Vaporization Cutting

- Laser heats surface to vaporization
- Forms keyhole (hole where the beam penetrates)
- Now light highly absorbed in hole
  (light reflects with the hole until absorbed)
- Vapor pressure from boiling material stabilizes the molten walls
- Material gets ejected from hole (as vapour)
  can condense and form Dross at bottom and top
- In materials that do not melt, just the vapor escapes
  eg Wood, carbon, some plastics

![Sketch of laser-drilled hole.](Figure 13-21)

![Kerf produced by laser cutting.](Figure 13-16)
Vaporization Cutting Formulas

• Recall the velocity of melt front formulas

\[ v_s = \frac{H}{\rho(CT_v + L_v)} \]

• where H is power density absorbed per square area

• The temperature at the surface from the uniform illumination formulas for the vaporization point

\[ T(0,t) = \frac{2H}{k} \frac{\sqrt{\alpha t}}{\pi} \]

Thus the time for vaporization is

\[ t_v = \frac{\pi}{\alpha} \left[ \frac{T_v k}{2H} \right]^2 \]
Vaporization Cutting Values

- If we had a 2 KW laser focused to 0.2 mm
  Then average power is

  \[ H = \frac{2000}{\pi r^2} = 6.3 \times 10^{10} \text{ Wm}^{-2} \]

- Can estimate \( v_s \) and \( t_v \)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) kg/m(^3)</th>
<th>( L_f ) kJ/kg</th>
<th>( L_V ) kJ/kg</th>
<th>( C_p ) J/kgC</th>
<th>( T_m ) C</th>
<th>( T_v ) C</th>
<th>( K ) W/mK</th>
<th>( V ) m/s</th>
<th>( t_v ) ( \mu \text{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>19300</td>
<td>185</td>
<td>4020</td>
<td>140</td>
<td>3410</td>
<td>5930</td>
<td>164</td>
<td>0.64</td>
<td>3</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2700</td>
<td>397</td>
<td>9492</td>
<td>900</td>
<td>660</td>
<td>2450</td>
<td>226</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Iron</td>
<td>7870</td>
<td>275</td>
<td>6362</td>
<td>460</td>
<td>1536</td>
<td>3000</td>
<td>50</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Titanium</td>
<td>4510</td>
<td>437</td>
<td>9000</td>
<td>519</td>
<td>1668</td>
<td>3260</td>
<td>19</td>
<td>1.2</td>
<td>0.09</td>
</tr>
<tr>
<td>Stainless steel (304)</td>
<td>8030</td>
<td>~300</td>
<td>6500</td>
<td>500</td>
<td>1450</td>
<td>3000</td>
<td>20</td>
<td>0.97</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Fusion Cutting: Melt and Blow

- Once melt is formed
  use gas flow to blow away materials
- Do not need to vaporize,
  thus power reduced by factor of about 10

Fig. 3.7. Interactions at the cutting front.
Fusion Melting Estimates

- Can use the heat balance type relationship

\[ H = wt_c V_c \rho \left[ C_s (T_m - T) + L_f + m'L_v \right] \]

- \( H \) = effective power input from laser
- \( C_s \) = specific heat of solid phase
- \( L_f \) = Latent Heat of Fusion: energy for melting
- \( L_v \) = Latent Heat of Vaporization: energy to vaporize
- \( m' \) = fraction of the melt vaporized
- \( T_m \) = is the melting point, \( T \) starting temp.
- \( t_c \) = material thickness
- \( w \) = width of cut (kerf)
- \( \rho \) = density of material

- Rearranging for a common cutting parameter

\[ f_m = \frac{H}{t_c V_C} = \frac{w \rho \left[ C_s (T_m - T) + L_f + m'L_v \right]}{J m^{-2}} \]

- \( f_m \) is generally a function of cutting speed and gas velocity
- Note there is a small cooling effect caused by the gas flow

Fig. 3.3. Volume melted and removed during cutting.
### Table 3.4

Average severance energies for CW CO₂ laser cutting found experimentally from a variety of sources (principally 8, 9).

<table>
<thead>
<tr>
<th>Material</th>
<th>Lower Value P/Vt J/mm²</th>
<th>Higher Value P/Vt J/mm²</th>
<th>Average P/Vt J/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Steel + O₂</td>
<td>4</td>
<td>13</td>
<td>5.7</td>
</tr>
<tr>
<td>Mild Steel + N₂</td>
<td>7</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>Stainless Steel + O₂</td>
<td>3</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Stainless Steel + Ar</td>
<td>8</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Titanium + O₂</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Titanium + Ar</td>
<td>11</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Aluminium + O₂</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Copper + O₂</td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Brass + O₂</td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Zirconium + O₂</td>
<td></td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Acrylic Sheet</td>
<td>1</td>
<td>3</td>
<td>1.2</td>
</tr>
<tr>
<td>Polythene</td>
<td>2.7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.7</td>
<td>6.2</td>
<td>3</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>1.6</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.5</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>ABS</td>
<td>1.4</td>
<td>4</td>
<td>2.3</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1.4</td>
<td>4</td>
<td>2.3</td>
</tr>
<tr>
<td>PVC</td>
<td>1</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Formica</td>
<td>51</td>
<td>85</td>
<td>71</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>Fibre Glass (epoxy)</td>
<td></td>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td>Wood: Pine (yellow)</td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Oak</td>
<td></td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>Mahogany</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Chipboard</td>
<td>45</td>
<td>76</td>
<td>59</td>
</tr>
<tr>
<td>Fibreboard</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Hardboard</td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>Plywood</td>
<td>20</td>
<td>65</td>
<td>31</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Alumina</td>
<td>15</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Silica</td>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>Ceramic Tile</td>
<td></td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>Leather</td>
<td></td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Cardboard</td>
<td>0.2</td>
<td>1.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Carpet (auto)</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Asbestos Cement</td>
<td></td>
<td></td>
<td>5.0</td>
</tr>
</tbody>
</table>

N.B. These figures do not apply to Nd-YAG pulse cutting where the mechanism is different: for example, for mild steel Nd-YAG values are between 15-200 J/mm².
Reactive Fusion Cutting

- When gas used reacts with gas (usually oxygen) burn reaction adds energy to effect
- Steel typically 60% added energy
- Titanium 90% added energy
- However can reaction can chemically change the work face eg titanium gets brittle from oxygen

![Diagram of Laser beam and nozzle setup](image_url)

*Fig. 3.22. A High Pressure Ring Nozzle used for “Clean Cut” Technique (27).*
Cutting Speed vs Power

Fig. 3.4. $P/t$ vs $V$ for mild steel.

Fig. 3.5. $P/t$ vs $V$ for stainless steel.

Fig. 3.6. $P/t$ vs $V$ for titanium.
Reactive Fusion Cutting Striations

- Reactions create a burn front
- Causes striations in material
- Seen if the cut is slow

Fig. 3.9. Striation formation due to sideways burning.

Fig. 3.8. The stepwise formation of striations.
### Behavior of Materials for Laser Cutting

- Generally break down by reflectivity and organic/inorganic

<table>
<thead>
<tr>
<th>Table 3.7</th>
<th>Behaviour of Different Materials to Laser Cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
<td><strong>Material</strong></td>
</tr>
<tr>
<td>High Reflectivity (Need for Fine Focus)</td>
<td>Gold, Silver, Copper, Aluminium, Brass</td>
</tr>
<tr>
<td>Medium/High Reflectivity</td>
<td>Most metals</td>
</tr>
<tr>
<td>High Melting Point</td>
<td>W, Mo, Cr, Ta, Ti, Zr</td>
</tr>
<tr>
<td>Low Melting Point</td>
<td>Fe, Ni, Sn, Pb</td>
</tr>
<tr>
<td>High Oxide Melting Point (Dross Problems)</td>
<td>Cr, Al, Zr</td>
</tr>
<tr>
<td>Low Reflectivity</td>
<td>Most non metals</td>
</tr>
<tr>
<td>Organics</td>
<td></td>
</tr>
<tr>
<td>Tendency to char</td>
<td>PVC, Epoxy, Leather, Wood, Rubber, Wool, Cotton</td>
</tr>
<tr>
<td>Less tendency to char</td>
<td>Acrylics, Polythene, Polypropylene, Polycarbonate</td>
</tr>
<tr>
<td>Inorganics</td>
<td></td>
</tr>
<tr>
<td>Tendency to crack</td>
<td>Glass, Natural Stones</td>
</tr>
<tr>
<td>Less tendency to crack</td>
<td>Quartz, Alumina, China, Asbestos, Mica</td>
</tr>
</tbody>
</table>

See also list of the cuttability of many materials in Industrial Laser Annual Handbook 1990 pp3-6, published Penwell Books, Tulsa, Oklahoma, USA.
Controlled Fracture and Scribing

Controlled Fracture

- Brittle materials vulnerable to thermal stress fracture
- Heat volume: it expands, creates tensile stress
- On cooling may crack
- Crack continue in direction of hot spot
- Mostly applies to insulators eg Sapphire, glass

Scribing

- Create a cut point in the material
- Forms a local point for stress breakage
- Use either a line of holes or grove

<table>
<thead>
<tr>
<th>Table 3.5</th>
<th>Controlled Fracture Cutting Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Thickness mm</td>
</tr>
<tr>
<td>99% Al2O3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Soda Glass</td>
<td>1.0</td>
</tr>
<tr>
<td>Sapphire</td>
<td>1.2</td>
</tr>
<tr>
<td>Quartz (cryst)</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Cold Cutting or Laser Dissociation

- Uses Eximer (UV) lasers to cut without melting
- UV photons 3.5 - 7.9 eV
- Enough energy to break organic molecular bonds
- eg C=H bond energy is 3.5 eV
- Breaking the bonds causes the material to fall apart: disintegrates
- Does not melt, char or boil surface
- eg ArF laser will create Ozone in air which shows the molecular effects

Table 9.1  Strengths of some common molecular chemical bonds compared with excimer laser photon energies.
Eximer Laser Dissociation

- Done either with beam directly or by mask
- Short Laser pulse absorbed in 10 micron depth
- Breaks polymer bonds
- Rapid rise in local pressure as dissociation
- Mini explosions eject material

Fig. 9.1 The short-duration UV excimer laser pulse rapidly breaks chemical bonds in a polymer within a restricted volume to cause a mini-explosion that ejects material.
Eximer Micromachining

- Can carve complex structures into organics, plastics
- Called Photoablation
- Also shape inorganics glasses/crystals
  like Nd:Yag,
  quartz difficult (not absorbing)
- Composites: cuts the organic binders easily
  no wear like blades

Fig. 9.3 40 μm notches machined in a human hair with an ArF excimer laser.
Etching with Eximers

- Each pulse removes materials
- However definite threshold effect
- Also saturation,
  because beam does not penetrate
- Many organics just top microns absorbs

**Fig. 9.7** Rate for etching polyimide per pulse versus fluence with the three principal excimer lasers.

**Fig. 9.8** Rate for etching PET per pulse versus fluence with the three principal excimer lasers.
Threshold Effect in Photoablation

- If too low get cone shaped structures
- Only local dissociations
- High power, smooth sidewalls

Fig. 9.14 Etches in polyimide with a KrF laser (a) just above the etching threshold, showing cone like structures, (b) smooth etching at a fluence ≈10 times the threshold for etching.
**Corneal Sculpting**

- Laser cold cutting used to shape the cornea to correct vision
- LASIK: Laser-Assisted In Situ Keratomileusis
- Cornea absorbed 193 nm in 4 microns
- Directly ablates cornea materials
- Use a computer controlled shaping pattern
- 50-100 microns cuts for up to 7 diopters change
- Cuts may require up to 90% reduction in areas with surgery
- Eximer leaves a very smooth surface
- Current price $1000-4000 per eye (depending on complexity)

---

**Fig. 9.53** Machining with an ArF laser and image projection on to the cornea a mask consisting of (a) a variable circular aperture producing a larger radius for myopia correction, (b) a variable annular aperture producing a smaller radius for hyperopia correction. Similar profiles can be obtained using rotating wedged slit aperture masks or sacrificial masks of variable thickness placed on to the cornea.
Comparison of Diamond Surgery & Laser Eye Surgery
- Older Diamond Eye Surgery is much rougher
- Laser photoablation is very smooth
- Problem is eye infections rates of up to 25% for laser systems

Fig. 9.52  Floor of corneal keratectomy cut in the stroma of a human eye with (a) a trephine diamond knife and (b) an ArF excimer laser. Photograph courtesy of Prof. J. Marshall, Institute of Ophthalmology, University of London, UK.
Laser Eye Surgery Systems

- Commercial systems available requiring no laser knowledge

Fig. 9.55 Front view of a myopia-corrected cornea showing variable aperture cuts. The two reflected spots of light are from the ablated region (centre of photo) and the untreated region (left). Since both spots are a similar size the ablated surface is as smooth as the untreated cornea. Photograph courtesy of Taunton Technologies Inc, Monroe, Conn, USA.

Fig. 9.56 Excimer laser ophthalmic system used for refractive surgery. The cornea is machined with 193 nm radiation at a fluence of $\approx 100 \text{ mJ/cm}^2$ in $\approx 30 \text{ s}$ at a repetition rate of 10 pps. Photograph courtesy of Taunton Technologies Inc, Monroe, Conn, USA.