Shock temperature of stainless steel and a high pressure—high temperature constraint on thermal diffusivity of Al 2 O 3

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Shock Temperature of Stainless Steel and a High Pressure – High Temperature Constraint on Thermal Diffusivity of Al_2O_3.

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Abstract

Time dependent shock temperatures were measured for stainless steel (SS) films in contact with transparent anvils. The anvil/window material was the same as the driver material so that there would be symmetric heat flow from the sample. Inferred Hugoniot temperatures, T_h, of 5800–7500K at 232–321GPa are consistent with previous measurements in SS. Temperatures at the film-anvil interface (T_i), which are more directly measured than T_h, indicate that T_i did not decrease measurably during the approximately 250ns that the shock wave was in Al_2O_3 or LiF anvils. Thus an upper bound is obtained for the thermal diffusivity of Al_2O_3 at the metal/anvil interface at 230GPa and 6000K of $\kappa \leq 0.00096 cm^2/s$. This is a factor of 17 lower than previously calculated values, resulting in a decrease of the inferred T_h by 730k. The observed shock temperatures are combined with temperatures calculated from measured Hugoniots and are used to calculate thermal conductivities of Al_2O_3. Also we note that since there was no measurable intensity decrease during the time when the shock wave propagated through the window, we infer from this that Al_2O_3 remained transparent while in the shocked state. Thus sapphire is a good window material to at least 250GPa for shock temperature measurements for metals.

Introduction

There have been several studies on the shock temperatures of iron using optical measurements of the interface radiation to infer the Planck temperatures and emissivities. These interface temperatures, T_i, are used to infer the Hugoniot temperature, T_h, as a function of shock pressure. Several authors have suggested that optical radiation in these experiments is not actually emitted from the metal-window interface and some light may be coming from the shocked anvil material[1]. There is also an uncertainty in the values of the constants, such as the thermal diffusivity of the anvil material, that are used in the calculation of T_h from T_i. Since the calculations of McQueen et al, 1970 [2] predict a lower shock temperature for 304 stainless steel (SS) than for iron, this study focuses on the shock temperatures and thermal properties of SS. If there is a systematic difference between the measured shock temperatures of SS and iron, and those differences are consistent with the predictions, then it can be inferred that the optical radiation is coming from the metal-anvil interface, rather than from within the shocked anvil. Also two different anvil materials are used and the consistency of the observed interface temperatures can be used to infer that a non-significant contribution of the radiation is originating within the anvil.

Additionally, a new target configuration is used to constrain the thermal diffusivity of the anvil. The previous configuration [3] used metal drivers and $10\mu m$ thick films so that the there would be no predicted decrease in the interface temperature with time. Thus the T_i could be related to the T_h as in Tan and Ahrens 1990[4]. The new, or "sandwich" configuration has a thinner film of 1 μm and the same material for the anvil and the driver. This allows heat to diffuse out of the hot metal into the relatively colder anvil material so that the temperature is expected to decrease at the interface. The magnitude of the temperature decrease with time is dependent on the thermal diffusivities of the metal and the anvil. Since the thermal conductivity of the metal is well constrained by the Weideman-Franz law, we are effectively measuring the thermal diffusivity of the anvil at high pressure. We assume that specific heats are well known for both media. It could be argued that some or all of the decrease in radiation with time could be due to the anvil material becoming opaque [5]. However, for film thicknesses of 10 μm, no measurable temperature decrease is expected due to thermal diffusion. Thus if we employ 10 μm films and observe no measurable temperature decrease, then we can conclude that the anvil material remains transparent.

Methods

Previous studies used the target configuration shown in Figure (1 a). For this configuration the interface temperature is not expected to decrease with time and it is dependent on the T_h [4]. Two shots, indicated by "S" in Figure 4, used a "sandwich" configuration as shown in Figure (1 b). Here the driver and the anvil materials are the same and the metal is $1\mu m$ thick. In this geometry, after the shock wave traverses the metal, the thin metal is sandwiched between cooler anvil material. The resulting heat flow should symmetric about the center plane of the metal film and is simple to model. Moreover, heat conduction occurs such that, on the time scale of the present experiments ($\sim 250ns$), the interface temperature can be observed to decrease.

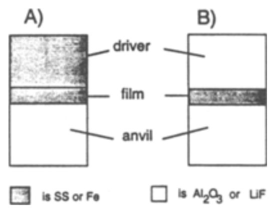

Figure 1: Target configurations a) previous target with a metal driver and a thick film. b) "sandwich" configuration with a thin film and anvil material same as driver.

Calculations summarized in Figure 6 show that a resolvable temperature decrease of 500 K should be detectable in a $\sim 250ns$ time interval. This is the approximately the time required for the shock propagation through the anvil.

The radiation from the target was measured using a 6 channel pyrometer (Figure 2). The radiation calibration was performed with a tungsten ribbon filament lamp and the procedure was similar to that of Boslough and Ahrens [5].

Shock experiments were performed on the Caltech two stage light gas gun. Projectile velocities are in the range of $5.4km/s$ to $6.8km/s$, resulting in shock pressures between $231 - 321GPa$. Tantalum flier plates were employed and the shock pressures were calculated using the same parameters for equation of state of Ta, SS, Al_2O_3 and LiF as in our previous work [6], and references therein.

Calculations

The observed radiation intensities, corrected with the calibration data, are then fit to the Planck function using an iterative least squares method to obtain the T_i and emissivity, ϵ. ϵ was assumed to be wavelength independent for this calculation. Then the temperature was corrected from T_i to the shock Hugoniot temperature, T_h (Figure 4) as explained by Bass et al 1989[6]. The temperature was calculated at a series of times for each shot. We assumed a simple melting line and neglected the difference between solidus and liquidus. From these measurements we find that the melting point of SS is 5800 K $\pm$ 300K at 250GPa. We see that there is a systematic difference between the shock temperatures for iron and those for SS which agree with the calculations by McQueen et al 1970

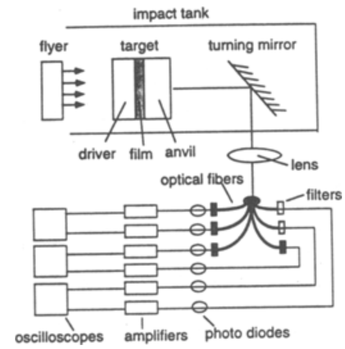

Figure 2: 6 channel optical pyrometer. Lens projects target image onto optical fiber bundle. Bundle is split into 6-subbundles which lead to 6 50nm wide optical filters 6 photodiodes and 6 linear amplifiers. Resultant signals are recorded on oscilloscopes.

[2]. Additionally the time dependence of interface temperatures for the sandwich shots show that T_i decreases by no more than 5 K in 250 ns. (figure 5) The flatness of the radiation versus time curves for all pressures and film thicknesses and anvil materials implies that the LiF and Al_2O_3 anvils are not becoming measurably opaque under shock loading to 140 and 240 GPa respectively.

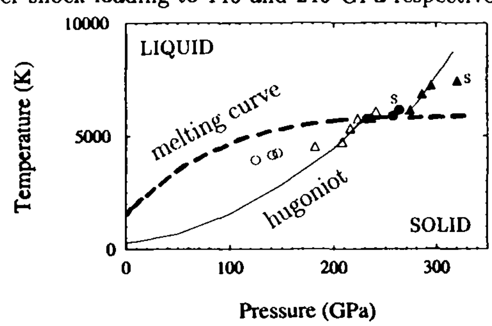

Figure 3: The phase diagram of stainless steel from shock temperature measurements. Open and solid symbols are observed interface temperatures and inferred Hugoniot temperatures; Circles and triangles are data from LiF and Al_2O_3 windows; arrow represents pressure at which melting is observed by Hixon et al [7].

Also heat is not diffusing out of the thin films and into the Al_2O_3 anvils at a rate fast enough to cause a measurable temperature decrease. The heat conduction can be modeled by a symmetric boundary value problem with the ordinary heat flow equation, equation (1).

$$\frac{d^2T}{dx^2} = \frac{1}{\kappa}\frac{dT}{dt} \qquad (1)$$

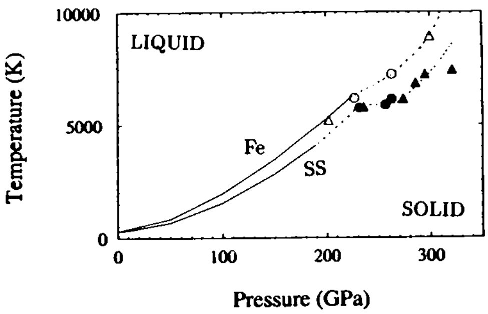

Figure 4: Comparison of the Shock temperatures of iron and stainless steel Open symbols are data for iron, solid symbols are for stainless steel. Circles are for LiF, triangles are for Al_2O_3 anvils

Here T is the temperature of the medium at position, x, and time, t, and κ is the thermal diffusivity. The initial temperature distribution is shown in figure 6, as t_0 and is described by the equations (2) and (3).

$$T(t=0, x < x_0) = T_1 \tag{2}$$

$$T(t=0, x > x_0) = 0 \tag{3}$$

The diffusivities of the three regions are approximated to be that of the anvil material, however, because the anvil diffusivity is much lower than that of of the metal by a factor of 10^3, so the anvil's thermal conductivity controls heat conduction from the metal. This approximation allows an analytic solution to the problem.

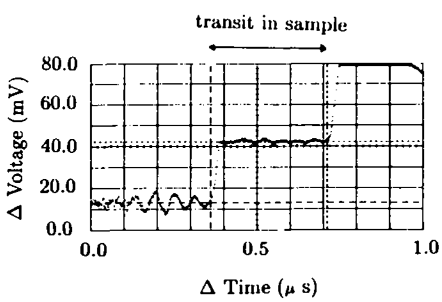

Figure 5: Time dependence of interface radiation from sandwich configuration with 1 μm SS, shot #'s 246 and 247

$$T = T_o + \frac{1}{2}T_1 \left\{ erf[\frac{a-x}{2\sqrt{\kappa_1 t}}] + erf[\frac{a-x}{2\sqrt{\kappa_1 t}}] \right\} \tag{4}$$

Figure 6 shows that in order to get a 50 K decrease, which is the smallest resolvable, we would require a time of $\sim$ 300 ns, which is about the time of our experiments. Since we did not see this temperature decrease we can use this information to calculate a bound to the thermal diffusivity, κ.

$$\kappa = \rho C_p / K \leq .00046 cm^2/s \tag{5}$$

Where ρ is the density, C_p is the heat capacity and K is the thermal conductivity. Since K is the least well constrained of the three variables, we can assume that the major uncertainty is due to inadequate knowledge of K. We thus calculate that $K \leq 0.84 W/mK$. This value is 4.5 times lower than that predicted by the method of Tan and Ahrens, 1990[3]. Upon substituting this value into the calculated value for T_h to obtain a revised value of 6600k for shot 247, which is 730K less than the value previously calculated.

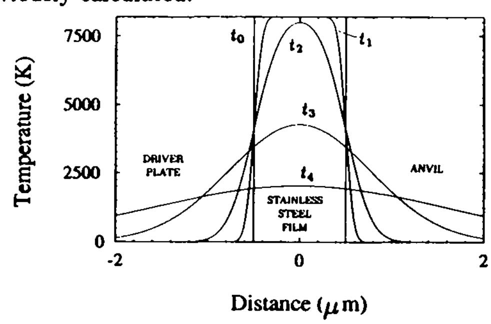

Figure 6: Analytical model of heat flow from an initial temperature distribution, at t_0 (Eq. 4)

Conclusion

For stainless steel shocked up to 321 GPa in the sandwich configuration, with 1 μm films, the best fit temperature at the interface decreases no more than 5 K after 250 ns. The constancy of the radiation intensity with time implies that sapphire shocked to 250 GPa is not becoming measurably absorptive. Within the errors of the measurement, enough heat is not conducting out of the film into the sapphire to create a measurable temperature difference at the interface. Since the diffusivity of Al_2O_3 is much less than that for SS, Al_2O_3 limits heat conduction at the interface. Thus we may apply our simple model of the sandwich configuration to determine that the diffusivity of Al_2O_3 is $\leq .00046 cm^2/s$ at 321Gpa and 5800K. This is a factor of 4.5 lower than the calculated value of Bass and Ahrens [6].

In addition, the measured shock temperatures of the stainless steel samples were consistent independent of the anvil material (LiF or Al_2O_3). Moreover below 250 GPa good agreement exists between our previous iron shock temperature data [8, 6] and recent data of Yoo et. al.

[9] using diamond anvils. On the other hand, theoretically and experimentally there was a systematic difference between T_h data for iron and stainless steel films films between 500 to 1500K and 220 and 300 GPa. This difference is consistent with the calculated temperature difference by McQueen et al 1970. However McQueen's temperature calculation assumed a value of 3R for iron and not the 5R value found theoretically by Bonness et. al. [10].

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