

# Laser Cutting



ME 677: Laser Material Processing  
Instructor: Ramesh Singh

# Outline

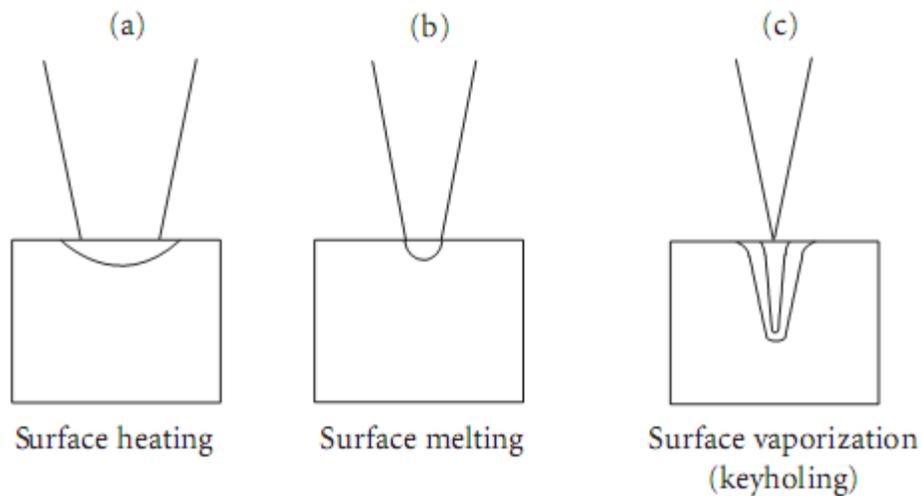
- Materials Processing Parameters
- Process Description
- Mechanisms of Laser Cutting



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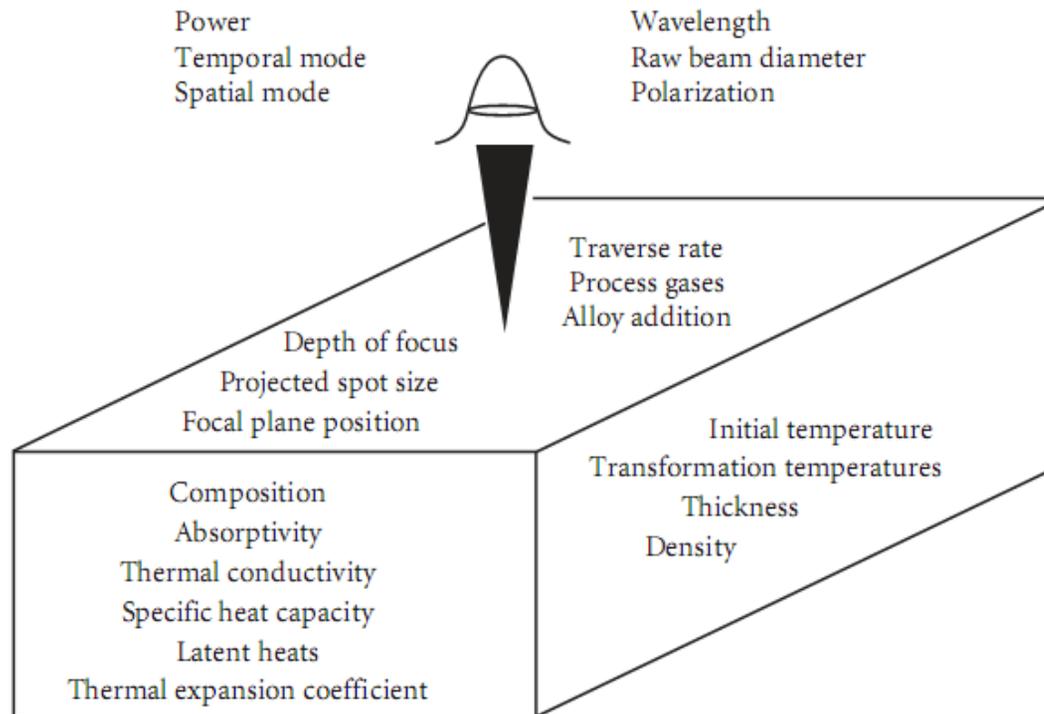
# Effect of Power Density

- Power density is the key process driver
- Power Density (Intensity)=  $P/\pi r^2$



# Process Variables for Material Processing

- The other important process variables:

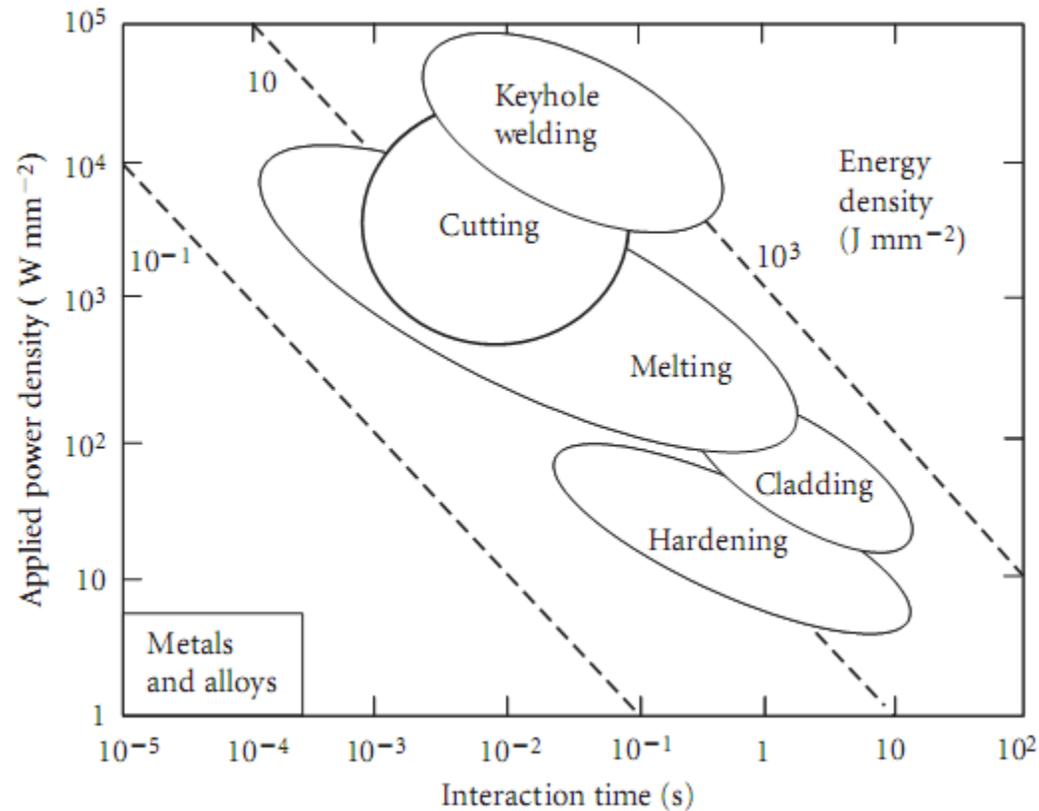


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# Interaction Time and Empirical Process Chart

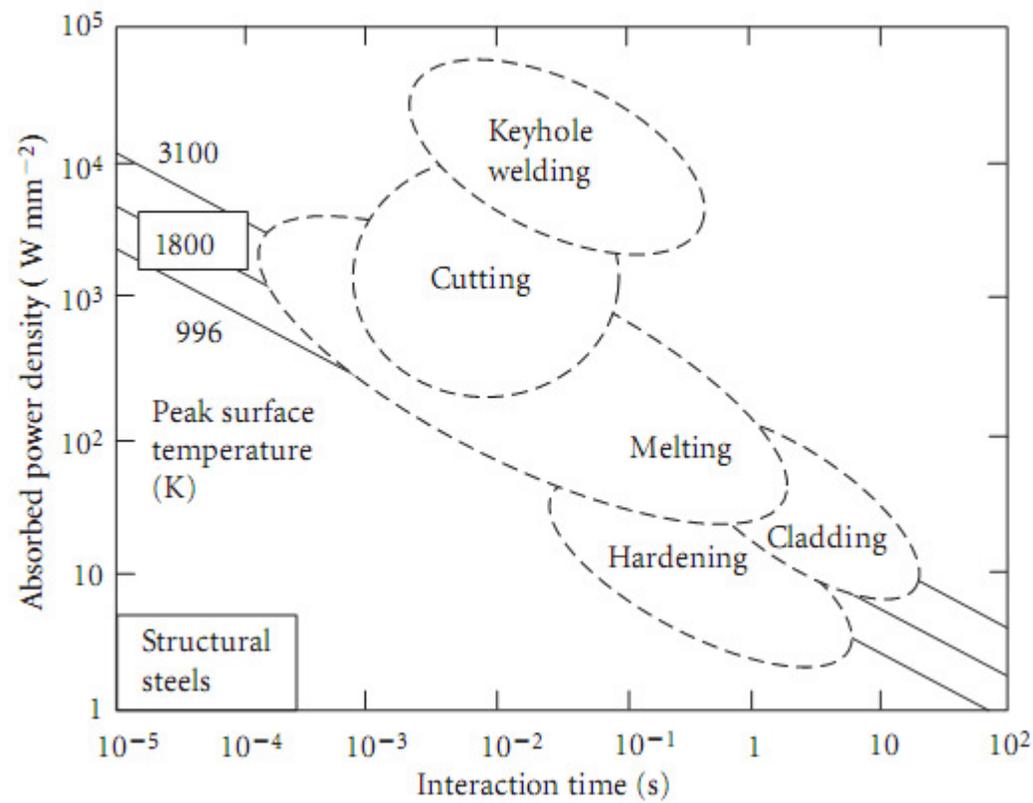
- Interaction time,  $\tau = 2 r/v$   
where  $r$  = beam radius and  $v$  = velocity



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# Structural Steel



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# Cutting

- Laser cutting is able to cut faster and with a higher quality than competing processes:
  - Punch, plasma, abrasive waterjet, ultrasonic, oxyflame, sawing and milling
- Can be automated
- 80% industrial lasers in Japan are used for metal cutting



**Table 3.1. Comparison of Different Cutting Processes**

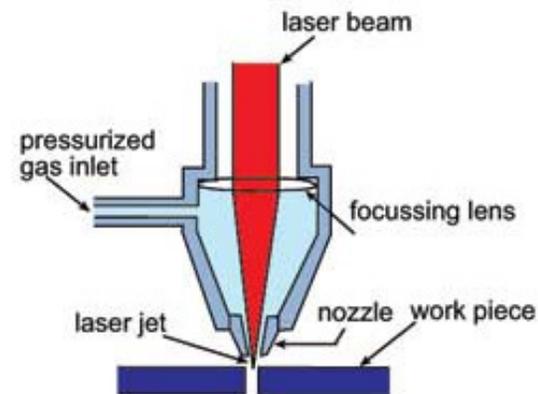
QUALITY	Laser	Punch	Plasma	Nibbling	Abrasive Fluid Jet	Wire EDM	NC Milling	Sawing	Ultrasonic	Oxy Flame
Rate	✓	✓	✓	✗	✗	✗	✗		✗	✗
Edge Quality	✓	✓	✗	✗	✓	✓	✓	✗	✓	✗
Kerf Width	✓	✓	✗		✓	✓		✗		
Scrap and Swarf	✓	✓		✗	✓			✗		✓
Distortion	✓		✗		✓		✓		✓	✗
Noise	✓	✗	✗		✗					✗
Metal+Nonmetal	✓		✗		✓		✓		✓	
Complex Shapes	✓	✗	✓							
Part Nesting	✓	✗			✓					
Multiple Layers	✗	✓								
Equipment Cost	✗				✗			✓		✓
Operating Cost						✗		✓		✓
High Volume	✓	✓		✗					✗	
Flexibility	✓	✗	✓	✓	✓	✗			✗	
Tool Wear	✓	✗	✓	✗	✓		✗	✗	✗	✓
Automation	✓	✓	✓	✗	✓	✗	✓			✗
HAZ	✓	✓	✗		✓	✓	✓			✗
Clamping	✓	✗	✓		✓		✗	✗		✗
Blind Cuts	✓	✓	✓	✓		✗	✗		✗	✓
Weldable Edge	✓	✓	✗	✓	✓	✓	✓		✓	✗
Tool Changes	✓	✗	✓		✓					✗

✓ Point of particular merit  
 ✗ Point of particular disadvantage  
 (Further comparisons can be found in ref 1)

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# Typical Cutting Setup



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# Process Characteristics

- It is one of the faster cutting processes.
- The work piece does not need clamping but workholding is advisable to avoid shifting with the table acceleration and for locating when using a CNC program
- Tool wear is zero since the process is a non contact cutting process.
- Cuts can be made in any direction polarization may affect process efficiency
- The noise level is low.
- The process can be easily automated with good prospects for adaptive control in the future.
- No expensive tooling changes are mainly "soft". That is they are only programming changes. Thus the process is highly flexible.
- Some materials can be stack cut, but there may be a problem with welding between layers.
- Nearly all engineering materials can be cut. They can be friable, brittle, electric conductors or non conductors, hard or soft.
  - Only highly reflective materials such as aluminium and copper can pose a problem but with proper beam control these can be cut satisfactorily.

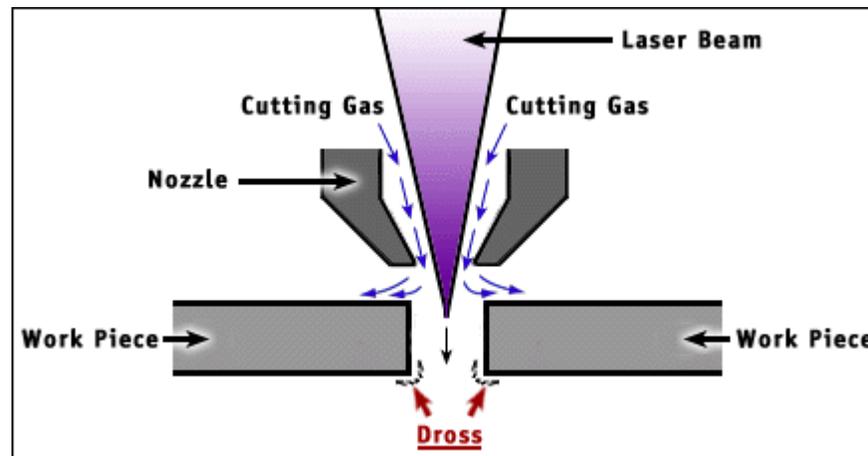


# Process Response

- The cut can have a very narrow kerf width giving a substantial saving in material. (Kerf is the width of the cut opening)
- The cut edges can be square and not rounded as with most hot jet processes or other thermal cutting techniques.
- The cut edge can be smooth and clean. It is a finished cut, requiring no further cleaning or treatment.
- The cut edge can be directly re-welded with little to no surface preparation.
- There is no edge burr as with mechanical cutting techniques. Dross adhesion can usually be avoided.
- There is a very narrow HAZ (Heat Affected Zone) and very thin re-solidified layer of few  $\mu\text{m}$ , particularly on dross free cuts. There is negligible distortion.
- Blind cuts can be made in some materials, particularly those which volatilise, such as wood or acrylic.
- Cut depth depends on the laser power. 10-20mm is the current range for high quality cuts. Some very high power fiber lasers could cut 50 mm.



# Dross

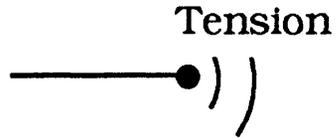


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# Process Mechanisms

- The beam is traversed over a programmed path and material removal occurs due to multiple mechanisms
- Melting
  - Material exhibiting molten phase of low viscosity, notably metals and alloys, and thermoplastics, are cut by the heating action of a beam of power density on the order of  $10^4 \text{ Wmm}^{-2}$
  - The melt is assisted by shearing action of a stream of inert or active assist gas, results in formation of a molten channel through the material called a kerf (slot).
- Vaporisation
  - Suitable for materials that are not readily melted (some glasses, ceramics and composites)
  - Materials can be cut by vaporization that is induced by a higher beam power density ( $>10^4 \text{ Wmm}^{-2}$ )
- Chemical Degradation
  - A kerf can be formed in many organic materials by chemical degradation caused by the heating action of the beam.



<b>Table 3.2.</b>		Different ways in which the laser can be used to cut.
Method	Concept	Relative Energy
1. Vaporisation		40
2. Melt and blow		20
3. Melt, burn and blow		10
4. Thermal stress cracking		1
5. Scribing		1
6. "Cold cutting"		100



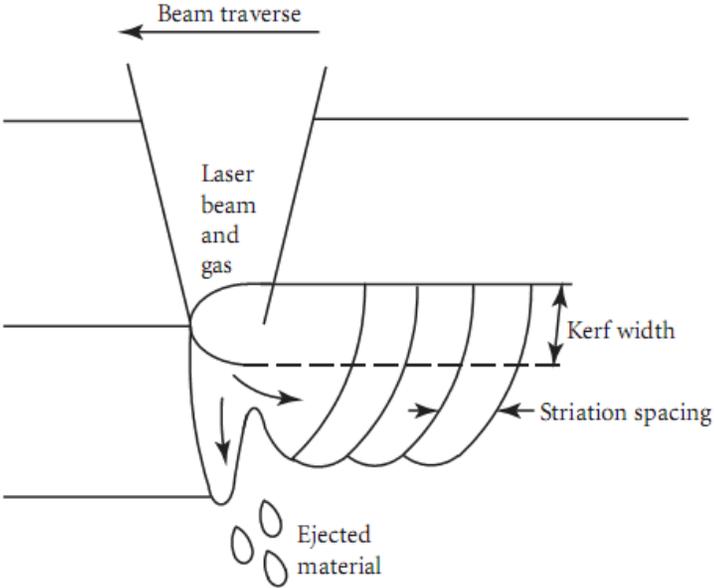
# Material Removal Mechanism in Different Materials

**Table 14.1** Mechanisms of laser cutting for various engineering materials (a suitable mechanism is indicated by ✓)

Material	Inert gas melt shearing	Reactive gas melt shearing	Vaporization	Chemical degradation	Scribing
Ferrous alloys	✓	✓	–	–	–
Non-ferrous alloys	✓	✓ (Ti)	–	–	–
Polymers	✓ (Thermoplastics)	✓ (Thermosets)	✓ (PMMA)	(Thermosets)	–
Ceramics	✓	–	–	–	✓
Glasses	✓	–	–	–	✓
Elastomers	–	–	–	✓	–
Composites	✓	–	–	✓ (Woods)	✓



# Inert Gas Melt Shearing or Melt and Blow



Viewed from Top

Fig. 3.3.

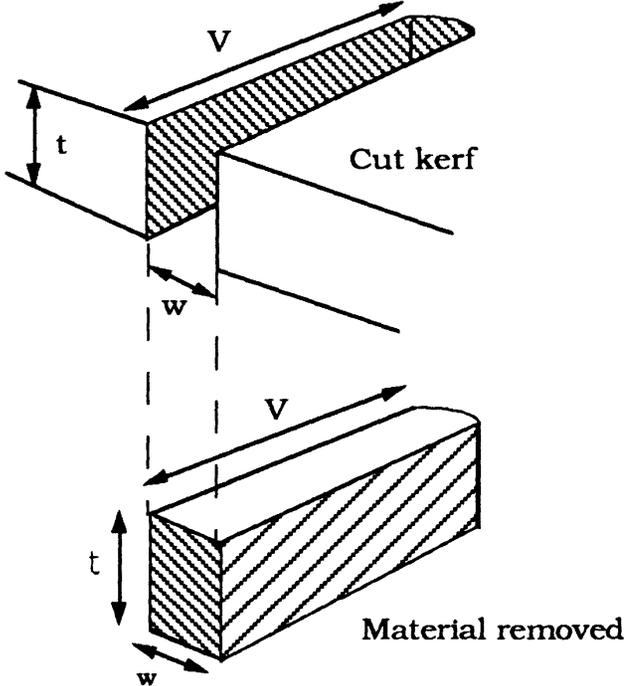


Fig. 3.3. Volume melted and removed during cutting.



# Melt and Blow

- Once a penetration hole is made or the cut is started from the edge, then
- A sufficiently strong gas jet could blow the molten material out of the cut kerf to prevent the temperature rise to the boiling point any further
- Cutting with inert gas jet requires only one tenth of the power required for vaporization
- Note that the ratio latent heat of melting to vaporization is 1:20.



# Modeling of the Process

$$\eta P = wtV\rho[C_p\Delta T + L_f + m' L_v]$$

$$\frac{P}{tV} = \frac{w\rho}{\eta} [C_p\Delta T + L_f + m' L_v]$$

where:

P = Incident power W

w = Average kerf width m

t = Thickness m

V = Cutting speed m/s

m' = Fraction of melt vaporised

L<sub>f</sub> = Latent heat of fusion J/kg

L<sub>v</sub> = Latent heat of vaporisation  
J/kgK

ΔT = Temperature rise to cause  
melting K

η = Coupling coefficient

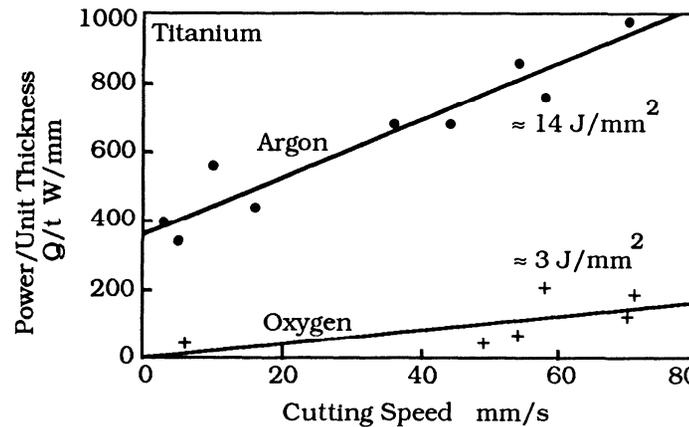
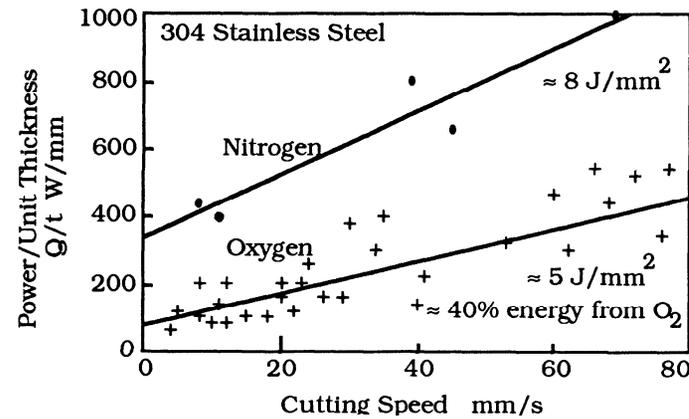
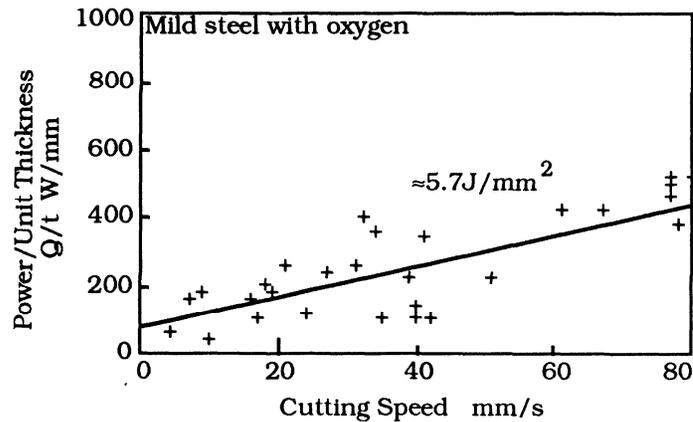
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# Melt and Blow

- The group  $[P/tV]$  is constant for the cutting of a given material with a given beam.

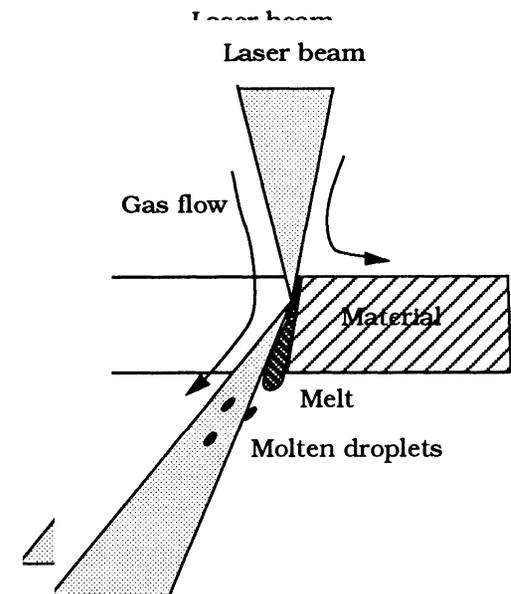


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# Cutting Action

- The beam is incident on the surface
  - Most of the beam passes into the hole or kerf
  - some is reflected off the unmelted surface
  - some may pass straight through.
- At slow speeds the melt starts at the leading edge of the beam and much of the beam passes clean through the kerf without touching if the material is sufficiently thin



# Detailed Melting Blowing Mechanism

- The absorption is by two mechanisms:
  - Mainly by Fresnel absorption , i.e., direct interaction of the beam with the material –
  - By plasma absorption and reradiation. The plasma build up in cutting is not very significant due to the gas blowing it away.
- The power density on the cutting front is  $F \sin \theta$ . This causes melting which is then blown away by the drag forces from the fast flowing gas stream.
- At the bottom of the kerf the melt is thicker due to deceleration of the film and surface tension retarding the melt from leaving.
- The gas stream ejects the molten droplets at the base of the cut into the atmosphere.



# Formation of Striations

- As the cut rate is increased the beam is automatically coupled to the work piece more efficiently due to reduced losses through the kerf .
- Also the beam tends to ride ahead onto the unmelted material. When this occurs the power density increases since the surface is not sloped
- The melt proceeds faster and is swept down into the kerf as a step. As the step is swept down it leaves behind a mark on the cut edge called a striation.
- The cause of striations is disputed, there are many theories:
  - The step theory
  - critical droplet size causing the melt to pulsate in size before it can be blown free
  - The sideways burning theory.
- There are conditions under which no striations occur. These are governed by gas flow or by pulsing at the frequency of the natural striation



# Striations

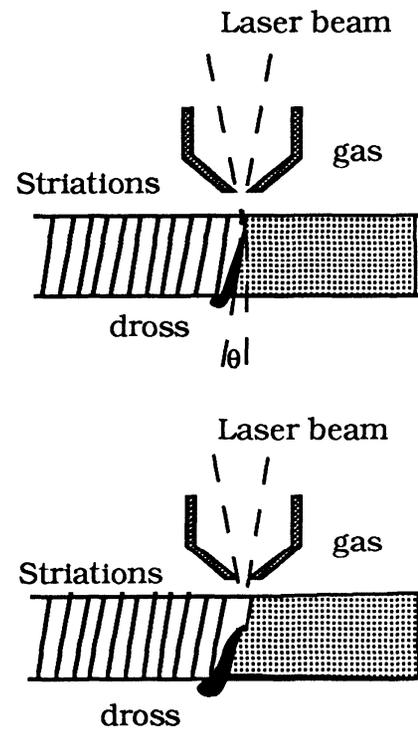


Fig. 3.8. The stepwise formation of striations.

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# Reactive Fusion Cutting

- If the assisting gas is also capable of reacting exothermically an extra heat source is added to the process.
- The gas passing through the kerf is not only dragging the melt away but also reacting with the melt.
- Usually the reactive gas is oxygen or some mixture containing oxygen.
- The burning reaction starts usually at the ignition temperature on the top.
- The oxide is formed and is blown into the kerf and will cover the melt lower down which slows the reaction and may even cause break in the striation lines .



# Reactive Fusion ..

- The amount of energy supplied by the burning reaction varies with the material
  - with mild/stainless steel it is 60%
  - with a reactive metal like titanium it is around 90%.
- Cutting speeds could be doubled using this technique.
- Typically, the faster the cut, the less heat penetration and the better the quality.
- A chemical change in the workpiece may happen due to reactive fusion.
  - With titanium this can be critical since the edge will have some oxygen in it and will be harder and more liable to cracking.
  - With mild steel there is no noticeable effect except a very thin re-solidified layer of oxide on the surface of the

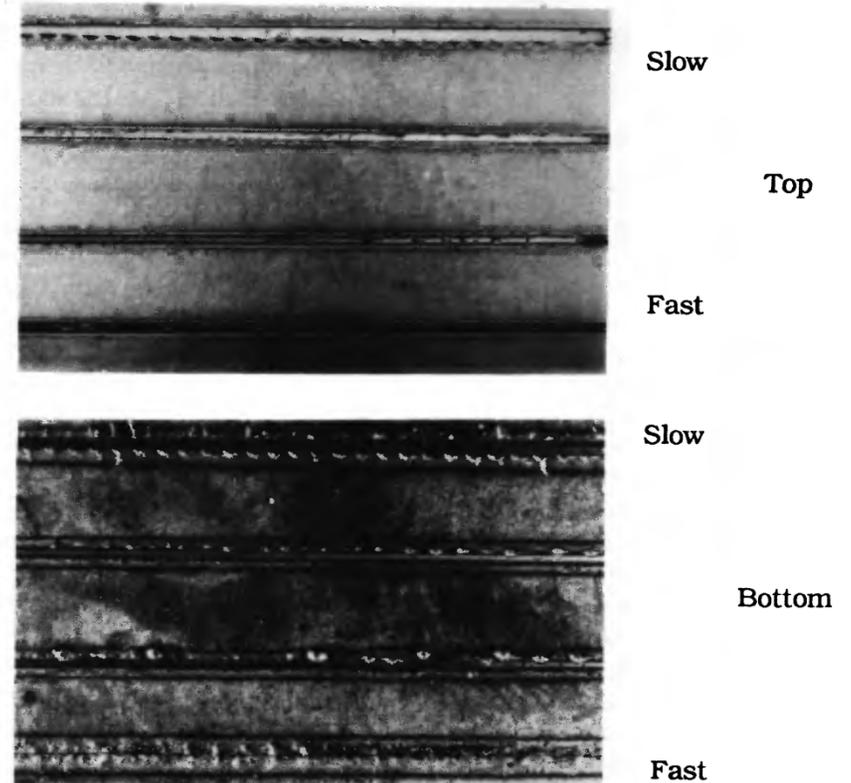
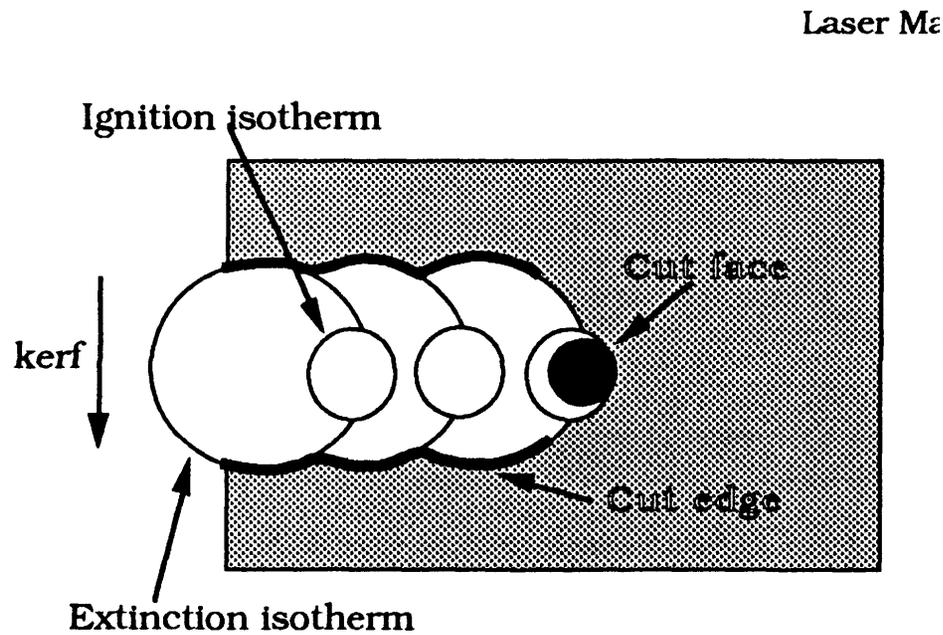


# Reactive Fusion...

- The dross is an oxide (instead of metal)
  - Mild steel flows well and does not adhere to the base metal
  - With stainless steel the oxide is made up of high melting point components such as  $\text{Cr}_2\text{O}_3$  (melting point  $\sim 2180^\circ\text{C}$ ) and hence this freezes quicker causing a dross problem.
  - Aluminum exhibits similar behavior
- Due to the burning reaction a further cause of striations is introduced
  - In slow cutting (lower than the burning reaction speeds) the ignition temperature will be reached and burning will occur from the ignition point proceeding outward in all directions



# Striations in Reactive Fusion Cutting



# Controlled Fracture Process

- Brittle material are vulnerable to thermal fracture can be quickly and neatly severed by guiding a crack with a fine spot heated by a laser
- The laser heats a small volume of the surface causing it to expand and hence to cause tensile stresses all around it
- If there is a crack in this space, it will act as a stress raiser and the cracking will continue in direction of the hot spot
- The speed at which a crack can be guided is of the order of m/s
- When the crack approaches an edge, the stress fields become more complex



# Controlled Fracture

- Advantages:
  - The speed, edge quality and precision are very good in glass cutting.
  - Effective for straight cuts
- Disadvantages:
  - Difficult to create profiled cuts such as for the manufacture of car wing mirrors
  - Difficult to model and predict near the edges



# Processing Range for Controlled Fracture

<b>Table 3.5</b>		<b>Controlled Fracture Cutting Rates</b>		
<b>Material</b>	<b>Thickness mm</b>	<b>Spot Diameter mm</b>	<b>Incident Power W</b>	<b>Rate of separation m/s</b>
<b>99% Al<sub>2</sub>O<sub>3</sub></b>	<b>0.7</b>	<b>0.38</b>	<b>7</b>	<b>0.3</b>
	<b>1.0</b>	<b>0.38</b>	<b>16</b>	<b>0.08</b>
<b>Soda Glass</b>	<b>1.0</b>	<b>0.5x12.7</b>	<b>10</b>	<b>0.3</b>
<b>Sapphire</b>	<b>1.2</b>	<b>0.38</b>	<b>12</b>	<b>0.08</b>
<b>Quartz (cryst)</b>	<b>0.8</b>	<b>0.38</b>	<b>3</b>	<b>0.61</b>



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# Scribing

- This is a process for making a groove or line of holes either fully or partially penetrating
- This sufficiently weakens the structure so that it can be mechanically broken
- Typically materials processed are silicon chips and alumina substrates
- Quality is measured by the lack of debris and low heat affected zone
- Thus low energy, high power density pulses are used to remove the material principally as vapor

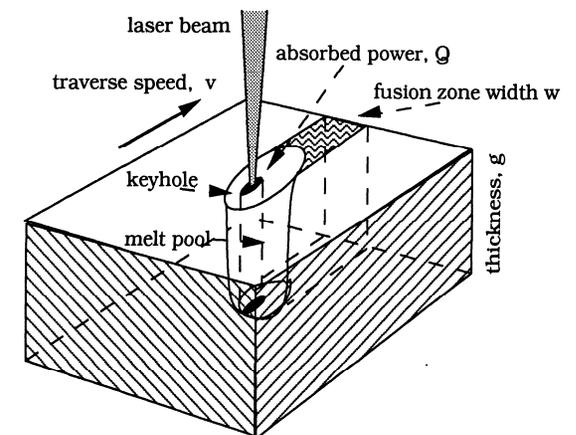


# Vaporization Cutting

- The focused beam in vaporization cutting first heats up the surface to boiling point and generates a keyhole.
- The keyhole causes a sudden increase in the absorptivity due to multiple reflections and the hole deepens quickly.
- As it deepens so vapor is generated and escapes blowing ejecta out of the hole or kerf and stabilizing the molten walls of the hole
- This is the usual method of cutting for pulsed lasers or in the cutting of materials which do not melt such as wood, carbon, and some plastics.



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# Vaoporization

- The rate of penetration of the beam into the workpiece can be estimated from a lumped heat capacity calculation assuming
  - 1D heat flow
  - Conduction is ignored
  - The penetration rate is similar to or faster than the rate of conduction
  - volume removed per second per unit area = penetration velocity,  $V$  m/s



# Vaporization

$$\frac{F_0}{V} = \rho [L_f + L_v + C_p (T_v - T_0)] \text{ where:}$$

- 1-D heat flow

$F_0$	= Absorbed power density	(W/m <sup>2</sup> )
$\rho$	= Density of solid	(kg/m <sup>3</sup> )
$L$	= Latent heat of fusion and vaporisation	(J/kg)
$C_p$	= Heat capacity of solid	(J/kg°C)
$T_v$	= Vaporisation temperature	(°C)
$T_0$	= Temperature of material at start	(°C)

$$T_{zt} = \frac{2F_0}{k} \left\{ \alpha t^{\frac{1}{2}} \operatorname{ierfc} \left( \frac{z}{2\sqrt{\alpha t}} \right) \right\}$$

$$\operatorname{ierfc}(u) = \frac{e^{-u^2}}{\sqrt{\pi}} - u(1 - \operatorname{erf}(u))$$

$$T(0, t) = (2F_0 / K) [(\alpha t) / \pi]^{0.5}$$

*Time \_to \_vaporization*

$$t_v = \frac{\pi}{\alpha} \left[ \frac{T_B K}{2F_0} \right]^2$$

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# Cold Cutting

- High powered UV Excimer lasers exhibit cold cutting
  - The energy of the ultraviolet photon is 4.9eV which is similar to the bond energy for many organic materials.
  - If a bond is struck by such a photon then it may break
  - When this radiation is shone onto plastic with a sufficient flux of photons that there is at least one photon/bond then the material just disappears without heating leaving a hole with no debris or edge damage



# Picture of Hair Micromachining via Excimer



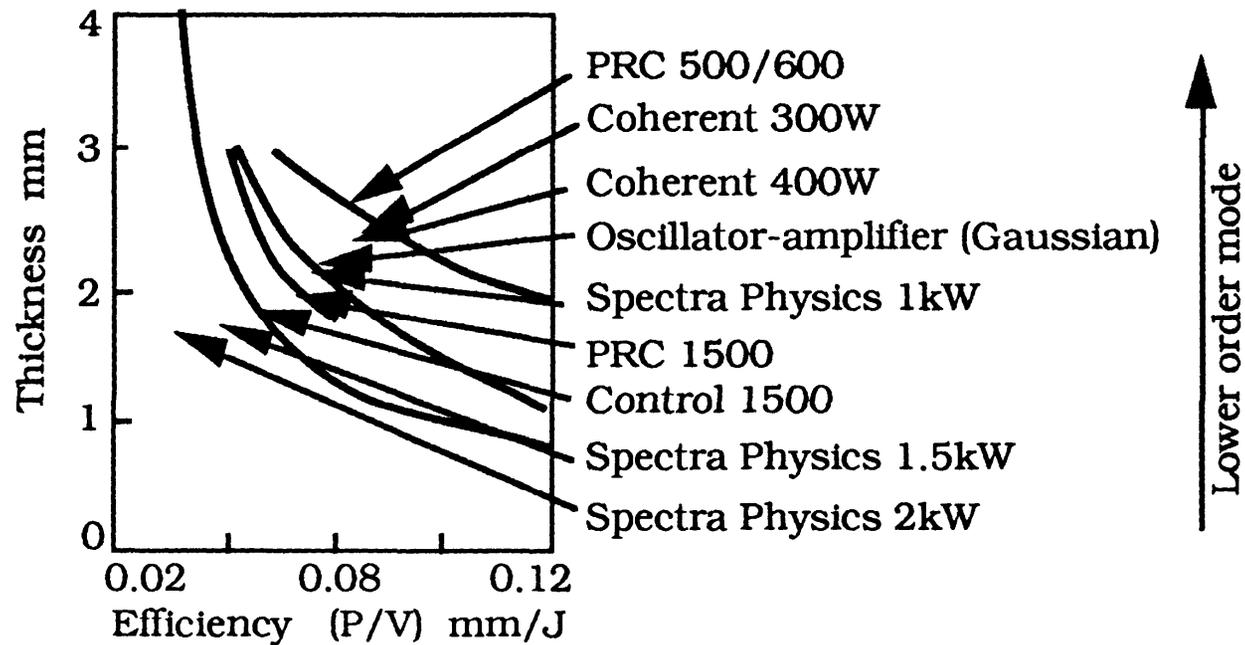
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# Effect of Spot Size

- The principle parameters are laser power, traverse speed, spot size and material thickness .
- Spot size acts in two ways:
  - Firstly, a decrease in spot size will increase the power density which affects the absorption and
  - Secondly, it will decrease the cut width.
- Lasers with stable power and low order modes - usually true TEM<sub>00</sub> modes cut considerably better than other modes

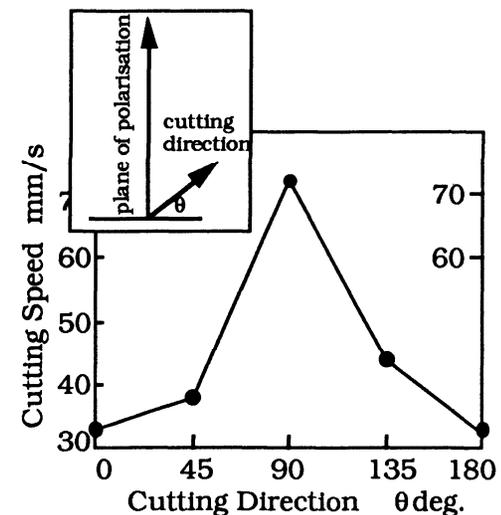


# Spot Size



# Effect of Beam Polarization

- The maximum cutting speed could be doubled, cutting in one direction as opposed to one at right angles when cutting with a plane polarised laser beam.
- Nearly all high powered lasers have folded cavities which favours the amplification of radiation whose electric vector is at right angles to the plane of incidence.



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# Wavelength

- The shorter the wavelength the higher the absorptivity for most metals
- Thus YAG radiation is preferable to CO<sub>2</sub> radiation but the poor mode structure of most YAG lasers the benefit is offset
- Fiber lasers with good beam mode could have an advantage



# Summary

- Basics of laser cutting
- Mechanisms
- Factors affecting laser cutting



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