Temperature measurement of fine wires by photothermal radiometry

T. Borca-Tasciuc and G. Chen

Mechanical and Aerospace Engineering Department, University of California at Los Angeles, Los Angeles, California 90095

(Received 11 June 1997; accepted for publication 25 August 1997)

This work reports temperature measurement of fine wires using the photothermal radiometry (PTR) technique. In this method, a laser is employed to create a small periodic temperature perturbation on the wire and thus a small modulation of the thermal emission signal from the wire. The temperature of the wire is derived from the ratio of the photothermal emission signals at two different wavelengths. Temperature measurement is performed on an electrically heated metallic wire of 127 μm in diameter. A calibration procedure is developed to account for the emissivity difference at the two signal wavelengths. The measured temperatures by the PTR technique are in good agreement with the thermocouple readings at different laser modulation frequencies. The possibility of extending the technique to optical fibers is discussed based on Mie scattering theory. Calculations suggest that the PTR technique can be used to measure temperature of optical fibers during the fiber drawing process by choosing an appropriate excitation laser and the signal wavelengths. © 1997 American Institute of Physics. [S0034-6748(97)04511-5]

I. INTRODUCTION

Wire drawing is a common industrial process and in situ temperature measurement techniques can be used for the quality control of the process. The temperature measurement of wire-type materials, however, is not easy because of (1) the small diameter of the wire and (2) the wire motion and vibration during the drawing process. Due to the motion of the wire, noncontact temperature measurement is necessary. Radiation pyrometry is often the preferred method for noncontact temperature measurement and has been studied extensively in the past. The research effort is directed at overcoming the uncertainties of the emissivities of the samples. Examples of the solutions include the two-color and multicolor pyrometry, and the recently developed interferometric pyrometry. The multicolor pyrometry methods are based on the elimination of emissivity through ratio or curve fitting, while the interferometric pyrometry is based on direct in situ calibration of the sample emissivity. Direct application of these methods to wire-type materials, however, is difficult due to (1) the small and nonplanar geometry of the target, (2) the vibration and motion of the wire, and (3) the ambient radiation effect.

A possible solution for the temperature measurement of wire-type materials is the photothermal radiometry (PTR) technique. A photothermal process involves the conversion of the photon energy into the thermal energy of the sample. The sample temperature change can generate various detectable signals such as surface reflectivity, acoustic and thermal waves, and thermal emission. Photothermal effects have been employed in numerous applications including thermophysical and electronic property characterization, nondestructive testing, and optical spectroscopy. In the PTR technique, the temperature of the sample is perturbed by an external radiation source, typically a laser. The perturbation in the thermal radiation signal is detected by a radiation detector. This signal depends on the temperature of the sample as well as on the temperature variation created by the external radiation source. The sample temperature can be inferred from the detected signal. Photothermal effect created by both modulated and pulsed laser heating has been utilized to measure the temperature of stainless steel samples situated in a furnace. Markham et al. combined such a photothermal effect with a spectrometer to develop an emissivity-independent surface temperature measurement technique for monitoring combustion processes. A recent study used the normalized photothermal emission signal for emissivity-independent surface temperature measurement.

This work explores the potential of PTR for temperature measurement of fine wires. The technique is applied to measure the temperature of a metallic wire of 127 μm in diameter. Temperature readings from the PTR method are in good agreement with the thermocouple readings. The potential of this method for optical fiber drawing process monitoring is discussed based on the Mie scattering theory.

II. EXPERIMENTAL SYSTEM

Figure 1 shows the experimental system for implementing the PTR technique for measuring the temperature of a 127 μm nickel–aluminum wire used to make K-type thermocouples. The wire is heated by passing a dc current through it and its temperature is measured by a K-type thermocouple made of 50-μm-diam wires. A 4X microscope objective is employed to focus a modulated argon laser beam to the wire. Thermal emission of the sample from the irradiated area is collected by an infrared lens and detected by a liquid-nitrogen cooled InSb detector. A germanium window integrated into the detector blocks the argon beam scattered into the optical system. The signal is sent to a lock-in amplifier and computer for data processing. The wavelengths of the thermal radiation are selected by two infrared filters centered at 3.205 and 4.51 μm, respectively. The bandwidths of the filters are calculated from their transmission spectra provided by the manufacturer as 111 nm for the 3.205 μm filter and 65...
nm for the 4.51 µm filter for an equivalent peak transmissivity of 100%. At this stage, the signal at each wavelength is collected in separate runs and no attempt has been made to collect data at the two wavelengths simultaneously. The modulated PTR signal can be expressed as

$$S_{\text{ac}} = C_{\lambda} \varepsilon_{\lambda} \frac{\partial E_{\text{bl}}}{\partial T} T_{\text{ac}} A_{\text{ac}},$$

where $C_{\lambda} (= \tau_{0\lambda} B_{\lambda} F \Delta \lambda)$ is a system constant depending on wavelength ($\lambda$) and bandwidth ($\Delta \lambda$), the detector responsivity ($B_{\lambda}$), the geometrical view factor ($F$), and the optical transmissivity ($\tau_{0\lambda}$) from the wire to the detector; $\varepsilon_{\lambda}$ is the wire emissivity, $E_{\text{bl}}$ the blackbody emissive power, $T_{\text{ac}}$ the ac temperature rise of the sample, and $A_{\text{ac}}$ the area of the ac affected region. The ratio of the ac signals at two different wavelengths can be used to eliminate the ac temperature rise and area in Eq. (1):

$$G(T) = \frac{S_{\lambda_{1\text{ac}}}}{S_{\lambda_{2\text{ac}}}} = K \frac{\varepsilon_{\lambda_{1}} \frac{\partial E_{\text{bl}_{1}}}{\partial T} \frac{1}{\lambda_{1}}}{\varepsilon_{\lambda_{2}}} \frac{\partial E_{\text{bl}_{2}}}{\partial T} \frac{1}{\lambda_{2}} \exp \left[ C_{2} \frac{1}{\lambda_{1}} - \frac{1}{\lambda_{2}} \right],$$

where $K$ represents the ratio of the products of the transmissivity of the optical system and the detector responsivity at the two wavelengths, and $C_{2}$ (14 387.69 µmK) is a constant. The ratio of the sample emissivities at the two wavelengths runs into the classical problem in two-color pyrometry. Often, wavelengths are chosen such that the emissivities are equal to each other. For the current work, it is found that the emissivities of the wires are very different at the two chosen wavelengths and calibration will be carried out.

### III. RESULTS AND DISCUSSION

Figure 2 shows the photothermal radiation signals from the wire at two wavelengths and two different laser modulation frequencies. The laser power was set at 10 mW. In this case, the maximum dc temperature rise caused by the laser heating as determined by the thermocouple was $\sim 5$ K, depending on the wire temperature.

Figure 3 shows the ratio of the PTR signals at two different wavelengths. To obtain the temperature of the wire from the ratio of the PTR signals at the two wavelengths, Eq. (2) is calculated based on the information on the filters and the detector provided by manufacturers and by assuming that the emissivities of the sample at the two wavelengths are equal to each other. The solid line in Fig. 3 is the result of this calculation. The experimental results differ significantly from the theoretical calculation based on the assumption of equal emissivities at the two wavelengths, but are very close to each other at different frequencies.

The major cause of the discrepancy between the theoretical calibration curve and experimental results is attributed to the unequal emissivities of the wire at the two wavelengths. Such unequal emissivities can be caused by the diffraction effect of the wire. This diffraction effect can be further strengthened by the oxide formation around the wire. Another possibility for the observed discrepancy is that the laser beam introduces a large dc temperature rise. This is ruled out by positioning the thermocouple close to the laser spot and by using a small laser power. The thermocouple reading combined with a simple heat conduction model in-
indicates that the maximum difference between the peak and the recorded temperatures is within 10 K.

Calibration is carried out in order to compensate for the emissivity variation. The calibration is realized by passing an ac current superimposed on the dc current. The heat generation in the sample by the electrical current is then

\[ q = \left( V_{dc} + V_{ac} \sin \omega t \right)^2 / R, \]

where \( R \) is the electrical resistance and \( V \) the voltage drop across the wire. Such a heat source will create a temperature oscillation in the wire. The first-order harmonic of the wire temperature oscillation is measured at the two wavelengths and the ratio of the signals is taken.

The cross symbols in Fig. 3 represent the calibration results, which show a very good agreement between the laser and electrical heating of the wire. A comparison of the thermocouple temperature reading and the PTR temperature reading based on the calibration curve is shown in Fig. 4. The maximum temperature difference between the two methods is about 1%–2%.

In order to study the influence of the motion of the wire and/or the laser beam during a photothermal pyrometry measurement, the laser beam is shifted slightly off the axis of the wire. Experimental results show that the signal ratio is not influenced by this relative motion, although the signal itself varies. If signals at both wavelengths are collected simultaneously, the temperature measurement error caused by the vibration of the wire can be eliminated.

The above-described experiment is on a metallic wire. In the fiberoptic industry, there is a strong demand for temperature measurement techniques applicable to the optical fiber-drawing process. To extend the PTR method to optical fibers, the transparency of optical materials must be taken into consideration. First, the excitation laser must be chosen at a wavelength that the fiber absorbs, although the absolute absorptivity of the fiber at the excitation wavelength is not critical as long as the absorbed energy can raise the fiber temperature by a few degrees. Good candidates of the excitation lasers include CO₂ or CO laser for modulated heating of the fiber. The key factor for measuring the temperature of optical fibers by the PTR technique is to choose the right wavelengths for receiving the infrared radiation from the fiber. The emissivity of the fiber at chosen wavelengths should be large and should be relatively independent of the fiber diameter if the variation of the latter is large. If the variation of the fiber diameter is small, the latter requirement can be relaxed.

Calculations have been carried out based on the optical properties of SiO₂ and the Mie scattering theory of an infinitely long cylinder. Figure 5 shows the calculated emissivity as a function of the fiber diameter at several wavelengths. Similar calculations have been performed for aluminum wires and the obtained emissivity is less than 0.1. The emissivity values of fibers with a diameter \( \sim 100 \mu m \) are at least comparable to the metallic wire used in the above experiment, if not much larger. Based on the emissivity values and wavelength, the photothermal emission signals can be estimated and compared to the signal levels obtained for the Ni–Al wire. Figure 6 shows the calculated signal level of the fiber at different wavelengths normalized to the signal at

\[ \text{FIG. 4. Comparison of the thermocouple and photothermal radiometry temperature readings for the 127 \mu m Ni–Al wire.} \]

\[ \text{FIG. 5. Calculated emissivity of a glass fiber as a function of its diameter at different wavelengths. Optical constants of SiO₂ are assumed for the calculations.} \]

\[ \text{FIG. 6. Calculated PTR signals from a 100-\mu m-diam glass fiber at different wavelengths normalized to that of an Al–Ni wire at 3.2 \mu m. The emissivity of the Al–Ni wire is assumed to be 0.7 to account for the effect of oxidation.} \]
3.2 μm for the Ni–Al wire. The emissivity of Ni–Al wire is assumed to be 0.7 (for both 3.2 and 4.5 μm) in these calculations. This large value of emissivity is used to account for the effect of the oxidation of the wire. Since strong signals are detected at both 4.5 and 3.2 μm for the Ni–Al wire, as shown in Fig. 2, the signals from optical fibers should be strong enough for reliable detection at any wavelength between 5 and 10 μm in the temperature range of interest for optical fiber drawing. Finally, Fig. 7 shows the ratio of the signals at several pairs of wavelength combinations. The ratio for 3.2 and 4.5 μm is slightly different from that in Fig. 3 since it is assumed here that the interference filters have identical bandwidths. This figure suggests that the 5 and 8 μm wavelength combination for optical fibers leads to a temperature sensitivity even better than the 3.2 and 4.5 μm combination used for the Ni–Al wire. These calculations indicate that the PTR technique can be extended to optical fibers.

To summarize, this work has demonstrated temperature measurement of fine metallic wires by the PTR technique with an accuracy between 1% and 2%. Further improvement in the temperature measurement accuracy is possible by collecting data simultaneously at both wavelengths and by improving the optical system. Calculations carried out based on the Mie scattering theory suggest that the technique can be extended to measure fiber temperature during the optical fiber drawing process.

ACKNOWLEDGMENT

This work is supported by a NSF Young Investigator Award to G.C.