Laser-Matter Interaction with Pulsed Lasers

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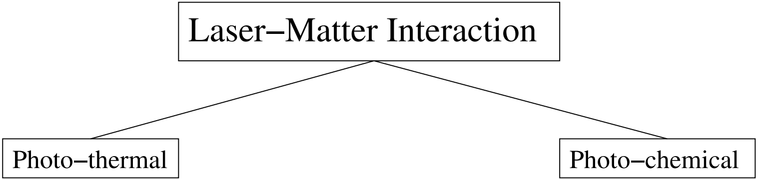
ME 677: Laser Material Processing



- Photo-thermal: Photons are absorbed causing heating effects (metals/non-metals)
- Photo-chemical: Absorbed photons cause chemical degradation

Metals Nonmetals

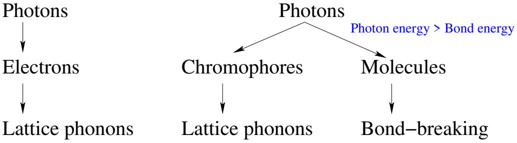
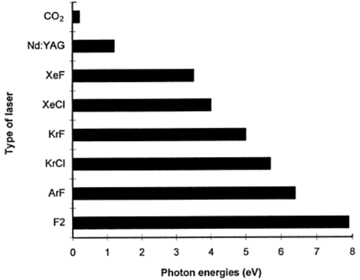
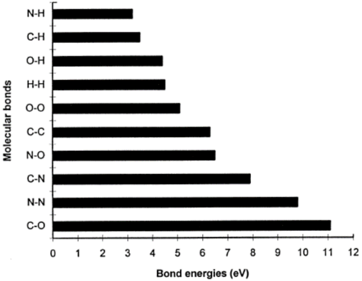


Photo-Chemical Interaction





- Photo-chemical interaction occurs only of $h\nu > B.E.$ (B.E. is bond energy)
- Causes chemical decomposition of the target material
- Involves chemical reactions
- Excimer laser interaction of polymers usually involve a combination of photo-chemical and photo-thermal mechanisms

Physics of Photo-thermal Interaction

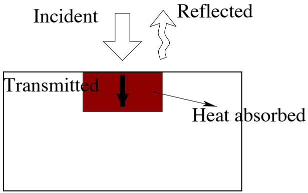
- Heat Conduction Equation:

$$\rho c_p \frac{\partial T}{\partial t} = K\nabla^2 T + S \qquad (1)$$

$$S = \alpha I(x), \qquad (2)$$

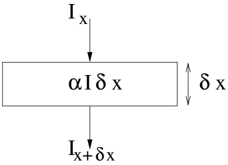
- With a moving boundary:

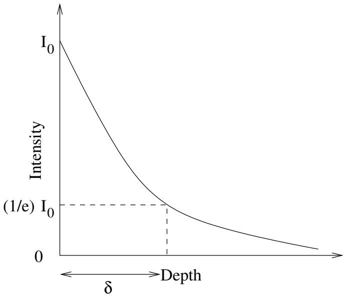
$$\rho c_p \left(\frac{\partial T}{\partial t} - \frac{\partial x}{\partial t}\bigg|_{x=0} \frac{\partial T}{\partial x} \right) = K\nabla^2 T + S \qquad (3)$$



ρ: density, c_p: specific heat, I: intensity,
T: Temperature, K: thermal conductivity, α: absorption coefficient,
S: heat source term, I_L: Laser intensity, I_0: Intensity at the surface
R: Reflectivity

Beer-Lamber Law



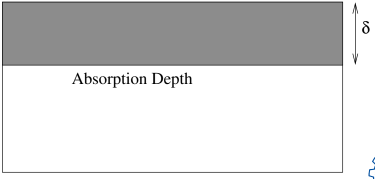


$$I_{x+\delta x} - I_x = -\alpha I \delta x \qquad (4)$$

$$\Rightarrow \frac{dI}{I} = -\alpha I dx \qquad (5)$$

$$I(x) = I_0 \exp(-\alpha x) \qquad (6)$$

$$I_0 = (1 - R) I_L$$



Microscopic View

Photons ⟶ Electrons ⟶ Lattice phonons

⟵ Thermal Relaxation Time (TRT) ⟶

- Thermal relaxation time (TRT) is $\sim$ picoseconds
- One-step model is applicable only if pulse duration (t_p) is $\ll$ TRT

Two-step Model

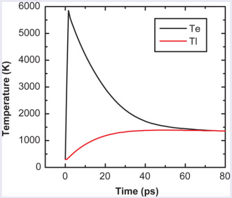
1. Electron subsystem: Photons $\rightarrow$ Electrons

$$\rho_e c_e \frac{dT_e}{dt} = K\nabla^2 T_e + S - G(T_e - T_l)$$

G– Electron-phonon coupling factor

2. Phonon subsystem: Electrons $\rightarrow$ Phonons

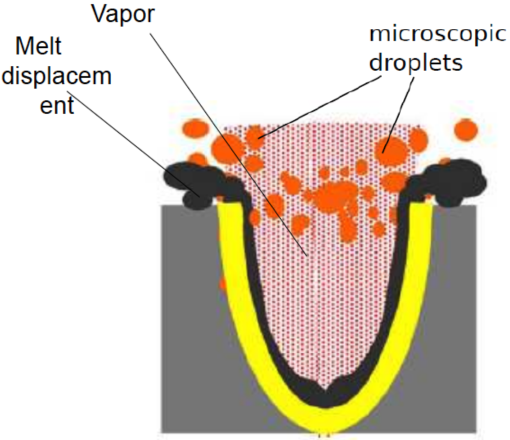
$$\rho_l c_l \frac{dT_l}{dt} = G(T_e - T_l)$$

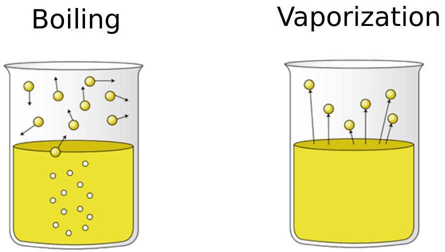


Source: Optics Express, 21(12), 14698-14711 (2013)

Material Removal Mechanisms

- Vaporization
- Melt expulsion
- Explosive boiling
- Coulomb explosion





Source: www.byjus.com

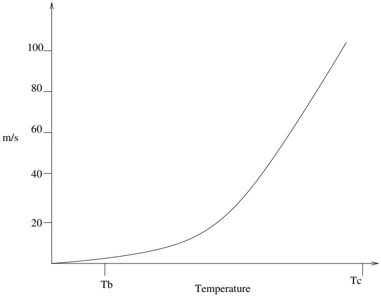
- Passage from condensed phase (sol or liq) to vapor phase
- Occurs by virtue of emission of particles
- Depends on surface temperature
- Normal boiling occurs only if pulse duration $> 100\ \mu s$

Hertz-Knudsen Equation:

$$u_s = P_s \sqrt{\frac{M_w}{2\pi k_b T_s}}, \qquad (7)$$

Clausius-Clapeyron Equation:

$$P_s = P_0 \exp\left[\frac{L_v}{k_b}\left(\frac{1}{T_b} - \frac{1}{T_s}\right)\right], \quad (8)$$



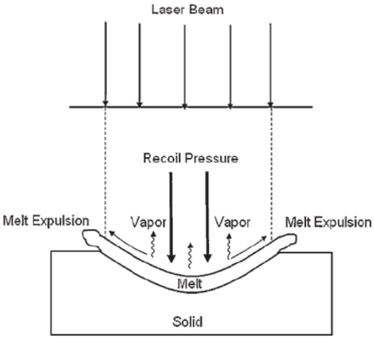
u_s: Surface recession rate (m/s)
T_s: Surface temperature
P_s: Saturated vapor pressure
M_w: Molecular weight
k_b: Boltzmann's constant

Melt Expulsion

- Occurs due to vapor/plasma recoil pressure
- The liquid splashes out from the sides of the crater

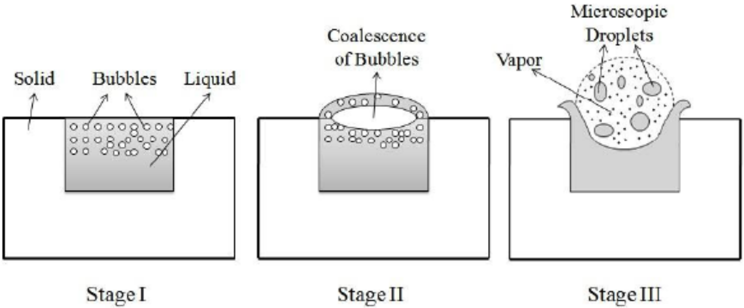
Undesirable!

Forms a cap or hump along the machined edge



Source: N.B. Dahotre and S.P. Harimkar (2008), Laser Fabrication and Machining of Materials, Springer, NY.

Explosive Boiling



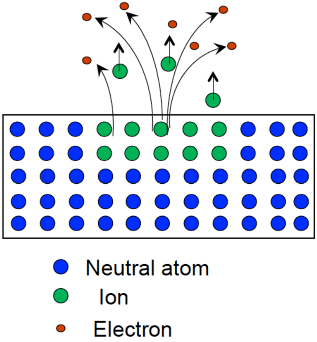
- Occurs due to super heating
- Due to high heating rates, T reaches close to Tc (Critical Temperature)
- Density fall rapidly after 0.8 Tc
- Leads to phase explosion near 0.9 Tc
- The liquid breaks down into vapor and liquid droplets

Coulomb Explosion

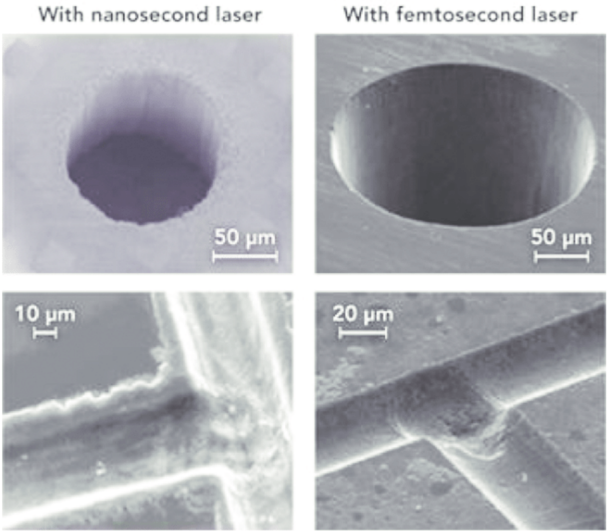
- Occurs for tp<1ps, under electron-phonon non-equilibrium
- Electrons are ejected out of the surface
- High electric field exists due to electron ejection
- The electric field breaks the bonds and ejects metal atoms (ions)
- Non-thermal process
- Also called as 'cold ablation'

Very desirable

No heat affected zone

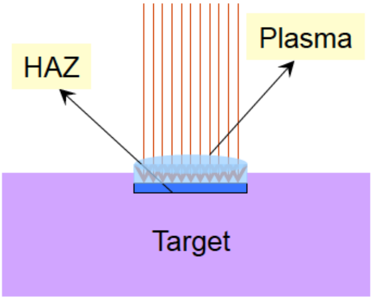


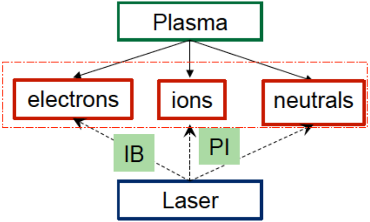
Nanosecond v/s Femtosecond Laser Processing



Source: High Energy and Short Pulse Lasers, Publisher: INTECH, pp.21

Plasma Shielding





Mechanisms of Photon Absorption

1. Inverse-Bremsstrahlung (IB)
2. Photo-Ionization

- IB occurs at all laser wavelengths
- PI occurs only if photon energy > Ionization Potential

- Ionization
  Saha Equation:

$$\frac{n_e n_i}{n_a} \approx 2.4 \times 10^{21} T_{pl}^{3/2} \exp(-E_I/k_b T_{pl}), \tag{9}$$

$n \rightarrow$ number density; e, i, a represent electron, ion and neutral atom, respectively.

- Inverse Bremsstrahlung Mechanism ($\alpha_{ib} = \alpha_{ea} + \alpha_{ei}$)
  (i) Elelctron-atom

$$\alpha_{ea} = \frac{e^2 n_e}{\pi m_a c \omega^2} (n_a) \sqrt{\frac{8 k_b T_e}{\pi m_a}}, \tag{10}$$

(ii) Elelctron-ion

$$\alpha_{ei} = \frac{3.7 \times 10^8}{\sqrt{T_e}\omega^3} [1 - \exp(-h\nu/k_b T_e)] n_e n_i \tag{11}$$

- Photo-Ionization

$$\alpha_{pi} = \sigma_{pi} n_0 \tag{12}$$

$n_0 \rightarrow$ number density of neutrals
$\sigma_{pi} \rightarrow$ photo-ionization cross-section

$$\sigma_{pi} \approx 2.9 \times 10^{-21} \frac{E_I - E^*}{(h\nu)^3} \tag{13}$$

$E_I \rightarrow$ Ionization potential
$E^* \rightarrow$ Energy of excited state
Only if $\implies h\nu > E_I - E^*$
Typical values of σ_{pi} are in the range of 10^{21} m^{-2}

- Plasma shielding: Laser intensity after passing through the plasma

$$I_{sh} = (1 - R_{pl}) I_L \exp\left(-\int_0^{h_{pl}} (\alpha_{ib} + \alpha_{pi}) dx\right) \tag{14}$$

Plasma Shielding: Intensity Drop