LASER THERMOELASTIC GENERATION IN METALS ABOVE MELT THRESHOLD

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INTRODUCTION.

There has been extensive work on pulsed laser generation of ultrasound in opaque solids, that explores in depth the surface thermo-elastic and ablative regimes. By contrast, little has been known on ultrasound generation in the intermediate regime where the laser pulse energy is sufficient to cause near-surface melting, but is below the vaporization threshold. There is a need for better understanding of this intermediate regime, because laser ultrasound provides a non-contact and remote approach for examination of melting and re-solidification both on short time scales in hostile environments such as those found for irradiated nuclear reactor's fuels. An approach is presented for calculating thermoelastic generation of ultrasound in a metal plate exposed to nanosecond pulsed laser heating, sufficient to cause melting but not ablation [1].

METHODS.

The main thrust of this work is to show how the calculation of the thermal and elastodynamic fields can be separated. Thermal simulations are conducted on the required fine grid for a thin sub-surface layer, and the outcome expressed in the form of radially symmetric time-dependent distributions of surface forces parallel and normal to the illuminated surface. The epicentral displacement response to these force distributions is then calculated by two methods. The first is on the basis of elastodynamic Green's functions evaluated using the Cagniard generalized ray method. The second is using finite element (FEM) simulations. Numerical simulations are reported of the epicentral displacement response of a 3.12 mm thick tungsten plate irradiated with a 4 ns pulsed laser beam with Gaussian spatial profile, at intensities below and above the melt threshold. In our simulations, the laser beam diameter (708 μm) is much larger than the thermal diffusion length (1 μm), which is much larger than optical penetration (or skin) depth (22 nm) of tungsten. Under these conditions we have treated laser pulse induced heat propagation from the surface of laser irradiated metals as one-dimensional heat conduction problem. Detailed consideration is given to the spatial and temporal profiles of the laser pulse, penetration of the laser beam into the sample, the appearance and subsequent growth and then contraction of the melt pool, and the time dependent thermal conduction in the melt and surrounding solid throughout. The excitation of the ultrasound takes place during and shortly after the laser pulse, and occurs predominantly within the thermal diffusion length of a micron or so beneath the surface. It is shown how, because of this, the output of the thermal simulations can be expressed as axially symmetric transient radial and normal surface force distributions.

RESULTS AND DISCUSSION.

We have established the detailed spatio-temporal evolution of heat conduction of the irradiated sample due to the incidence of a laser pulse, including the temperature rise of the solid phase preceding the melting, and the appearance, subsequent growth and then contraction and disappearance of the melt pool due to re-solidification. With these we have identified three regimes of stress evolution: (1) presence of lateral compressive stress in solid that has undergone mild heating without melting, (2) absence of lateral stress in the molten metal, (3) presence of lateral tensile stress in re-solidified and cooling solid. The gradient of the lateral stress, integrated over depth, represents the evolving radial force distribution, which can be regarded as acting at the surface. From the radial surface, stress distributions the radial and normal surface forces were computed. Then we convolved surface force distributions with plate's Green's functions. We have also performed FEM calculations of the epicentral displacement response to surface forces and find very good agreement with Green's functions calculations.

CONCLUSIONS.

Metal-to-liquid phase transition in tungsten induced by a pulsed-laser was investigated by elastodynamic Green's functions and FEM methods. Numerical simulations indicate that the arrival time of longitudinal waves is insensitive to the onset of melting but that of shear waves is delayed by 5.5 ns for the range of used pulsed energies, which is consistent with the early experimental trend [2] and can be used to monitor the induced solid-liquid phase transition.

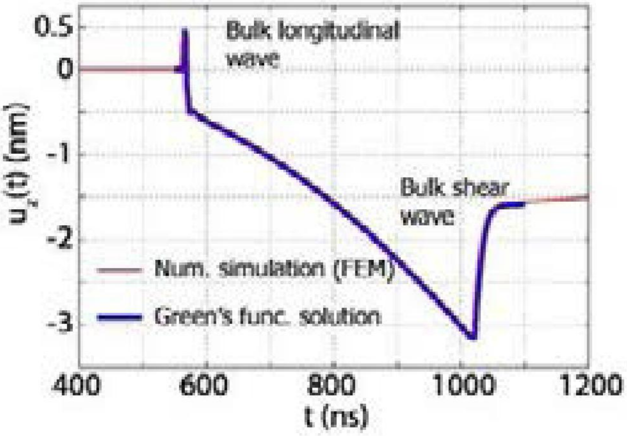

Figure 1. Effect of melting on the epicentral displacement amplitudes at the arrival of compressional and sheer waves.

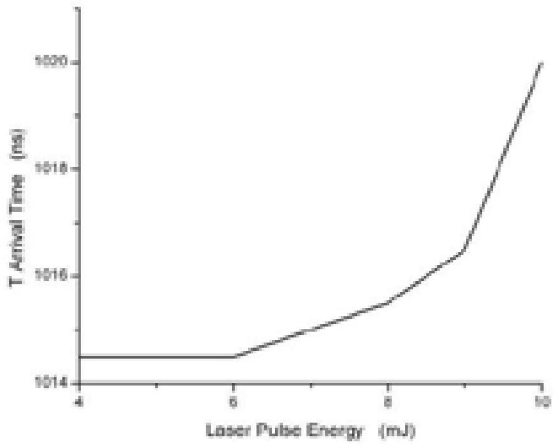

Figure 2. Sheer wave arrival time delay vs laser pulse energy.

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