Laser Machining Processes

- Laser heat processing divided into 3 regions
- Heating
- Melting
- Vaporization

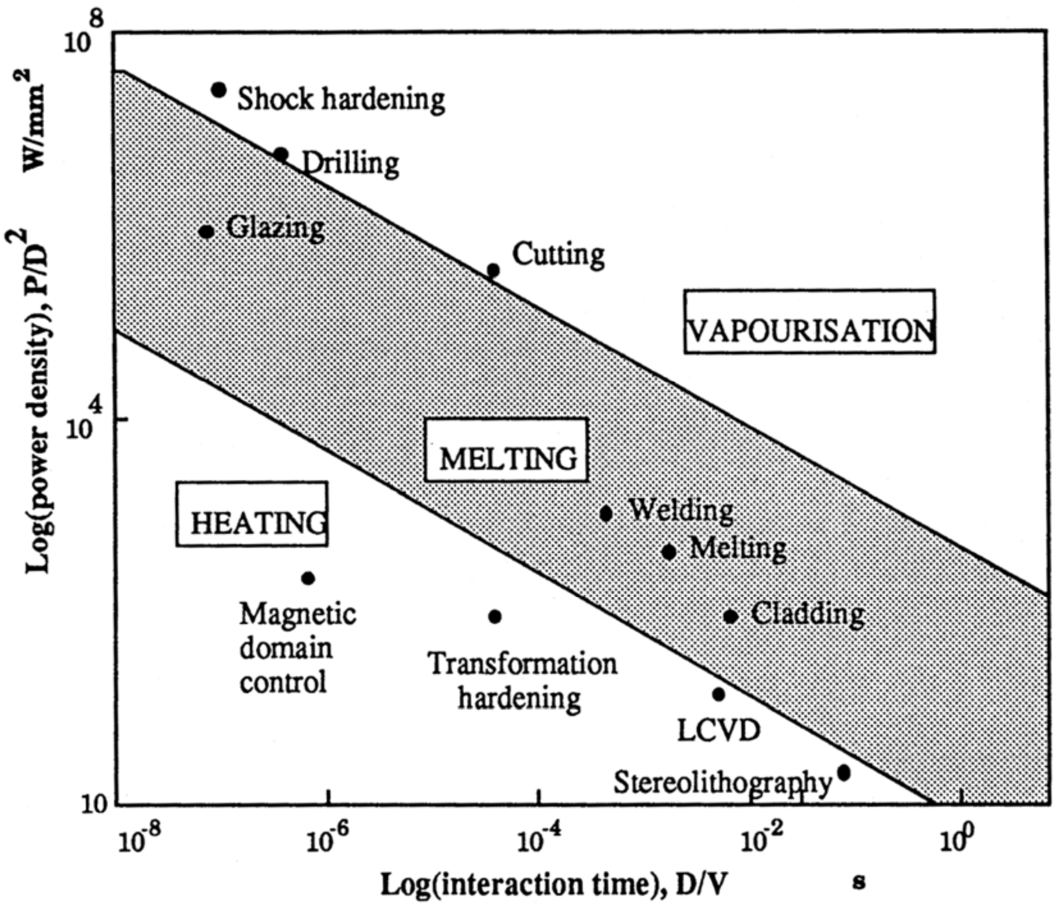


Fig. 6.1. Range of laser processes mapped against power density per unit time.

Laser Surface Treatment

Annealing or Transformation Hardening

- Surface hardness

Surface Melting

- Homogenization, recrystallization

Alloying

- Changing surface composition
- Improves corrosion, wear or cosmetic properties

Cladding

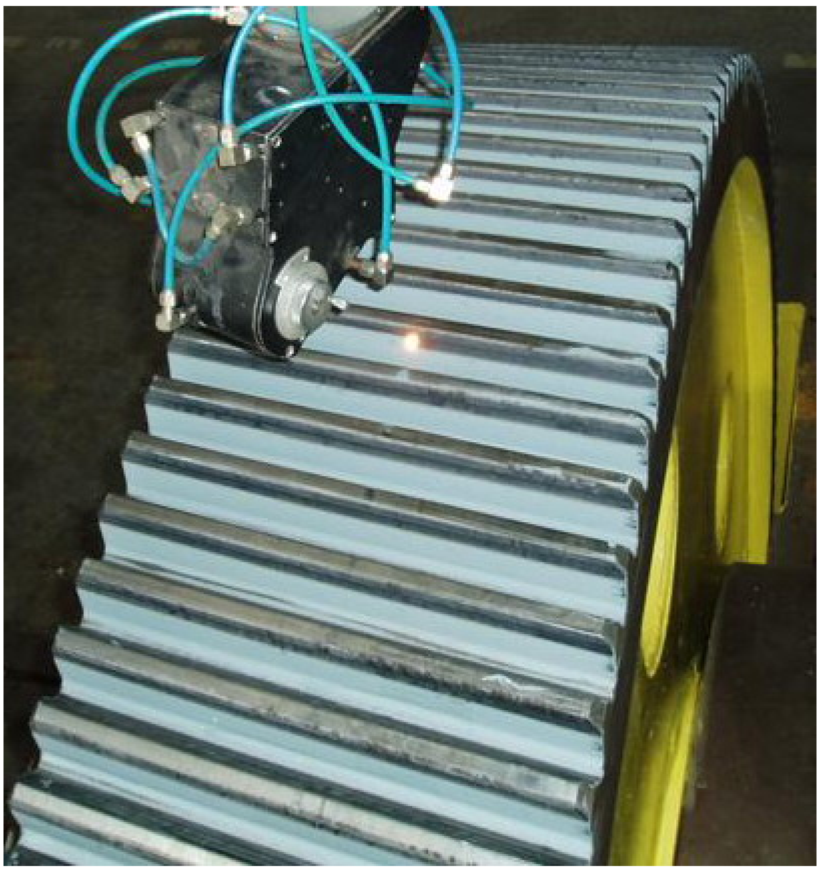
- Applying a different material to surface
- Improves corrosion, wear or cosmetic properties

Texturing

- Changing surface appearance

Plating

- By Chemical Vapor Deposition



Laser Annealing

- Uses the rapid, local, high temperature, heating and cooling (quenching)
- Materials where heating with quenching changes characteristics
- Best examples: Iron/Steel
- With laser can make local changes in material parameters
- Increase hardness, strength
- Temper (make more ductile)

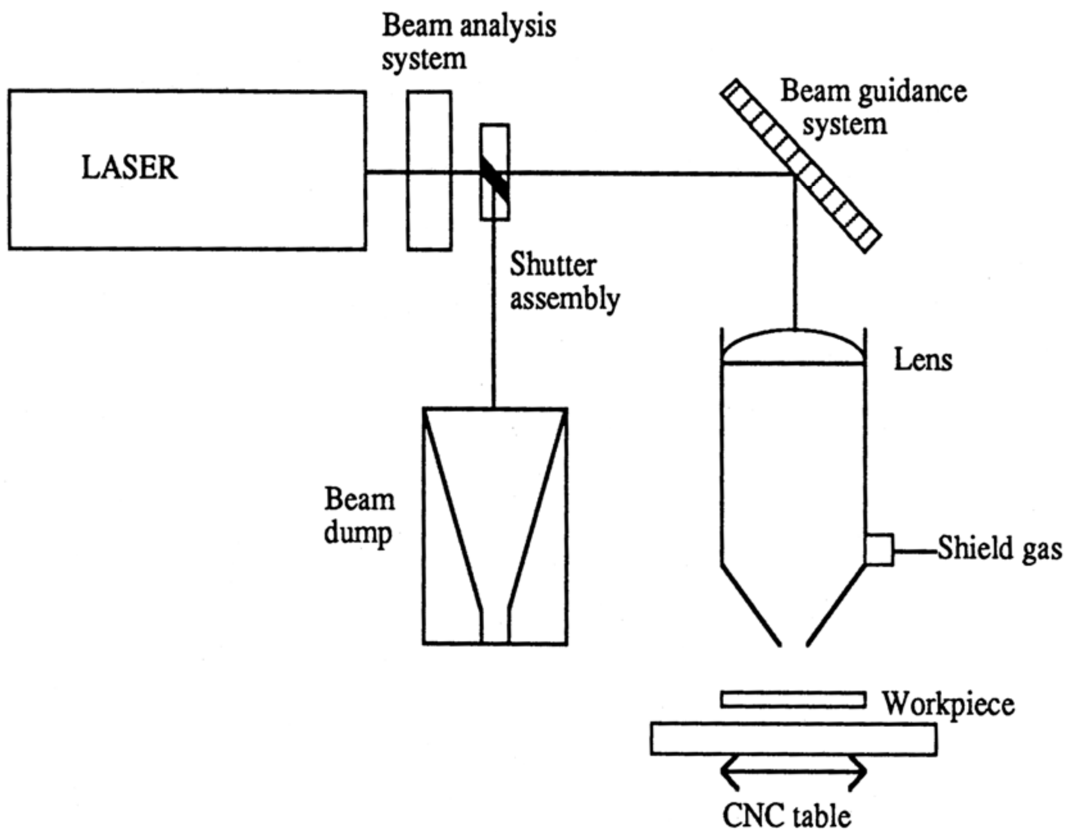
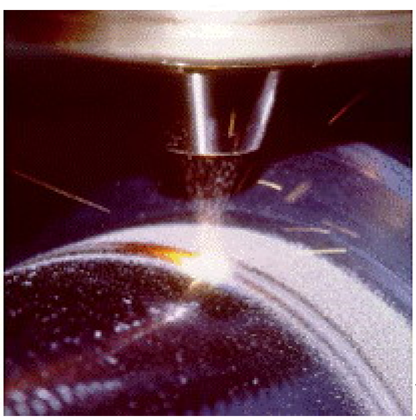


Fig. 6.4. Experimental arrangement for laser heat treatment.



Laser annealing of shaft

Laser Hardening of Steel

- Steel (Iron/Carbon combination)
- Many different crystal phases with
  different hardness/ductility tradeoffs
- At 800°C 4% carbon steel changes to Austenite form
- Causes carbon to redistribute
- If quenched < 1 sec get Martensite
  very hard but brittle layer
- Classical example Damascus Steel blades
- Called Case Hardening
- Can be applied by laser to just local areas

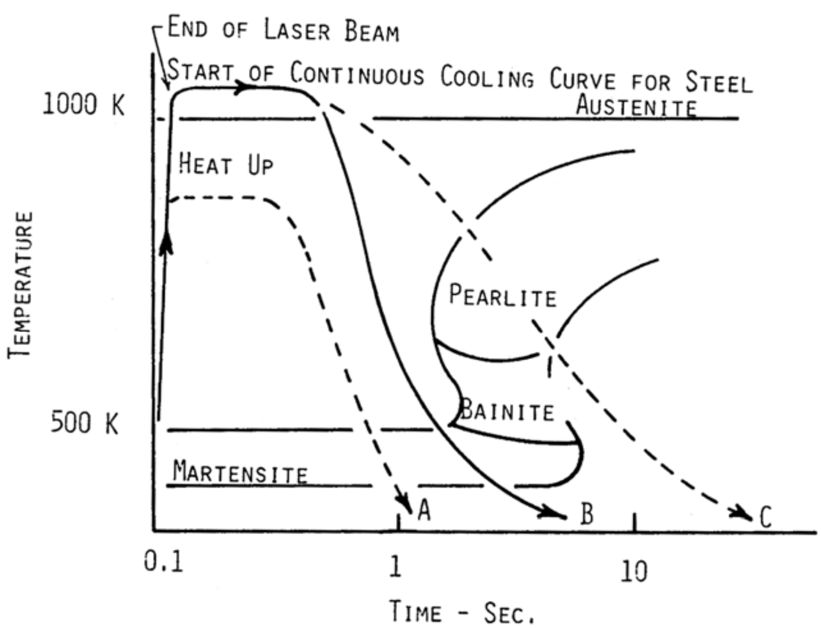
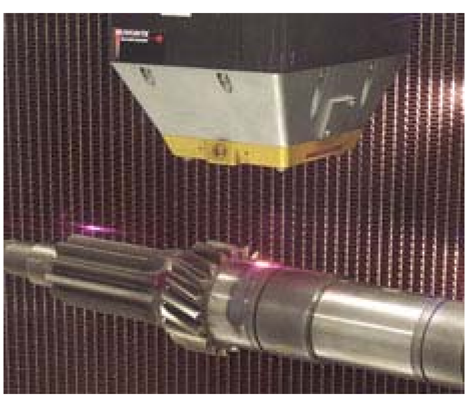


Fig. 4.6. Metallurgical description of laser heat treatment.

Damascus Steel



Laser heat treating a transmission shaft.

Saw tooth hardened by laser

Laser Parameters and Case Hardening

- Can tradeoff laser power and time
- Recall from uniform heating the surface temperature

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

- Thus for the same material T is proportional to $H\sqrt{t}$
- Thus doubling power cuts time by 4
- However depth of heat zone is changed because

$$\frac{T_m}{T_v} = \sqrt{\pi}\ ierfc\left[\frac{z}{2\sqrt{\alpha t}}\right]$$

- When $\sqrt{\alpha t}$ is small z change is large

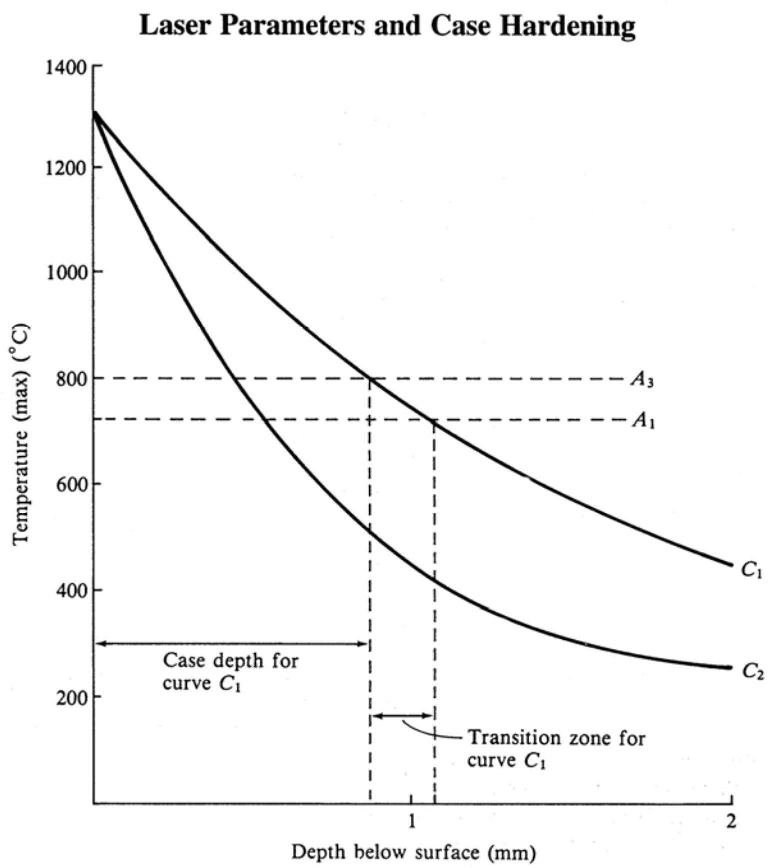


Fig. 5.8 Curves showing the maximum temperatures reached as a function of depth in 1045 steel. Curve C_1 corresponds to a heat input of $2.5 \times 10^7\ W m^{-2}$ applied for 0.4 s, while C_2 corresponds to $5 \times 10^7\ W m^{-2}$ applied for 0.1 s. The intersection of these curves with the horizontal lines corresponding to the temperatures A_3 and A_1 enables the appropriate case-hardening depths and transition zones to be determined.

Spreading the Laser Beam

- To evenly heat the surface
- Defocus the laser beam
- Transport surface (rastor scan the beam)
  either straight, zig zag or circular
- Mirrors can spread the beam to wider areas

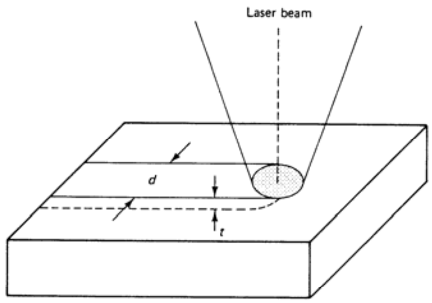


Figure 13-2 Defocused laser beam incident on workpiece for heat treating.

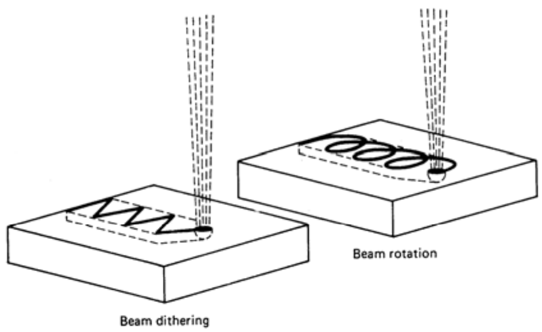
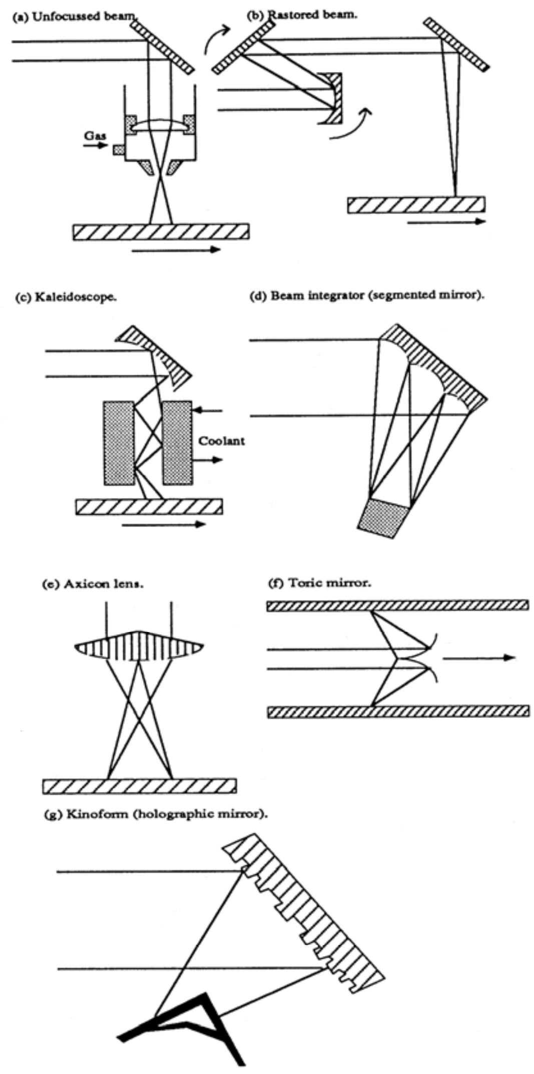


Figure 13-3 Active methods for spreading out a laser beam for surface treatment applications.



Modification of Surface Reflectivity

- Reducing reflectivity important for lower power requirements
- Basic level set by material reflectivity
- But can modify this by surface treatment
- Roughen surface: increases scatter
- Oxidize surface (very good for iron)
- Coat surface
- Most useful for Annealing, not useful if melting occurs
  melt destroys these processes

Table 6.1 Typical values of the reflectivity of various surfaces to 10.6μm radiation at normal angles of incidence.

Surface Type	Reflectivity %		
	Direct	Diffuse	Total
Sandpaper roughened (1μm)	90.0	2.7	92.7
Sandblasted (19μm)	17.3	14.5	31.8
Sandblasted (50μm)	1.8	20	21.8
Oxidised	1.4	9.1	10.5
Graphite	19.1	3.6	22.7
Molybdenum sulphide	5.5	4.5	10.0
Dispersion paint	0.9	0.9	1.8

Laser Recrystallization of Poly Silicon

- Poly Silicon is common conductor in IC's
- Grain size very sensitive to production temperature
- But want low temperatures to reduce effects on substrate
- Poly Si's electrical charaterisitics << than single crystal Si
- Use laser recrystallization to get near single crystal behavior
- Some attempts to build stacked transistors

  one transistor above another

recrystallized poly Si used as the 2nd layer

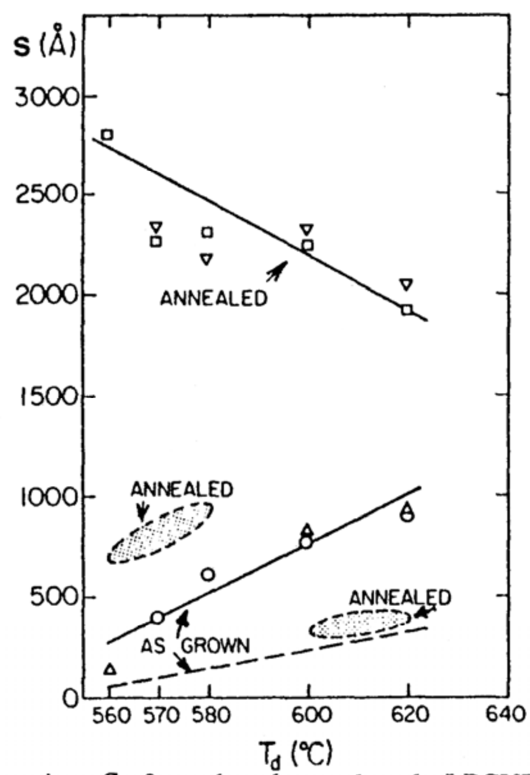


Fig. 15 Average crystallite size **S** for phosphorus-doped LPCVD silicon layers as-grown (o = interface, Δ = surface), and annealed at 1000°C (◊ = interface, ∇ = surface) as a function of

Laser Recrystallization of Poly Silicon

- Successfully recrystallized silicion
- However do not need laser to do this:
- Used just regular light sources
- Called Rapid Thermal Annealing

Laser Recrystallization of Poly Silicon

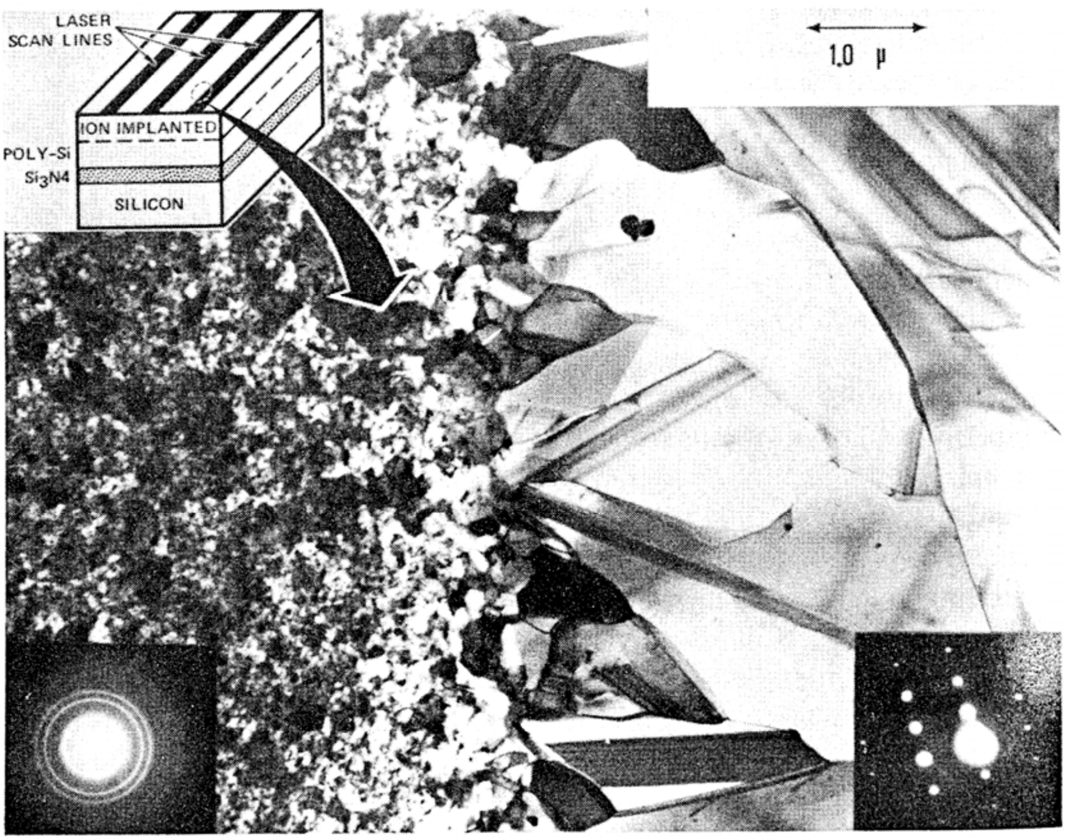


Fig. 7.16. Growth of large grain polysilicon from small grain CVD poly by scanning CW laser beam.

Laser Surface Melting

- Want to melt the surface locally
- Melt & rapid solidification
  get fine homogeneous structures (recrystallize)
- Little thermal penetration
  thus small thermal distortion for sensitive materials
- Melt gives surface finishes within 25 microns
  reducing finishing work
- Process flexibility: easy to software control

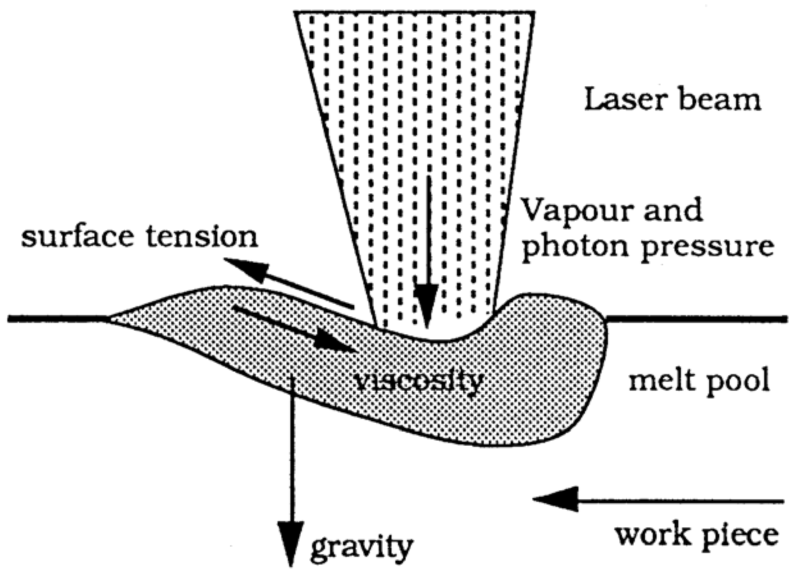


Fig. 6.23. forces on the melt pool.

Case Iron Laser Surface Melting

- Melting causes carbon redistribution
- Forms Martensite & Cementite phases
  significantly increase hardness of Cast Iron

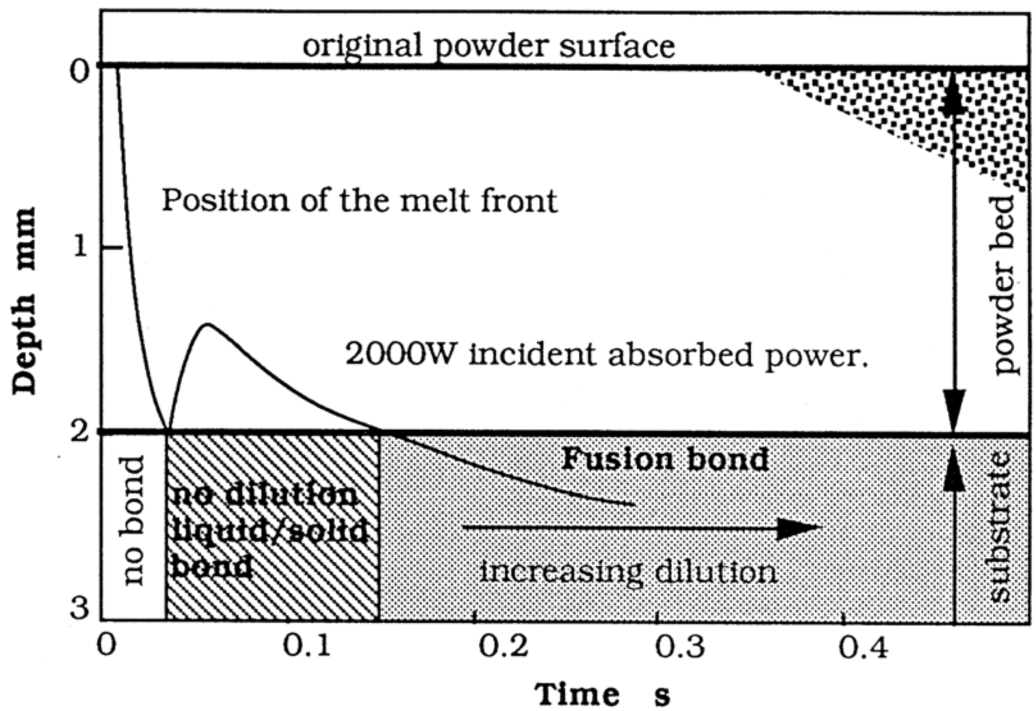
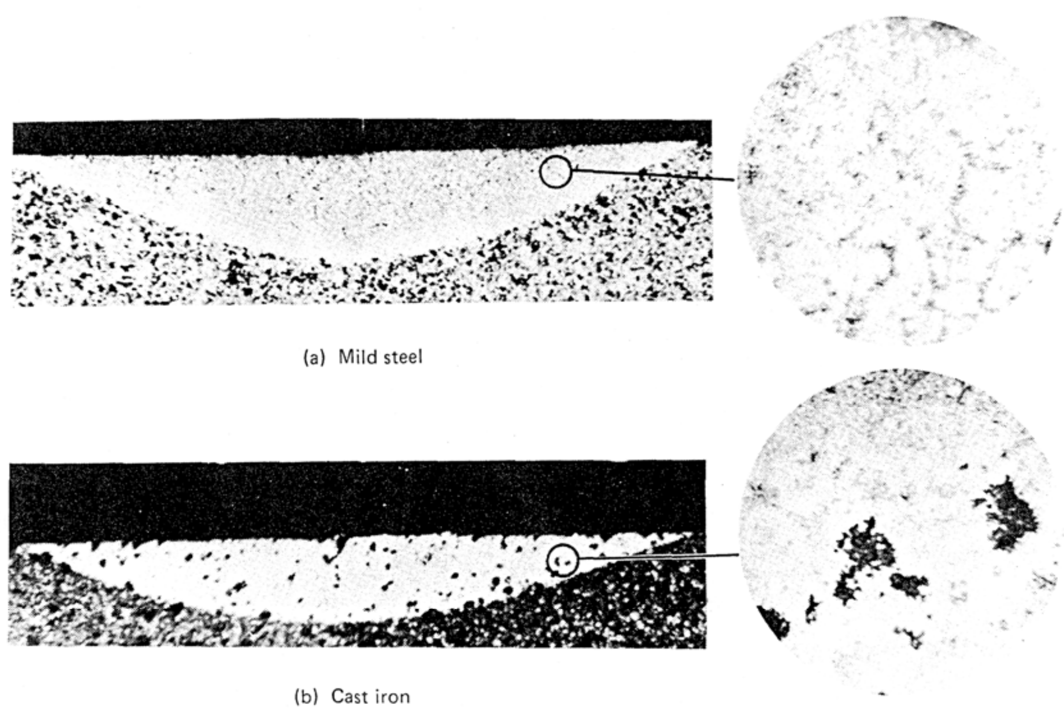


Fig. 6.26. Theoretical calculation of the position of the melt front during preplaced powder cladding (51).



(a) Mild steel

(b) Cast iron

Figure 13-5 Micrographs of heat treat tracks. (Courtesy of Saginaw Steering Gear, Division of GMC.)

Titanium

- Laser heating creates very fine crystal structure
- Must be done in inert atmosphere

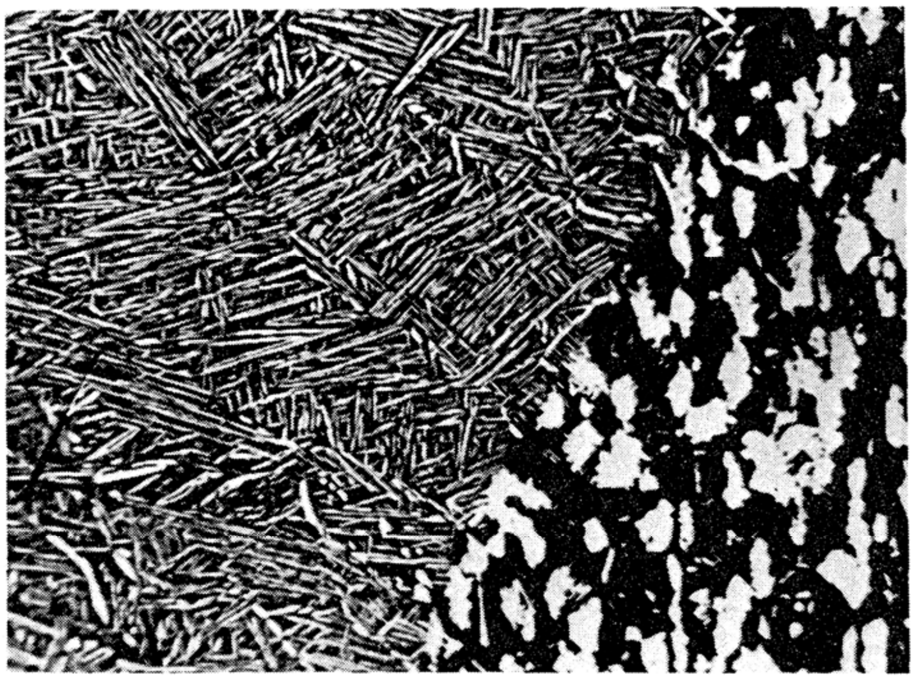


Fig. 6.19. Micrograph showing the fine basket weave structure produced in laser surfa melting IMI550 (28) (P = 1.6kW; V = 200mm/s; D = 0.5mm). X 100

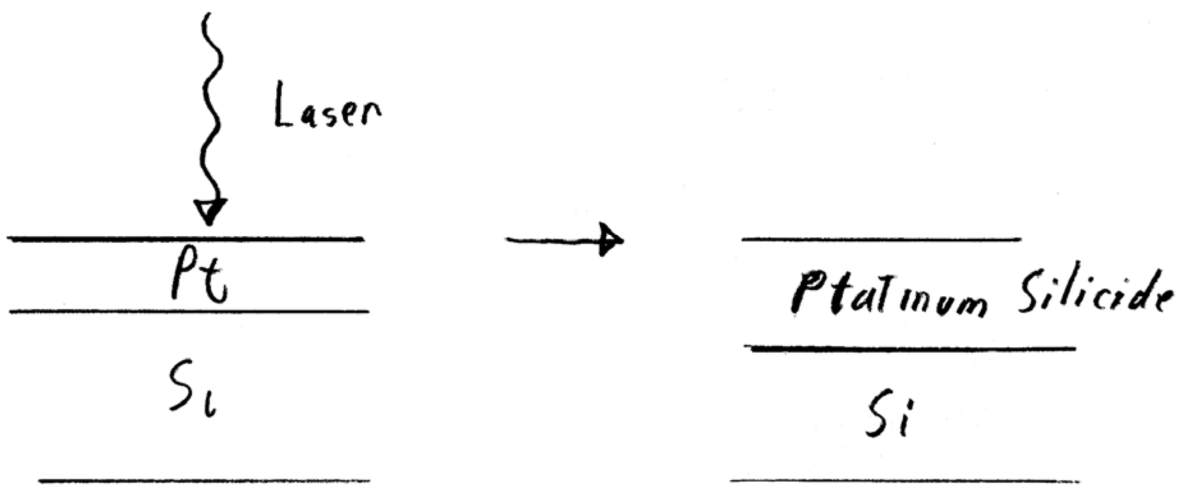
laser welded Titanium

Laser Surface Alloying

- Coat surface with film of another material
- Melt layer with laser locally
  (may inject material into melt pool also)
- Rapid quenching
- Alloyed layer has fine microstructure, nearly homogeneous
- Many materials alloyed into substrates
- Some materials only possible with rapid quench of laser
- Thickness form 1 to 2000 microns

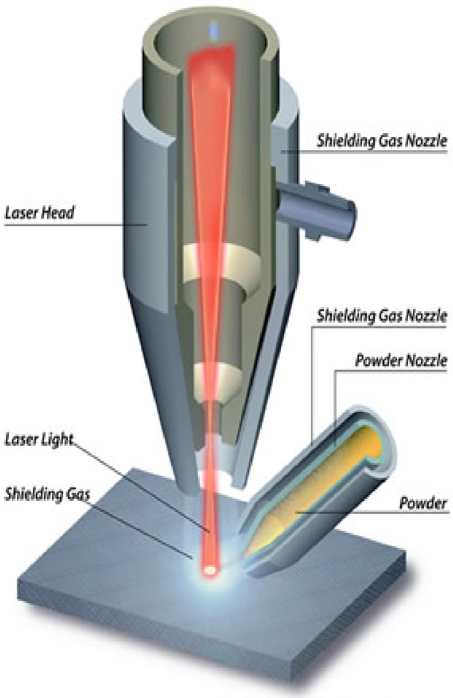
Applications

- Cast Iron: Cr, Si, C makes expensive steel surface
  on cheap iron mass
- Steel: Cr, N, Mo, B
- Aluminium: Si, C, N, Ni alloying

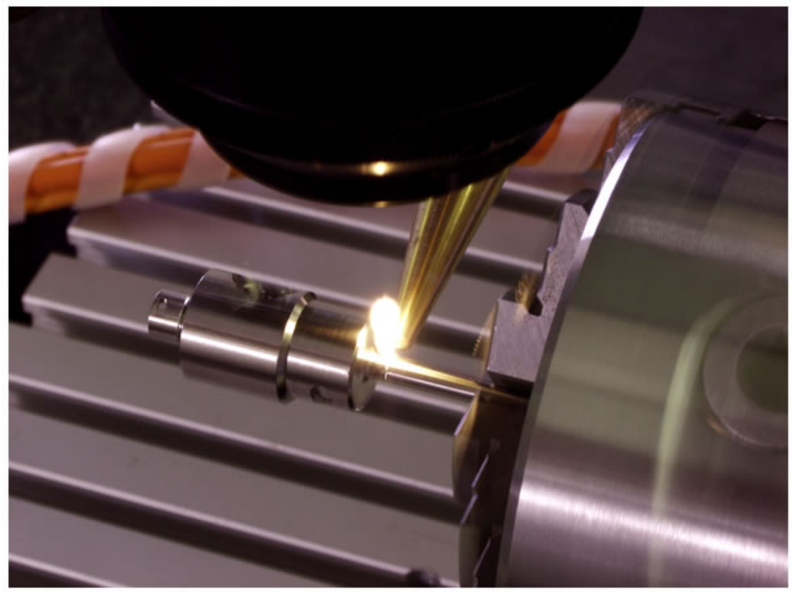


Laser Cladding

- Overlay one material with another
- Usually powders or Chemical Vapours are sources
- Most common industrial is powder process
- Powder blown onto surface
- Laser melts power to surface cladding



(Picture: non-coaxial powder feed)



Laser Cladding

- Powder could be pre-placed
- Melt goes rapidly through powder
- Powder has little thermal contact with substrate
- When molten heat load increase due to good thermal contact
- Then melt into substrate and fuse with it
- Use reflective dome above powder
- Recovers powder

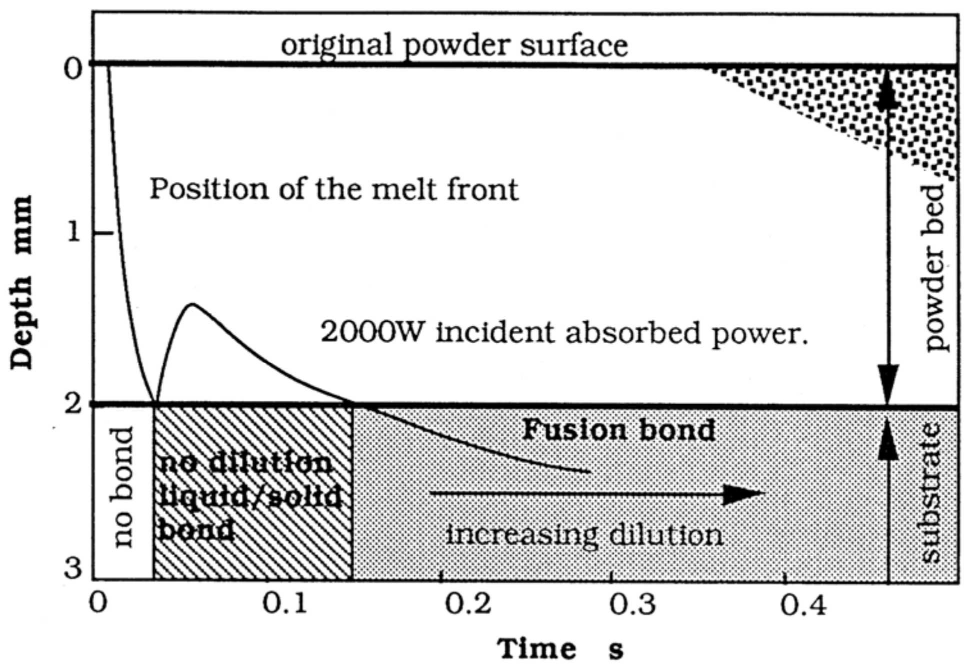
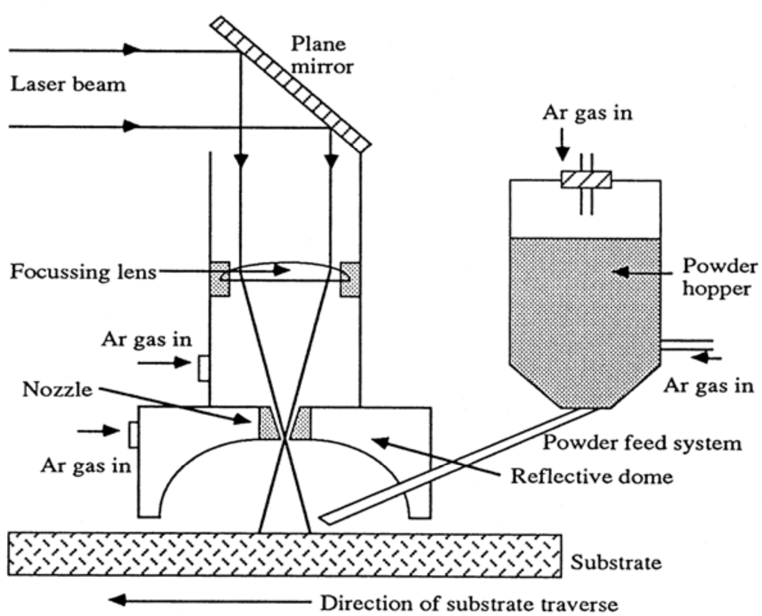


Fig. 6.26. Theoretical calculation of the position of the melt front during preplaced powder cladding (51).



Laser Cladding

- Shows big improvement when surface roughness changes
- Power sensitive to cladding thickness

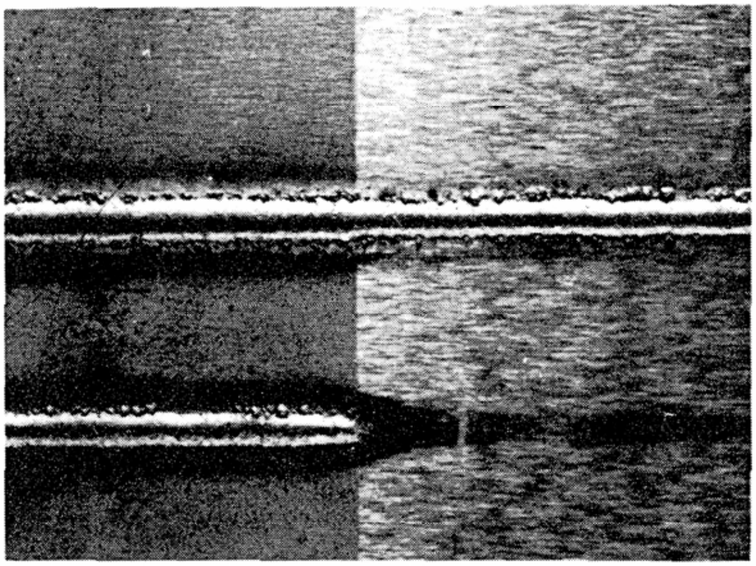
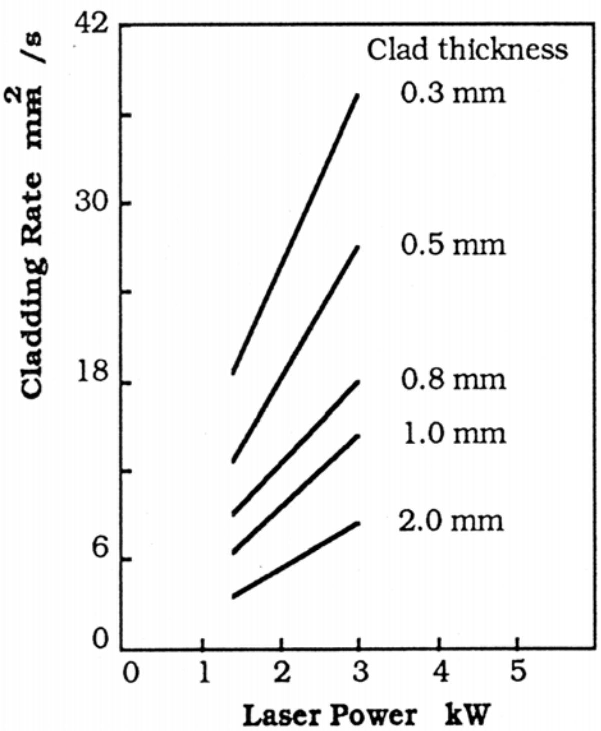
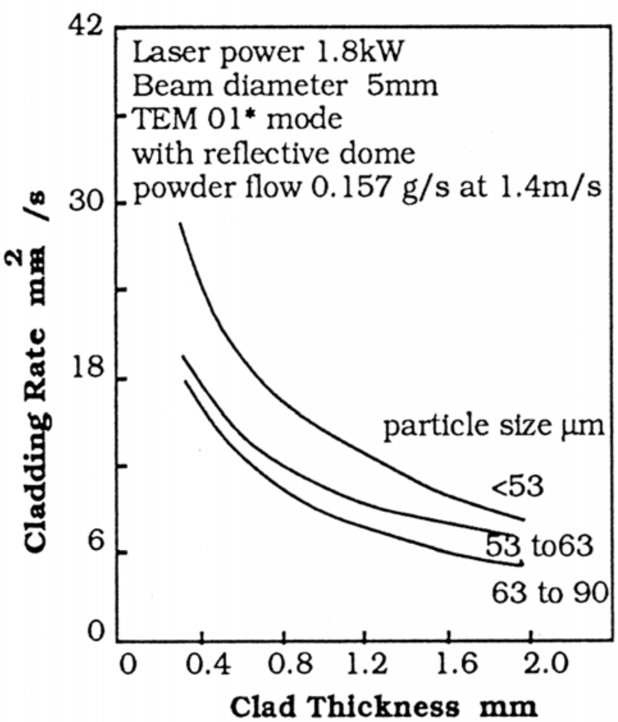


Fig. 6.28. The left side of the substrate was shot blasted. The right side had a ground finish. The upper track was made without the reflective dome; the lower track was made using the dome to recycle reflected energy (38).



(a)



(b)

Laser Welding

- Laser welding involves melting two surfaces together
- Generally two types
- Conduction weld: just melt but do not vaporize
- Keyhole weld, some vaporization and deep weld

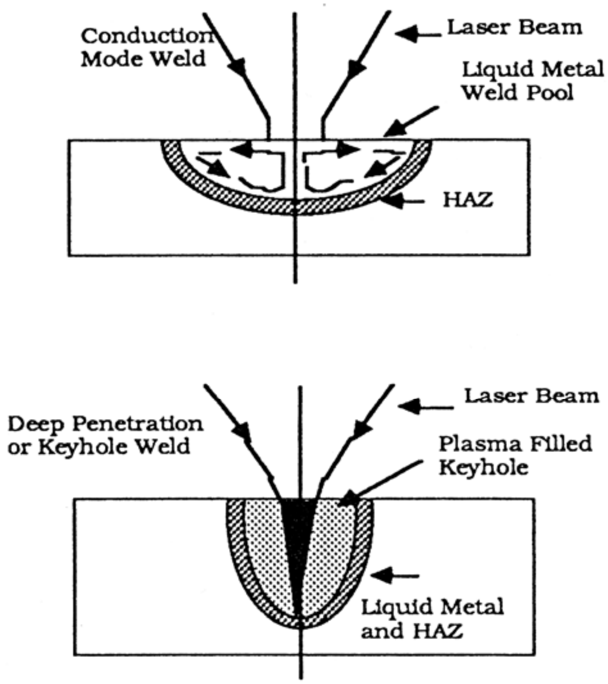


Fig. 4.6. Conduction limited and "keyhole" type welds.

Figure 13-11 Micrograph of laser weld.

Keyhole weld

- May need to melt two or more layers
- Melt pole stabilized by vapor

Table 4.3	Main Characteristics of Laser Welding
Characteristic	**Comment**
High energy density -"keyhole" type weld	Less distortion
High processing speed	Cost effective (if fully employed)
Rapid start/stop	Unlike arc processes
Welds at atmospheric pressure	Unlike EB welding
No X-rays generated	Unlike EB
No filler required (autogeneous weld)	No flux cleaning
Narrow weld	Less distortion
Relatively little Heat Affected Zone (HAZ)	Can weld near heat sensitive materials
Very accurate welding possible	Can weld thin to thick materials
Good weld bead profile	No clean up necessary
No beam wander in magnetic field	Unlike EB
Little or no contamination	Depends only on gas shrouding
Relatively little evaporation loss of volatile components	
Difficult materials can sometimes be welded	
Relatively easy to automate	General feature of laser processing
Lasers can be time shared	General feature of laser processing

Power and Laser welding types

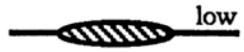
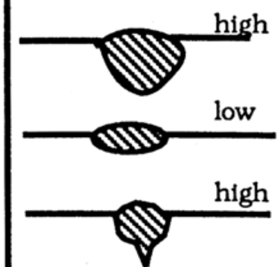
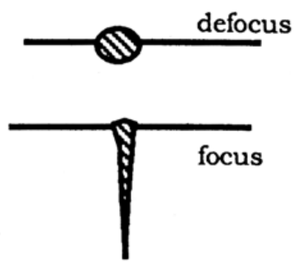
Table 4.1	Relative Power Densities of Different Welding Processes	
Process	Heat Source Intensity W/m^2	Fusion zone profile
Flux Shielded Arc Welding	$5x10^6 - 10^8$	
Gas Shielded Arc Welding	$5x10^6 - 10^8$	
Plasma	$5x10^6 - 10^{10}$	
Laser or Electron Beam	$10^{10} - 10^{12}$	

Table 4.2	Relative Joining Efficiencies of Different Welding Processes
Process	Approximate Joining Efficiency mm2/kJ
Oxy Acetylene Flame	0.2 - 0.5
Manual Metal Arc (MMA)	2 - 3
Tungsten Inert Gas (TIG)	0.8 - 2
Submerged Arc Welding (SAW)	4 - 10
High Frequency Resistance Welding	65 - 100
Electron Beam (EB)	20 - 30
Laser	15 - 25

Keyhole Welding of Lasers

- May need to melt two or more layers
- Use keyhole melt pool stabilized by vapour

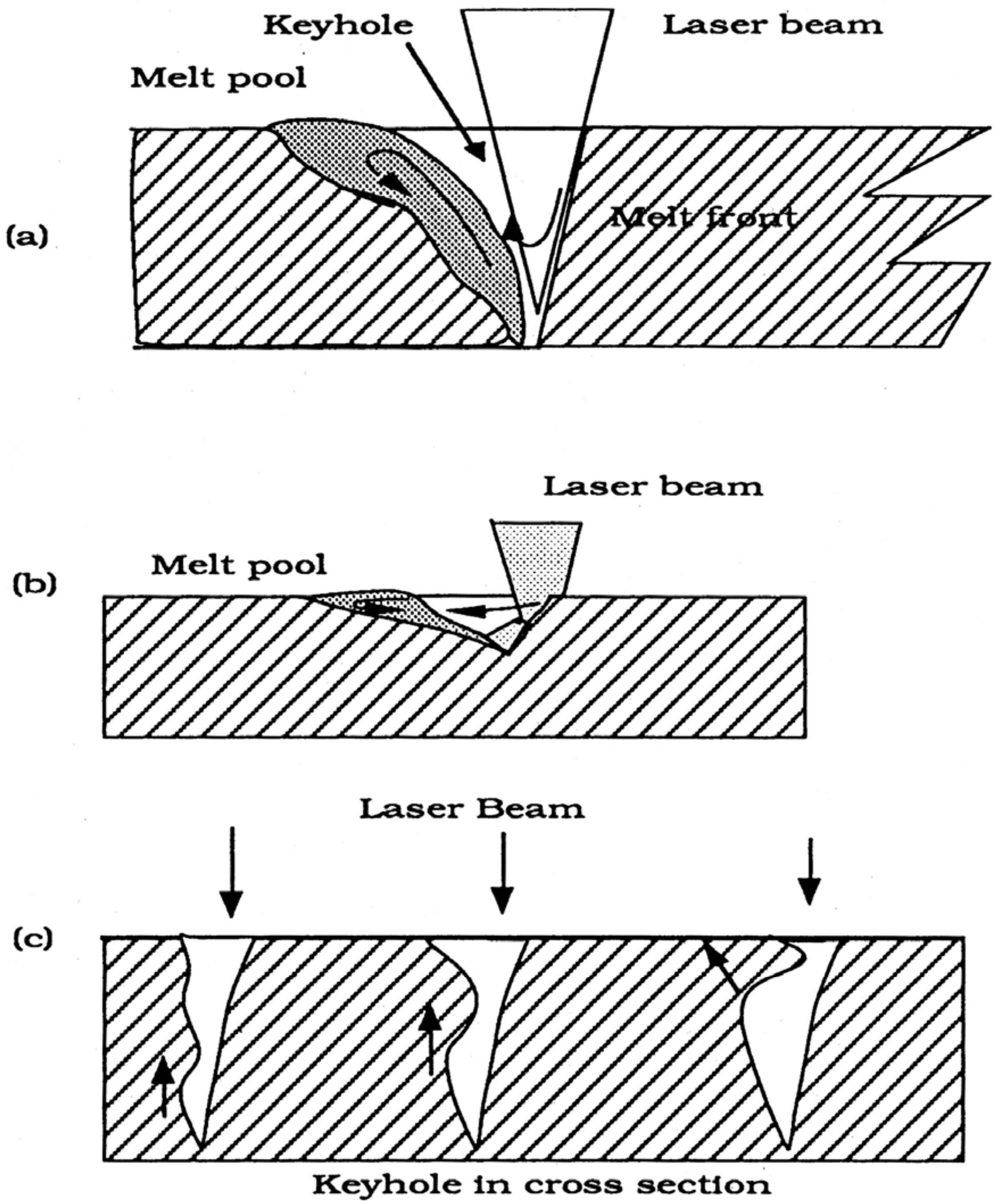


Fig. 4.7. Approximate shape and flow pattern in laser welds.

Plasma Absorption

- If get too much vapor can form plasma
- Laser ionizes vapor
- Plasma heavily adsorbs beam
- Get a pulse effect as plasma comes off

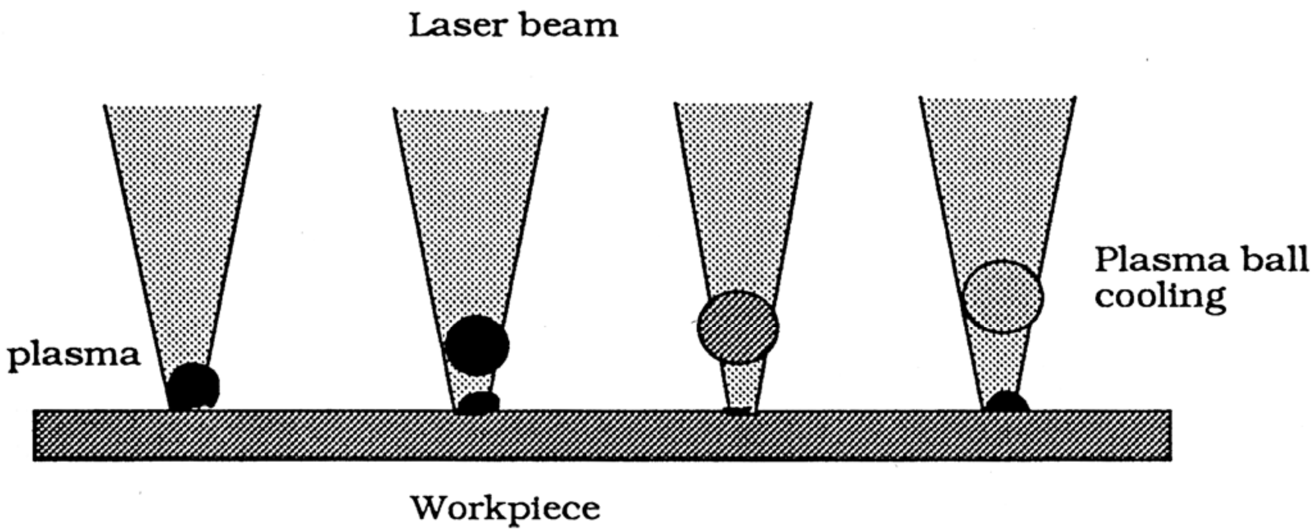


Fig. 4.9. Illustration of the blocking effect of the plasma if there is no side jet removing it.

Gas shielding

- Use inert gas flow to shield weld
- also reduces plasma effect if high flow

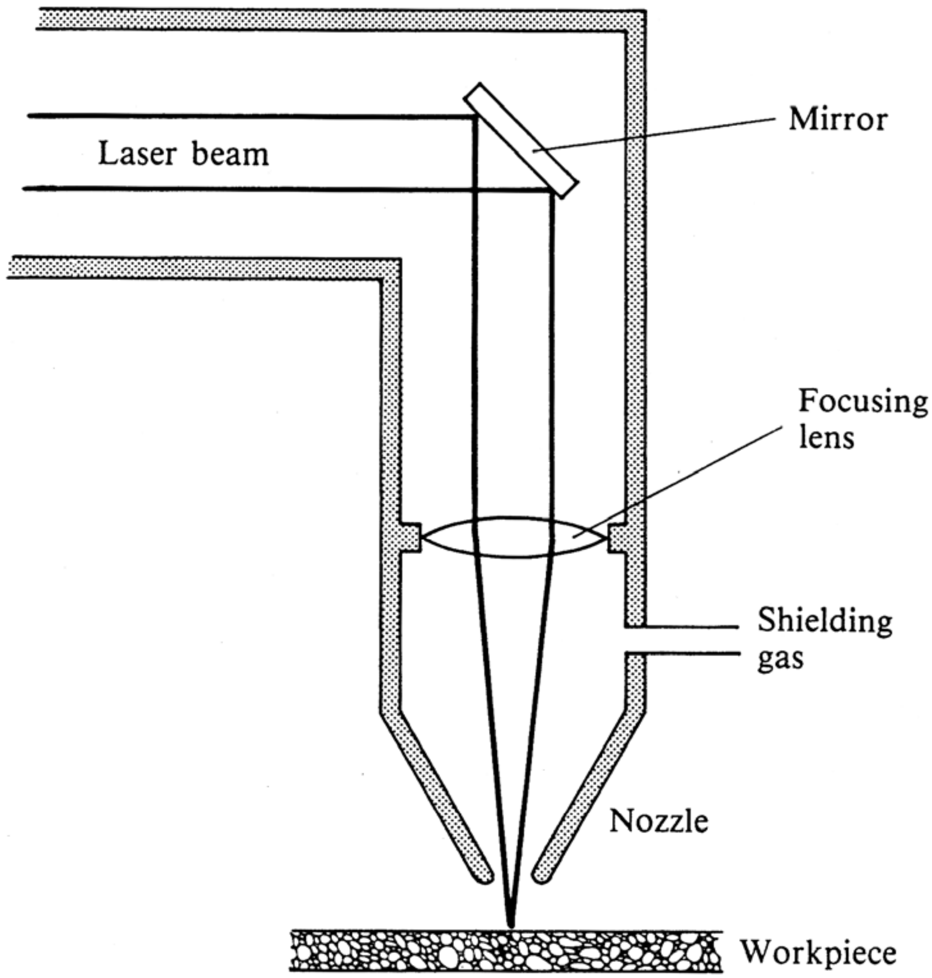
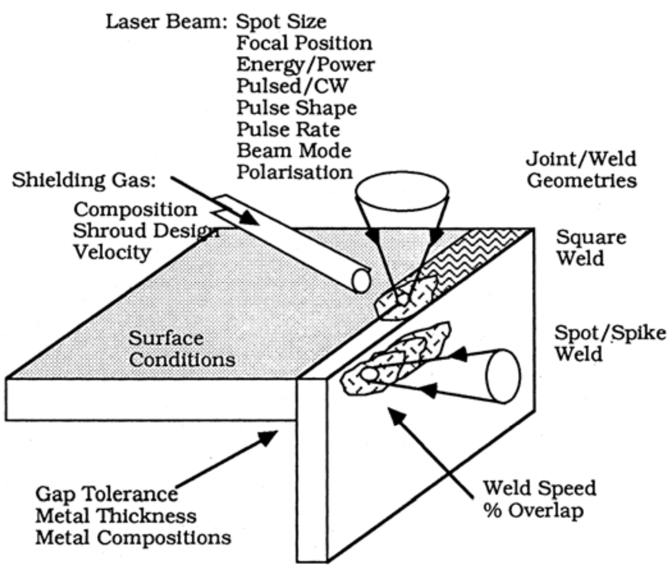
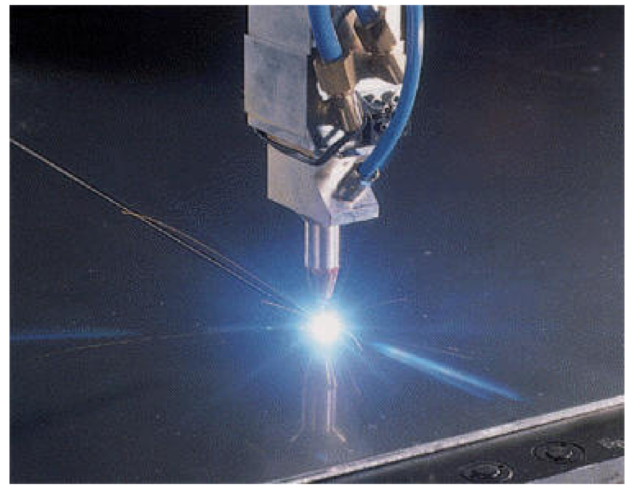


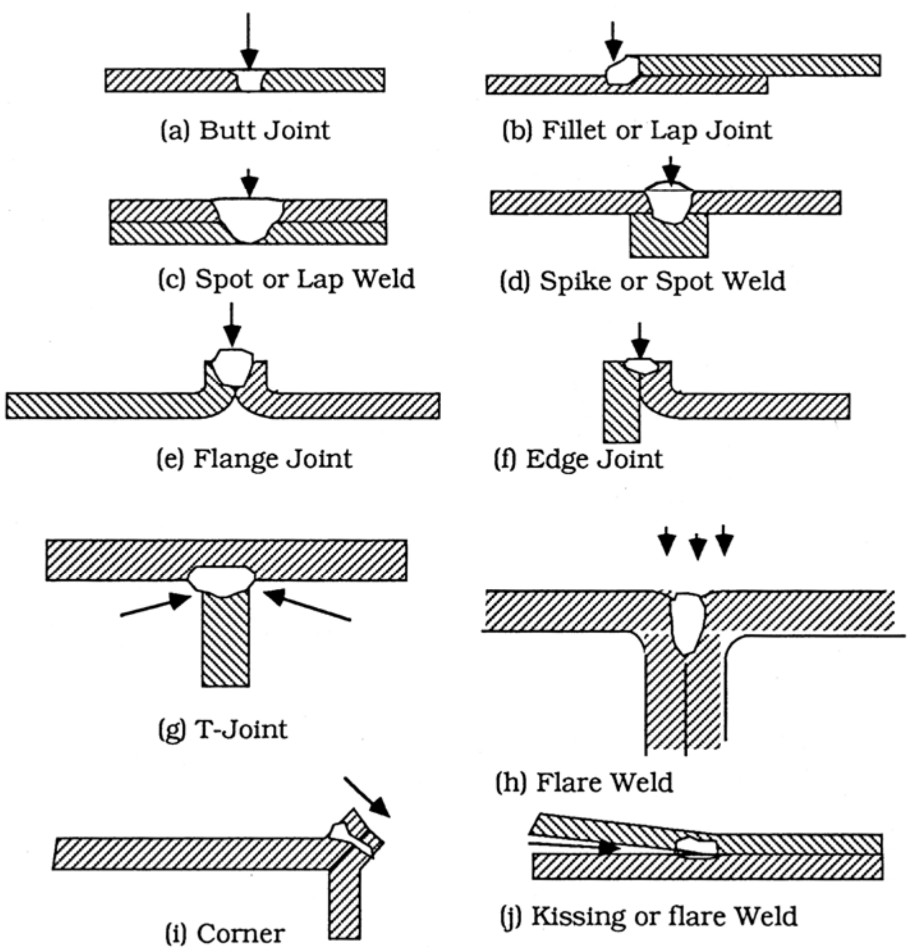
Fig. 5.11 Schematic beam focusing head design for laser welding when using a shielding gas.

Laser Welding Setup

- Many laser parameters affect welding
- Affected also by type of weld
- Gap between materials important
- All the classic weld joints can be done by laser

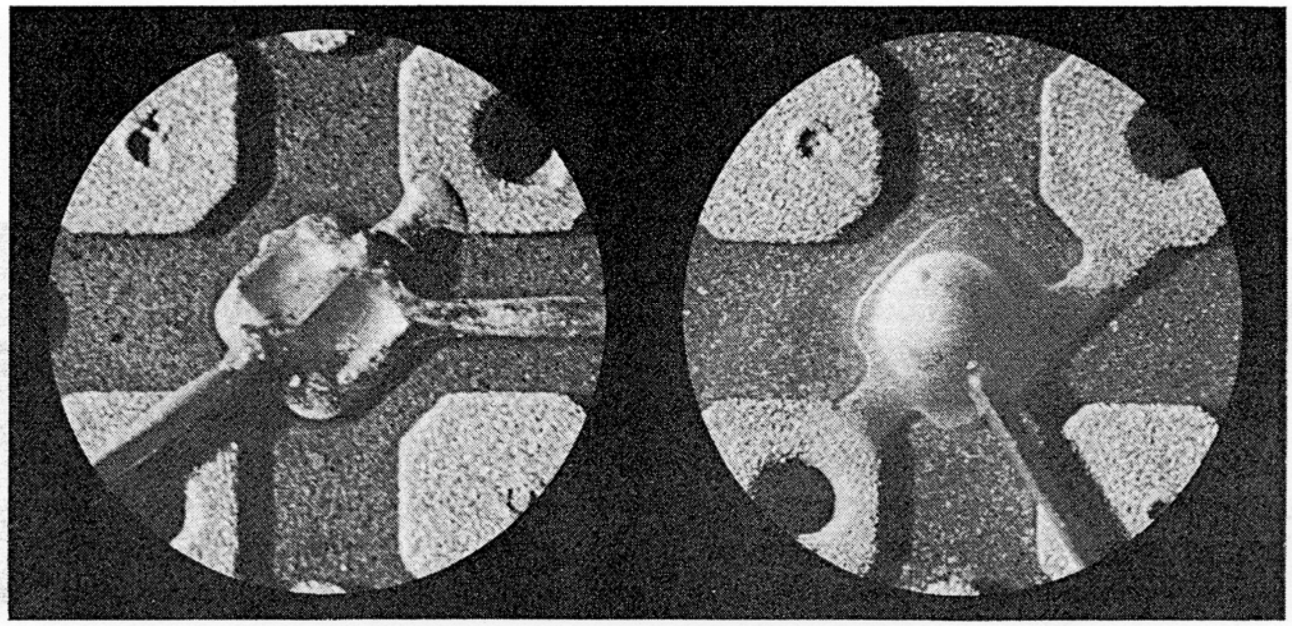






Microelectronic Applications

- Use laser to make microwelds on circuits
- Used for bonding wires rather ball bonder
- Widely used in production:
  make many welds at once
- 20% stronger and can be done closer together



(a) (b)

Fig. 5.14 A comparison between (a) a conventionally made microweld and (b) one made with a laser (CO_2). The connecting wires in fact link chips in a microcomputer. According to Amdahl the laser-made welds are cleaner, some 20% stronger and, because of increased precision, enable the components to be some 90% closer together (Courtesy Amdahl Corporation).

Laser Cutting Advantage

- Accounts for 82% of CO_2 laser work
  43% of Nd:Yag (1986)
- Cut width (Kerf) very narrow
- Edges square, not rounded
- Cut edge very smooth, can be welded directly
- Little edge burr compared to others methods
- Heat Affected Zone (HAZ) thin, hence little distortion
- Cutting done in hidden areas
- Cut depth is limited (1-2 cm) and controllable
- Very fast cut, no clamping needed
- No noise
- Wide range of materials (including brittle & fragile)

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)

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

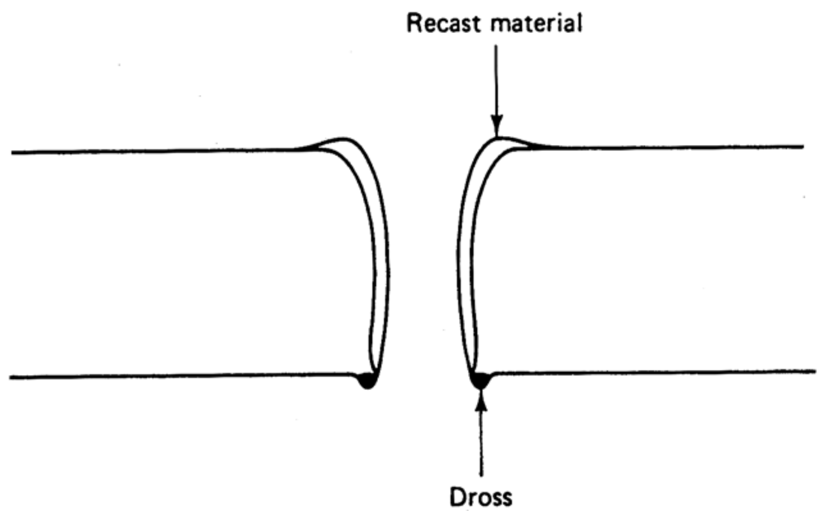


Figure 13-21 Sketch of laser-drilled hole.

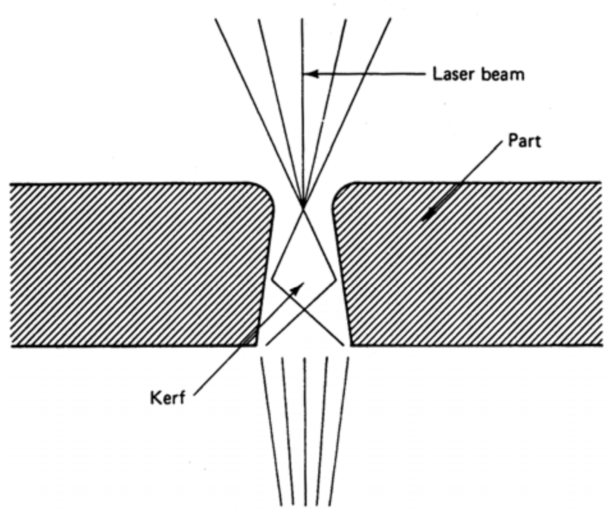


Figure 13-16 Kerf produced by laser cutting.

Vaporization Cutting Formulas

- Recall the velocity of melt front formulas

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

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

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

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

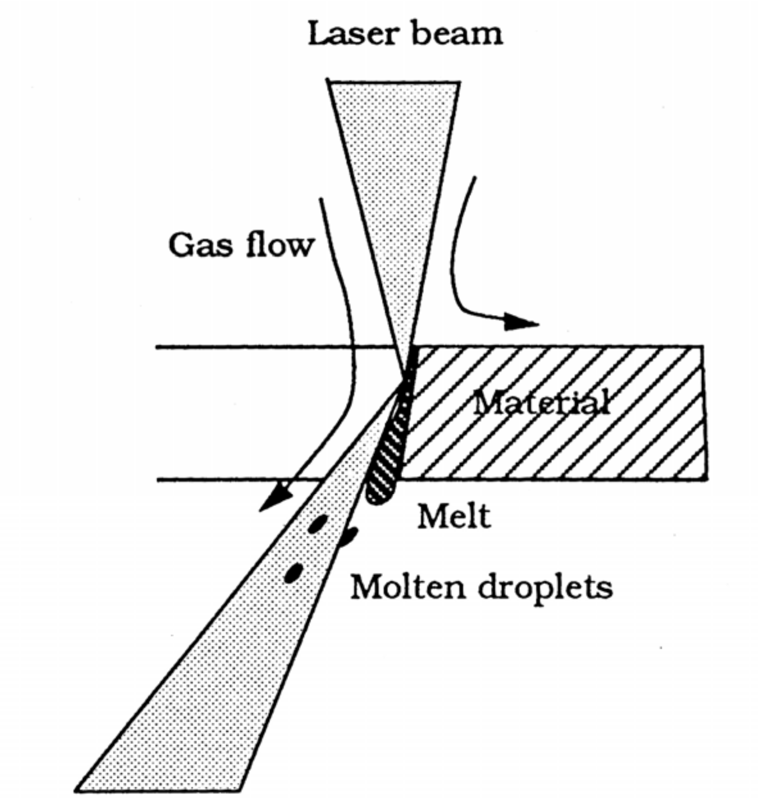


Fig. 3.7. Interactions at the cutting front.

Fusion Melting Estimates

- Can use the heat balance type relationship

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

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

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

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

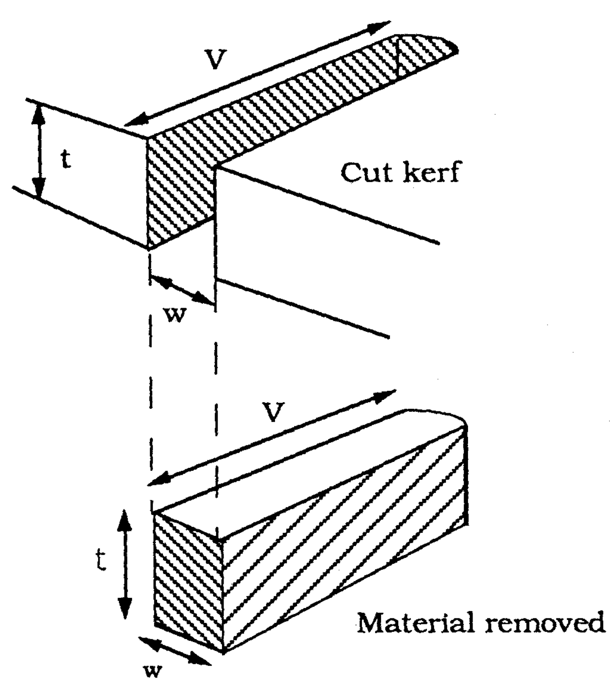


Fig. 3.3. Volume melted and removed during cutting.

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			