Laser Welding

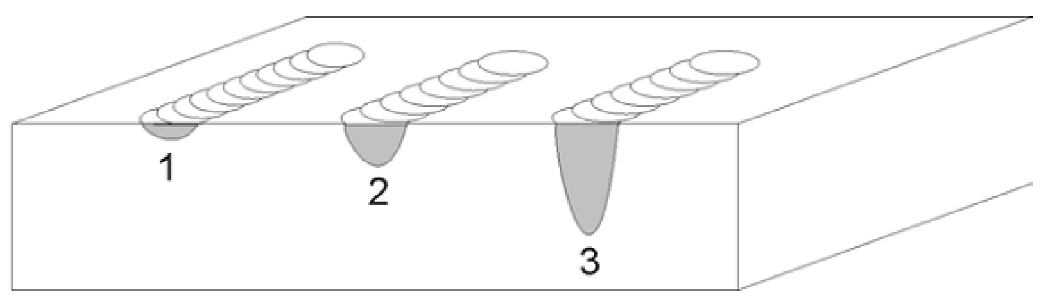
ME 677: Laser Material Processing
Instructor: Ramesh Singh

Outline

- Process Description
- Mechanisms of Laser Welding

Laser Welding-Basics

- Laser welding is a non-contact process that requires access to the weld zone from one side of the parts being welded
- The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli-seconds.
- There are typically three types of welds:
  - Conduction mode
  - Conduction/penetration mode
  - Penetration or keyhole mode.



Laser Welding-Basics

- Conduction mode welding is performed at low energy density forming a weld nugget that is shallow and wide.
- Conduction/penetration mode occurs at medium energy density, and shows more penetration than conduction mode.
- The penetration or keyhole mode welding is characterized by deep narrow welds.
  - In this mode the laser light forms a filament of vaporized material know as a "keyhole" that extends into the material and provides conduit for the laser light to be efficiently delivered into the material.
  - This direct delivery of energy into the material does not rely on conduction to achieve penetration, and so minimizes the heat into the material and reduces the heat affected zone.

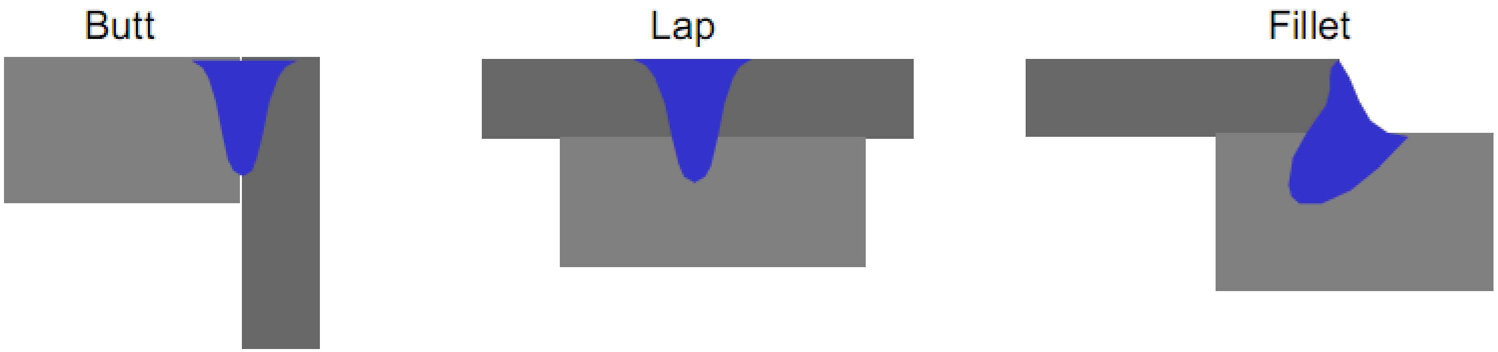
Conduction Welding

- Conduction joining describes a family of processes in which the laser beam is focused :
  - To give a power density on the order of 10^3 Wmm^{-2}
  - It fuses material to create a joint without significant vaporization.
- Conduction welding has two modes:
  - Direct heating
  - Energy transmission.

Direct Heat

- During direct heating,
  - heat flow is governed by classical thermal conduction from a surface heat source and the weld is made by melting portions of the base material
- The first conduction welds were made in the early 1960s, used low power pulsed ruby and CO_2 lasers for wire connectors
- Conduction welds can be made in a wide range of metals and alloys in the form of wires and thin sheets in various configurations using
  - CO_2, Nd:YAG and diode lasers with power levels on the order of tens of watts
  - Direct heating by a CO_2 laser beam can also be used for lap and butt welds in polymer sheets

Welding Configurations



Transmission Welding

- Transmission welding is an efficient means of joining polymers that transmit the near infrared radiation of Nd:YAG and diode lasers
- The energy is absorbed through novel interfacial absorption methods
- Composites can be joined provided that the thermal properties of the matrix and reinforcement are similar.

Transmission Welding

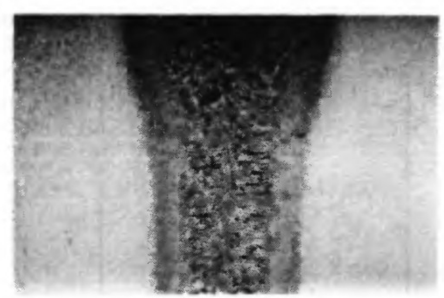
- The energy transmission mode of conduction welding is used with materials that transmit near infrared radiation, notably polymers
- An absorbing ink is placed at the interface of a lap joint. The ink absorbs the laser beam energy, which is conducted into a limited thickness of surrounding material to form a molten interfacial film that solidifies as the welded joint
- Thick section lap joints can be made without melting the outer surfaces of the joint
- Butt welds can be made by directing the energy towards the joint line at an angle through material at one side of the joint, or from one end if the material is highly transmissive.

Laser Soldering and Brazing

- In the laser soldering and brazing processes, the beam is used to melt a filler addition, which wets the edges of the joint without melting the base material.
- Laser soldering started to gain popularity in the early 1980s for joining the leads of electronic components through holes in printed circuit boards. The process parameters are determined by the material properties.

Penetration Laser Welding

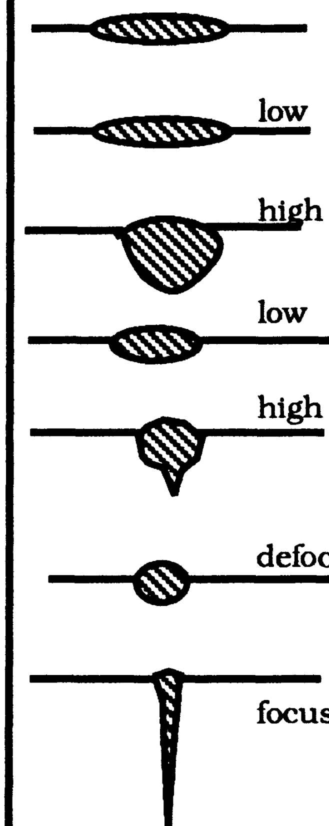
- At high power densities all materials will evaporate if the energy can be absorbed. Thus, when welding in this way a hole is usually formed by evaporation
- This "hole" is then traversed through the material with the molten walls sealing up behind it
- The result is what is known as a "keyhole weld. This is characterized by its parallel sided fusion zone and narrow width



Laser Welding Efficiency

- A term to define this concept of efficiency is known as the "joining efficiency"
- The joining efficiency is not a true efficiency in that it has units of (mm^2joined /kJ supplied)
  - Efficiency=V.t/P (the reciprocal of the specific energy in cutting) where V = traverse speed, mm/s; t = thickness welded, mm; P = incident power, kW.

Comparison

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

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Joining Efficiency

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

Joining Efficiency

- The higher the value of the joining efficiency the less energy is spent in unnecessary heating
  - Lower heat affected zone (HAZ)
  - Lower distortion
- Resistance welding is most efficient in this respect because the fusion and HAZ energy is only generated at the high resistance interface to be welded
- Laser and electron beam also have good efficiencies and high power densities

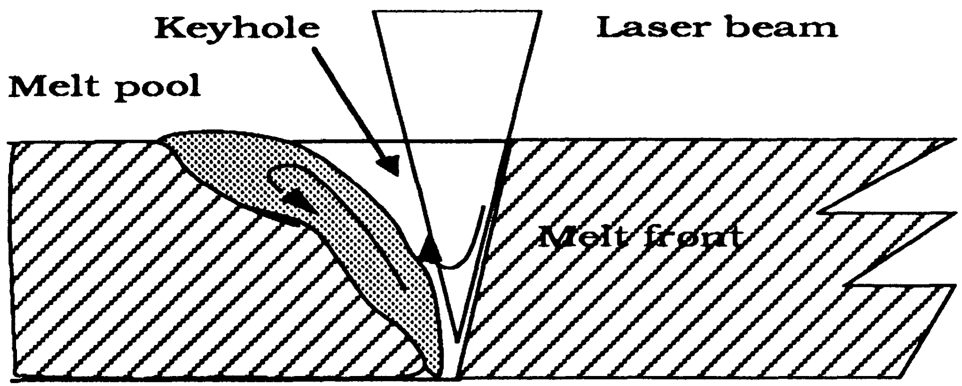
Mechanism

- In "keyhole" welding in which there is sufficient energy/unit length to cause evaporation and hence a hole in the melt pool
- This hole is stabilized by the pressure from the vapor being generated
- In some high powered plasma welds there is an apparent hole, but this is mainly due to gas pressures from the plasma or cathode jet rather than from evaporation
- The "keyhole" behaves like an optical black body in that the radiation enters the hole and is subject to multiple reflections before being able to escape
- Nearly all the beam energy is absorbed once the keyhole is formed
- This can be both a blessing and a nuisance when welding high reflectivity materials
  - Reasonably power is needed to start the "keyhole"
  - as soon as the key hole has started then the absorptivity jumps from 3% to 98% which could potentially damage the weld structure

Mechanism

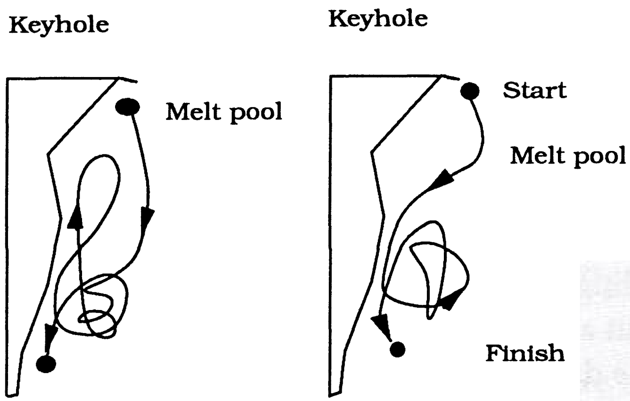
- Two principle areas of interest
  - Flow structures which directly affects the wave formation in the weld pool and frozen bead geometry
  - Absorption mechanism
    - Fresnel absorption (absorption during reflection from surface)
    - Inverse Bremmstrahlung leading to plasma re-radiation
  - It affects
    - Flow stability
    - Entrapped porosity

Keyhole



(a)

Flow Pattern in Pool



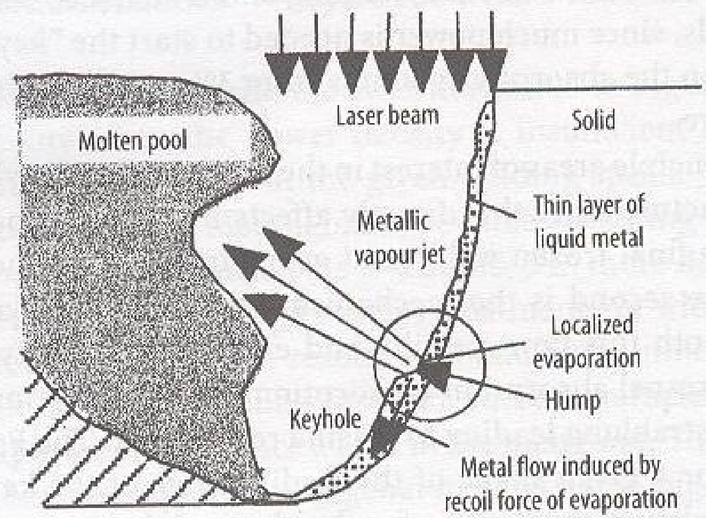


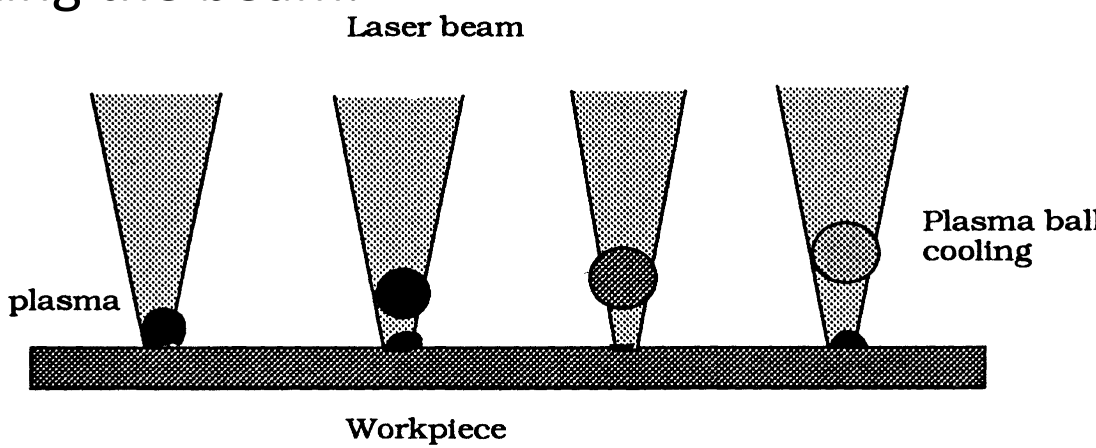
Figure 4.6 Side view illustration of the keyhole shape and beam absorption.[3]

Keyhole Shape and Absorption

- The keyhole walls are fluctuating with flow velocities up to 0.4 m/s
- The thin melt on the leading edge flows downward with fluctuations as in a wave
- Any hump on the surface will cause localized higher absorption and an explosion due to instantaneous evaporation
- This sends a vapor jet through the rear molten pool causing stirring and bubble entrapment
- The usual flow in molten pool has vortex

Plasma Blocking

- The keyhole contains considerable metal vapor, which is partially absorbing and hence capable of forming a plasma on further heating
- This hot plasma vapor emerging from the keyhole may ionize the shroud gas.
- Ionized gas has free electrons and is thus capable of absorbing or even blocking the beam.

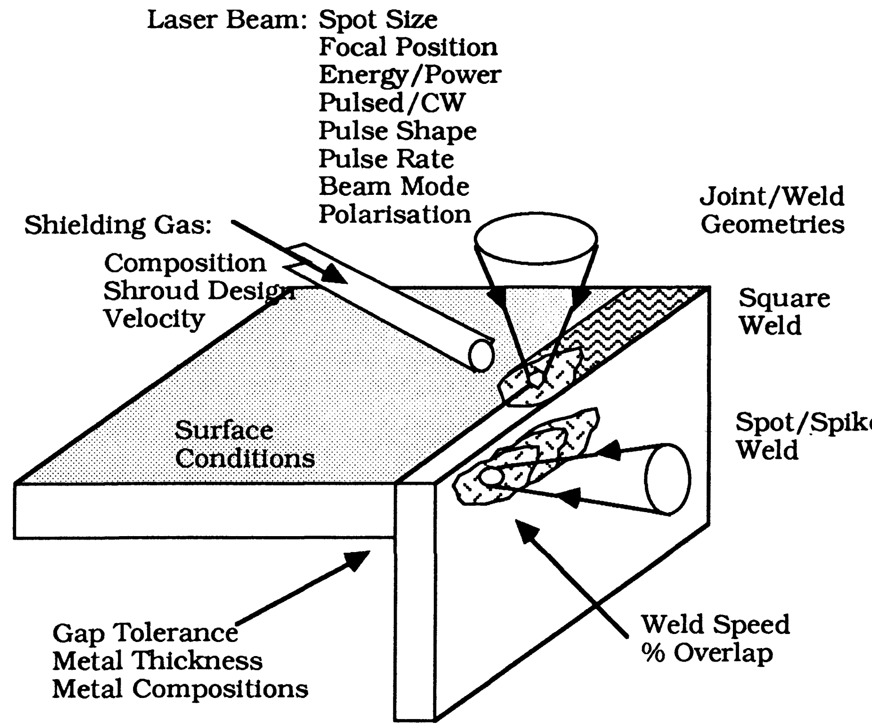


Plasma Blocking

- If there is no gas to blow the plasma away the plasma is formed intermittently due to the "blocking" of the beam
- Mechanism is debatable:
  - whether plasma is opaque enough at the temperatures measured to block the beam
  - or the effect just noted is due to the plasma scattering the beam by variations in refractive index

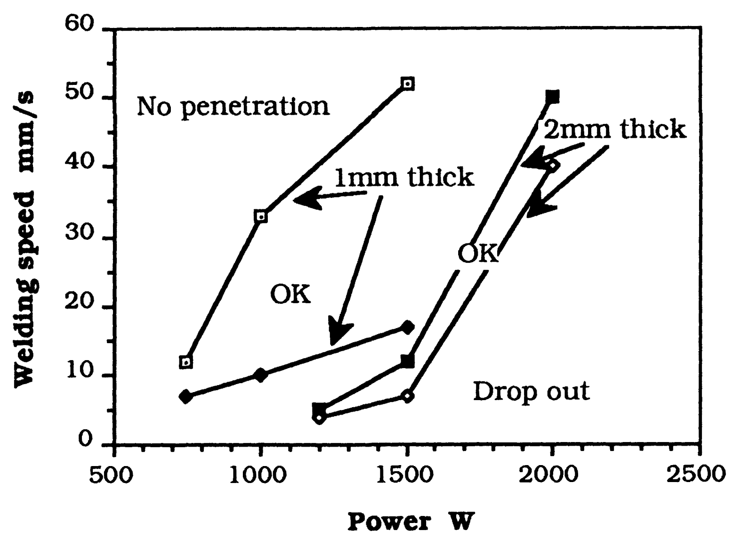
Operating Characteristics

- Beam Properties:
  - Power, pulsed or continuous
  - Spot size and mode
  - Polarisation
  - Wavelength
- Transport Properties:
  - Speed
  - Focal position
  - Joint geometries
  - Gap tolerance
- Shroud Gas Properties:
  - Composition
  - Shroud design
  - Pressure/velocity
- Material Properties:
  - Composition
  - Surface condition



Effect of Continuous Power

- There are two main problems in welding:
  - lack of penetration
  - or the inverse, "drop out".
- These are the boundaries for a good weld for a given power
- The maximum welding speed for a given thickness rises with increase in power
- The fall off shown at the higher power levels of 2kW could be attributed to the poorer mode structure given by most lasers when working at their peak power



Welding speed vs power for Ti-6Al-4V

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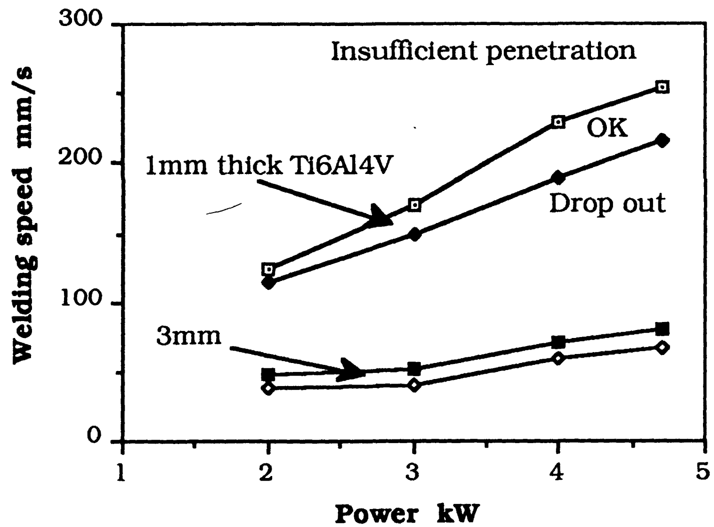
Effect of Continuous Power

- For higher powers the operating window is larger.



Laser Welding Line Solution

$$T = \frac{Q_1}{4\pi K}\int_0^t \mathrm{Exp}\left[-\frac{(x-x')^2+(y-y')^2}{4\alpha(t-t')}\right]\frac{dt'}{(t-t')}$$

```
Integrate[1/(4 π k (t - t1)) Exp[-((x - v t1)^2 + y^2)/(4 α (t - t1))], {t1, 0, t}]
```

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In[9]:= Integrate[Ql/(4 π k t) Exp[-((x + v t)^2 + y^2)/(4 α t)], {t, 0, ∞}]
```

$$\frac{1}{4 k \pi} Ql\ \mathrm{If}\left[\mathrm{Re}\left[\frac{v^2}{\alpha}\right] > 0\ \&\&\ \mathrm{Re}\left[\frac{x^2+y^2}{\alpha}\right] > 0,\ 2 e^{-\frac{v x}{2\alpha}}\ \mathrm{BesselK}\left[0, \frac{\sqrt{\frac{v^2}{\alpha}}}{2\sqrt{\frac{\alpha}{x^2+y^2}}}\right],\right.$$

```
Integrate[E^(-((t v + x)^2 + y^2)/(4 t α))/t, {t, 0, ∞}, Assumptions -> Re[v^2/α] > 0 && Re[(x^2 + y^2)/α] > 0]
```

Final Solution

$$T = T0 + \frac{1}{4 k \pi} Ql\, e^{-\frac{v x}{2 \alpha}} \, \mathrm{BesselK}\left[0, \frac{\sqrt{\frac{v^2}{\alpha}}}{2\sqrt{\frac{\alpha}{x^2 + y^2}}}\right] \approx \frac{Ql}{2 k \pi} e^{-\frac{v x}{2 \alpha}} \, \mathrm{BesselK}\left[0, \frac{V R}{2 \alpha}\right]$$

Boundary conditions

$$\frac{\partial T}{\partial x} = 0 \text{ as } x \to \infty; \quad \frac{\partial T}{\partial y} = 0 \text{ as } y \to \infty; \quad \frac{\partial T}{\partial z} = 0 \qquad \text{and } -\frac{\partial T}{\partial R} 2\pi R k g \to Q \text{ as } R \to 0$$

Asymptotic solutions for cooling can be found for the temperature

$$\frac{\partial T}{\partial t} = 2\pi k \rho C \left[\frac{vg}{Q}\right]^2 (T - T_0)^3$$

The non dimensional plots

$Y = 0.483X$

$Y = 2vR/\alpha = vw/\alpha$

$R = distance$ from heat source;

w = thickness=2 R

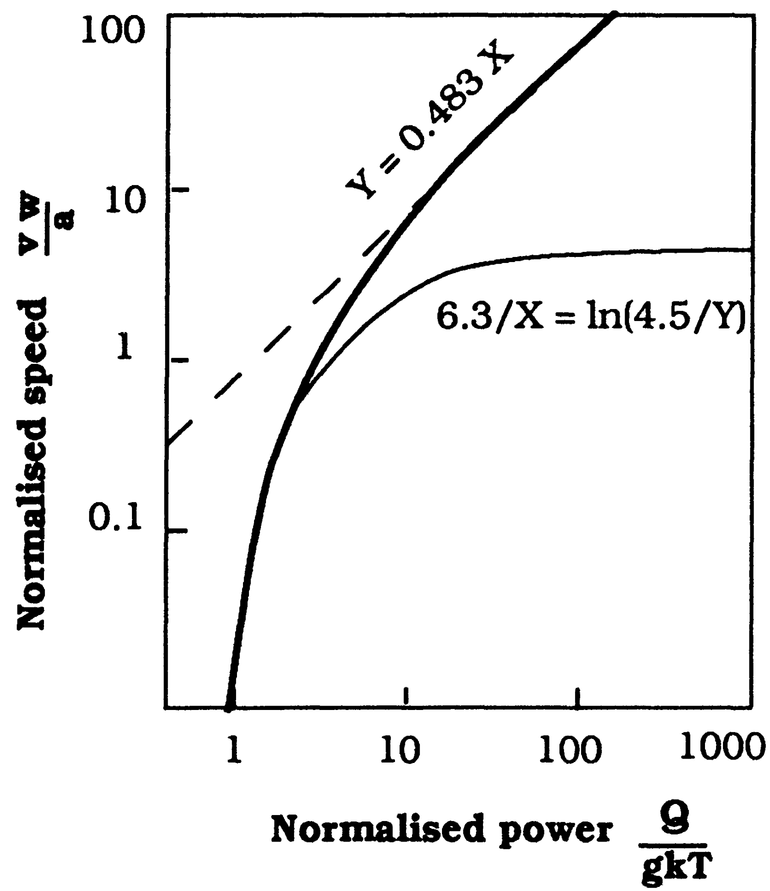
$X = Power/KgT$

$\alpha = k/\rho C$

$Power = P(1-r)$

$0.483(P(1-r)/KgT) = vw/\alpha$

$0.483P(1-r) = vwg\rho CT$



Extent of HAZ

- Extent of heat affected zone is function of welding speed
  - A good estimate is when Fourier number =1

$$F = \frac{\alpha . t}{x^2} = 1$$

$$x = \sqrt{\alpha . t} = \sqrt{\alpha . \frac{D}{v}}$$

$$HAZ \propto P$$

$$HAZ \propto \sqrt{\alpha . \frac{D}{v}}$$

where

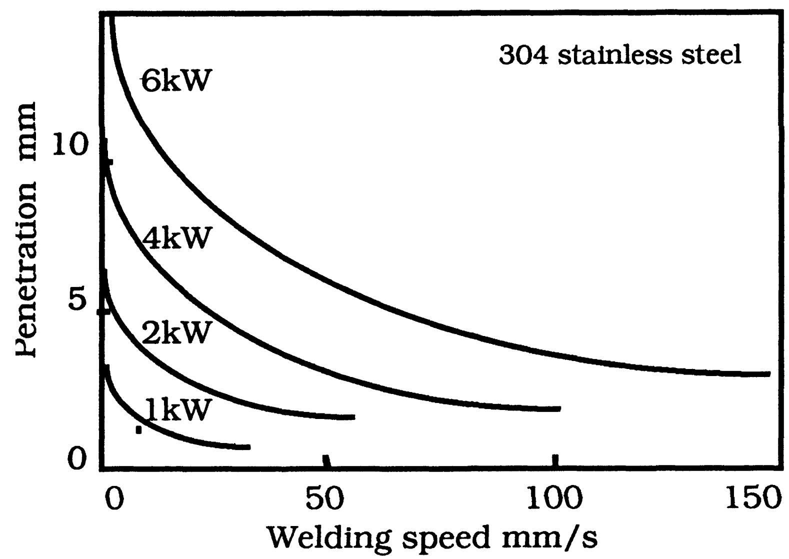
$x = extent\_of\_HAZ$

$\alpha = thermal\_diffusivity$

$t = interaction\_time$

$D = effective\_beam\_dia$

$v = welding\_speed$

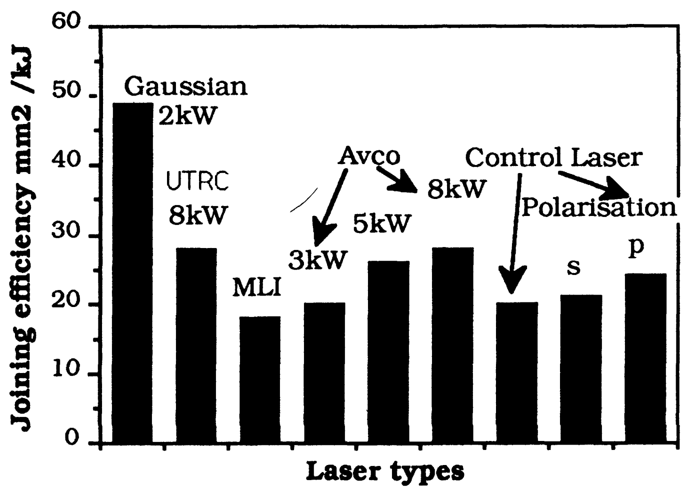


Pulsed Power

- The use of pulsed power allows two more variables:
  - pulse repetition frequency (PRF),
  - % overlap to be considered.
- The welding speed is decided by :
  - spot size x PRF x (1-% overlap).
- Speed is independent of power.
- Penetration is a function of power and likewise the weld bead quality.
  - Too much power causes vaporization and material ejection as in drilling
  - Thus for welding the pulse is usually longer than for drilling and shaped to have a smaller initial peak.

Spot Size and Mode

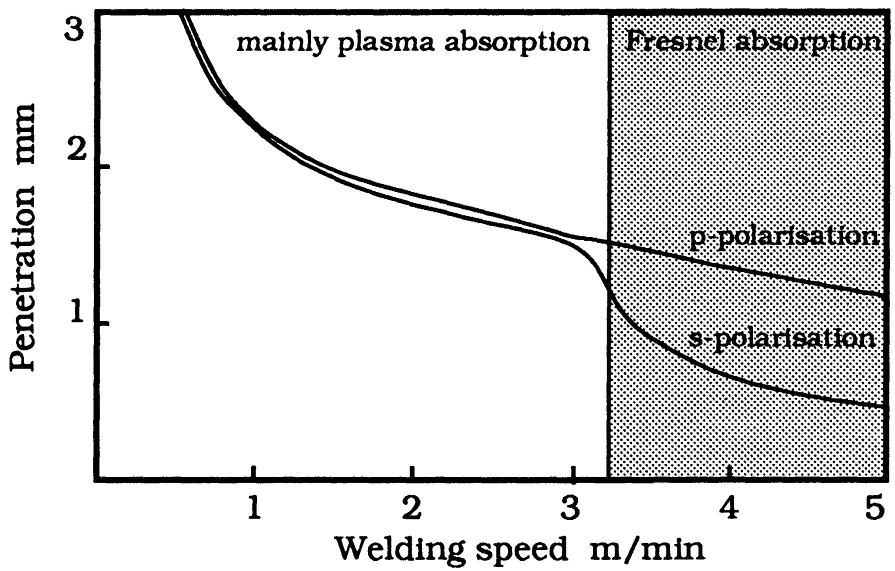
- The joining efficiency is greatly affected by the mode as illustrated by various researchers
- True TEM00 modes provide highest joining efficiencies



Polarization

- Polarization should have no effect on laser welding since the beam is absorbed inside a keyhole and hence it should be absorbed regardless of the plane of polarization unlike cutting
- Some second order events have been noted by Beyer et al. which show the effect of polarization
  - variation in penetration
  - The weld fusion zones are also wider for the case of s-polarisation (perpendicular to the plane of incidence)
- This phenomenon is due to two absorption mechanisms.
  - At slow speeds the plasma absorption dominates and the beam is absorbed by inverse Bremsstrahlung effects in the keyhole generating a plasma
  - As the speed increases,the Fresnel absorption (absorption by reflection on front face) gains importance due to the cooler plasma being less absorbing.

Polarization



Wavelength

- Due to the high absorptivity within the "keyhole" there is little operational difference when welding with long or short wavelengths
- In welding with a conduction limited weld then the surface reflectivity becomes extremely important:
  - The lower reflectivity with the shorter wavelengths gives a distinct advantage to Excimer, YAG or CO lasers over the CO_2 laser.
- Shorter wavelengths do not get absorbed quickly by plasma therefore they are more useful in welding

$$\alpha = n^2 \lambda^2 T^{3/2}$$

Speed

- The effect of speed on the welding process is principally described by the
  - overall heat balance equation due to time for conduction
  - Additional effects
    - Weld bead
    - Shrouding high speed welds

Speed

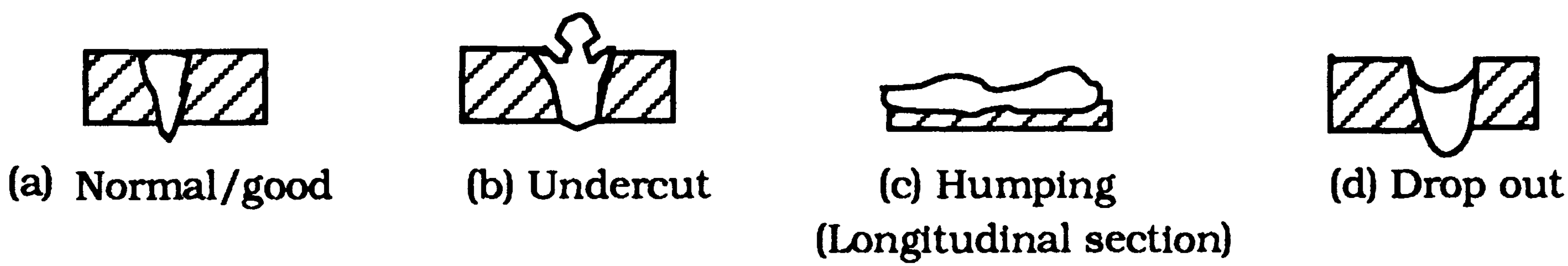
- As the speed increases the pool flow pattern and size changes
- At slow speeds
  - the pool is large and wide and may result in drop out
  - the ferrostatic head is too large for the surface tension to keep the pool in place and so it drops out of the weld leaving a hole or depression.
- At higher speeds
  - the strong flow towards the centre of the weld in the wake of the keyhole has no time to redistribute and is hence frozen as an undercut at the sides of the weld
- If the power is high enough and the pool large enough then the same undercut proceeds and edge freezing occurs leaving a slight undercut but the thread of the pool in the centre

Speed

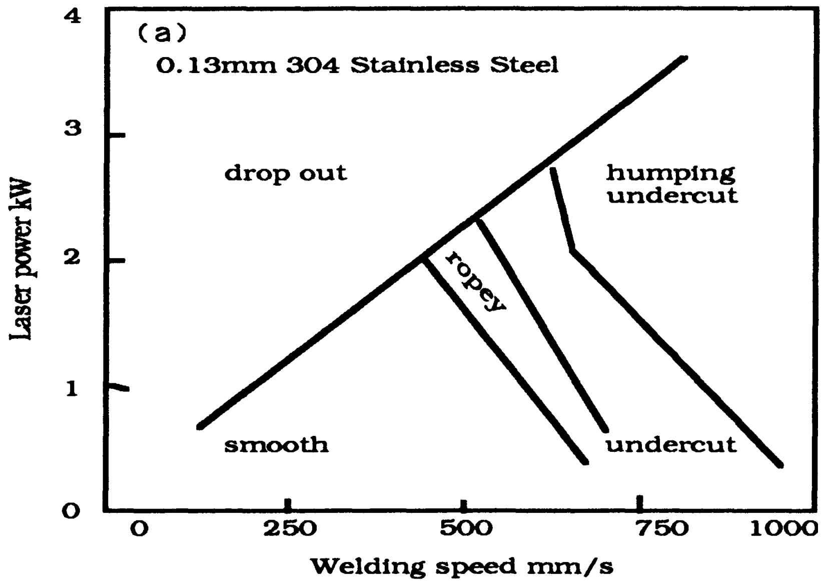
- The center has a pressure which is a function of the surface tension and the curvature

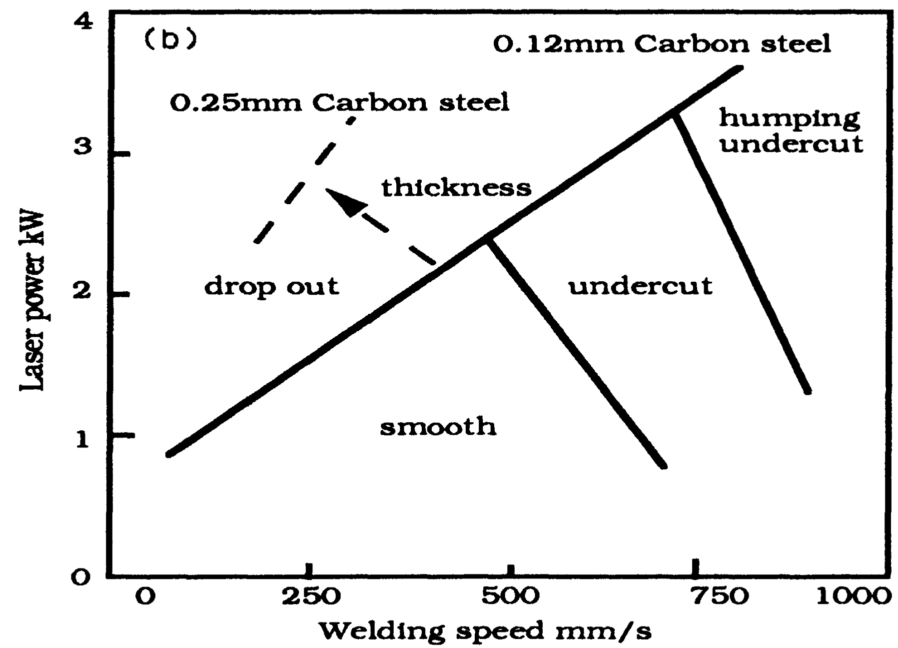
$$p = \gamma / r^2$$

- This leads to pressure instability causing the "pinch" effect
- The regions of high curvature flow to regions of lower curvature resulting in large humps



Map of speed Vs. Weld bead





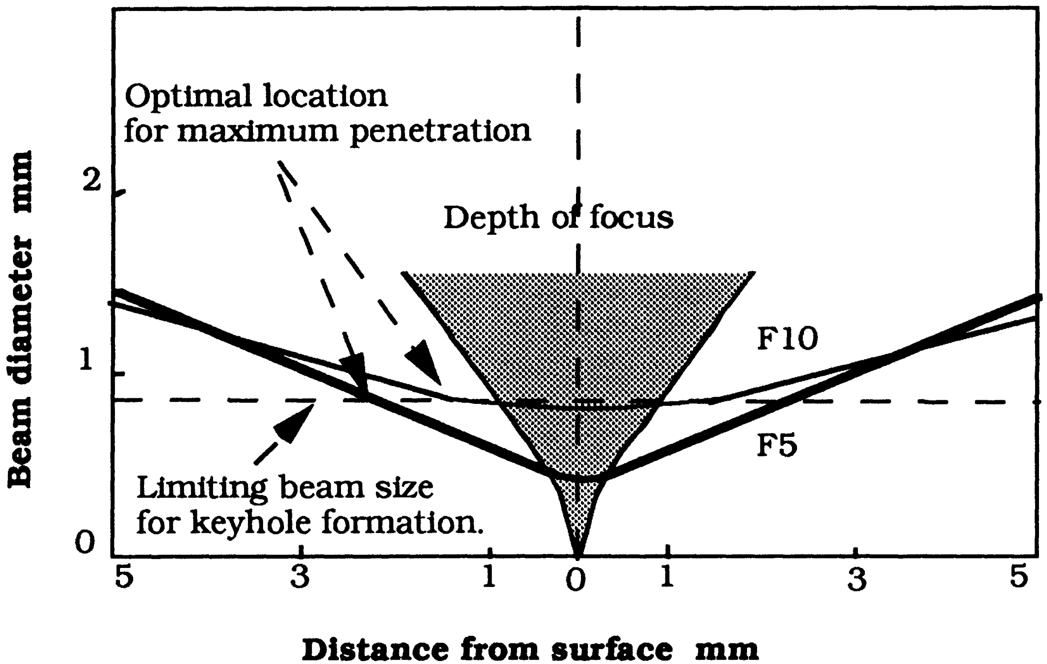
Focal Position

- the focal point should be located within the workpiece to a depth of around 1mm for maximum penetration.
- The power density should be sufficient to generate a "keyhole"
- The requisite power should stay in the keyhole to increase the penetration.

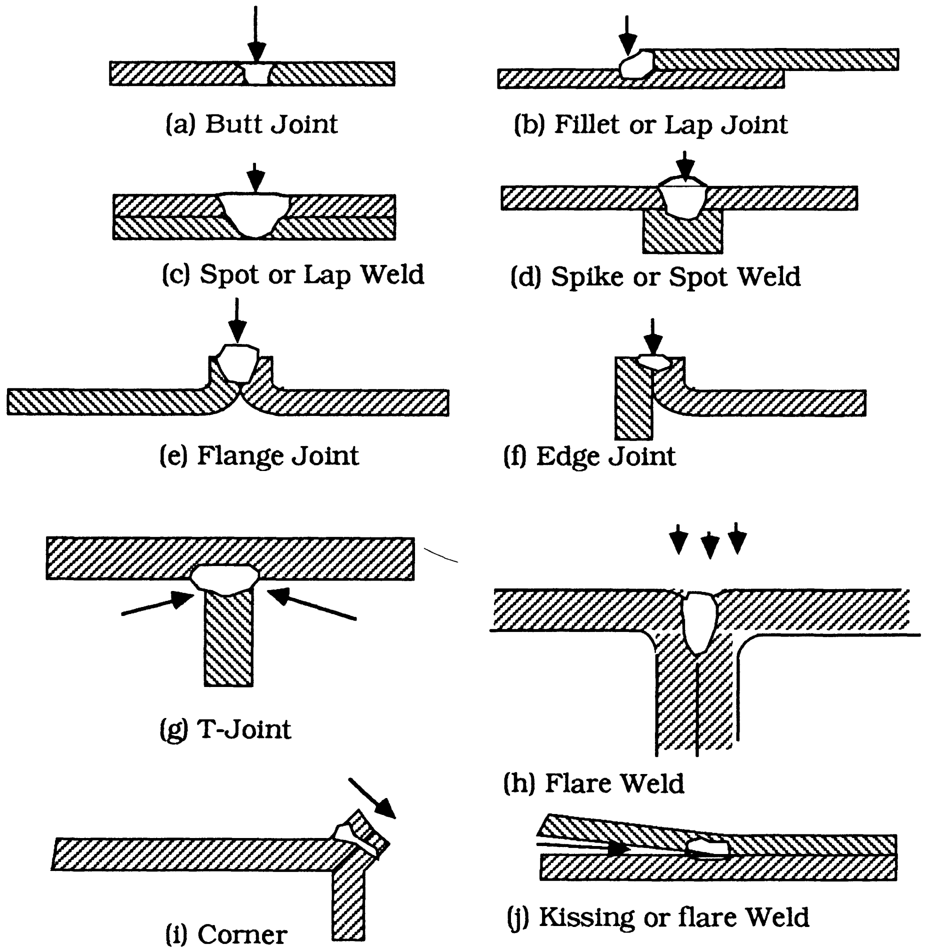
$$z_f = \pm 2.56 F^2 M^2 \lambda$$

$$d_{\min} = 2.4 F M^2 \lambda$$

Depth of Penetration



Laser Weld Geometry



Effect of Gap

- In butt joints the gap must be small enough that the beam can not pass straight through the joint
- The gap should be smaller than half the beam diameter (<200 μm)
- For welds where there is a large gap the beam is sometimes rotated by rotating the lens off axis from the beam
- There is a chance of some drop out or a underfill in the weld
- It could be corrected by adding filler material as a wire or powder
- The welds which do not require filler material are called "autogenous"

Gap Analysis

For butt welds,

$$A\beta\Delta T w t_p = g t_p$$

$$g = A\beta\Delta T w$$

where:

β = Coefficient of thermal expansion.

ΔT= Temperature change, approx: melting point

w = Weld width

t_p= Sheet thickness

g= Gap width

A= Constant

B= Constant

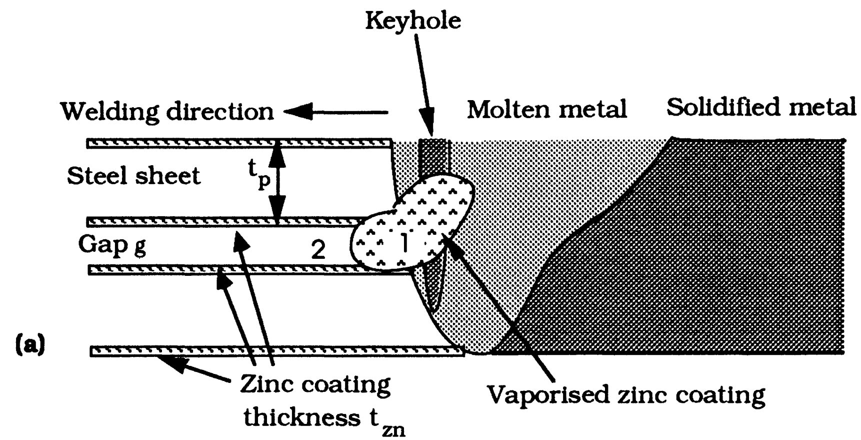
Gap Analysis

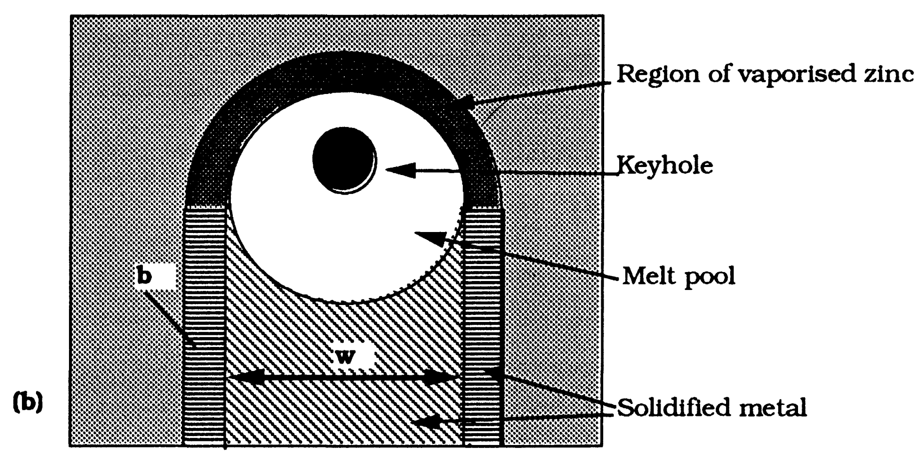
- For lap welds (gap between plates):

$$B\beta\Delta T w 2t_p = gw$$

$$g = B\beta\Delta T 2t_p$$

Gap Analysis- Volatile Material





Volatile Material

- Volume generated at interface

$$(w + 2b)Vt_{zn}\rho_s)/\rho_v$$

- The vapor escapes as it is formed around the melt pool at a velocity .The volume escaping through the lap

$$= \frac{v_2\pi(w + 2b)g}{2}$$

- The maximum velocity

$$v_2 = \frac{2Vt_{zn}\rho_s}{\pi g\rho_v}$$

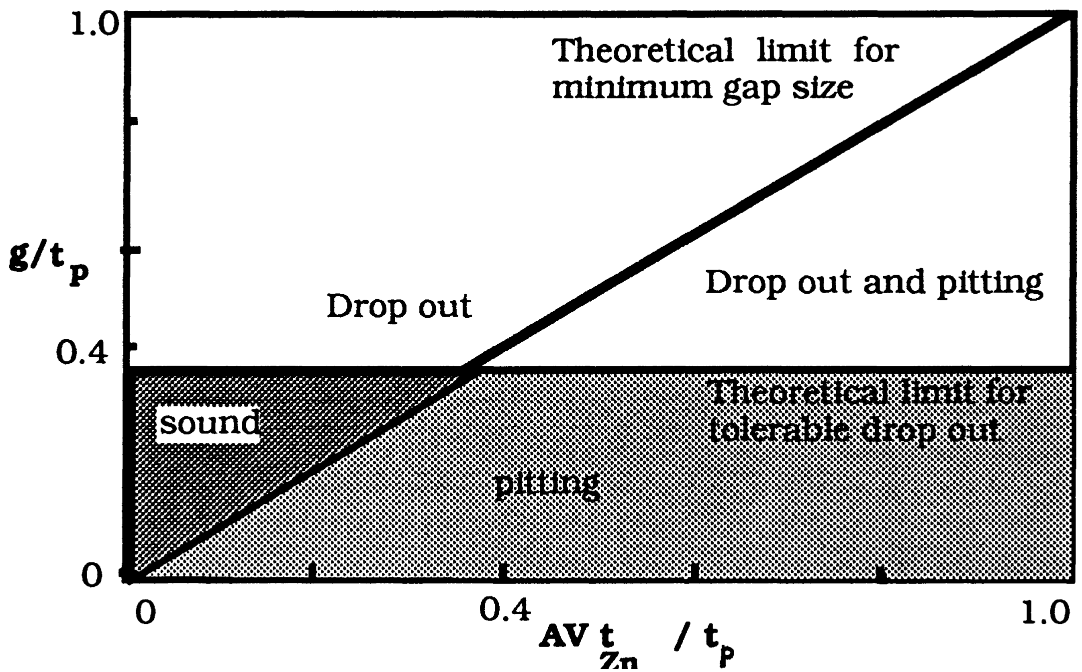
Escape Velocity

- The escape velocity can only be achieved with an acceleration pressure.
- This pressure must not exceed the ferrostatic head in the weld pool

$$v_2 = \sqrt{\frac{2\Delta P_{12}}{\rho_v}} = \sqrt{\frac{2\rho_L g t_p}{\rho_v}}$$

- Find g

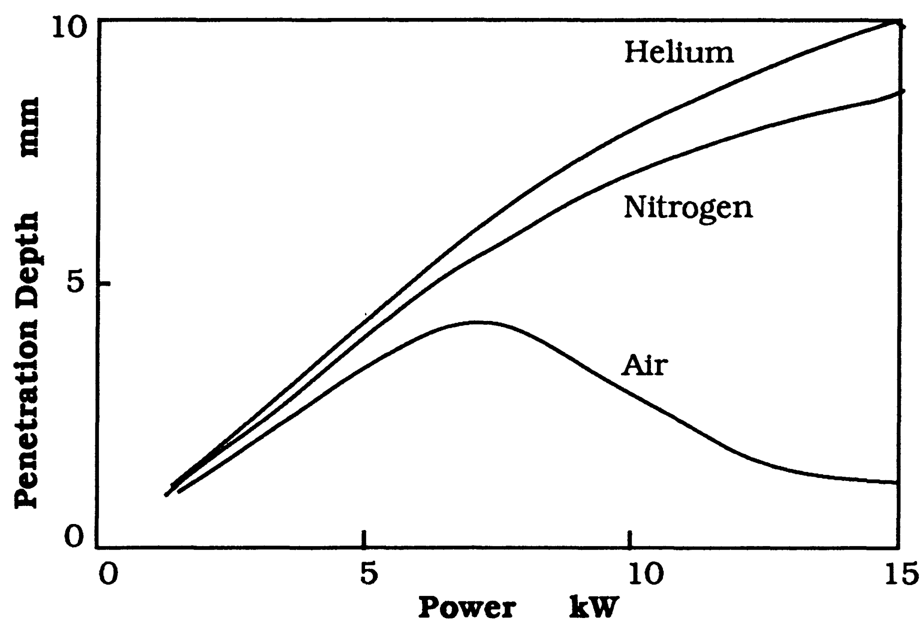
Gap Effect


1.0
0.4
0
g/tp
Theoretical limit for
minimum gap size
Drop out
Drop out and pitting
sound
Theoretical limit for
tolerable drop out
pitting
0
0.4
1.0
AV tZn / tp

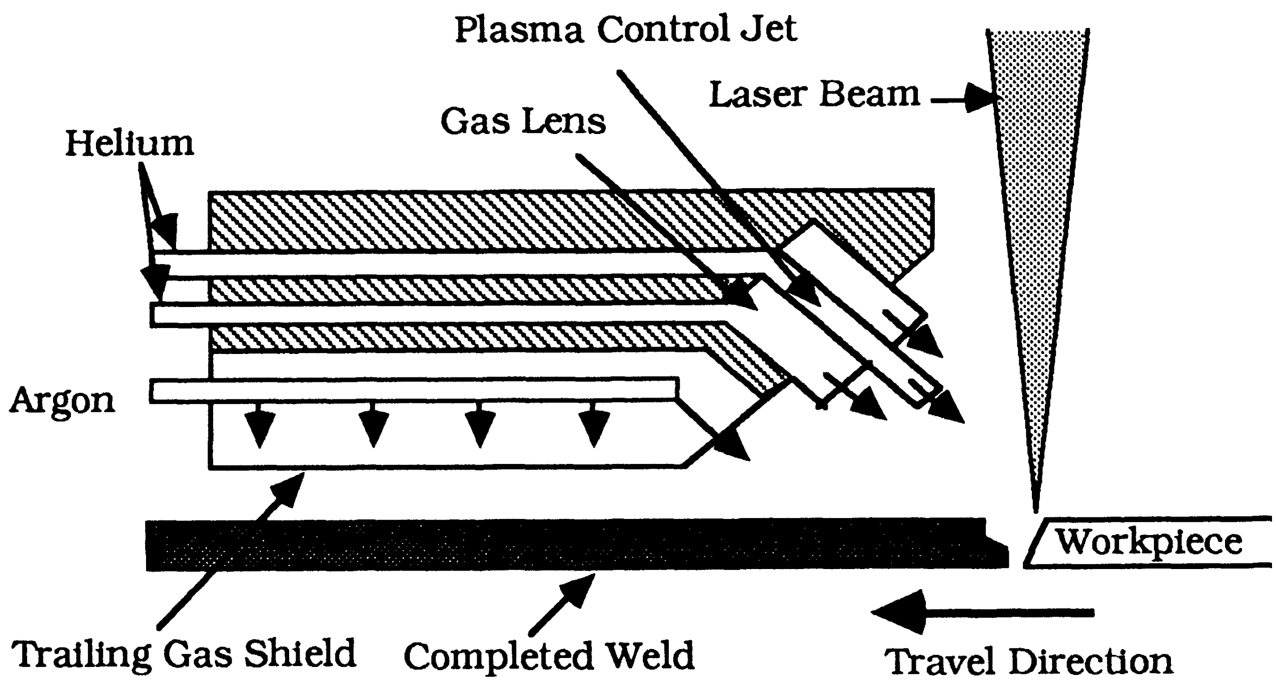
Shroud Gas

- The gas shroud can affect the formation of plasma which may block the beam and thus the absorption of the beam into the workpiece
- The formation of plasma is thought to occur through the reaction of the hot metal vapors from the keyhole with the shroud gas
- It is unlikely due to the fast emission of vapor from the keyhole that the shroud gas enters the keyhole
- The plasma blocking effect will be less for those gases having a high ionization potential
- Helium is favored, in spite of its price, as the top shroud gas in laser welding. The shroud underneath the weld would be of a cheaper gas, e.g. argon, N2 or CO2.

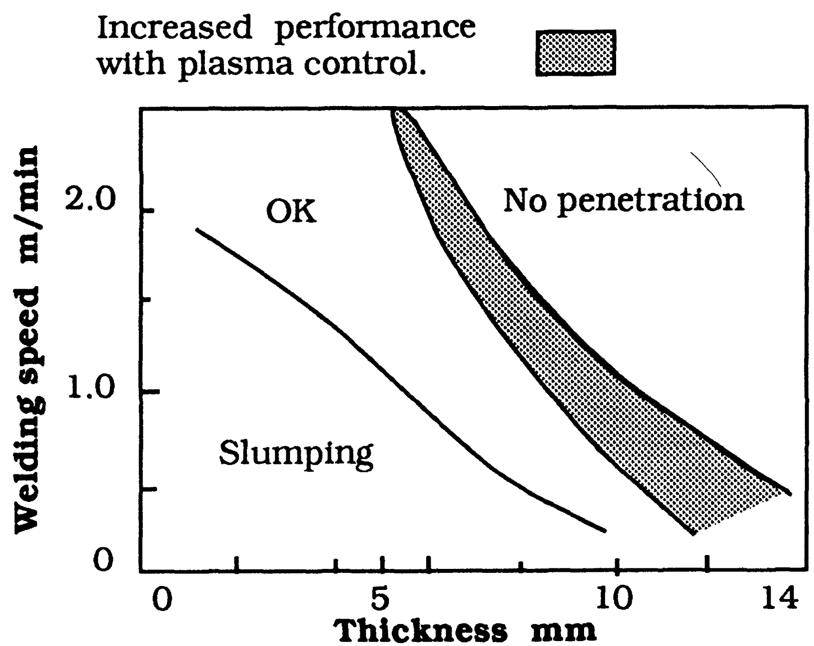
Effect of Shroud Gas



Shroud Design



Shroud Design



Material Properties

- The main issues laser welding are:
  - crack sensitivity,
  - porosity,
  - HAZ embrittlement
  - poor absorption of the radiation.
- For welds of dissimilar metals there is the additional problem of the possible formation of brittle intermetallics.
- Crack sensitivity refers to centreline cracking, hot cracking or liquation
- cracking.
- It is due to the shrinkage stress building up before the weld is fully solidified and strong enough to take the stress.
- It usually happens in metal alloys having a wide temperature range over which solidification occurs, e.g. those with high C, S, P contents.

Table of Weld Characteristics

Table 4.7	Laser Welding Characteristics for Different Alloy Systems
Alloy	Notes
Al Alloys	Problems with: 1. Reflectivity - requires at least 1kW 2. Porosity 3. Exeessive fluidity - leads to drop out
Steels	O.K.
Heat Resistant Alloys: e.g. Inco 718, Jetehet M152, Hastelloy	O.K. but: 1.Weld is more brittle, 2. Segregation problems, 3. Cracking
Ti Alloys	Better than slower processes due to less grain growth
Iridium Alloys	Problem with hot cracking

Process Variations

- Arc Augmented Laser Welding
  - the arc from a TIG torch mounted close to the laser beam interaction point will automatically lock onto the laser generated hot spot
  - The temperature required for this phenomenon is around 300 °C above the surrounding temperature
  - The effect is either to stabilize an arc which is unstable due to its traverse speed or to reduce the resistance of an arc which is stable
  - The locking only happens for arcs with a low current and therefore slow cathode jet; that is, for currents less than 80A.
  - The arc is on the same side of the workpiece as the laser which allows doubling of the welding speed for a modest increase in the capital cost

Process Variations

- Twin Beam Laser Welding
  - If two laser beams are used simultaneously then there is the possibility of controlling the weld pool geometry and the weld bead shape
  - Using two electron beams, the keyhole could be stabilized causing fewer waves on the weld pool and giving a better penetration and bead shape.
  - An excimer and CO2 laser beam combination showed improved coupling for the welding of high reflectivity materials, such as aluminium or copper could be obtained
  - The enhanced coupling was considered principally due to
    - altering the reflectivity by surface rippling caused by the excimer
    - a secondary effect coining from coupling through the excimer generated plasma.