

# Measurement of instantaneous temperature in shock-loaded nonmetallic solids

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(Received 11 November 1988; accepted for publication 7 November 1989)

The feasibility of direct measurement of temperature in shock-loaded, nonmetallic solids within microseconds using a foil thermocouple of 200 Å thickness has been studied over a range of pressure from 0.5 to 4 GPa. The foil thermocouple and thermopile (200 Å thickness) were designed and used to measure the temperature rise in shock-compressed polymethylmethacrylate (PMMA). The method used to manufacture the gauges is spelled out in detail in this paper. The results agree with calculated PMMA temperatures when the shock pressure is below 2.2 GPa. Above this pressure the measured temperature rise is far higher than the calculated values. This result appears to be very similar to that obtained earlier by Bloomquist and Sheffield.

## I. INTRODUCTION

For decades there has been a recognized need to measure temperature directly in shock-compressed solids in order to determine experimentally a complete equation of state,<sup>1</sup> or to study chemical activity under shock-loading conditions,<sup>2</sup> but this is very difficult in solids. Some successes in inferring the temperature of shock-compressed solids based on measurements of infrared radiation have been reported.<sup>3</sup> This method has been limited to cases where transparent materials are shocked to high temperatures; successful methods for measurements in opaque solids have not yet been found.<sup>4,5</sup> Using thermally sensitive films<sup>6</sup> to measure temperature was found to be only a qualitative method. A special thermocouple has been designed in order to reduce thermal inertia of sensor.<sup>7</sup> This method has been used to measure the temperature in explosive welding.<sup>8</sup> This method has not been widely applied, because several problems still exist. The measurement of temperature in shock-compressed solids using various foil materials and configurations has been widely studied in recent years. For example, a 5-μm-thick (or more) foil thermocouple,<sup>9-13</sup> a 5-μm-thick copper foil,<sup>14,15</sup> a 1-μm-thick copper thermistor foil,<sup>16</sup> and a 5-μm-thick nickel gauge<sup>17</sup> were studied. Based on conventional models of heat conduction, it is not possible to get thermal equilibrium between the foil and host material (with 1- or 5-μm-thick foil) within microseconds. Bloomquist and Sheffield<sup>11</sup> proposed that the thermal conduction of PMMA in intense dynamic loading may be orders of magnitude faster than in normal loading (when the foil probe is perpendicular to the plane of the shock), but this proposal has neither been validated nor eliminated. Certainly this is a very interesting problem. None of the above methods is adequate to measure temperature within microseconds in shock-loaded solids.

## II. THEORETICAL ANALYSIS

In order to measure temperature in shock-loaded nonmetallic solids with a foil thermocouple, there are several problems which must be solved. First of all, the thermal inertia of the foil must be small enough that the real temperature of the host material can be measured in microseconds. Sec-

ond, the effect of pressure on thermopower  $S$  must be quantitatively determined, because the thermopower is a function of temperature and pressure. Hydrostatic compression experiments by Bridgman<sup>18</sup> and Bundy<sup>19</sup> indicate that  $S(T, P)$  can be written in the form

$$S(T, P) = S(T, 0) + \eta P, \quad (1)$$

where  $\eta$  is the coefficient of pressure, and  $T$  and  $P$  are temperature and pressure, respectively. If the thermocouple was reasonably selected, the effect of pressure on thermopower would be below several percent. If the experimental factors, such as dimensions of both target and projectile, impact velocity, etc., are all determined, shock pressure and its duration in the target can then be determined. The loading duration was in the range of 1.2–4 μs in our experiments. It is very important to carefully select the thickness of the foil, because thermal equilibrium between the foil and the host material is a necessary condition to be able to measure the actual temperature of the host.

It was assumed that the host materials and the foil thermocouple material are all uniform and isotropic and that their thermal properties do not change as the temperature changes. All planes perpendicular to the  $X$  axis were assumed to be isothermic planes, except the lateral free surface. Thermal loss in the direction perpendicular to the  $X$  axis was assumed to be negligible because loading time was very short. The heat flux through the edges of the foil junction was assumed to be negligible in comparison with the heat flux through the flat surfaces. Both chromel and alumel are alloys of nickel so the difference of their thermal properties was assumed negligible in comparison with the properties of the host material, making it unnecessary to treat the foil as a two part system. With these assumptions the problem can be modeled as a one-dimensional heat-conduction problem.<sup>20,21</sup> The characteristic time  $T_c$  in which a temperature change occurs is  $(C_p \rho L^2)/\lambda$ , where  $C_p$ ,  $\rho$ , and  $\lambda$  are specific heat, density, and heat-conduction coefficients, respectively, and  $L$  is the characteristic dimension. Taking polymethylmethacrylate (PMMA) for example, if the foil thermocouple is affected by the temperature 2 mm away from the foil thermocouple, the characteristic time is about

30 s. In shock experiments the loading time is several micro-seconds, so the effective distances must be very small. A one-dimensional heat-conduction model with infinite boundaries is used. We are interested in determining what the thickness of the foil thermocouple can be in order to measure the actual temperature of the host material during the time available in a shock experiment. Initial conditions for the problem are that the temperature of the host material-foil thermocouple system will be assumed to jump instantaneously from ambient values to their shock-compressed values,  $T_1$  (host) and  $T_2$  (foil), at time zero.

Since only the temperature rise  $T(x,t)$  in the foil is of interest, the temperature of the foil just after shock passage will be chosen as the zero of temperature axis, and the temperature difference between the foil and the host material at the time will be represented by  $T_0 = T_1 - T_2$ . [Notice: The real temperature of the foil is  $T_2 + T(x,t)$ .] The one-dimensional temperature diffusion equation with initial conditions [ $T(x,0) = T_0$ ,  $|x| > a$ ;  $T(x,0) = 0$ ,  $-a < x < a$ ] was used in our calculation, where  $a$  is half the foil thickness. Since the foil is put on with vapor deposition, there is intimate contact between the foil and the host material. Therefore we assume that the temperature and the heat flux are continuous at the interface  $x = \pm a$  between the host and foil. The solution for the problem was accomplished using Green's function and the "image" method. This process is similar to that used by Grover and Urtiew<sup>22</sup> and Bloomquist and Sheffield.<sup>11</sup> A solution with an infinite sum of error functions was obtained and an asymptotic series was adopted to calculate error function. The measured temperature of the host material, with respect to the foil thermocouple, can be expressed as a relative temperature rise,  $T(x,t)/T_0$  (%). {Although the ratio of the measured temperature to the real temperature of the host should be  $[T_2 + T(x,t)]/T_1$ , the ratio  $T(x,t)/T_0$  is more suitable to indicate the change in temperature of the foil as a function of time due to heat conduction.} If  $T(x,t)/T_0 = 0$ , the measured temperature is that of the shock-compressed foil itself. If  $T(x,t)/T_0 = 1$ , the measured temperature is actually that of the host.

The results of the calculation for several foil materials and thicknesses are given in Table I and Fig. 1. Material parameters used in the calculations are given in Table II.

As seen, it is not possible for the foil and the host material to come near thermal equilibrium with foil thicknesses of 1 or 5  $\mu\text{m}$  in the few microseconds time available. For exam-

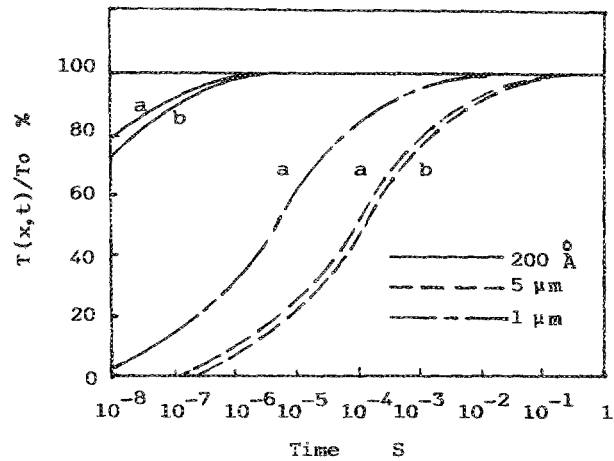


FIG. 1. Heat-conduction calculation results obtained from the solution of the diffusion equation for temperature vs time. The host material is PMMA. Foil thicknesses are shown as 200 Å, 5 and 1  $\mu\text{m}$ . (a) Copper foil; and (b) nickel foil (include foil thermocouple of chromel alumel).

ple, measured relative temperature rise  $T(x,t)/T_0$  with a chromel-alumel foil thermocouple ( $a = 2.5 \mu\text{m}$ ) in 1  $\mu\text{s}$  is only 6.7%. However,  $a = 100 \text{ Å}$ ,  $T(x,t)/T_0$  jumps to 96.5% during the same time. Therefore, an extremely thin foil thermocouple was designed for our experiments. Its thickness  $2a$  is about 200 Å and the calculations indicate the error of the temperature measured should be within a few percent of that of the host material.

### III. THE FOIL THERMOCOUPLE TECHNIQUE

The selection of a proper thermocouple should take account of the measurement range of the temperature and the effect of pressure on thermopower. The expected thermoelectric emf can be obtained from the following equation<sup>9</sup>:

$$\begin{aligned}\Phi_{b-a} &= \Phi_b - \Phi_a \\ &= - \int_{T_r}^{T_j} S_{a-b}(T',0) dT' \\ &\quad - \frac{1}{2} P(\eta_a - \eta_b)(T_j - T_r),\end{aligned}\quad (2)$$

where  $\Phi$  and  $T$  are electric potential and temperature, respectively, and  $S(T,P)$  is the thermopower of the thermocouple. The subscripts  $a$  and  $b$  refer to two materials comprising the thermocouple, i.e., chromel and alumel.  $T_j$  and  $T_r$  are the temperature at the measuring and reference junctions, respectively. The first term in Eq. (2) expresses the electric potential associated with the temperature difference at normal pressure. It can be related to the temperature at the point of interest with the aid of a standard thermocouple table. The second term represents the contribution of the

TABLE I. Results of calculations.

Foil thickness	Time	$T(x,t)/T_0$ (%)		
		PMMA-Ni <sup>a</sup>	Composite-Ni <sup>a</sup>	PMMA-Cu
$a = 100 \text{ Å}$	1 $\mu\text{s}$	96.5	98.6	...
	4 $\mu\text{s}$	98.2	99.3	...
$a = 2.5 \mu\text{m}$	1 $\mu\text{s}$	6.7	15.0	10.0
	4 $\mu\text{s}$	13.0	27.4	...
$a = 0.5 \mu\text{m}$	1 $\mu\text{s}$	...	...	31.8

<sup>a</sup> Chromel and alumel are represented with Ni.

TABLE II. Parameters of materials.

Materials	$\rho$ g/cm <sup>3</sup>	$C_p$ cal/g K	$\lambda$ cal/cm s K	$D = \lambda / \rho C_p$ cm <sup>2</sup> /K
PMMA	1.181	0.3511	0.00054	0.0013
Composite	1.8	0.25	0.003	0.00667
Ni	8.75	0.105	0.15	0.163
Cu	8.9	0.089	1.145	1.45

pressure to the thermoelectric emf. A series of pressure coefficients  $\eta$  for different thermocouples have been given by Bundy.<sup>19</sup> The pressure coefficient of chromel-alumel thermocouple is

$$\eta_{Cr} - \eta_{Al} = 0.12 \mu V \text{ GPa}^{-1} \text{ K}^{-1} \quad (3)$$

and is less than the other materials. This pressure correction corresponds to about a 0.89% decrease in the expected emf at 3 GPa for chromel-alumel. Because of this and also the fact that temperatures up to 1573 K can be measured with this type of thermocouple, chromel-alumel was used in these experiments.

In order to make a foil thermocouple with a thickness of 200 Å, a vacuum deposition technique was used. The actual method will be described later. Each pole of the thermocouple was deposited on the target separately. The design was such that the measuring junction was in the shock-compressed region of the target and the reference junction as shown in Fig. 2 was on the lateral surface on the target (which was always at 1 atm). In order to increase the signal-to-noise ratio and measuring accuracy, a thermopile (a series connection of eight thermocouples) was made by means of a special mask (see Fig. 2). Several experiments were done to confirm that this foil thermocouple design would reliably measure the temperature. First, it was confirmed that the chemical composition of chromel and alumel were the same before and after vacuum deposition. Second, it was determined that the emf was zero in the circuit if both poles of the thermocouple were made of the same material (chromel, alumel, or aluminum) when the specimen was shock loaded to a pressure of 4 GPa. These experiments also demonstrated that the electric disturbance was eliminated under our experimental condition. The shock demagnetization effect observed by Bloomquist, Duvall, and Dick<sup>9</sup> was not observed in our experiments. Third, in order to calibrate the measured emf versus temperature for the foil thermocouple under ambient pressure conditions, chromel and alumel were vacuum deposited separately on a thin, long sheet of alumina. The measuring junction was kept at a high temperature and the reference junction at ambient temperature.

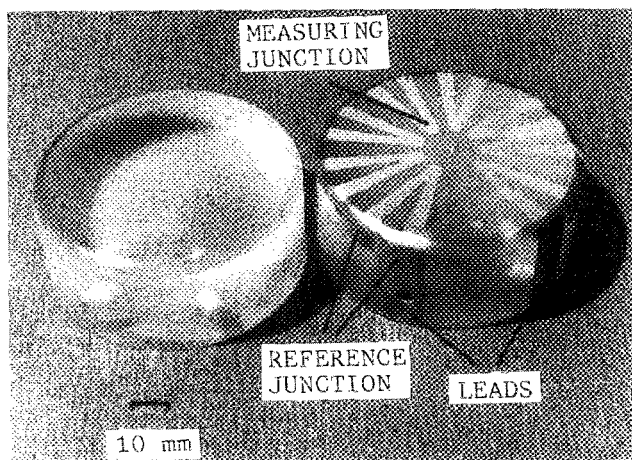


FIG. 2. Photograph of the target before and after depositing thermopile. Outside diameter is 70 mm.

The temperature of the reference junction was always monitored because of the possible problems with heat conduction in the alumina sheet. The calibration experiment was conducted in a vacuum to eliminate oxidation at high temperature. The thermopile thickness was measured by multiple-beam interferometry. The foil thermocouples (thermopile) were put on the target specimen using the following procedure. On the polished and cleaned surface of a PMMA specimen, the material making up the foil thermocouple was deposited by heating a tungsten wire on which the chromel (or alumel) was wound, in order to evaporate it. A polished and cleaned flat of PMMA was then glued to the prepared specimen. Care was taken to remove all of the bubbles from the glue layer between the flat and the specimen by vacuum outgassing. In order to reduce the thickness of the glue layer, the two parts were put together and then the assembly was loaded along the axis. Two types of glue were used in our experiments. One was chloroform which dissolves PMMA. Using it insures the foil thermocouple is embedded in PMMA, but skill is required because it solidifies so fast that removing all of the bubbles is difficult. The other glue was CX 212 epoxy and was supplied by the ChunSu Co. It is easy to control the solidifying time and remove all of the bubbles using fresh epoxy materials. Because the specific heat and shock impedance of epoxy are close to those of PMMA, epoxy glue was used in our experiments. After this assembly was completed, a flat of 2024 Al was epoxied to the front of the assembly, being careful to eliminate air bubbles at this interface also (see Fig. 3).

#### IV. EXPERIMENTAL SETUP

One-dimensional strain, shock-compression experiments were achieved using a light gas gun. Its caliber was 100 mm. The emf was measured using a TCJ-2000 transient converter and a Tektronix 7834 oscilloscope. Sampling time was 0.1  $\mu s$  per point. Voltage sensitivities of 50 and 100 mV were used, depending on the projectile velocity. The TCJ-2000 transient converter was dynamically calibrated. Resolution of the measured voltages was  $512 \pm 2$ , levels for the full-scale voltage resulting in a temperature resolution of about 2.5 K. All the possible electrical and magnetic disturbances were analyzed in advance and eliminated by the use of appropriate measures, for example, electric and magnetic shielding techniques.

A series of experiments was carried out using foil thermopile of 200 Å thickness as illustrated in Fig. 2. In fact, the thickness of a single pole of the thermocouple was 100 Å. (Below this thickness an instability of the thermoelectric property may occur.) The foil thermocouple junction was 200 Å thick, i.e., the thickness of each pole was 200 Å and they overlapped. With this configuration the shock wave propagated in a direction perpendicular to the foil thermopile junctions on the specimen.

The effect of lateral relief waves on measured temperature was considered when the experiment was designed. Eight measuring junctions were distributed in an annular array. The dimensions of the specimen were designed so the normal relief wave arrived at the measuring junction before the lateral relief wave. Reference junctions were located on

the lateral free surface to ensure they were always at one atmosphere pressure during the entire loading process. Small metallic pieces and screws were used to connect the lead wires to the thermopile leads. The other ends of the lead wires were connected to the TCJ-2000 transient converter.

The thermopile/PMMA specimen was epoxied into a target ring using epoxy, which did not cover the reference junctions. A 2024 Al impactor was glued on the front of a foam polystyrene projectile. Shock loading was achieved by projectile impact as indicated in Fig. 3. Projectile speed was measured by means of electric shorting pins. With the projectile speed known, impedance matching and the known Hugoniot of PMMA and 2024 Al were used to calculate the impact pressure and the subsequent pressure in the PMMA.

## V. RESULTS AND DISCUSSION

A typical measured voltage waveform obtained from the experiments is shown in Fig. 4. Measured temperature results of the six experiments on PMMA are plotted in Fig. 5, and information about each experiment is listed in Table III. The emfs and corresponding temperatures were taken from the peak value constant portion of each record. Temperatures were determined from a standard thermocouple table for a chromel-alumel thermocouple. The ambient temperature at the time of the experiment was taken as the temperature of the reference junction.

The pressure behind the shock in 2024 Al front plate was calculated for each shot using the Rankine-Hugoniot equations and the  $U_s - U_p$  relation ( $U_s = 5.328 + 1.338U_p$ ) for 2024 Al.<sup>23</sup> Particle velocity in the aluminum  $U_p$  is equal to one half the impactor (projectile) velocity because both the impactor and the front plate of the specimen were made of the same material. The shock pressure in

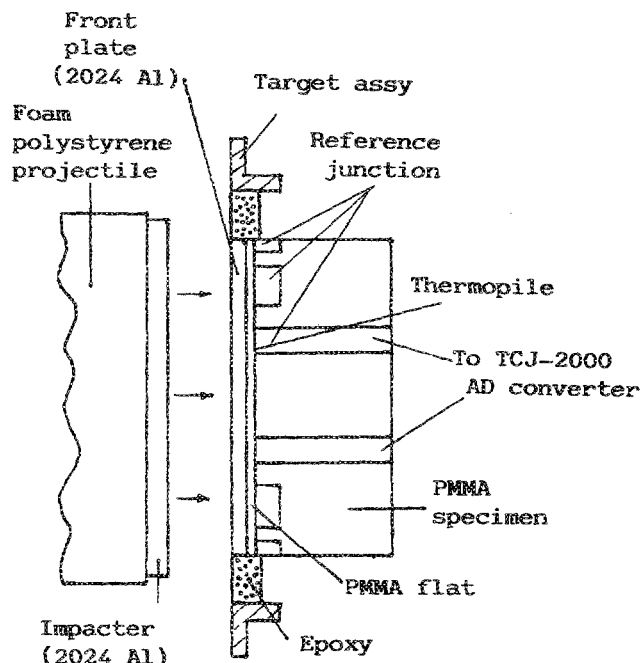


FIG. 3. Experimental configuration for the thermopile experiments. The thermopile was sandwiched between a PMMA flat and a PMMA specimen. They were stuck together with CX 212 epoxy or chloroform.

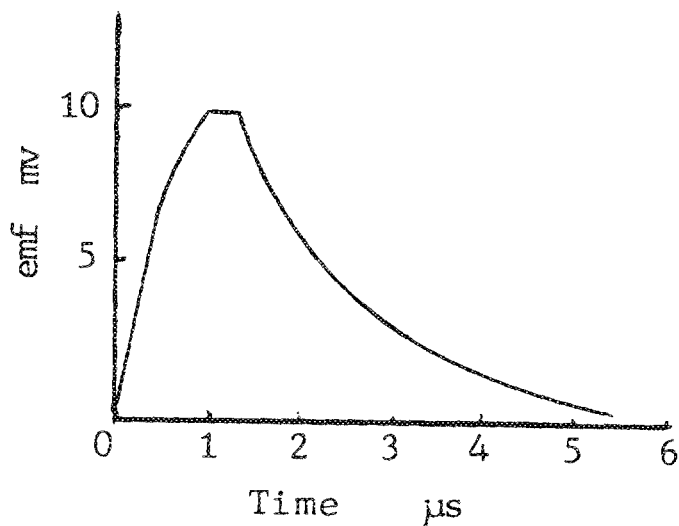


FIG. 4. Representative waveform of measured voltage for the shock-compressed PMMA target. Projectile velocity was 984 m/s, impactor thickness was 4 mm, and the thermopile (eight chromel-alumel thermocouples connected in series) thickness was 200 Å. From the record we see that the rise time was 0.9 μs and peak value duration was 0.3 μs. The peak voltage corresponds to a temperature rise of 244 K.

the PMMA was calculated using shock-impedance matching<sup>23</sup> using the known Hugoniot of PMMA. Two types of 2024 Al with different elastic strengths were used in our experiments. The effect of initial strength on impact pressure above 2 GPa was only about 2%–3%, depending on impactor velocity. Because of this, the effect of strength was ignored and it was still possible to estimate the pressure in the PMMA specimen. The results from the six experiments are shown in Fig. 5.

The emf history observed in these experiments consists of a smooth rise followed by a relatively short constant portion (peak value) (see Fig. 5). The length of the constant

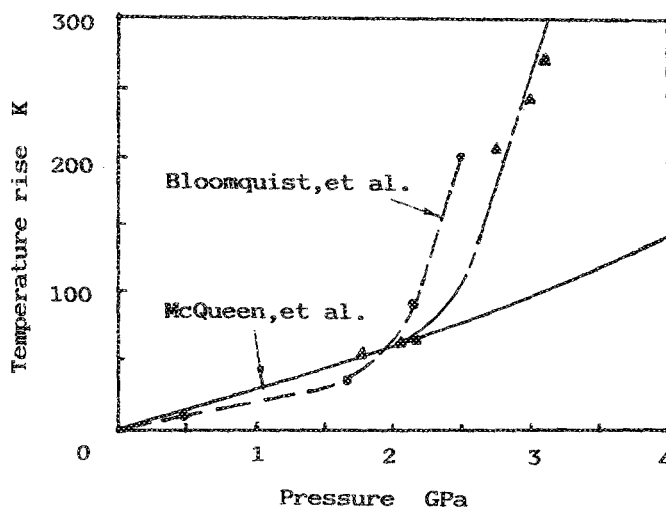


FIG. 5. Temperature rise as a function of pressure in the PMMA. The solid line represents previous calculations of the expected temperature rise based on shock wave data and zero pressure thermal constants by McQueen *et al.* (see Ref. 23). The circle-dots and associated dotted line represent the data of Bloomquist and Sheffield (see Ref. 11). The triangle-dots and dash line represent the present data.

TABLE III. Results of experiments.

Shot No.	Projectile velocity (km/s)	Impactor materials	Impactor thickness (mm)	Rise time ( $\mu$ s)	Peak value ( $\mu$ s)	Time before temperature decrease ( $\mu$ s)	Pressure <sup>a</sup> (GPa)	Measured emf (mV)	Indicated temperature rise (K)
8501	0.634	2024 Al <sup>b</sup>	4	0.9	0.4	1.3	1.80	2.3 <sup>c</sup>	57
8502	0.728	2024 Al <sup>b</sup>	4	1.0	0.4	1.4	2.08	2.7 <sup>d</sup>	66
8503	0.763	2024 Al <sup>b</sup>	12	1.5	0.7	2.2	2.13	2.8 <sup>c</sup>	69
8602	0.906	2024 Al <sup>c</sup>	12	1.6	0.6	2.2	2.70	8.5 <sup>c</sup>	209
8603	0.984	2024 Al <sup>c</sup>	4	0.9	0.3	1.2	2.97	9.9 <sup>c</sup>	244
8604	1.020	2024 Al <sup>c</sup>	12	1.7	0.7	2.4	3.08	11.0 <sup>c</sup>	271

<sup>a</sup> Pressure calculated from projectile velocity and Hugoniot relations:  $\rho_0 = 2.785 \text{ Mg/m}^3$ ;  $U_s = (5.328 + 1.338 U_p) \text{ km/s}$  for 2024 Al; and  $\rho_0 = 1.185 \text{ Mg/m}^3$ ,  $U_s = (2.572 + 1.536 U_p) \text{ km/s}$  for PMMA, as well as a shock-impedance match.

<sup>b</sup> Annealed state. Yield strength: 0.098 GPa.

<sup>c</sup> Natural aging after quenching. Yield strength: 0.295 GPa.

<sup>d</sup> Glue method: chloroform glue (chloroform: PMMA = 10:1).

<sup>e</sup> Glue method: CX 212 epoxy glue.

portion depends on the thickness of the impactor (see Table III). Thicker impactors give longer recording times before the rarefaction reduces the pressure. When the thickness of the impactor was 4 and 12 mm, the time the PMMA was at pressure was estimated to be about 1.3 and 4  $\mu$ s, respectively. At the beginning, the emf signal rises in a constant manner for about 0.3  $\mu$ s and then rises more gradually to the peak in about 0.6  $\mu$ s more (a total time of 0.9  $\mu$ s). This is postulated to be due to the temperature rise of the foil thermocouple itself, followed by a thermal equilibration time between the foil thermocouple and the host material. When the constant portion time of 0.3  $\mu$ s is added to the 0.9- $\mu$ s rise time, a total time of 1.2  $\mu$ s is obtained for the 4-mm-thick impactor. This is approximately equal to the time the PMMA is at pressure before the rarefaction comes in. When the 12-mm-thick impactor was used, below the 4- $\mu$ s time, the PMMA would have been at pressure in a one-dimensional experiment. Lateral release waves from the side of the specimen are a likely reason for the shorter recording times. The measured PMMA shock temperatures are plotted in Fig. 5. When the pressure is below 2.2 GPa, the observed temperatures lie near the calculated shock-compressed temperature rise of McQueen *et al.*<sup>23</sup> The marked deviation from expected behavior above 2.2 GPa implies an exothermic reaction which raises the temperature rapidly with pressure. This result is very similar to Bloomquist and Sheffield's results<sup>11</sup> in which thicker thermocouples were put in perpendicular to the shock front rather than parallel to the shock front as in the case in these experiments. Based on our heat-conduction calculations which indicate that a temperature of 97% of the actual temperature for the 200-Å-thick foil should be reached in 2  $\mu$ s, we feel we are measuring the actual temperature. It appears that Bloomquist and Sheffield were also measuring actual temperature even though the calculations indicate a relative temperature rise  $T(x,t)/T_0$  of only 7% for the 5- $\mu$ m-thick foil thermocouple in 2  $\mu$ s. Further investigation of the physical processes that made the thicker, perpendicular thermocouples record similar temperatures to the much thinner parallel thermocouples is necessary.

## VI. CONCLUSIONS

It has been theoretically and experimentally shown that measuring temperature in nonconducting solids in microseconds using a 200-Å-thick foil thermocouple is feasible. The method of depositing the special thin thermocouple is discussed and the technique for embedding them in the PMMA host material is discussed. The method has been successfully used to measure temperature rise in a shock-compressed PMMA target in our experiments. The results of measured temperature in shock-loaded PMMA agree with the calculations by McQueen *et al.* when the shock pressure is below 2.2 GPa. Above this pressure the measured temperature rises higher than the calculated values and similar to those obtained by Bloomquist and Sheffield.<sup>11</sup> A very interesting phenomenon is observed; thicker thermocouples embedded perpendicular to the shock front give results that are similar to those obtained from thin thermocouples put in parallel to the shock front. Further research is necessary to understand the physical reasons for this.

## ACKNOWLEDGMENTS

The authors wish to thank Shen Letian, Chen Shuxia, Yong Daguang, and Li Tianyou for their assistance in light gas gun experiments, Yong Yemin and Wu YuYan for attending early research, and Tan Qingming, Bai Yilong, and Zhao Shida for helpful discussions. This work was sponsored by the National Nature Science Foundation of China and Laboratory of Mechanics of Material Process.

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