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Melt dynamics and melt-through time in continuous wave laser heating of metal films: Contributions of the recoil vapor pressure and Marangoni effects

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ABSTRACT

The relative contributions of evaporation and melt expulsion due to the recoil vapor pressure and Marangoni effects to the laser damage and melt dynamics in continuous wave (CW) laser interactions with free-standing aluminum films are evaluated in two-phase hydrodynamic simulations. In order the establish the dominant damage mechanisms in different irradiation regimes, the results of hydrodynamic simulations are compared with the predictions of several simplified models that only account for a subset of the involved processes. The hydrodynamic simulations performed in the range of film thickness from 0.2 mm to 4 mm and laser spot radius from 0.1 mm to 1 cm reveal only a marginal effect of the Marangoni stresses on the overall picture of melt flow and the melt-through time. The recoil pressure effect, on the contrary, is capable of strongly decreasing the melt-through time in a certain range of laser intensity. At laser intensities below this range the melting process is largely defined by heat transfer in the radial direction, while at laser intensities above this range the thickness of the molten pool and the efficiency of melt expulsion decrease and evaporation becomes the primary mechanism of material removal from the center of the laser spot. The range of laser intensities where the melt-through time is controlled by the recoil pressure effect is not unique and depends on the film thickness. A simple two-phase one-dimensional thermal model of laser melting, where melt expulsion due to the recoil pressure effect is accounted for based on the Bernoulli integral, is developed and found to be capable of accurate prediction of the melt-through time above a certain level of laser intensity. The one-dimensional thermal model captures all qualitative trends revealed in the direct hydrodynamic simulations and can be used as a robust engineering tool for the first-order estimation of the conditions for CW laser damage of metal films.

1. Introduction

High-power continuous wave (CW) lasers are used in various industrial applications that involve welding, drilling, and cutting of various materials [1], as well as in studies aimed at evaluation of laser damage in a beamed energy attack [2,3]. The irradiation conditions in CW laser – material interactions are characterized by broad ranges of laser spot diameters, from tens of micrometers [4] to tens of centimeters [2,5], and laser intensities, up to 10^9 W cm^{-2}, which are accessible with either powerful CO_2 lasers or compact CW laser systems based, e.g., on single-mode fiber lasers [4,6]. Even the maximum levels of power density accessible with CW lasers are still orders of magnitude smaller than the energy densities that can be generated with short and ultra-short pulsed lasers [7]. Correspondingly, the extreme levels of superheating required for the onset of volumetric ablation through phase explosion or explosive boiling, which play a major role in material removal with short pulsed lasers [8–10], are not achieved with CW lasers.

The primary mechanisms of CW laser damage and material removal are evaporation and melt expulsion from the center of the laser spot. The latter process of radial outflow of the melt from the center of the laser spot usually results in the formation of a large rim of resolidified material around the spot edge [1,7] or spattering of a liquid layer [4]. The traces of the melt flow are usually clearly visible at experimental images of metal surfaces irradiated by high-power CW lasers [6]. The melt expulsion decreases the characteristic thickness of the molten pool in the central part

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of the laser spot and increases the velocity of propagation of the solid-liquid interface, thus, rising the efficiency of laser drilling and reducing the melt-through time in laser damage to metal films. An additional process that may strongly affect the rate of material removal and the characteristics of laser damage is the heterogeneous oxidation at the laser spot. The oxidation can lead to the formation of an oxide film that can substantially change the optical, thermal, and mechanical properties of the surface. The energy release during the exothermal heterogeneous oxidation and gas-phase burning of the vaporized material can serve as a source of secondary heating of the irradiated surface [11] and increase the rate of material removal from the center of the laser spot [12].

The two main driving forces responsible for melt expulsion from the laser spot are the recoil pressure created by the active evaporation process and the Marangoni effect. Both of these effects arise from nonhomogeneous, often Gaussian [7], distribution of the deposited energy across the laser spot and, correspondingly, nonhomogeneous distribution of surface temperature.

The melt expulsion by the recoil pressure is caused by the spatial variation of the normal stress exerted by vapor pressure within the laser spot. The gradient of vapor pressure induces melt flow from the high-pressure region at the spot center towards the low-pressure periphery of the molten pool [13–15]. A substantial influence of the recoil vapor pressure on the dynamics of the molten pool was also observed in recent particle-resolved multiphase simulations of Selective Laser Melting (SLM) of metal powders, e.g., [16], where the recoil pressure was found to play an essential role in trapping small voids inside resolidified material in a process that involves collapse of depressions appearing at the surface of the molten pool in the regime of keyhole formation.

The Marangoni or thermocapillary effect involves the formation of strong tangential stresses on a non-uniformly heated surface of the molten pool due to the dependence of the surface tension on temperature, e.g., [17]. Since the surface tension of liquid metals decreases with increasing temperature, e.g., [18], the Marangoni stresses act in the direction opposed to the direction of the surface temperature gradient. In the case of laser heating, the temperature usually peaks at the center of the laser spot and the Marangoni stresses induce melt flow from the center to the periphery of the spot, thus providing an additional contribution to melt expulsion. At high heating rates and small thicknesses of the molten layer, the Marangoni stresses can lead to the rupture of the molten layer [19], melt spattering, and formation of droplets [20].

At very high laser intensities, the melt expulsion can result in the removal of most of the melt [4] from the irradiated area. At moderate laser intensities, however, the efficiency of both mechanisms of the melt expulsion discussed above decreases, and an external gas flow applied either as a shear flow parallel to the irradiated target [3,5,21] or a jet directed towards the center of the spot [22,23] is used to intensify the melt removal and increase the speed of laser processing or cutting. The combination of material softening at temperatures close but not exceeding the melting temperature and an airflow-induced pressure difference between two surfaces of the irradiated film can also contribute to the damage of a metal film heated by a CW laser before the film melts to its full depth, as has been discussed in Ref. [2]. In the absence of an external gas flow or a substantial pressure difference on the two sides of the film (e.g., in irradiation of a pressurized container), one can expect that the laser damage is largely defined by the melting of the film to its full depth.

The majority of computational studies that apply hydrodynamic modeling to the analysis of laser melting are focused on large aspect ratio (ratio of the depth of the laser keyhole to its diameter) laser drilling at high laser intensities, when material removal from the keyhole is dominated by vaporization and melt expulsion caused by the recoil effect, e.g. [24]. The relative importance of the individual mechanisms responsible for the melt expulsion and removal is typically not discussed, although, for very high laser intensities characteristic for ultrashort laser pulses, a negligible contribution of the Marangoni effect has been reported for laser melting of glass targets [25]. For moderate laser intensities and moderate-to-small keyhole aspect ratios, the reports of pure hydrodynamic simulations are scarce (see, e.g., review in Ref. [1]) and the relative contributions of the recoil and Marangoni effects to the melt removal and target damage are not well understood. The estimations made by Semak and Matsunawa [13] predicted the overall strong effect of the recoil pressure, which was confirmed in simulations performed by Yilbas and Mansoor [14]. At the same time, Ajaev and Willis [19] and Willis and Xu [20] reported a negligible effect of the recoil pressure on the melt flow in laser melting of thin films, which was dominated by thermocapillary stresses in their simulations. Han and Liou [26] also concluded that the melt flow is mainly caused by the thermocapillary stresses, but pointed out that the contribution of the recoil pressure is not small and should not be neglected.

The goal of the computational study reported in the present paper is to explore the contributions of the vapor recoil and Marangoni effects to the CW laser melting and damage of aluminum films in a broad range of process parameters realized in both laser damage and material processing applications. The processes of laser heating, melting, and melt flow are investigated in a series of simulations performed with a two-phase hydrodynamic model. The films with thicknesses that do not exceed the laser spot diameter are considered, and the simulations are continued until the time when the melting front reaches the back surface of the film. This time is further referred to as the melt-through time and is considered as the primary measure of the laser damage. One of the main finding of the simulations is that the Marangoni effect only marginally changes the melt-through time for all conditions considered in this study. This conclusion contradicts the results previously reported in Refs. [19,20,26]. At the same time, for a fixed film thickness, there is a certain range of laser intensities, where the recoil vapor pressure has a strong effect on the melting process and reduces the melt-through time by a factor of two as compared to the simulations where melt expulsion is not taken into account. We also show that the results of two-dimensional (2D) hydrodynamic simulations are in qualitative (and, for sufficiently high laser intensities, quantitative) agreement with results obtained with a simple and robust one-dimensional (1D) thermal model, where the effect of melt expulsion is accounted for based on the Bernoulli integral.

2. Hydrodynamic model of CW laser melting

The hydrodynamic simulations are performed for a planar freestanding aluminum film of thickness H_0 irradiated by a CW laser. The laser is assumed to irradiate the target in the direction normal to the initial film surface, producing an axially symmetric Gaussian distribution of laser intensity with respect to the center of the laser spot, as schematically shown in Fig. 1(a). Absorption of laser energy by the target material induces its melting and flow of the molten material. These processes are assumed to be 2D and axisymmetric and are considered in the central part of the computational domain shown as $OA'B'C$ in Fig. 1(b). In the periphery of the computational domain, beyond the region affected by laser melting, the heat conduction equation is solved to ensure realistic representation of heat transfer from the central part of the laser spot. The position of the free surface BC is described by the height function $H_w(r,t)$, where r is the radial distance from the axis of