Transient Temperature Measurement Using Embedded Thermocouples

by D. Rittel

ABSTRACT-The response time of thermocouples is generally considered to be a limiting factor when transient temperature changes need to be assessed in solids. As an example, transient temperature changes which develop during dynamic straining of materials, adiabatic shear band formation, dynamic fracture and related fields are often investigated using sophisticated noncontact measurement techniques such as infrared detectors. In these phenomena, the time scale is of the order of the microsecond. In this paper, the authors revisit the application of thermocouples to such measurements using small embedded thermocouples (ETC). Experiments with dynamically loaded polymeric disks (characteristic strain rate of 10^3 s^{-1}) show that the thermocouples record transient temperatures with a short typical rise time of 10 μs as a result of the conversion of plastic deformation into heat. This observation is corroborated by the solution of the temperature distribution in a sphere subject to constant surface temperature which predicts the same fast reaction. Specifically, considering a sphere which is representative of the sensing bead, the average temperature is shown to rise in a few microseconds. These theoretical results can be used to deconvolve the experimental results with respect to a calculated impulse response of the sensor to recover the actual temperature variations. The results show that small thermocouples can be embedded to yield useful information about the transient temperature evolution in a solid. This technique is easy to use and provides an important complement to other noncontact techniques.

Introduction

The need for temperature measurement is often encountered in experimental mechanics. Considering specifically solid mechanics, the generation of heat in a plastically deforming solid has been investigated by Taylor and Quinney.[1] These authors showed that the major part of the plastic strain energy invested in deforming a metal is converted into heat. This effect can be evidenced, for example, by holding a tensile specimen of a ductile steel just after fracture and noting that it may be very hot. Another effect is the thermoelastic effect related to volume changes. Both effects have been thoroughly characterized for quasi-static deformations by Dillon[2] and Dillon and Tauchert.[3] In the recent years, the thermoelastic effect has been taken into account and visualized using infrared cameras .[4]

D. Rittel (SEM Member) is Senior Lecturer, Faculty of Mechanical Engineering, Technion, Israel Institute of Technology, 32000 Haifa, Israel.

Original manuscript submitted: August 21, 1997
Final manuscript received: February 9, 1998.

When the temperature changes are of *transient* nature as in impact, fracture mechanics and related fields, the temperature changes occur on very short time scales and measurements are quite delicate to perform. The techniques can broadly be classified in two classes: contact and noncontact probing techniques. The first technique can be characterized by thermocouples, and the second can be characterized by various kinds of thermal detectors.[5] Each technique has its distinct advantages, and the key characteristic of the employed technique is its response time or the characteristic time required to sense a transient temperature change. Recent work[6,7] has shown that infrared detectors are characterized by very short rise times (a few microseconds).

Earlier work has shown that thermocouples have longer rise times in general. The general belief is that the thinner the thermocouple, the shorter the response time as a result of the smaller effective diameter of the welded sensing bead. Numerous studies have addressed the response of thermocouples.[8] The typical rise time can be calculated and is found to be of the order of the millisecond and more for thermocouples which are brought into contact with the substrate for surface measurements. Further improvement has been achieved by developing special thin sensing junctions so that the effective response reaches several tens of microseconds.[9] These are special thermocouples aimed at surface measurements which cannot be manufactured easily in the laboratory and require a separate calibration.

As an example, it is interesting to compare measurements carried out in metals with surface-welded thermocouples[10] and infrared detectors.[7] Despite the fact that different fracture conditions (Mode I vs. Mode II running cracks) are investigated, the measured temperatures nevertheless vary by several orders of magnitude. The same difference can be found for polymers, between surface measurements[11] and infrared measurements.[12]

The last technique to be mentioned, which is addressed in this paper, is the embedded thermocouple technique. Here, a thermocouple is embedded in the conductive medium to be probed. This technique is not employed extensively; one example can be found in Chou *et al*.[13] These authors investigated the temperature developed during the deformation of various polymers at different rates of straining. They introduced the (relatively thick) thermocouple at the bottom of a hole, firmly pressing it for better interfacial thermal conductivity. Their results show a noticeable temperature rise with the straining carried out at low to medium strain rates (tensile machines). At the higher strain rates, these authors calculated the temperature rise but did not actually measure it, since there were some doubts concerning the response of

the thermocouple. In their experiments, dynamic loading was applied and measured using a Kolsky bar. The estimated temperature rise was of the order of 15°C for polymethylmethacrylate (PMMA).

Very recently, Trojanowski et al.[14] investigated the temperature rise due to high strain-rate impact on epoxy disks using infrared detectors. Here too, the dynamic loading was applied using a Kolsky bar. For this material, the temperature rise did not exceed 45°C at a true strain of 0.8 and a strain rate of the order of 2500 s^{-1}.

The embedded thermocouple technique (ETC) is especially appealing for investigations with polymers. Specifically, it is shown that the ETC is characterized by very short response times of the order of 10 μs. which makes it particularly suitable for impact mechanics studies.

The paper has four main parts. The first is a description of the experimental setup followed by a presentation and discussion of the results. The next section addresses theoretical aspects of the transient thermocouple response.

Experimental

A first series of experiments was carried out on 10 mm diameter, 5 mm thickness disks made of commercial polycarbonate (PC) and PMMA. A 4 mm long, 0.3 mm diameter hole was drilled at midthickness of the disk to allow embedding of the sensing tip of a T-type (copper constantan) thermocouple. The thermocouple wire was 127μm in diameter. The hole was carefully sealed with an acrylic liquid polymer (Technovit, Kulzer) whose thermal properties are assumed to be close to those of the investigated polymers. As the sealing was hermetically closed, optimal contact between the thermocouple and the investigated material was expected to be achieved. Eight such disks of each material were tested (Fig. 1).

An additional series of 10 specimens was prepared in a different fashion. Here, we used liquid polystyrene (PS) (Serifix, Struers) to cast 30 mm diameter disks into which thermocouples were introduced. This procedure was adopted to yield optimal contact between the material and the sensing bead. The thickness of the specimen and the exact location of the sensing tip were variable as a result of the manufacturing procedure.

The experiment consisted of sandwiching the disk between two instrumented bars (Kolsky bars) to record the applied stress and temperature pulses, as shown in Fig. 1. The first (incident) bar was used to record the incident and reflected stress pulses for timing purposes. Consequently, we did not use the signals from the second (transmitter) bar, since we did not intend to assess the stresses or strains in the specimen. The characteristic impact velocity was around 30 m/s. The strain gage (incident bar) and thermocouple signals were recorded simultaneously on a Nicollet 490 digital (12-bit) oscilloscope. Both signals were fed directly and differentially into the scope.

While the exact strain rates were not determined in each test, a representative figure would be $\dot{s} = 3.0 \times 10^3 s^{-1}$ based on the pulse duration and a representative strain of 0.2.

Result

Figure 2 shows typical results for the above-mentioned experiments. These are "raw" signals which are not synchronized in the sense that the stress pulse is measured ahead of the specimen. In our setup, the incident stress waves reach the specimen typically 72 μs after being recorded at the strain gage on the incident bar. The signal reflected at the specimen-bar interface is detected after the 144 μs necessary for the strain gage interface round-trip. It should be noted that as long as the specimen remains sandwiched between the bars, it is repeatedly hammered by the waves propagating back and forth in the incident bar.

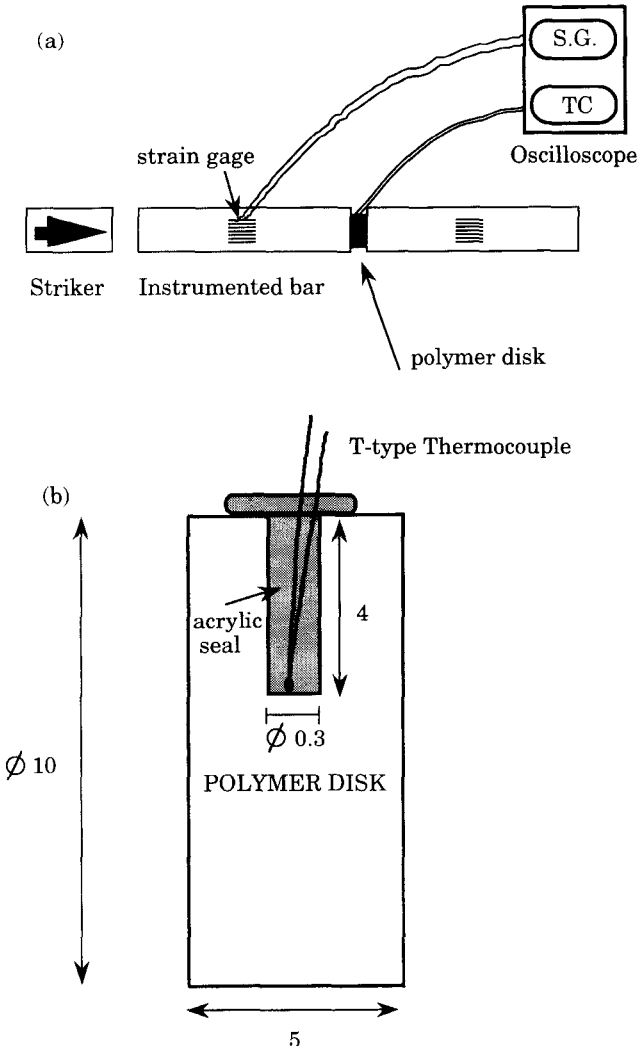

Fig. 1-Experimental setup. (a) The polymer disk specimen is sandwiched between the instrumented Kolsky bars. The incident strain gage and thermocouple signals are fed into the oscilloscope. (b) The polymer disk with the embedded thermocouple (all dimensions in mm)

Until impact, the thermal signal remains constant, after which it starts to rise. At a later time, the signal oscillates violently, most likely as a result of thermocouple damage due to specimen failure. In Figs. 3-5, we present results for each type of experiment after having shifted the thermal signal by the above-mentioned delay to obtain a common time origin based on the strain gage reading.

For the PC specimens (Fig. 3), the temperature rises stepwise twice until specimen failure. The first temperature rise occurs past a certain delay after initial impact (typically 10-20 μs). As the stress wave hits the specimen again, a coincident second temperature rise is distinctly observed during

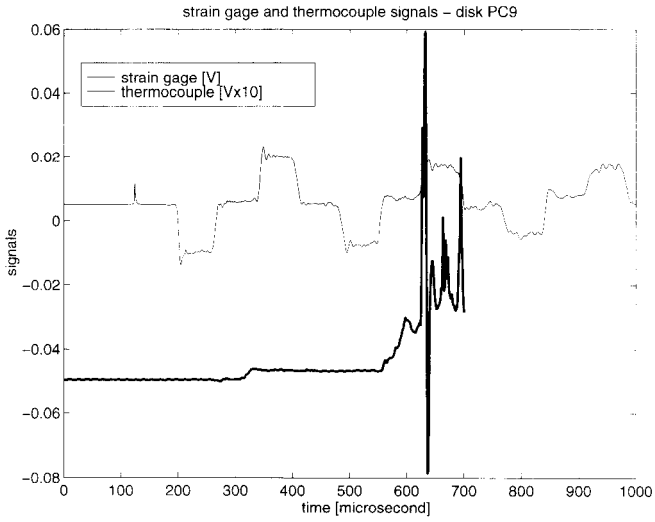

Fig. 2-Characteristic unsynchronized signals recorded in an experiment. The stress wave and the thermal signals are measured at different locations. Note the waves traveling back and forth in the bar. The thermal signal increases stepwise and ultimately starts to oscillate violently at specimen failure

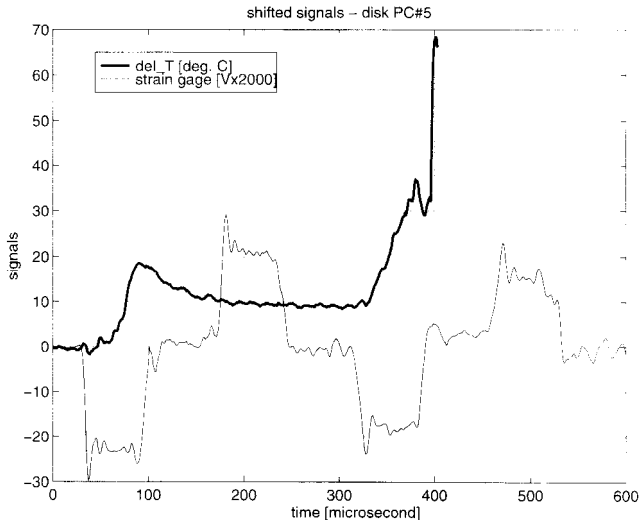

Fig. 3-Synchronized temperature rise and strain gage signals for a polycarbonate (PC) disk. Note the small time lag of the thermal signal with regard to the strain gage reading. The second impact causes the second temperature rise followed by fracture

which the specimen generally fails. A smaller delay between the stress and the thermal signal is observed. The typical rise times are very small (of the order of 10 μs). The specimen is recovered as a flattened disk whose elevated temperature is felt easily. The typical temperature rise lies in the range of 10°C to 20°C.

For the other investigated materials (PMMA and PS), the thermal signals rise very shortly after impact. They last for a short period until specimen failure. In all cases, the specimen shatters into pieces, one of which may still contain the thermocouple. Here too, the typical rise times are very small (of the order of 10 us).

Figure 4 shows two types of behaviors for the same material. In the first case [Fig. 4(a)], the specimen shatters a

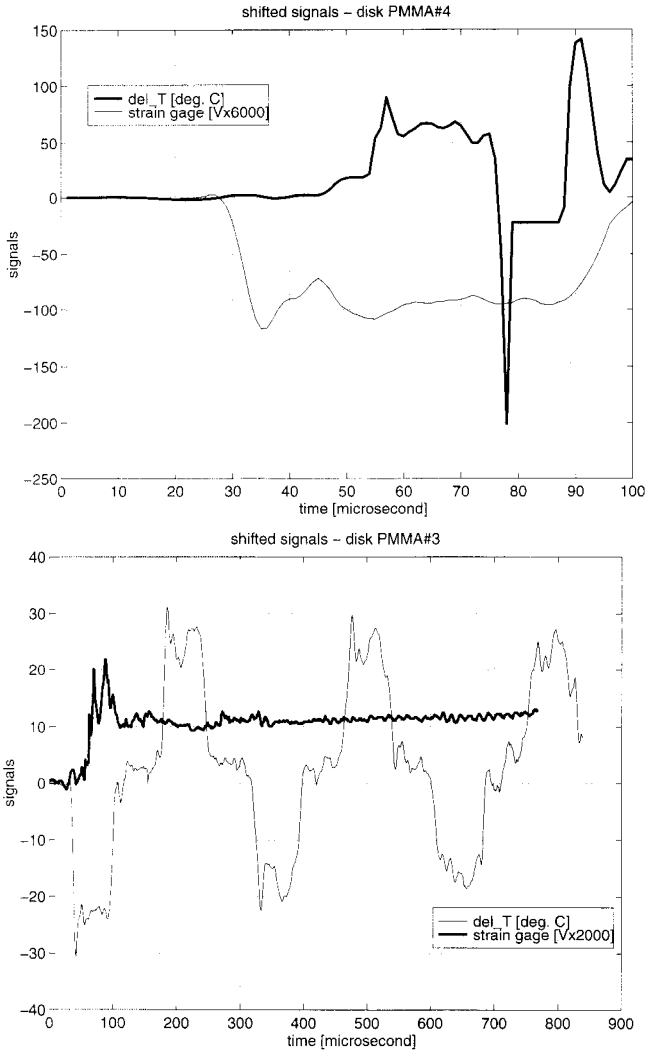

Fig. 4-Synchronized temperature rise and strain gage signals for polymethylmethacrylate (PMMA) disks. (a) The specimen fails very soon after impact. The recording is short. Note the rapid rise of the thermal signal. (b) As previously, but the thermocouple remains trapped and intact in a fragment. As such, the recording goes on over a longer duration with regard to the case shown in (a)

very short time after impact, past the initial lag of 20 μs. In the second case [Fig. 4(b)], the specimen failed past the first impact, but the thermocouple remained most likely intact in a fragment. As a result, the temperature increases very slowly past impact, and the subsequent impacts are not felt. The same qualitative behavior is observed for the PS specimens (Fig. 5). The specimens sustain little plastic deformation and shatter shortly after the first impact. In these experiments, the temperature rise varies from an average of 60°C [Fig. 4(a)] to 10°C-20°C [Figs. 4(b) and 5].

A common point to all the experiments is that the thermal signal is quiet until the wave has actually reached and interacted with the specimen. This indicates that the thermocouple does not pick stray signals from the surrounding instrumentation. Furthermore, regardless of the investigated material or specimen, the temperature rises in a short time, typically of the order of a few microseconds.

The thermal signals are different between PC and the other two polymers because they are recorded over a longer dura-

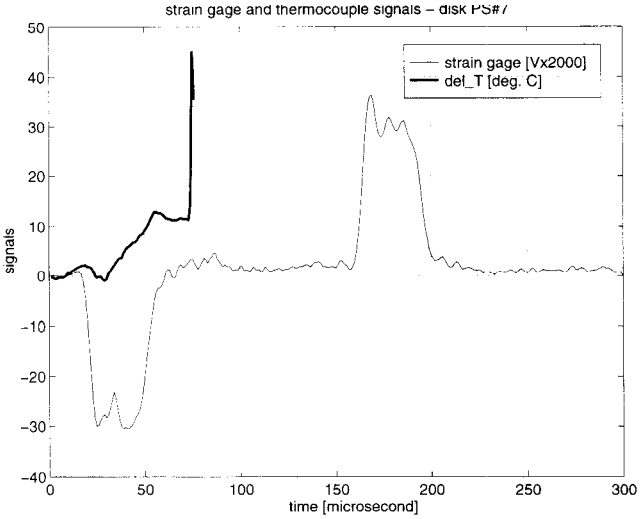

Fig. 5-Synchronized temperature rise and strain gage signals for a polystyrene (PS) disk. The behavior is quite similar to that of the PMMA disk shown in Fig. 4(a). Here, the specimen was prepared by casting the liquid polymer around the thermocouple

tion of time. Of the three materials, PC is more ductile, and thus is capable of sustaining noticeable inelastic deformation, even at high strain rates characteristic of these experiments. The other two brittle materials sustain little inelastic deformation and shatter thereafter. The thermal signal is thus shorter and of a different nature.

Two kinds of specimens are tested: those into which the thermocouple was embedded after machining the specimen and those into which the thermocouple was introduced prior to curing. Despite this difference, all specimens exhibit the same thermal response. This indicates good thermal contact in all cases.

The temperature rise is caused by two factors: plastic deformation and fracture. As also noted by Trojanowski *et al.*,[14] it is difficult to separate these effects. A more exact assessment of the temperature rise requires a constitutive law for the investigated material and an accurate knowledge of the (strain dependent) fraction of the strain energy which is converted into heat.

Three different setups were used to measure transient temperature changes, including embedded coarse,[13] fine thermocouples (present work) and infrared detection.[14] At this stage, we observe that the order of magnitude of the temperature increase that we measured is very similar to those previously reported. Further assessment of the accuracy of the temperature determination will require additional experimental work.

A strict definition of the rise time of the thermocouple requires the possibility of applying a controlled heat source. While this is done customarily with bare thermocouples by, for example, plunging them into a fluid, here the heat source for calibration should be internal. Such source cannot be generated easily, other than by a chemical reaction or as in the present case through the conversion of plastic deformation energy into heat. At this point it must be emphasized that these experiments were carried out to assess the applicability of the technique. A detailed study of polymer response per se is beyond the scope of the present paper (see Chou *et al.*[13]).

We observed that the initial temperature increase lags behind the applied strain, and that this is mostly evident in the first impact. The reasons for the lag can be attributed to two factors: the first would be the inherent response of the sensor, and the second would be related to the kinetics of yielding of the polymers. We suggest that the second factor should be dominant, since the lag is essentially observed at the first impact. This corresponds also to the observations of Chou *et al.*[13] and of Trojanowski *et al.*[14] that the heat output is smaller at low strains.

The experiments reported here show that the embedded thermocouple has a very short response time of the order of 10 μs. As such, this technique is suitable for transient temperature measurements.

Transient Response of the Embedded Thermocouple

Additional insight into the transient response of such a thermocouple is gained by considering the sensing bead as a sphere of radius *a* to which constant surface temperature To is prescribed (unit step). The average temperature of the sphere is given by[15]

$$T_{\mathrm{av}}(t) = T_0 - \frac{6T_0}{\Pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e - \frac{\kappa n^2\Pi^2 t}{a^2}. \qquad (1)$$

Figure 6(a) represents the response of a 130-μm radius sphere with a thermal conductivity is of 10^{-5}m^2/s. From this figure, it can be seen that a significant (average) response can be obtained in very short times (of the order of 15 μ).

For the sake of comparison, we have plotted in Fig. 6(b) the experimentally recorded response of an identical thermocouple (T type, 130-μm radius of sensing bead) dipped into boiling water. In this convection case, the thermocouple reacts with a much slower transient response (of the order of several milliseconds).

For the embedded sphere, the exact temperature distribution *T(r, t)* is given by

$$T(r,t) = T_0 + \frac{2aT_0}{\Pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\frac{n\Pi r}{a}e - \frac{\kappa n^2\Pi^2 t}{a^2}. \quad (2)$$

Equation (2) can be differentiated with respect to time to describe the impulse response of the thermocouple. This response can subsequently be used to deconvolve the measured signal in order to extract the actual temperature signal.

With this approach, a physical choice must be made as to the effective depth reff at which this response is to be calculated. In Fig. 7, we have plotted the unit impulse response for the above-mentioned thermocouple in which the effective depth was chosen to be 10 percent of the radius beneath the surface. This choice is of course arbitrary because we have no a priori knowledge of an effective depth required to generate the thermoelectric effect.

This response can be used indicatively to deconvolve the experimentally recorded signals from the thermocouple. Figure 8 shows the measured and deconvolved signals for a PC specimen. While the deconvolution process may contribute its own noise to the measurement, Fig. 8 shows that the actual (deconvolved) signal occurs a bit earlier, faster with slightly higher values than the measured signal.

As mentioned previously, the use of eq (2) requires one to make a choice concerning the relevant depth at which the thermoelectric effect is generated. Here it must be noted that

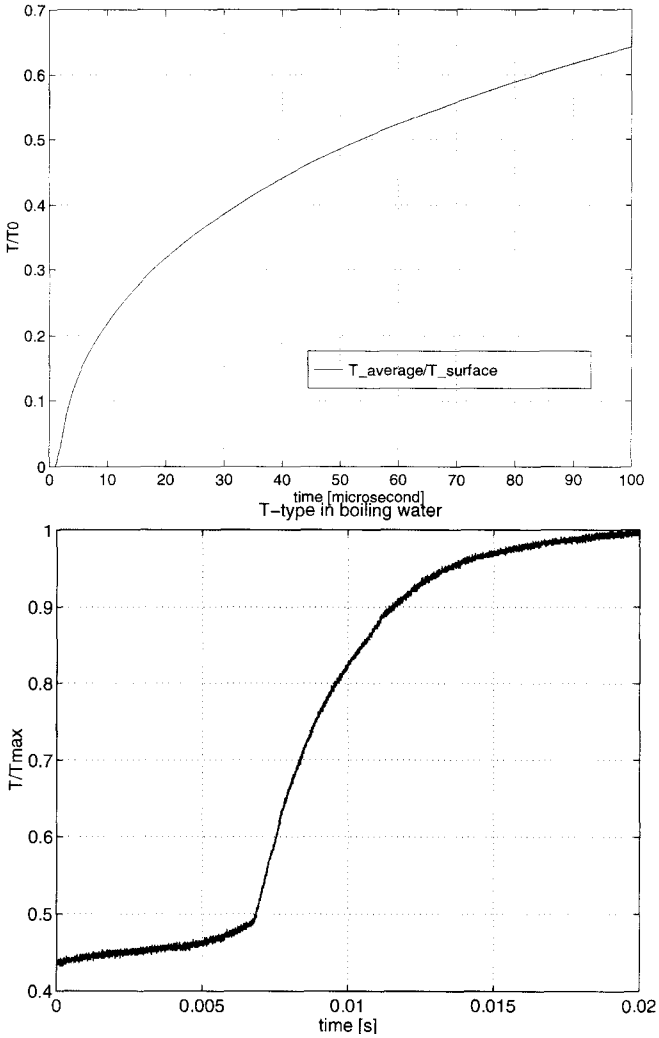

Fig. 6-(a) Calculated average temperature [eq (1)] in a 130 μm radius sphere representative of the thermocouple sensing tip. Prescribed unit step surface temperature T0. (b) Experimentally determined response of the same thermocouple quickly dipped into boiling water

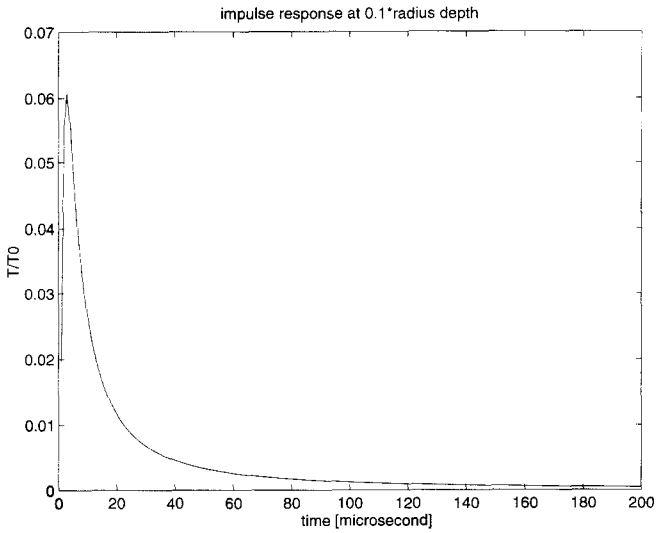

Fig. 7-Calculated impulse response [time derivative of eq (2)] for a prescribed unit step surface temperature. The temperature is calculated at a depth of 0.1 times the radius (130 μm) of the sphere

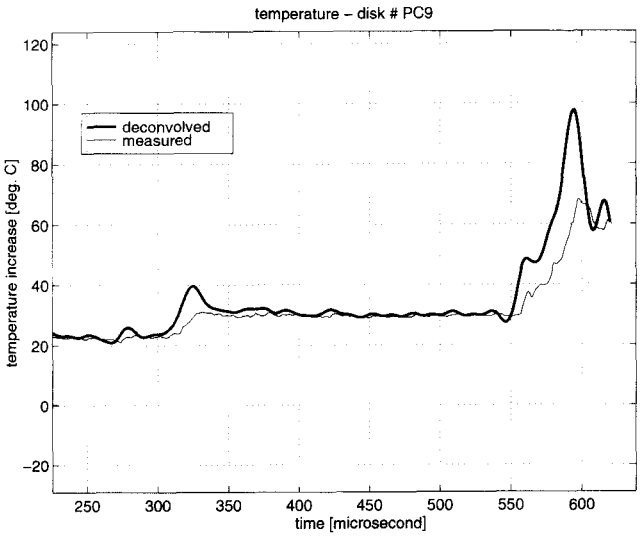

Fig. **8---Measured and deconvolved thermal signals. The deconvolution is performed with regard to the impulse response shown in Fig. 7. Note that the deconvolved signal rises faster and earlier, and reaches higher values**

the milder the selected impulse response (e.g., by choosing a greater effective depth), the greater the difference between the deconvolved and measured results. The tendency will be for increasingly steeper and larger deconvolved signals.

As an alternative, eq (1) may be used as a basis if the sensing tip is very thin so that temperature gradients are not too strong in the bead. In this case, the average value is closer to the actual temperatures in the bead. With this alternative, the concept of effective depth is no longer needed.

Regardless of the selected equation, the embedded sphere is representative of our thermocouple and as such it explains the very fast observed response. It should be noted that Chou *et al.*[13] treated the response of the embedded thermocouple using convection heat transfer principles, thus indicating slower response times. Our results indeed show that, with intimate contact between the bead and the material, the problem can be treated as a conduction problem to explain the high response times observed.

Chou's results suggested that embedded thermocouples are suitable for work at high rates of deformation. Our results certainly agree and, moreover, extend the range of application of the technique. Therefore, the ETC is thus shown to be quite attractive for measuring transient temperatures in solid mechanics experiments. As such, it is a valuable addition to noncontact measurement techniques which require more sophisticated equipment. At present it is applied to the study of polymeric response, but it could be extended to other materials if sealant with adequate thermal properties is used.

Summary and Conclusions

1. The embedded thermocouple (ETC) technique has been evaluated as a tool to measure transient temperature changes in solids.

2. Experiments have been carried out on three types of polymers subjected to high velocity impact (typically 30 m/s).

3. The temperature recordings show that the embedded thermocouple measures the transient temperatures which are generated as a result of the conversion of strain energy into heat. The response time of the thermocouple is typically of the order of 10 us.
4. The response of the thermocouple can be predicted by examining the solution of the transient heat equation for a sphere subjected to constant surface temperature. The expressions for the average temperature and the temperature distribution both show a very short rise time similar to that measured in our experiments.
5. The predicted impulse response can be used to deconvolve experimental recordings in order to improve experimental accuracy.
6. The present results show that the technique can be employed to investigate transient problems in polymers. It has the potential of being applied to other materials.
7. As such, the ETC is a valuable simple addition to existing but sophisticated noncontact measurement techniques. This is also a valuable tool for cases in which the investigated object is hidden from a potential detector.

Acknowledgments

This research is supported by the Israel Science Foundation under Grant 030-039 and by the Technion VP Fund for the Promotion of Research. Dr. R. Levin's assistance is gratefully acknowledged.

References

1. Taylor, G.I. and Quinney, H., "The Latent Energy Remaining in a Metal After Cold Working," Proc. Roy. Soc. A, 143, 307-326 (1934).

2. Dillon, 0. W, Jr., "Coupled Thermoplasticity" J. Mech. Phys. Solids, 11, 21-33 (1963).

3. Dillon, 0. W, Jr. and Tauchert, T.R., "The Experimental Technique for Observing the Temperatures Due to the Coupled Thermoelastic Effects," Int. J. Solids Struct., 2, 385-391 (1966).

4. Rauch, B.J. and Rowlands, R.E., "Thermoelastic Stress Analysis," Handbook on Experimental Mechanics, 2nd ed., ed. A.S. Kobayashi, SEM VCH, New York (1993).

5. Zehnder AT and Rosakis, A.J., "On the Temperature Distribution at the Vicinity of Dynamically Propagating Cracks in 4340 Steel," J. Mech. Phys. Solids, 39 (3), 385-415 (1991).

6. Marchand, A. and Duffy, J., "An Experimental Study of the Formation Process of Adiabatic Shear Bands in a Structural Steel," J. Mech. Phys. Solids, 36 (3), 251-283 (1988).

7. Zhou, M., Rosakis, A.J., and Ravichandran, G., "Dynamically Propagating Shear Bands in Impact-loaded Prenotched Plates. (-Experimental Investigations of Temperature Signatures and Propagation Speed," J. Mech. Phys. Solids, 44 (6), 981-1006 (1996).

8. Wally, K., "The Transient Response of Beaded Thermocouples Mounted on the Surface of a Solid," ISA Transactions, 17 (1), 65-70 (1978).

9. Bendersky, D., "A Special Thermocouple for Measuring Transient Temperatures," Mech. Eng., 117-121 (Feb. 1953).

10. Shockey, D.A., Kalthoff, J.F., Klemm, W., and Winkler S., "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," EXPERIMENTAL MECHANICS, *23,140-145 (1983).*

11. Doll, W., "Application of an Energy Balance and an Energy Method to Dynamic Crack Propagation," Int. J. Fract., 12 (4), 595-605 (1976).

12. Fuller, K.N.G., Fox, PG., and Field, JE., "The Temperature Rise at the Tip of a Fast-moving Crack in Glassy Polymers," Proc. Roy. Soc. A, 341, 537-557 (1975).

13. Chou, S.C., Robertson, K.D., and Rainey, JH., "The Effect of Strain Rate and Heat Developed During Deformation on the Stress.strain Curve of Plastics," EXPERIMENTAL MECHANICS, *13, 422432(1973).*

14. Trojanowski, A., Ruiz, C., and Harding, J., "Thermomechanical Properties of Polymers at High Rates of Strain," J Physique, colloque C3, 447-452 (1997).

15. Carslaw, H.S. and Jaeger, J. C., Conduction of Heat in Solids, Oxford University Press, Oxford (1959).