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by

K. H. Leong

Argonne National Laboratory, Argonne, Illinois 60439
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General Considerations

The optimal use of lasers requires the understanding of the primary parameters pertinent to laser beam-material interactions. Basically, the laser beam is a heat source that can be controlled to deliver a wide range in intensities and power. When interacting with a material, reflection at the surface, and transmission and absorption through the material occur. The material interaction process is governed by the irradiance (power/unit area) of the incident beam and the interaction time resulting in an amount of heat /energy applied to the material per unit area.

The laser beam is a flexible heat source where its intensity and interaction with materials can be controlled by varying the power and size of the beam or the interaction time. For any material, a minimum amount of energy has to be absorbed for the material to be ablated by the laser beam, i.e., a solid has to be heated to liquefy and then vaporize. Under certain conditions, the photon energy may be able to break the molecular bonds of the material directly. In general, the energy absorbed is needed to vaporize the material and account for any heat that may be conducted away. Consequently, the interaction is a heat transfer problem. The relevant parameters are the heat flux and total heat input to the material. The corresponding parameters for the laser beam-material interaction are the irradiance of the beam and the interaction time. The product of these two parameters is the energy applied per unit area. A high irradiance beam may be able to ablate a material rapidly without significant heat transfer to surrounding areas.

For drilling or cutting materials, a high intensity beam is required for laser ablation with minimal heat lost to the surrounding areas. However, at high beam irradiance (>1 GW cm^{-2} for Nd:YAG beams), plasma formed from ionization of gases and vapor will partially absorb or diffract the beam. Reduced penetration of the material results. Similarly, in welding using CO2 lasers where the beam irradiance is ~1 MW cm^{-2}, the plasma plume formed decreases penetration. A high velocity jet of inert gas is usually used to blow away the plasma.

If we consider the interaction time as the pulse length of the beam, the length of the heat affected zone (HAZ) can be estimated by the equation:

$$L_h \sim (\alpha_t \tau_p)^{1/2} \qquad (1)$$

The heat affected length given by equation (1) for sandstone is shown in Fig. 1. Negligible (<1μm) heat effects occur for pulse widths <1 μs. As the interaction time increases, melting and vaporization of the material at the surface may occur and heat is diffused into the material. A better representation of the pertinent parameters and the type of laser beam-material interaction that occurs is depicted in Fig. 2.

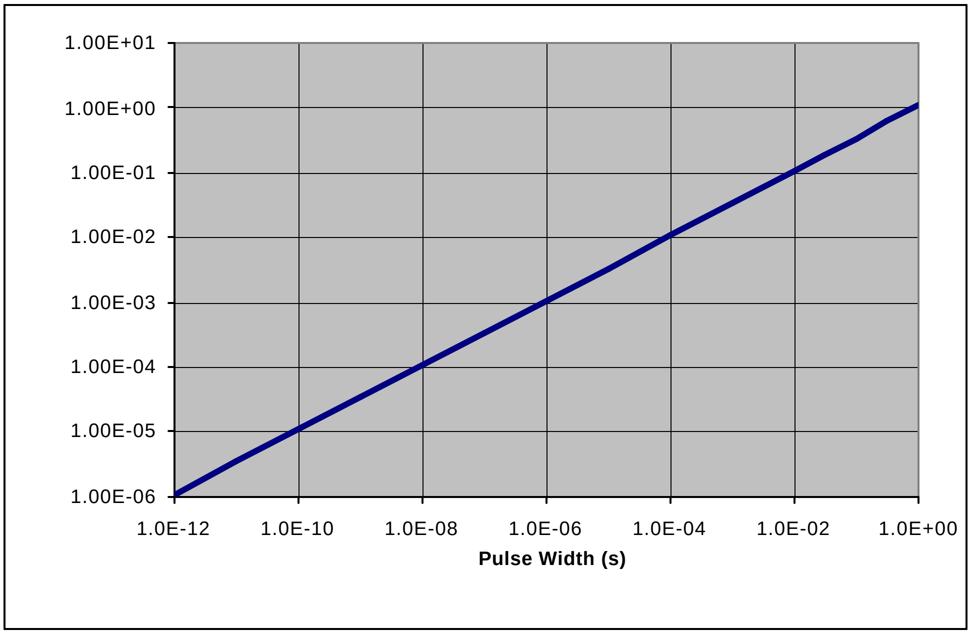

Figure 1. Heat affected length for sandstone with α_t=0.0113 cm^2s^{-1} at different laser pulse widths.

The different regimes of laser processing applications are illustrated in Fig. 2 where the abscissa is the interaction time and the ordinate is the irradiance (based on [1]). The product gives the fluence or energy deposited per unit area of the material. For high thermal conductivity materials like metals, a long interaction time would produce a substantial heat affected zone. Conversely, the long interaction time and high thermal conductivity would require a higher fluence for the process.

If we follow the fluence requirements for melting and vaporizing the material, we can define the regimes of heating, melting and vaporization as shown in Fig. 2. For ultra-short or sub-picosecond pulses, there is insufficient time for heat to conduct or diffuse into the material and insignificant melting occurs. The ultra-high irradiance breaks apart the molecular components directly from the solid phase to the gas phase. Hence the process is surface limited and ultra-precise machining can be accomplished. The process described is ideal for precision drilling of all types of solids. However, the speed of the process is limited by the power, i.e. the product of the pulse energy and repetition rate. Since femtosecond lasers that produce these ultrashort pulses are costly and are low in power (a few Watts), high speed macro-drilling (e.g. drilling of cooling holes in turbine blades) is carried out with higher power (>100W) lasers using ms pulses where some melting and heat affected zone occur. The use of ms pulses during the drilling process causes melt to be ejected and is actually more efficient than femtosecond pulses as not all the drilled material is vaporized as for the ultrashort pulse case. As the interaction time increases, the energy spent on creating the heat affected zone and melting will tend to decrease the energy efficiency of the process.

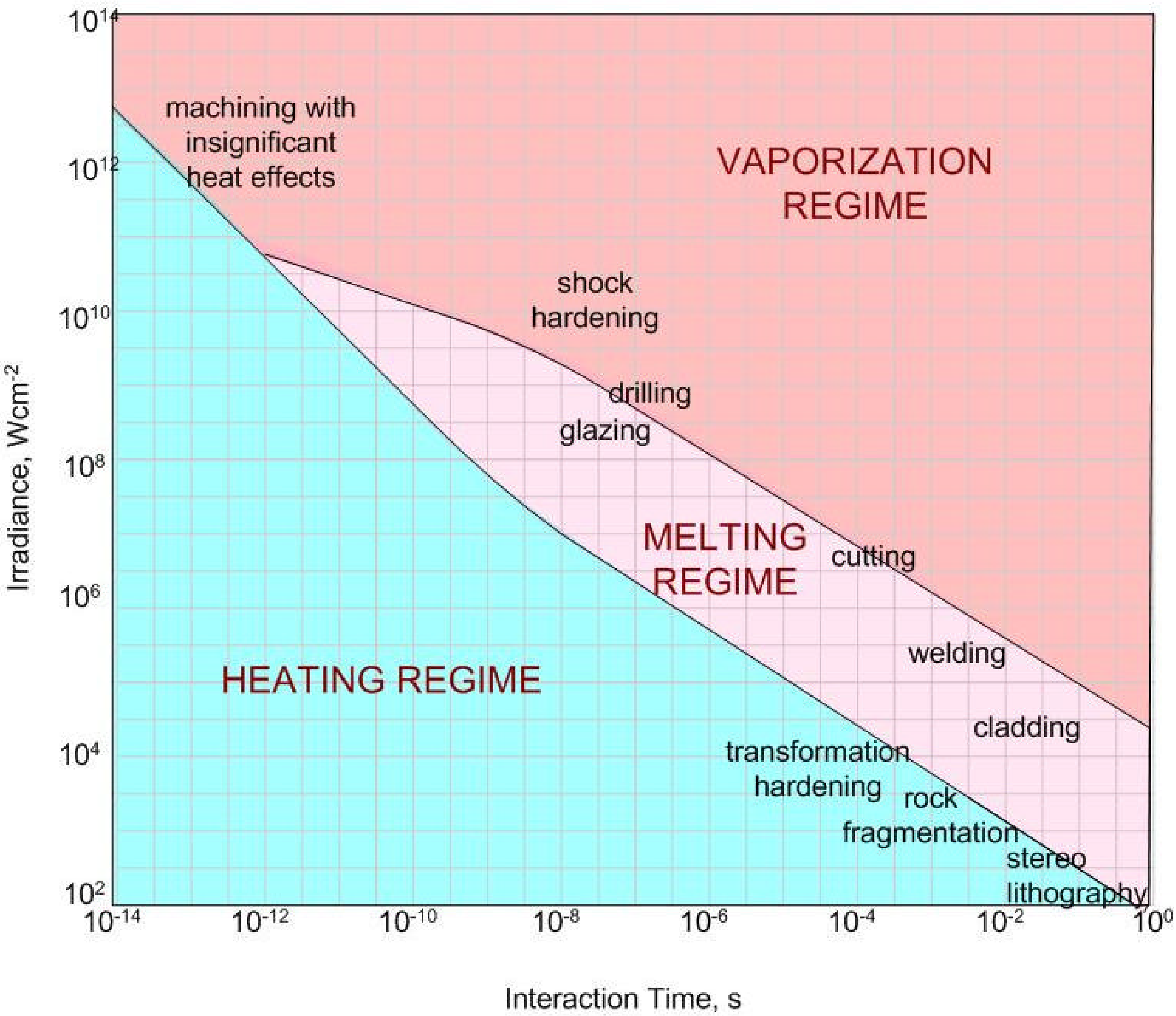

Figure 2. Laser processes mapped according to irradiance and interaction times.

For the case of welding, the process requires melting. Fig. 2 indicates that we have a broad process window (except for ultrashort pulses) where micro-welding to macro-welding can be carried out with a wide range of process speeds. The above discussion illustrates the process requirements in terms of laser beam irradiance and interaction time or pulse widths. Given a process and quality requirement, Fig. 2 helps to define the range of irradiance and interaction time needed. Equation (1) can then be used to determine the extent of the HAZ. The laser power or pulse energy and widths can then be determined given a process speed and spot size required. A suitable laser can then be selected.

Interaction with Rocks

Conventionally, a high irradiance beam is used in drilling to melt and vaporize or eject the melt. Recent data indicate that an alternate method can be used to drill rock. At relatively low irradiance, a laser beam can cause fragmentation of the rock. The specific energy required to drill sandstone and shale by fragmentation required <1 $kJcm^{-3}$ [2, 3]. Conventional laser drilling often requires >10$kJcm^{-3}$. For the fragmentation process to remain efficient, i.e. minimal melting or vaporization, the rock fragments formed from the interaction process will have to be removed to expose new solid rock for processing. If we start at an irradiance and interaction time regime to avoid melting for rock fragmentation, increasing the power, i.e. the irradiance may move the process into the melting regime. The same will also occur if the interaction time is increased. This deduction is consistent with the experimental results obtained where the interaction or pulse times for both CO_2 and Nd:YAG lasers were restricted to <1s to avoid melting of the sand at irradiances of ~$1kWcm^{-2}$ [2,3].

The major types of rock considered are limestone, sandstone and shale. Each of these rock types has a different composition [2, 4]. Limestone is essentially calcium carbonate and some magnesium oxide. Sandstone consists of quartz (85%), feldspar (10%) and other minerals while shale is similar with quartz (35%), feldspar (20%) and clays (45%). In addition to the minerals, rocks may contain varying amounts of adsorbed water. The porosity varies from 0.6% for limestone, 3% for shale to >20% for sandstone. The thermal diffusivity is $7.5x10^{-3}$ cm^2s^{-1} for shale, $8.1x10^{-3}$ cm^2s^{-1} for limestone and $11.3x10^{-3}$ cm^2s^{-1} for berea gray sandstone. See table 1.

	Limestone	Sandstone	Shale
Quartz		85%	35%
Feldspar		10%	20%
Clays			45%
Calcium carbonate	Bulk		
Magnesium oxide	Some		
Porosity	0.6%	>20%	3.%
Thermal Diffusivity cm^2/s	8.1×10^{-3}	11.30×10^{-3} (berea gray)	7.5×10^{-3}

Table 1. Rock compositions

To determine the effect of laser irradiance on a rock sample, the absorption coefficient of the rock constituents and their temperature stability need to be examined. The absorption coefficients for the major rock constituents are listed in Table 2. Some values are not readily available and may require a more thorough literature survey to ascertain. The most energy efficient process is to heat and vaporize the more volatile components producing a sudden volume expansion that will cause fragmentation, leaving grains or agglomerates of sand that can be removed by mechanical or gas assisted means. This method can be applied to sandstone and shale that consist mostly of quartz particles that are transparent to a broad spectrum of wavelengths and have a high melting point (>1600C). The water and more volatile components that are more absorptive of the incident laser radiation can then be vaporized. A short interaction time, allowing for the energy absorption and vaporization, will result in a high pressure pulse that will fracture the sandstone. The mechanisms considered (see Fig. 2 and Table 2) indicate that the Nd:YAG laser wavelength with lower absorption by the quartz particles and shorter pulses will be more efficient. Some of the fractured rock and particles will be ejected during the process. The remaining fractured rock will have to be removed by a gas assist to avoid being melted by further interaction with subsequent beam pulses. An alternative to the use of short pulses is the application of a high irradiance CW beam coupled with a high pressure gas assist to enable fast ejection of the fractured rock constraining the interaction time. However, this alternate method is not expected to be as energy efficient since the interaction time of the fragments with the CW beam is >1ms even for fragments traveling at near sonic speeds.

Limestone, however, has a different structure and composition. It consists of mostly solid calcium carbonate that has a melting point of 1100C and decomposition temperature of 899C. Rock fragmentation is limited and drilling of limestone will require high irradiance for melting and decomposition. Ejection of melt with assist gas will increase the efficiency of the process.

A hot plume of excited gas and particles is produced during the laser-rock interaction process at sufficient irradiance. This plume interacts with the laser beam, absorbing and scattering a fraction (~10-20%) of the energy. This hot plume may also diffuse the beam [6]. The beam irradiance that will cause ionization of a gas is inversely proportional to the square of the wavelength and inversely proportional to the pressure of the gas [7]. For particle-free air at 1 atmospheric pressure, the irradiance for breakdown exceeds 10^{11} Wcm^{-2} for 1.06 µm radiation. The presence of particles and contaminant gases from the laser-rock interaction will lower the breakdown irradiance substantially to $<10^7$ Wcm^{-2} [8]. At 100 atmospheres, the irradiance for breakdown will be $<10^5$ Wcm^{-2}. This lowering of the breakdown irradiance results in the formation of a high intensity plasma during the beam-rock interaction that tends to shield the beam and decreases the processing effectiveness. The effect can be ameliorated greatly by using an inert gas (argon or helium) jet to blow the plasma away from the region of interaction. This gas jet can also serve a dual purpose by helping to eject the fragmented rock.

Material	**Absorption Coefficient (cm^{-1})**		**Melting Temperature (C)**
	1.06 µm	10.6 µm	
Aluminum oxide (feldspar)			2980
Calcium carbonate			1100, d 899
clay			
Magnesium oxide			2852
Silica	$10x10^{-6}$	>10	1610
water	0.33	$7.0x10^2$	100 (boiling)

Table 2. Absorption coefficients and melting temperature of rock constituents.
Data from [5], CRC Handbook of Chemistry and Physics.

Status of Modeling Effort

Our initial efforts have elucidated the pertinent parameters in the beam-rock interaction process. The physical understanding of the process and its controlling parameters is necessary before formulating a predictive model. The subsequent tasks are as follows:

1. Perform a thorough literature survey to obtain the thermophysical properties of rock constituents. These properties include absorptivity at relevant laser wavelengths, specific heat, heat of vaporization, boiling point, and thermal expansion coefficients.

2. Initiate a 1-D heat transfer model to examine the probability of fragmentation of a multicomponent rock material. This will be a transient model that will take into account the short interaction times of laser pulses.

Task 1 is essential for input into Task 2. Improved understanding of the rock fragmentation process can be gained from a simple 1-D model that may also help to delineate major controlling factors. The initial model can then be refined and developed into a more representative 3-D model for optimization of beam parameters. Substantial energy savings can be gained by using rock fragmentation instead of conventional laser drilling. The predictive model will delineate the rock types suitable for fragmentation and also aid to optimize parameters for both fragmentation and conventional laser drilling.

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