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MODELING AND COMPUTATION OF PULSED LASER MATERIALS PROCESSING

THOMAS P. SVOBODNY

This paper is dedicated to Max Gunzburger

Abstract. Pulsed laser materials processing incorporates many physical processes, the modeling of which requires disparate techniques. We focus on two closely related topics that arise in laser processing. First, we illustrate by use of numerical simulation the distinction between metals and ceramics in their response to laser fluence. Second we explain recent experiments that indicate that the substrate heater is a strong control parameter in laser processing, and this can be understood from the point of view of shock dynamics.

Key Words. Laser ablation, melting, nonlinear heat conduction, plume dynamics, plume shape, emission spectroscopy, shock, substrate heating, temperature gradient, time-of-flight, vorticity, phase transition, heat conduction, radiation, thermophysical modeling

1. Introduction

Lasers have a wide range of uses in materials processing. Besides the surface ablation of material and structural destruction of high-power lasers, lasers can be used at lower energy settings for annealing, machining, welding, hardening, glazing, as well as promoting of chemical reactions on the surface and in the bulk ([1], [2]). An example of the wide range of laser usage in processing is given by the deposition of films of high temperature superconductors; lasers are used not only in the ablation-deposition process, but in treatment and deposition of metallic and ceramic substrate elements and in post-deposition treatment. Practically all materials can be treated using lasers. However the setting of power parameters is a function of the energy absorbed in the light/material interaction and the thermal properties of the specific material. Thus, there may be a difference of several orders of magnitude of the power settings to accomplish a particular task for different materials. And of course, different lasers will be better matches than others for a particular task on a given material. The actual light energy available to a workpiece depends on the laser power, frequency, optical train, and ambient atmosphere. The energy absorbed depends on the optical properties of the material, the surface finish, and temperature and phase of the material. This energy is converted into heat available for conduction, radiation, and the latent heat of melting and vaporization. When the laser intensity is high enough, material will be ablated from the surface. The ablation process involves supercritical phase transitions, material strength, shocks, and plasma formation. The resulting plume can then be used for deposition on a substrate. Laser deposition is currently the subject of much

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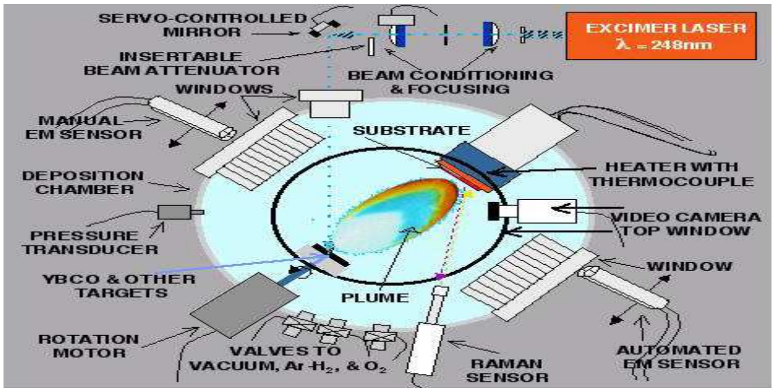

FIGURE 1. In-situ real-time process control pulsed laser deposition system.

interest for its possibilities in manufacturing films. Pulsed laser deposition (PLD) is a method for making very high quality films, and is considered, to be, among the available methods, the best compromise between speed and quality, at least for the foreseeable future. Deposition processes have been used to grow many different metals and semiconductors, including Ag, Al, Cu, Ni, Cd, Cr, Nb, V, Si, GaAs, and their oxides.

This paper deals with two topics illustrating how modeling and computation are aiding the applied scientist in laser materials processing. The first topic deals with the difference in light/matter interaction between metals and oxides, in particular in identifying thresholds for the onset of ablation. Practically all materials can be treated using lasers. However the setting of power parameters is a function of the energy absorbed in the light/material interaction and the thermal properties of the specific material. Thus, there may be a difference of several orders of magnitude of the power settings to accomplish a particular task for different materials. And of course, some lasers will be better matches than others for a particular task on a given material. The actual light energy available to a workpiece depends on the laser power, frequency, optical train, and ambient atmosphere. The energy absorbed depends on the optical properties of the material, the surface finish, and temperature and phase of the material. This energy is converted into heat available for conduction, radiation, and the latent heat of melting and vaporization. A challenge that arises in the numerical modeling is the fact that the thermophysical properties of different classes of materials are highly temperature dependent. It is useful to approach numerical experimentation in a manner analogous to physical experiments, using nondimensional constants that can characterize different regimes of interaction. We have assembled a database of optical and thermophysical properties for metals, alloys, and ceramics. These include Ag, Al, Cu, Ni, Al_2O_3, CuO, NiO, CeO_2, , UO_2, Y_2O_3, ZrO_2, and $YBa_2Cu_3O_7$. We treat both single-crystal transparent dielectrics and “black” phase ceramics. The lasers that we have considered range from the UV (ArF, KrF, XeCl), to VIS (ruby), and IR (Nd:YAG). Although some lasers, such as Nd:YAG and ruby are capable of sustaining power for milliseconds, we restrict attention to pulsed lasers with pulselength in the range 10ns to 100ns. This is taken up in section 2.