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A heat conduction model for three layers and application to shock temperature measurements for metals

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Abstract

A heat conduction model for three parallel layers of dissimilar materials is proposed to describe the heat flow through the sample/μm-size high-temperature layer/window after passage of a strong shock front. This model provides a possible approach to shock temperature measurements for metals using a disc sample. Using this model we derived a shock temperature or melting temperature of meteoritic iron based on the observed interfacial temperature by optical radiometry techniques. The data sets determined are in agreement with those measured using a film sample of stainless steel analogous to meteoritic iron in composition.

1. Introduction

In shock temperature measurements for metals or alloys using optical radiometry techniques, a thin film is required to deposit on a transparent window (sapphire or LiF crystal) so that a gapless contact of the sample with the window can be achieved. An ideal interface model [1] proposed by Grover is then used to derive shock temperature from the observed interfacial temperature. Recently, a careful examination of the ideal interface model has indicated that the driver/film gap would result in a high-temperature layer (HTL), which could disturb to a varied degree the heat flow at the film/window interface [2]. This is one of principal reasons that the melting curve of iron measured in the megabar range using a film/window set-up is always located above that measured at static pressures or evaluated from theoretical calculations. Therefore, we preferred to use a disc sample instead of a film one. In this work, we attempt to establish a universal 'three-layer model' to describe the one-dimensional heat flow through the sample/HTL/window, and to apply this model to measure Hugoniot temperatures or melting temperature of meteoritic iron.

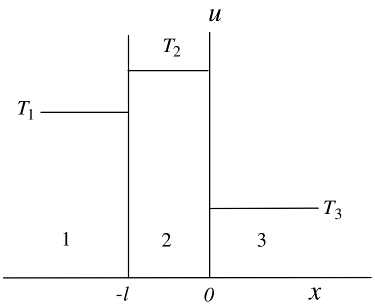

Figure 1. A sketch of temperature distributions in three parallel layers of dissimilar media.

2. Theoretical considerations

Figure 1 is a sketch of temperature distributions in three parallel layers ($i = 1, 2, 3$) of dissimilar materials, where T_1, T_2, T_3 denote temperatures of layer 1, 2, and 3, respectively; l denotes the thickness of layer 2; $x = 0$ is at the 2–3 interface; $x = -l$ is at the 1–2 interface. According to the Fourier heat conduction equation ($\partial^2 u_i/\partial x^2 - \kappa_i^{-1}\,\partial u_i/\partial t = 0$, $i = 1, 2, 3$), initial conditions ($u = T_1, -\infty < x < -l; u = T_2, -l < x < 0; u = T_3, 0 < x < \infty$), and boundary conditions ($u_1 = u_2$ and $-K_1\frac{\partial u_1}{\partial x} = -K_2\frac{\partial u_2}{\partial x}$ at $x = -l$; $u_2 = u_3$ and $-K_2\frac{\partial u_2}{\partial x} = -K_3\frac{\partial u_3}{\partial x}$ at $x = 0$; $u_3 = T_3$ as $x \to \infty$; $u_1 = T_1$ as $x \to -\infty$), the 2–3 interfacial temperature, $u_{23}(t)|_{x=0}$, can be obtained by doing a *Laplace* transformation:

$$u_{23}(t)|_{x=0} = T_2 - \frac{T_2 - T_3}{\alpha_{23} + 1} - \frac{2\alpha_{23}(T_2 - T_3)}{(\alpha_{23} + 1)(\alpha_{23} - 1)} \sum_{n=0}^{\infty} r^n \operatorname{erfc}\big(nl/\sqrt{\kappa_2 t}\big) - \frac{2\alpha_{23}(T_2 - T_1)}{(\alpha_{21} + 1)(\alpha_{23} + 1)} \sum_{n=0}^{\infty} r^n \operatorname{erfc}\big[(n + 1/2)l/\sqrt{\kappa_2 t}\big] \tag{1a}$$

where $\alpha_{ij}^2 = (\rho c K)_i/(\rho c K)_j$, $i \neq j$, ρ, c and K denote density, specific heat, and thermal conductivity, respectively, $r = \frac{(\alpha_{21}-1)(\alpha_{23}-1)}{(\alpha_{21}+1)(\alpha_{23}+1)}$, $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$, $\operatorname{erf}(x)$ is the error function. $u_{23}(t)|_{x=0}$ can be rewritten as

$$u_{23}(t)|_{x=0} = T_1 - \frac{T_1 - T_3}{\alpha_{13} + 1} + \frac{2\alpha_{23}(T_2 - T_3)}{(\alpha_{23} + 1)(\alpha_{23} - 1)} \sum_{n=0}^{\infty} r^n \operatorname{erf}\big(nl/\sqrt{\kappa_2 t}\big) + \frac{2\alpha_{23}(T_2 - T_1)}{(\alpha_{21} + 1)(\alpha_{23} + 1)} \sum_{n=0}^{\infty} r^n \operatorname{erf}\big[(n + 1/2)l/\sqrt{\kappa_2 t}\big]. \tag{1b}$$

Equation (1a) shows that $u_{23}|_{t\to 0}^{x=0} = T_2 - (T_2 - T_3)/(1 + \alpha_{23})$ as $t \to 0$, implying that the heat flow at the 2–3 interface can be described by the Grover model; equation (1b) shows that $u_{23}|_{t\to\infty}^{x=0} = T_1 - (T_1 - T_3)/(1+\alpha_{13}) = u_{13G}$ as $t \to \infty$, that is, the layer 2 seems to be absent as if the thermal relaxation time is long enough. At $x = 0$, the temperature variation from $t = 0$ to $t \to \infty$ is $\Delta u_{23}|_{x=0} = u_{23}|_{t=0}^{x=0} - u_{23}|_{t\to\infty}^{x=0} > 0$ if $T_1 > T_3$. So a temperature spike would be presented at the very beginning on the interfacial temperature–time profile, which would then approach an equilibrium temperature, in contrast to the temperature–time profile in the case of ideal interface. In practice, the observed time of radiance history at the interface is definite, so the influence of the thin layer 2 on the observed interfacial temperature $\Delta u_{23}(t)|_{x=0}$ can be estimated from

$$\Delta u_{23}(t)|_{x=0} = \frac{2\alpha_{23}(T_2 - T_3)}{(\alpha_{23}+1)(\alpha_{23}-1)} \sum_{n=0}^{\infty} r^n \operatorname{erf}\big(nl/\sqrt{\kappa_2 t}\big) + \frac{2\alpha_{23}(T_2 - T_1)}{(\alpha_{21}+1)(\alpha_{23}+1)} \sum_{n=0}^{\infty} r^n \operatorname{erf}\big[(n+1/2)n/\sqrt{\kappa_2 t}\big]. \quad (2)$$

This 'three-layer model' can be applied to describe the heat conduction of sample/ μm-gap/window set-up after passage of the shock front. The layer 2 corresponds to HTL resulting from the sample/window gap under shock compression. $u_{23}|_{t\to\infty}^{x=0} = u_{13G} = T_I$ as $t \to \infty$, suggesting that the influence of HTL on shock temperature measurement can be ignored if the thermal relaxation time is long enough. However, the observed time of interfacial radiances is about a few hundred nanoseconds. So the addition temperature resulting from the heat disturbance of HTL should be subtracted from the observed interfacial temperature $T_{I,obv}$ (or $u_{23}|_{t=t_p}^{x=0}$), where t_p denotes the presence time of emission plateau, regarding the time of shock wave arrival at the interface as the reference time. Actually, the driver (sample) and HTL can be regarded as one kind of material, and suffer the same shock pressure. Thus we have approximations: $\alpha_{21}^2 \to 1$; $r \to 0$. So the real interfacial temperature, T_I (or u_{13G}), can be obtained from

$$u_{13G} = u_{23}|_{t=t_p}^{x=0} - \Delta u_{23}|_{t=t_p}^{x=0} = T_{I,\,obv} - \frac{\alpha_{13}(T_2 - T_1)}{1+\alpha_{13}} \operatorname{erf}\big(0.5l/\sqrt{\kappa_2 t}\big) \quad (3)$$

($n = 0$, zero-order approximation).

3. Experimental attempts

The disc-sample/window set-up was used to measure the shock temperature of meteoritic iron (Fe 93.65%, Ni 6.35%). A highly polished disc sample of ~23.6 mm in diameter and ~2 mm in thickness was carefully sandwiched between an Fe driver and a sapphire or LiF window polished to mirror finish to form the target assembly. A projectile consisting of a polycarbonate sabot and an Fe or W-alloy flyer was accelerated to a desired velocity by a two-stage light gas gun, impacting the target assembly and shocking the sample. Thermal radiation emitted from the sample/window interface was detected by a six-channel pyrometer at discrete wavelengths of 450–800 nm, which was calibrated using a standard lamp prior to each shot. A mask was used so that only light from the central area of the sample reached the pyrometer. The spectral data were recorded using TEK684 digital oscilloscopes.

A typical radiance history observed at the sample/window interface is shown in figure 2, in which the radiance presents a spike at the very beginning, and immediately relaxes and almost presents a plateau (corresponding to the observed interfacial temperature, $T_{I,obv}$) in 100–150 ns (figure 2). Such an interface–time profile is in good agreement with the predicted profile from 'three-layer model' (figure 3). The $T_{I,obv}$ is obtained by fitting spectral radiances at discrete wavelengths to Planck grey-body function (figure 4), and the real interfacial temperature is determined from equation (3).

The measured shock-melting temperature data sets for meteoritic iron (figure 5) are basically consistent with the results for stainless steel 304 [3] containing about 20% nickel measured using a film/sample assembly. The determination of melting temperature (T_M) at the impedance pressure (P_R) is based on the assumption that T_I can be regarded as the T_M at P_R if the sample was shocked or released into the mixed phase or liquid phase region [4, 5]. The determined T_M data sets are approximately located along the Lindemann melting curve, which intersects the Hugoniot temperature (T_H) curve at about 250 GPa. This shock-melting pressure is in agreement with the result of high-pressure sound velocity measurements for iron [6].

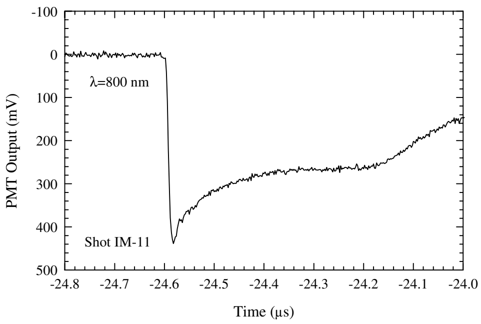

Figure 2. A typical radiance at $\lambda = 800$ nm emitted from the meteoritic iron/sapphire interface (shot IM-11).

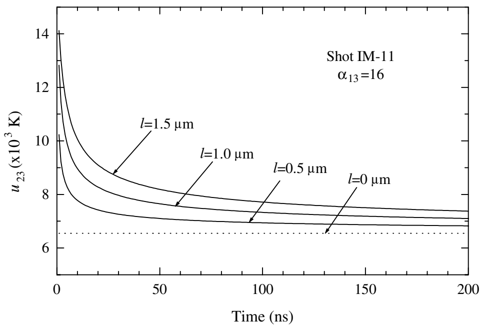

Figure 3. The interfacial temperature variations with time from the 'three-layer model' calculations.

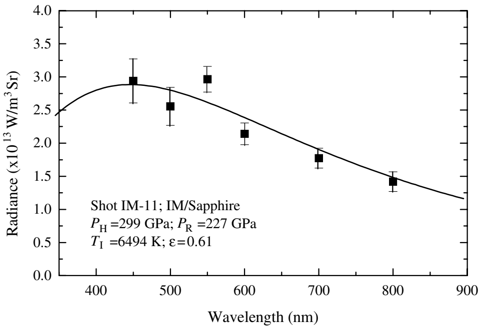

Figure 4. A representative Planck grey-body spectrum fitted with observed radiances at discrete wavelengths.

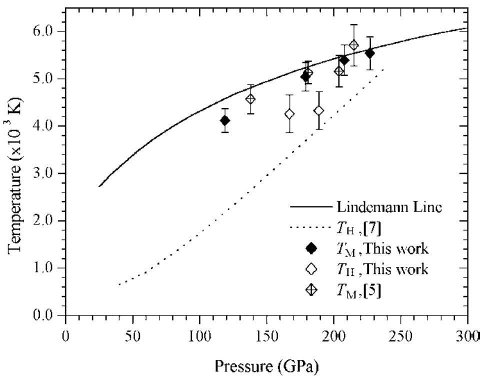

Figure 5. Temperatures of meteoritic iron as a function of pressure.

4. Summary

The one-dimensional heat conduction through three parallel layers of dissimilar materials is modelled, and applied to measure the shock temperature or melting temperature of meteoritic iron. The preliminary theoretical considerations and experimental results show that this experimental method for shock temperature measurements for metals or alloys on the basis of three-layer model seems to be practicable and effective.

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