Analysis of laser-induced hydrodynamic phenomena in the laser shock cleaning process

Bukuk Oh¹, Dongsik Kim¹, and Jong-Myoung Lee³

¹Department of mechanical engineering, POSTECH, Pohang 790-783, Korea
³Laser Engineering Group, IMT Co. Ltd., Uiwang 449-860, Korea

E-mail: dskim87@postech.ac.kr

Abstract. The hydrodynamics including the optical breakdown and shock wave formation is central to the analysis of the laser shock cleaning (LSC) process. In this work, a 2-dimensional theoretical model is proposed for computation of the hydrodynamic phenomena occurring in the LSC process. It is demonstrated that the results of the numerical computation are in good agreement with experimental observations and reveal the details of the physical mechanisms underlying the LSC process. Furthermore, the hydrodynamics of gas jet injection to sweep the detached particles away is investigated employing the theoretical model.

1. Introduction

Recent studies on the laser shock cleaning (LSC) have shown that the LSC process is effective for removing submicron particles from solid surfaces as a non-contact, dry method [1-3]. In the LSC process, the hydrodynamic phenomena including laser-induced breakdown (LIB) and evolution of temperature, pressure, and density are important in determining the cleaning efficiency. Consequently, several investigations were recently performed to analyze the hydrodynamic phenomena using optical detection methods [2,3]. The results of the hydrodynamic analysis were compared with the particle-removal efficiency, revealing the correlation between the hydrodynamics and the cleaning efficiency [3]. However, in the previous studies, the experimental data were analyzed based on the simple blast wave theory [4]. Accordingly, previous studies could not explain some important characteristics of the process, such as asymmetry of the shock wave shape and cleaning efficiency. Though the LIB phenomenon is relatively well understood [5-7], no theoretical analysis has been performed on the LIB-induced flow and its interaction with a solid surface. This work proposes a theoretical model for the hydrodynamics in the LSC process, i.e., LIB, shock formation, propagation, and interaction with a solid surface and external flow. The computation model is based on the multiphoton/avalanche ionization rate equation, two-dimensional Navier-Stokes equations, the scalar transport equations for ions and electrons, and the energy equation. Using the proposed theoretical model, numerical computation is carried out to reveal the details of the flow phenomena. Furthermore, preliminary studies are performed on the hydrodynamics of gas jet injection for eliminating the detached particles. Though it is obvious that optimizing the external flow is critical for preventing redeposition of the detached particles, the effect of the external flow on the LSC process has never been systematically examined. To verify the proposed model, the computation results are compared with the experimental results obtained by the laser flash photography. In the experiment, a Q-switched laser (wavelength $\lambda = 1064$ nm, full width at half maximum FWHM = 6 ns) and a N₂-pumped dye laser ($\lambda = 640$ nm,
FWHM= 4 ns) are used to generate LIB and for ns time-resolved visualization of the process, respectively. Details of the experimental setup can be found in our previous work [2,3].

2. Theoretical modelling

The LIB can be modeled via the multiphoton ionization (MPI) and the impact ionization by electron/atom collision as the laser irradiance with order of $10^{13}$ W/cm² is high enough to activate these ionization mechanisms. Equation (1) shows the ionization model used in the present work, considering the avalanche ionization and MPI mechanisms [6] ($n_e$, $n_i$: electron and atom concentration [cm⁻³], $\nu$: ionization collision frequency [Hz], $K$: multiphoton order, $I(t)$: laser intensity [W/cm²], $\omega$: laser frequency [Hz], $t$: time [s], $h$: Planck’s constant [Js]):

$$\frac{\partial n_e}{\partial t} = mn_e + \left[ \frac{n_e A}{K^{3/2}} \right] I^K(t), \quad A = \sigma^K / \omega^{2K-1} h^K (K-1)!$$

(1)

Though an analytical expression for the MPI coefficient $A$ is given in the above equation [8], the precise value of the photon cross section $\sigma$ is unknown though it is in general of the order of $10^{-16}$ cm² [9]. Accordingly, the photon cross section $\sigma$, i.e., $A$, has been estimated experimentally by fitting the value to the experimentally measured shock-propagation speed. The estimated photon cross section is $\sigma=2.4\times10^{-16}$ cm². In the fitting process, the difference between the calculated and measured shock wave velocities was minimized for a propagation distance $r=3$ mm by varying the photon cross section from $1.0\times10^{-16}$ to $1.0\times10^{-15}$ cm². Variation of the photon cross section leads to changes in the hydrodynamic phenomena. For example, the maximum pressure varies from 0.8 to 2.0 MPa at $r=2$ mm for the cross section from $1.0\times10^{-16}$ to $1.0\times10^{-15}$ cm², respectively. However, numerical calculation shows that varying the photon cross section does not affect the qualitative nature of the flow structure, which justifies our estimation of the $\sigma$ value. Other parameters such as the shock intensity can also be used to determine the $\sigma$ value but the choice of a fitting scheme did not result in meaningful changes in the computation results. The initial electron number density has been assumed to be zero. It is noted that presence of impurities with low ionization potential can affect the ionization rate but the change did not affect the overall computation result with a properly adjusted $\sigma$ value. The incident laser pulse energy is absorbed by the inverse Bremsstrahlung process through electron-ion collisions. This absorption process is modeled by the plasma absorption coefficient [10]. Expansion of the high-temperature plasma is followed by shock wave generation. The subsequent hydrodynamic motion has been modeled by 2-dimensional transport equations for mass, momentum, and energy conservation [11]. The transport equations are simultaneously solved for atoms, ions, and electrons.

3. Results and discussion

Numerical simulation was carried out for LIB of N₂ by a Q-switched Nd:YAG laser ($\lambda=1064$ nm, FWHM=6 ns, ambient pressure $P_0=1.0$ atm). The results of the numerical simulation show good agreement with the experimental results qualitatively. Furthermore, the magnitude of the physical variables is also in reasonable agreement with the experiment although the present model is two-dimensional. For instance, the calculated maximum pressure at $r=2$ mm is 1.1 MPa while the measured value is 1.0 MPa [2]. Figure 1 shows the pressure field calculated by numerical simulation, indicating good agreement with the experimental result by the laser flash photography. Notable is that the present model gives the asymmetric flow features that the simple blast wave theory cannot predict. Initially, the high temperature/pressure core occurs at the focal point. As the shock wave expands, the density and pressure around the focal point becomes smaller than those at the shock front. Correspondingly, the absorption coefficient has two peaks at the shock-laser intersection, one at the
left-propagating shock front and the other at the right-propagating front. This bipolar distribution of the absorption coefficient causes the egg-shaped, multi-point shock wave generation. The temperature of plasma generated by LIB ($I=1.34 \times 10^{13} \text{ W/cm}^2$, pulse energy $E=310 \text{ mJ}$) increases up to $2 \times 10^5 \text{ K}$ at the end of the pulse. As the shock wave expands the temperature at the plasma core decreases to 7000 K at 2 $\mu$s, which is close to that reported in a similar numerical calculation of LIB ($\lambda=1064 \text{ nm}, \text{FWHM}=7 \text{ ns}, P_0=0.8 \text{ atm}, E=300 \text{ mJ}$) [7].

Figure 2 shows the calculated average shock wave speed for a position 3 $\mu$m from the focal point (average value along the laser beam axis). In the focal region, the degree of ionization becomes 100% during the laser pulse and the ionization front moves away from the focal point. Consequently, the shock wave speed and pressure become eventually saturated as the laser irradiance is enlarged. These results explain the experimental observation of the saturation behaviour [2]. Figure 3 displays the pressure field after the shock front contacts the sample surface. It reveals that the intensity of the shock wave is larger in the left-hand side than in the right-hand side. This is because the incident laser beam is first absorbed when it intersects the left-running shock front and the reminder is absorbed later. Our previous investigation on the spatial distribution of the cleaning efficiency indicated this asymmetry of the efficiency experimentally [3] and this calculation explains the physical mechanism.

Figure 4(a) exhibits the pressure and horizontal-velocity distributions in the region close to the sample. The pressure and velocity values were computed at a height of 100 $\mu$m above the sample surface. The symbol $x$ represents the direction parallel to the sample and $x=35 \text{ mm}$ is right below the focal point. The initially bell-shaped high pressure core expands forming a spherical shock wave as time elapses. As the shock wave expands, a rarefaction zone is formed behind the shock front and the adverse pressure gradient can induce backward flows. These backward flows complicate the flow structure and may cause the secondary stagnation regions.

To prevent redeposition of the detached contaminant, external gas jets are normally ejected through a nozzle in the practical LSC process. In this work, the effect of the gas jet ejection on the flow field was examined for a 2 mm-wide nozzle attached on the left end of the sample surface ($x=0$). The nozzle blows N$_2$ gas at a flow rate of 20 $l/min$ (velocity: 20 m/s). Figure 4(b) shows the effect of the blowing on the pressure and horizontal-velocity distributions. The flow rate 20 $l/min$ is a typical value used in practical LSC processes. The computation reveals that gas jet ejection has only a negligible effect on the flow field, and thus on the particle removal force, in the initial stage with order of 1 $\mu$s. On the other hand, the long-term flow structures occurring over order of 100 $\mu$s are strongly affected by the external flow (see the third low in figure 4). The blowing enhances the sweeping flow motion over an increased surface area, suggesting a reduced chance of particle redeposition. However, the stagnation region has not been completely removed with the gas blowing, which is because the blown gas flows against the LIB-induced flow in some regions. Consequently, further investigations are required for
optimizing the blowing process. Particularly, the motion of particles in the flow field over the surface and the role of suction nozzles as well as multiple nozzles need to be studied systematically.

4. Conclusions
In this work, a theoretical model for the hydrodynamics has been proposed for elucidating the LSC process. Numerical computation of the LSC process does not only show good agreement with experimental observations but also explains the details of the hydrodynamic phenomena. The plasma formation is found to be asymmetric, leading to higher shock intensity in the upstream region of laser irradiation. The backward flows induced by shockwave propagation complicate the flow structure and may cause the secondary stagnation regions. Blowing a gas from a nozzle has negligible effect on the flow field in the initial stage where particle is detached by shock impingement. However, it significantly enhances the long-term sweeping flow, decreasing the chance of particle redeposition.

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