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MATERIAL PROPERTIES

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ELLIPSOMETRY IN THE STUDY OF DYNAMIC MATERIAL PROPERTIES

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Abstract. Measurements of the time-dependent absolute temperature of high-explosive (HE) shocked surfaces provide valuable constraints on the equations-of-state (EOS) of materials and of the state of ejecta from those surfaces. In support of these dynamic surface temperature measurements, we are developing techniques for measuring the dynamic surface emissivity of shocked metals in the near-infrared (IR). These consist of time-dependent laser polarimetric measurements, using several approaches. We include here a discussion of these polarimeter techniques. Polarimetry permits an accurate determination of the dynamic emissivity at a given wavelength, and may also provide a signature of melt in shocked metals.

INTRODUCTION

Measurements of the time-dependent absolute temperature of HE-shocked surfaces provide valuable constraints on the EOS of materials and of the state of ejecta from those surfaces. These temperatures lie in the range of 0.04 to 0.2 eV, corresponding to shock-heating of surfaces to temperatures from about 400 K to 2000 K. This is equivalent to IR wavelengths from about 1 to 6 microns.

The dynamic (and in some cases static) emissivities over these wavelength ranges are not well known, and can only be approximately inferred from multichannel pyrometer measurements, limiting the accuracy of these temperature measurements. Polarimetry permits a complementary determination of the dynamic emissivity by measuring the real and imaginary parts of the index of refraction. These emissivity measurements can be used with pyrometer data at similar wavelengths to calculate true

temperatures. Dynamic emissivity data may also provide an indication of phase change. Once the emissivity is derived at one wavelength, a multichannel pyrometer permits determination of the emissivity at all the other pyrometer wavelengths, since the temperature is independent of wavelength.

FIGURE 1. Graphic depiction of laser ellipsometry. A laser beam in a known polarization state S from a polarizer is reflected off a surface. The polarization state S' of the scattered or reflected beam is measured in the analyzer. Knowledge of both S and S' permits an inference of the optical properties (n, k, ϵ) of the sample surface at the laser wavelength.

Programmatically, in addition to providing EOS constraints, the ellipsometry measurement technique is applicable to various geometries. Also, melt influences spall, phase transitions, and ejecta characteristics.

EMISSION MEASUREMENTS

Typical multichannel pyrometric temperature studies of dynamically-shocked surfaces utilize emissivities bounded at the lower end by the static value and at the higher end by 1, the maximum possible value. Depending on the material and the speed of the shock, this may or may not be valid at a phase transition. For example, in the case of a non-

FIGURE 2. Typical spectral behaviour of emissivity with wavelength. Note the large variation of absolute values, depending on the surface finish. Compared here are two rolled finishes with a 32-microinch finish and a metallographic polish. Note also here that $de/d\lambda < 0$ while $d^2e/d\lambda^2 > 0$.

magnetic niobium wire, explosively driven by high current, the emissivity drops through melt. This can be seen in Figure 3. In the case of a high-current driven magnetic nickel wire, on the other hand, at melt the emissivity is seen to rise, as shown in Figure 4. Here the Kerr effect, or the introduction of birefringence proportional to the square of the shock-induced electric field, has been ignored. However other factors besides the Kerr effect can drive the emissivity up during shock heating. For example, surface roughness will certainly increase the emissivity, in the absence of melt. The dynamic emissivity may therefore be a more sensitive indicator of melt than the radiance temperature.

FIGURE 3. Reduction of emissivity at the melt transition in an exploding non-magnetic niobium wire. The radiance temperature assumes unity emissivity.

FIGURE 4. Increase in emissivity at the melt transition in an exploding magnetic nickel wire.

EXPERIMENTAL TECHNIQUES

Three ellipsometers are being developed using three somewhat different approaches. All three are currently operating at 1550 nanometers, which is about the longest wavelength at which both visible-optics work and an industry-standard laser is available. This relatively short wavelength should still permit some overlap with pyrometric temperature measurements below 1000 K. It is hoped that once this wavelength regime has been explored, we will develop infrared ellipsometers up

to about 6 microns. However these will pose some technological challenges. In the presence of shock background light, an ultimate modulation-frequency goal is 1 gigahertz with 12-bit recording for 1000:1 effective dynamic range. However again it will be some time before this speed will be realized.

A commercial reference instrument has been purchased from Containerless Research (CRI) in Evanston, Illinois. This instrument has been upgraded to meet our demanding field requirements and is being tested. A conservatively-built 4-channel instrument, some of its features are as follows. Laser power is currently 200 milliwatts, upgradeable to 2000 milliwatts. Rougher surface finishes will require this power. Modulation frequency is currently 50 MHz, and is limited by the following considerations. The 4-channel sampling frequency, always twice the modulation frequency, is currently limited to 100 MHz at 12 bits. However also the existing four 2-mm diameter InGaAs detectors are limited to 100 MHz. Faster speeds can be realized by underfilling, say, 1-mm or even 0.5-mm diameter detectors. This instrument is shown schematically in Figure 5.

CRI POLARIMETER

FIGURE 5. Schematic layout of CRI ellipsometer.

A second field instrument is being assembled with slightly different features. Instead of 4 channels it will have 6 balanced channels, offering some redundancy in remote field operations under adverse conditions. Using smaller fiber-coupled pin-diode detectors, a modulation frequency of 200 MHz has

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FIGURE 6. Schematic layout of Buttler ellipsometer.

already been test with stacked 8-bit recording. The laser power output is 1200 milliwatts at 1550 nonometers. Figure 6 illustrates this ellipsometer schematically.

A third instrument is being assembled at Bechtel Nevada's Special Technology Laboratory (BN/STL) in Santa Barbara, California. This instrument also uses three channel-pairs, for a total of six channels.

The BN/STL instrument will have several noteworthy features. Polarization effects in beamsplitters will be avoided by using near-normal incidence. As in the Buttler instrument, complementary outputs provide background-light and common-mode noise suppression. Minimizing the number of surfaces avoids unwanted reflections. Equal coupling is only required within each pair of fibers, not between all pairs. Sensitivity to angular tilt should be reduced. Finally, the construction will be simple and stable to avoid adjustments in the field. Laser power at 1550 nanometers will be 2000 milliwatts. As in the Buttler instrument, stacked 8-bit recording will be used. The BN/STL instrument is shown schematically in Figure 7.

FIGURE 7. BN/STL ellipsometer schematic.

ERRORS AND UNCERTAINTIES

Sources of error include alignment errors and polarization impurities as well as noise sources. Also there may be incomplete or incorrect polarization of the probe beam, probe beam laser noise, calibration errors, digitizer clocking errors and jitter, electronics noise, poor sample reflectivity, and depolarization of the probe beam by the sample roughness so that the analytical form of the Mueller matrix is not applicable. Furthermore noisy signals may result from the geometry of the measurement, as in the case of exploding wires or loss of surface reflectivity at shock breakout in the case of explosively shocked surfaces. Nevertheless the ongoing program of modeling the CRI ellipsometer, for example, indicates that typical errors, noise and imprecision produce tolerable errors in the output.

ELLIPSOMETRY AT THE GAS GUN

FIGURE 8. CRI reference ellipsometer at the single-stage gas gun. Here PSG and PSD refer to the polarization state generator and detector, respectively. After calibration and before the shot, the two rails are toed back out. Nothing is touched above the rails.

GOALS AND SUMMARY

Near and long-term objectives include acquisition of emissivity data at near-IR wavelengths for materials of interest. These should improve the accuracy of pyrometric temperature measurements. Also, variation of emissivity at melt may provide a signature of phase transitions. The spatial resolution of this technique is on the order of 1 to 10 mm. Comparison of diamond-anvil measurements at static high pressure and temperature with shock conditions at the same high pressure and temperature will be interesting, since the crystal structure may be different in the two cases.

A wide variety of diagnostics are anticipated for these instruments. Local testing will include cooperative efforts in neutron resonance spectroscopy (NRS), laser shock-physics, gas-gun shock experiments, HE-shock tests at BN/STL, and exploding wire work. Shown in Figure 8 is the CRI instrument setup at the local single-stage gas gun. Preliminary results will be discussed.