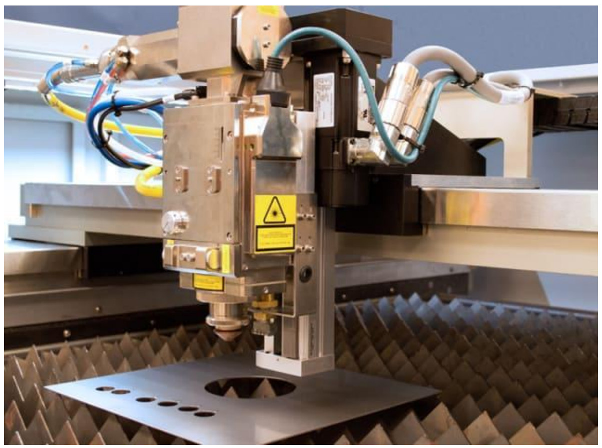
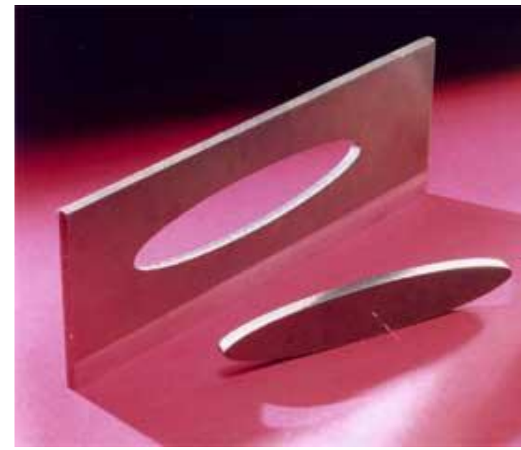
Laser Machining Processes

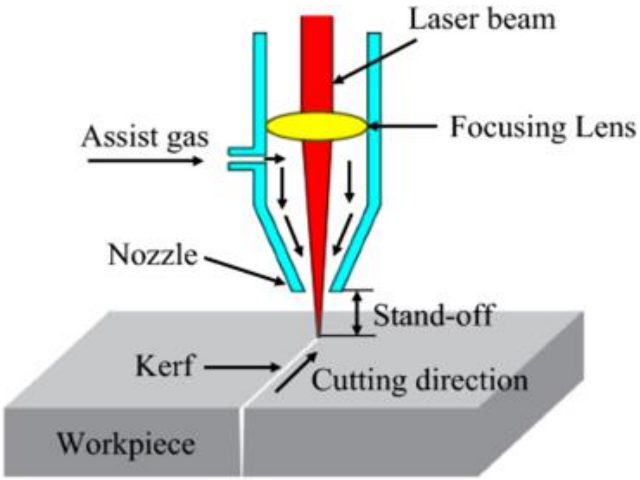
SLSE / PG First Year

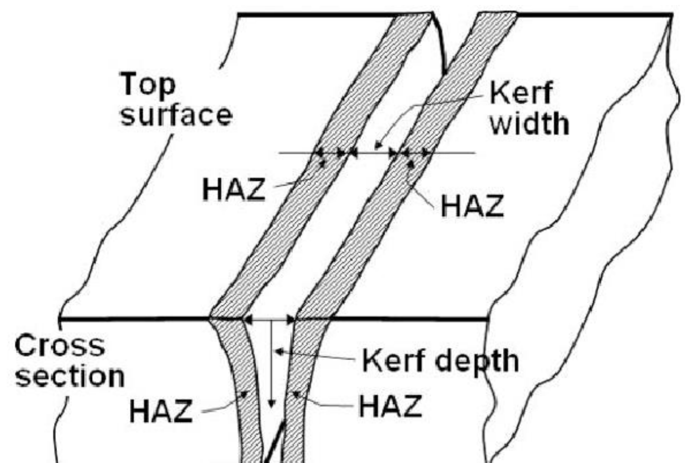
Laser Cutting-Introduction

- A focused laser beam is directed onto the surface of the workpiece to rapidly heat it up, resulting in melting and/or vaporization, depending on the beam intensity and workpiece material
- The power density required is typically of the order of 106–107 W/cm^2 for metals





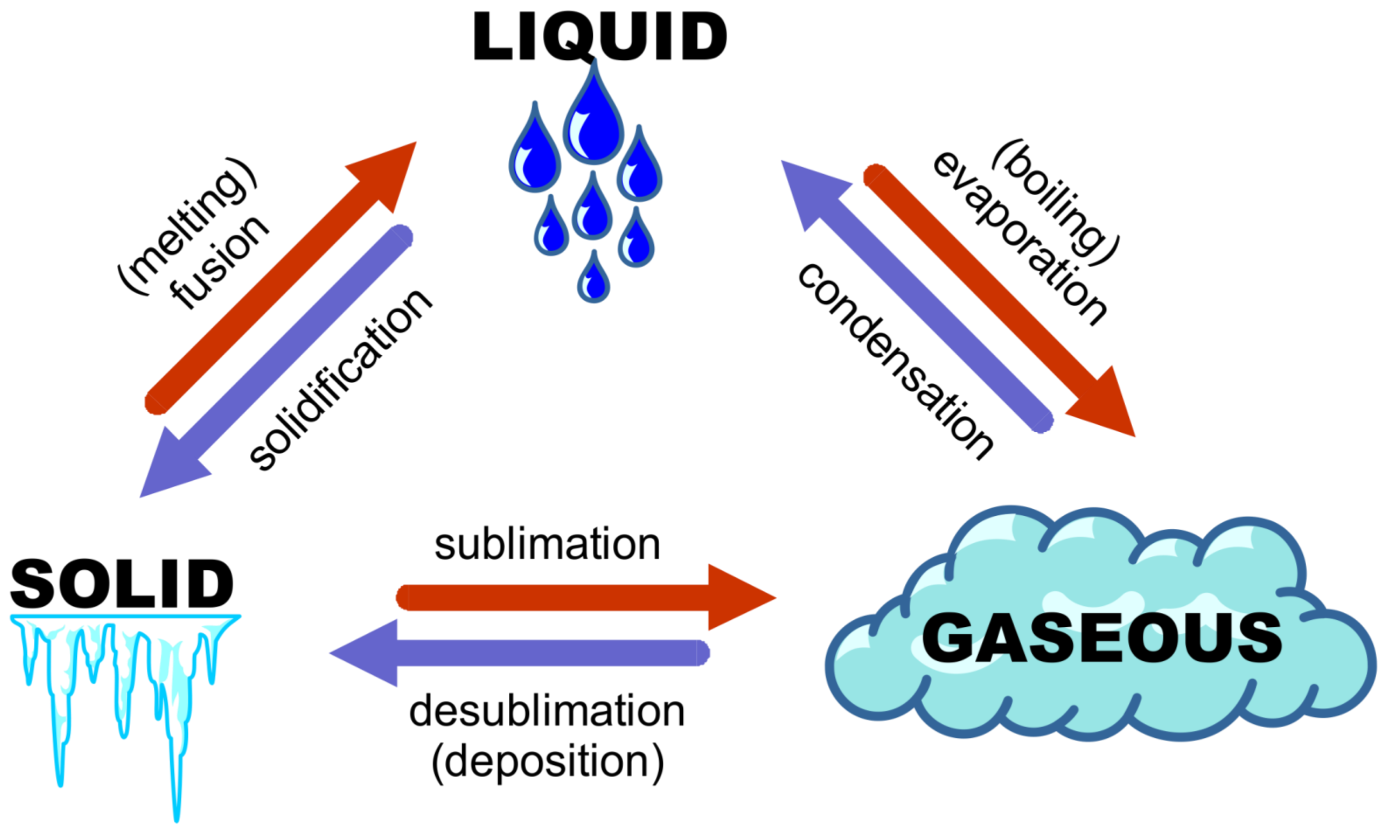




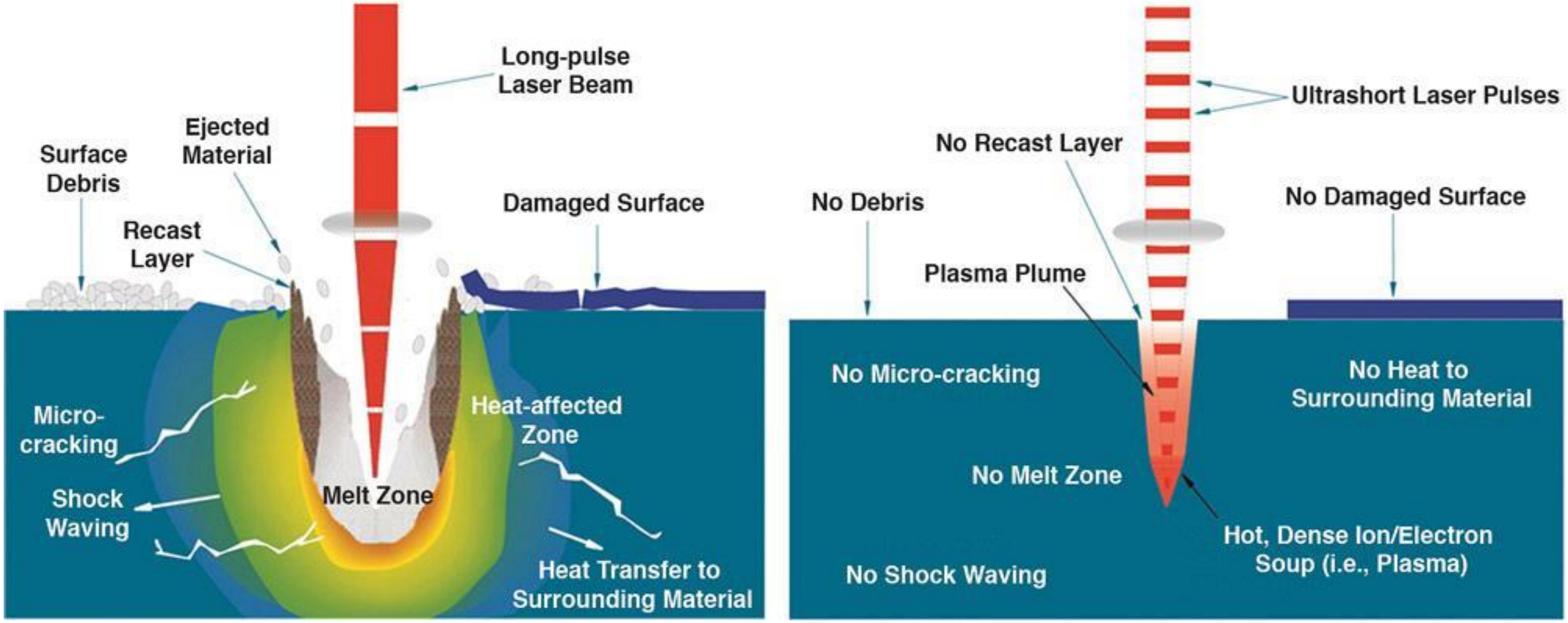
Forms of Laser Cutting

The process of laser cutting can occur in one of the three forms

1. Fusion cutting
2. Sublimation cutting
3. Photochemical ablation



Removal Mechanism



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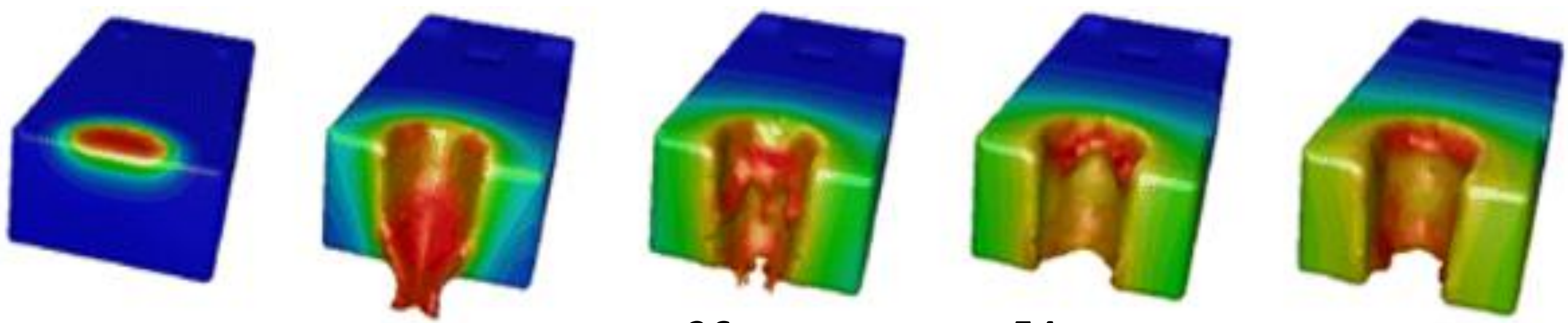
- Fusion cutting involves melting of the base material, which is then ejected using a high-pressure assist gas.
- The assist gas may be an inert gas, in which case the energy for melting is provided entirely by the laser beam.
- It may also be oxygen (or air), which reacts with the base metal, and the resulting exothermic reaction provides additional energy to enhance the process.
- The term fusion or clean cutting is sometimes used to indicate inert gas assisted cutting, while the process involving exothermic reaction is then referred to as gas cutting.



1.7 ms 12 ms 26 ms 54 ms 105 ms

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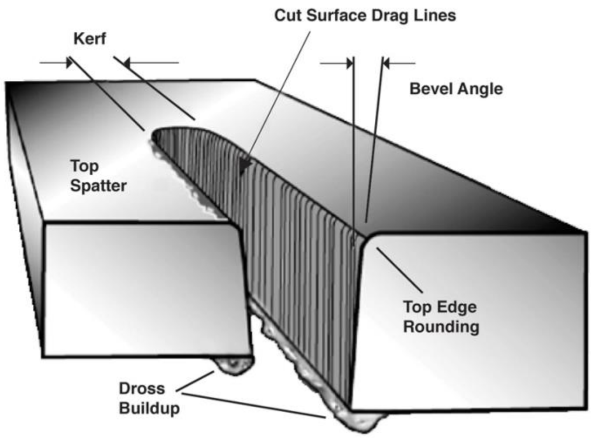
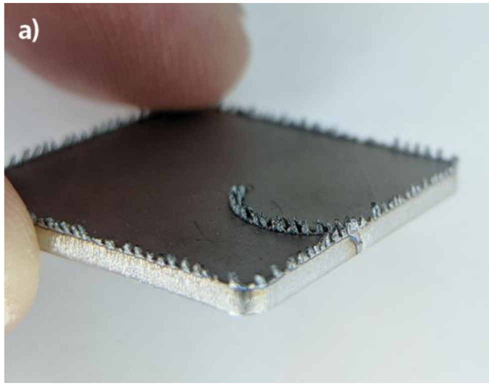
- A major problem of fusion cutting is the formation of striations (valleys and peaks that run along the thickness) on the cut surface and dross (molten material that clings to and solidifies on the underside of the cut edge as burr) at the lower cut edge.

- However, the fusion cutting process is more efficient, requiring less energy per unit volume of material removed as compared to the other methods.





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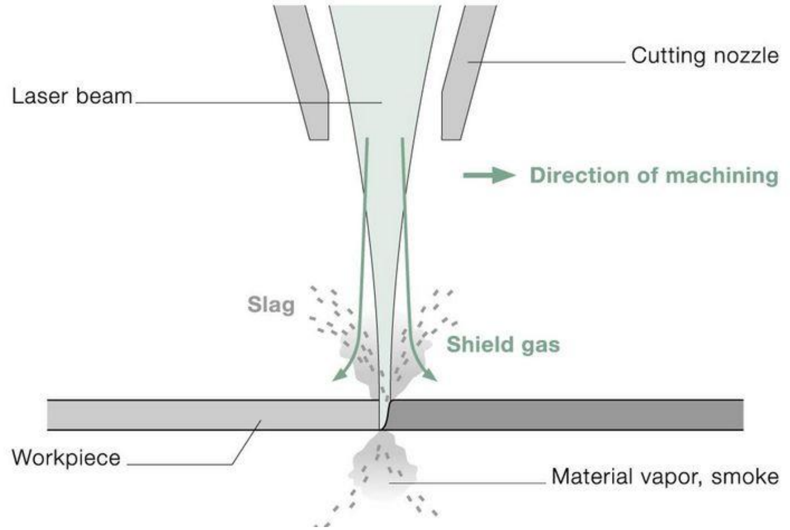
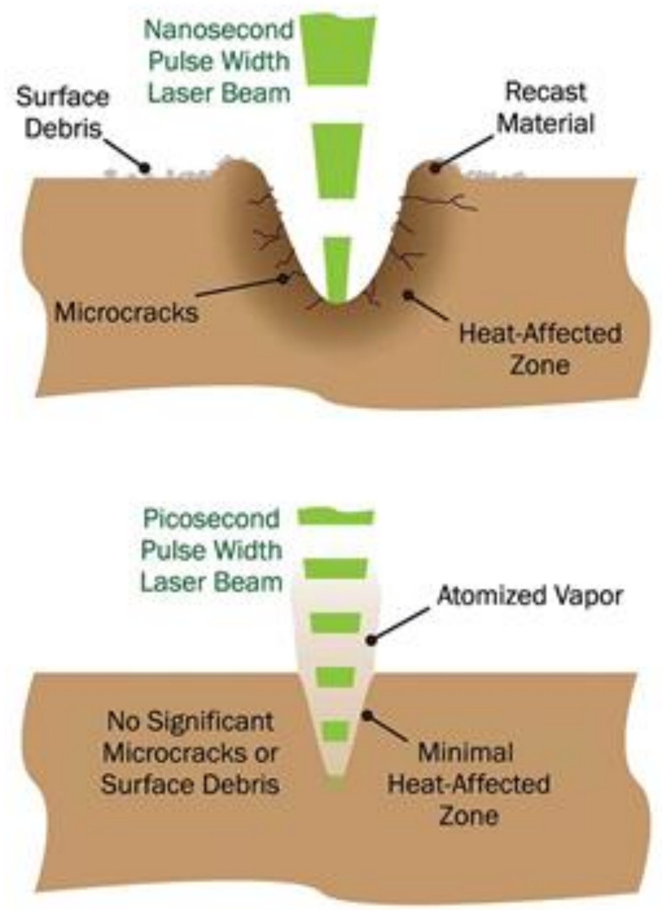
- In this process, the idea is to use the laser to vaporize the material with as little melting as possible.
- In the kerf, the material vapor creates high pressure that expels the molten material from the top and bottom of the kerf.
- The process gas – nitrogen, argon, or helium – serves solely to shield the cut surfaces from the environment. It ensures that the edges remain oxide free.





Forms of Laser Cutting

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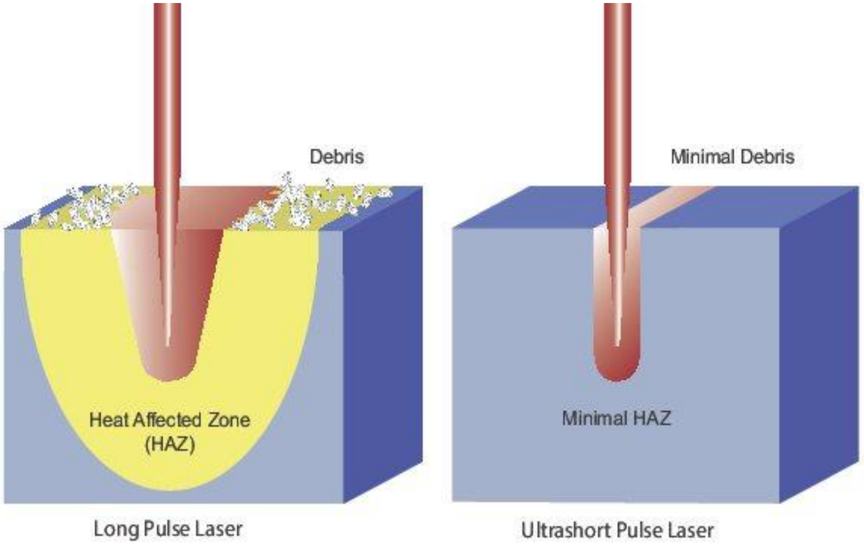
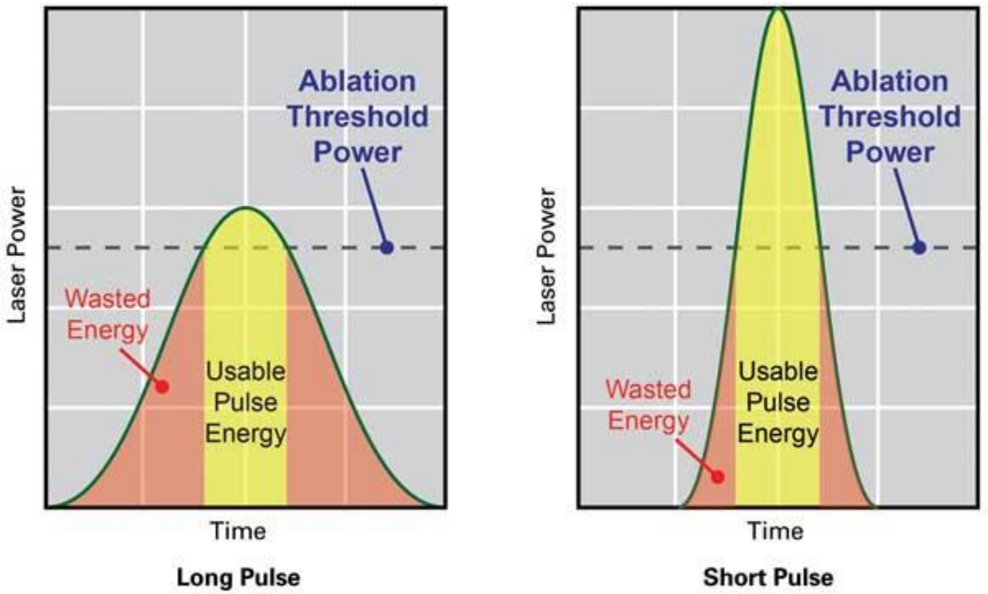
- More energy is needed to vaporize metal than to melt it. For this reason, sublimation cutting requires high laser power and is slower than other cutting processes. However, it produces high-quality cuts.
- Many non-metal materials are regularly processed with sublimation cutting. Typical materials include: Plastic and Materials that do not melt, such as wood, cardboard, or foam





Forms of Laser Cutting

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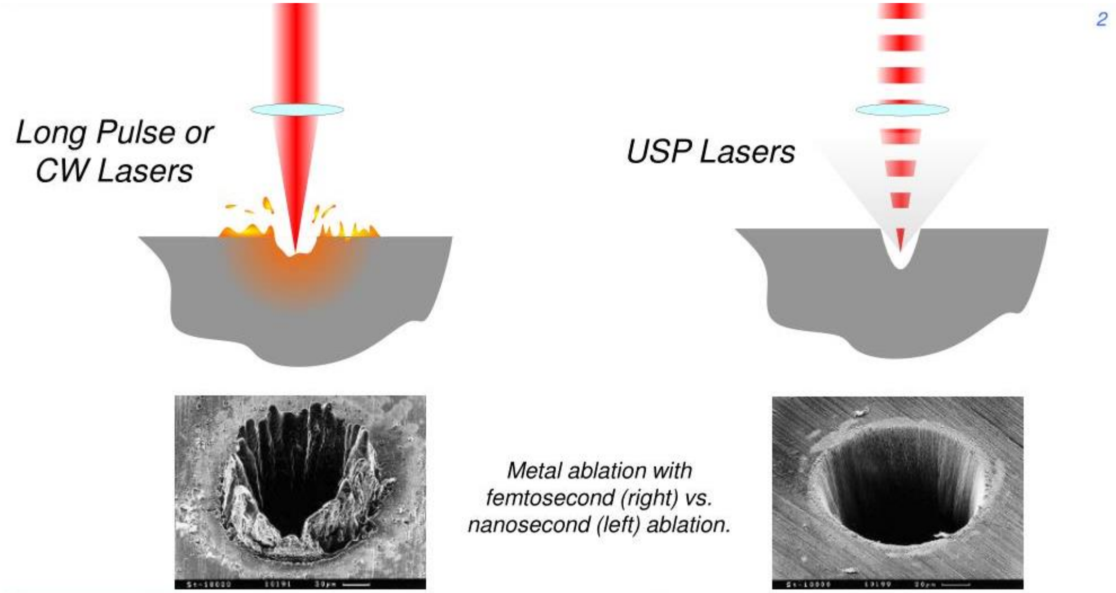
3. Photochemical ablation

- It is limited to thin sections since more energy is required to remove a unit volume of material as compared to fusion cutting.

- It has the advantage of a narrower kerf width and higher quality surface. Pulsed beams with high peak power may be necessary when surface quality is critical.



Forms of Laser Cutting

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1. Fusion cutting
2. Sublimation cutting
3. Photochemical ablation

- There are two dominant processes responsible for the ablation – photochemical processes that break chemical bonds in the molecule and photothermal processes that heat the sample.
- It is generally believed for lasers operating at visible or infrared wavelengths (Nd:YAG), that photothermal processes in the sample are dominant.
- With the far-UV (<200 nm) laser irradiation, when the photon energy is larger than the energy of the chemical bonds in the molecule, photochemical processes are responsible for the onset of ablation.
- It has been reported that the presence of photochemical processes has lowered the ablation threshold due to the release of additional energy from exothermic reactions into the irradiated sample
- The process occurs almost immediately (about 20 ns duration), and since the thermal conductivity of organic materials is relatively low, the resulting edges are well defined, with minimal thermal damage to the surrounding area. Thus the cut region is cleaner and smoother compared to that obtained using CO_2 and Nd:YAG lasers.
- The process is sometimes referred to as cold cutting since little heat is generated.

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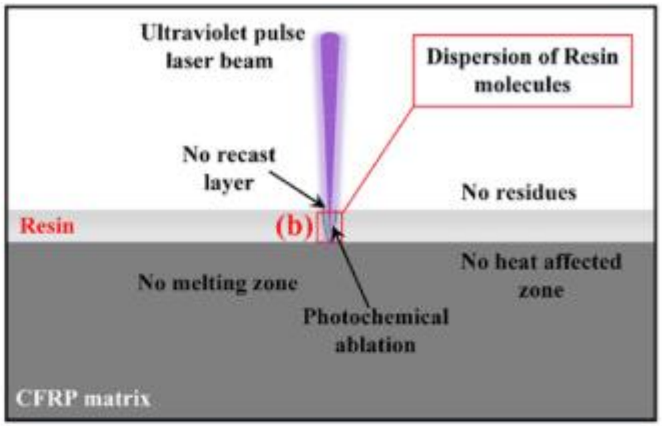
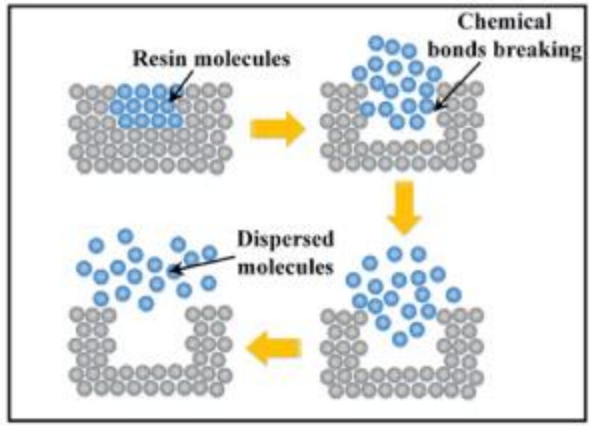
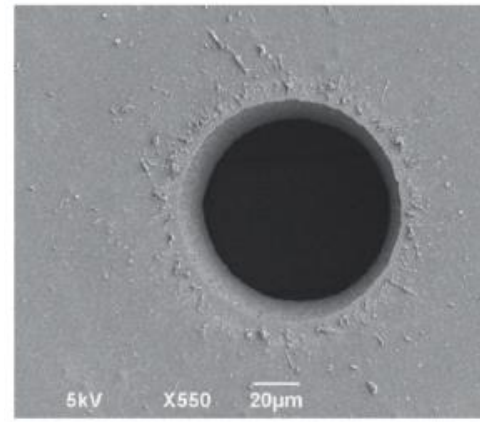
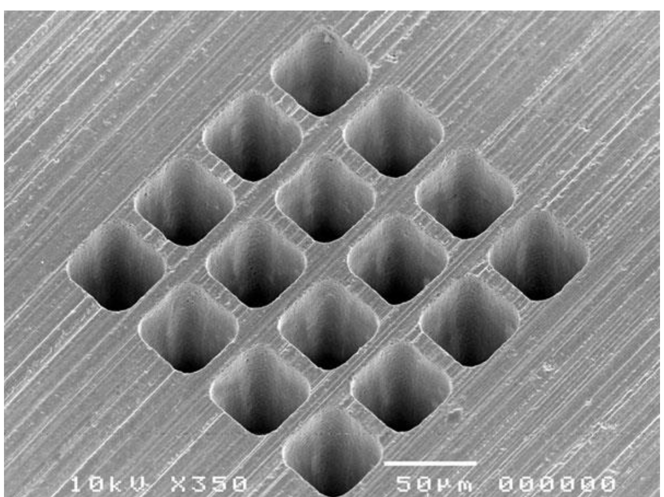
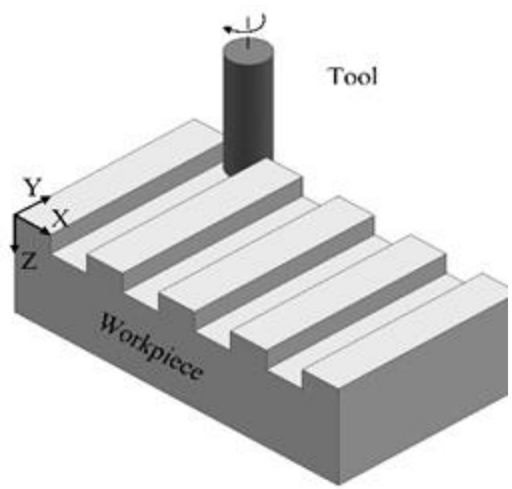
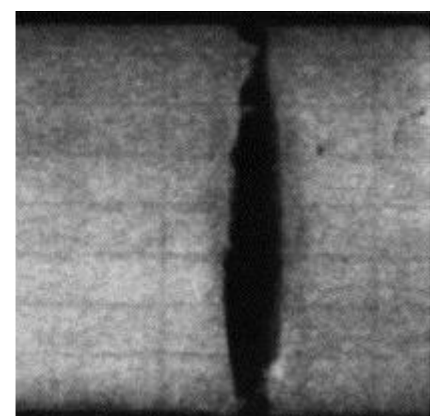






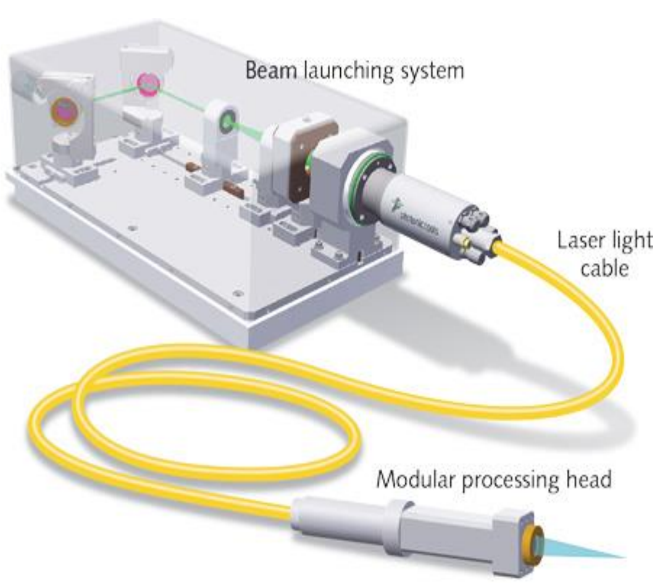


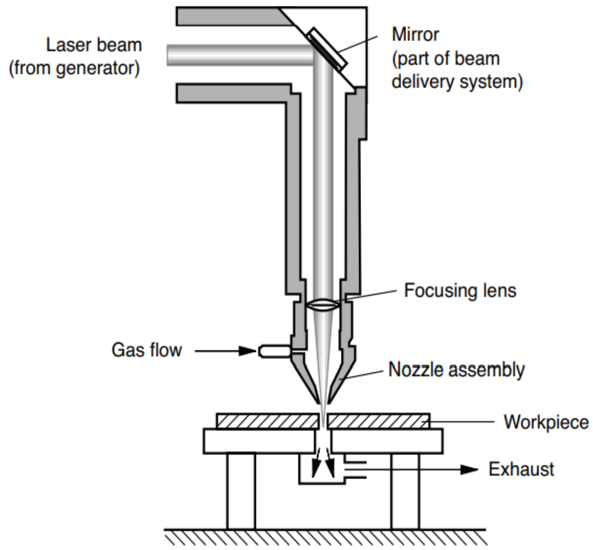




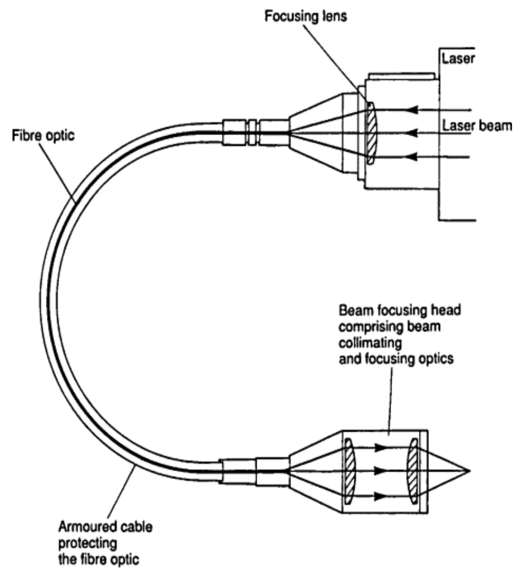
Components of Laser Cutting system

1. Laser generator (Source)
2. A beam delivery system
3. A nozzle assembly (1–2 mm) with assist gas (3–25 bar). The distance from the nozzle tip to the workpiece surface is typically maintained constant at about 0.3-0.6 mm to minimize expansion of the gas flow.
4. A motion unit (Computer Numerically Controlled (CNC))
5. An exhaust to dispose the removed material





Components of a laser cutting system.



Processing Conditions

The principal parameters that affect the laser cutting process include the following:

1. Laser Beam power
2. Beam characteristics
3. Traverse speed
4. Assist gas type and flow
5. Location of focal point relative to the workpiece surface.

1. Laser Beam power

- The power is the most significant
- An increase in power increases the maximum thickness that can be cut
- The kerf width and dimension of HAZ increases as **laser power** increases

Possible Cutting Conditions for CO_2 Laser Cutting of Different Materials

Material	Thickness (mm)	Power (*W*)
Carbon steel	0.5	250
Carbon steel	1.5	400
Carbon steel	3.0	600
Carbon steel	6.0	1200
Stainless steel	1.0	1000
Stainless steel	1.5	1500
Stainless steel	3.0	1800
Stainless steel	6.0	2000
Aluminum	1.0	1200
Aluminum	1.5	1500
Aluminum	3.0	1800
Titanium	1.0	800
Titanium	1.5	900

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Beam Characteristics

1. Beam mode
2. Stability
3. Polarization
4. Beam form (pulsed or continuous wave).

- The beam mode is an indication of how the energy intensity is distributed over the beam cross section.
- In laser cutting, it is desirable to have the beam distribution as close as possible to the fundamental or Gaussian distributed TEM_{00} mode. This is the mode that can be focused to the laser's theoretically smallest possible focal size and thus the highest density for a given power.
- This reduces the kerf width, and increases cutting speeds and thickness of materials that can be cut. Since higher order or multimode beams are more spread out, they result in larger focal spot sizes and thus lower power density for the same output power.

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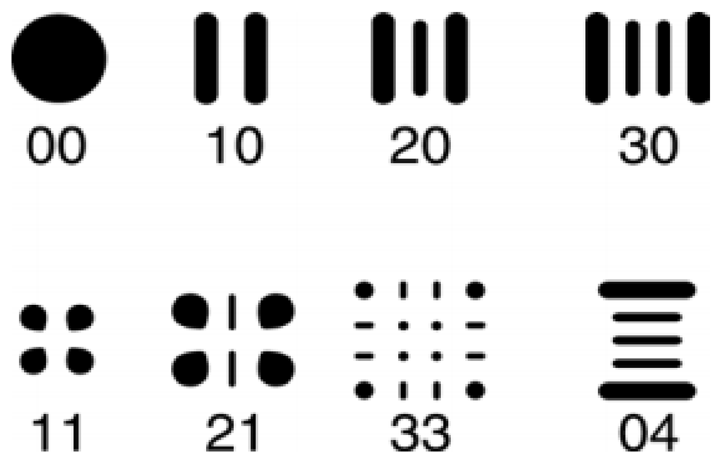
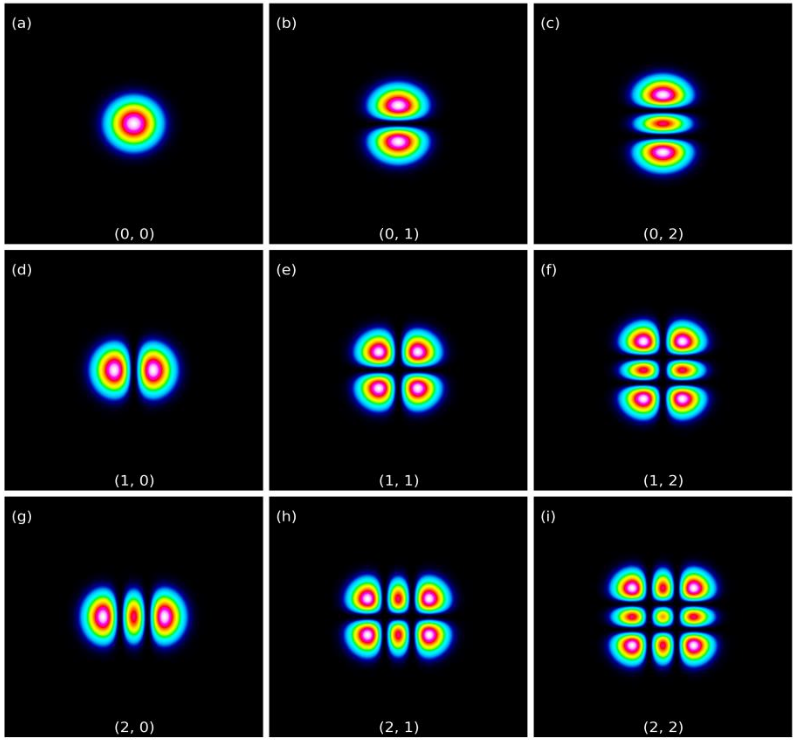


Transverse Gaussian mode patterns with *n*, *m* indicated.



The n and m subscripts in the TEM_{nm} mode designator refer to the number of intensity nodes along the x and y axis, respectively.

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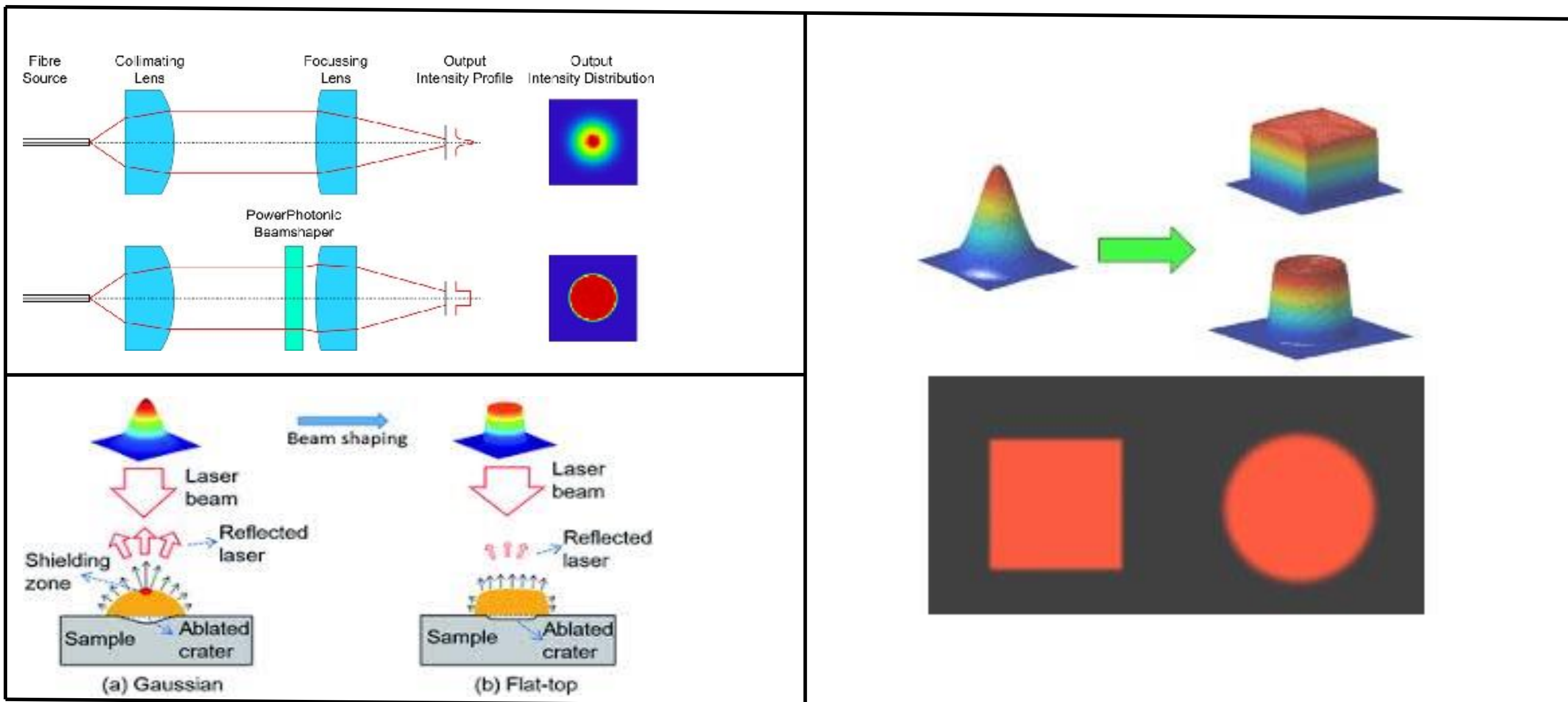

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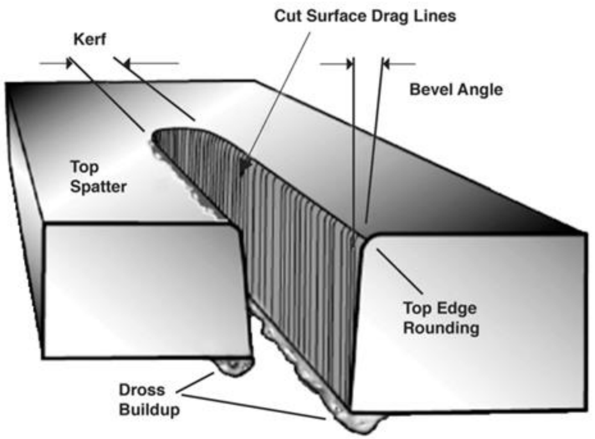

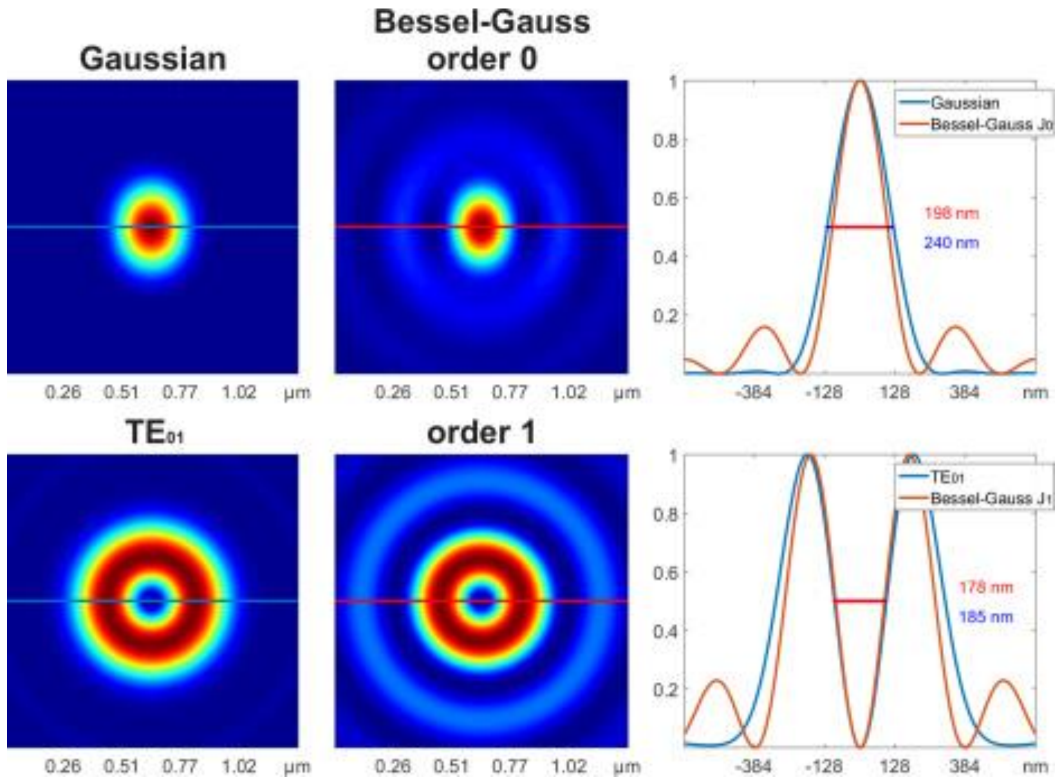

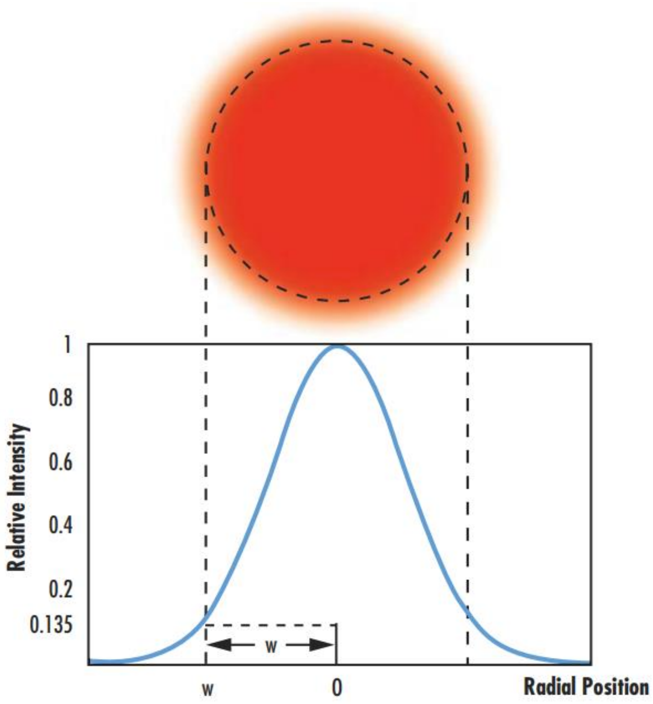

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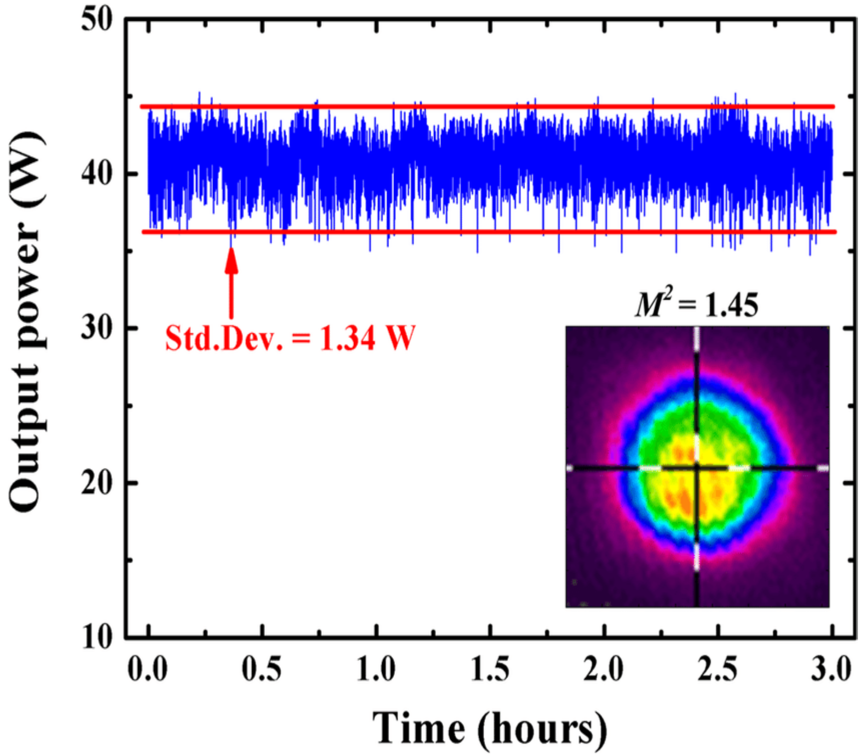
Beam Stability

- Stability of the beam is necessary to ensure that the beam power, mode, and direction (pointing stability) remain constant with time
- An unstable beam affects the tolerances and surface finish achievable with laser cutting
- A stable beam thus reduces variations in product output and enhances quality. The stability of the beam is a characteristic of the laser generator, and depends on its design



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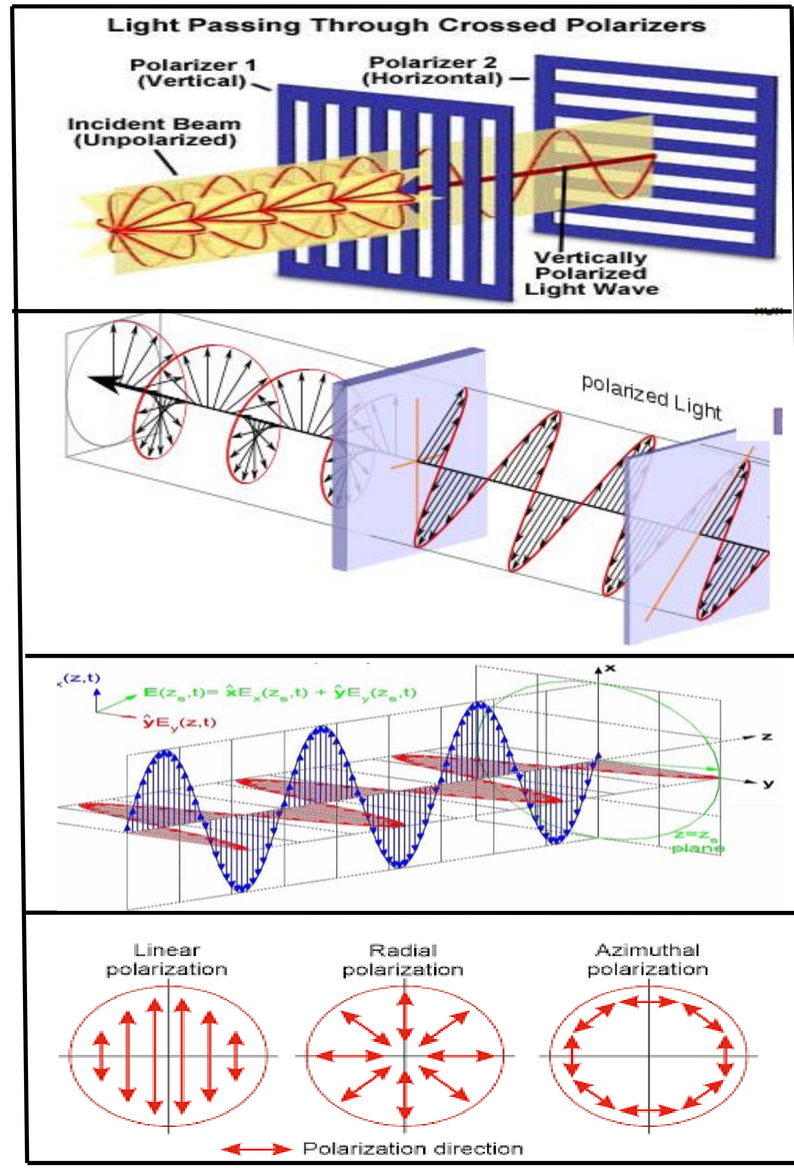

<u>Polarization</u>

- The polarization of an electromagnetic wave (made up of electric and magnetic fields) is defined as the direction along which the electric field vector (E) points
- Unpolarized light is "polarized" in all directions. The electric fields are oriented in all directions
- Reflections are minimised (and consequently light absorption is at a maximum) when a linearly polarised beam has its electric field orientation set parallel to the plane of incidence (at angles of incidence greater than 80° and less than 90°)

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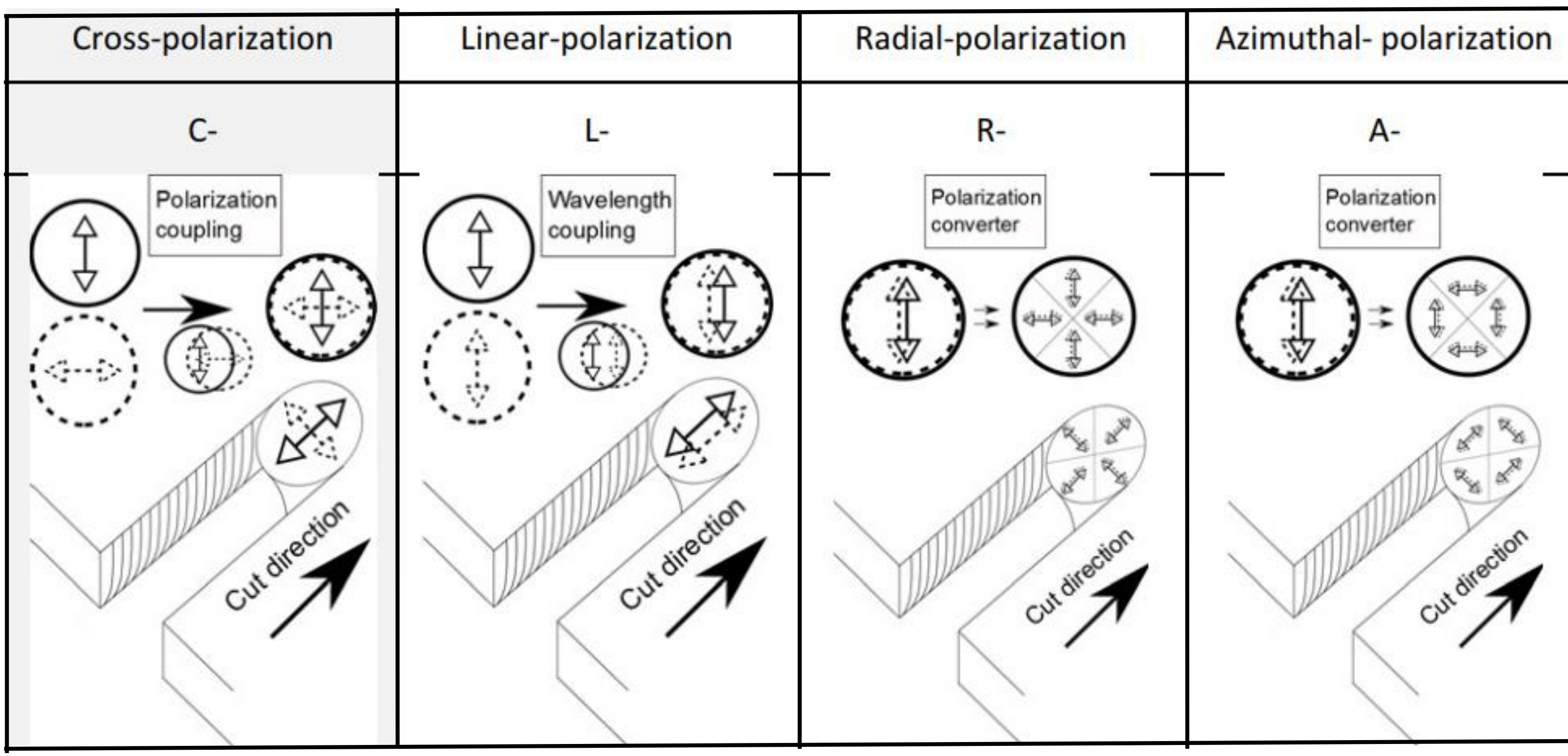

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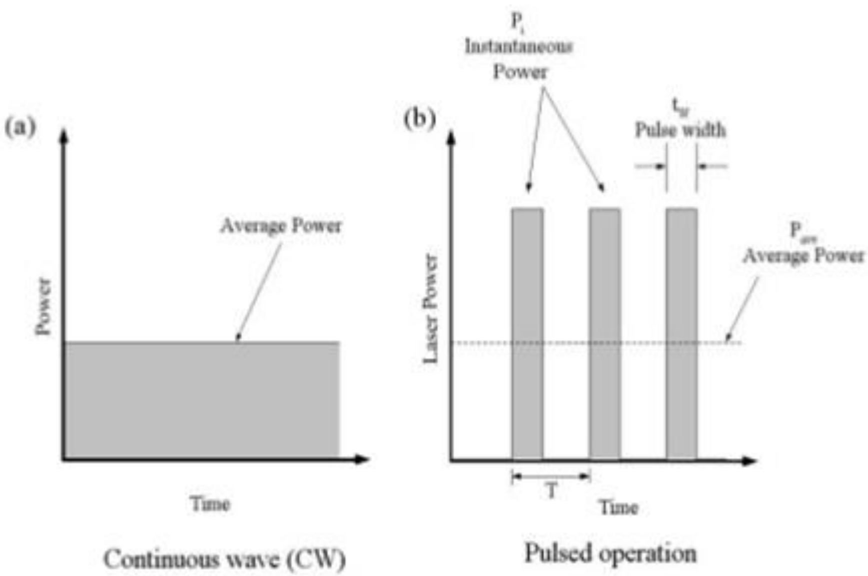
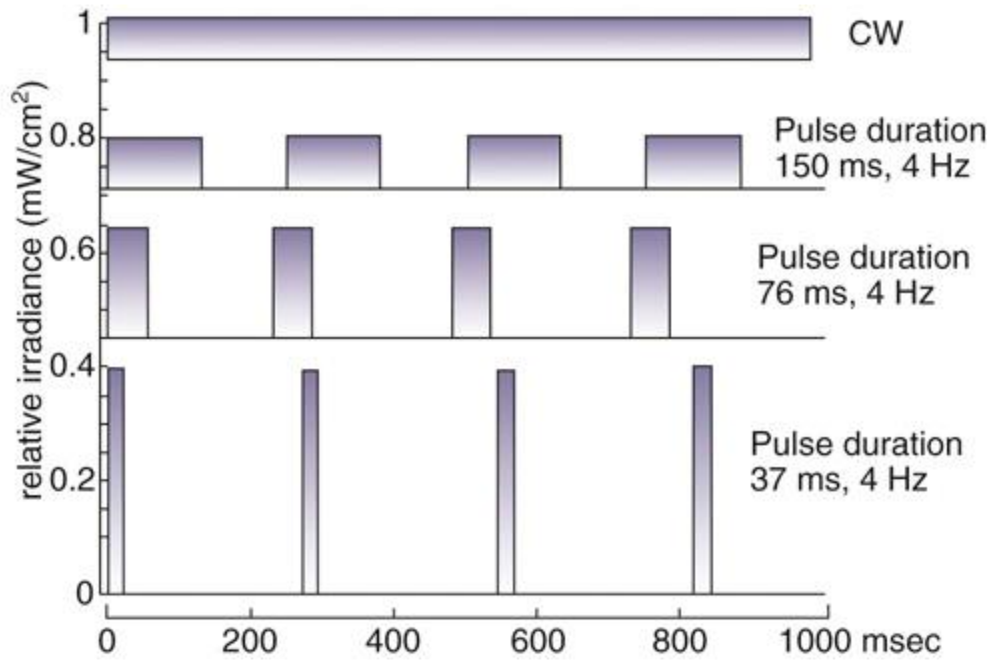
Beam Form

Both pulsed and continuous wave (CW) beams can be used for laser cutting, with CW beams being more common.





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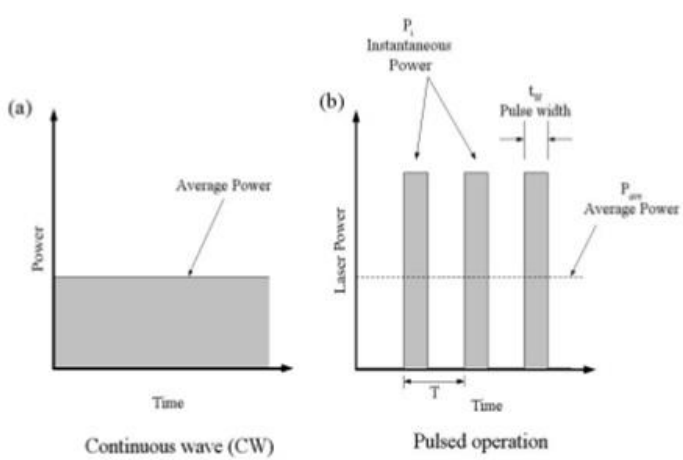
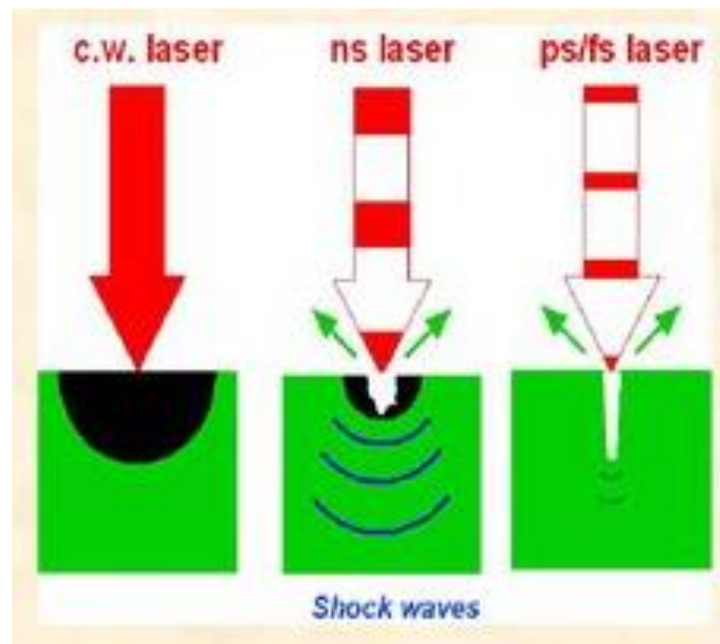
Beam Form

- For pulsed beams, the quality of cut is affected by the pulse duty
- Furthermore, as the material cools down between pulses at low pulse frequencies, there is a greater likelihood of forming dross
- Making it easier to process highly reflective and/or high thermal conductivity materials.





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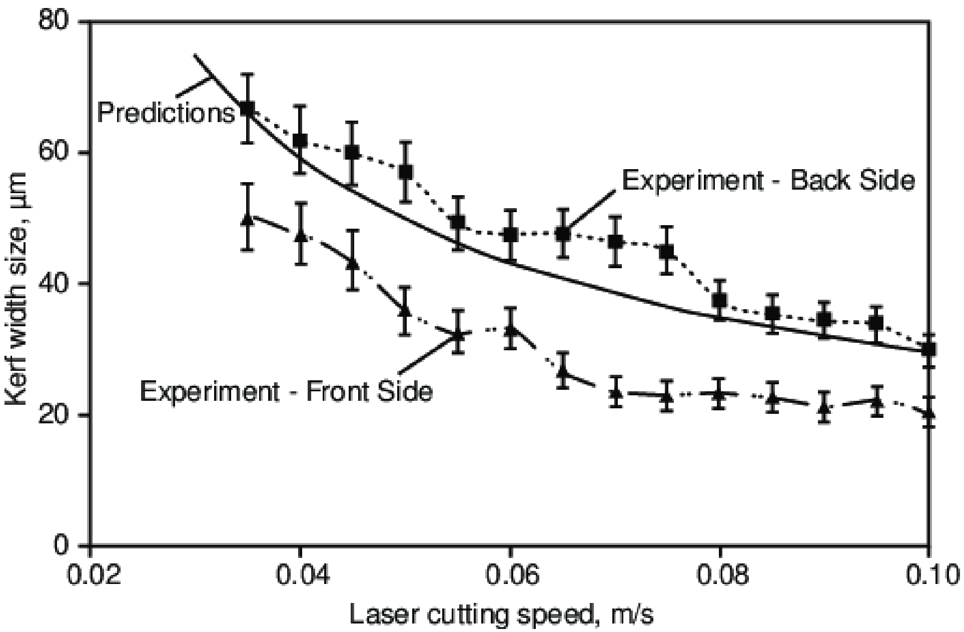

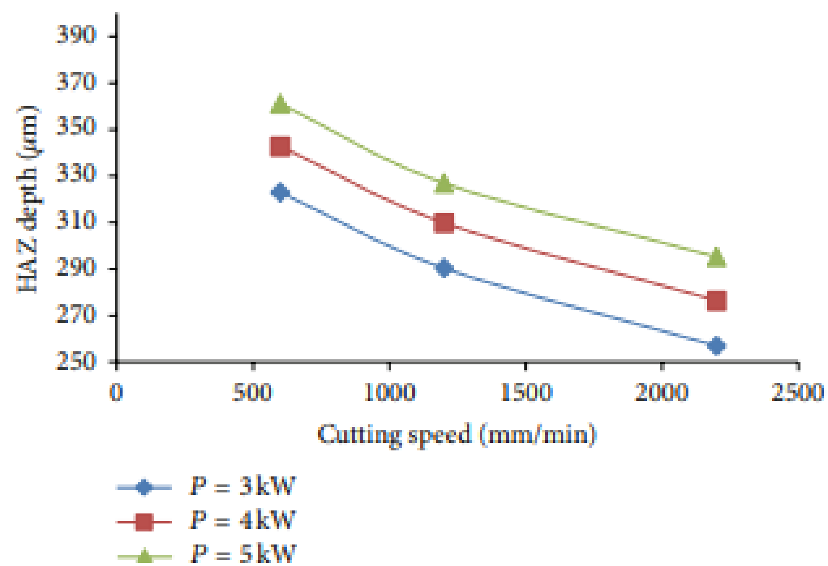

Effect of laser power and cutting speed on HAZ depth

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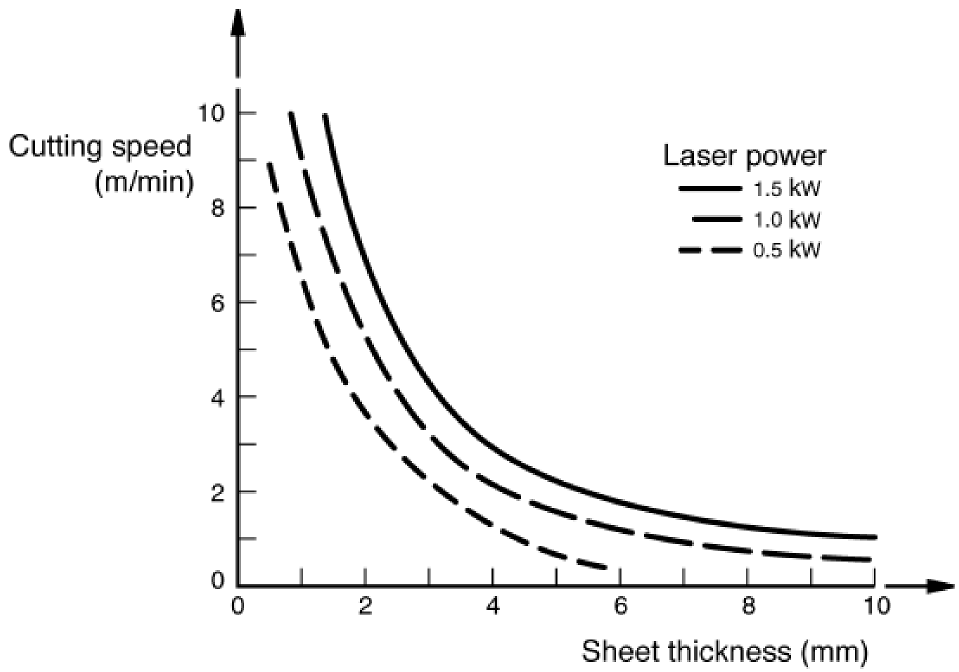

Variation of cutting speed (maximum cutting rates) with workpiece thickness in oxygen-assisted laser cutting of steel plate.

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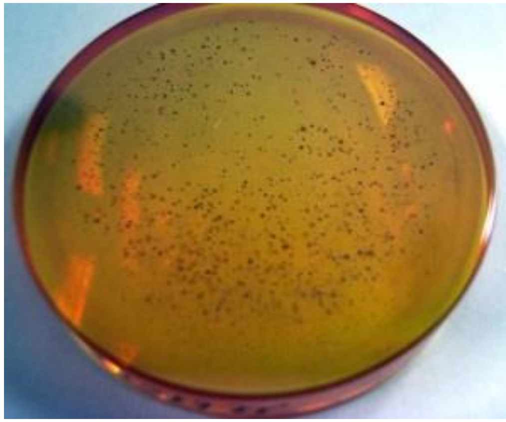
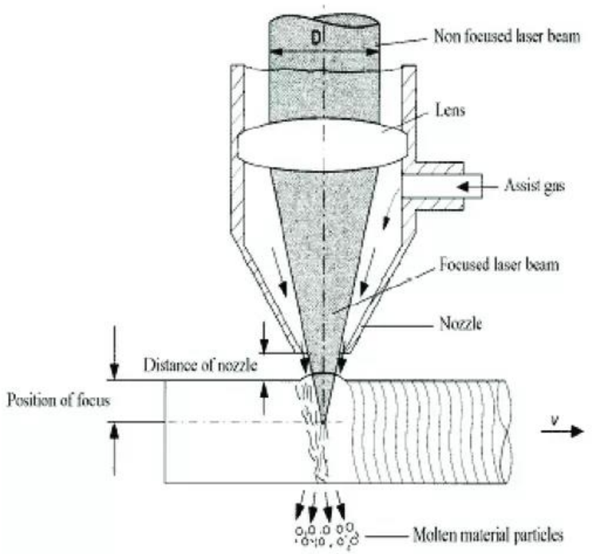
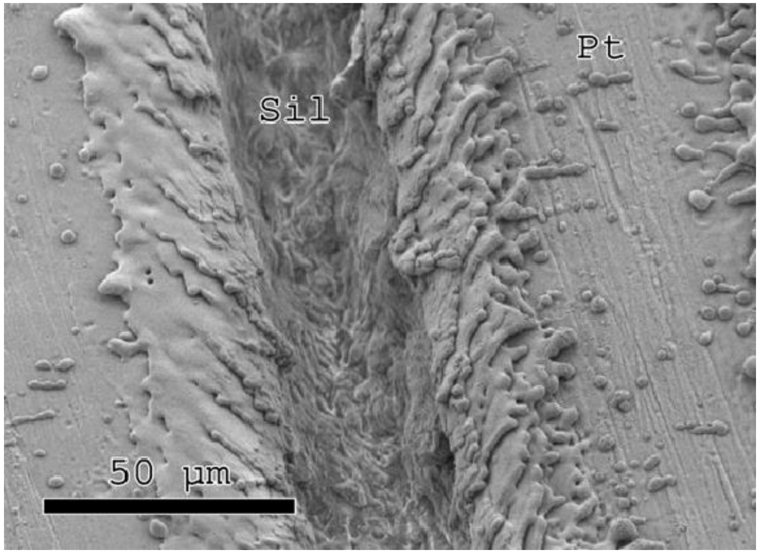


- ❑ Ejection of the molten metal through the backside of the workpiece
- ❑ Protects the lens from spatter
- ❑ Acts as a heat source where it results in an exothermic reaction that aids in cutting, such as may occur in oxygen-assisted cutting of steel.





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fect of Different Types of Assist Gases

- Oxygen or air is used for exothermic reaction while cutting (improve the cutting efficiency)
- Air may introduce other gases such as nitrogen into the cut surface, making it more brittle. Air is cheaper, but would require higher flow rates
- One setback of oxygen-assisted cutting is the deposition of an oxide layer on the cut surface, giving it a dark appearance.
- Depending on the subsequent use of the cut parts, it may be necessary to clean off this oxide layer (by grinding or wire brushing).
- Inert gas (usually argon) is used to assist in ejecting the molten metal without oxidation.
- Furthermore, higher pressures are then necessary to reduce dross formation.

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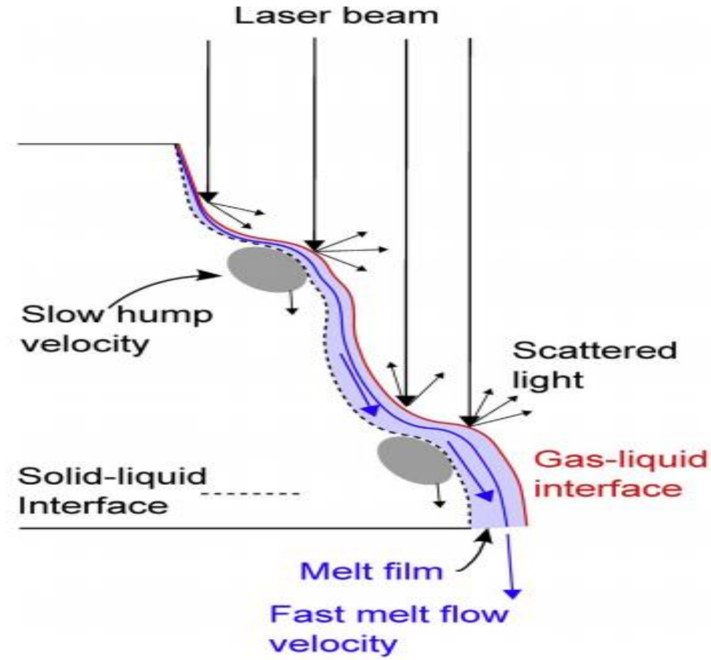
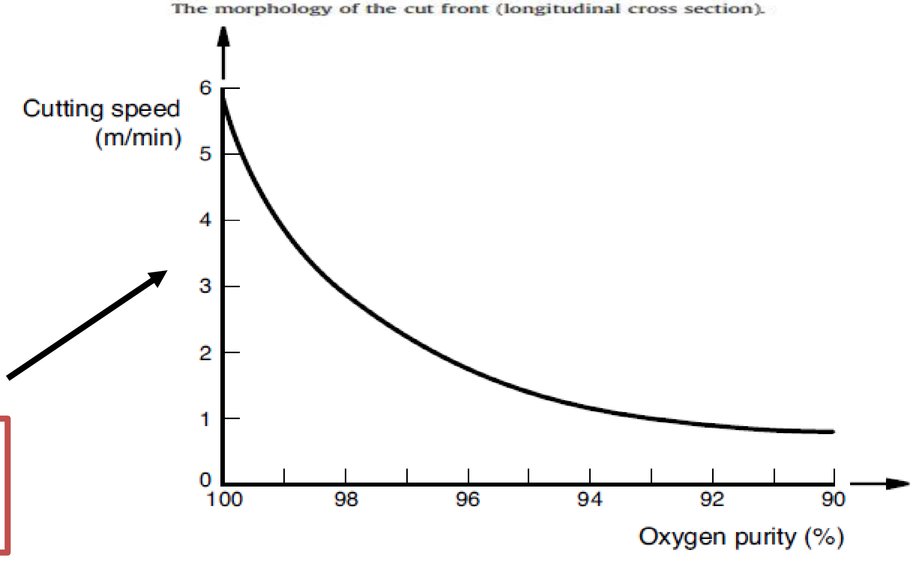


The morphology of the cut front (longitudinal cross section).

fect of Different Types of Assist Gases

Small levels of impurity can cause significant deviations in cutting performance (such as a reduction in maximum cutting speed or increase in dross formation) compared to that of the pure gas, be it oxygen or inert gas. This sensitivity to contamination is due to the build up of a boundary layer of the contaminant at the liquid–cut front interface. It decreases the oxidation rate of the material, thereby lowering the energy input to the cut zone.



Mild steel of thickness 2 mm, P=800 W at 2.5 bar pressure.

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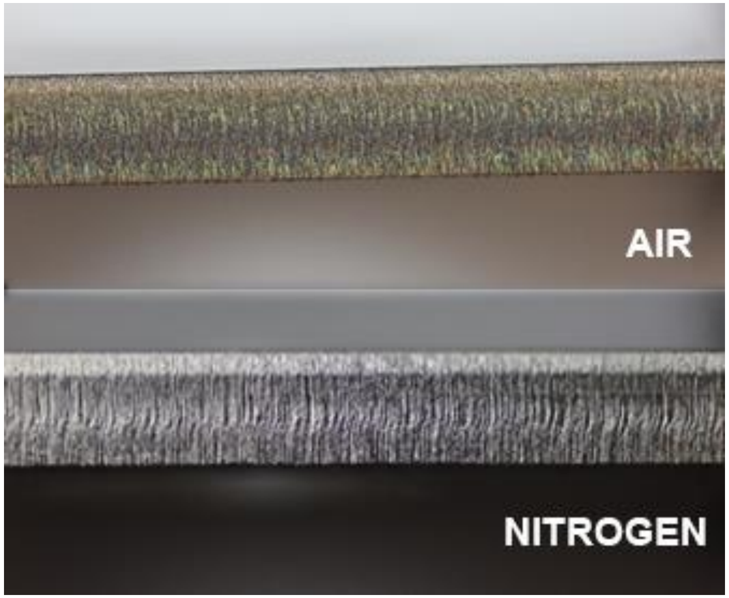
<u>Oxygen-Assisted Cutting</u>

- In addition to the exothermic reaction that results, the use of oxygen assist in cutting also reduces the viscosity and surface tension for some metals, making it easier for the molten metal to flow. The oxide film formed also tends to increase beam absorption.
- The maximum cutting speeds achieved depend on the thermal properties of the metal. For inert gas-assisted cutting, higher speeds are obtained for low-melting and low-thermal conductivity metals. Maximum cutting speeds are higher for oxygen assisted cutting, compared to inert gas-assisted cutting of titanium, zirconium, and niobium due to the relatively high exothermic energy associated with these metals.

Processing Conditions



1. Laser Beam power
2. Beam characteristics
3. Traverse speed
4. Assist gas type and flow
5. Location of focal point relative to the workpiece surface.

__Oxygen-Assisted Cutting__

❑ However, the surface quality obtained is relatively poor. This is due to the fact that the oxidation region cannot be limited to the beam irradiating region as a result of the high exothermic energy. The relatively low cutting speeds achieved with aluminum and zinc is due to the high melting temperature of their oxides.

❑ Care must be used in oxygen-assisted cutting since excess oxygen may result in overreaction or uncontrollable burning away from the main cutting direction, especially for thick materials. That may increase striation formation, and thus, roughness.

Processing Conditions

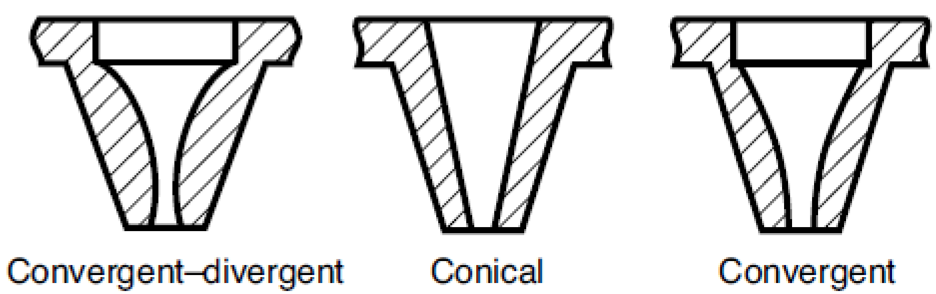
The principal parameters that affect the laser cutting process include the following:

1. Laser Beam power
2. Beam characteristics
3. Traverse speed
4. Assist gas type and flow
5. Location of focal point relative to the workpiece surface.

__Gas Nozzles__

❑Some of the nozzle designs that are commonly used for coaxial application of a gas jet during laser cutting. The most commonly used ones are the conical, convergent, and convergent–divergent designs.

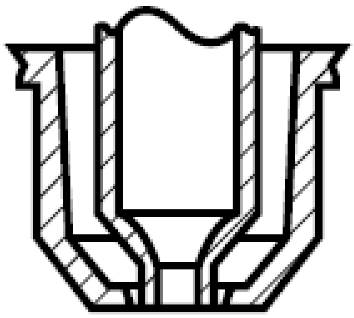
❑Low or subsonic flow rates from a coaxial nozzle are found to produce repeatable results, especially when the nozzle is positioned close to the workpiece, that is, with a standoff (nozzle to work) distance of about 0.1–1.5 mm.



Processing Conditions

The principal parameters that affect the laser cutting process include the following:

1. Laser Beam power
2. Beam characteristics
3. Traverse speed
4. Assist gas type and flow
5. Location of focal point relative to the workpiece surface.

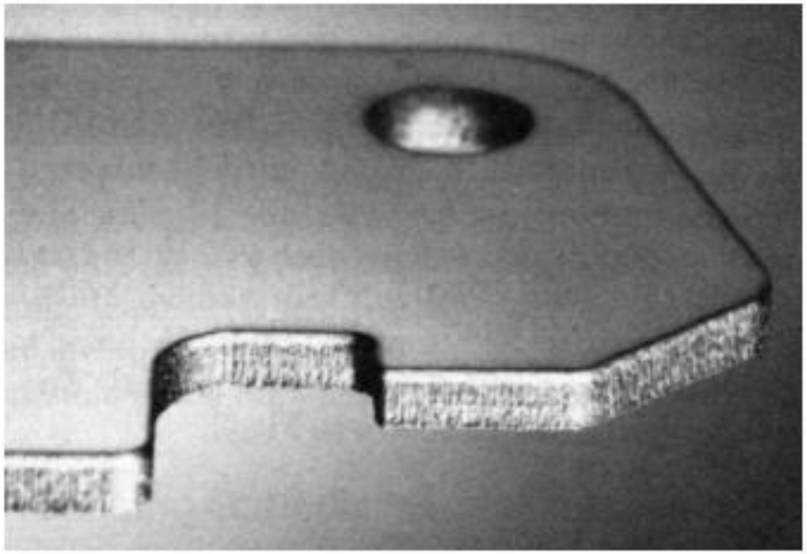


Ring

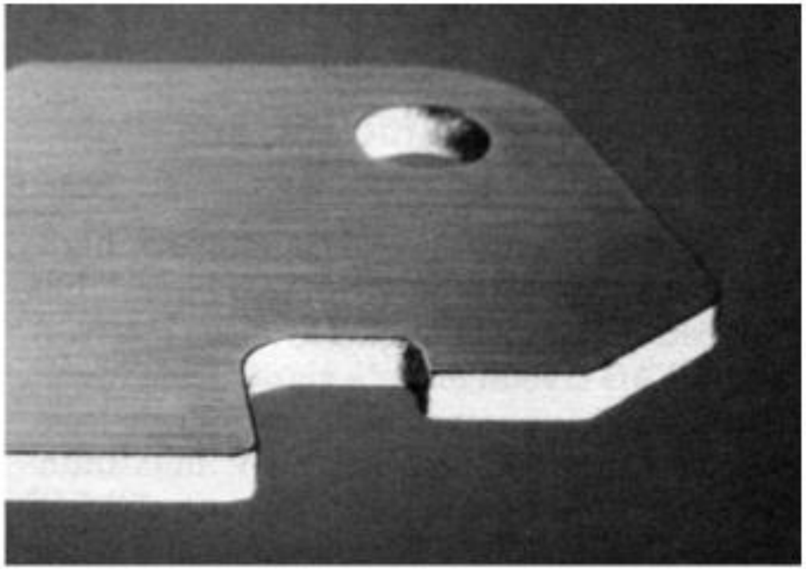
Gas Nozzles

- A version of the ring nozzle design that has been shown to produce drossles, oxide free edge when it is used to cut metals, especially stainless steel and aluminum of thicknesses up to about ≈3.5 mm. The resulting process has been referred to as the "clean-cut" technique.
- The low-pressure (about 1 atm) non-oxide gases flowing through the inner nozzle protects the lens from the vapor plume, while the high-pressure (about 5 atm) non-oxide gases flowing through the outer nozzle remove viscous material.

Comparison of the cut quality obtained for a 2 mm thick stainless steel plate cut using a traditional oxygen gas assist and the “clean-cut” method.



Stainless steel using oxygen gas

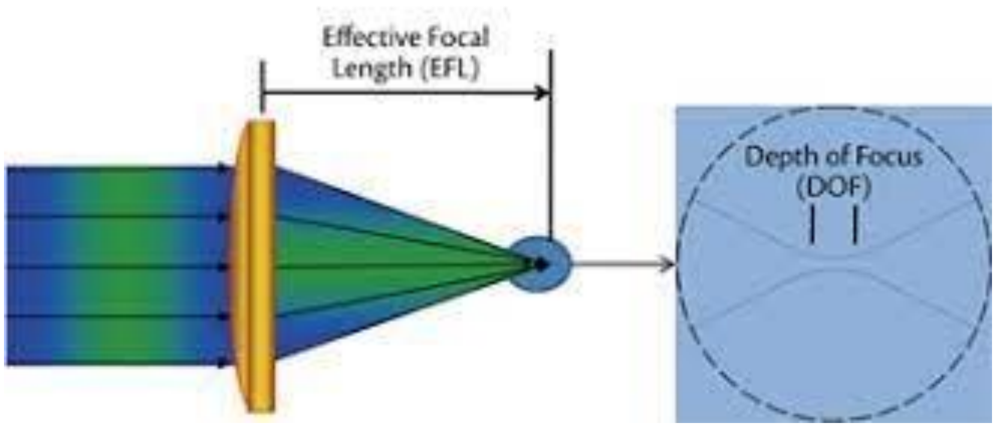


Stainless steel using the “clean-cut” method

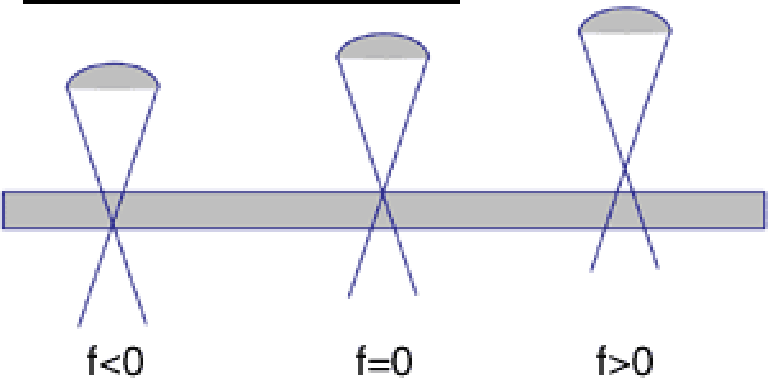
Processing Conditions

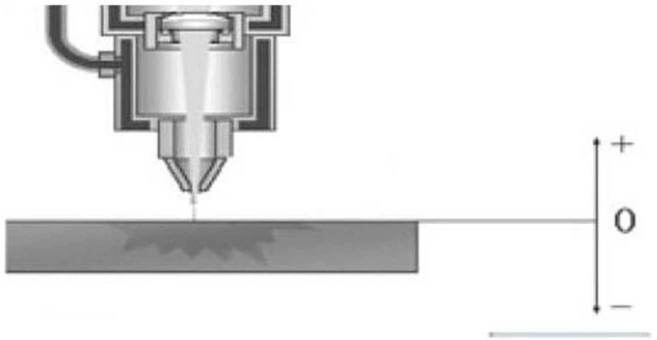
The principal parameters that affect the laser cutting process include the following:

1. Laser Beam power
2. Beam characteristics
3. Traverse speed
4. Assist gas type and flow
5. Location of focal point relative to the workpiece surface.

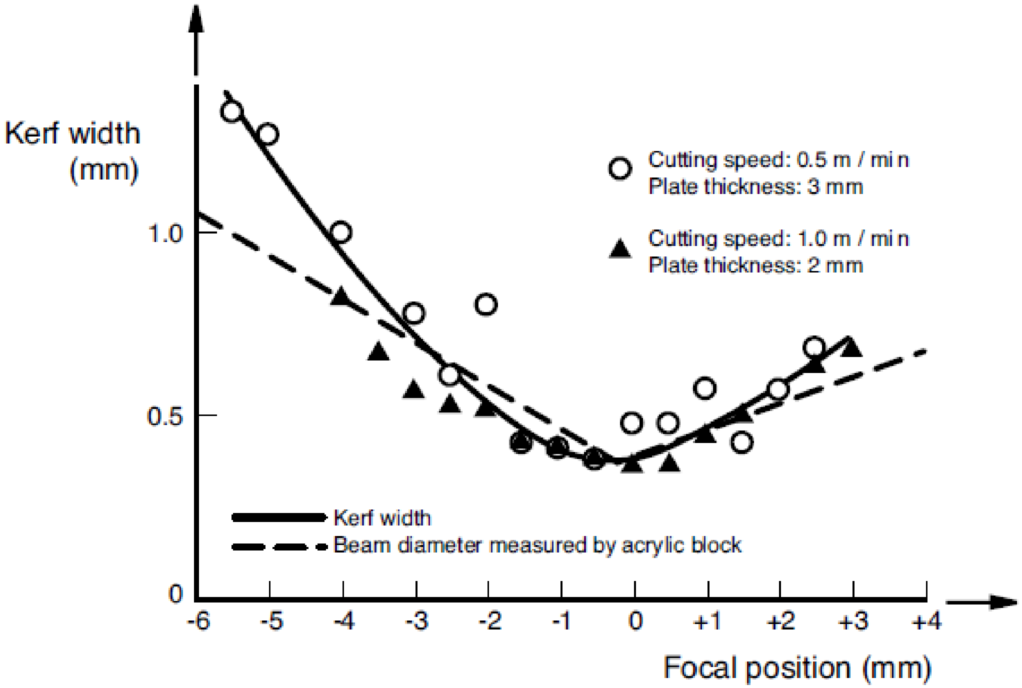


Effect of Focal Position



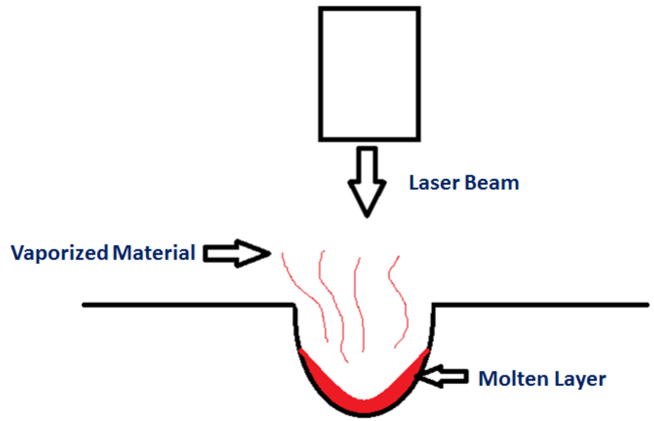


Focus position and direction



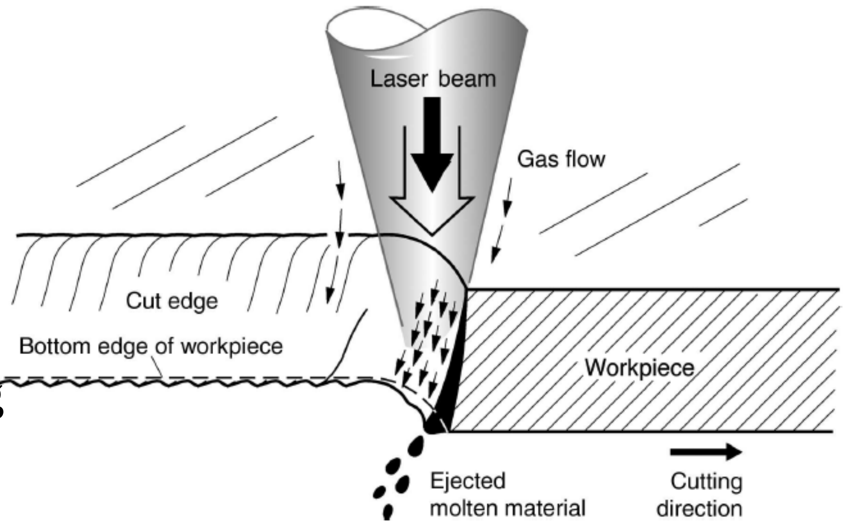
Principle of Laser Removal

1. Absorbed laser radiation.
2. Energy due to exothermic reaction between the base material and assist oxygen gas.

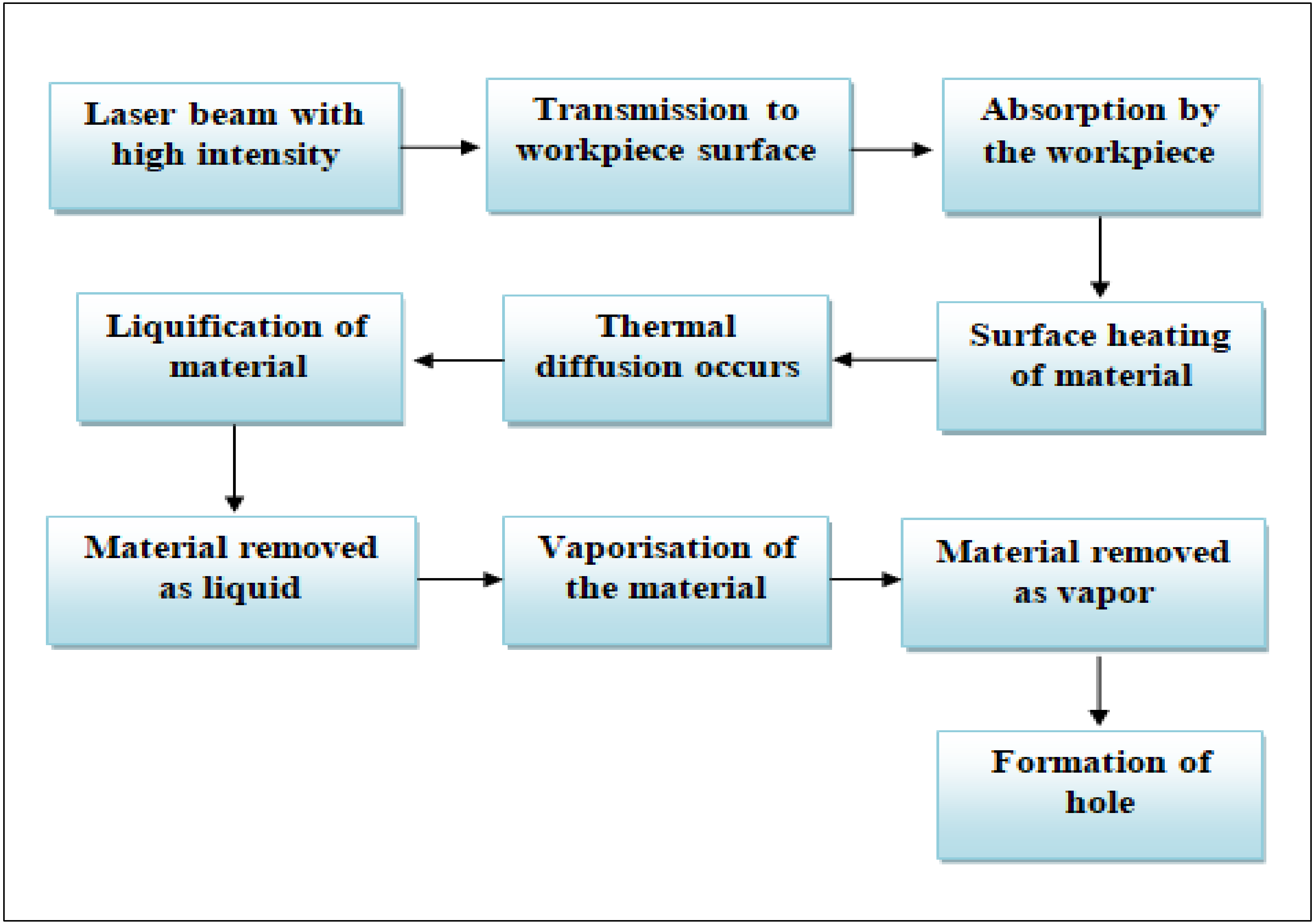


laterial removal thus occurs by
Evaporation from the surface of the molten layer.
Ejection from the lower surface of the workpiece due to friction between the as flow and the surface of the molten layer.

Energy is lost from the process by
1. Heat conduction.
2. Evaporation from the erosion front.
3. Melting of solid metal.
4. Ejection of the molten metal.
5. Reflection, radiation, and convection cooling by the gas flow. For subsonic gas flow, the convection cooling effect is found to be negligible.

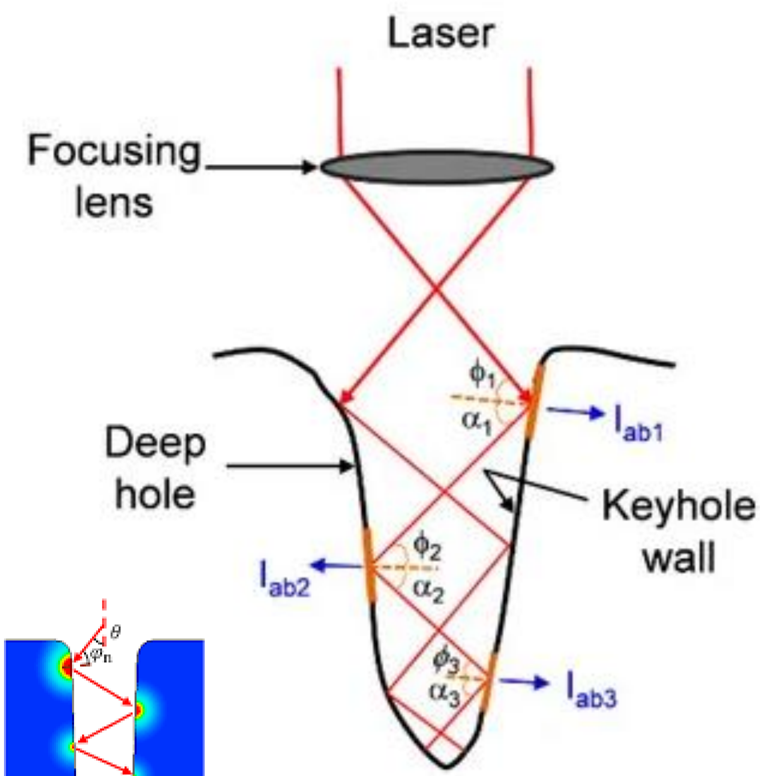


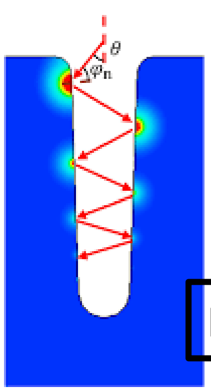
Mechanism of Laser Removal



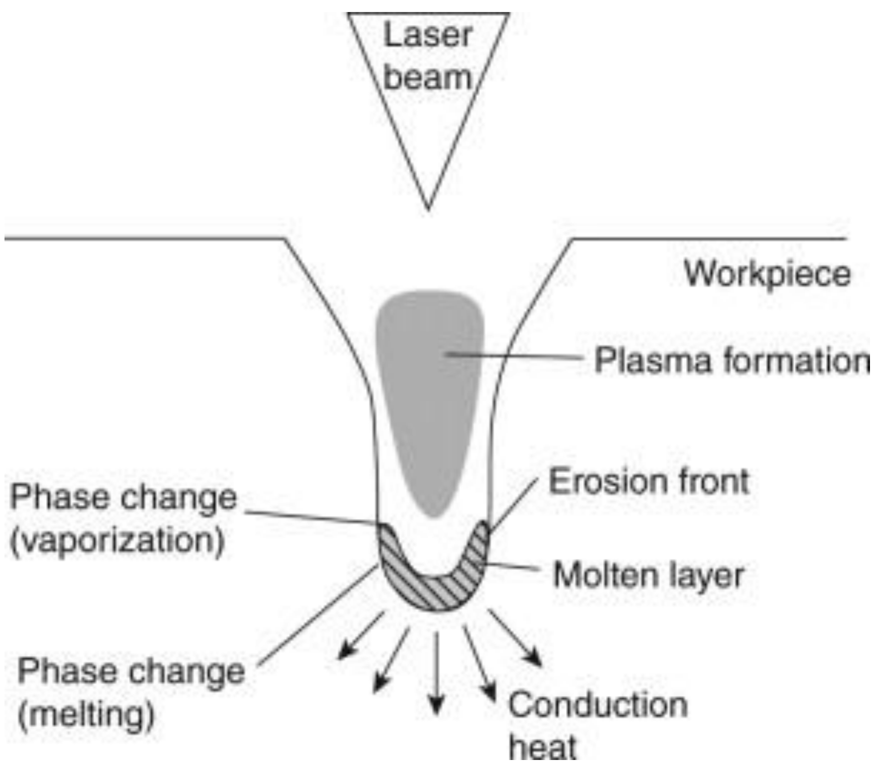
Beam Absorption During Laser Cutting

- Absorption of the laser beam during cutting may be enhanced by a number of phenomena, including surface roughness, oxide formation, and plasma formation.
- Absorption may be by Fresnel absorption or by inverse bremsstrahlung





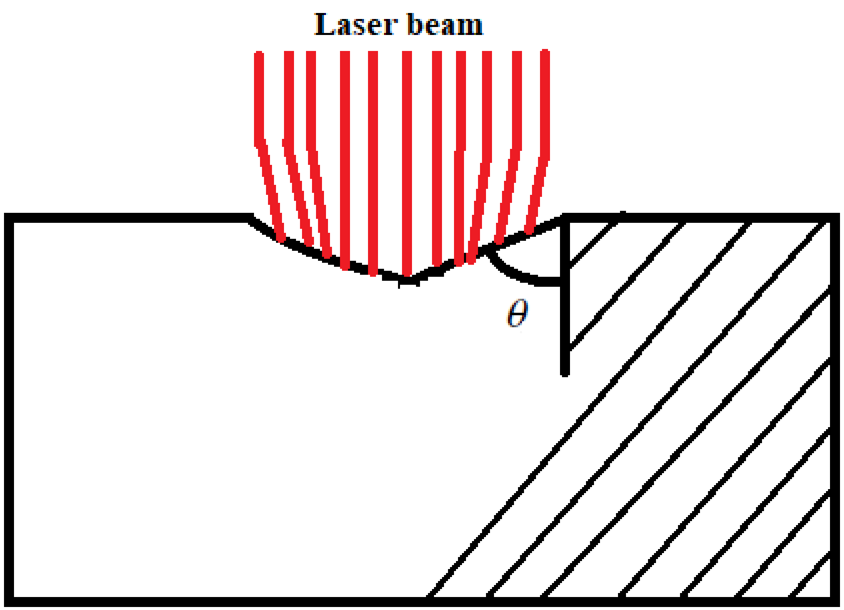
Fresnel absorption

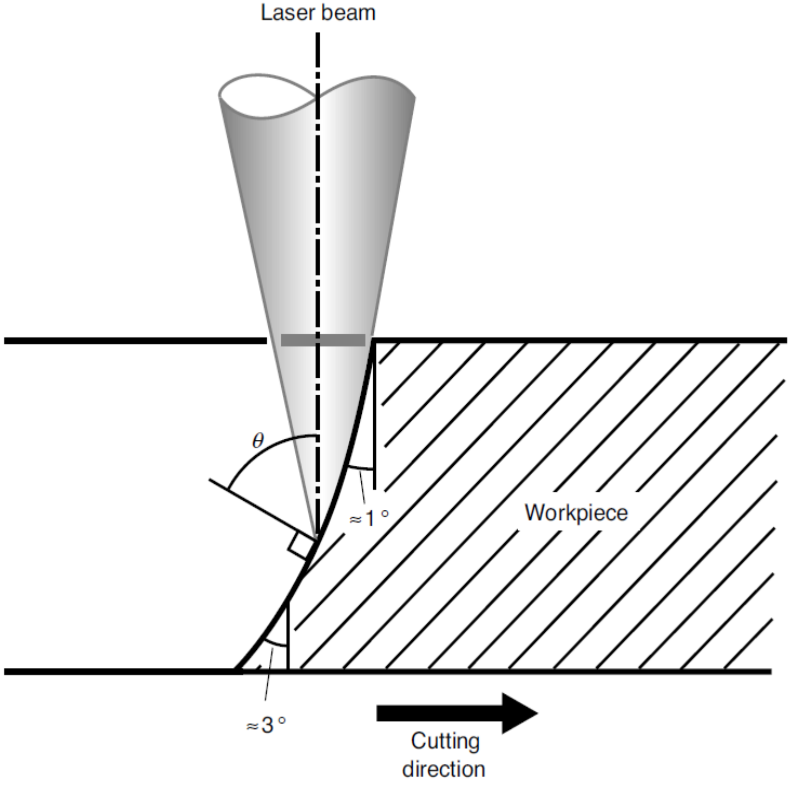


Inverse bremsstrahlung

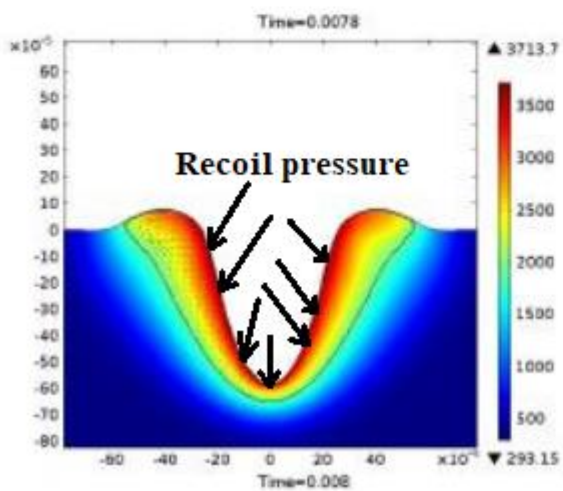
Beam Absorption During Laser Cutting

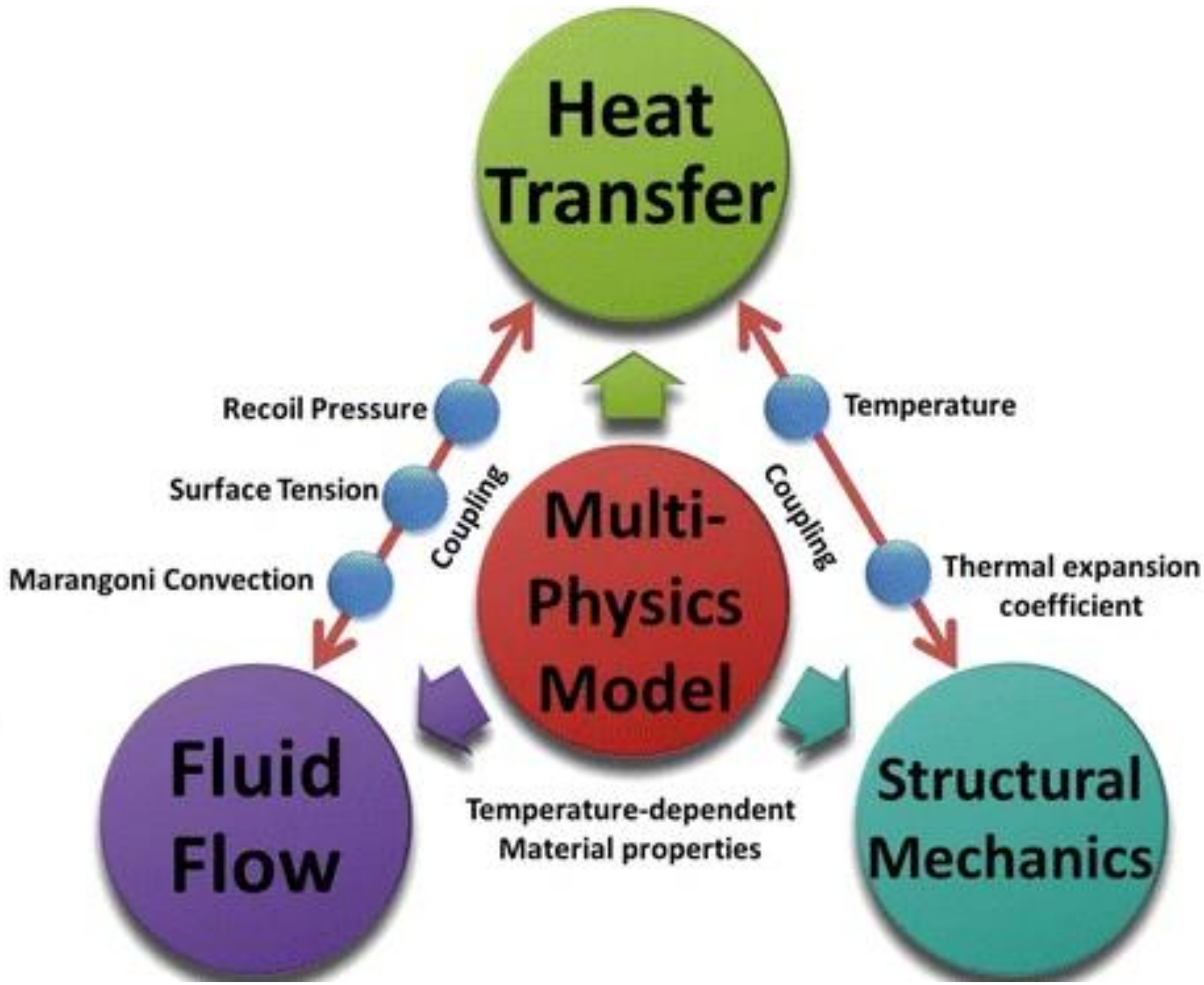
- Absorption efficiency of the laser beam in cutting varies with the beam intensity
- At low intensities, the cutting front is relatively flat, and that results in high absorption since the angle of incidence is then almost zero, that is, the laser beam is almost normal to the workpiece surface.
- At very high intensities, the cutting front is almost vertical, resulting in almost 90◦ incidence, at which the absorption is relatively low



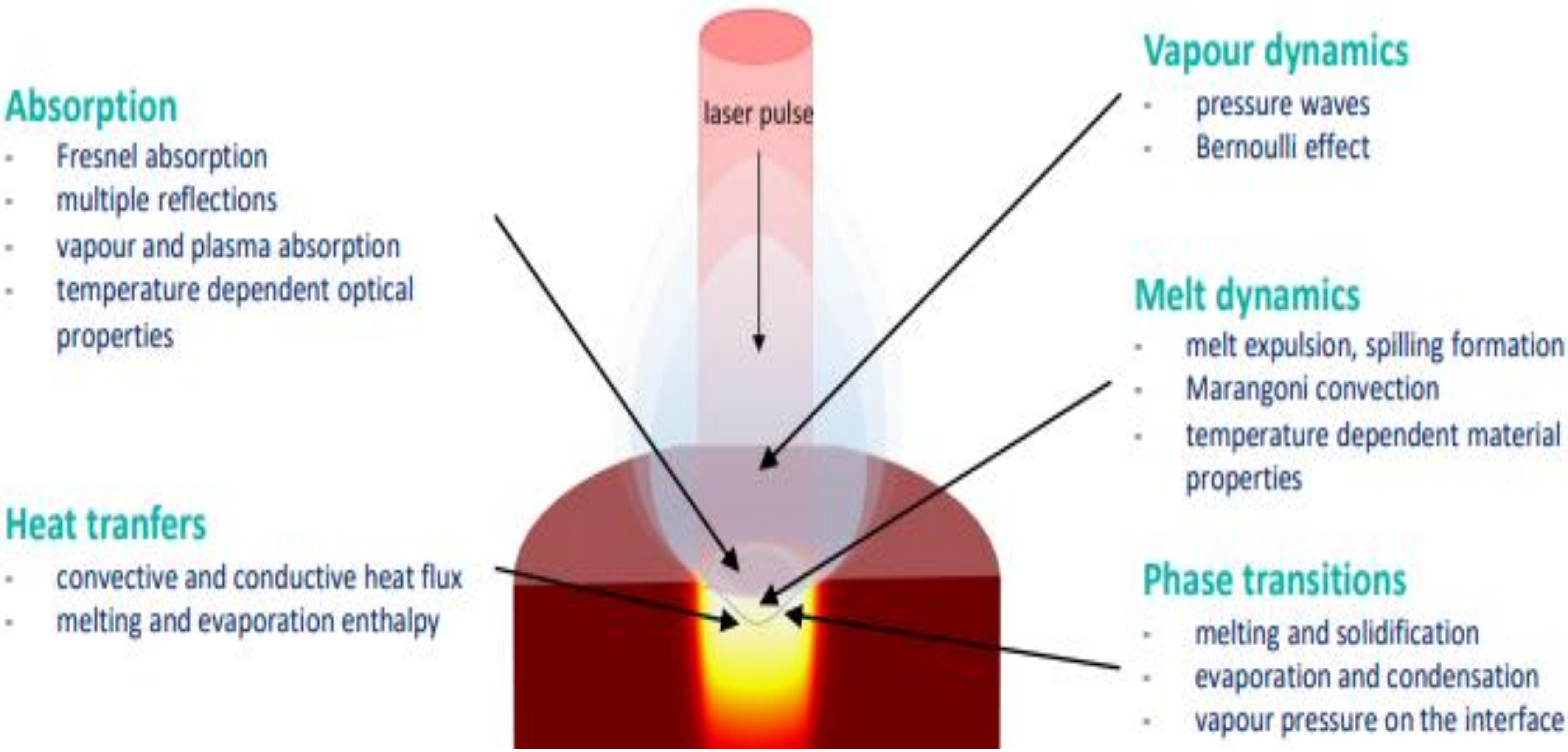


Process modeling





Boundary conditions



Equations

The governing equation for heat flow

$$\rho c_p \frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q_s$$

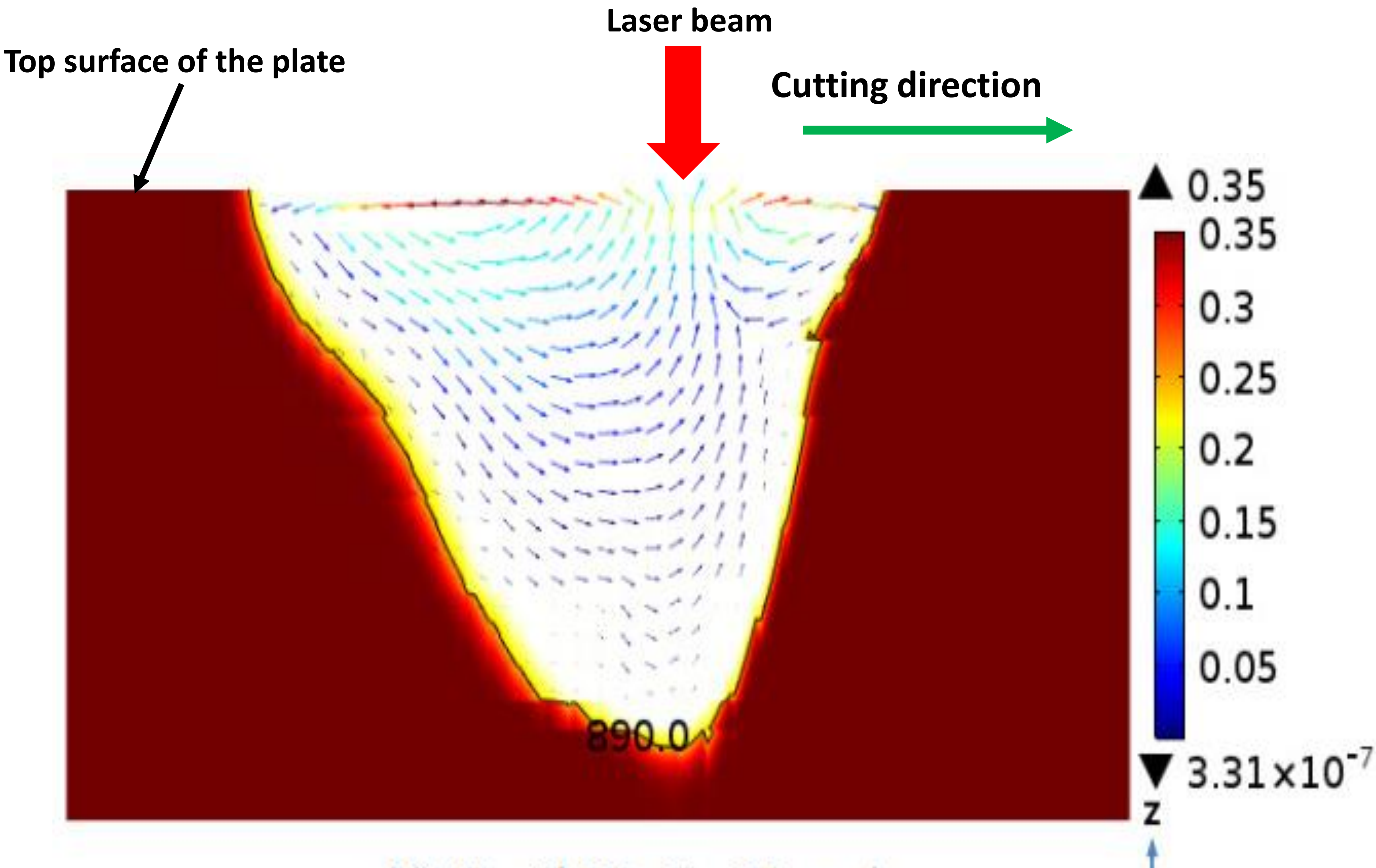
Continuity equation (Conservation of Mass)

$$\frac{\partial \rho}{\partial \mathrm{t}} + \nabla .(\rho u) = 0$$

Navier-Stokes Equation (Conservation of Momentum)

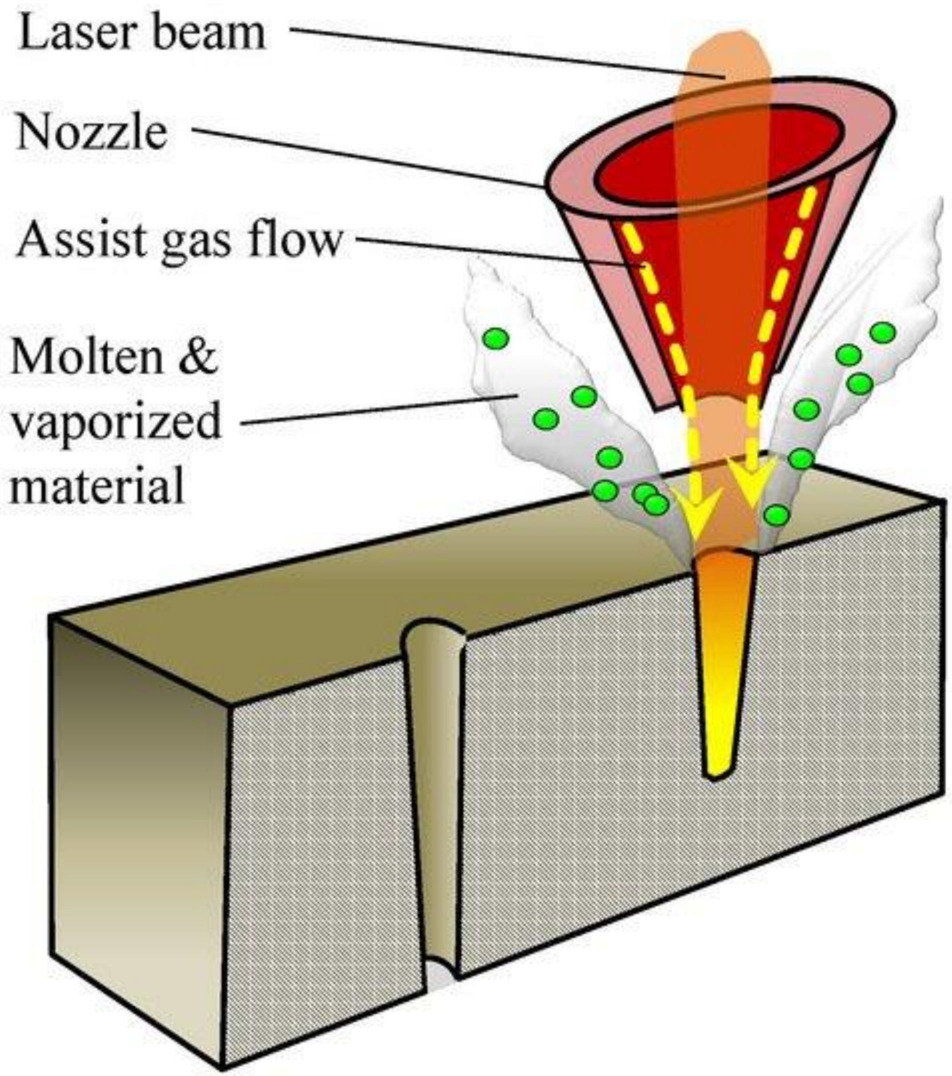
$$\rho \frac{\partial u}{\partial t} + \rho (u.\nabla) u = \nabla .[-pI + \mu(\overrightarrow{\nabla u} + (\overrightarrow{\nabla u})^T)] - \rho(1 - \beta(T - T_m))\vec{g} + \vec{F}$$

Melt flow during the initial heating



(d) P= 5kW, V= 25mm/s

Gas flow


Laser beam
Nozzle
Assist gas flow
Molten &
vaporized
material

Energy calculation

Energy required to melt and vaporize the material can be calculated the following thermal energy balance equation.

Q_a (Absorbed energy) = Heat up the solid to the melting temperature (Q_1) + Latent heat of melting (Q_2) + Heat up the molten material to the vaporization temperature (Q_3) + Latent heat of vaporization (Q_4) + Energy losses by conduction, convection, radiation (Q_L)

$$Q_a = m_a \cdot C_p \cdot \Delta T_m + m_a \cdot L_m + m_a \cdot C_p \cdot \Delta T_v + m_a \cdot L_v + Q_L$$

$$Q_a = m_a \cdot C_p \cdot \Delta T_m + m_a \cdot L_m + m_a \cdot C_p \cdot \Delta T_v + m_a \cdot L_v$$

$$Q_a = \rho V \left(C_p \cdot \Delta T_m + L_m + C_p \cdot \Delta T_v + L_v \right)$$

Energy calculation

$C_p \rightarrow$ Specific heat (J/kg.k) ; $L_m \rightarrow$ Latent heat of melting per unit mass (J/kg) ; $L_v \rightarrow$ Latent heat of vaporization per unit mass (J/kg) ;

$m_a \rightarrow$ mass of the heated substance (kg),

$T_m \rightarrow$ Melting temperature (°C), $T_v \rightarrow$ vaporization temperature (°C); $\Delta T_m = T_m - T_0$, $\Delta T_v = T_v - T_m$;

$\rho \rightarrow$ density (kg/m^3) ; V = Volume (m^3).

Problem 1. A 2.5 mm thick aluminum plate is cut using a 1.5 kW laser. If the resulting kerf width is 0.3 mm; the ambient temperature is 25°C; and 5% of the incident laser beam is absorbed by the plate, determine the cutting speed. You may assume that there is no vaporization, and that there are no energy losses by conduction, convection, or radiation.

Solution:

Average density, $\rho = 2700\ \text{kg/m}^3$
Average specific Heat, $c = 900\ \text{J/kgK}$
Latent heat of fusion, $L = 397\ \text{kJ/kg}$
Melting temperature, $T_\text{m} = 660.4^\circ$ C

From equation (10.1), we have

$$Q_\text{a} = q \times t = m_\text{a} c_p \Delta T_\text{m} + m_\text{a} L_\text{m} + m_\text{a} c_p \Delta T_\text{v} + m_\text{a} L_\text{v} + Q_\text{l}$$

where q is the power supplied, and t is the cutting time. Since it is assumed that there is no vaporization, and that there are no energy losses by conduction, convection, or radiation, we have

$$q \times t = m_\text{a} c_p \Delta T_\text{m} + m_\text{a} L_\text{m} = \rho V (c_p \Delta T_\text{m} + L_\text{m})$$

$$q \times t = \rho \times l \times w_\mathrm{k} \times h(c_p \Delta T_\mathrm{m} + L_\mathrm{m})$$

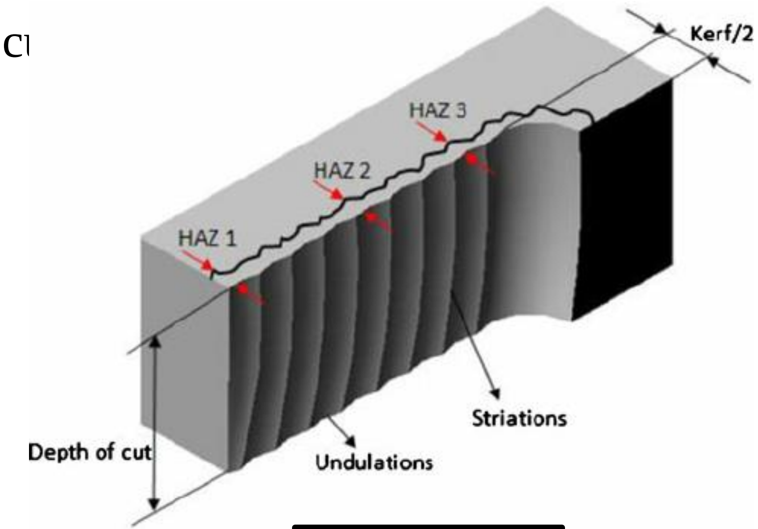
where l is the length of the cut that is made, w_k is the kerf width, and h is the plate thickness. Thus the average cutting speed, u_c, is

$$\begin{aligned} u_\mathrm{c} &= \frac{l}{t} = \frac{q}{\rho \times w_\mathrm{k} \times h(c_p \Delta T_\mathrm{m} + L_\mathrm{m})} \\ &= \frac{1500 \times 0.05}{2.7 \times 10^{-6} \times 0.3 \times 2.5(900 \times (660.4 - 25) + 397 \times 10^3)} \\ &= 38.23 \text{ mm/s} = 2.3 \text{ m/min} \end{aligned}$$

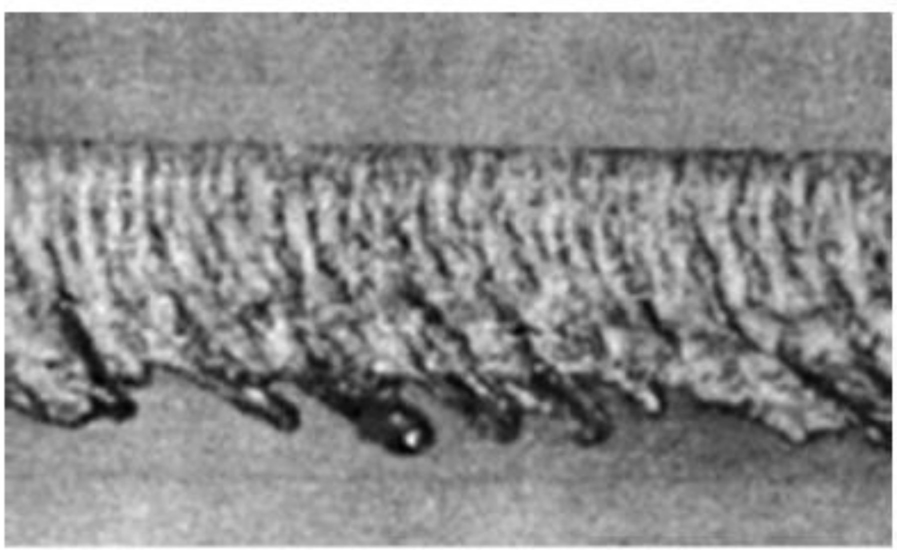
Quality of the cut

The major factors that determine the quality of the c
part

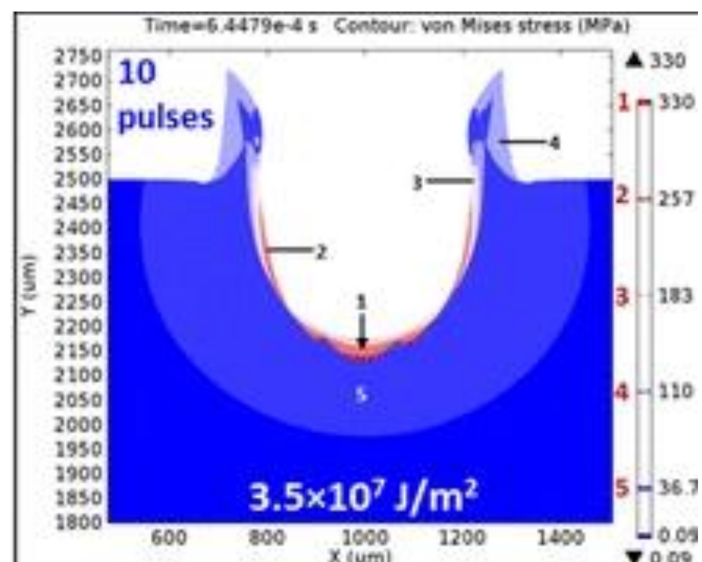
- Vibrations in the motion unit.
- Fluctuations in the laser power.
- Fluctuations in the gas flow.
- Hydrodynamics of the molten metal flow.



Striations



Dross formation



Hydrodynamics

Materials consideration in laser cutting

Metals

- Carbon steels **(Low or Mild, Medium and High)**
- Galvanised steel
- Stainless steel (**Austenitic, Ferritic, Martensitic, Duplex)**
- Aluminium and its alloy **(1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx)**
- Copper and its alloy (**Brass, Beryllium, etc.,)**
- Titanium and its alloys (**Ti 6Al-4V , Ti 6AL-4V ELI, Ti 3Al 2.5, Ti 5Al-2.5Sn)**
- Nickel and its alloy (Nickel-Iron, Nickel-Copper, Nickel-Molybdenum, Nickel-Chromium, etc.,

Non-Metals

- Polymers
- Composites
- Glasses, ceramics, wood, paper and cardboard

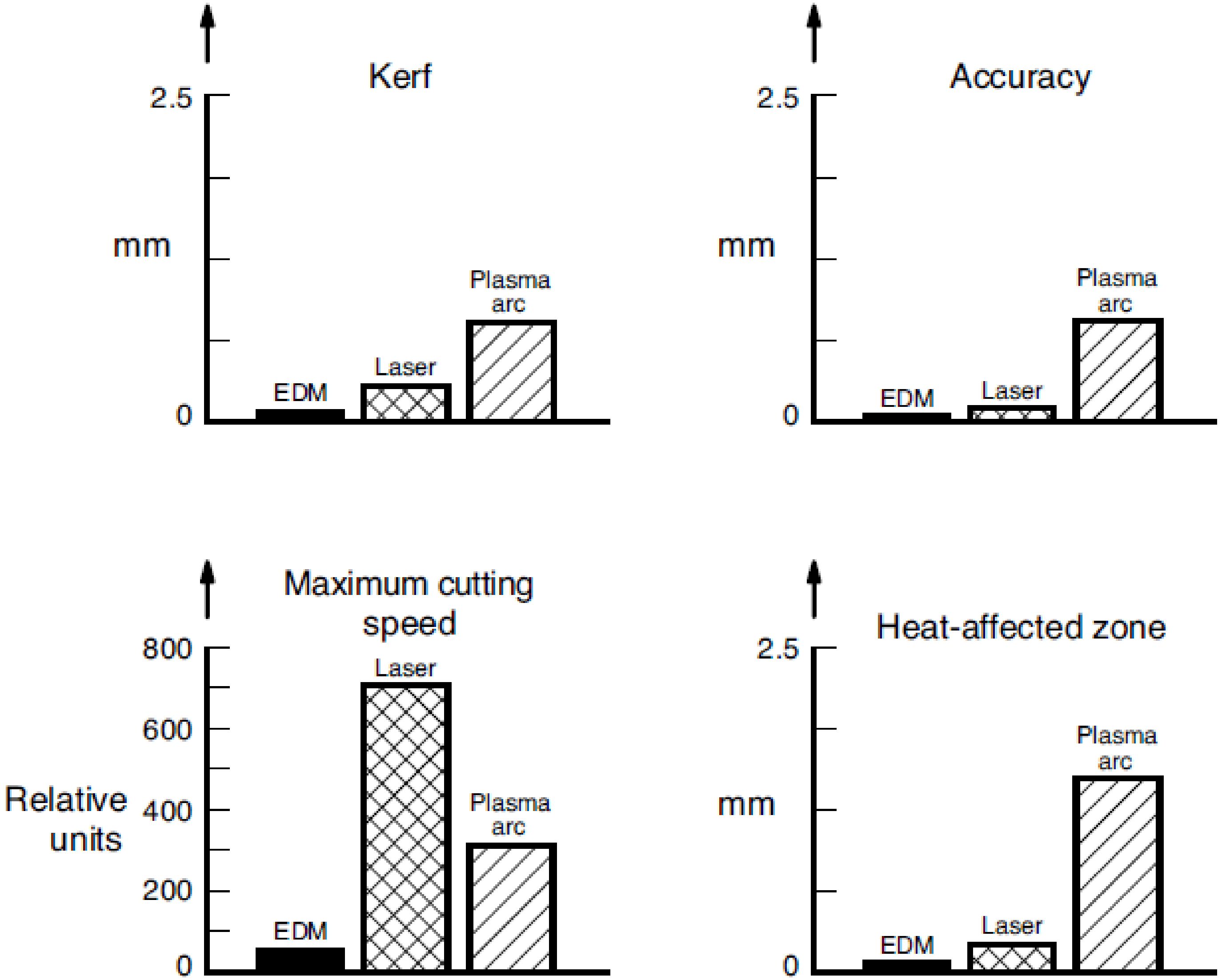
Advantages of Laser Cutting

- Capable of cutting many materials (paper to diamond) and thicknesses (upto 100 mm)
- Cutting narrow kerf widths, which promotes material savings
- Easily and accurately repeatable
- Efficient processing, as multiple jobs or parts, can be nested and cut in a single program
- No secondary clean up process required for most materials
- Non-contact process (damage to the material is minimised)
- Relatively high cutting speeds.
- Low Lead Times with No Need to Replace or Modify Tooling

Disadvantages of Laser Cutting

- Not all types of metals can be cut with laser cutting. For example, metals like copper and aluminum can't be cut using this technology.
- Lead to the combustion of some materials
- High energy required
- The initial capital cost of a laser cutting system is relatively high
- Rate of production depends on the material
- Poorly adjust lasers can cause burning

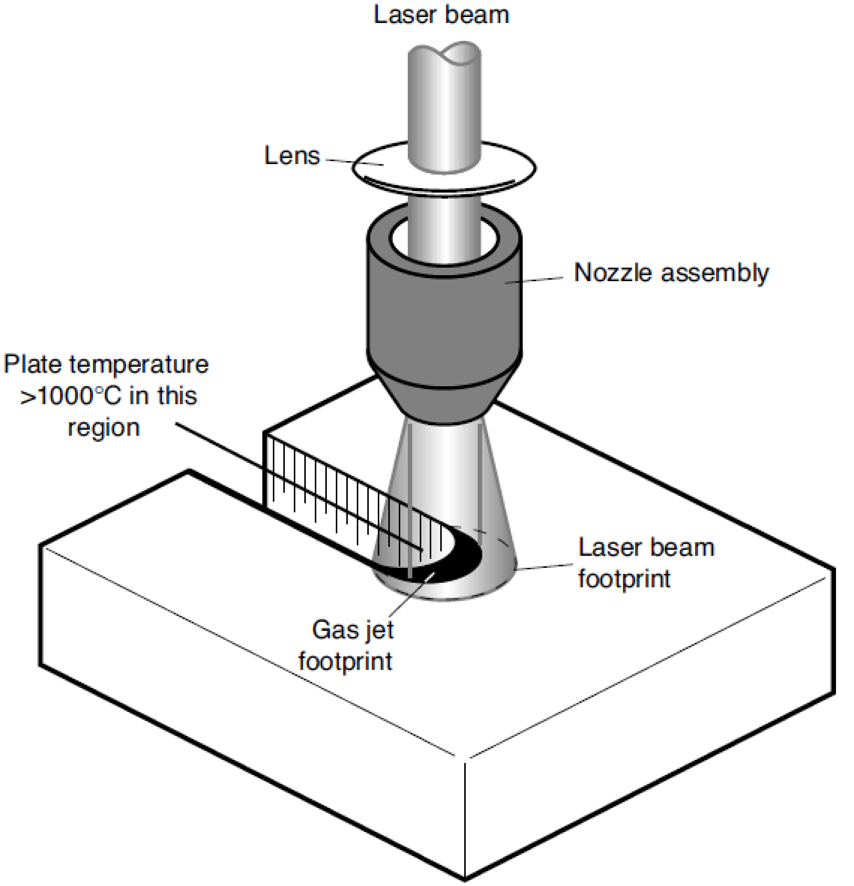
Comparison with Conventional Processes



Comparison of electrical discharge machining (EDM), laser cutting, and plasma arc cutting processes.

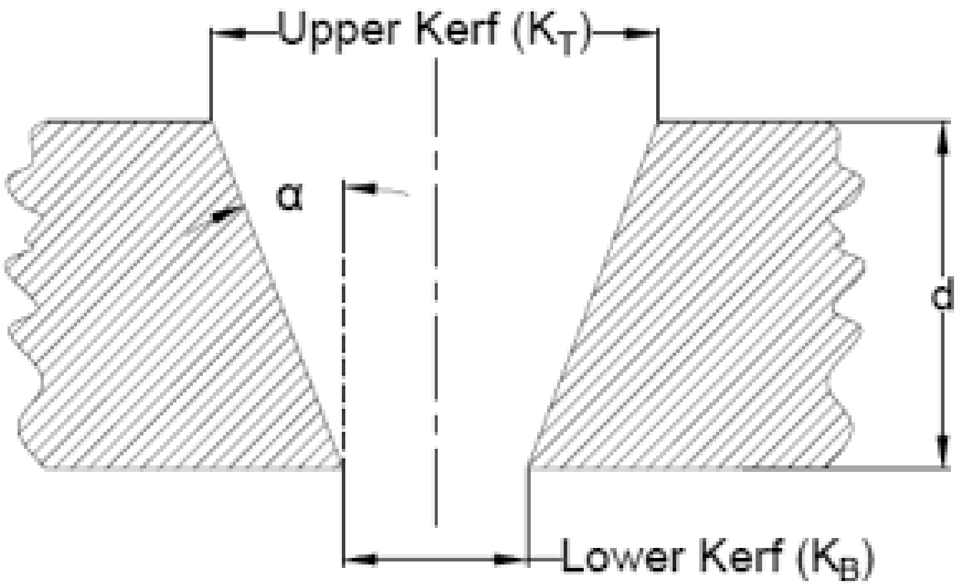
Special Techniques

- Laser-assisted oxygen cutting process (Lasox).
- Conventional laser cutting is limited to thicknesses of up to 25mm, which can be achieved with a laser power of about 3kW in steels.
- In this process, the laser beam preheats the surface of the workpiece to a temperature close to its melting temperature (>1000◦C for steels), and this promotes melting of the workpiece by an oxygen gas jet which flows coaxially with the beam. Once the reaction is initiated on the surface, it continues through the workpiece thickness.



Special Techniques

- 20–50 mm steel plates can be cut with laser power levels of 700–1100 W at speeds of 0.15–0.5m/min if the beam diameter on the workpiece surface is 4 mm, gas jet diameter is 3 mm, nozzle exit diameter is 2.5 mm, gas pressure is about 8 bar, and the beam absorptivity is 30%.
- The taper angle is also less than 1°.



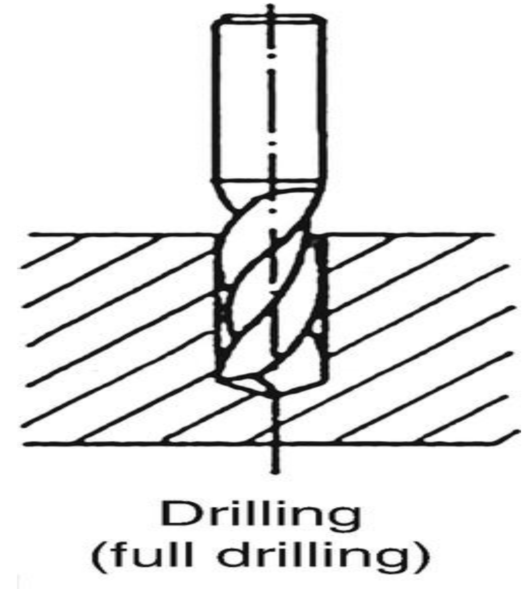
$$Tan \propto = \left(\frac{K_T - K_B}{2d}\right)$$

LASER DRILLING

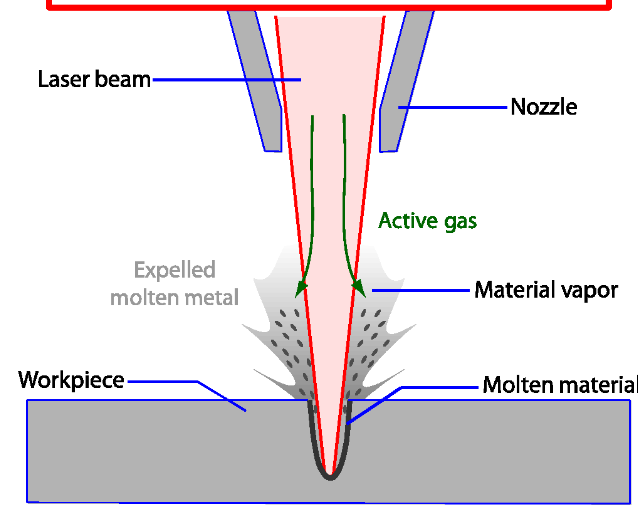
Laser drilling

1) Applying a laser beam to heat up the material to its melting point or vaporization temperature.
2) When vaporization occurs, it generates a keyhole that results in increased absorptivity, further increasing the hole depth.
3) The molten material or vapor formed is blown away using an assist gas.

- Basic process parameters
- Analysis of the process
- Advantages and disadvantages of laser drilling
- Applications

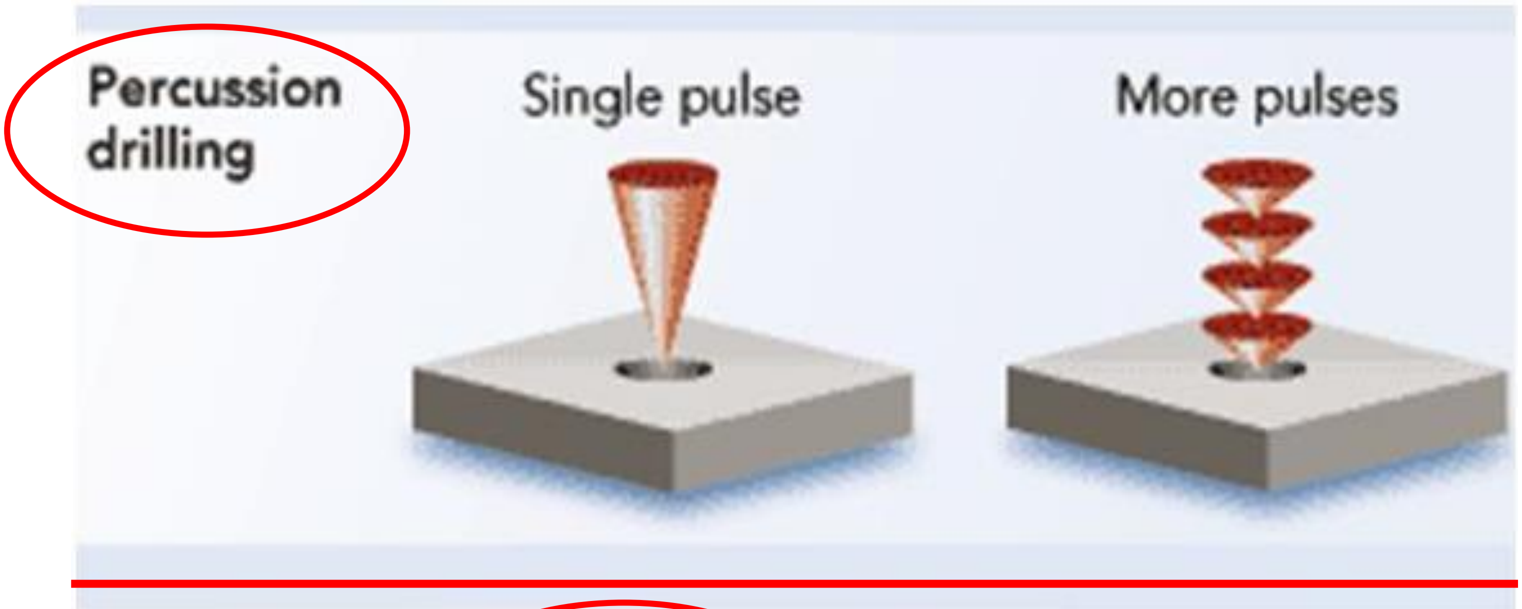


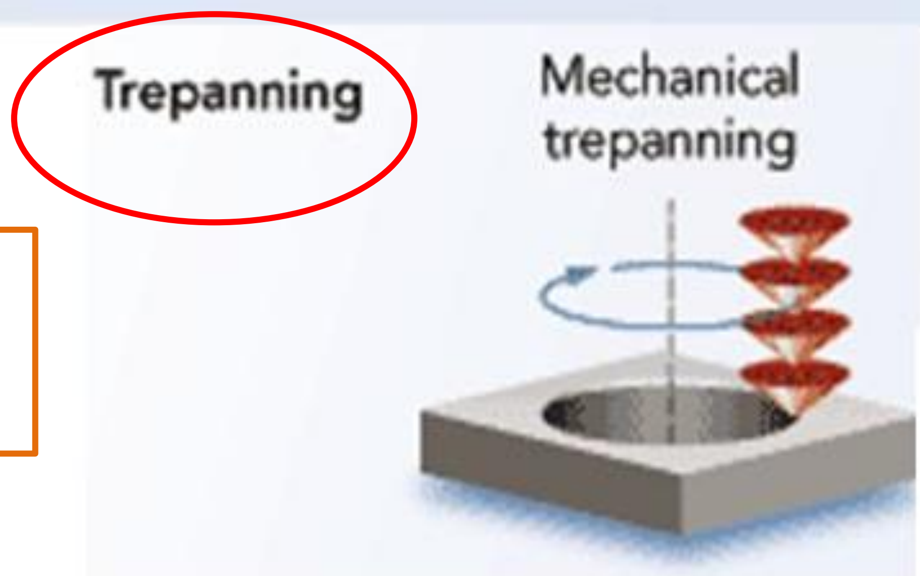
Conventional drilling



Laser drilling

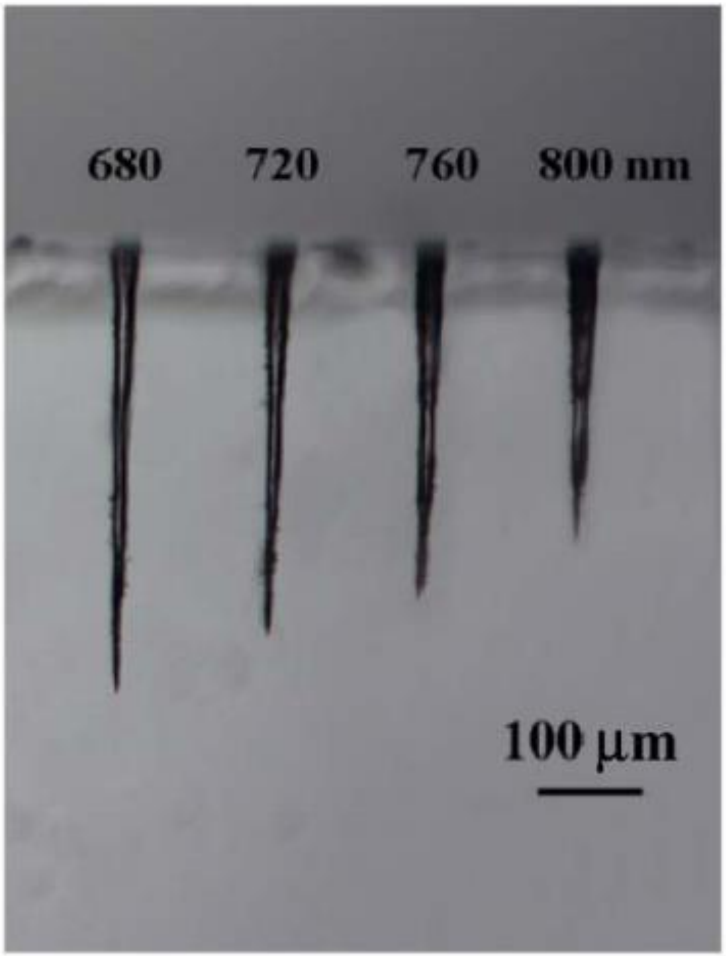
Forms of Laser Drilling

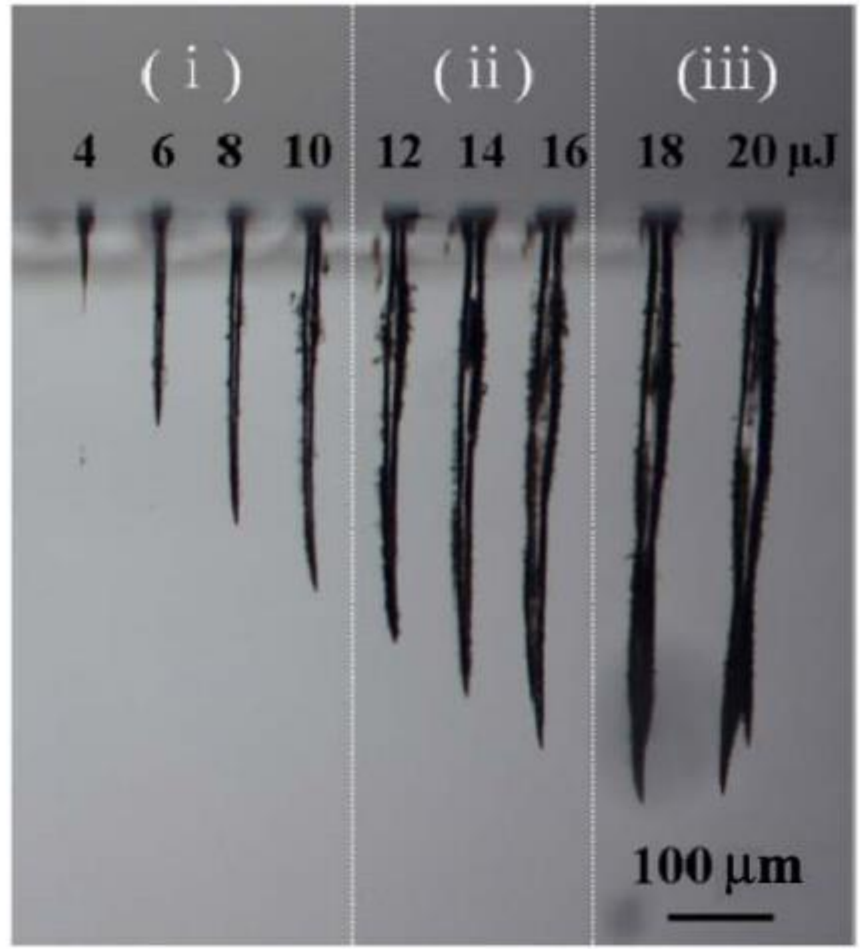




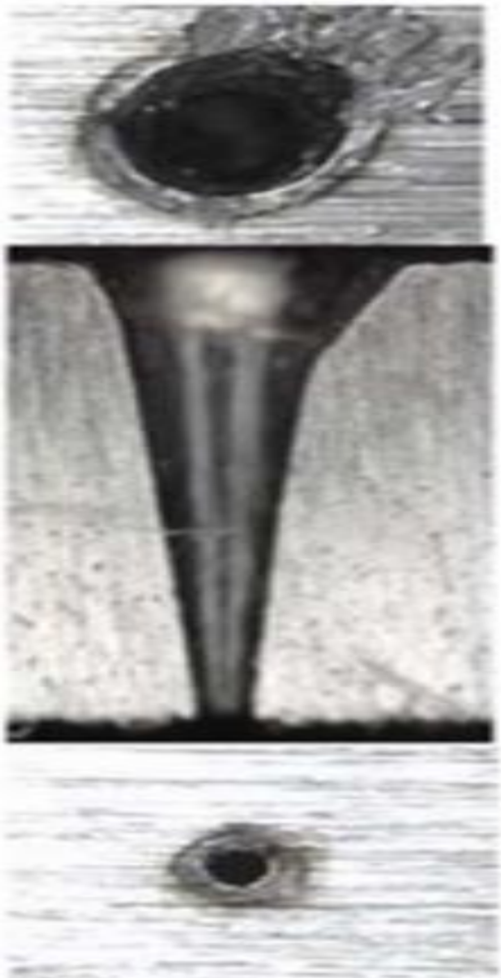
- ***Single-Pulse Drilling***
- ***Multi-pulse Drilling***
- ***Trepanning Drilling***

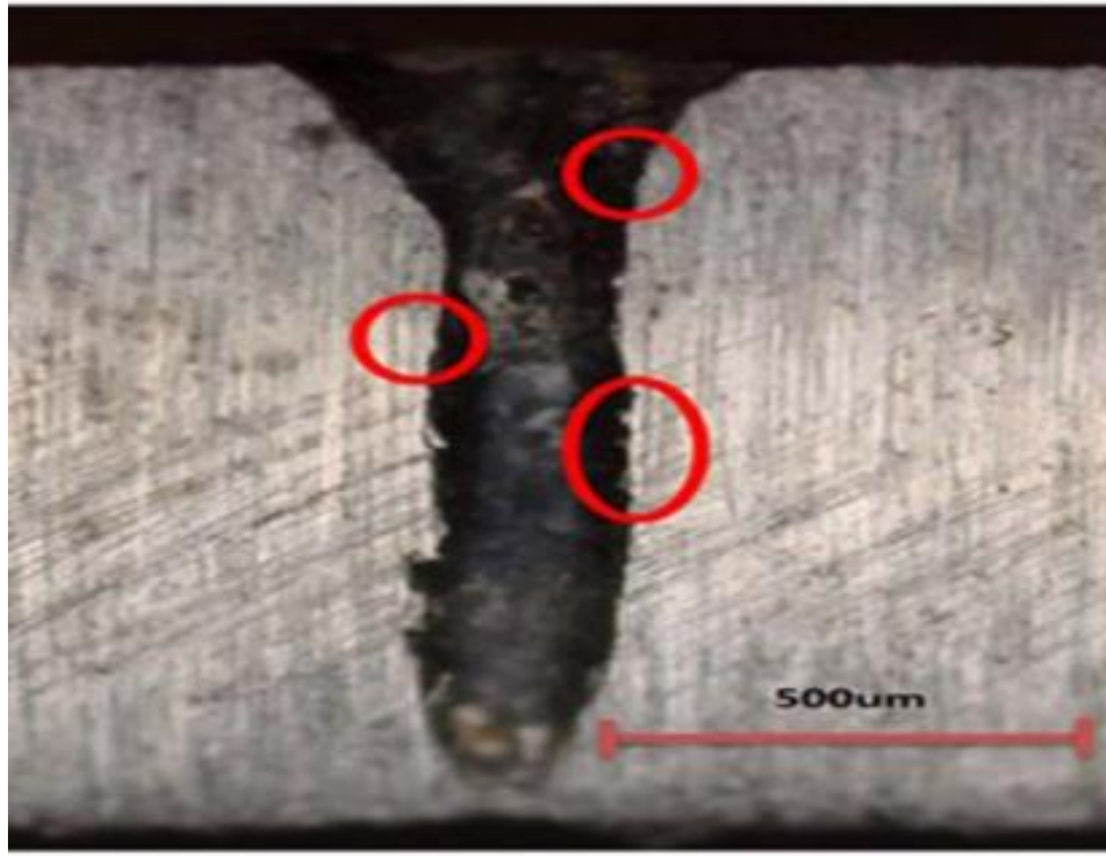
Hole produced using single-pulse drilling



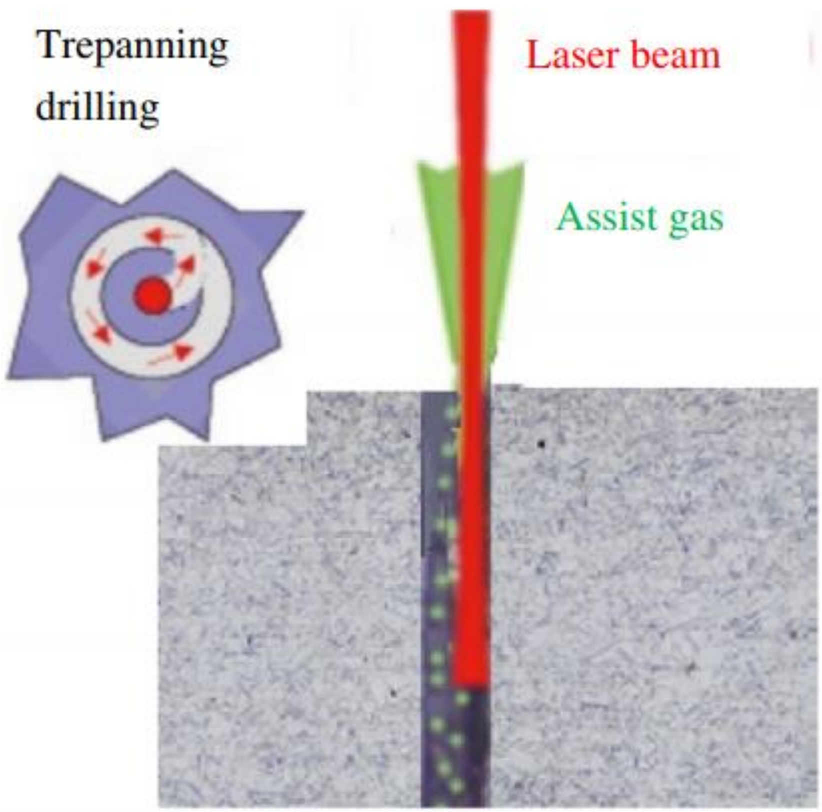


Hole produced using Multi-pulse drilling

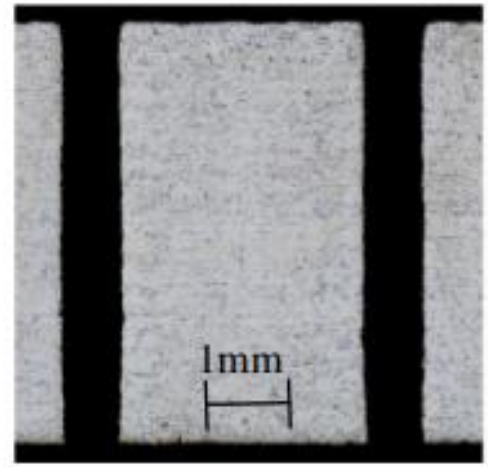




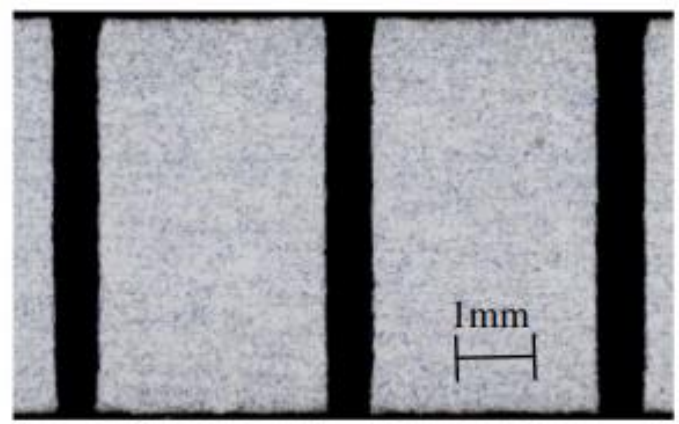
Hole produced using Trepanning drilling



Laser trepanning drilling method



Microscopic image of hole drilled at 6J



Microscopic image of hole drilled at 200Hz

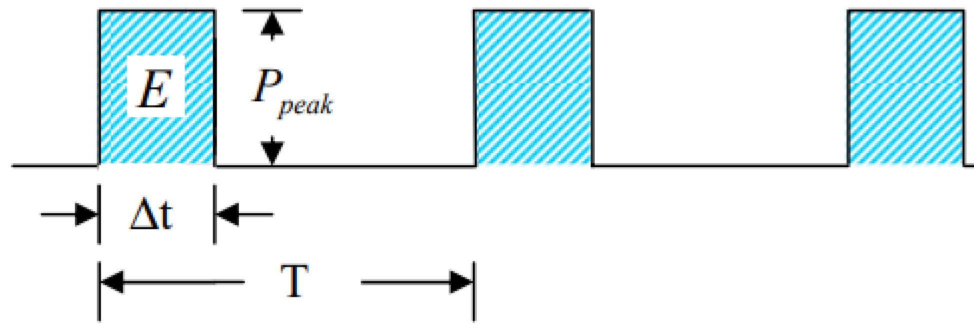
Process Parameters

The principal parameters associated with percussion laser drilling are

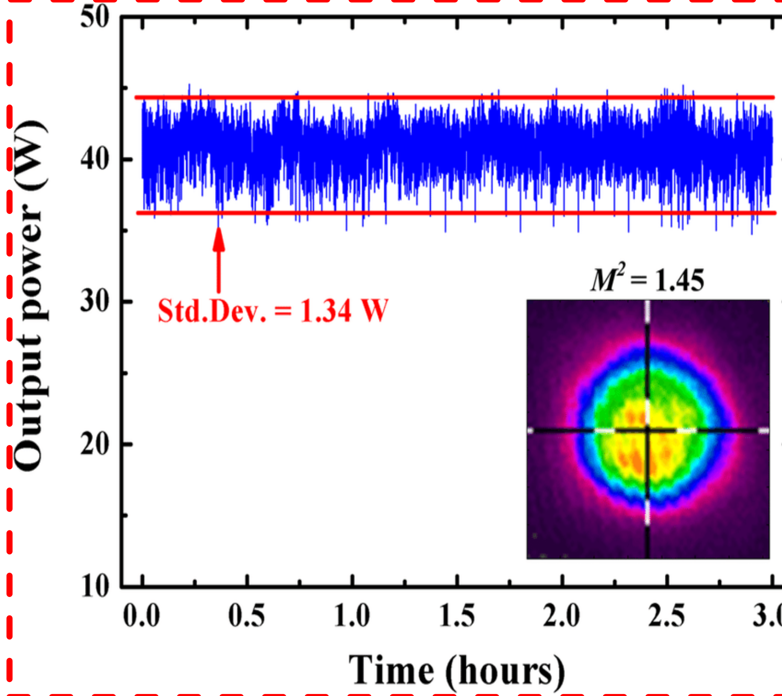
- Beam characteristics (inputs),
- Process characteristics (outputs), and
- Process defects.

Beam Characteristics

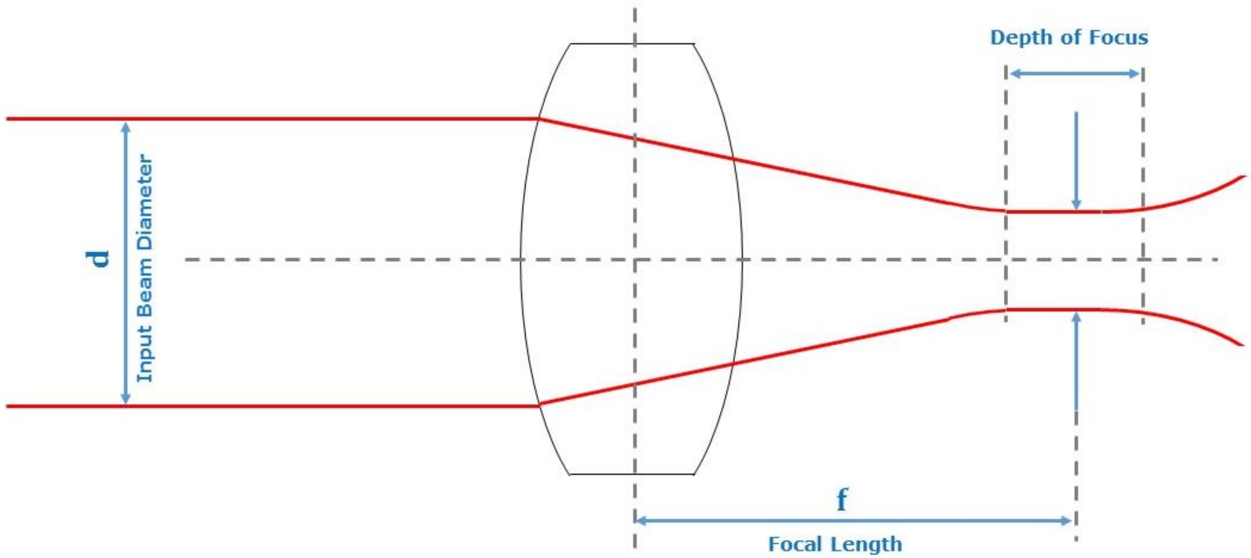
- Pulse Energy
- Pulse Duration
- Number of Pulses
- Beam Quality

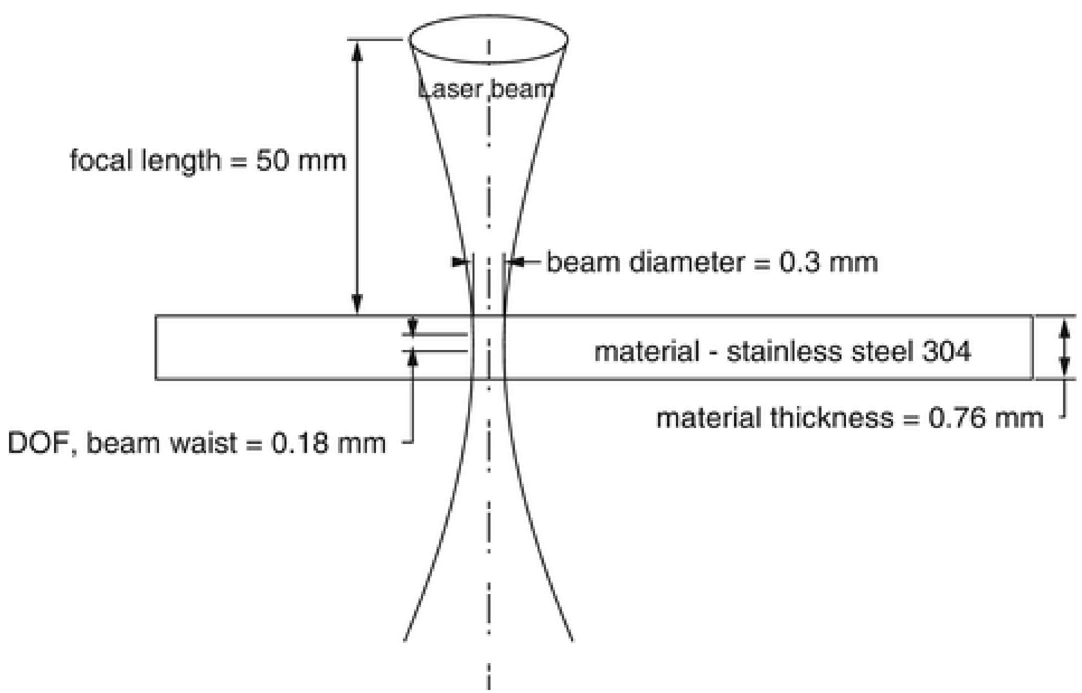


Beams of lower M2 values or higher quality can be focused to a smaller diameter and also have a longer depth of focus. This increases penetration depth for drilling and cutting, while improving hole quality (high depth-to-diameter ratio with reduced taper), especially for small diameter holes.



Depth of focus



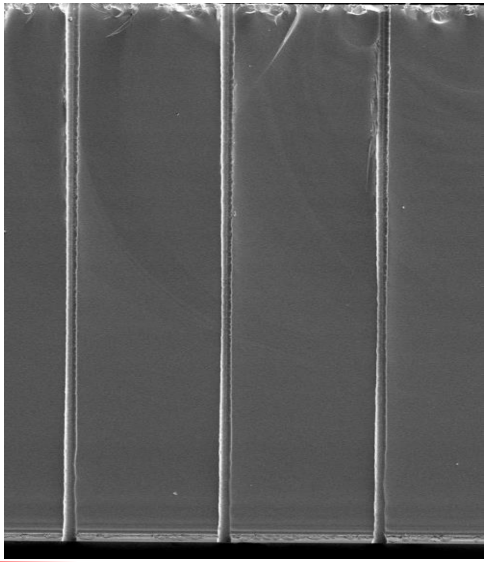


Drilling Characteristics

- Hole Diameter
- Hole Depth
- Drilling Angle

Hole Depth

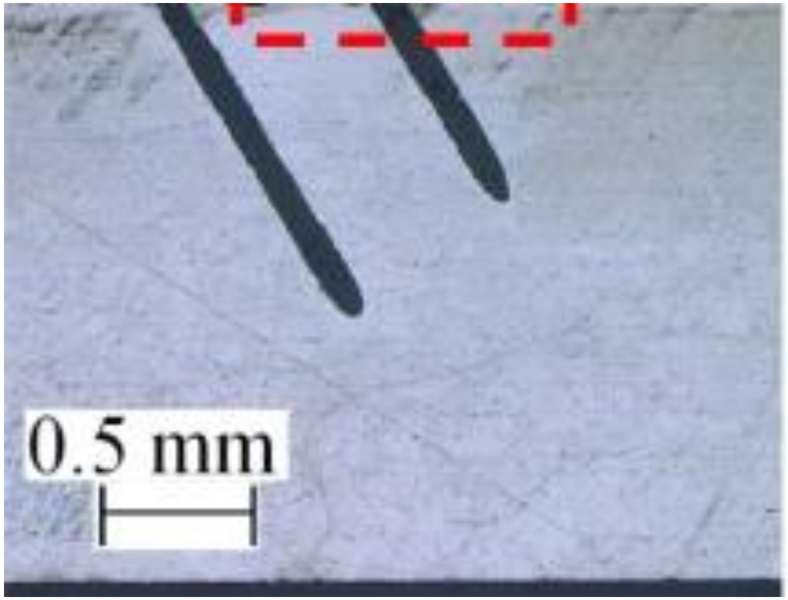
Depth to diameter ratios as high as 30:1 can be achieved.



Hole Diameter

Methods/Lasers	Hole diameter
Ultrafast lasers (Nano, Pico, Femto)	Micro holes **(1 µm to 1 mm)**
Percussion	1 mm to 1.5 mm
Trepanning	>1.5 mm

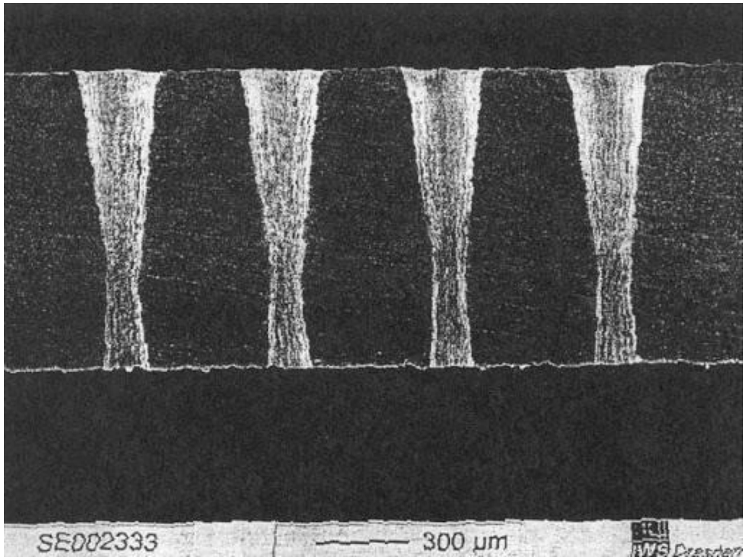
Drilling Angle

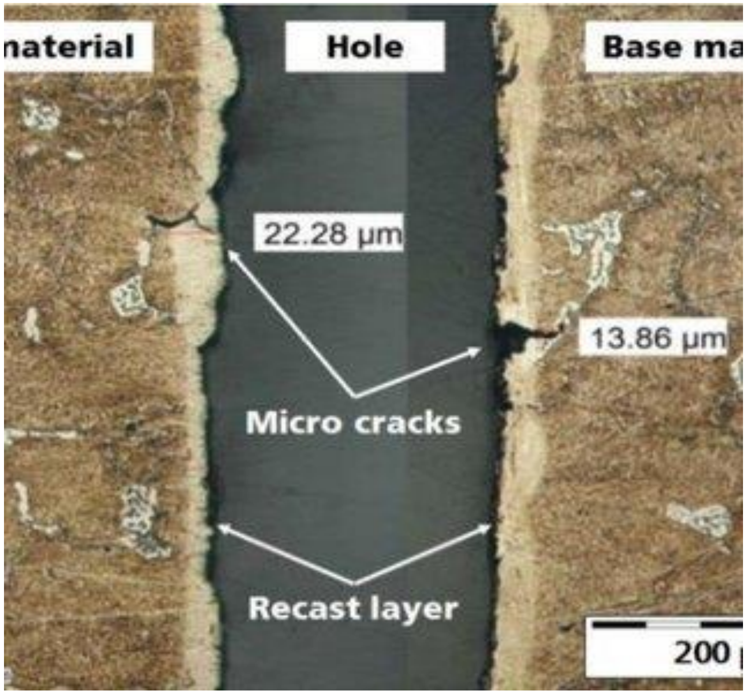


Process Defects

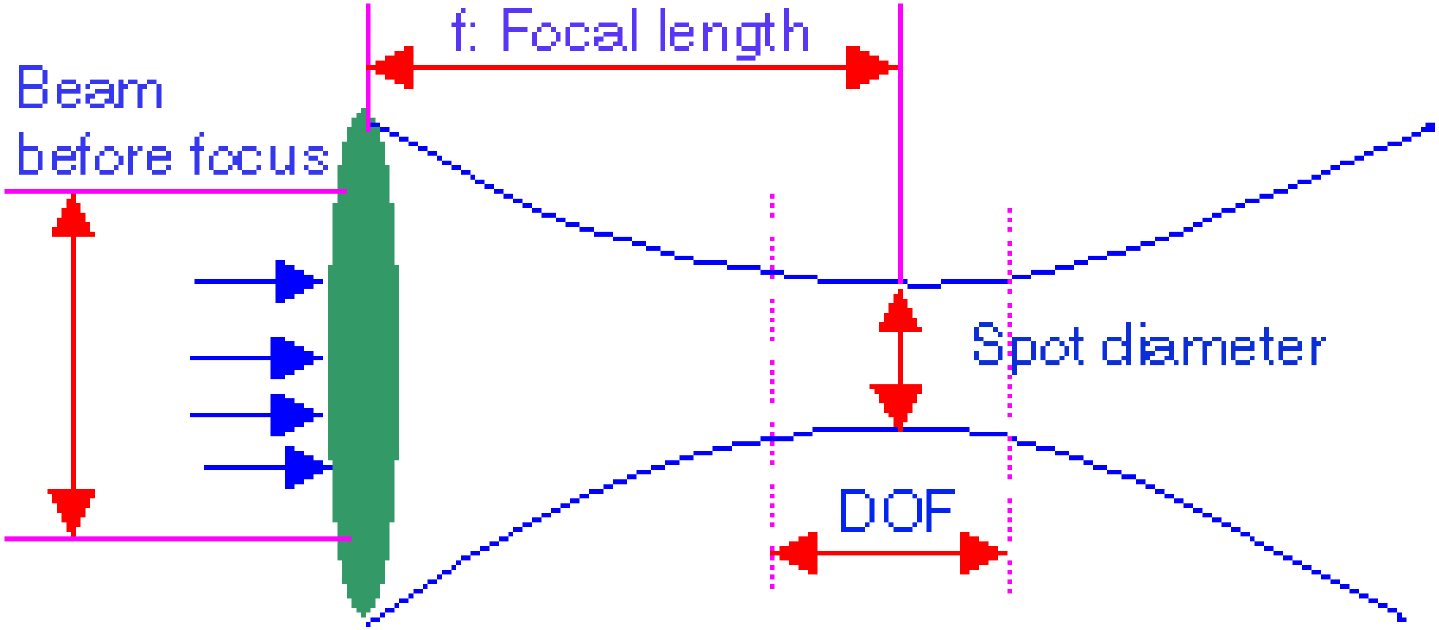
- Taper of the hole walls
- Recast
- Microcracking

The microcracks in the laser-drilled holes are formed due to the thermal mismatch between the laser beam energy and the cold workpiece, and subsequent cooling effect induced by assist process gas during the laser processing. This causes large temperature gradients near the hole surface.





Depth of focus



$$DOF = (8\lambda/\pi)(f/D)^2$$

Analysis of Material Removal During Drilling

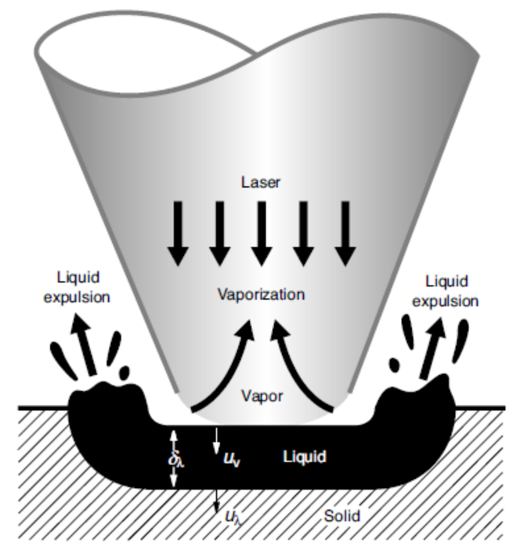
Ablation may occur by normal vaporization (**insignificant at time scales shorter than 1 ns, and also for very low temperatures**), normal boiling, or phase explosion.

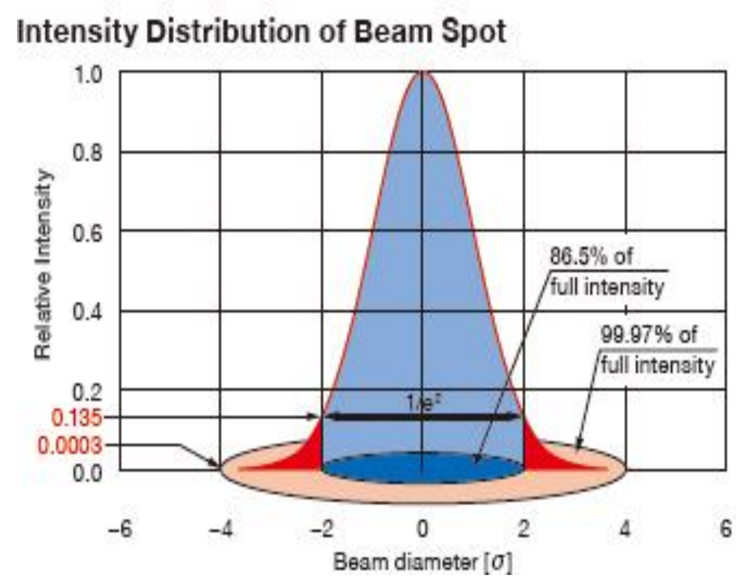
<u>Normal boiling</u>

- Requires a relatively long pulse period
- The normal boiling process occurs within the absorption depth (**how deeply light penetrates**) ($1/\alpha$, where α is the absorption coefficient)
- The absorption depth is a useful parameter which gives the distance into the material at which the light drops to about 36% of its original intensity, or alternately has dropped by a factor of $1/e$.
- The temperature gradient at the surface and also directly beneath it is zero (i.e., $\partial T/\partial z = 0$)

<u>Phase explosion</u>

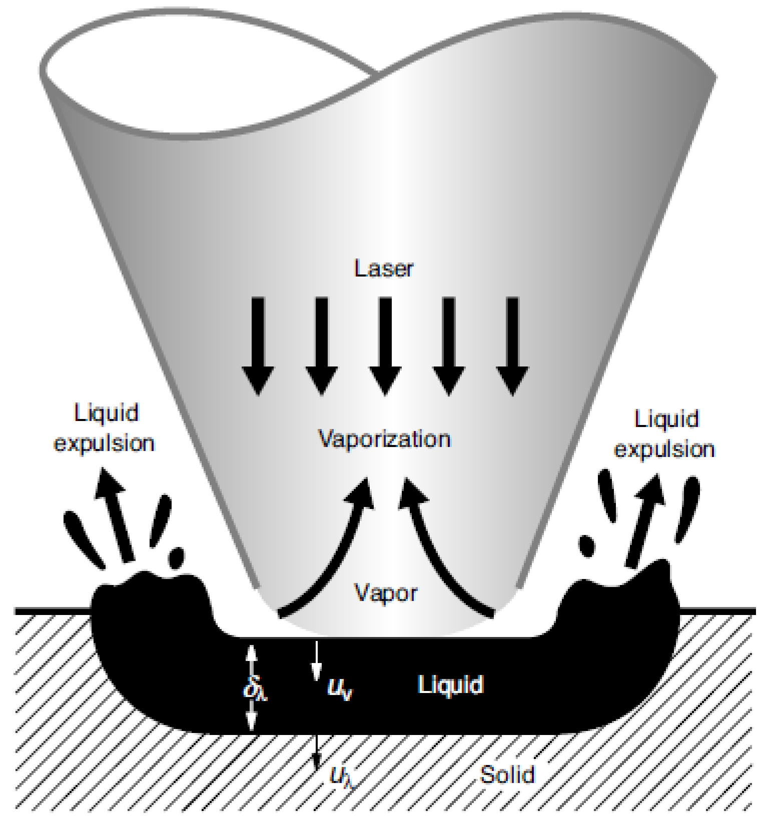
- The laser fluence has to be sufficiently high such that the temperature of the surface and the region immediately beneath it reaches about 90% of the thermodynamic critical temperature (i.e. $0.90T_{ct}$)
- The material undergoes a rapid transition from a superheated liquid to a vapor/liquid droplet mixture.





Analysis of Material Removal During Drilling

The rate at which the drilled surface recedes during normal vaporization, that is, the drilling velocity, ud, can be obtained from the Hertz–Knudsen equation as

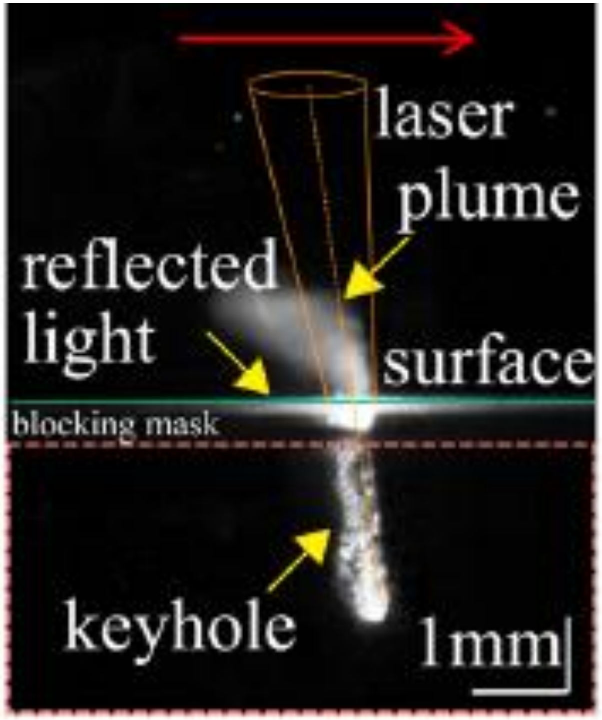


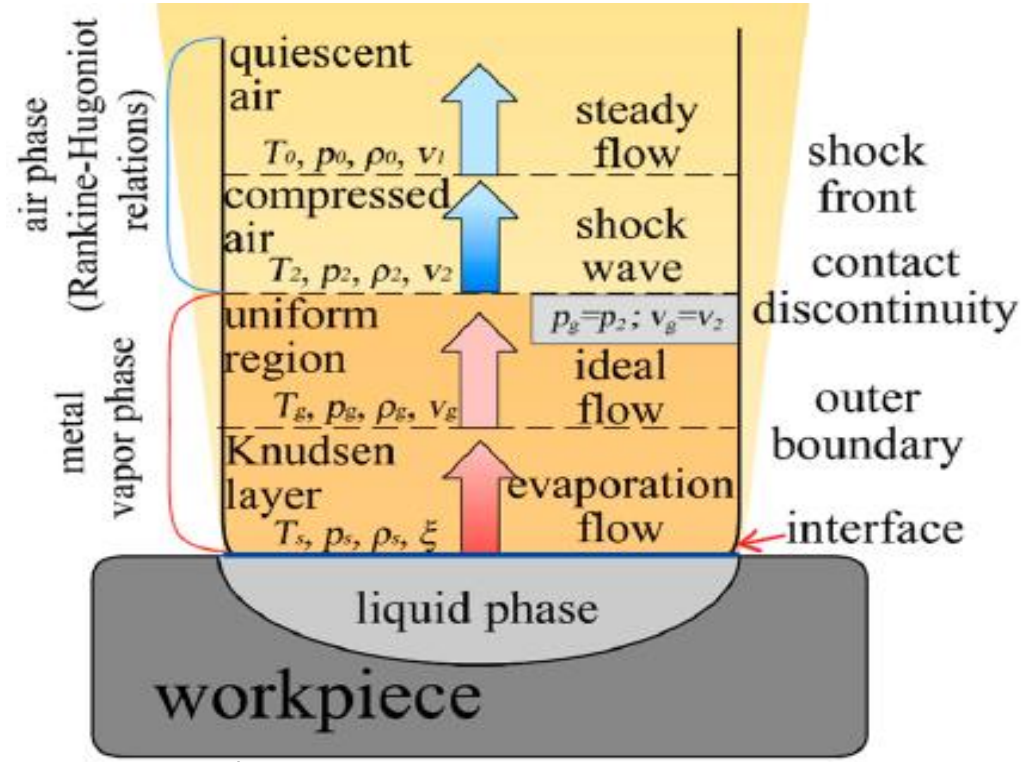
$$u_d = \left.\frac{\partial z}{\partial t}\right|_{z=0} = \frac{k_c P_s {\lambda_a}^3}{\sqrt{(2\pi m_m k_B T)}}$$

$$\approx \frac{k_c P_a {\lambda_a}^3}{\sqrt{(2\pi m_m k_B T)}} \exp\left[\frac{L_v m_m}{k_B}\left(\frac{1}{T_v} - \frac{1}{T}\right)\right]$$

where kc = condensation (or vaporization) coefficient, Lv = latent heat of vaporization (J/kg), m_m = mass of the atom or molecule (particle)(kg), Pa = ambient gas pressure (boiling pressure) (Pa), Ps = saturated vapor pressure (Pa), Tv = vaporization (boiling) temperature corresponding to Pa, with the assumption that there is no vapor present in the ambient, and no recondensation (K), and λa = mean atomic spacing of the target (m).

Analysis of Material Removal During Drilling





- Vapour plume is characterized by a total of three transition layers across which the properties of the medium change from one equilibrium state to another.
- The Knudsen layer is estimated to be a few molecular mean-free paths thick, in order to allow for the molecular collisions to occur, that bring the molecules into a state of translational equilibrium at the outer edge of the Knudsen layer.
- The front of the expanding plume is a shock wave that propagates into the stagnant ambient gas. The shock wave causes a sharp increase in temperature and pressure of the ambient gas just behind it. (pressure and velocity field is uniform, but the temperature and density undergo significant changes)

T_{vk} and ρ_v outside of the Knudsen layer

When the gas particles reach the outer boundary of the Knudsen layer, the velocity distribution function for the particles is a Maxwellian distribution, in which T_{vk} and ρ_v are the temperature and density of the gas at the outer boundary, respectively.

$$\frac{T_{vk}}{T_l} = \left[\sqrt{1+\pi\left(\frac{m_u(\gamma_v-1)}{2(\gamma_v+1)}\right)^2} - \sqrt{\pi}\frac{m_u(\gamma_v-1)}{2(\gamma_v+1)}\right]^2$$

$$\frac{\rho_v}{\rho_s} = \sqrt{\frac{T_l}{T_{vk}}}\left[(m_u{}^2+1/2)e^{m_u{}^2}\mathrm{erfc}(m_u) - \frac{m_u}{\sqrt{\pi}}\right] + \frac{T_l}{2T_{vk}}\left[1-\sqrt{\pi}m_u e^{m_u{}^2}\mathrm{erfc}(m_u)\right]$$

Vapour pressure

There is a pressure rise at the liquid–vapor interface, and this propagates as a pressure wave. The pressure change across the wave front, which may be considered as a pressure discontinuity, is given by

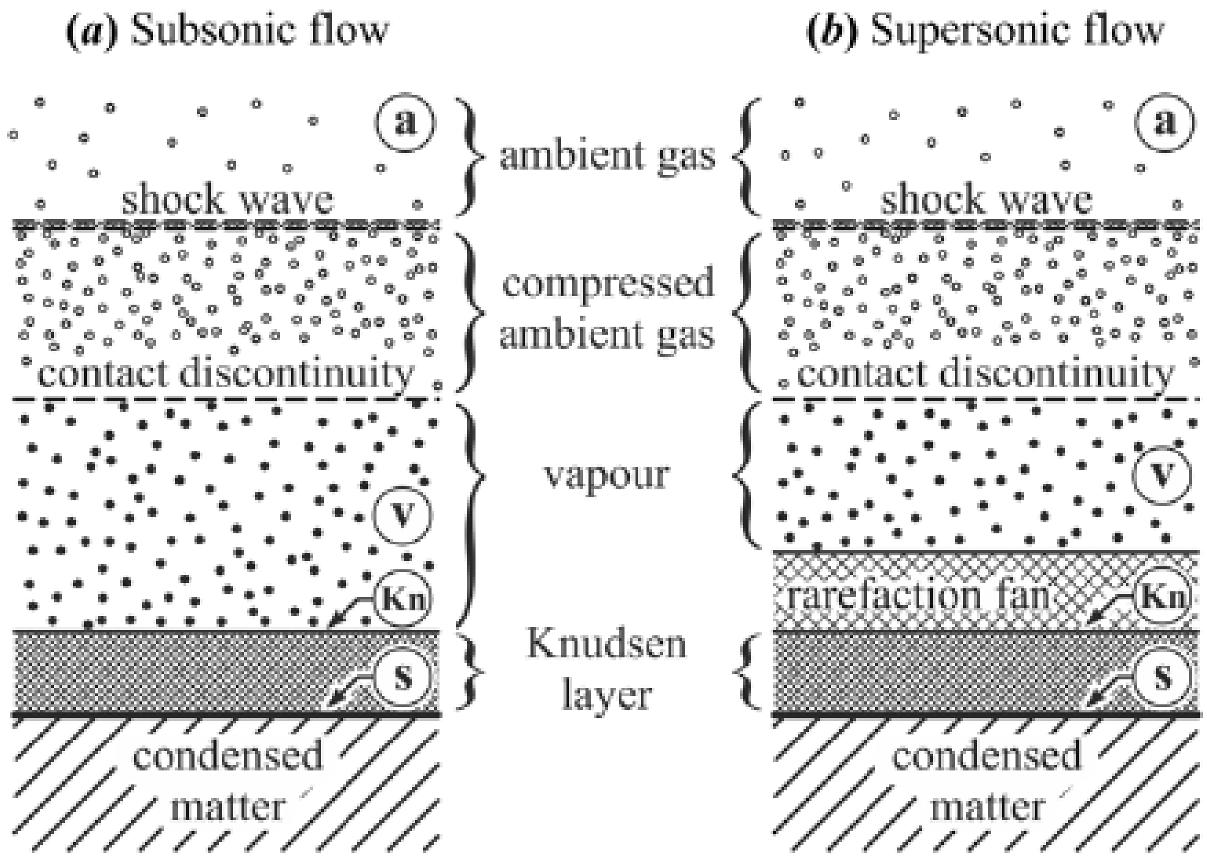
$$\frac{P_{\mathrm{v}}}{P_{\mathrm{a}}} = 1 + \gamma_{\mathrm{a}} M_{\mathrm{h}} \frac{u_{\mathrm{v}}}{u_{\mathrm{a}}} \left[\frac{\gamma_{\mathrm{a}} + 1}{4} M_{\mathrm{h}} \frac{u_{\mathrm{v}}}{u_{\mathrm{a}}} + \sqrt{1 + \left(\frac{\gamma_{\mathrm{a}} + 1}{4} M_{\mathrm{h}} \frac{u_{\mathrm{v}}}{u_{\mathrm{a}}} \right)^2} \right]$$

$$M_{\mathrm{h}} = m_{\mathrm{u}} \sqrt{\frac{2}{\gamma_{\mathrm{v}}}}$$

where c_p and c_v are the specific heats at constant pressure and volume, respectively (J/kg K); $\mathrm{erfc}(m_{\mathrm{u}}) = \frac{2}{\sqrt{\pi}} \int_{m_u}^{\infty} \mathrm{e}^{-x^2}\, \mathrm{d}x$ = complementary error function; m_{u} is the

$\frac{u_k}{\sqrt{2R_{gv}T_{vk}}}$ (m kg$^{1/2}$/sJ$^{1/2}$); M_h is the flow Mach number of the vapor leaving the Knudsen layer; m_g is the molecular weight of the ambient gas (kg/mol); m_v is the molecular weight of the vapor (kg/mol); P_a is the ambient pressure (Pa); P_s is the saturated vapor pressure (Pa); P_v is the vapor pressure (Pa); P_{vk} is the vapor pressure at the edge of the Knudsen layer (Pa); $R_g = 8.314$ is the universal gas constant (J/mol K); $R_{ga} = \frac{R_g}{m_g}$ is the gas constant for the ambient gas (J/kg K); $R_{gv} = \frac{R_g}{m_v}$ is the gas constant for the vapor (J/kg K); T_a is the ambient temperature (K); T_l is the liquid temperature at the vaporizing surface (K); T_{vk} is the vapor temperature at the edge of the Knudsen layer (K); u_k is the mean vapor velocity at the edge of the Knudsen layer (m/s); u_a is the speed of sound in the ambient gas (m/s); u_v is the speed of sound in the vapor (m/s); ΔH_{vm} is the molar enthalpy of vaporization (J/mol); γ_a is the ratio of specific heats for the ambient gas; $\gamma_v = c_p/c_v$ is the ratio of specific heats for the vapor, considering the vapor to be a monatomic gas; ρ_s refers to the saturated vapor density at the liquid temperature, T_l (kg/m^3); ρ_v refers to the vapor density at the edge of the Knudsen layer (kg/m^3).

Analysis of Material Removal During Drilling



In supersonic case, a rarefaction wave takes the vapor from the sonic state at the Knudsen layer to a supersonic state away from the Knudsen layer.

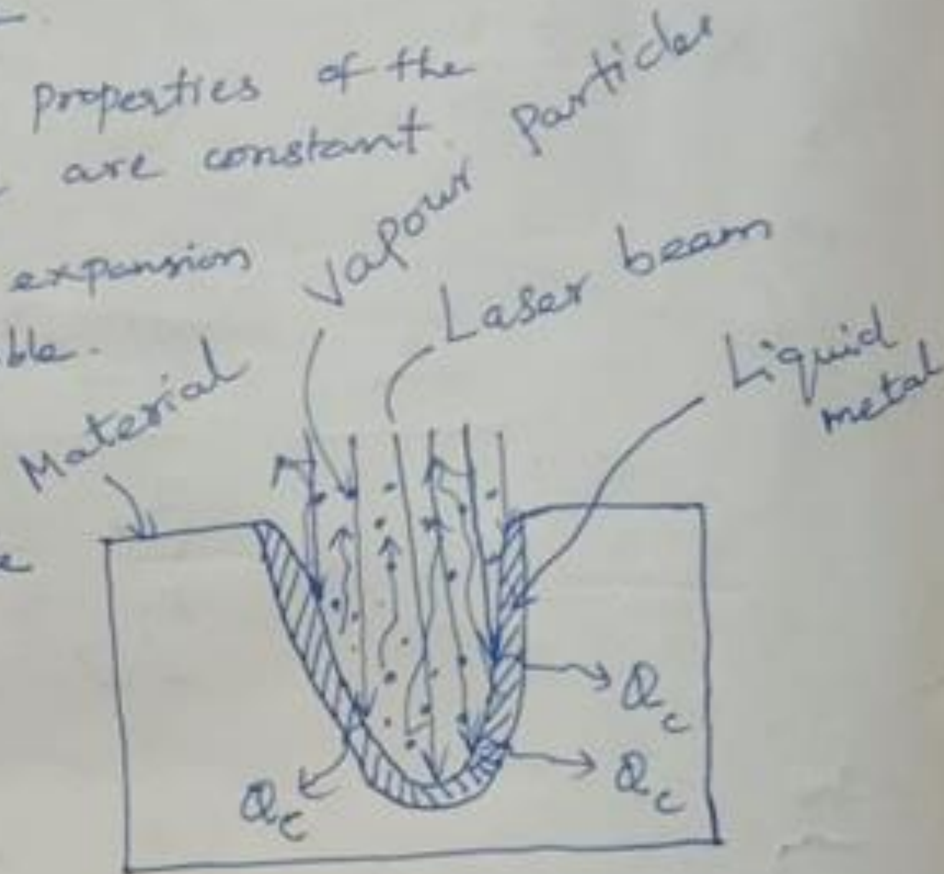
Approximate Analysis to estimate the Velocity of the drilling Process

(i) Heat conduction & Vapour absorption losses are negligible.

(ii) thermal properties of the material are constant.

(iii) thermal expansion is negligible.

(iv) Skin depth is negligible



Energy flux carried away with the expulsed material to be equal to the power density absorbed by the material, I_a.

$$I_a = \phi_V \cdot \Delta H_V + \phi_L \cdot \Delta H_L$$

$\Delta H \rightarrow$ Latent heat (J/kg)

$\phi \rightarrow$ Expulsion rate (Kg/m²·s)

V → vapour
L → Liquid

Drilling velocity, $u_d = \dfrac{I_a}{\rho \times L_H}$ (m/s)

$$u_d = \frac{1}{\rho}\left(\phi_V + \phi_L\right)$$

The quasistatic temperature distribution (T) neglecting Phase changes and Conductive losses can be written as

$$T = \frac{I_a'}{\rho \cdot c_p \cdot u_d} \exp\left(-\frac{\xi u_d}{k}\right)$$

$$I_a' = I_a - \phi_v \cdot L_v$$

$L_v \rightarrow$ latent heat of evaporation (J/kg)

$k \rightarrow$ thermal diffusivity (m^2/s)

$\xi \rightarrow$ moving co-oridinate in the direction of u_d.

The rate of evaporation ϕ_v, of a hot surface at a temperature T_h is obtained from the Hertz-Knudsen eqn

$$\phi_v = (1-R)\, P_s \left(\frac{m_m}{2\pi k_B T_h}\right)^{1/2}$$

$k_B \to$ Boltzmann's constant (J/K),

$m_m \to$ mass of the molecule (kg)

$R \Rightarrow$ Reflection coefficient

Saturated Vapour pressure, P_s

$$P_s = P_a \exp\left[\frac{L_p}{k_B T_v}\left(1 - \frac{T_v}{T_h}\right)\right]$$

L_p is the heat of evaporation per particle (J/particle)

$P_a \rightarrow$ ambient pressure (Pa)

$T_h \rightarrow$ Hot surface temperature (K)

$T_v \rightarrow$ Evaporation temperature (K)

Thickness δ_1 of the liquid layer formed by heat conduction may be calculated

$$\delta_1 = \left(\frac{k}{u_d}\right) \ln\left(\frac{T_h}{T_m}\right)$$

$T_m \rightarrow$ melting temperature (K)

The pressure, p, of the evaporating surface acting on the liquid layer pushes the liquid radially outward with a velocity u_1

$$u_1 = \left(\frac{2p}{\rho}\right)^{1/2}$$

The expelled liquid escapes through an opening that is determined by the beam radius, ω, of an area A_e

$$A_e = 2\pi\omega\delta_1$$

The liquid expulsion rate (ϕ_L) with respect to the irradiated surface

$$\phi_L = \left[\left(\frac{2K}{\omega}\right)\ln\left(\frac{T_h}{T_m}\right)\right]^{1/2} P_s^{1/4}\, \rho^{3/4}$$

Problem : An Nd:YAG laser generates pulses of intensity $60\,\text{MW/cm}^2$ for drilling $200\ \mu\text{m}$ diameter holes in a tungsten plate. Estimate the drilling speed that can be achieved for this operation. Assume ambient temperature and pressure of 25°C and 0.1 MPa, respectively, and that the diameter of the hole is the same as the beam diameter.

Solution:

Some of the material properties are obtained from Appendices 10D and 10E as

Average density, $\rho = 19254\ \text{kg/m}^3 = 19.254 \times 10^{-6}\ \text{kg/mm}^3$
Average specific heat, $c_p = 134\,\text{J/kgK}$
Latent heat of fusion, $L_m = 220\,\text{kJ/kg} = 220,000\,\text{J/kg}$
Melting temperature, $T_m = 3410°\text{C} = 3683\ \text{K}$
Latent heat of vaporization, $L_v = 4815\,\text{kJ/kg} = 4815 \times 10^3\ \text{J/kg}$

Evaporation temperature, $T_v = 5700°C = 5973$ K
Thermal conductivity, $k = 151.2$ W/mK $= 0.1512$ W/mm K.

Other needed properties are

Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K
Avogadro's number, $N_0 = 6.023 \times 10^{23}$ molecules
Atomic weight, $W_a = 183.8$ g/mol $= 0.1838$ kg/mol

Calculated properties

Particle mass, $m_p = 0.1838$ kg$/6.023 \times 10^{23} = 3.05 \times 10^{-25}$ kg/particle
Heat of vaporization per particle, $L_p = 4815 \times 10^3$ J/kg $\times 3.05 \times 10^{-25} = 14.69 \times 10^{-19}$ J/particle
Incident power density is given by $I_a = 60$ MW/cm$^2 = 60 \times 10^4$ W/mm^2
Thermal diffusivity, $\kappa = \frac{k}{\rho c_p} = \frac{0.1512}{19.254 \times 10^{-6} \times 134} = 58.6$ mm^2/s $= 58.6 \times 10^{-6}$ m^2/s.

We assume an initial value for the drilling speed of 2.5×10^4 mm/s = 25 m/s, which is used to estimate the hot surface temperature using equation (15.30):

$$T - T_0 = \frac{I_a{}'}{\rho c_p u_\mathrm{d}} \exp\left(-\frac{\xi u_\mathrm{d}}{\kappa}\right)$$

but

$$I_\mathrm{a}{}' = I_\mathrm{a} - \phi_\mathrm{v} L_\mathrm{v}$$

Since ϕ_v is not known, we initially use $I_\mathrm{a}{}' = I_\mathrm{a}$ to estimate the hot surface temperature.

From equation (15.33), assuming a constant specific heat, the hot surface temperature can be expressed as

$$T_\mathrm{h} = T_0 + \frac{I_\mathrm{a}}{\rho c_p u_\mathrm{d}} - \frac{L_\mathrm{m}}{c_p}$$

or

$$T_\mathrm{h} = 25 + \frac{60 \times 10^4}{19.254 \times 10^{-6} \times 134 \times 2.5 \times 10^4} - \frac{22 \times 10^4}{134}$$

$$\Rightarrow T_\mathrm{h} = 7686^\circ\mathrm{C} = 7959\,\mathrm{K}$$

Now from equation (15.32), the saturation pressure is given by

$$P_s = P_a \exp\left[\frac{L_p}{k_B T_v}\left(1 - \frac{T_v}{T_h}\right)\right]$$

Now $P_a = 10^5\ \mathrm{N/m^2} = 0.1\ \mathrm{N/mm^2}$. Thus,

$$P_s = 0.1 \times \exp\left[\frac{14.69 \times 10^{-19}}{1.38 \times 10^{-23} \times 5973}\left(1 - \frac{5973}{7959}\right)\right]$$

$$= 8.537\ \mathrm{MPa}\,(\mathrm{N/mm^2}) = 8.537 \times 10^6\ \mathrm{Pa}\,(\mathrm{N/m^2})$$

Therefore, from equation (15.31),

$$\phi_v = (1 - R) P_s \left(\frac{m_p}{2\pi k_B T_h}\right)^{1/2}$$

$$= (1 - 0.2) \times 8.537 \times 10^6 \left(\frac{3.05 \times 10^{-25}}{2\pi \times 1.38 \times 10^{-23} \times 7959}\right)^{1/2}$$

$$= 4540\ \mathrm{kg/m^2} s$$

And from equation (15.37)

$$\phi_{\mathrm{l}} = \left[\left(\frac{2\kappa}{w}\right)\ln\left(\frac{T_{\mathrm{h}}}{T_{\mathrm{m}}}\right)\right]^{1/2} P_{\mathrm{s}}{}^{1/4}\rho^{3/4}$$

$$= \left[\left(\frac{2\times 58.6\times 10^{-6}}{0.100\times 10^{-3}}\right)\ln\left(\frac{7959}{3683}\right)\right]^{1/2} \times [8.537\times 10^{6}]^{1/4}\times [19254]^{3/4}$$

$$= 8.4\times 10^{4}\ \mathrm{kg/m^2s}$$

This indicates that under these conditions, melting is the predominant mode of material removal. Now from equation (15.29), the drilling velocity is given by

$$u_{\mathrm{d}} = \frac{1}{\rho}(\phi_{\mathrm{v}} + \phi_{\mathrm{l}})$$

$$u_{\mathrm{d}} = \frac{1}{19254}(84000 + 4540)$$

$$= 4.6\ \mathrm{m/s} = 4.6\times 10^{3}\ \mathrm{mm/s}$$

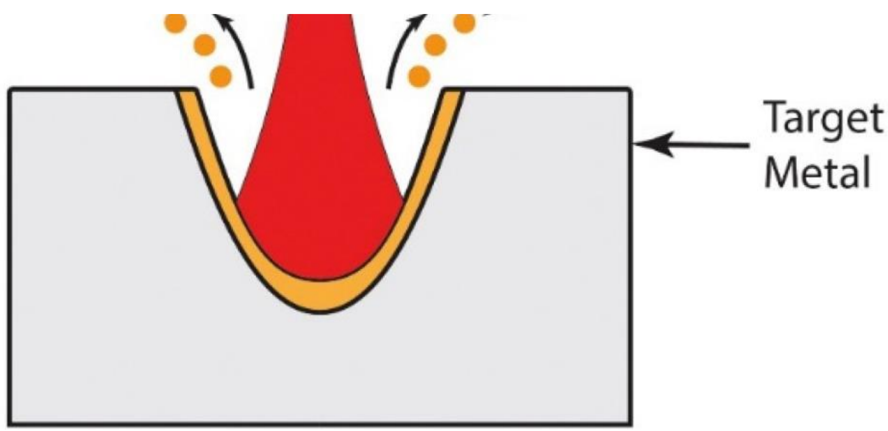
This is about an order of magnitude lower than the original estimate. Thus an iteration is necessary. The calculated value for ϕ_{v} can be used to update the value of $I_{\mathrm{a}}{}'$ during the iteration process.

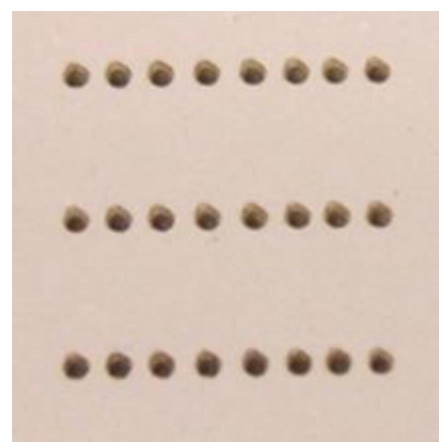
Advantages of Laser Drilling

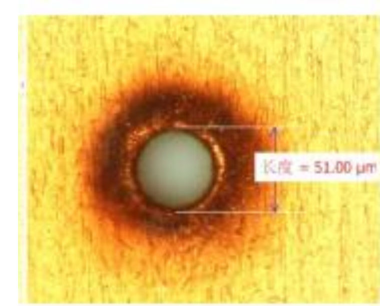
- It is a noncontact process. There are no machining forces, and thus no deflection of a tool and/or workpiece that would result in dimensional errors in the part produced, or wear of the tool.
- Accurate location of holes. In conventional drilling, the drill often deflects on coming in contact with the workpiece, resulting in drill “wandering”. This affects accuracy of hole location and orientation.
- There is no chip formation, and thus no need for elaborate chip disposal systems. However, an appropriate exhaust system is often necessary for the vaporized material.
- High depth to diameter aspect ratios
- Ability to drill difficult-to-machine materials such as diamond, ceramics, and highly refractory metals, on which conventional drilling performs poorly.
- Ability to drill holes with difficult entrance angles. Drilling of holes with low entrance angles is quite difficult with conventional drills. However, with laser drilling, entrance angles as low as 10◦ are possible.
- Ability to drill very small holes.
- High degree of flexibility, enabling a number of operations to be combined in a single setup.
- Since lasers can be used continuously without interruption, high duty cycles are achieved, resulting in relatively high production rates.

Disadvantages of Laser Drilling

- Inability to produce precision blind holes. Lasers are more suited to producing through holes.
- Inability to drill deep holes. The hole depths that are achieved by laser drilling are relatively small, being typically a few millimeters deep. As the hole depth increases, the diameter begins to enlarge due to beam expansion, resulting in a tapered hole.
- Holes that are close to an edge, and those that intersect other holes are often not effectively produced by laser drilling.





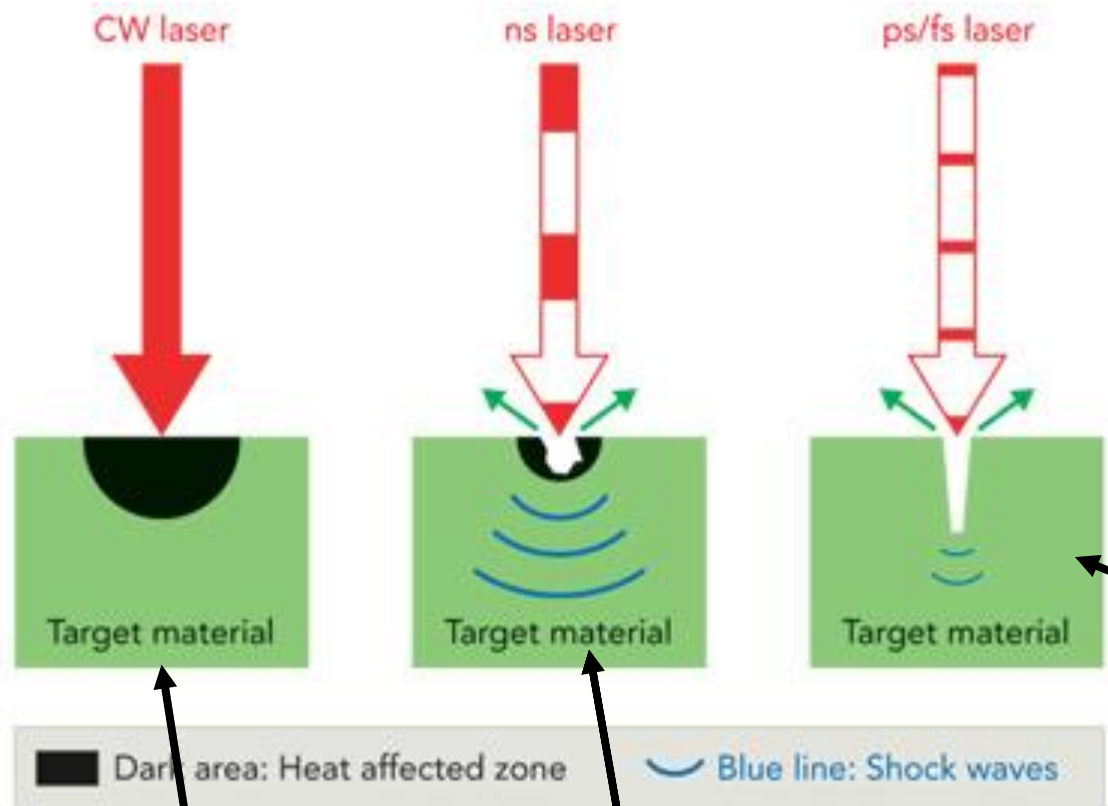


New Approaches

- ✓Laser Micromachining
- ✓Laser Assisted Machining

Laser Micromachining

The ultrafast lasers essentially vaporize matter without generating heat affected zone



primarily by melting

melt expulsion driven by the vapor pressure

the laser pulse duration is much shorter than the timescale for energy transfer between free electrons and the material lattice. So, extremely high pressures and temperatures can be attained in a very small (µm) depth. However, the absorbed energy heats the material very quickly past the melting point, directly to the vapor phase with its high kinetic energy. The material is removed by direct vaporization away from the surface without formation of a recast layer. This provides negligible HAZ and very fine, sharp features.

Basic mechanisms of ultrafast laser material processing

The dissipation of the absorbed energy in bulk material, and the corresponding material removal, takes place mostly after the laser pulse duration. Two major mechanisms have been studied: 1) thermal vaporization, where the electron-phonon collisions increase the local temperature above the vaporization point, and 2) Coulomb explosion, where excited electrons escape from the bulk materials and form a strong electric field that pulls out the ions within the impact area.

According to these two mechanisms of material removal, femtosecond laser ablation can be divided into two regimes: strong ablation dominated by thermal vaporization at intensities significantly higher than the ablation threshold(critical fluence 1013W/cm^2), and gentle ablation governed by the Coulomb explosion near the ablation threshold.

Ultrafast laser usage

As shown above, femtosecond lasers can be used for microprocessing many types of materials: metals, polymers, semiconductors, ultrahard materials, transparent materials, tissues, etc.

Typically, metals have very short laser penetration depth (tens of nm) and strong optical absorption — hence the laser ablation threshold is relatively low compared to transparent materials. In contrast, wide-bandgap materials require high laser-pulse intensities Therefore, the laser ablation threshold for wide-bandgap materials is also relatively higher. Some wide-bandgap materials include diamond, silicon carbide (SiC), aluminum nitride (AlN), gallium nitride (GaN), and boron nitride (BN).

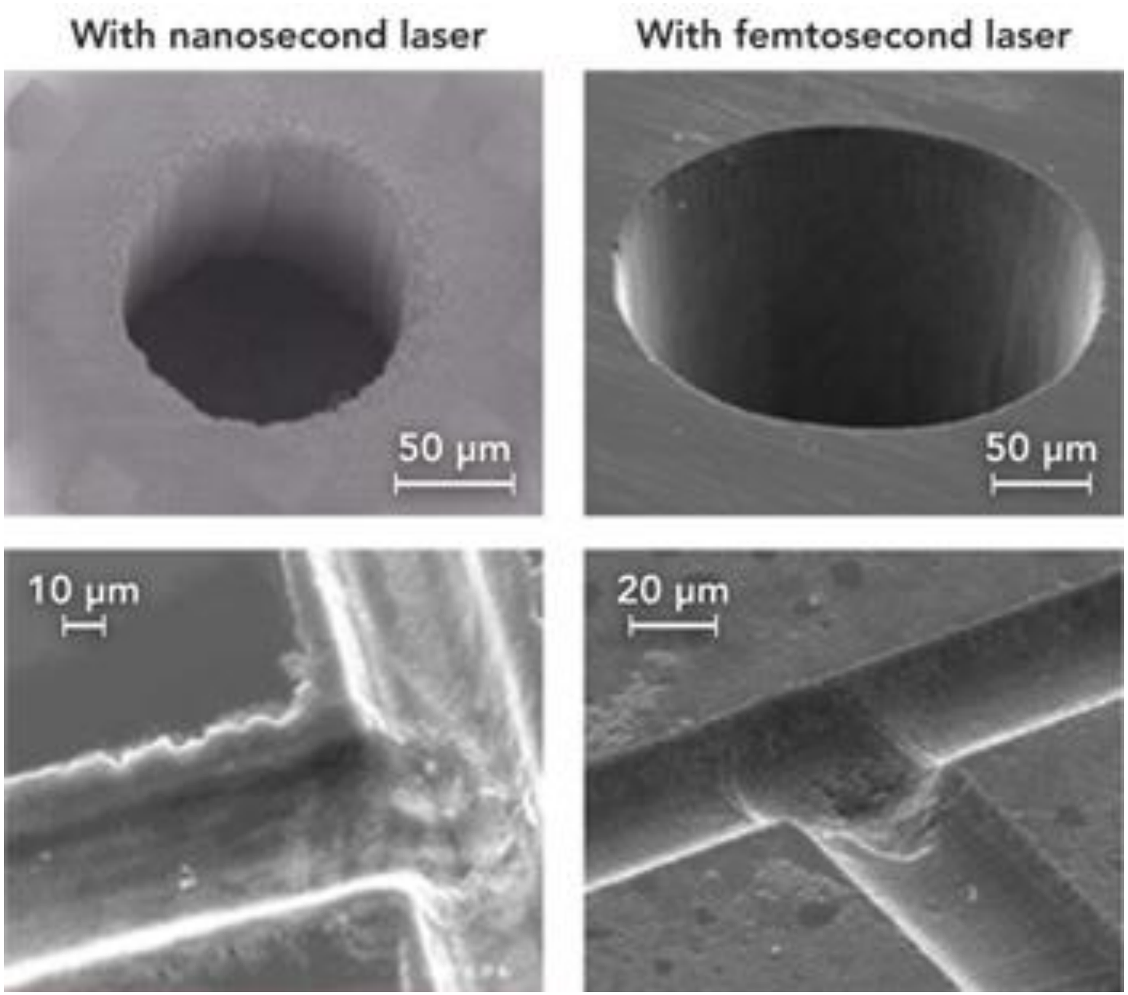
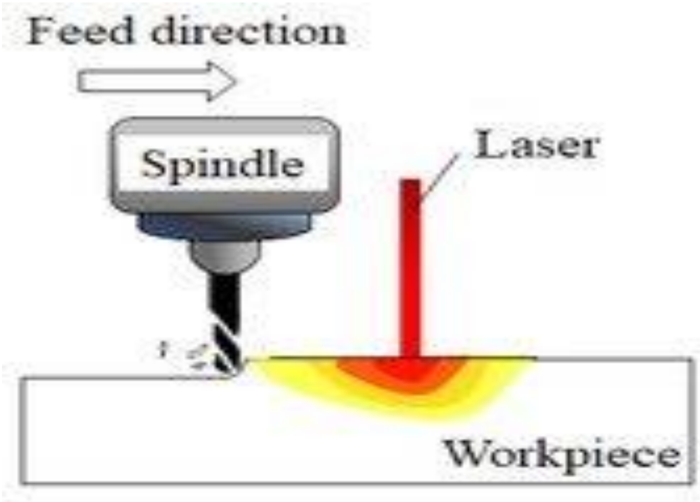


FIGURE 10. Laser processing examples on glass with a 266 nm (UV) ns-laser (left-side) and with a 780 nm 100-fs laser (right-side).

Laser-Assisted Machining

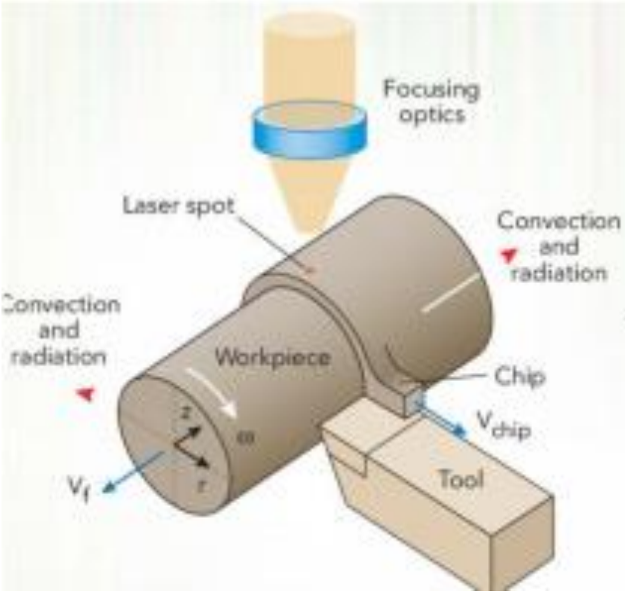
- Advance material such as Aluminum alloy, Titanium alloy, Nickel-Based Super Alloys, Ceramics, Composites etc. are difficult to machine using conventional machining
- Localized heating of such material can be used for relatively easy machining
- Localized heating of material during machining is known as thermally assisted machining (TAM)
- TAM soften the workpiece which reduces the yield strength, hardness and strain hardening
- TAM leads to change of deformation behavior from brittle to ductile

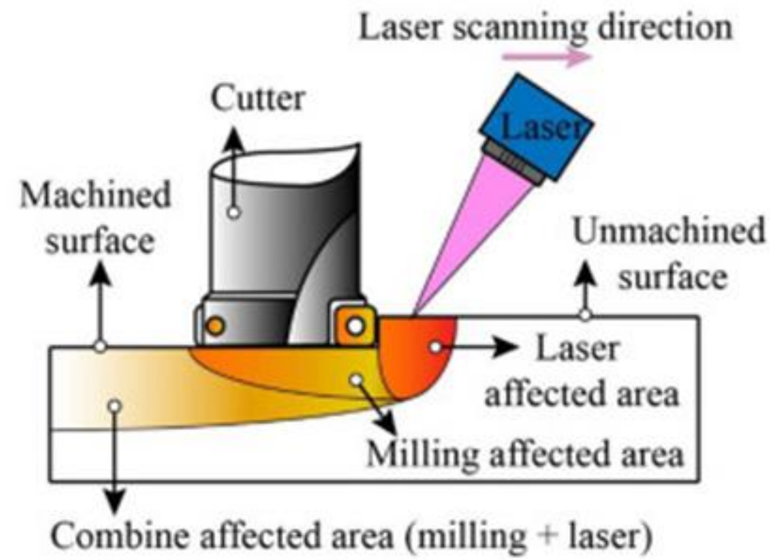


Laser Assisted Machining Processes

- Laser-Assisted Turning
- Laser-Assisted Milling/Grinding
- Laser-Assisted Waterjet Machining

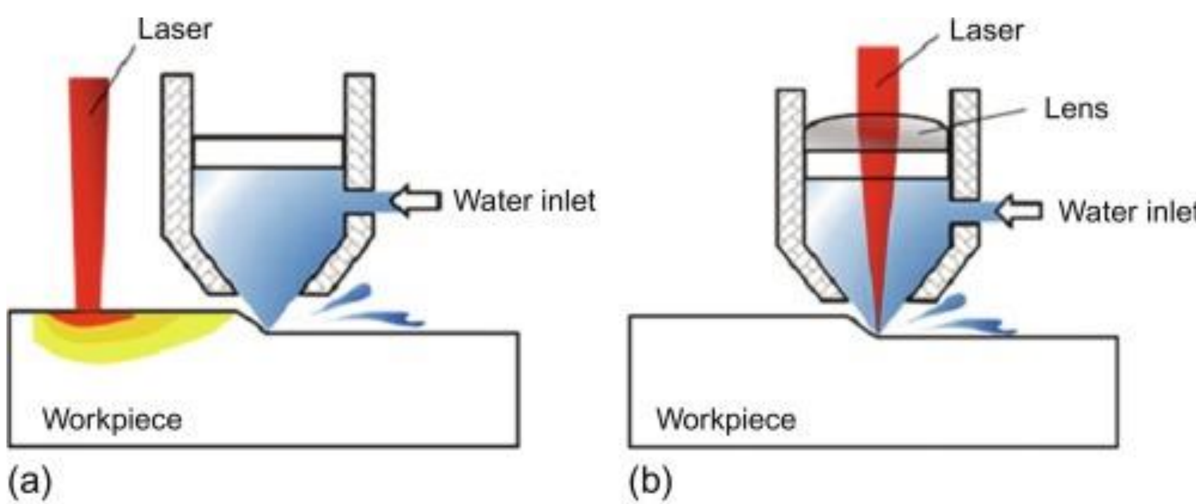
Laser Assisted Machining Processes





Laser-Assisted Turning

Laser-Assisted Milling/Grinding



Laser-Assisted Waterjet Machining

Thank you