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Temperature and emissivity measurement in dynamic experiments using an advanced infrared detector array technique

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Abstract. A new thermography method is presented to measure the absolute temperature history in dynamic experiments of very short duration. By superposing a known infrared radiation to the naturally emitted specimen radiation, both the specimen's emissivity and temperature are determined from the measurements of a custom-made detector array. As a result, this method can be used without prior knowledge of the specimen's optical properties. At the same time, the temperature measurement accuracy is substantially improved in comparison with other established methods. Since the specimen's emissivity is measured in addition to the temperature, this method may also be used to study the coupling between the evolution of the optical and mechanical properties under dynamic loading.

1. INTRODUCTION

Reliable measurements of the temperature history during high strain rate experiments provide an important basis for the development of thermo-mechanical constitutive models of engineering materials. Due to the short duration of high strain rate experiments, infrared techniques have been proposed in the literature to measure the temperature rise during Split Hopkinson Pressure Bar (SHPB) experiments [1–4]. Using a special optical system, the radiation coming from the specimen is recorded by an infrared detector. The relationship between the recorded signal and the specimen temperature is typically established through a calibration procedure on undeformed specimens.

As an alternative, the specimen's surface temperature may be calculated based on the detector signal using basic physical relationships. For this calculation, the specimen's surface emissivity needs to be known. The relationship between the surface emissivity and the temperature may be inferred from the above calibration procedure. However, the emissivity is also affected by surface roughness changes throughout a thermo-mechanical experiment. To take this effect into account, some authors performed the calibration procedure using both undeformed and deformed specimens [2, 5]. The results of Kappor and Nemat-Nasser [2] show that deformation-induced surface alterations may change the temperature estimates by as much as 15°C for a total temperature rise of about 90°C. In the present paper, we propose a new experimental method that provides both real-time temperature and surface emissivity measurements throughout high strain rate experiments.

2. TEMPERATURE MEASUREMENT TECHNIQUE

2.1 Theoretical background

We briefly outline the theoretical basis of the proposed infrared temperature measurement technique. The reader is referred to [6] for further details. The main feature of the technique is the simultaneous determination of the surface temperature and surface emissivity. This is achieved

through two simultaneous infrared radiation measurements: we measure the radiation coming from the specimen surface with and without the addition of the reflection of the radiation emitted from a well-known source. In the following, we outline the mathematical description of this experiment which yields a system of equations that can be used to identify the temperature and surface emissivity of the specimen based on the radiation measurements.

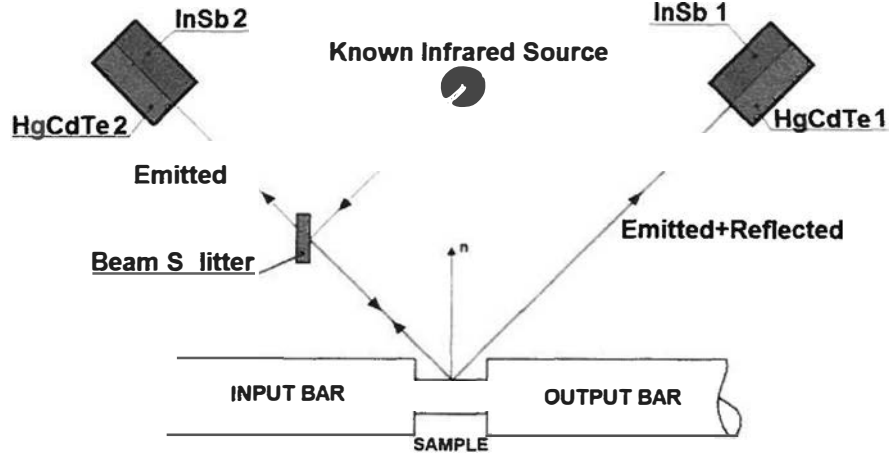


Figure 1. Schematic of experimental set-up.

The optical system is built such that the output signal S of an infrared detector is proportional to the energy (rate) of the electromagnetic waves radiated by the specimen. This proportionality factor a depends on the wave length λ of the radiation, $a = a(\lambda)$; it is a function of the optical system, notably the sensitivity of the detector, the transmission coefficients of the mirrors and the solid angles of the system. Its dependency can be determined prior to a dynamic experiment as it does not depend on the specimen properties. For a specific wave length, the radiation coming from a specimen of temperature θ_S corresponds to the sum of the emitted and reflected radiation,

$$S/a = eL^0(\theta_S) + rL^0(\theta_A). \quad (1)$$

$e = e(\lambda, \theta_S, \epsilon)$ and $r = r(\lambda, \theta_S, \epsilon)$ denote the wave length and temperature dependent surface emissivity and surface reflection factors, respectively. Furthermore, e and r depend on the deformation ϵ of the specimen. According to the definition of the emissivity of a material, the wave length dependent function $L^0(\theta)$ is given by Planck's radiation law for a black body

$$L^0(\lambda, \theta) = \frac{2hc^2\lambda^{-5}}{hc} \quad (2)$$

$$e^{k\lambda\theta} - 1$$

with Planck's constant h , Boltzmann's constant k and the speed of light c . The second term of the sum in (1) accounts for the reflection of the radiation coming from the environment of known temperature θ_A . If the specimen is opaque for radiation of wave length λ , we have the relationship $r = 1 - e$ and Eq. 1 may be rewritten as

$$S/a = eL^0(\theta_S) + (1 - e)L^0(\theta_A). \quad (3)$$

As mentioned above, measurements are also performed when the radiation from an additional source of temperature θ_E is reflected at the specimen surface. In this case, the signal ΔS is superposed to the measurement S ,

$$\Delta S/a = A(1 - e)L^0(\theta_E). \quad (4)$$

Here, A represents the fraction of the reflection lobe corresponding to the solid angle used for the measurement. A series of experiments has shown that A is independent of the wavelength, but dependent on the specimen surface roughness. It is reemphasized that all other variables used in Eqs. 3 and 4 depend on the wave length.

If the experiments are performed for two distinct wave lengths λ_1 and λ_2 , we have 4 distinct measurements: $S_1 = S(\lambda_1, \theta_S)$, $S_2 = S(\lambda_2, \theta_S)$, $\Delta S_1 = \Delta S(\lambda_1, \theta_S)$ and $\Delta S_2 = \Delta S(\lambda_2, \theta_S)$. Denoting the known calibration factors by $a_1 = a(\lambda_1)$ and $a_2 = a(\lambda_2)$, we may determine the unknown specimen temperature θ_S and the three unknown coefficients A , $e_1 = e_1(\lambda_1, \theta_S, \epsilon)$ and $e_2 = e_2(\lambda_2, \theta_S, \epsilon)$ for a given strain ϵ from the following non-linear system of equations:

$$\begin{aligned}
S_1/a_1 &= e_1 L^0(\lambda_1, \theta_S) + (1 - e_1) L^0(\lambda_1, \theta_A) \\
S_2/a_2 &= e_2 L^0(\lambda_2, \theta_S) + (1 - e_2) L^0(\lambda_2, \theta_A) \\
\Delta S_1/a_1 &= A(1 - e_1) L^0(\lambda_1, \theta_E) \\
\Delta S_2/a_2 &= A(1 - e_2) L^0(\lambda_2, \theta_E)
\end{aligned} \tag{5}$$

2.2 Experimental set-up

Figures 1 and 2 show a schematic and photograph of the experimental set-up, respectively. Two 2-color infrared detector units are used to perform four simultaneous measurements. The detectors are cooled with liquid nitrogen to maintain an operating temperature of 77 K. Each detector unit contains an InSb and an HgCdTe detector. The response time of the detectors is of the order of a few nanoseconds and thus much smaller than the characteristic time step of our measurements. DC amplifiers are used with a passing band of up to 1 MHz.

The view angles of the two 2-color detectors are symmetric with respect to the normal n at the surface of the sample. Thus, the radiation detected by each detector unit is modulated by the same spectral emissivity. At the same time, it is assumed that there is no retro-reflection [6]. The recording of purely emitted radiation (without any reflected radiation added) requires a view angle that is exactly opposite to the lighting angle of the reflected radiation. Here, we employed a special optical system that is composed of a set of flat and parabolic off-axis gold treated mirrors. Note that the gold surface treatment of the mirror is necessary to ensure a very good reflection over the spectral ranges used for the detection (about 98% in our case).

3. RESULTS AND DISCUSSION

Two SHPB tests on two polycarbonate samples are performed. The SHPB system comprises 12 mm diameter steel bars and a corresponding 0.4 m long striker bar. Using a striker speed of about 26 m/s, a strain rate of about 2400 s^{-1} is achieved. The two samples have the same dimensions and mechanical properties, but we intentionally applied a different surface finish during machining. After verifying the specimen equilibrium, we calculated the stress-strain curve from the direct estimates of the output force based stress and the average strain (Figure 3).

The temperature rise during these tests is determined using the proposed infrared method. Figure 4a shows the corresponding temperature evolution for both experiments. According to our measurements, the temperature rises by about 10°C as the total strain increases from 0 to 0.37. The measured curves feature a high frequency noise of a maximum amplitude of $\pm 3^\circ\text{C}$. Note that the curves for both tests lie on top of each other (Figure 4). This indicates that the temperature measurement technique is not affected by the surface roughness of the specimens. For reference, we also calculated the mechanical work done throughout the experiment (smooth black curves). Subsequently, the temperature evolution is estimated based on the assumption that this work is

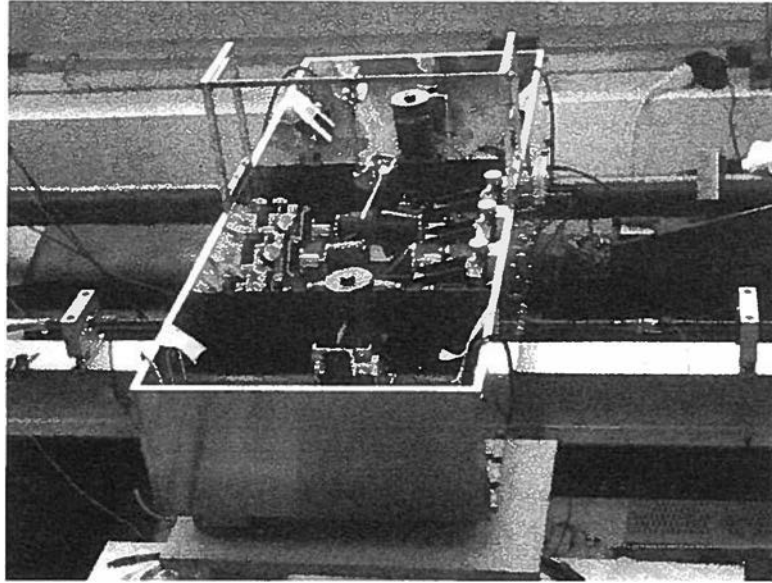


Figure 2. Photograph of optical detector system.

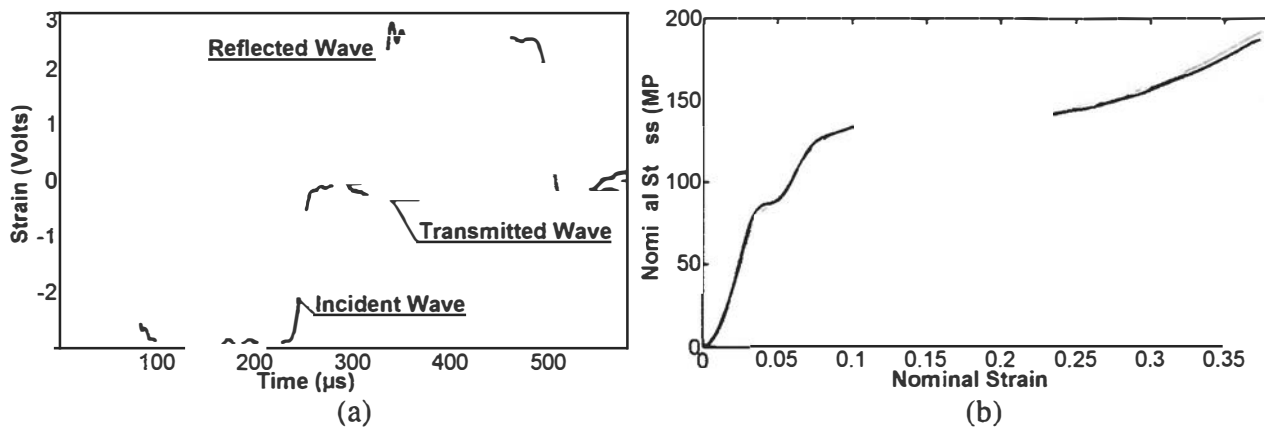


Figure 3. (a) Recorded waves, (b) stress-strain curve for both tests at 2400/s.

converted into heat. The comparison with the infrared measurements clearly shows that this assumption is not valid for the present material.

Moreover, we also plotted the evolution of the emissivity for the specimen of low surface roughness in Figure 4b. The InSb detectors show an increase of the emissivity from about 0.9 to 0.98. In the range of wavelengths of the HgCdTe detectors, the computed change in emissivity is much smaller; it increases from 0.75 to about 0.8. We compared these results with the emissivity measurements for the undeformed specimens. The comparison of these curves suggests that deformation-induced emissivity changes need to be taken into account.

4. CONCLUSION

A new infrared technique for measuring the temperature evolution during SHPB tests has been presented. The unique feature of this technique is its ability to measure both the temperature and surface emissivity of a specimen throughout a dynamic experiment. This is achieved by using two

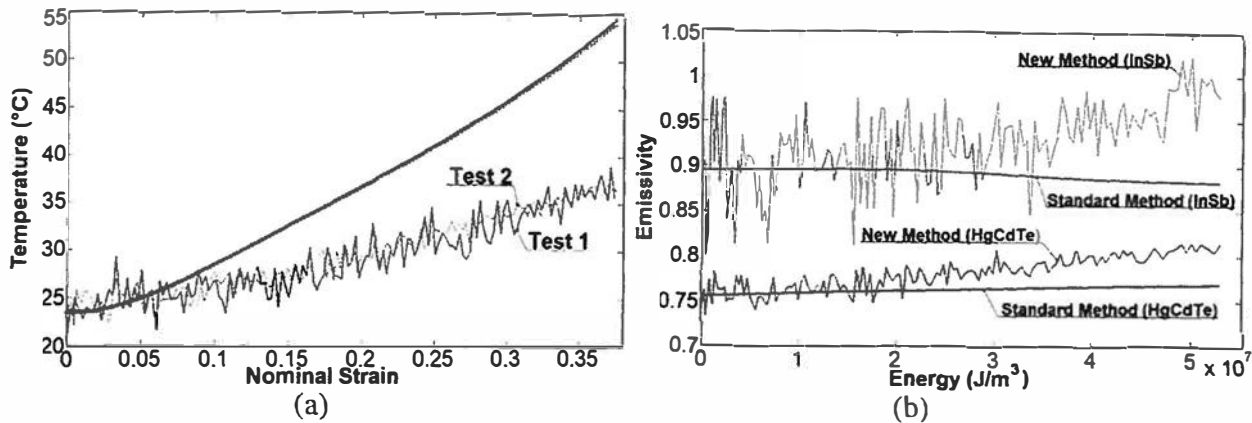


Figure 4. Thermal measurements: (a) evolution of the temperature as a function of the applied strain, (b) evolution of the emissivity as a function of the strain energy.

pairs of infrared detectors of different wavelength along with a well-known source of radiation that is reflected on the specimen surface. The results for a SHPB experiment at a strain rate of 2400/s are shown to illustrate the measurement capabilities of the proposed method.

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