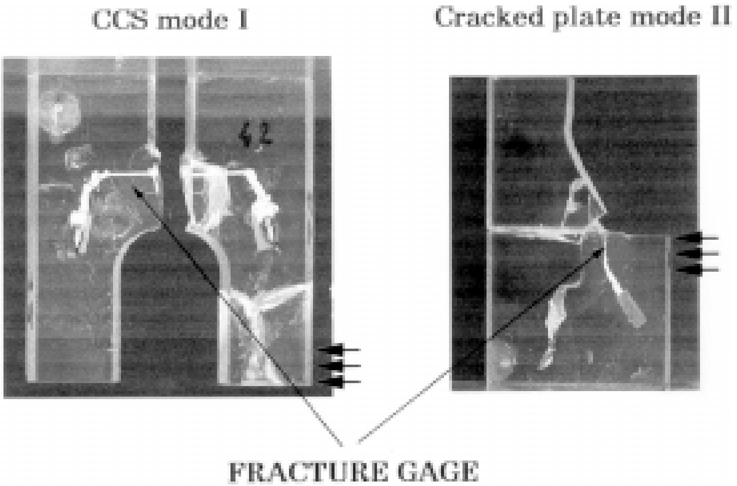

Figure 1. Specimens used in this study. Both specimens comprise a notch and a small fatigue crack. A single wire fracture gage and the thermocouple (not visible) instrument the specimen at 1 mm ahead of the crack-tip on each side. The specimens are in contact with an instrumented bar. Loading is indicated by the arrows. Both specimens experience mixed-mode loading, the CCS in dominant mode I and the edge cracked plate in dominant mode II.

Next the temperature drop is calculated at a distance $x \geqslant r_p$ using (5). Typical values of $\alpha = 10^{-4}/°K$ and $\rho c = 10^6 \mathrm{J/m^3}/°K$ yield a relative temperature change of $\Delta T/T_0 = 0.146$ at $x = 2r_p$. This amounts to a temperature drop of 43°C from 20°C (RT). Such result shows that a significant temperature drop can develop in the close vicinity of the crack-tip over characteristic distances which are indeed of the order of microstructural parameters (grain size for instance).

The observation of noticeable crack-tip cooling has been reported earlier. Clear experimental evidence can be found in the experiments of Fuller et al., (1975). These authors investigated propagating cracks in various polymers and the temperature was recorded using an infrared detector. Their results show that before the crack-tip reached the detector, a noticeable temperature drop is observed. However, although they mention it, these authors did not investigate this effect. Rather, they considered the *temperature rise only*. Similar evidence is also found in the work of Weichert and Schönert (1978) who modeled the crack-tip as a propagating heat source. Here again, the emphasis is on the maximal temperatures which develop. Yet in their experiments with glass plates, the temperature recording clearly shows that fracture *initiates during the cooling phase*.

In the following section, we will present our results about transient crack-tip measurements.

3. Results

3.1. THE EXPERIMENTAL SETUP

The experimental setup consists of an instrumented (Kolsky) bar which is brought into contact with the specimen. The specimen is not supported by special fixtures and fracture occurs as a result of inertia only (one point impact experiments). A striker is fired against the bar to induce a compressive pulse whose magnitude is set by the impat velocity (typically 8 m/s to 65 m/s) and whose duration depends on the length of the striker. At the area of contact between the specimen and the bar, the boundary conditions are thus well-defined (forces and displacements) and they can be used in a finite element model of our experiments to calculate the stress intensity factors (Rittel et al., 1997a). The lack of symmetry of the loading causes mixed-mode to develop (Maigre and Rittel, 1993). As shown in Figure 1, two kinds of specimens are used. First is the CCS (Compact Compression Specimen) in which the crack is subjected to mixed-mode loading with a dominant mode I component (Rittel et al., 1992). The second specimen is the edge cracked plate in which the crack experiences almost pure mode II loading initially, then followed by mixed mode loading (Mason et al., 1992).

The selected material is commercial PMMA for which experimental information is widely available (see e.g., Rittel and Maigre, 1996). In all the specimens, a fatigue crack was carefully grown prior to the experiments.

Two important parameters of the experiment are the fracture time and the transient temperature.

The first is measured by means of a single wire fracture gage silk screened on the surface of the specimen in the vicinity of the crack-tip. This gage performs satisfactorily for cases where the crack opens during its propagation. In a previous study, Maigre and Rittel (1996) showed that a typical delay of 10 μs is observed between the fracture time measured by the surface fracture gage and the onset of fracture in the bulk of the specimen. Similar observations were made by Aoki and Kimura (1993) who investigated the caustic pattern formation in a finite element simulation.

By contrast, when fracture starts without marked opening, as in the case of side impact of a cracked plate, the indication of fracture is no longer reliable to an extent comparable to the previous case. Transient temperature measurements are generally performed using infrared detectors due to their fast response (see, e.g., Zhender and Rosakis, 1991). The transient response of welded thermocouples is generally considered as too slow for this kind of experiment. Indeed, a typical figure for the rise time, dictated by *convection* considerations, would be between 1 ms to 5 ms as could be noticed by plunging a fine bead (typically 130 μ radius) into hot water. This figure limits the use of thermocouples which are bound to the surface of a specimen. By contrast, when the same thermocouple is *embedded* into the (polymeric) specimen, intimate contact is prescribed all over the surface of the sensor. In this case, it is observed that the response of the thermocouple is much shorter (of the order 10 μs), as the thermal problem is related to *conduction* only. This point is in perfect agreement with the solution of the temperature distribution of a sphere with a prescribed surface temperature (Carslaw and Jaeger, 1959). The fast response was observed in planar impact of polymeric disks into which a thermocouple was embedded (Rittel, 1998). Consequently, we use the embedded thermocouple technique (ETC) to investigate temperature changes ahead of the crack-tip.

The *simultaneously* available information in a typical experiment is therefore the mechanical history (loads, displacements, stress intensity factors), the thermal recording at a point, and an indication of the onset of crack propagation. ‘Post-mortem’ investigations (not reported here) are carried out using optical and scanning electron microscopy.

The fracture gage and the thermocouple are typically located 1 mm ahead of the crack-tip, one on each side of the specimen (Figure 1).

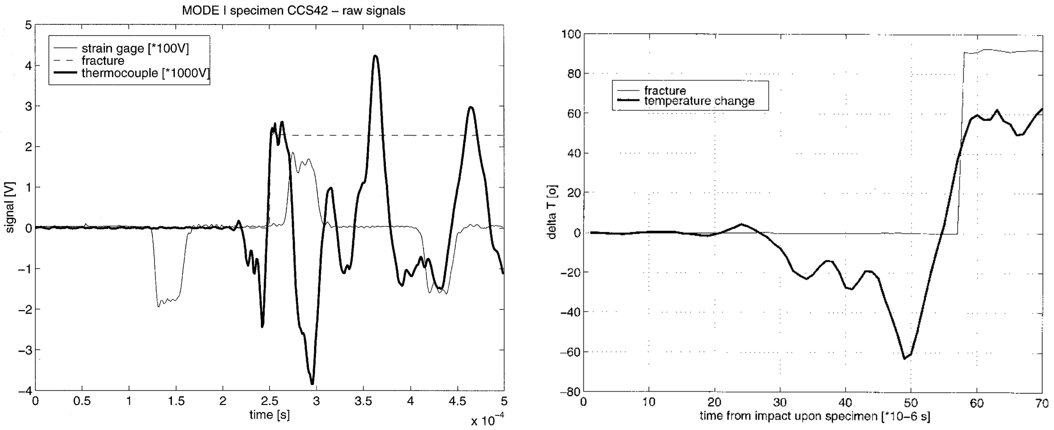

Figure 2. (a) Mode I experiments. Typical thermal and strain signals recorded in a typical dynamic mode I loading experiment. The signals are measured in different locations: the strain gate signal is measured on the Hopkinson bar and the thermal and fracture signals on the specimen itself. The specimen is loaded 72 μs after being measured on the strain gage. When the stress wave interacts with the crack, a marked temperature decrease is observed. Past fracture violent thermal oscillations indicate thermocouple deterioration. (b) Close-up view on the thermal and fracture signals. The common time origin is chosen as the instant when the stress wave enters the specimen. About 30 μs later the temperature drops noticeably. Fracture is detected when the crack-tip breaks the timing wire and the temperature rises at this instant. Actual crack initiation occurs during the cooling phase.

3.2. MODE I EXPERIMENTS

The following results were established on a sample size of 12 CCS. Figure 2(a) shows a typical recording of the transient thermal and mechanical data. The data shown in this figure are not synchronized as the strain is measured on the incident bar ahead of the specimen while fracture and thermal data are measured on the specimen itself. Until the compressive pulse reaches the specimen/bar interface, the thermal signal is perfectly quiet. Then past a typical delay of 30 μs, a noticeable temperature drop is observed prior to the onset of crack propagation as signaled by the fracture gage. Beyond this point, the thermal signal oscillates violently which indicates most likely that it has been damaged. Figure 2(b) shows the synchronized thermal and fracture data with the time origin set as the instant where the stress wave hits the specimen. The temperature drop is of several tens of degrees and the exact figure varies from specimen to specimen (Rittel, 1998). This is easily understood if the exact crack path with respect to the thermocouple's bead is considered (equivalent to the distance noted r in Equation (5)). The closer the crack comes to the thermocouple, the lower the sensed temperature. When the crack-tip reaches the fracture gage (and the thermocouple), a noticeable temperature rise is recorded.

It can be noted that the magnitude of the observed temperature drop is by all means comparable to the predictions of (5). However, it is necessary to emphasize that the actual evolution of the temperature involves crack-tip motion toward the thermocouple, otherwise such low temperatures could not be sensed for the *stationary* crack situated 1 mm from the crack-tip. A simple numerical substitution similar to the one developed earlier shows that the anticipated temperature drop would be of the order of 3°C only at such distance.

The observed temperature rise when the crack-tip passes through the fracture gage reflects the fact that fracture is a dissipative process so that the moving crack-tip can be assimilated to a heat source, as in Weichert and Schönert (1978).

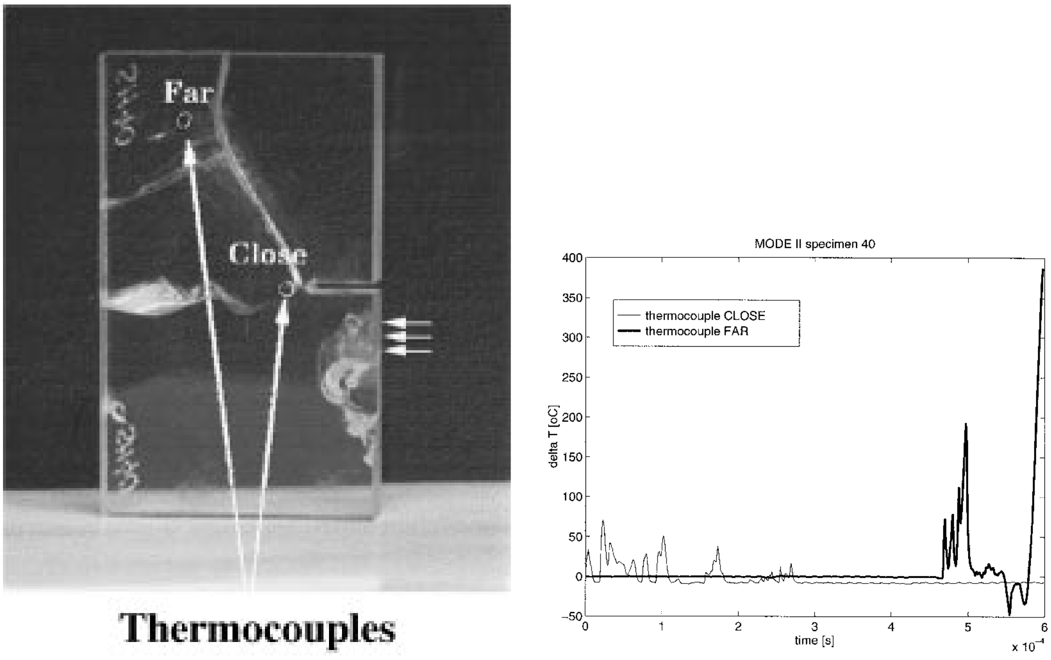

Figure 3. (a) Mode II specimen. This specimen was instrumented with two thermocouples, one ‘far’ from the crack-tip and the second ‘close’ to it. The initial crack started at a kink angle of about 70 avoiding the ‘close’ thermocouple initially. A secondary crack reached it later. After propagating in the specimen, a secondary crack diverted from the main crack and reached the ‘far’ thermocouple. (b) Thermal sequence corresponding to the experiment described in Figure 3(a). The recording was triggered by the ‘close’ signal. Note that the ‘far’ thermocouple was not affected by the stress wave during the initial 460 μs until reached by the secondary crack.

Fracture time, as detected by the timing wire, is delayed by about 10 μs with respect to the actual initiation time, as mentioned earlier. To this delay, one must add typically 3 μs to 10 μs for the crack to propagate over 1 mm and reach the fracture gage. Taking the cumulative delay into account, the present measurements indeed show that the crack started propagating earlier than detected, *during the temperature drop phase*.

Such thermal sequence is *identical* to that described by Fuller et al. (1975) who used a fixed infrared detector in front of which the crack propagated. However, the important difference is that we investigate the onset of crack propagation rather than the propagation phase itself.

The major point of this experiment is that it definitely shows that the thermoelastic effect is not negligible during dynamic crack initiation. This opens the way for an assessment of the competition between crack-tip plasticity and thermoelastic effects at the time of initiation under transient loading conditions.

3.3. MODE II EXPERIMENTS

We now report experiments which are more ‘classical’ than the previous ones, in a sense, since at least for adiabatic shear band formation, transient temperature fields have been measured and calculated (see e.g., Marchand and Duffy, 1988). The following results were established on a sample size of 8 edge cracked plates.

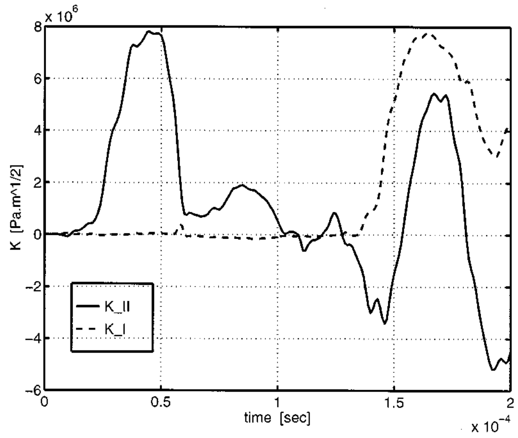

Figure 4. Simulated evolution of the mode I and mode II stress intensity factors in a typical side impact experiment. Note that the initial loading mode is of the mode II type only due to the restraining action of the crack faces on a negative mode I component. At later times, mixed I and II loading mode develops. The crack may start to propagate during either phase. The kink angle will indicate if opening fracture occurred during the mode II phase (larger angular values) or during the mixed-mode phase (smaller angular values).

3.3.1. *Preliminary experiments*

In a previous paper, we illustrated the claim that thermocouples can react quite rapidly provided the appropriate boundary conditions are met (i.e. embedding) (Rittel, 1998). Additional insight into the thermal signals involved in crack propagation can be gained by considering the following experiment. In this experiment, the specimen shown in Figure 3(a) was instrumented with two identical thermocouples in two distinct locations: one about 2 mm ahead of the crack-tip ('close' thermocouple) and the other near the free boundary of the sample ('far' thermocouple). The goal of this experiment was to test the response of the thermocouples in stress wave environment where one of them is also subjected to fracture phenomena. The stress wave itself was not recorded.

In Figure 3(b) the thermal recordings of each thermocouple are presented. In this experiment, the unexpected occurred in the sense that a small crack diverted from the main crack which ultimately reached the remote thermocouple too.

The overall recording sequence was triggered by the 'close' thermocouple. This thermocouple recorded a thermal signal over an initial duration of about 300 μs, after which the signal drops to its base level. Figure 3(a) shows that the main crack, which developed at about 70°, (initially) avoided the 'close' thermocouple which was (later) reached by a secondary crack. During that period the 'far' thermocouple indicated absolutely no thermal activity until about 460 μs. At this time, it shows a noticeable thermal signal until about 500 μs. Beyond that time the signal oscillates violently, indicating deterioration of the thermocouple. Examination of the specimen shows that a secondary crack diverted from the main crack and reached the 'far' thermocouple too. It is most likely this last fracture event which caused the thermal signal recorded at later times in the 'far' thermocouple.

We present this 'unintended' result to show that the thermocouple shows no activity other than that related to fracture (initiation and propagation).

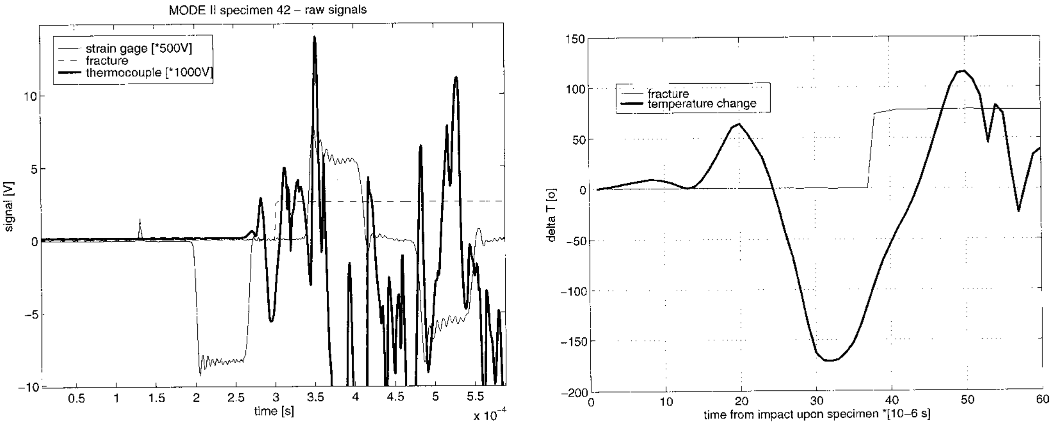

Figure 5. (a) Mode II experiments. Typical thermal and strain gage signals recorded in a typical dynamic mode I loading experiment. The signals are measured in different locations, similar to Figure 2(a). When the stress wave interacts with the crack, a marked temperature rise is observed. Past fracture violent thermal oscillations indicate thermocouple deterioration. (b) Close-up view on the thermal and fracture signals. The common time origin is chosen as the instant when the stress wave enters the specimen. About 15 μs later the temperature rises noticeably. Fracture is detected when the crack-tip breaks the timing wire and the temperature recording oscillates violently past this instant. Actual crack initiation occurs during the heating phase.

3.3.2. *Side impact experiments*

In Figure 4 we have plotted the characteristic evolution of the stress intensity factors of a typical experiment. As stated above, the crack experiences essentially mode II loading during the initial phase. This is due to the restraining action of the fatigue crack upon the negative mode I component which characterizes this kind of experiments (Lee and Freund, 1990; Rittel et al., 1997a,b). Then, at the later stage, the crack experiences mixed-mode loading including a postive mode I term. Depending on the material, failure can therefore consist of the following sequences:

- Opening fracture during the early mode II stage, thus resulting in a large value of the initial kink angle (typically 70°);
- Initial shear failure followed by opening at a lower angular value (as a result of mode-mix).

In Figure 5(a) we show a characteristic recording of the nonsynchronized mechanical and thermal data, as was shown in Figure 2(a). The stress wave reaches the specimen about 72 μs after being detected on the strain gage. Typically 15 μs later it interacts with the crack and simultaneously *a noticeable temperature rise is detected*. Here too the thermal data is oscillating violently past fracture. In Figure 5(b), the synchronized data are shown, with respect to the instant at which the specimen is loaded. The temperature rise is expected from a dissipative cause (plasticity and/or fracture) as the elastic shear strains do not contribute to a dilatancy related temperature rise.

The fracture gage indicates fracture about 35 μs. Keeping in mind that this indication relates to the *crack opening phase only*, the same reasoning as exposed previously can be applied here too (see also Figure 4). The actual beginning of the opening phase is likely to have started *at least* 10 μs prior to the detected fracture time (bulk vs. surface detection). To this delay, one must add another 3 μs to 10 μs necessary for the kinked crack to propagate over the distance separating the crack-tip from the fracture gage. This estimate of the actual crack initiation time indicates that fracture most likely *initiated during the heating phase* of the crack-tip material.

As with the mode I loading, the question rises as to the characteristic size of the mode II plastic zone, or the distance from the crack-tip over which a temperature rise is expected. We describe the plastic zone as a Dugdale strip of length r:

$$r = \frac{\Pi}{8}\left(\frac{K_{\mathrm{II}}}{\tau_y}\right)^2 \tag{7}$$

By consistency with the previous data, we assume typical *dynamic* values of $\tau_{yd} = 100\,\mathrm{MPa}$ and K_{II} is taken as $4\,\mathrm{MPa.m}^{1/2}$. Equation 7 yields a band length of 0.6 mm. This distance is very similar to the distance at which the thermocouple is located w/r to the crack-tip (1 mm).

Consequently, one can reasonably assume that the thermocouple senses the temperature rise even before crack-propagation.

4. Discussion

This paper reports results about transient thermal phenomena at the tip of a dynamically loaded crack. Two distinct crack-tip loading modes are considered: dominant mode I and dominant mode II. Transient crack-tip temperature changes are recorded using embedded thermocouples in PMMA samples.

The results show that for a dynamic mode I loading the crack-tip temperature *drops significantly* prior to crack propagation. Crack-propagation is understood as a moving heat source which contributes to the ensuing temperature rise. The observed amplitude of thermoelastic effect is consistent with the predictions of a simple LEFM (small scale yielding) analysis. Our result are qualitatively identical to those reported earlier by Fuller et al. (1975) who used infrared detectors.

The present work indicates that the thermoelastic effects should not be systematically overlooked when investigating dynamic crack *initiation* under dominant mode I.

For dynamic mode II loading, we observed, as expected, that the temperature rises significantly prior to or during crack propagation. At the present stage we cannot discriminate each of the dissipative processes.

Finally, the important point of this work is that, whether related to elastic or inelastic deformations, thermal aspects of dynamic crack initiation must be considered as potent factors in the determination of the fracture toughness of the material at different loading rates.

5. Conclusions

- Transient crack-tip temperature changes can be recorded at the tip of dynamically loaded cracks using the embedded thermocouple technique.
- Mode I causes the material in the elastic zone to cool significantly prior to crack initiation. This result corroborates theoretical estimates and similar observations using a different technique.
- Mode II causes, as expected, the crack-tip material to heat up significantly.
- *Both* the thermoelastic and thermoplastic effects are relevant to dynamic crack initiation.

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