Vaporization Cutting

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

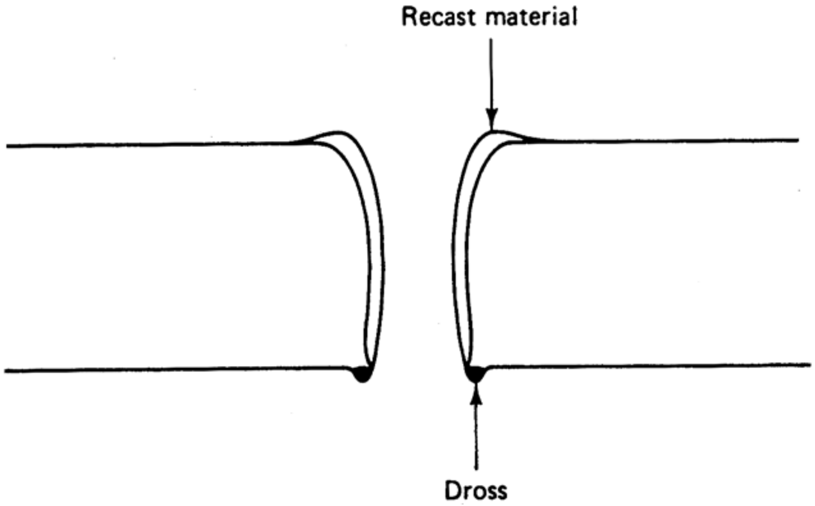


Figure 13-21 Sketch of laser-drilled hole.

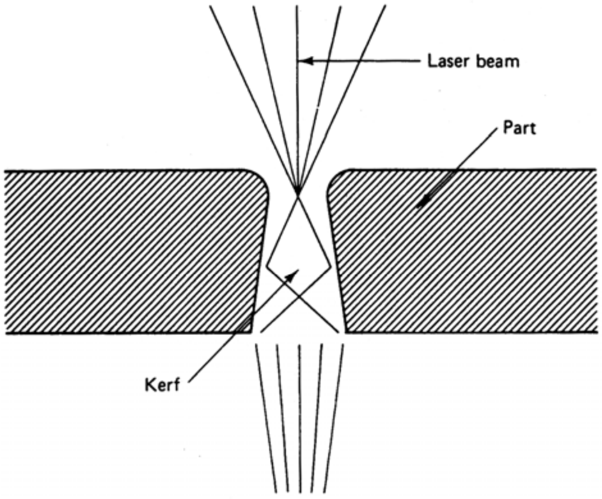


Figure 13-16 Kerf produced by laser cutting.

Vaporization Cutting Formulas

- Recall the velocity of melt front formulas

$$v_s = \frac{H}{\rho\left(CT_v + L_v\right)}$$

- where H is power density absorbed per square area
- and the temperature at the surface from the uniform illumination formulas for vaporization point

$$T\left(0,t\right) = \frac{2H}{k}\sqrt{\frac{\alpha t}{\pi}}$$

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

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

- Can estimate v_s and t_v

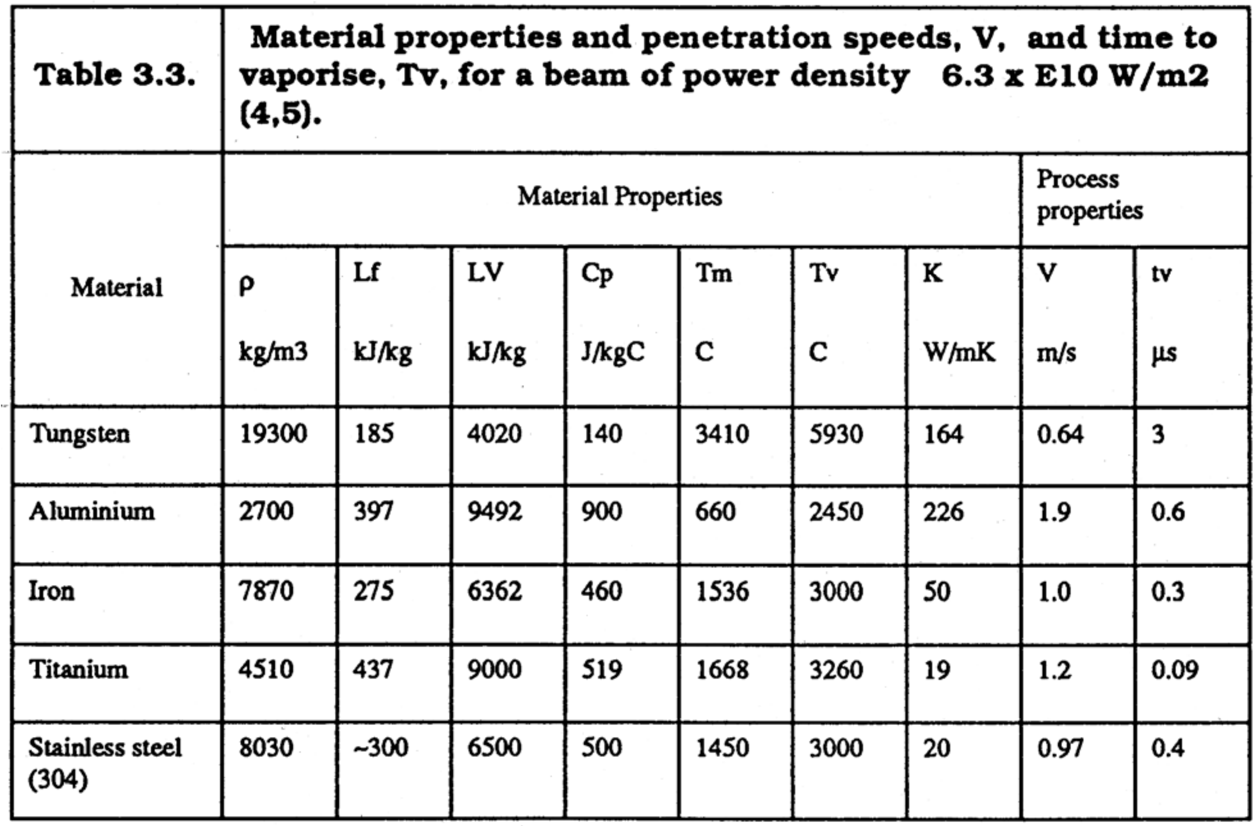


Table 3.3. **Material properties and penetration speeds, V, and time to vaporise, Tv, for a beam of power density 6.3 x E10 W/m2 (4,5).**

Material	Material Properties							Process properties	
	ρ kg/m3	Lf kJ/kg	LV kJ/kg	Cp J/kgC	Tm C	Tv C	K W/mK	V m/s	tv μs
Tungsten	19300	185	4020	140	3410	5930	164	0.64	3
Aluminium	2700	397	9492	900	660	2450	226	1.9	0.6
Iron	7870	275	6362	460	1536	3000	50	1.0	0.3
Titanium	4510	437	9000	519	1668	3260	19	1.2	0.09
Stainless steel (304)	8030	~300	6500	500	1450	3000	20	0.97	0.4

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

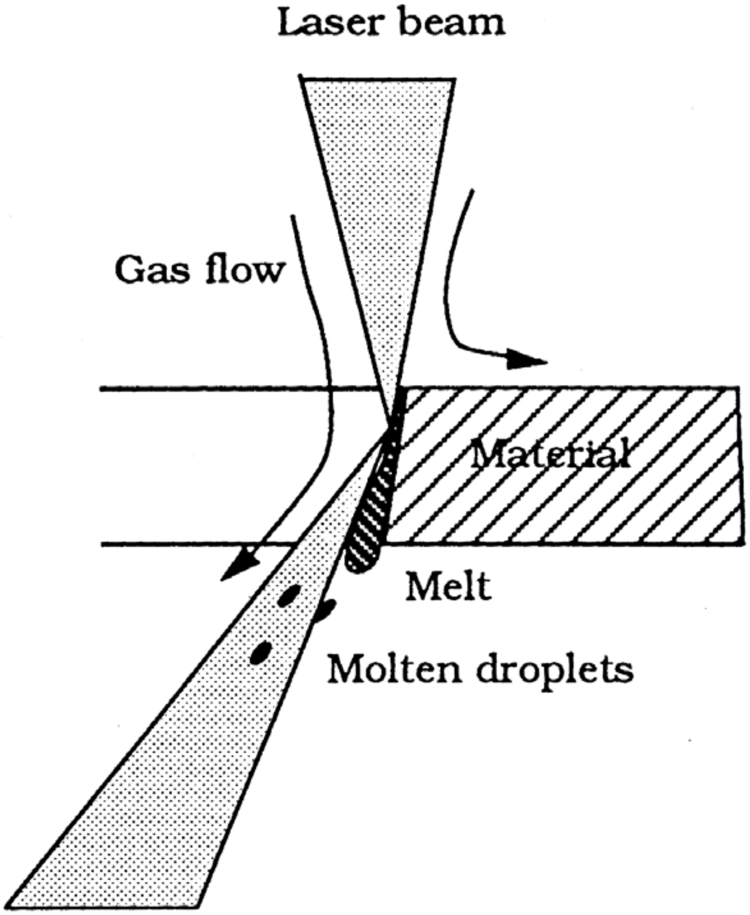


Fig. 3.7. Interactions at the cutting front.

Fusion Melting Estimates

- Can use the heat balance type relationship

$$H = w t_c V_c \rho \left[C_s (T_m - T) + L_f + m' L_V \right]$$

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 thicknes
w = width of cut (kerf)
ρ = density of material

- Rearranging for a common cutting parameter

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

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

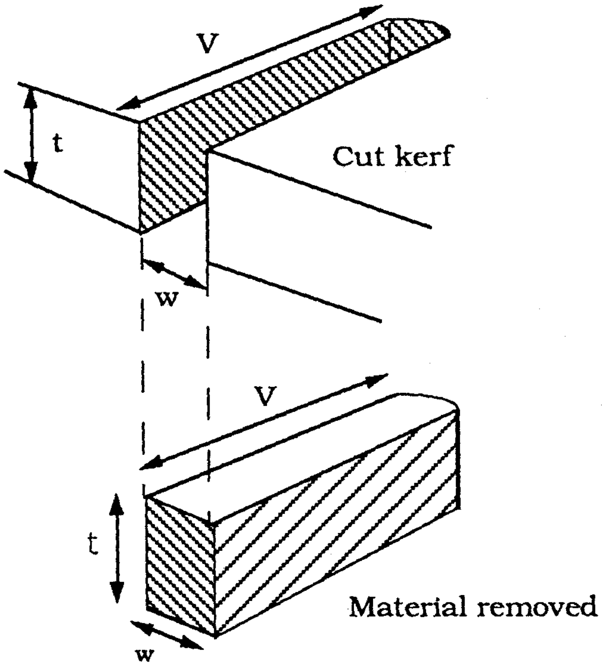


Fig. 3.3. Volume melted and removed during cutting.

Fusion Cutting CO_2 & Materials

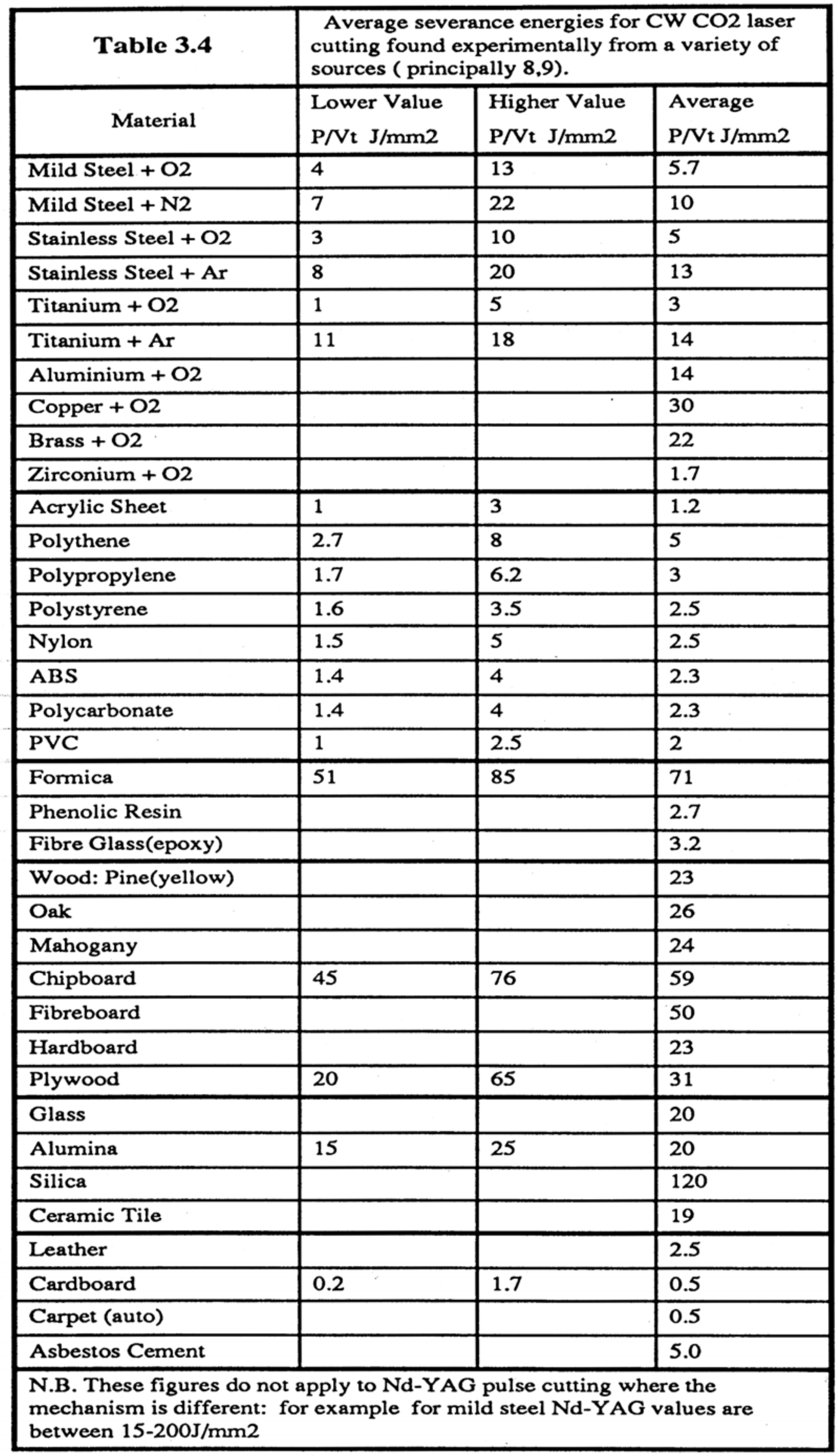


Table 3.4	Average severance energies for CW CO2 laser cutting found experimentally from a variety of sources (principally 8,9).		
Material	Lower Value P/Vt J/mm2	Higher Value P/Vt J/mm2	Average P/Vt J/mm2
Mild Steel + O2	4	13	5.7
Mild Steel + N2	7	22	10
Stainless Steel + O2	3	10	5
Stainless Steel + Ar	8	20	13
Titanium + O2	1	5	3
Titanium + Ar	11	18	14
Aluminium + O2			14
Copper + O2			30
Brass + O2			22
Zirconium + O2			1.7
Acrylic Sheet	1	3	1.2
Polythene	2.7	8	5
Polypropylene	1.7	6.2	3
Polystyrene	1.6	3.5	2.5
Nylon	1.5	5	2.5
ABS	1.4	4	2.3
Polycarbonate	1.4	4	2.3
PVC	1	2.5	2
Formica	51	85	71
Phenolic Resin			2.7
Fibre Glass(epoxy)			3.2
Wood: Pine(yellow)			23
Oak			26
Mahogany			24
Chipboard	45	76	59
Fibreboard			50
Hardboard			23
Plywood	20	65	31
Glass			20
Alumina	15	25	20
Silica			120
Ceramic Tile			19
Leather			2.5
Cardboard	0.2	1.7	0.5
Carpet (auto)			0.5
Asbestos Cement			5.0

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 15-200J/mm2

Reactive Fusion Cutting

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

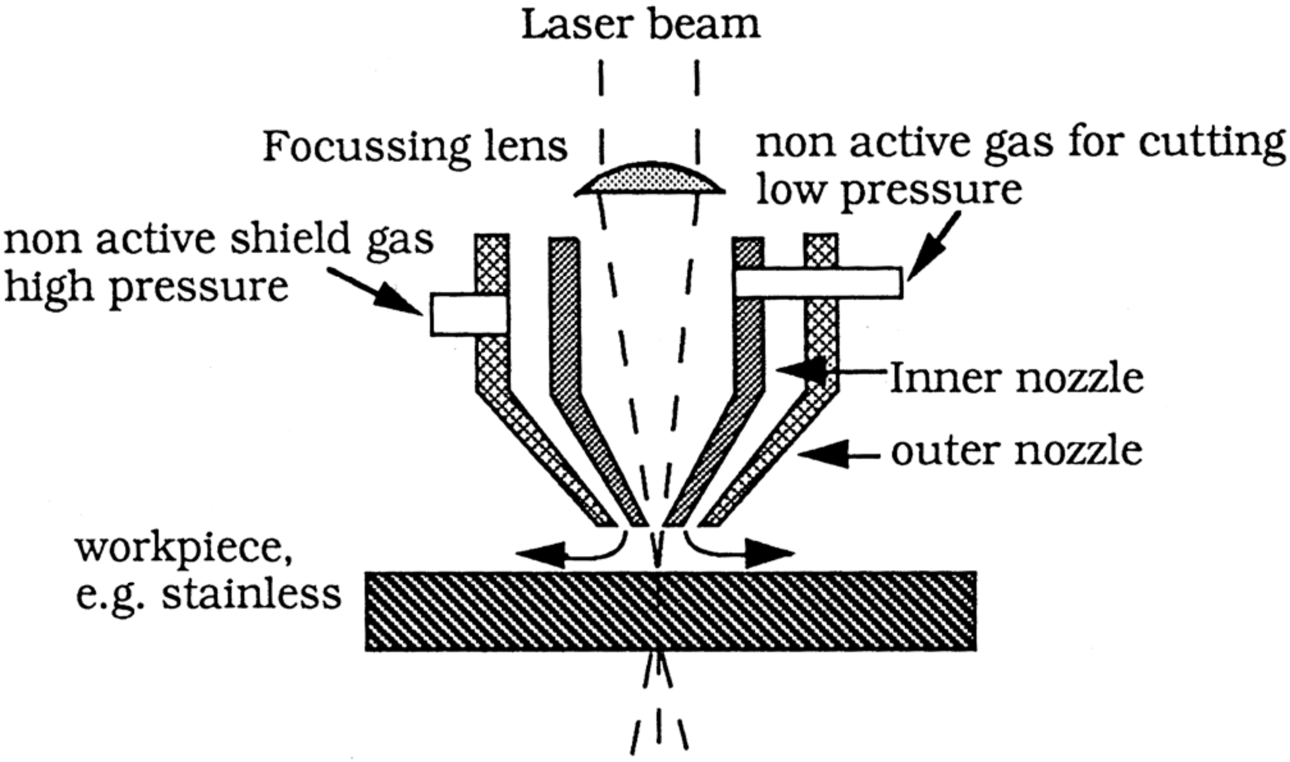


Fig. 3.22. A High Pressure Ring Nozzle used for "Clean Cut" Technique (27).

Cutting Speed vs Power

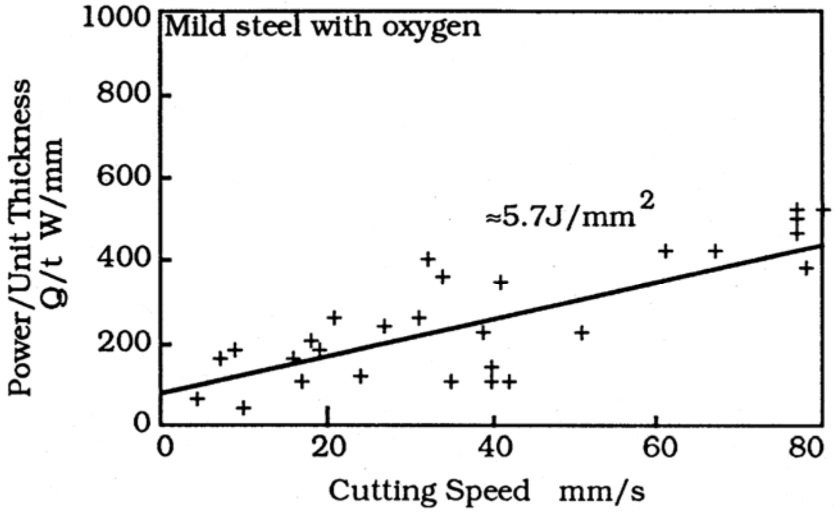


Fig. 3.4. P/t vs V for mild steel.

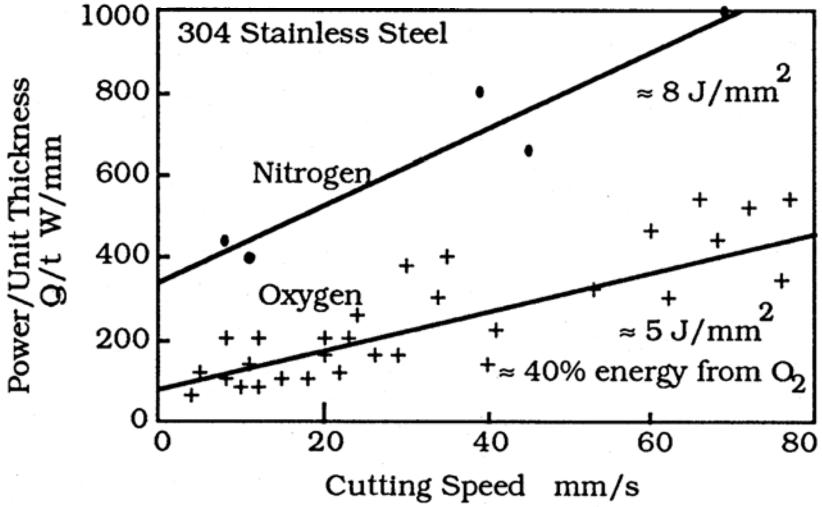


Fig. 3.5. P/t vs V for stainless steel.

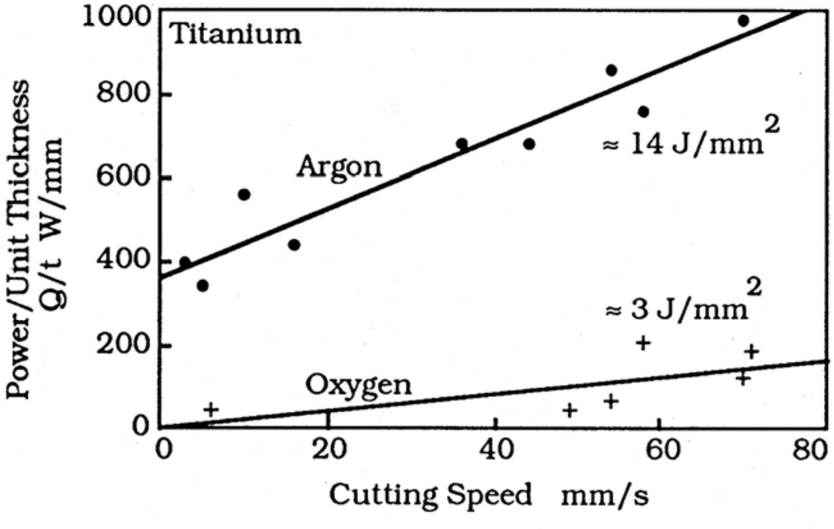


Fig. 3.6. P/t vs V for titanium.

Reactive Fusion Cutting Striations

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

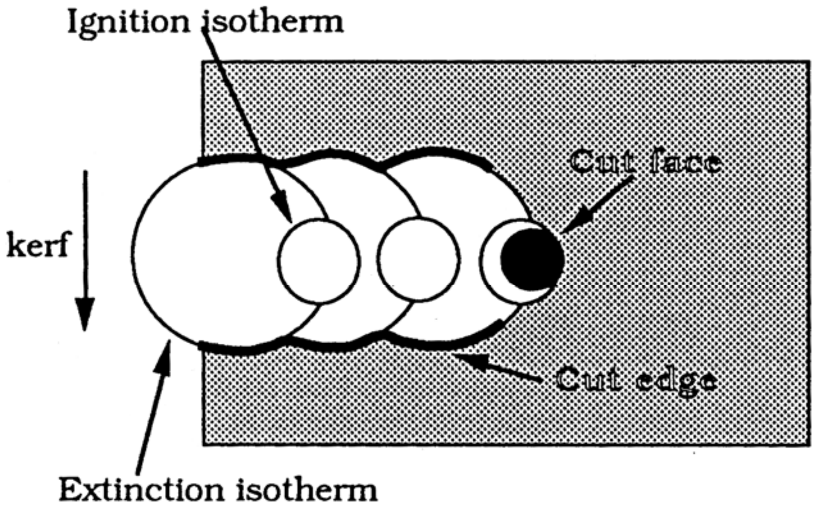
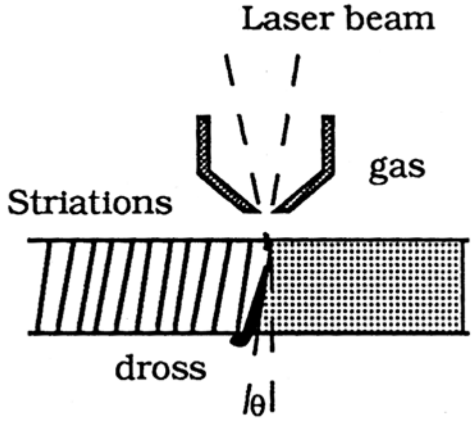


Fig. 3.9. Striation formation due to sideways burning.



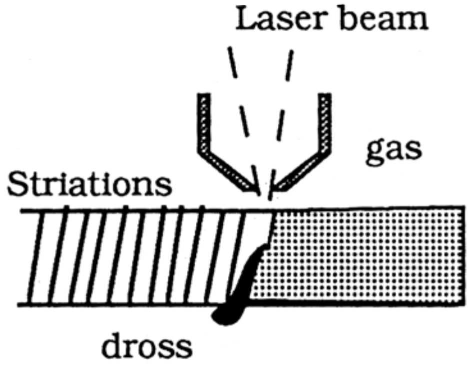


Fig. 3.8. The stepwise formation of striations.

Behavior of Materials for Laser Cutting

- Generally break down by reflectivity and organic/inorganic

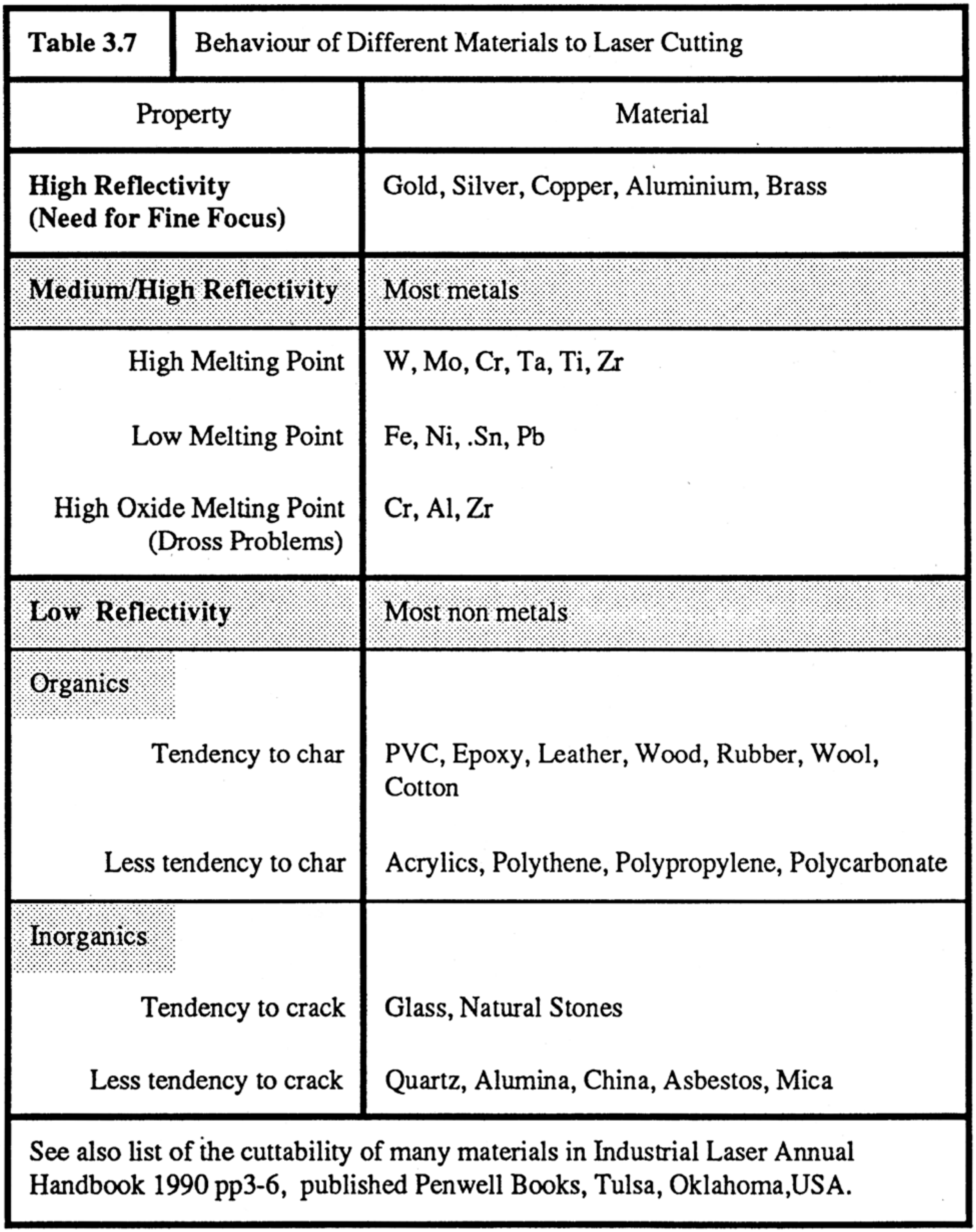


Table 3.7 Behaviour of Different Materials to Laser Cutting

Property	Material
High Reflectivity (Need for Fine Focus)	Gold, Silver, Copper, Aluminium, Brass
Medium/High Reflectivity	Most metals
High Melting Point	W, Mo, Cr, Ta, Ti, Zr
Low Melting Point	Fe, Ni, .Sn, Pb
High Oxide Melting Point (Dross Problems)	Cr, Al, Zr
Low Reflectivity	Most non metals
Organics	
Tendency to char	PVC, Epoxy, Leather, Wood, Rubber, Wool, Cotton
Less tendency to char	Acrylics, Polythene, Polypropylene, Polycarbonate
Inorganics	
Tendency to crack	Glass, Natural Stones
Less tendency to crack	Quartz, Alumina, China, Asbestos, Mica

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

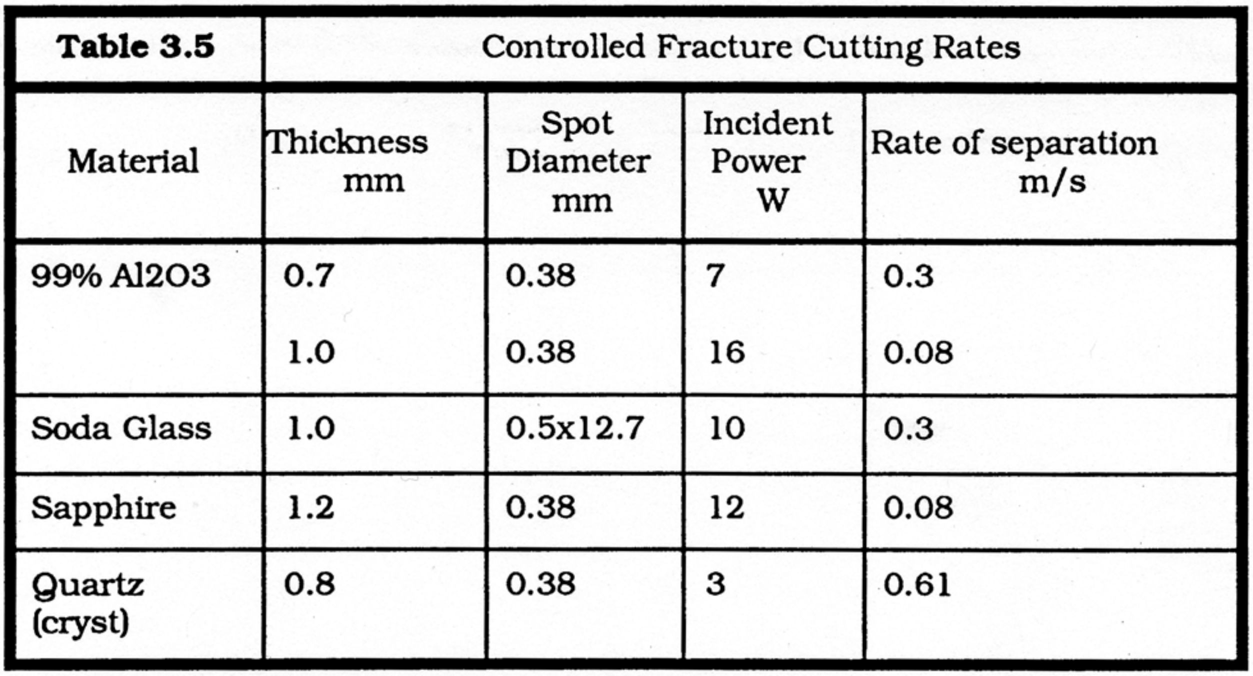
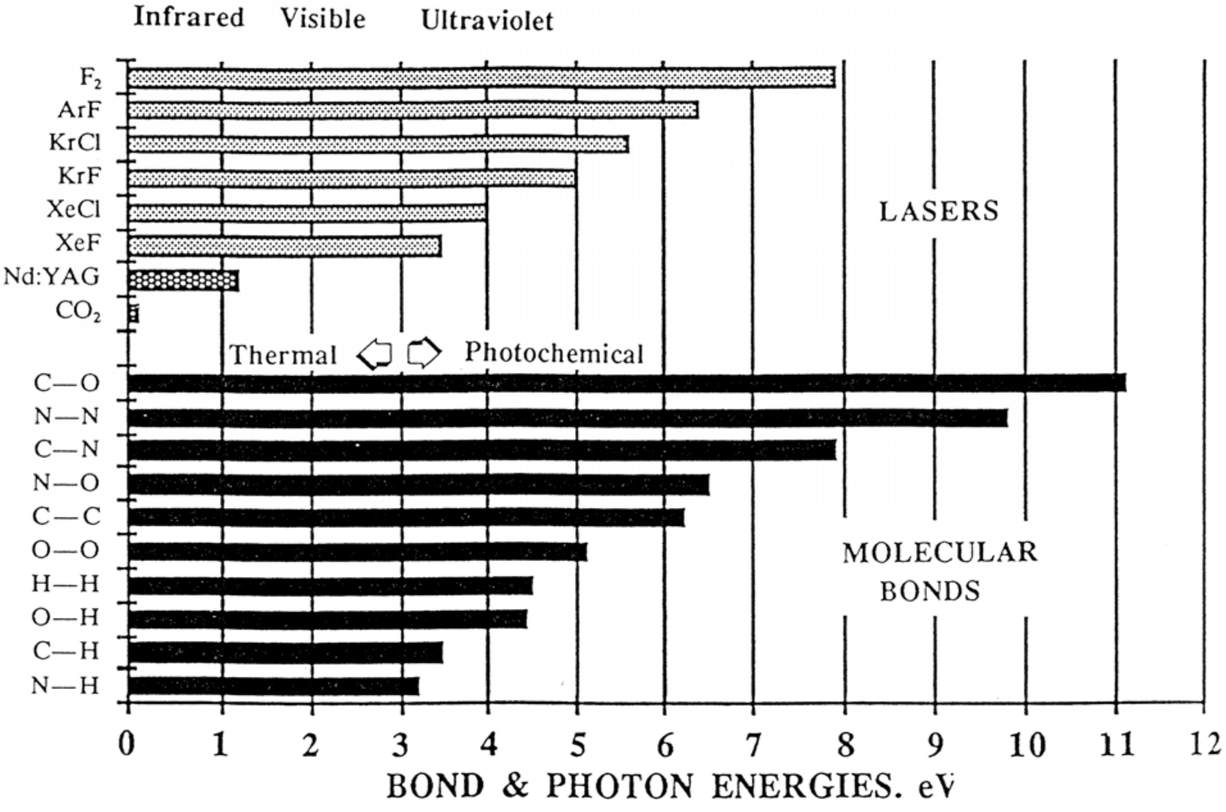


Table 3.5	Controlled Fracture Cutting Rates			
Material	Thickness mm	Spot Diameter mm	Incident Power W	Rate of separation m/s
99% Al2O3	0.7	0.38	7	0.3
	1.0	0.38	16	0.08
Soda Glass	1.0	0.5x12.7	10	0.3
Sapphire	1.2	0.38	12	0.08
Quartz (cryst)	0.8	0.38	3	0.61

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 3.5 eV
- Causes material to fall apart
- Does not melt, chare 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

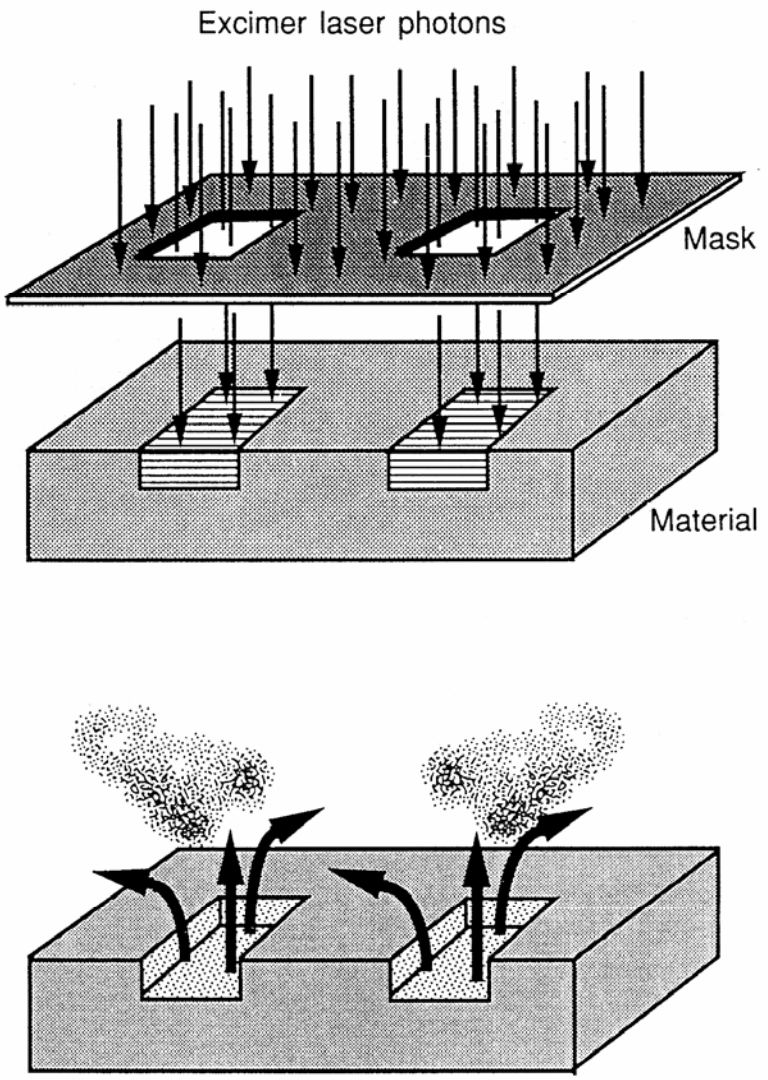


Fig. 9.1 The short-duration UV excimer laser pulse rapidly breaks chemical bonds in a polymer within a restricted volume to cause a mini-explosion that ejects material.

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

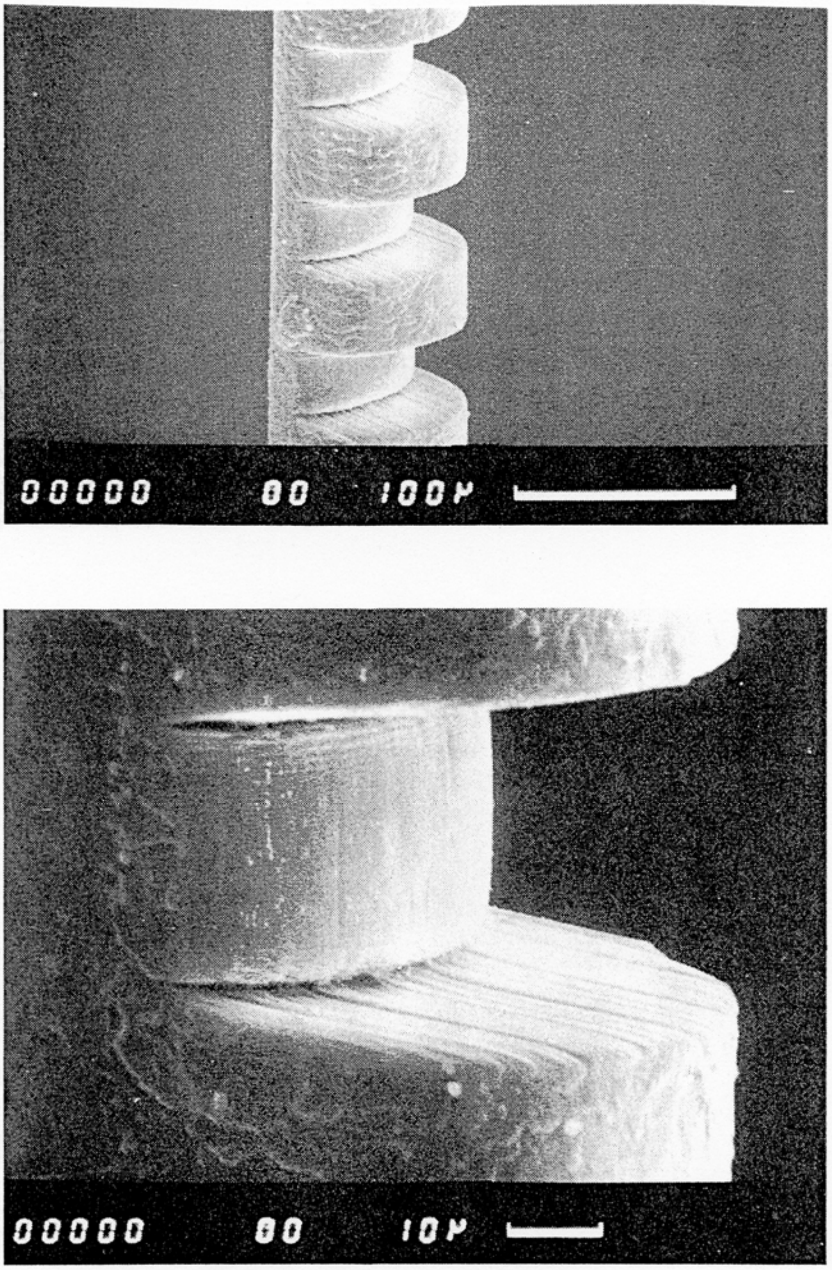


Fig. 9.3 40 μm notches machined in a human hair with an ArF excimer laser.

Etching with Eximers

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

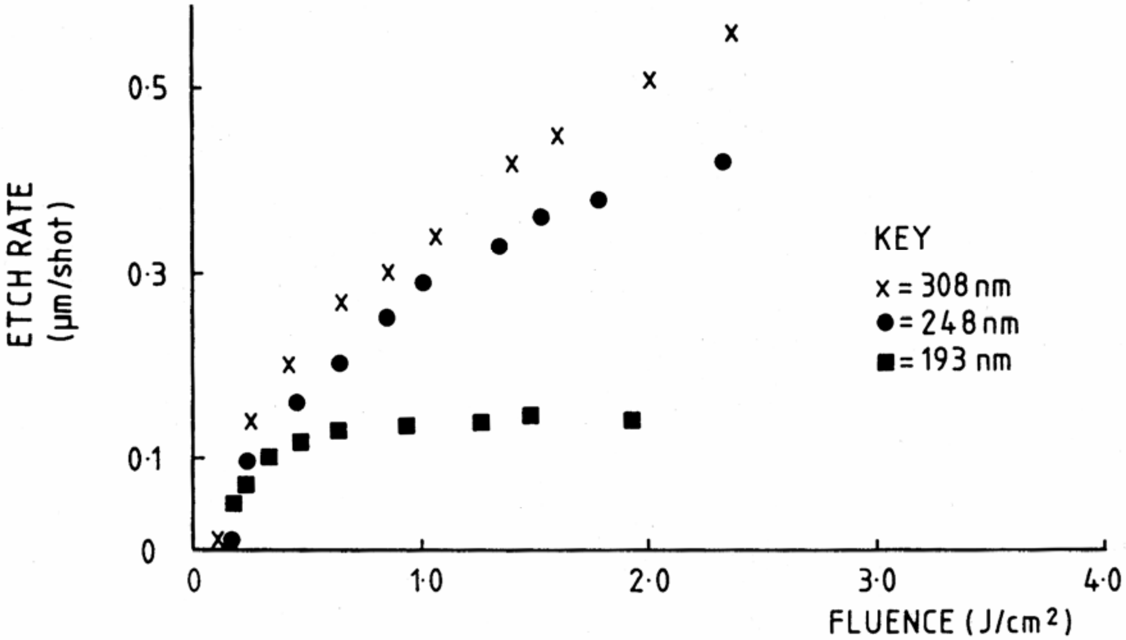


Fig. 9.7 Rate for etching polyimide per pulse versus fluence with the three principal excimer lasers.

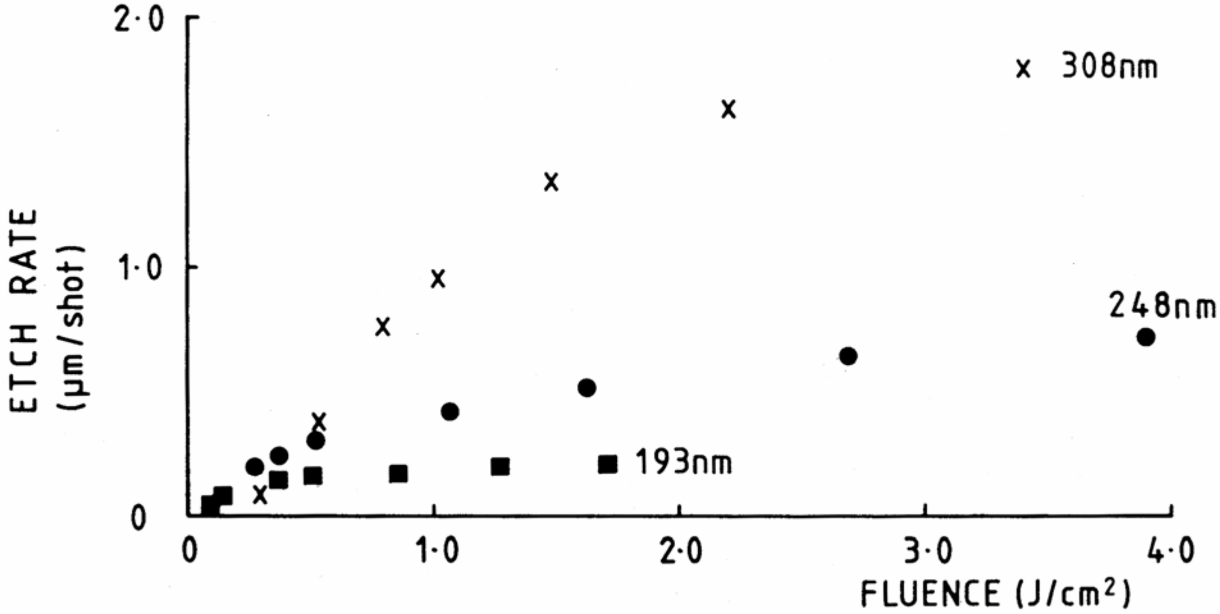
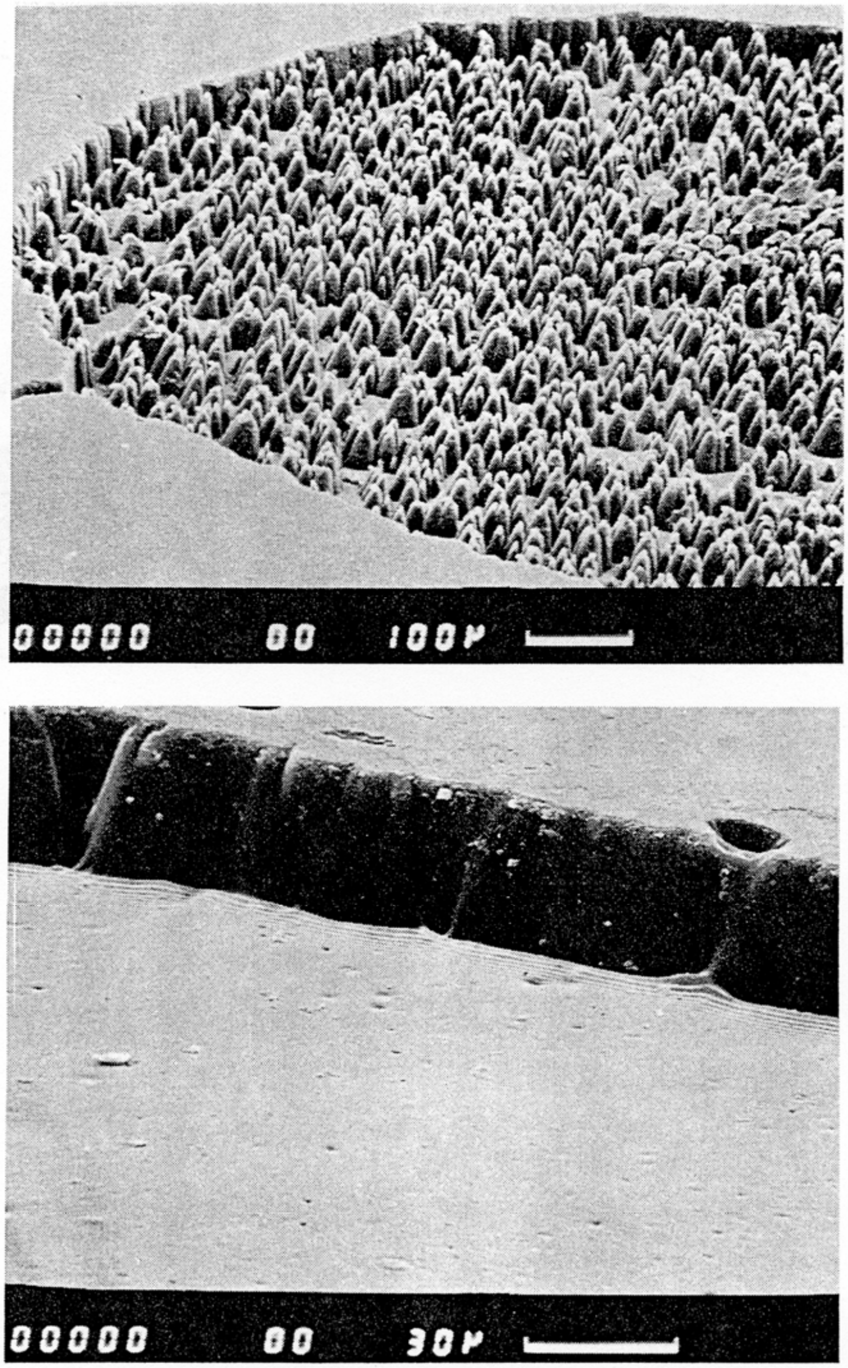


Fig. 9.8 Rate for etching PET per pulse versus fluence with the three principal excimer lasers.

Threshold Effect in Photoablation

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



(a) 0.23 J/cm²

(b) 2.33 J/cm²

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.

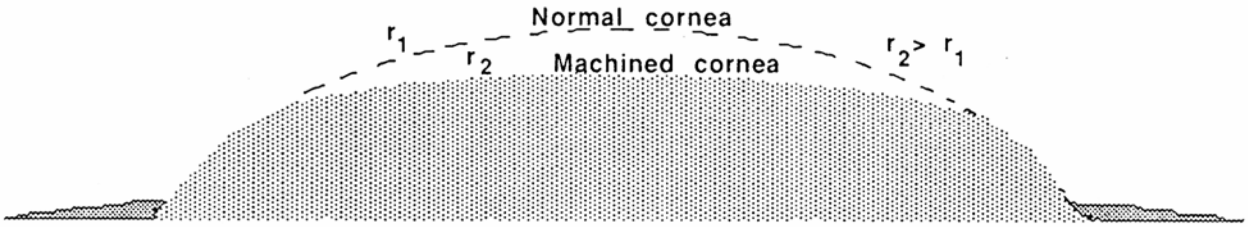
Corneal Sculpting

- Used to shape the cornea
- 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
- Knife Surgery is much rougher
- Cuts may require up to 90% reduction in areas with surgery
- Eximer leaves a very smooth surface
- Current price $4000 per eye

(a)

MYOPIA CORRECTION

(too much refraction)



(b)

HYPEROPIA CORRECTION

(too little refraction)

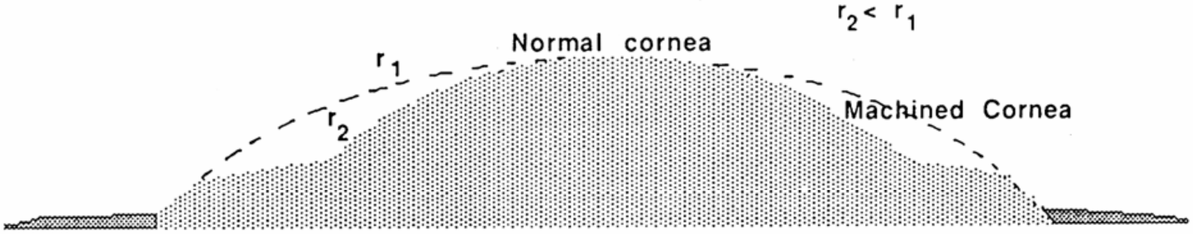


Fig. 9.53 Machining with an ArF laser and image projection on to the cornea a mask consisting of (a) a variable circular aperture producing a larger radius for myopia correction, (b) a variable annular aperture producing a smaller radius for hyperopia correction. Similar profiles can be obtained using rotating wedged slit aperture masks or sacrificial masks of variable thickness placed on to the cornea.

Comparison of Diamond Surgery & Laser Eye Surgery

- Diamond cuts are rough
- Laser photoablation is very smooth

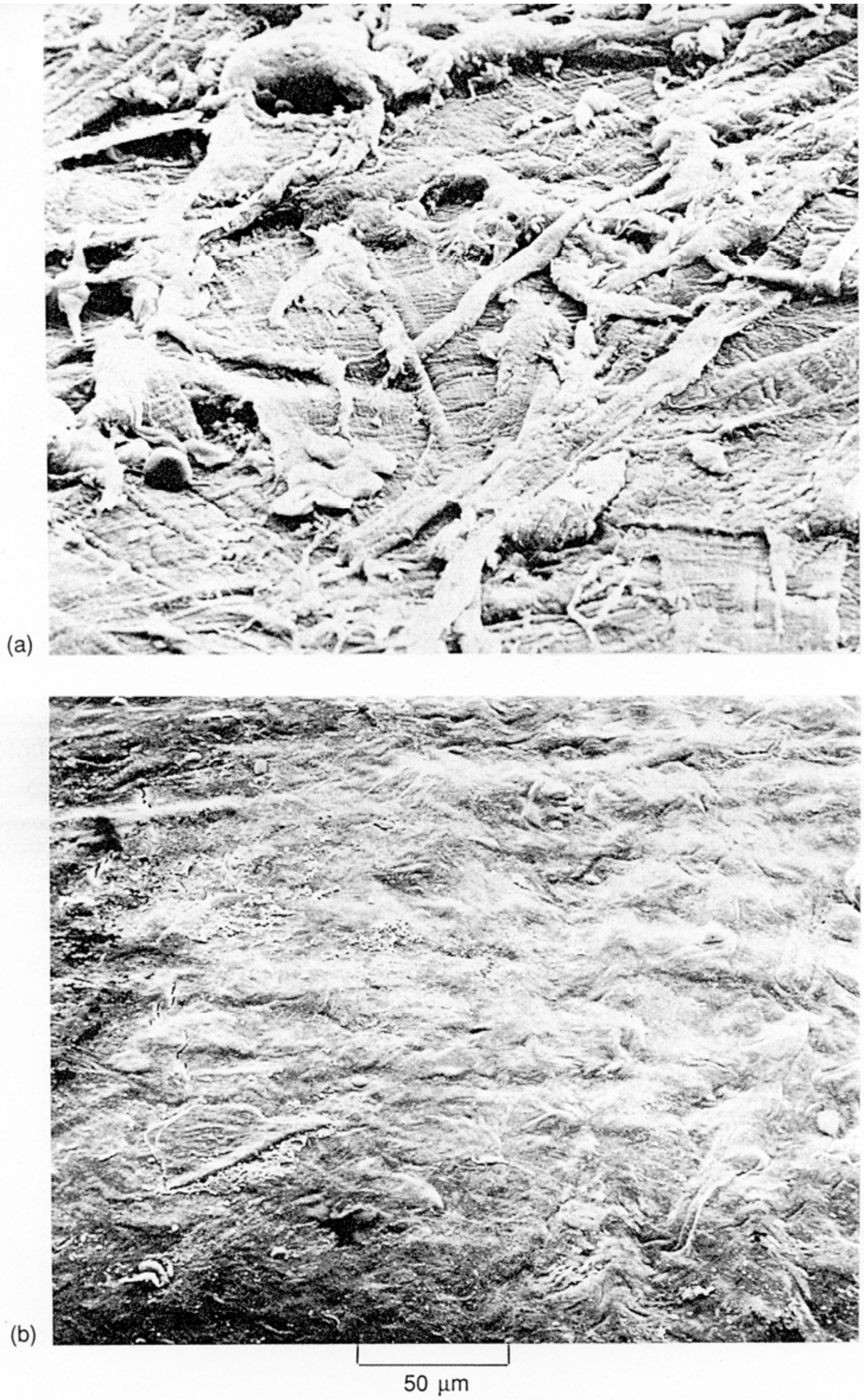


Fig. 9.52 Floor of corneal keratectomy cut in the stroma of a human eye with (a) a trephine diamond knife and (b) an ArF excimer laser. Photograph courtesy of Prof. J. Marshall, Institute of Ophthalmology, University of London, UK.

Laser Eye Surgery Systems

- Commercial systems available requiring no laser knowledge

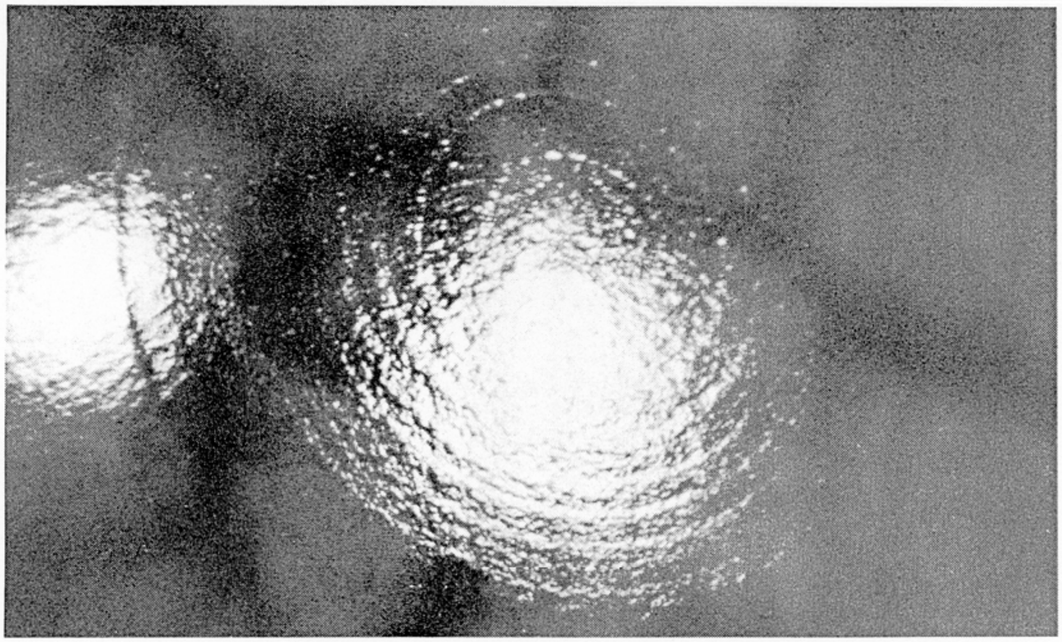


Fig. 9.55 Front view of a myopia-corrected cornea showing variable aperture cuts. The two reflected spots of light are from the ablated region (centre of photo) and the untreated region (left). Since both spots are a similar size the ablated surface is as smooth as the untreated cornea. Photograph courtesy 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 ≈100 mJ/cm^2 in ≈30 s at a repetition rate of 10 pps. Photograph courtesy of Taunton Technologies Inc, Monroe, Conn, USA.