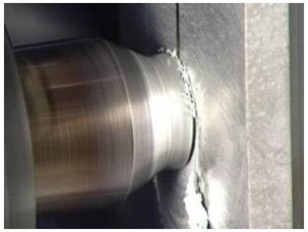
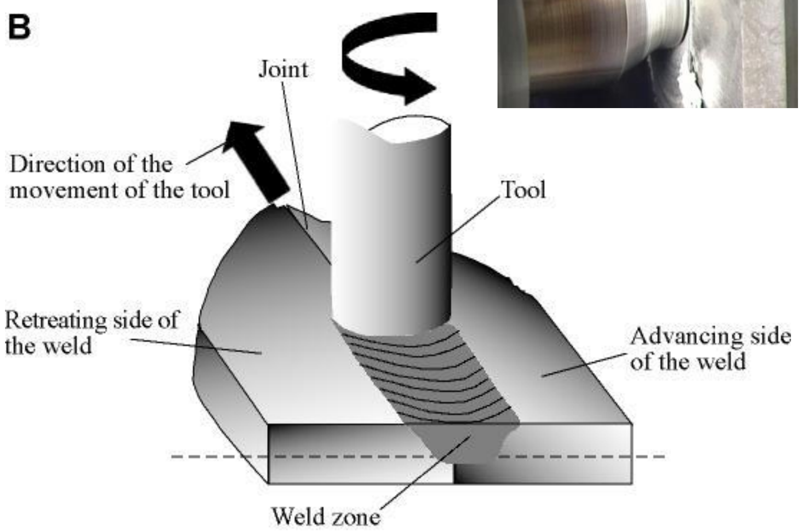
Friction Stir Welding - FSW

- Variation of FRW (invented by TWI, UK) in which rapidly rotating probe is plunged into joint between two plates being squeezed together.
- Frictional heating and softening occurs. Metals plasticized due to heat, from both sides intermix (stirred) and form weld.
- Refined grain structure; ductility, fatigue life and toughness good
- No filler metal or shielding gas, so no porosity or cracking. Low heat input and distortion. Access to 1 side enough
- Can weld metals that are often seen as incompatible. Parameters require careful control





Schematic of friction stir welding.

Friction Stir Welding - FSW

- Process variables include probe geometry (dia, depth and profile); shoulder dia (provides additional heat and prevents expulsion of softened metal from joint), rotation speed, force and travel speed
- Require little edge preparation and virtually no post weld machining due absence of splatter or distortion.
- 50mm thick Al plates welded single side process and 75mm with double sided process
- Cu, Pb, Sn, Zn, T have been welded with steel sheet/plates

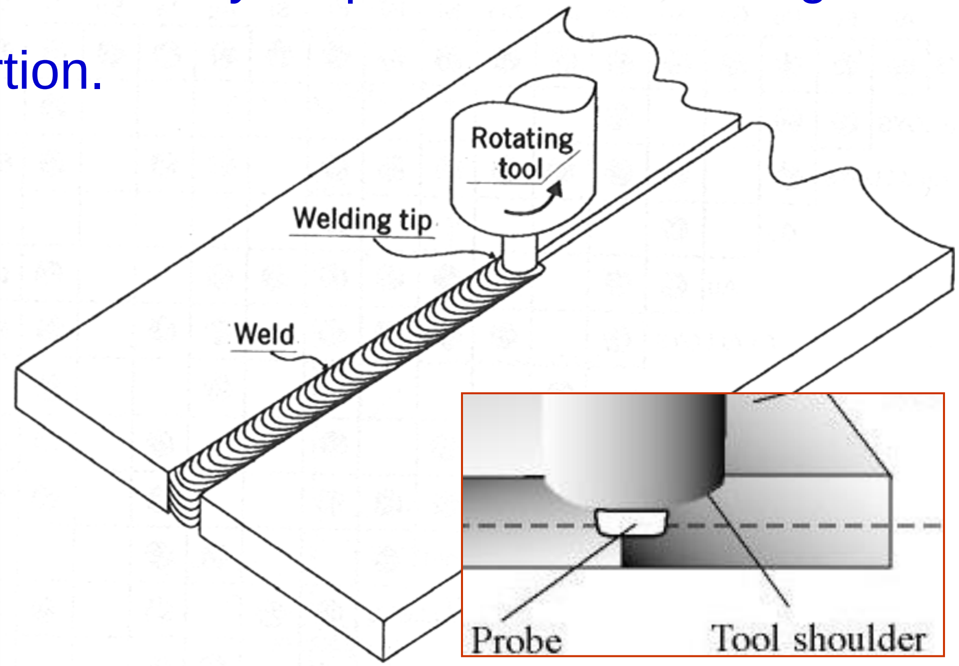
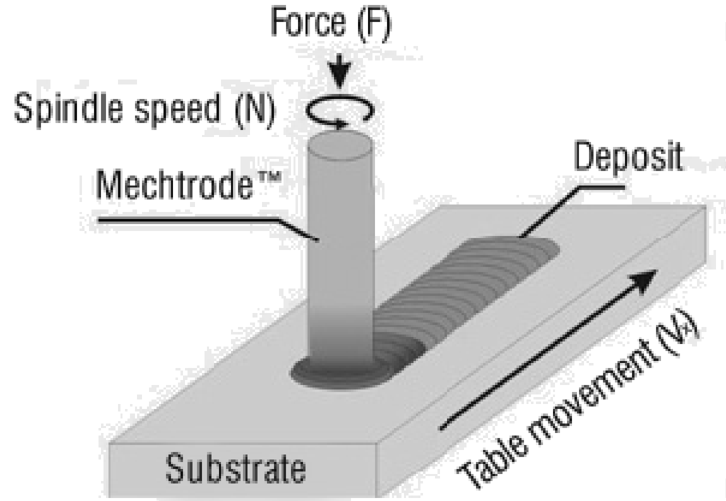
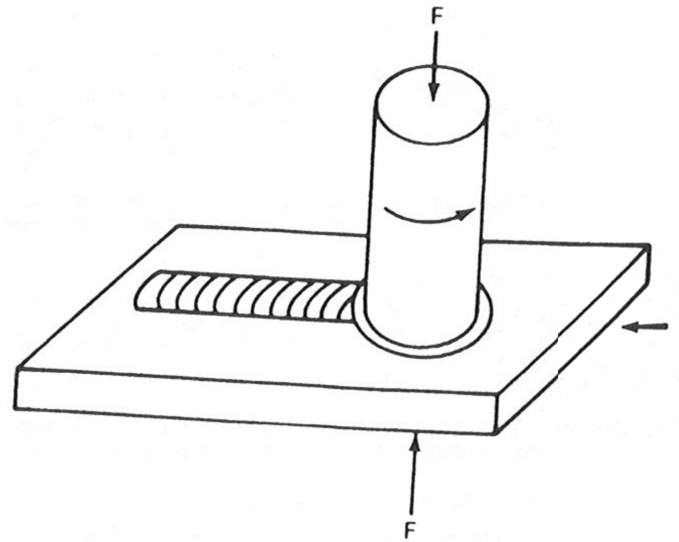


Figure 4.15 Schematic of friction stir welding.

Friction Stir Welding - FSW

- Friction Surfacing - Same principle as FSW. Used to deposit metal on surface of a plate, cylinder etc. For wear, corrosion resistance etc.
- By moving a substrate across the face of the rotating rod a plasticized layer between 0.2-2.5mm thick is deposited
- The resulting composite material is created to provide the characteristics demanded by any given application.





MECH 423 Casting, Welding, Heat Treating and NDT

Time: _ _ W _ F 14:45 - 16:00

Credits: 3.5   Session: Fall

Other Welding Processes

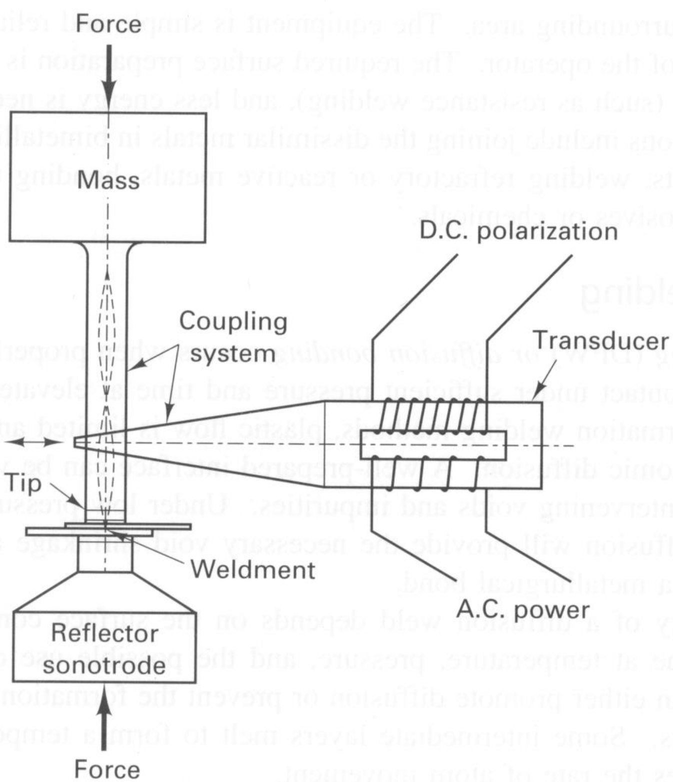
Lecture 10

Ultrasonic Welding   USW

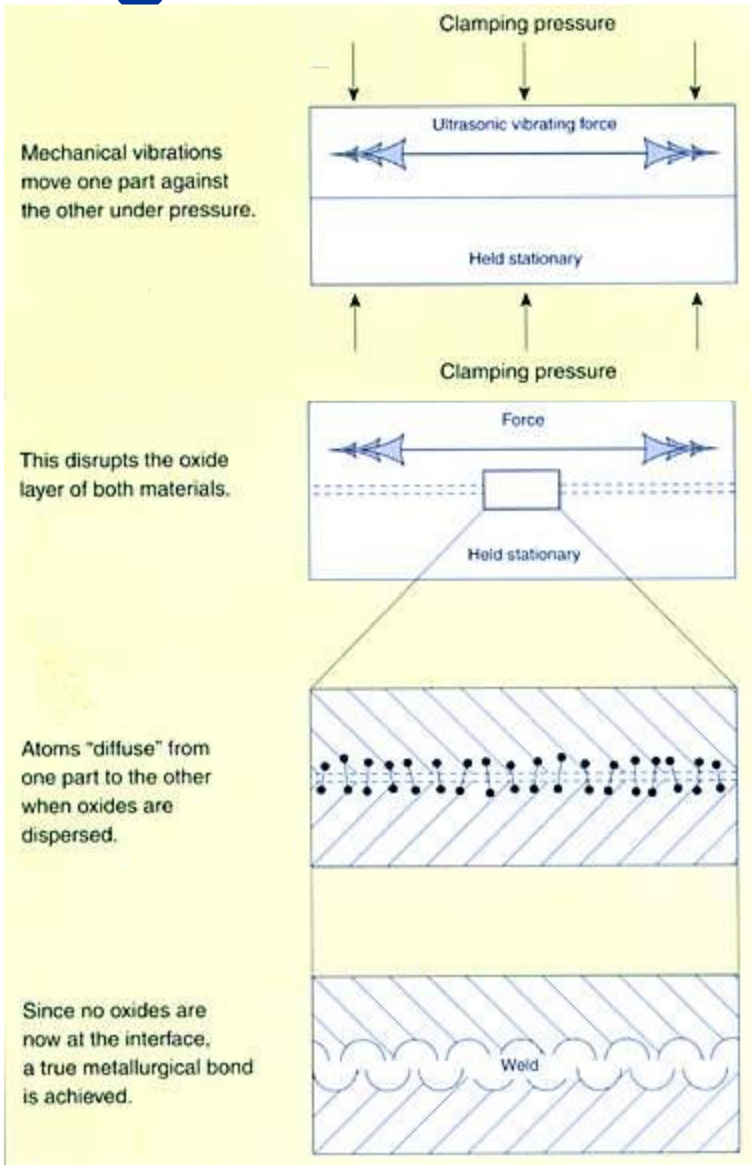
Vibrational motion causing friction.

- Localized high frequency (I0 - 20 kHz) shear vibrations between surfaces (lightly held together).
- (heating but not melting) . Rapid stress reversal removes oxide films and surface impurities allowing coalescence (atom-to-atom contact).
- Spot, ring, line and seam welds.
- Sheet/foil/wire 1 - 2.5 mm
  - Good for dissimilar materials + electronics (low heat) explosive casings. Plastics (can be done with vertical vibrations)
  - Efficient, less surface preparation and required skill

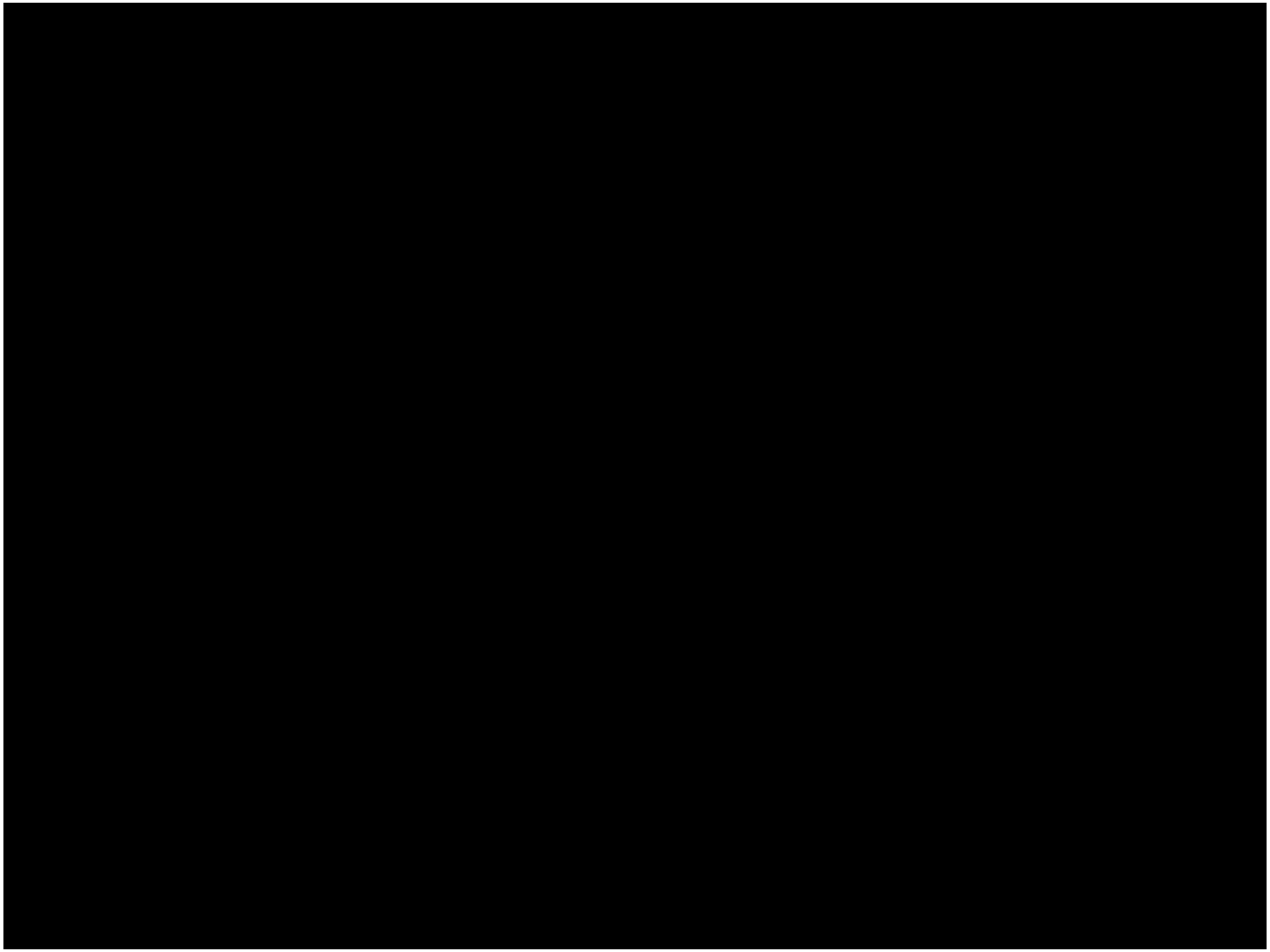
Ultrasonic Welding USW



Schematic of a wedge-reed ultrasonic spot welding system. Note the piezoelectric transducer used to supply needed vibrational energy to cause frictional heating.



Ultrasonic Welding USW



Ultrasonic Welding USW

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al ALLOYS	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be ALLOYS		●	●			●										●		
Cu ALLOYS			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe ALLOYS						●		●	●	●	●		●	●		●	●	●
Mg ALLOYS							●						●			●		
Mo ALLOYS								●	●		●			●		●	●	●
Ni ALLOYS									●	●	●			●		●	●	
Pd										●			●	●				
Pt ALLOYS											●	●		●		●	●	
Si													●	●				
Ag ALLOYS													●	●				●
Ta ALLOYS														●		●	●	
Sn															●			
Ti ALLOYS																●	●	
W ALLOYS																	●	
Zr ALLOYS																		●

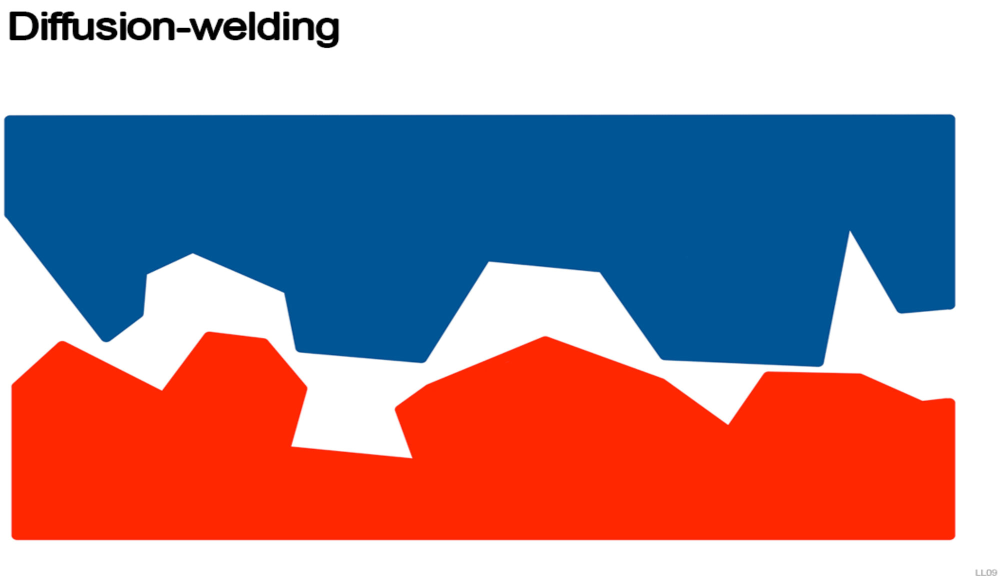
Metal combinations that can be ultrasonically welded

TABLE 36-1. Metal Combinations Weldable by Ultrasonic Welding

Metal	Aluminum	Copper	Germanium	Gold	Molybdenum	Nickel	Platinum	Silicon	Steel	Zirconium
Aluminum	×	×	×	×	×	×	×	×	×	×
Copper		×		×		×	×		×	×
Germanium			×	×		×	×	×		
Gold				×		×	×	×		
Molybdenum					×	×			×	×
Nickel						×	×		×	×
Platinum							×		×	
Silicon										
Steel									×	×
Zirconium										×

Diffusion Welding DFW

- AKA Diffusion Bonding. Heat + Pressure + time (no motion of workpieces)
- Filler metal may/may not. (not as high pressure for plastic deformation)
- $T < T_m$, allow diffusion over time (elevated temp to increase diffusion)
- Used for dissimilar + reactive refractory metals, Ti, Zr, Be, ceramics.
- Can produce perfect welds!
- Dissimilar materials can be joined (metal-to-ceramic).
- Used commonly for bonding titanium in aerospace applications. (Ti dissolves its surface oxide on heating).



- Quality of weld depends on surface condition. It is a slow process.

Explosive Welding EXW

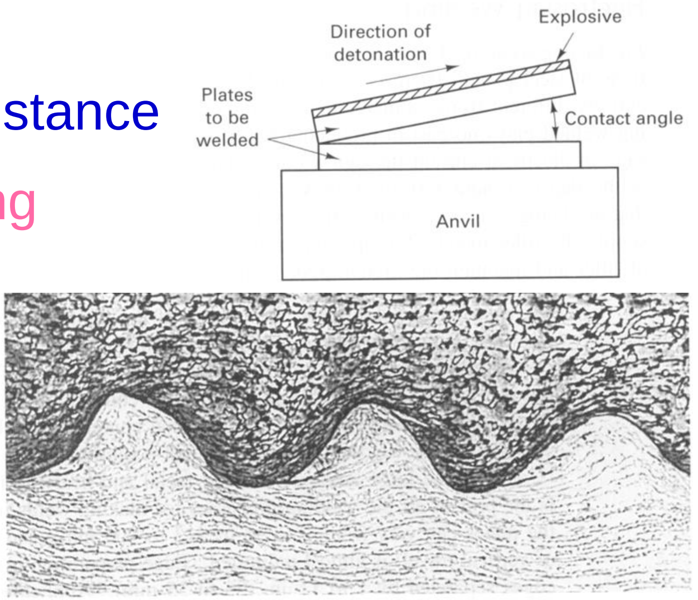


FIGURE 36-8 (*Top*) Schematic of the explosive welding process. (*Bottom*) Explosive weld between mild steel (top) and stainless steel (bottom), showing the characteristic wavy interface.

- Usually used for cladding (eg corrosion resistance sheet to heavier plate) large areas of bonding
- Pieces start out cold but heat up at faying surfaces.
- Progressive detonation (shaped charge and controlled detonation).
    - produces compressive shock wave forcing metals together.
    - air squeezed out at supersonic velocities cleaning off surface film causing localized heating.
    - deformation also causes heating, good atom contact. weld formed.
- low temperature weld (usually a distorted interface – wavy).

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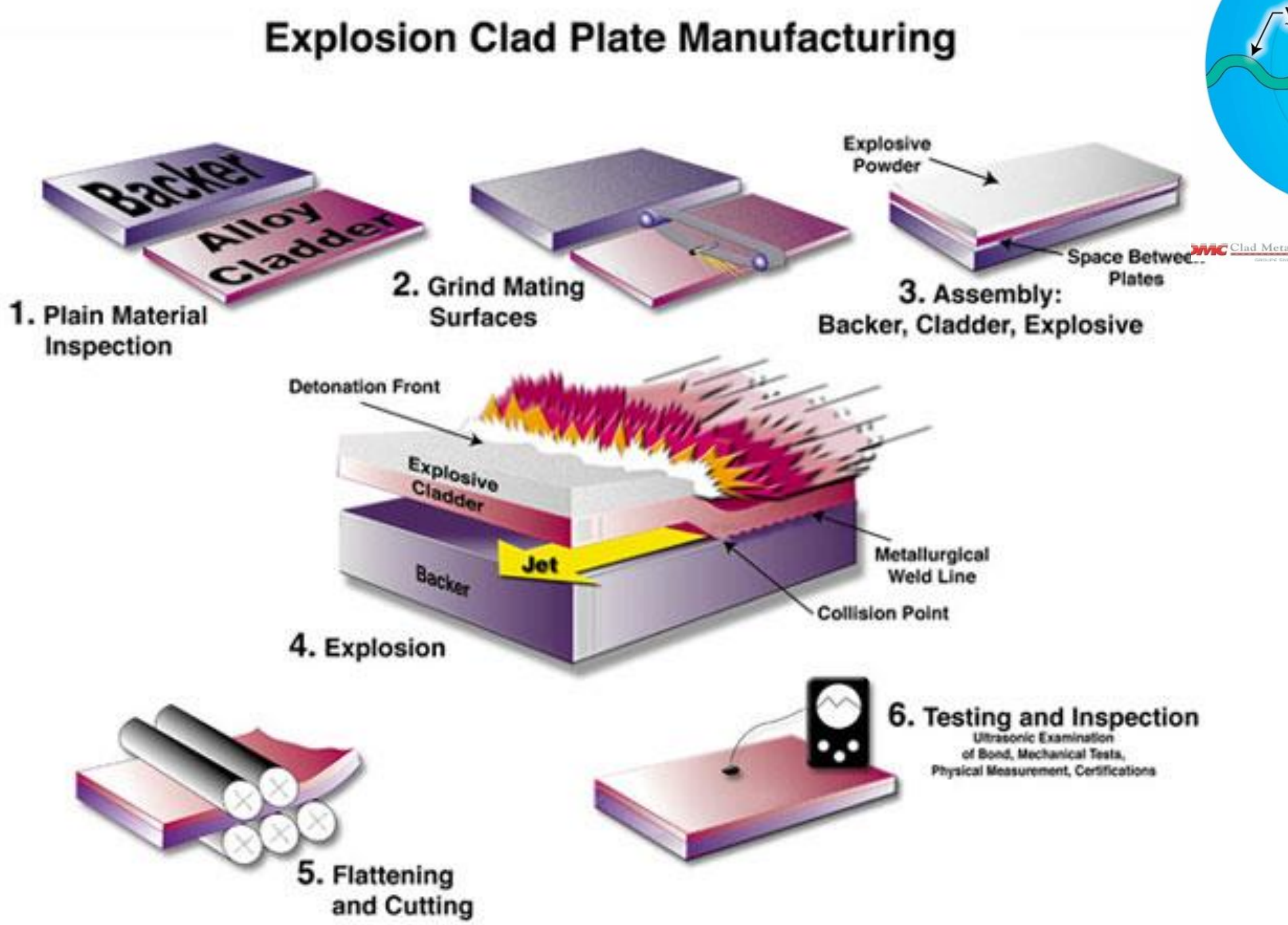
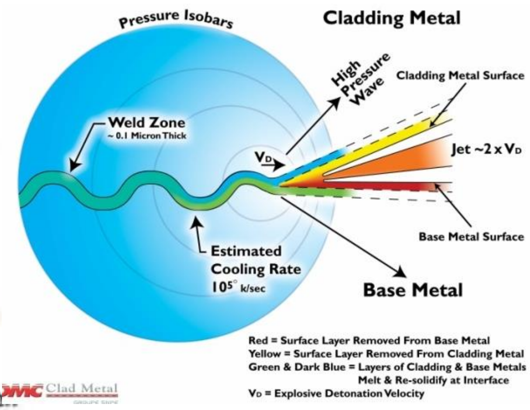
Explosive Welding EXW





Explosive Welding EXW

	ZIRCONIUM	MAGNESIUM	COBALT ALLOYS	PLATINUM	GOLD	SILVER	COLUMBIUM	TANTALUM	TITANIUM	NICKEL ALLOYS	COPPER ALLOYS	ALUMINUM ALLOYS	STAINLESS STEELS	ALLOY STEELS	CARBON STEELS
CARBON STEELS	●	●			●	●	●	●	●	●	●	●	●	●	●
ALLOY STEELS	●	●	●					●	●	●	●	●	●	●	
STAINLESS STEELS			●		●	●	●	●	●	●	●	●	●		
ALUMINUM ALLOYS		●				●	●	●	●	●	●	●			
COPPER ALLOYS					●	●	●	●	●	●	●				
NICKEL ALLOYS		●		●	●			●	●	●					
TITANIUM	●	●				●	●	●	●						
TANTALUM					●		●	●							
COLUMBIUM				●			●								
SILVER						●									
GOLD															
PLATINUM				●											
COBALT ALLOYS															
MAGNESIUM		●													
ZIRCONIUM	●														

- stainless 304 to low carbon steel;
- pure titanium to low carbon steel.
- Used for transition joints:
- Cu-steel, Cu-stainless steel, Cu-Al, Al-steel.

Commercially important metals that can be bonded by explosive welding

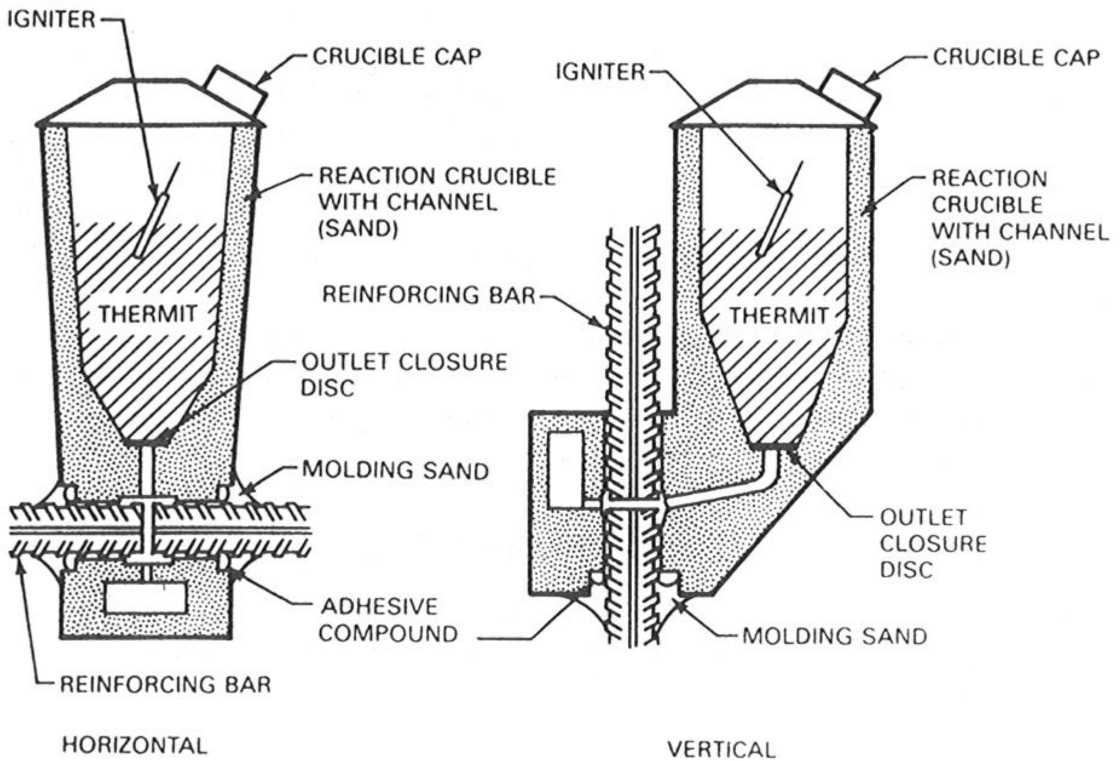
Other Welding Processes

Thermit Welding TW

- AKA aluminothermic; Use heat produced from highly exothermic chemical reaction between solids to produce melting and joining.
- Thermit is a mixture of 1 part AL to 3 parts Iron Oxide + alloys
- Chemical reaction: Metal Oxide + Reducing Agent
- E.g. $8Al + 3Fe_3 0_4 \rightarrow 9Fe + 4Al_2 0_3 + \text{heat}$
- RA MO M slag 2750°C (30secs)
- (Use a magnesium fuse to ignite usually at 1100°C)
- Also CuO plus Al. (superheated metal flows by gravity into the weld area providing heat and filler metal)
- Requires runners and risers to direct metal and prevent shrinkage
- Old technique, less common now

Thermit Welding TW

- Effective in producing economic welds in thick sections – less sophisticated eqpt. (can be used in remote applications)
- Casting repairs, railroad rails, heavy copper cables.
- Also copper, brasses, nickel chromium and manganese.



Typical arrangement of the Thermit process for welding concrete reinforcing steel bars, horizontally or vertically.

ElectroSlag Welding ESW

- Good for thick steel welds
- Arc used to start weld, but then heat produced by resistance heating of SLAG (1760°C) (different from SAW)
- Molten slag melts metal into pool + filler
- up to 65 mm deep slag layer - cleans/protects
- 12 - 20 mm deep weld pool
- Plates (water-cooled) keep liquids in.
- Vertical joints most common (circumferential as well)
- Thickness 13 - 90 mm!
- Building, Shipbuilding, pressure vessels, Castings
- Large HAZ, grain growth
- Large deposition rates (15-25 kg/hr/electrode).

ElectroSlag Welding   ESW

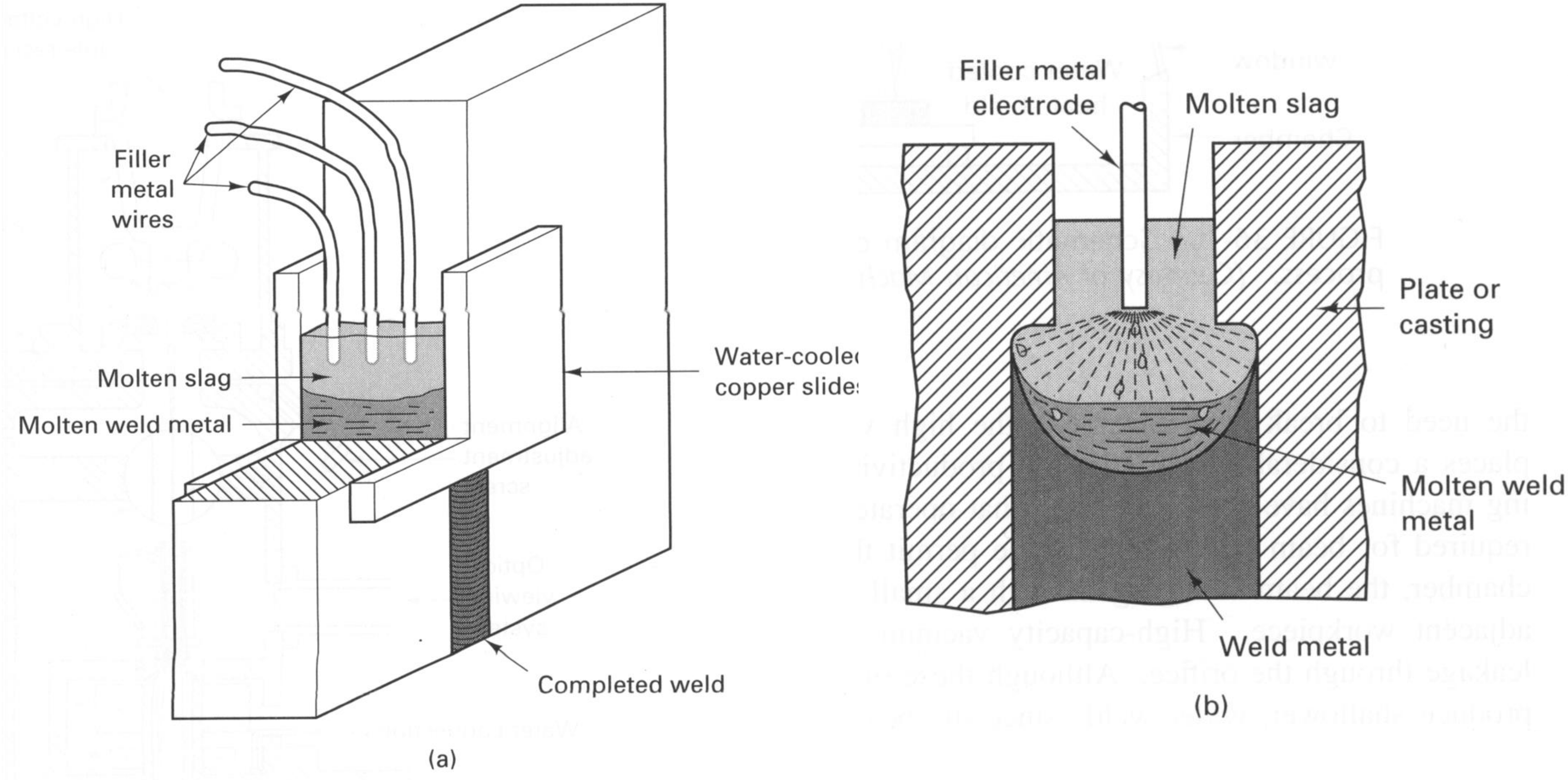
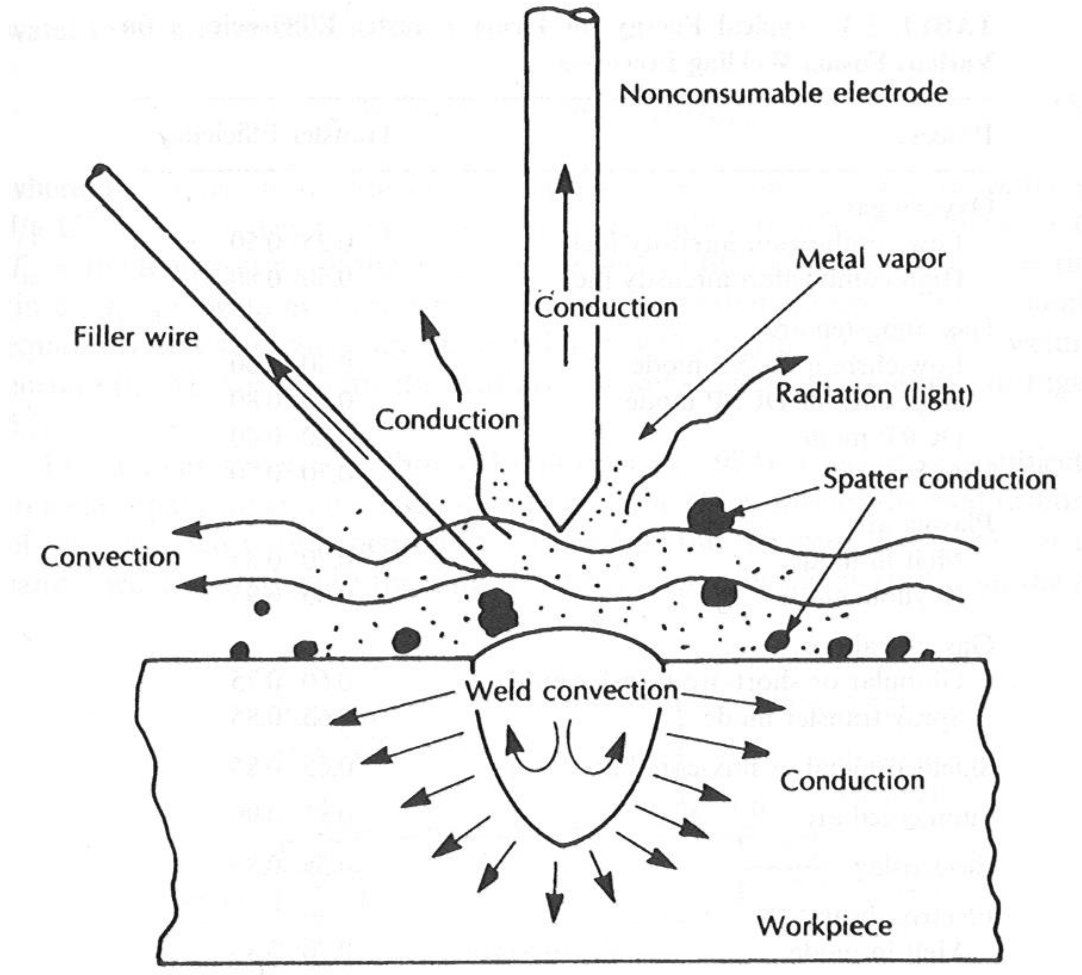


FIGURE 36-9 (*Top*) Arrangement of equipment and workpieces for making a vertical weld by the electroslag process. (*Bottom*) Cross section of an electroslag weld, looking through the water-cooled copper slide.

High Energy Density Beam W

- Electron beam welding (EBW) and Laser Beam Welding (LBW).
- Very high intensity beam of electromagnetic energy (electrons or photons).
- An important factor in welding is heat input – this has good and bad effects. Need high heat input to melt metals but high input will cause more heat affected area in workpiece. What we want is enough energy focussed into small area rather than spread out, i.e. maximize melting efficiency and minimize HAZ.
- Energy density is best way to describe “hotness” for welding. Measured in watts/m^2.
- Other factors to consider are energy losses during welding.
- Can measure energy losses (or heat transfer efficiency) for welding processes: low efficiency (0.25) high efficiency (0.9)

High Energy Density Beam W



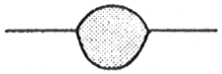
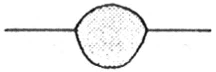
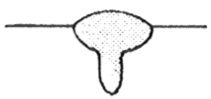
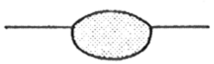
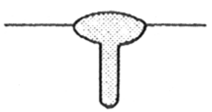
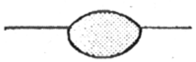
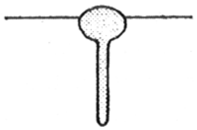
Causes of loss of energy during transfer from a welding source to the workpiece.

High Energy Density Beam W

TABLE 5.3 Typical Energy (or Heat) Transfer Efficiencies η for Various Fusion Welding Processes

Process	Transfer Efficiency
Oxyfuel gas	
Low combustion intensity fuel	0.25–0.50
High combustion intensity fuel	0.50–0.80
Gas–tungsten arc	
Low current DCSP mode	0.40–0.60
High current DCSP mode	0.60–0.80
DCRP mode	0.20–0.40
AC mode	0.20–0.50
Plasma arc	
Melt-in mode	0.70–0.85
Keyhole mode	0.85–0.95
Gas–metal arc	
Globular or short-arc transfer mode	0.60–0.75
Spray transfer mode	0.65–0.85
Shielded-metal or flux-cored arc	0.65–0.85
Submerged arc	0.85–0.99
Electroslag	0.55–0.85
Electron beam	
Melt-in mode	0.70–0.85
Keyhole mode	0.85–0.95+
Laser beam	
Reflective surfaces or vapors	0.005–0.50
Keyhole mode	0.50–0.75+

TABLE 5.2 Typical Values of Energy Density and the Type of Penetration for Various Sources Used in Welding

Process	Heat Source Intensity (Wm^{-2})	Condition	Fused Zone Profile
Flux-shielded arc welding	5×10^6 to 5×10^8		
Gas-shielded arc welding	5×10^6 to 5×10^8	Normal current	
		High current	
Plasma	5×10^6 to 5×10^{10}	Low current	
		High current	
Electron beam and laser	10^{10} to 10^{12}	Defocused beam	
		Focused beam	

Electron Beam Welding EBW

- Fusion welding - heating caused by EB from Tungsten filament.
- Beam is focused (ø0.8 - 3.2 mm) + can produce high temperatures
- Must be used in hard vacuum (10^{-3} – 10^{-5} atm) to prevent electrons from interacting with atoms/molecules in atmosphere.
- Imposes size restrictions (but vacuum cleans surfaces) + slow changeover – hence expensive.
- Some allow exterior sample welds but high losses, shallower weld depths & x-ray hazard; some machines operate with sample in “soft” vacuum (0.1-0.01 atm).
- high power + heat, deep, narrow welds, high speeds; V. narrow HAZ, deep penetration; no filler, gas, flux, etc.

Electron Beam Welding EBW

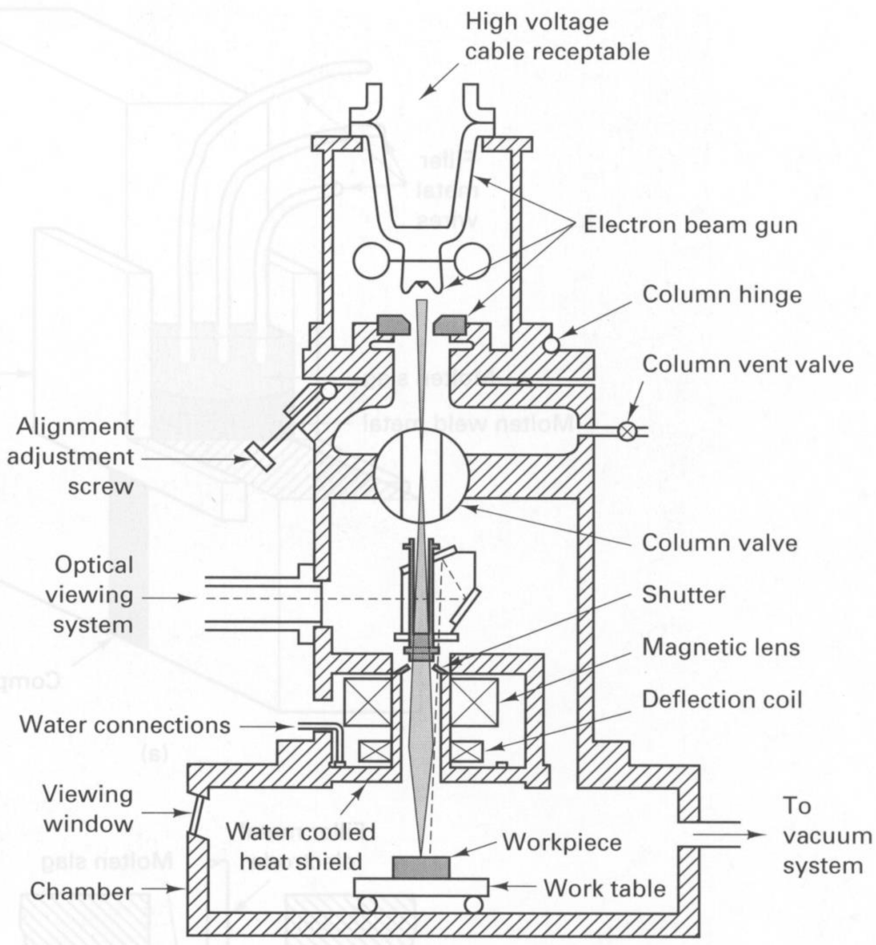


FIGURE 36-10 Schematic diagram of the electron beam welding process. *(Courtesy of American Machinist.)*

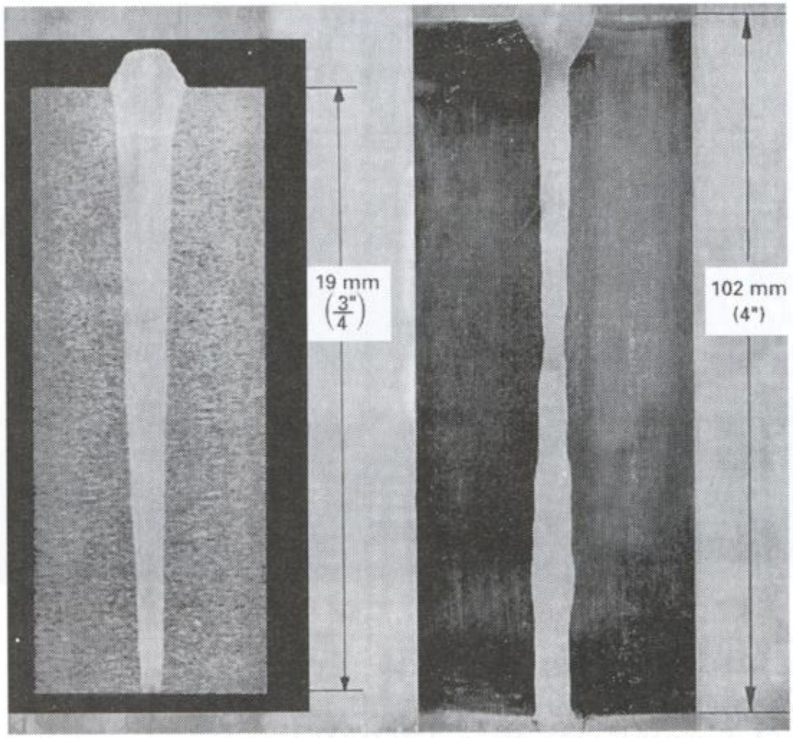
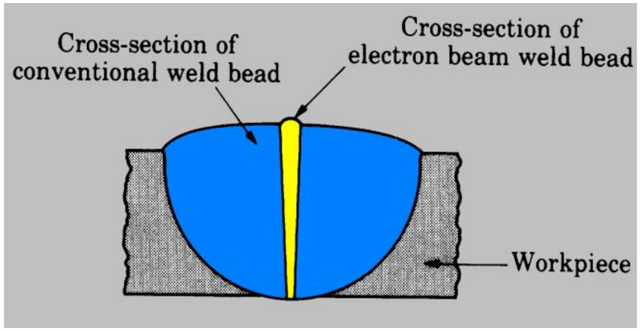


FIGURE 36-11 (*Left to right*) Electron beam welds in $\frac{3}{4}$-in.-thick 7079 aluminum, and 4-in.-thick stainless steel. *(Courtesy of Hamilton Standard*

Electron Beam Welding EBW

- Good for difficult-to-weld materials; Zr, Be, W
- But expensive equipment, joint preparation has to be good.
- EBW is normally done autogenously (i.e. no other filler metal) so joints must fit together very well - simple straight or square butt.
- Filler metal can be added as wire for shallow welds or to correct underfill in deep penetration welds.



- Usually used in keyhole mode.
- Electron absorption in materials high; so transfer efficiency > 90%.
- EBW is routinely used for specific applications in the aerospace and automotive industries.

Laser Beam Welding LBW

- Laser is heat source 10 kW/cm^2
- Thin column of vaporized metal when used in keyhole mode (focused)
- Narrow weld pool, thin HAZ
- Usually performed autogenously (without filler) but filler can be used on shallower welds.
- Usually used with inert shielding gas (shroud or box) or vacuum.
- Some materials reflect light so photon absorption and thus transfer efficiency varies on the material – highly reflective materials (Al) only 10% but for non-reflective materials (graphite) up to 90%.
- Special coatings can be used to increase efficiency.

Laser Beam Welding LBW

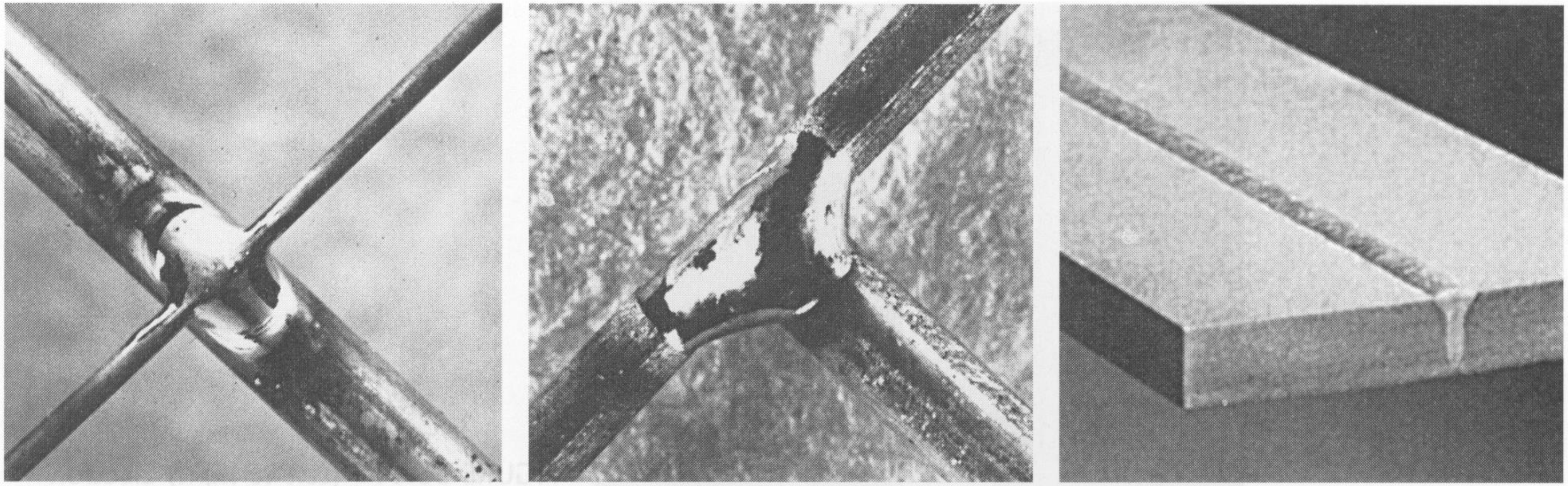
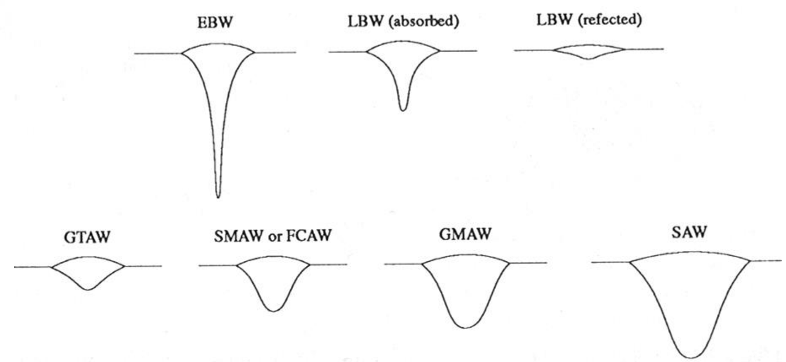


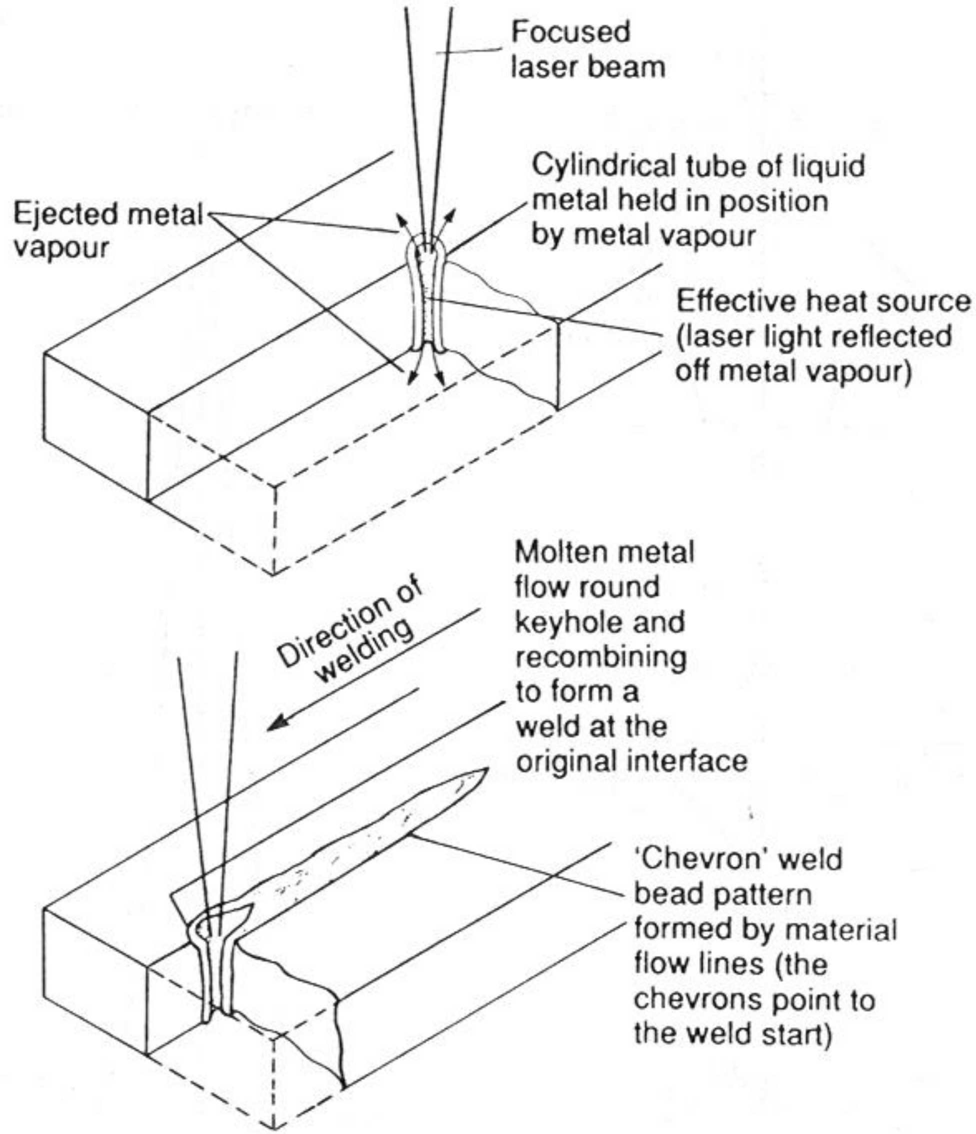
FIGURE 36-12 (*Left*) Small electronic welds made by laser welding. *(Courtesy of Linde Division, Union Carbide Corporation.)*, (*Right*) Laser butt weld of 0.125-in. (3-mm) stainless steel, made at 60 in./min (1.5 m/min) with a 1250-W laser. *(Courtesy of Coherent, Inc.)*



Schematic profiles of typical welds

Laser Beam Welding LBW

Isometric illustration of the movement of a keyhole in laser welding to produce a weld.



Laser Beam Welding LBW

- LBW is like EBW but: can be used in air; no x-rays generated
  - easy to shape, direct + focus LB by mirrors/optics etc.
  - no physical contact required - weld through window!
- Sharp focus allows v. small welds, low total heat (electronics)

1. The beam can be transmitted through air, vacuum is not required.
2. No X-rays are generated.
3. The laser beam is easily shaped, directed, and focused with both transmission and reflective optics (lenses and mirrors) and can be transmitted through fiber optic cables.
4. No direct contact is necessary to produce a weld, only optical accessibility. Welds can be made on materials that are encapsulated within transparent containers, such as components in a vacuum tube.

EBW & LBW Comparison

TABLE 3.3 Comparative Advantages and Disadvantages of Electron-Beam and Laser-Beam Welding Processes

EBW	LBW
1. Deep penetration in all materials	1. Deep penetration in many materials, but *not* in metals that reflect laser light of specific wavelengths because they are specular or because their vapors are reflective
2. Very narrow welds	2. Can be narrow (in keyhole mode)
3. High energy density/low linear input heat	3. Same
4. Best in vacuum, to permit electrons to move unimpeded	4. Can operate in air, inert gas, or vacuum
5. Usually requires tight-fitting joints	5. Same
6. Difficult to add filler for deep welds, except as preplaced shim	6. Same
7. Equipment is expensive	7. Same
8. Very efficient electrically (99%)	8. Very inefficient electrically (~12%)
9. Generates x-ray radiation	9. No x-rays generated

Flash Welding FW

- Two pieces (current-carrying) lightly touched and withdrawn to create arc (flash) between surfaces. (pre heat optional)
- Arc melts surface and cleans oxides. Pieces are then forced (70MPa) to produce joint.
- Current turned off and pressure maintained to complete solidification
- Upset may be removed by machining.
- Usually used for butt welding of similar and dissimilar solids or tubes.
- Surfaces to be square (flashing to be even)
- Expensive equipment but excellent welds.

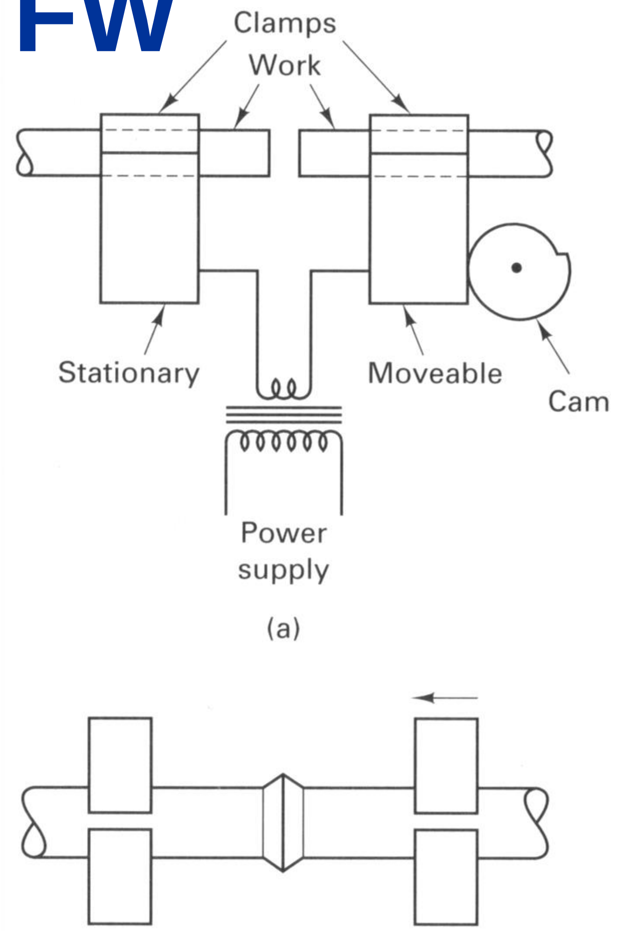


FIGURE 36-14 Schematic diagram of the flash welding process: (a) equipment and setup; (b) completed weld.

Welding of Plastics

- Used for thermo-plastics (heat-softening plastics - not thermosets or elastomers)
- In contrast/competition to
  - adhesive bonding: (requires surface cleaning and preparation, curing time etc.,
  - mechanical fastening: (not usually leak tight, thread stripping is common – requires metal insert).
- Very little heat required as relatively low melting points (cf metals).

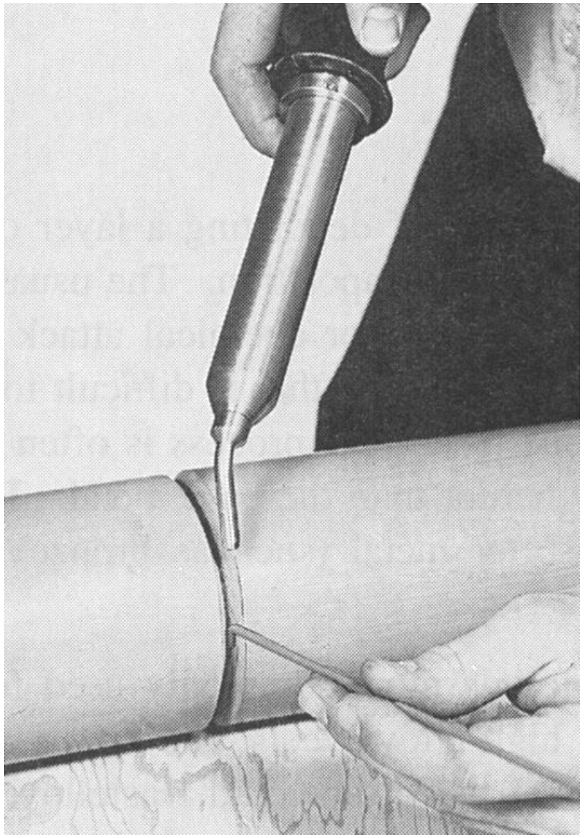


FIGURE 36-16 Using a hot-gas torch to make a weld in plastic pipe.

Welding of Plastics

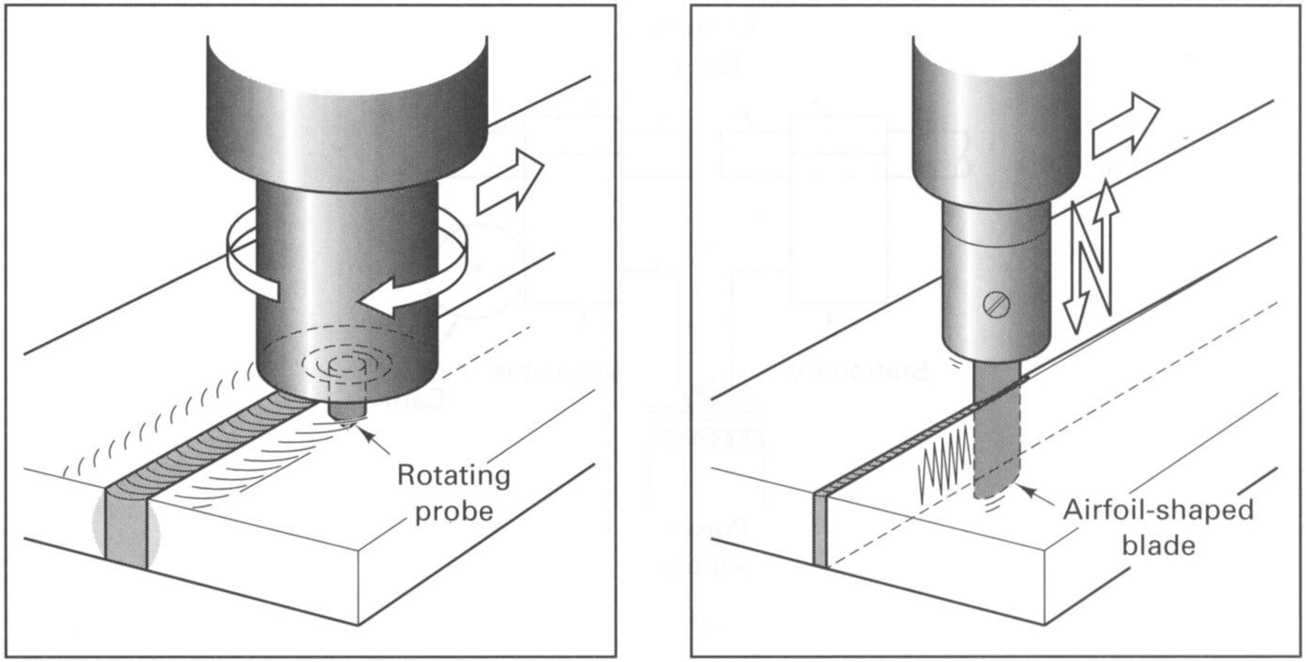


FIGURE 36-15 Friction stir welding using rotary and reciprocal motions to produce welds in plastics. The shoulder on the rotating probe provides additional friction heating to the top surface and prevents expulsion of the softened material from the joint. *(Courtesy of ASM International.)*

Now also used for metals (e.g. aluminum)

Welding of Plastics

- Mechanical/friction heat generation
  - USW; high frequency mechanical vibrations 20-80 kHz, 0.5 – 1.5 secs for welding, usually small components, large production runs.
  - FRW/spin welding. Very similar to friction welding of metals but melting occurs at faying surfaces. Good joints, simple preparation. Requires at least one component to have circular symmetry, with axis of rotation perpendicular to joint. Joint strengths are 50 to 95% of base material
  - vibration welding (like friction but sliding not rotating; also known as Linear Friction Welding)
  - FSW (also on metals): probe - "stirs" up material on either face by frictional heating, and traverses along leaving molten pool to cool.

Welding of Plastics

- External heat sources
- hot-plate welding: simplest method, parts are held against heated hotplate until surface melts and material softens
- hotplate is removed and parts are clamped together and cooled.
- 10 seconds for welding; good strength; limited joints (butt & lap).
- Hot gas welding: very hot "hair dryer" (air, N2, 02, CO2) Resistance coil heated to 200-300°C.
- Filler material usually used as plastic's do not "melt” into low viscosity liquid (cf. metals). So filler material is used to squeeze into softened joint. Often used for repair jobs (too slow for mfg & high operator skill)
- Implant welding: Use metal wire/foil inserted between parts to provide local resistance or induction heating. Plastic flows around inserts to form joint. (Similar to spot welds).

Brazing & Soldering - Introduction

- Welding involved **melting** the pieces of base metal (and filler metal) and solidifying the weld pool to make one piece. The weld is the same metal (system) as the workpiece.
- Brazing and Soldering involve joining workpieces **without** melting the workpieces.
- welding may not be the best choice.
  - heat of welding
  - materials possess poor weldability,
  - welding is expensive.
- In such cases low-temperature joining methods may be preferred.
  - brazing,
  - soldering,
  - adhesive joining
  - mechanical fasteners.

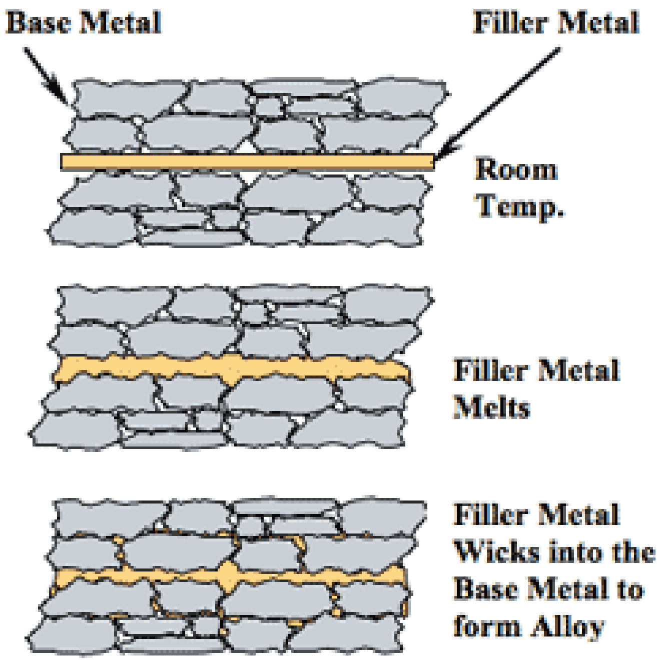
Brazing & Soldering - Introduction

- In brazing and soldering,
  - metal surfaces are cleaned,
  - components assembled or fixtured,
  - low-melting-point nonferrous metal is then melted
  - drawn into the space between the two solid surfaces by capillary action
  - allowed to solidify.
- **BRAZING**
- *Brazing* is the joining of metals by heat and a filler metal whose melting temperature is above 840°F (450°C)
- **BUT** below the melting point of the metals being joined.

Brazing

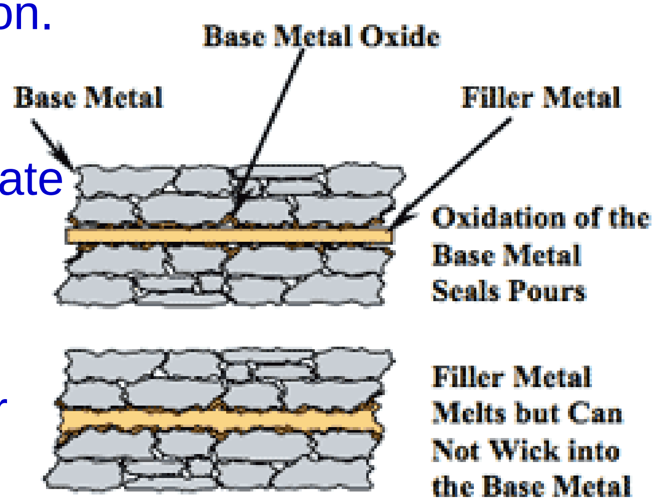
Main differences between welding & brazing:

- composition of the brazing alloy is different significantly from that of the base metal.
- The strength of the brazing alloy is substantially lower than that of the base metal.
- The melting point of the brazing alloy is lower than that of the base metal, so the base metal is not melted.
- Bonding requires capillary action, (flow related to viscosity of the liquid and joint geometry and surface wetting characteristics) to distribute filler between fitting surfaces.



Brazing

- Virtually all metals can be joined by some type of brazing metal. - suited for dissimilar metals, (ferrous to nonferrous, or metals with different mps, metal-ceramic).
- Less heating (c.f.welding) quicker, less energy.
- Lower temperatures reduce HAZ, warping, or distortion.
- Thinner/more complex joints. (closer tolerance, neat)
- Highly adaptable to automation/mass producing delicate assemblies. A strong permanent joint is formed.



Disadvantages of brazing:

- Small joint clearance to enhance capillary flow of filler metal
- subsequent heating can cause melting of the braze metal.
- susceptibility to corrosion; *filler metal is* different composition, joint is a localized galvanic corrosion cell. (reduced by proper material selection)

Nature & Strength - Brazed Joints

- Brazing forms a strong metallurgical bond at the interfaces.
- The bonding enhanced by clean surfaces, proper clearance, good wetting, and good fluidity.
- Strength can be quite high, certainly higher than the strength of the brazing alloy and possibly higher than the brazed metal.
- Bond strength is a strong function of joint *clearance*.
- If the joint is too tight, difficult for the braze metal to flow into the gap and flux may be unable to escape (will leave voids)
- There must be sufficient clearance so that the braze metal will wet the joint and flow into it under the force of capillary action.
- As the gap is increased beyond this optimum value, however, the joint strength decreases rapidly, dropping off to that of the braze metal itself.

Nature & Strength - Brazed Joints

- If the gap becomes too great, capillary forces may be insufficient to draw the material into the joint or hold it in place during solidification.
- Proper clearance varies, depending on type of braze metal. Ideal clearance is usually between (0.0005 and 0.0015 in.) (10 - 40μm) (an "easy-slip" fit).

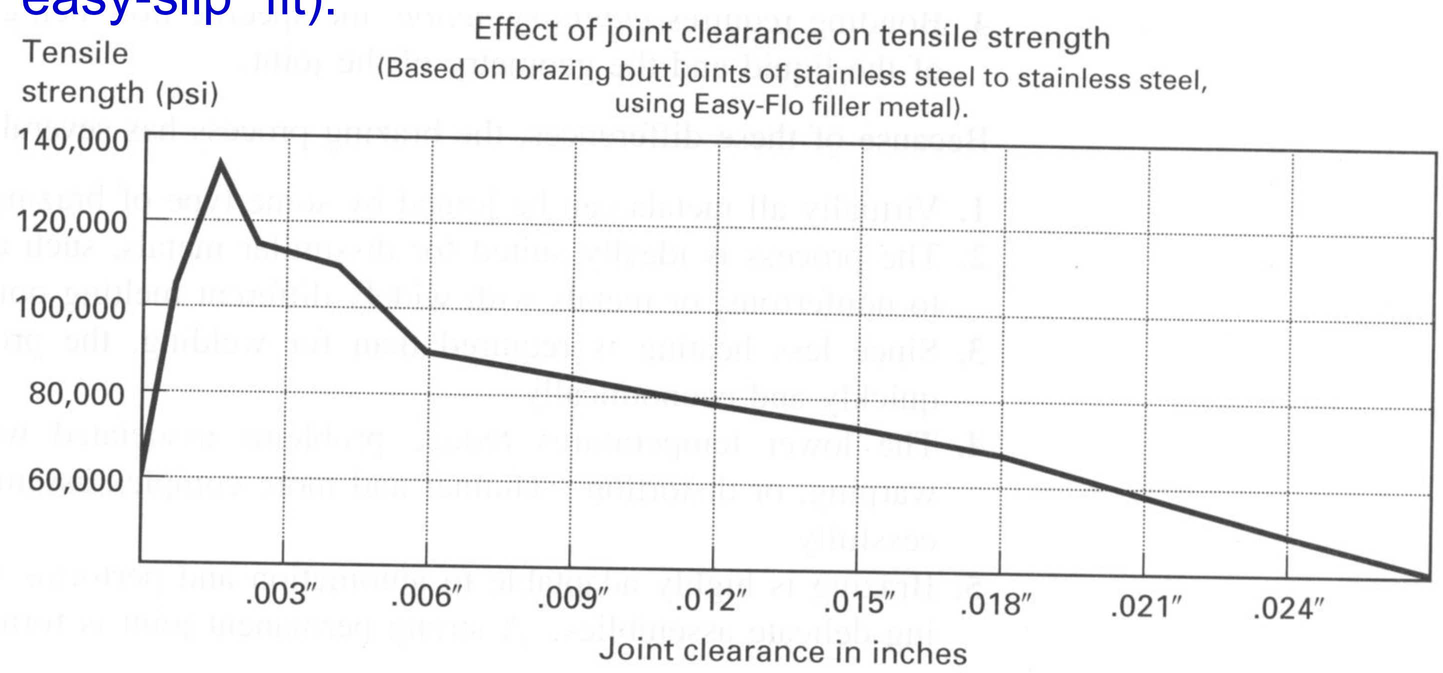


FIGURE 37-1 Typical variation of tensile strength with different joint clearances in a butt joint design. *(Courtesy of Handy & Harman).*

Nature & Strength - Brazed Joints

- Clearances up to (0.003 in.) (75 μm) can be accommodated with a more sluggish filler metal, such as nickel.
- When clearances > 0.003 < 0.005 in.(75-130 μm), acceptable brazing is difficult, and with gaps > 0.005 in. (130 μm) are impossible to braze.
- Joints should be parallel and clearances should exist at brazing temperature. Effects of thermal expansion should be compensated.
- **Wettability** – ability of liquid to spread and "wet" surface of solid.
- Function of the surface tensions between braze metal and base alloy. Usually good when surfaces are clean and alloys can form. Sometimes interlayers can be used to increase wettability e.g. tin-plated steel (tinned steel) is easier to solder with lead-tin solder.
- **Fluidity** – is a measure of how the liquid braze metal flows. Depends on the metal, temperature, surface cleanliness and clearance.

Brazing Metals

Brazing materials (MP between 450°C and Metal MP) selected based on:

- compatibility with the base materials, brazing temperature restrictions,
- restrictions due to service or subsequent processing temperatures,
- brazing process to be used, the joint design,
- anticipated service environment, desired appearance,
- desired mechanical properties (strength, ductility, and toughness),
- desired physical properties (electrical, magnetic, or thermal), and
- cost.
- Materials must be capable of "wetting" the joint surfaces, and partially alloying with the base metals.
- Most commonly used: copper and copper alloys, silver and silver alloys, and aluminum alloys.

Brazing Metals

TABLE 37-1. Some Common Braze Metal Families, Metals They Are Used to Join, and Typical Brazing Temperatures

Braze Metal Family	Materials Commonly Joined	Typical Brazing Temperature (°F)
Aluminum–silicon	Aluminum alloys	1050–1150
Copper and copper alloys	Various ferrous metals as well as copper and nickel alloys and stainless steel	1700–2100
Copper–phosphorus	Copper and copper alloys	1300–1700
Silver alloys	Ferrous and nonferrous metals, except aluminum and magnesium	1150–1800
Precious metals (gold-based)	Iron, nickel, and cobalt alloys	1650–2000
Magnesium	Magnesium alloys	1100–1150
Nickel alloys	Stainless steel, nickel, and cobalt alloys	1700–2200

- ***Copper*** - most commonly used brazing material.
- **Unalloyed copper** is used primarily for brazing steel and other high-melting-point materials, (high-speed steel and tungsten carbide).
  - Confined mostly to furnace operations in a protective hydrogen atmosphere; extremely fluid; requires no flux. Melting point is about 1084^{o}C and tight-fitting joints (75μm) are required.

Brazing Metals

- ***Copper alloys:***
  - Copper-zinc alloys; lower melting point than pure copper; used extensively for brazing steel, cast irons, and copper.
  - Copper-phosphorus alloys used for fluxless brazing of copper since the phosphorus can reduce the copper oxide film. Should not be used with ferrous or nickel-based materials, as they form brittle compounds with phosphorus.
- ***Pure silver*** is used in brazing titanium.
- ***Silver solders****;* alloys of silver and copper with paladium, nickel, tin, or zinc; brazing temperatures around 750°C; used in joining steels, copper, brass, and nickel.
- Although quite expensive, only small amount required; cost per joint is quite low. Also used in brazing stainless steels.

Brazing Metals

- ***Aluminum-silicon alloys****; (*6 to 12% silicon) used for brazing aluminum and aluminum alloys. Control of temperature essential.
- Braze metal is like base metal, galvanic corrosion is unlikely BUT control of the brazing temperature is critical (close to melting point of metal).
- In brazing aluminum, proper fluxing action, surface cleaning, and/or the use of a controlled-atmosphere or vacuum environment is required to assure adequate flow of braze metal.
- Nickel- and cobalt-based alloys offer excellent corrosion- and heat-resistant properties. (good at elevated temperature service conditions)
- Gold and palladium alloys offer outstanding oxidation and corrosion resistance, as well as electrical and thermal conductivity.

Brazing Metals

- Magnesium alloys are used to braze magnesium.
- Amorphous alloy brazing sheets produced by fast cooling metal (> I million ^{o}C per second). Resulting metal foils are extremely thin (0.04 mm) exhibit excellent ductility and flexibility, even when alloy itself is brittle.
  - Shaped inserts can be cut or stamped from the foil, inserted into the joint, and heated. Since the braze material is fully dense, no shrinkage or movement is observed during the brazing operation. A variety of brazing alloys are currently available in the form of amorphous foils.
- Nickel-chromium-iron-boron can be used for brazing assemblies requiring high temperature service. Boron diffuses into base metal and raises the melting point of remaining filler. Increases service temperature above MP of the braze alloy.

Fluxes

- In a normal atmosphere, heat causes formation of surface oxides that oppose wetting / bonding.
- Fluxes are used for:
    - dissolving oxides that may be on the surface prior to heating,
    - preventing the formation of oxides during heating,
    - lowering the surface tension of the molten brazing metal and thus promoting its flow into the joint.
- One of the primary factors affecting quality and uniformity of brazed joints is cleanliness. Fluxes will dissolve modest amounts of oxides, but they are not cleaners. Before flux applied, dirt, grease, oil, rust, and heat-treat scale should be removed.

Fluxes

- If the flux has little cleaning to do before heating, then it will be more efficient while brazing.
- Importance of fluxes in aiding "wetting" of base metal by filler metal (brazing & soldering)

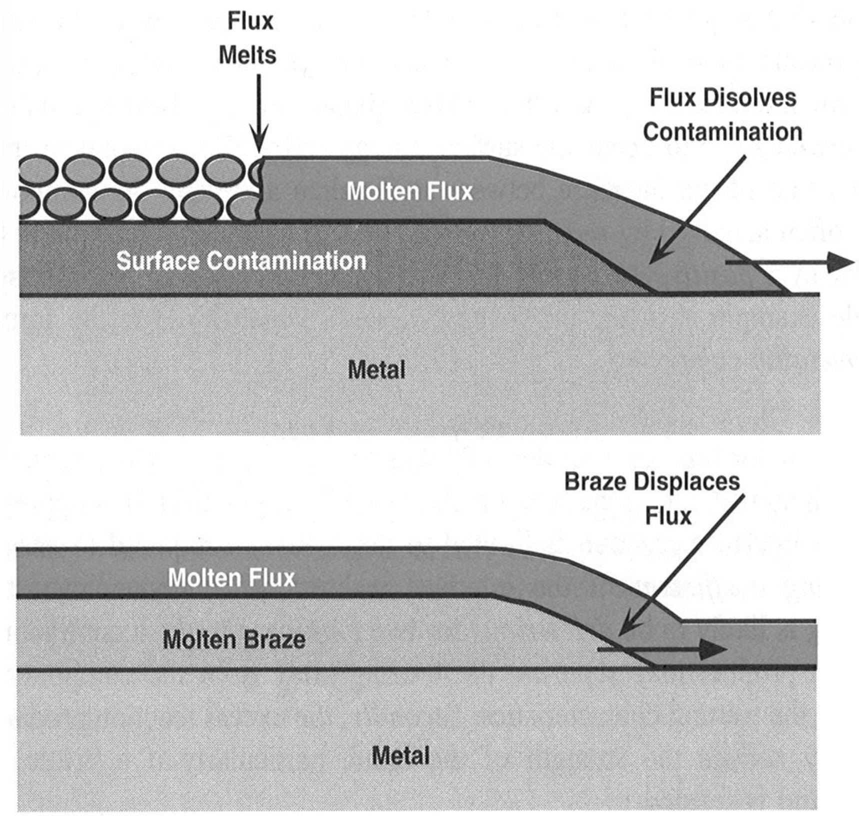
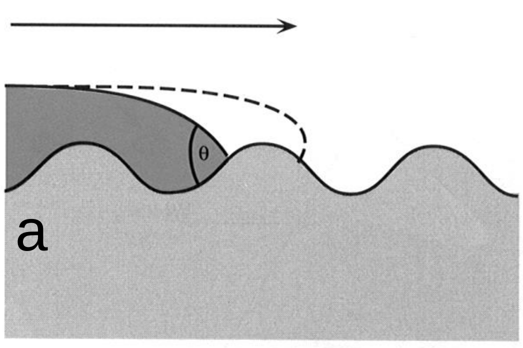


Fig. 7.2. All soldering and brazing procedures depend on a *flux* to wet the surfaces of the components and dissolve surface films and contamination, before being displaced by the molten braze or solder alloy (which must therefore also wet the components). (a) The flux *melts* and dissolves the film of surface contamination, completely *wetting* the cleaned surfaces of the components. (b) The molten braze or solder *displaces* the molten flux layer to wet the surfaces of the components, while itself being protected from the atmosphere by the molten flux.

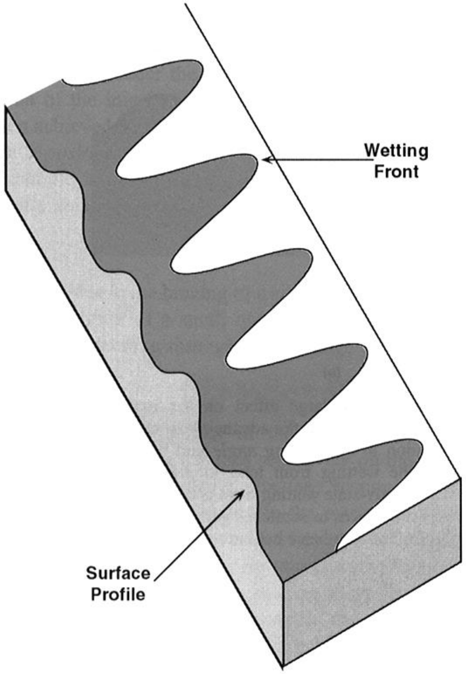
Fluxes

- Wetting When Soldering & Brazing

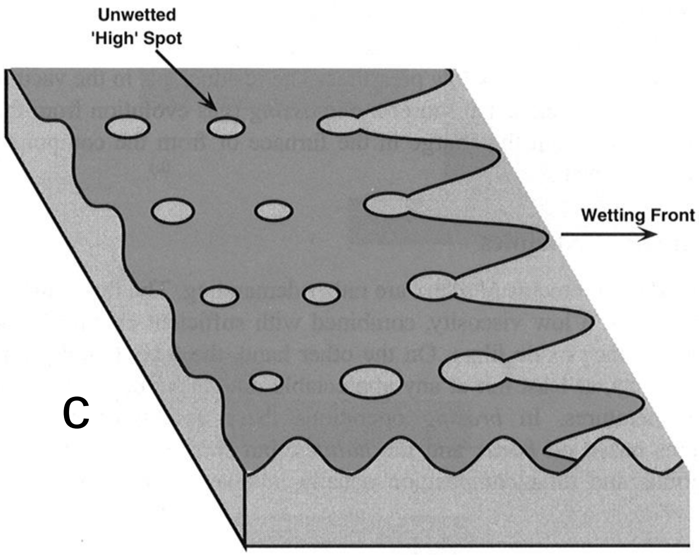


a

Fig. 7.3. The *surface* roughness has a large effect on the extent and rate of wetting. (a) Machining or grinding grooves *parallel* to the advancing front of the melt *inhibit* wetting by introducing a periodic variation in the *wetting angle* and hence in the spreading force. (b) Grooves *perpendicular* to the wetting front tend to *promote* wetting by introducing additional *capillary forces*. The steady-state wetting front is then *wavy*, with the melt 'sucked' into the grooves. (c) A *network* of grooves or scratches generally *promotes* wetting as a result of the additional *capillary forces*, but may leave behind *unwetted islands* ('high spots') if the roughness is extreme.



b



c

Fluxes

- ***Fused* Borax** in common use as a brazing flux. Modern fluxes with melting temperatures lower than borax; some more effective in removing oxidation
- Flux should be selected for compatibility with the metal being brazed
- Paste fluxes are utilized for furnace, induction, and dip brazing, - usually applied by brushing.
- Either paste or powdered fluxes used with torch brazing . Application is usually done by dipping the heated end of the filler wire into flux.
- Fluxes for aluminum - mixtures of metallic halide salts, with sodium and potassium chlorides.
- Most brazing fluxes are corrosive, - residue should be removed immediately after brazing. (particularly for aluminum - chlorides are particularly detrimental). Effort directed to developing fluxless procedures for brazing.

Applying the Brazing Metal

- Can be applied to joints in several ways.
- Oldest (and a common technique in torch brazing) uses rod or wire.
  - Joint area is heated to a temperature high enough to melt the braze alloy and keep it molten while flowing into joint. Braze metal is then melted by torch and capillary action draws it into the gap.
- Considerable labour and care necessary.
- To avoid these difficulties, braze metal is often applied to joint prior to heating - wires, shims, powder, or formed rings, washers, disks, etc.
- Rings or shims of braze metal can be fitted into internal grooves in the joint before assembly. Parts held together by press fits, riveting, staking, tack welding, or a jig, to maintain their proper alignment before brazing. Use springs to compensate for thermal expansion.
- Precladding of sheet material with braze alloy. (no capillary flow)

Applying the Brazing Metal

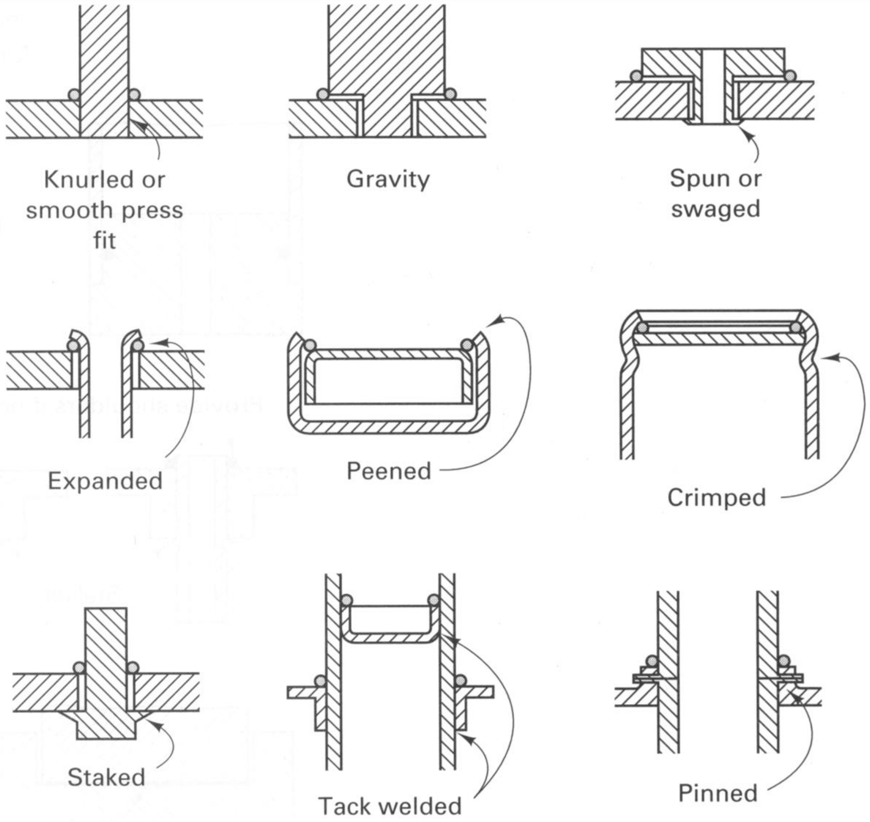


FIGURE 37-2 Methods of applying braze metal and positioning or fixturing various joints.

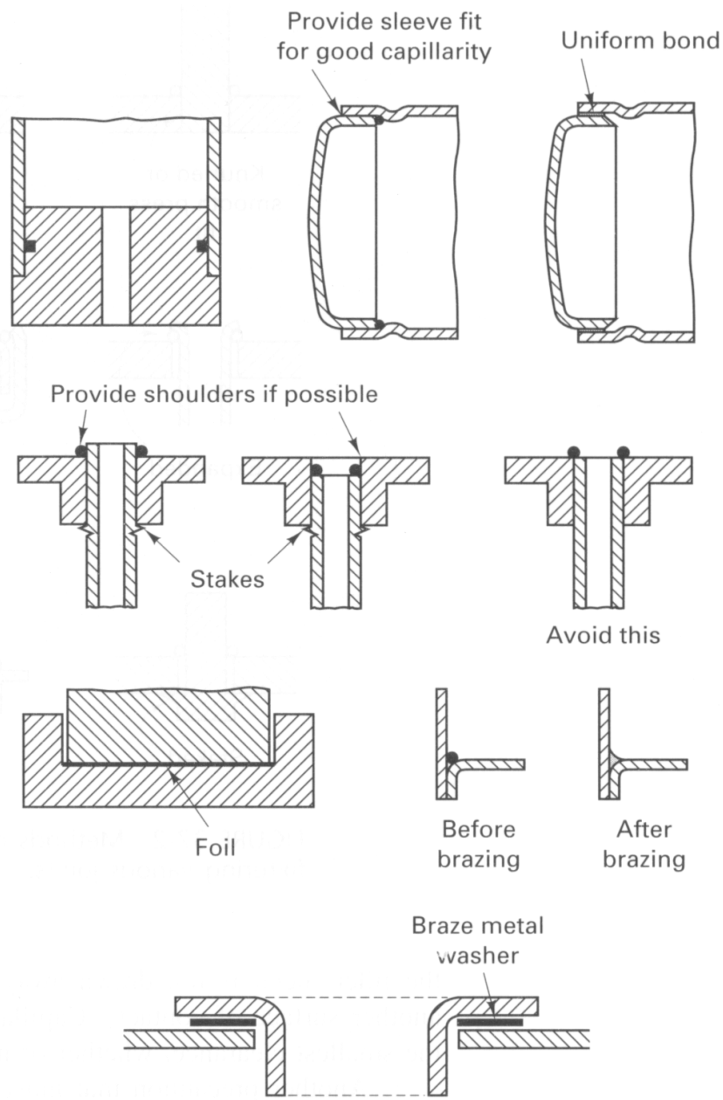


FIGURE 37-3 Techniques to apply brazing wire, foil, or sheet to assure proper flow into the joint.

Heating methods

- Things to consider- Size and shape, type of material, quality, quantity and rate of production. Temperature uniformity is important.
- Torch-brazing - gas torch flame. Most repair brazes use this but also many production applications. Flexible, simple, local heating only. Difficult temperature control, skill required.
- Furnace-brazing - Braze metal pre-applied. Components loaded into furnace (box or continuous). Controlled heating & atmosphere, no skill.
- Salt-bath Brazing - Dip into molten salt bath (c.f heat treating)
  - fast heat transfer; salt-bath prevents oxidation
  - uniform temperature, good for uneven thickness parts
- Dip-brazing - Assemblies dipped into bath of molten braze metal (wasteful) useful only for small parts.

Induction Brazing

High-frequency induction currents for heating. Used extensively:

- rapid heating - a few seconds for complete cycle.
- semiautomatic, only semiskilled labour is required.
- heating confined to joint area using specially designed coils and short heating times - minimizes softening and distortion; reduces scale and discoloration problems.
- uniform results are easily obtained.

- Coils are generally copper tubing (cooling water). Filler material can be added to the joint manually after heating, BUT usually use preloaded joints to speed the operation and produce more-uniform bonds.

Resistance Brazing

- Parts to be joined are pressed between two electrodes as a current is passed through.
- Unlike resistance welding, however, most of the resistance is provided by the electrodes, which are made of carbon or graphite. Thus most of the heating is by means of conduction from the hot electrodes.
- The resistance process is used primarily to braze electrical components, such as conductors, cable connectors, and similar devices. Equipment is generally an adaptation of conventional resistance welders.
- Infrared heat lamps, lasers, E-Beams can also be heat sources for Brazing

Brazed Joint DESIGN

- Use THIN layer of braze. To maximize load bearing ability of braze
- ensure proper joint clearance
- increase area of joint;
  - lap (shear)
  - Butt (used where joint strength not critical)
  - scarf
- Overlap-type joints are preferred.
- For good joints, a lap of 1-1.25 times metal thickness (t) can provide strong joint but for industrial production lap should be 3 to 6 t.
- This ensures failure of the base metal and not the joint.
- Alignment is less problem, capillary action easier; assembly usually easier. Maximum strength attainable.

Brazed Joint DESIGN

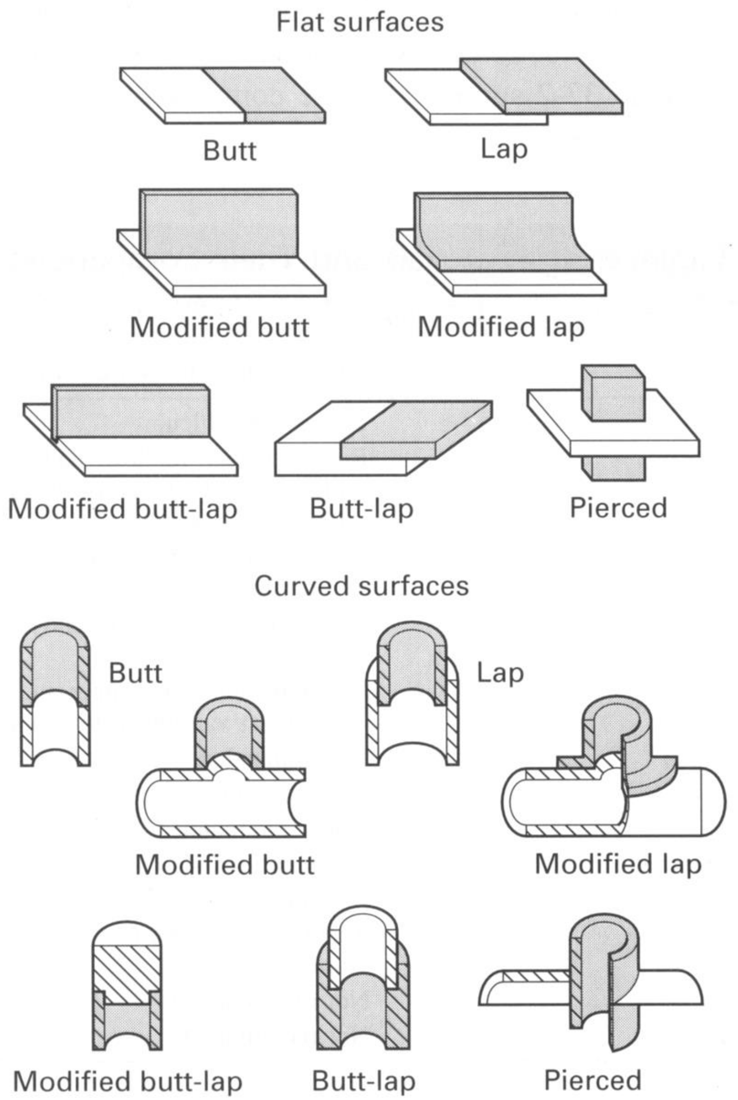


FIGURE 37-5 Some common designs of brazed joints for flat and curved surfaces. *(Adapted from* The Brazing Book, *Handy & Harman).*

FIGURE 37-4 Typical furnace-brazed assemblies. *(Courtesy of Pacific Metals Company.)*

Brazed Joint DESIGN

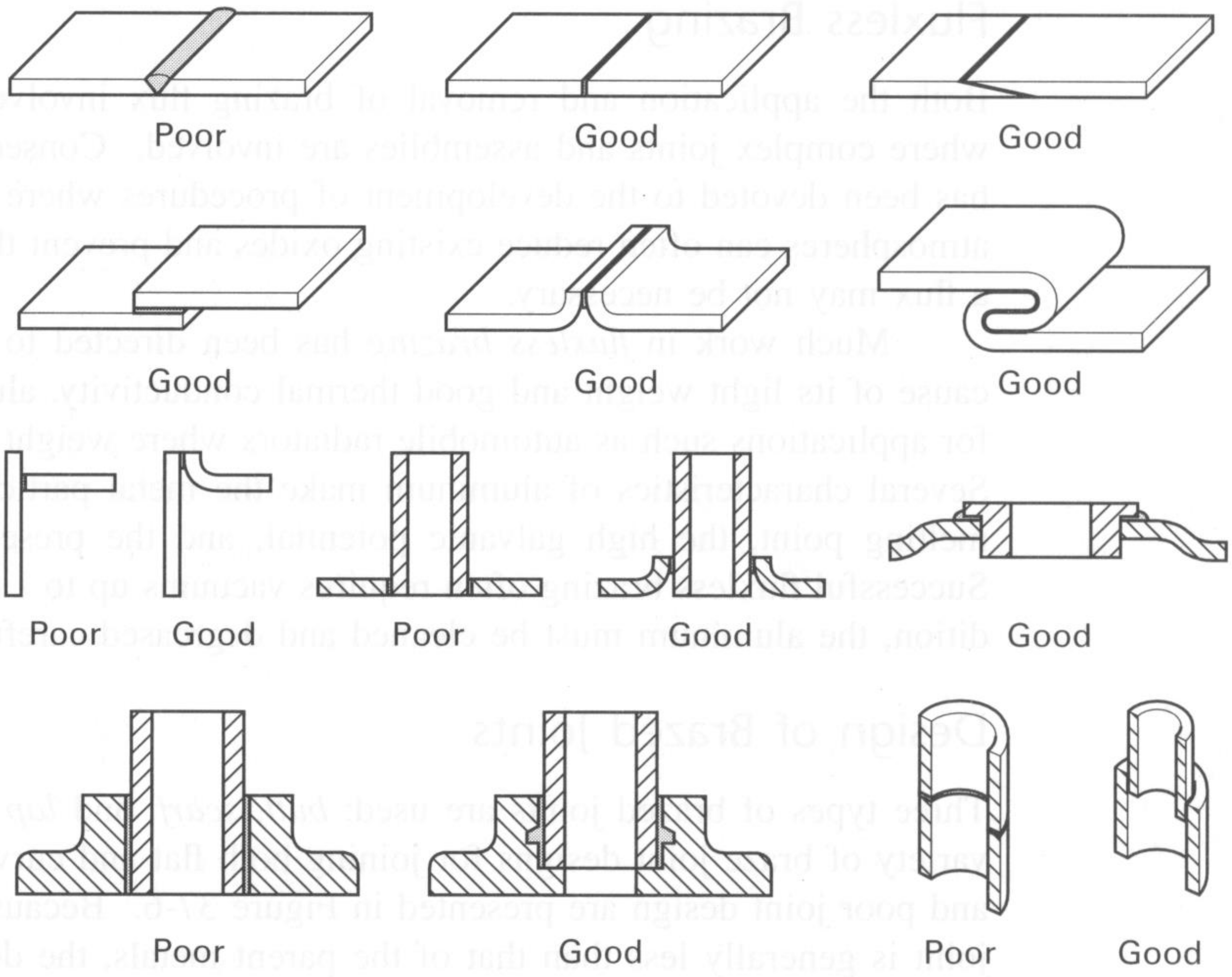


FIGURE 37-6 Examples of good and bad joint design for brazing.

Brazed Joint DESIGN

- Material effects should be considered during joint design - important role in braze strength

TABLE 37-2. Engineering Materials and Their Compatibility with Brazing

Material	Brazing Recommendation
Cast iron	Somewhat difficult
Carbon and low-alloy steels	Recommended for low- and medium-carbon materials; difficult for high-carbon materials; seldom used for heat-treated alloy steels
Stainless steel	Recommended; Silver and nickel brazing alloys are preferred
Aluminum and magnesium	Common for aluminum alloys and some alloys of magnesium
Copper and copper alloys	Recommended for copper and high-copper brasses; somewhat variable with bronzes
Nickel and nickel alloys	Recommended
Titanium	Difficult, not recommended
Lead and zinc	Not recommended
Thermoplastics, thermosets, and elastomers	Not recommended
Ceramics and glass	Not recommended
Dissimilar metals	Recommended, but may be difficult, depending on degree of dissimilarity
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Not recommended

Braze Welding

- Capillary action is not used to distribute filler metal. Filler is deposited by gravity (like OFW) using an oxyacetylene torch.
- Used as a lower temperature method for repairing steel and ferrous castings, joining cast irons.
- Since low temp, warping is minimized, and no change of crystal structure. Does not require wetting surfaces (no capillary)
- Allows build up of filler metal to achieve full strength though.

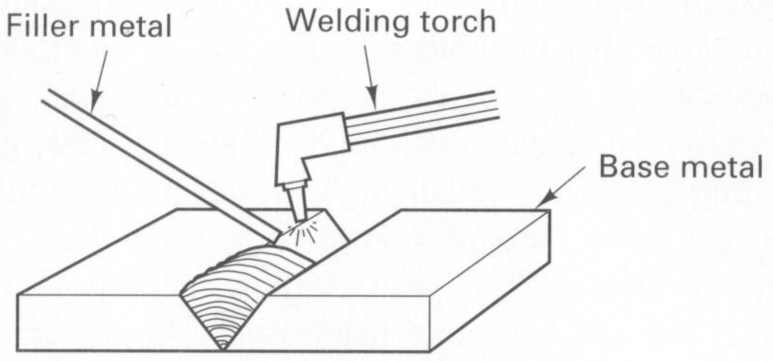


FIGURE 37-7 Schematic of the braze welding process.

Soldering

- Brazing-type operation where filler metal melting point is below 450^{o}C (840^{o}F). Typically used for connecting thin metals, electronic components (mostly where higher temperature should be avoided)
- Important steps in making a good soldered joint:
  - design of acceptable joint
  - selection of correct solder metal for the job
  - selection of proper flux
  - cleaning surfaces
  - application of flux, solder and heat to fill joint by capillary action
  - removing residual flux if required.

Solder Joint Design

- Used for wide variety of sizes, shapes and thickness joints. (clearance)
- Extensively used for electrical couplings and gas/air-tight seals.
- Shear strength is usually less than 2MPa. So if more strength required usually combined with other form of mechanical joint as seam-lock.
- Avoid butt joints, and soldering where joint is subject to peeling.
- Parts need to be held firmly until solder is completely solidified.
- Flux should be removed after soldering (method depends on type of flux; water, alcohol etc.).

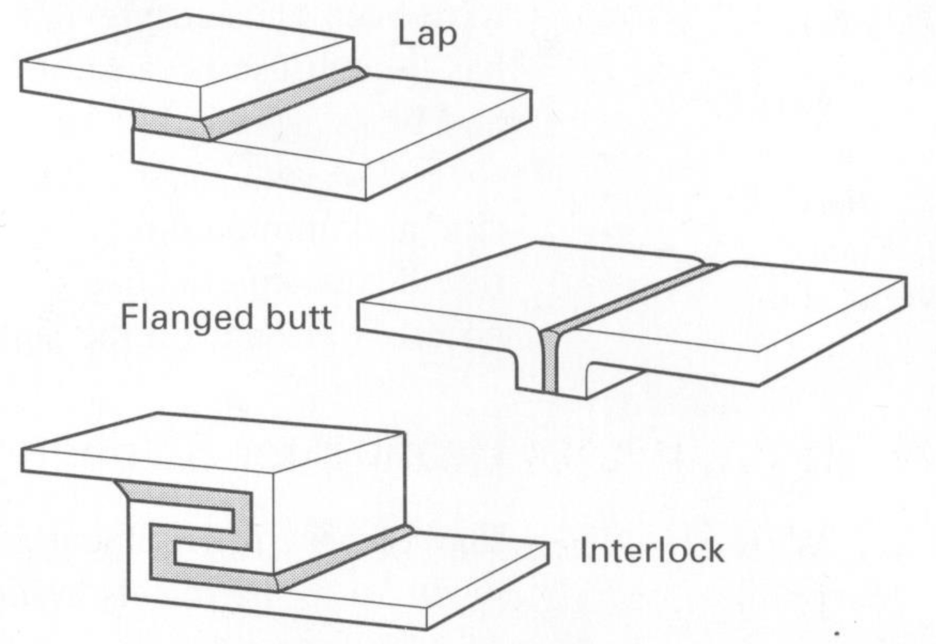


FIGURE 37-8 Some common designs for soldered joints. (C

Metals to be Joined

TABLE 37-4. Engineering Materials and Their Compatibility with Soldering

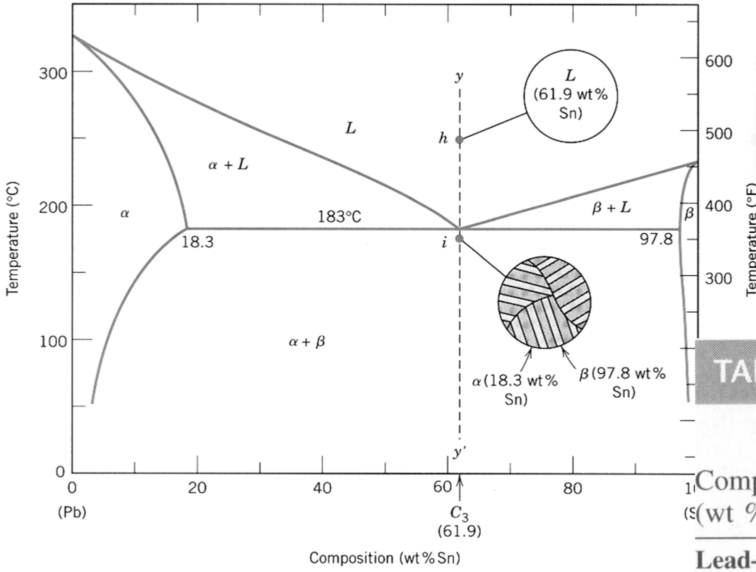
Material	Soldering Recommendation
Cast iron	Seldom used since graphite and silicon inhibit bonding
Carbon and low-alloy steels	Difficult for low-carbon materials; seldom used for high-carbon materials
Stainless steel	Common for 300 series; difficult for 400 series
Aluminum and magnesium	Seldom used; however, special solders are available
Copper and copper alloys	Recommended for copper, brass, and bronze
Nickel and nickel alloys	Commonly performed using high-tin solders
Titanium	Seldom used
Lead and zinc	Recommended, but must use low-melting-temperature solders
Thermoplastics, thermosets, and elastomers	Not recommended
Ceramics and glass	Not recommended
Dissimilar metals	Recommended, but with consideration for galvanic corrosion
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Not recommended

- Copper, silver, gold, tin plated steels easily joined
- Aluminum (has strong oxide film) so difficult to solder unless using special fluxes and modified techniques (used in automotive radiators)

Solder Metals

- Usually low MP alloys Lead-Tin alloys (+ antimony 0.5%)
  - low cost, reasonable mechanical properties.
  - Good knowledge base
  - plumbing, electronics, car-body dent repair, radiators.
- Tin is more expensive than lead, so lower tin compositions used unless lower melting point, higher strength, higher fluidity required.
- High melting point – higher lead content (cheaper)
- “Mushy” wiping solder has 30-40% tin.
- Low melting point solder has eutectic composition (62%Sn - 38%Pb) fast melting, fast freezing, high strength.

Solder Metals



- Lead-free solders - Used where lead toxicity may be a problem. (water supplies etc).

TABLE 37-3. Some Common Solders and Their Properties

Composition (wt %)	Freezing Temperature (°F) Liquidus	Solidus	Range	Applications
Lead–tin solders				
98 Pb–2 Sn	611	601	10	Side seams in three-piece can
90 Pb–10 Sn	576	514	62	Coating and joining metals
80 Pb–20 Sn	531	361	170	Filling and seaming auto bodies
70 Pb–30 Sn	491	361	130	Torch soldering
60 Pb–40 Sn	460	361	99	Wiping solder, radiator cores, heater units
50 Pb–50 Sn	421	361	60	General purpose
40 Pb–60 Sn	374	361	13	Electronic (low temperature)
Silver solders				
97.5 Pb–1 Sn–1.5 Ag	588	588	0	Higher-temperature service
36 Pb–62 Sn–2 Ag	372	354	18	Electrical
96 Sn–4 Ag	430	430	0	Electrical
Other alloys				
45 Pb–55 Bi	255	255	0	Low temperature
43 Sn–57 Bi	281	281	0	Low temperature
95 Sn–5 Sb	464	450	14	Electrical
50 Sn–50 In	257	243	14	Metal-to-glass
37.5 Pb–25 In–37.5 Sn	280	280	0	Low temperature

- Other alloys include
- Tin-antimony (higher melting points)
- Bismuth
- Tin-indium

Soldering Fluxes

- Same principles as brazing so surfaces must be clean; mechanical or chemical cleaning.
- Fluxes remove surface oxides:
- Corrosive: muriatic acid, zinc/ammonium chlorides. Al, steels, copper, brass, bronze….
- Non-corrosive: rosin (residue after distilling turpentine), good for copper, brass, tin or silver -plated surfaces

- **Heating for Soldering**
- Similar to brazing, (furnace and salt bath heating is not usually used)
- Wave soldering is used for wires while dip soldering for auto parts
- Hand soldering is done by solder iron and oxy fuel torch

MECH 423 Casting, Welding, Heat Treating and NDT

Time: _ T _ _ _17:45 - 20:15

Credits: 3.5 Session: Fall

Welding Joints & Metallurgy

Lecture 11

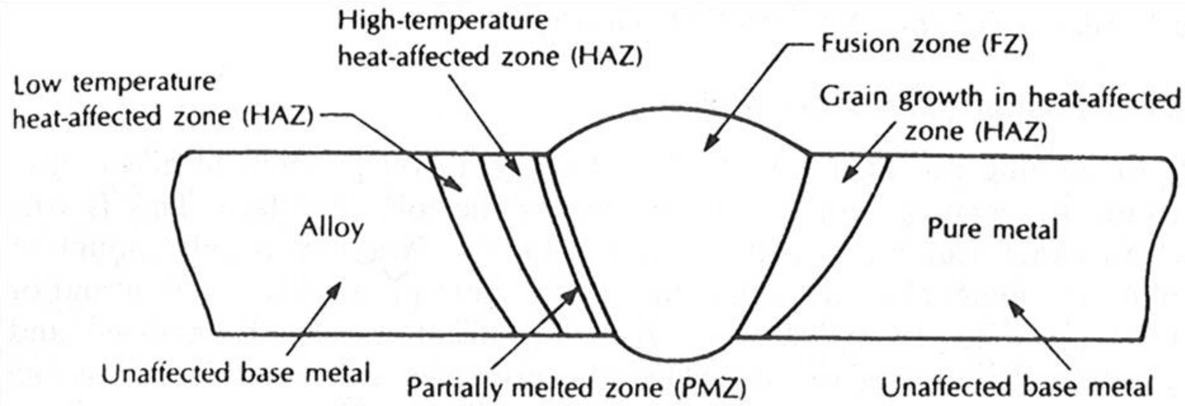
Flow of Heat in Welds

- Heat (energy) is introduced into workpiece to cause melting during fusion welding. Not all heat contributes to melting. Some conducted away raising temperature of surrounding material causing (unwanted) metallurgical & geometrical changes - AKA – HAZ.
- How the heat is distributed directly influences:
  - the rate and extent of melting; (affects weld volume, shape, homogeneity, shrinkage, distortion, related defects).
  - the rate of cooling and solidification; (solidification structure, related properties).
  - the rate of heating and cooling in the HAZ; (thermally induced stresses, cooling rate in solidification zone, structural changes in HAZ, distortion, residual stresses).

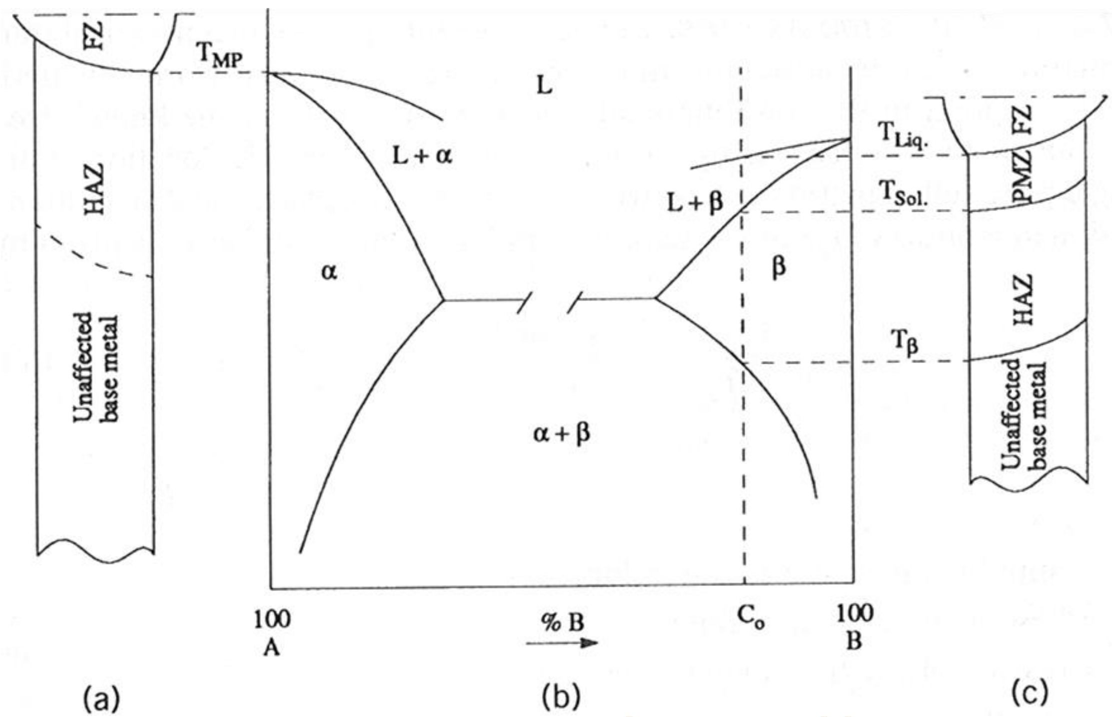
Weld Zones Prediction

- A fusion weld produces several distinct microstructural zones in both pure metals and alloys.
- Fusion zone, FZ: – portion of metal that is melted during welding (above Tm or TL for alloy).
- Partially Melted Zone, PMZ: – for an alloy where temperature is between TLiquidus and TSolidus. (No PMZ in pure metal).
- Heat Affected Zone HAZ: – portion of base material that was not melted but whose properties are affected by heat of welding (phase transformation, reaction).
- Unaffected Base Material UBM: – portion of base material which has not been affected by welding heat.

Weld Zones Prediction



The various microstructural zones formed in fusion welds between a pure metal (right) and an alloy (alloy).



Schematic of the distinct zones in a fusion weld in a pure metal (a) and an alloy (c) as these correspond to phase regions in the hypothetical phase diagram shown (b).

Simplified welding equations.

Peak Temperatures in solid metal:

$$\frac{1}{T_P - T_0} = \frac{(2\pi e)^{0.5} \rho C h y}{H_{net}} + \frac{1}{T_m - T_0}$$

where:

T_0 = temperature of workpiece at start of welding (K)

T_P = Peak temperature at distance y from fusion boundary (K)

T_m = melting temperature (or liquidus) of metal being welded (K)

ρ = density of metal ($g.m^{-3}$)

C = specific heat ($J.g^{-1}.K^{-1}$)

H_{net} = heat input ($J.m^{-1}$) = q/v = $\eta EI/v$ for arc welding processes

h = thickness of base material (m)

e = base of natural logarithms (2.718)

y = distance form fusion zone (= 0 at the fusion zone, where $T_P = T_m$) (m)

Solidification rate

The rate at which weld metal solidifies can have a strong effect on microstructure and properties.

Solidification time, S_t , in seconds:

$$S_t = \frac{LH_{net}}{2\pi k\rho C(T_m - T_0)^2}$$

where:

L = Latent heat of fusion (J/m^3)

T_0 = temperature of workpiece at start of welding (K)

T_m = melting temperature (or liquidus) of metal being welded (K)

k = thermal conductivity ($J.m^{-1}.s^{-1}. K^{-1}$)

ρ = density of metal ($g.m^{-3}$)

C = specific heat ($J.g^{-1} .K^{-1}$)

H_{net} = heat input ($J.m^{-1}$) = q/v = $\eta EI/v$ for arc welding processes

Cooling Rates

Final metallurgical state of FZ and HAZ is primarily determined by cooling rates. Affects fineness/coarseness of grains, homogeneity, phases, microconstituents etc. Especially in steels where some phase transformations are dependent on cooling rate (fast cooling can produce hard, brittle martensite).

For a single pass in a butt joint between thick plates (> 6 passes) of equal thickness:

$$R = \frac{2\pi k\left(T_C - T_0\right)^2}{H_{net}}$$

where:

R = cooling rate at the weld centreline (K/s)

T_0 = initial temperature of workpiece (K)

T_C = temperature at which cooling rate is calculated (K)

k = thermal conductivity ($J.m^{-1}.s^{-1}. K^{-1}$)

H_{net} = heat input ($J.m^{-1}$) = q/v = $\eta EI/v$ for arc welding processes

For thin plates (< 4 passes):

$$R = 2\pi k\rho C\left(\frac{h}{H_{net}}\right)^2 (T_C - T_0)$$

where:

R = cooling rate at the weld centreline (K/s)

T_0 = initial temperature of workpiece (K)

T_C = temperature at which cooling rate is calculated (K)

k = thermal conductivity ($J.m^{-1}.s^{-1}. K^{-1}$)

ρ = density of metal ($g.m^{-3}$)

C = specific heat ($J.g^{-1} .K^{-1}$)

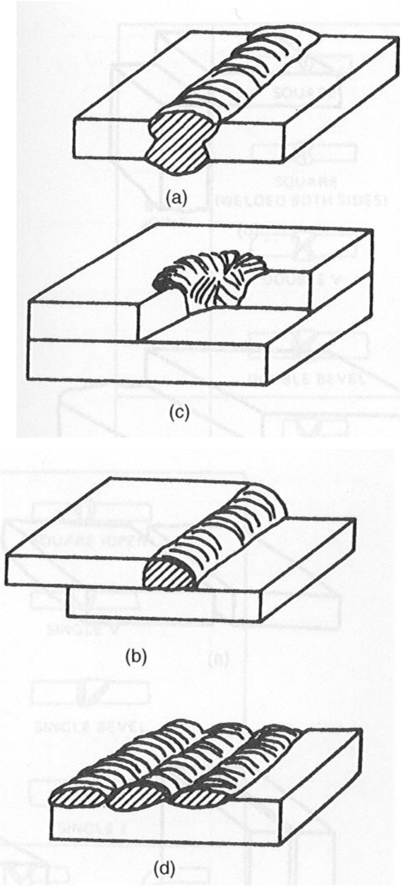
ρC = volumetric specific heat ($J.m^{-1} .K^{-1}$)

H_{net} = heat input ($J.m^{-1}$) = q/v = ηEI/v for arc welding processes

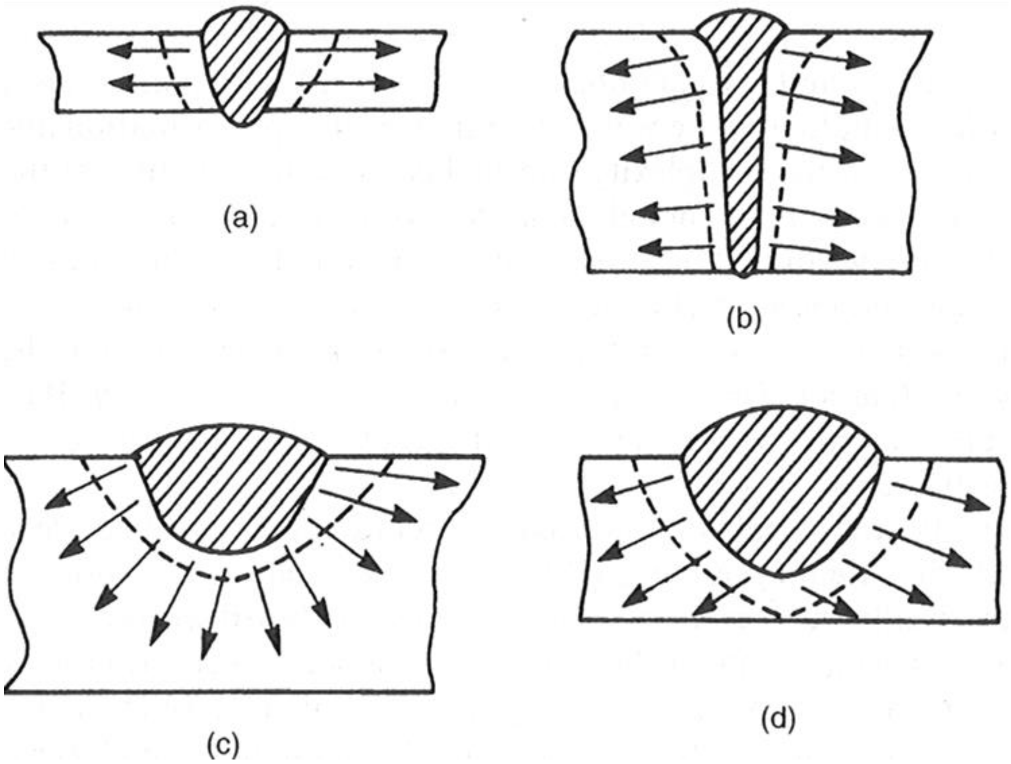
Note: increasing the initial temperature, T_0, (by preheating) decreases the cooling rate,R.

Weld Joint Configuration

- Heat flow in weld is affected by size and shape of weld.
- Surfacing or Bead welds, made directly, no surface preparation. Used for joining thin sheets, adding coatings over surfaces (wear resistance)
- Groove Welds – full thickness strength, done as V, Double V u, and J (one side prepared). The type of groove depends on the thickness of the joint, weld process and position



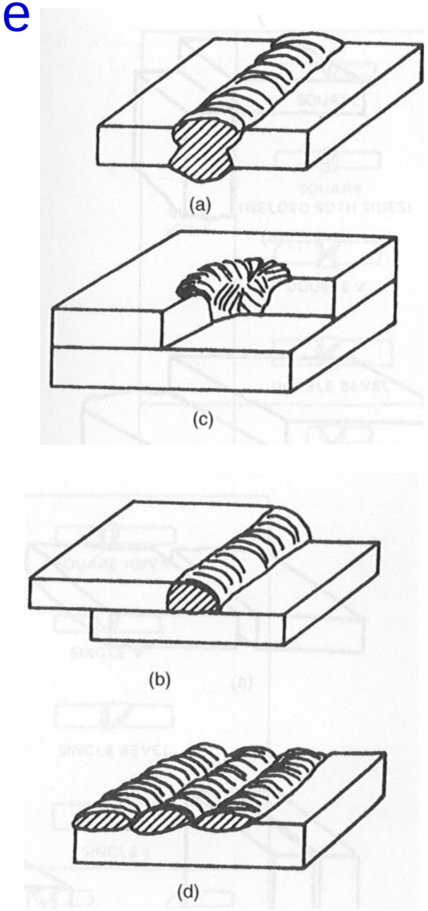
Fundamental types of welds, including (a) groove, (b) fillet, (c) plug, and (d) surfacing.



Schematic of the effect of weldment and weld geometry on the dimensionality of heat flow: (a) two-dimensional heat flow for full-penetration welds in thin plates or sheets; (b) two-dimensional heat flow for full-penetration welds with parallel sides (as in EBW and some LBW); (c) three-dimensional heat flow for partial- penetration welds in thick plate; and (d) an intermediate, 2.5-D condition for near-full-penetration welds.

Weld Joint Configuration

- Fillet Welds, used for tee, lap or corner joints. No edge preparation. Size of the weld is measured by the largest 45° right triangle that could be drawn in the weld cross section.
- Plug Weld – attach one part over another replacing rivets are bolts. Normally a hole is made on the top plate and welding done at the bottom of the hole
- Five basic weld designs and some typical joints are shown in the figure



Fundamental types of welds, including (a) groove, (b) fillet, (c) plug, and (d) surfacing.

Weld Joint Configuration

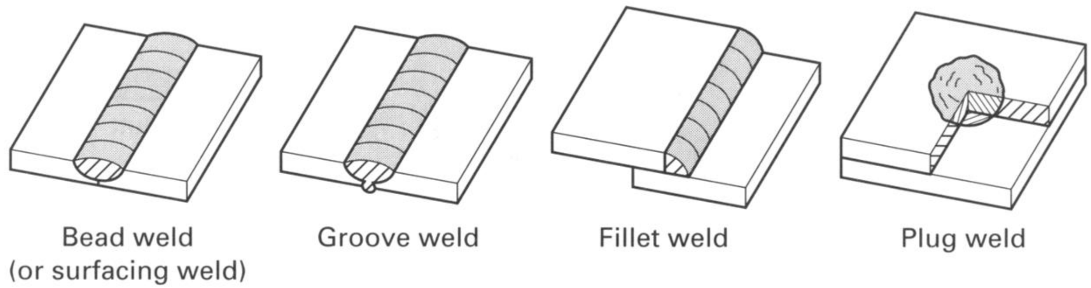


FIGURE 39-1 Four basic types of fusion welds.

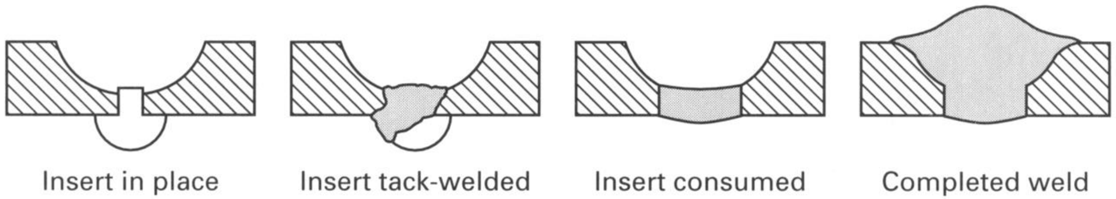


FIGURE 39-2 Use of a consumable backup insert in making fusion welds. *(Courtesy of Arcos Corporation.)*

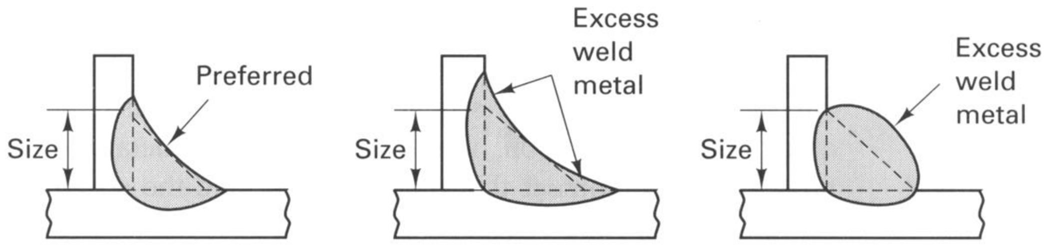


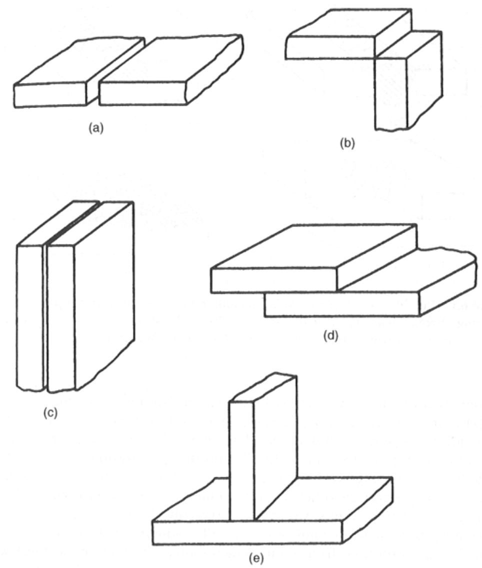
FIGURE 39-3 Preferred shape and the method of measuring the size of fillet welds.

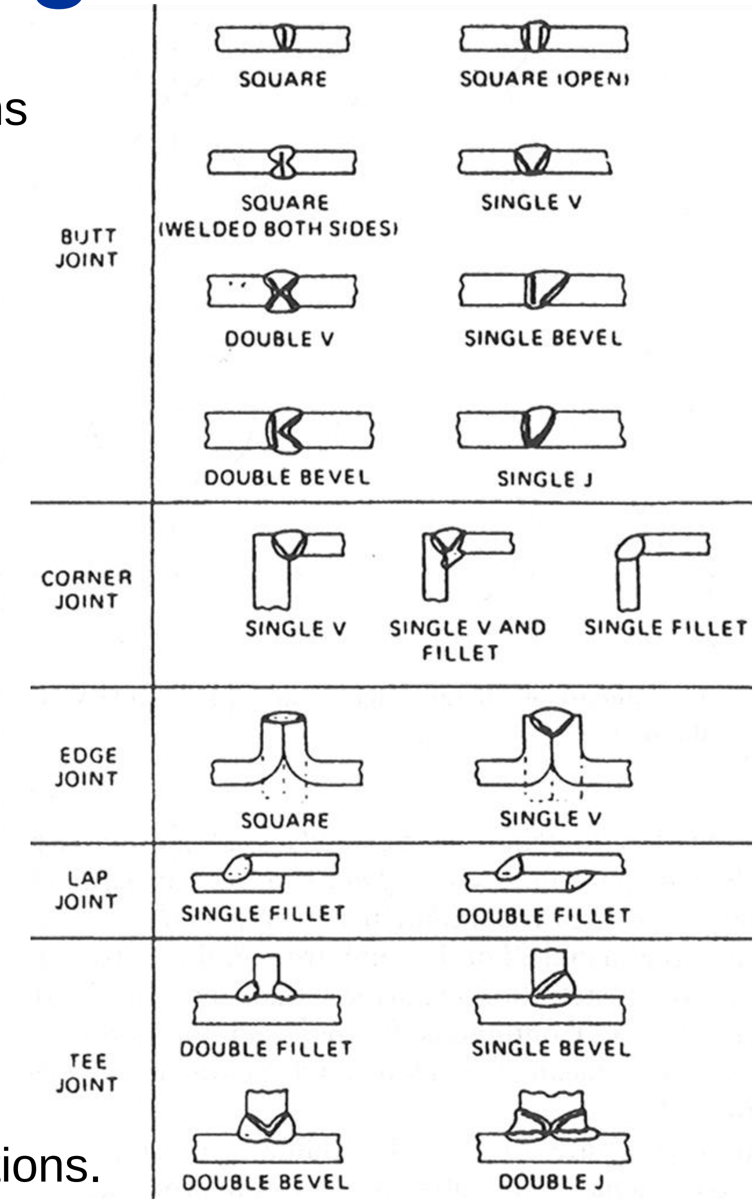
- Inserts are used in pipelines or other places where welding is restricted to one side only

Weld Joint Configuration

- Type of loading will decide the type of joint, to prevent failure
- Accessibility and cost are other considerations
- Cost is affected by the amount of weld metal, type of weld equipment, speed and ease of welding

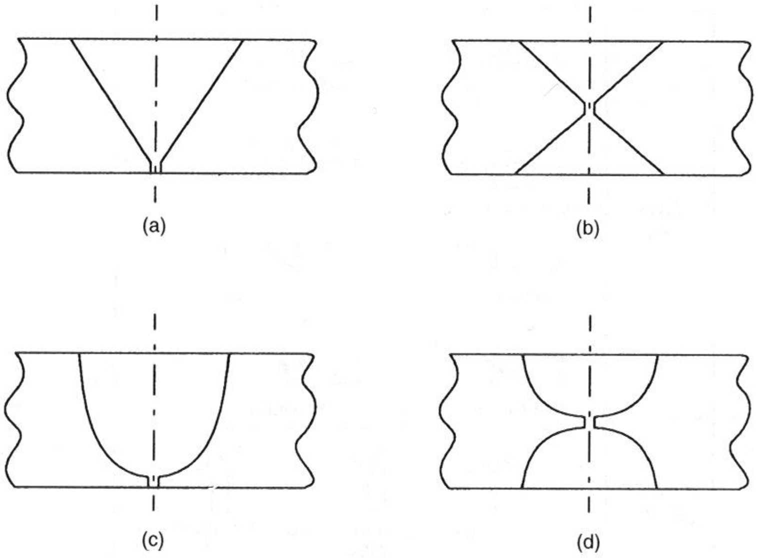
Five basic weld designs (a) butt, (b) corner, (c) edge, (d) lap, (e) tee.





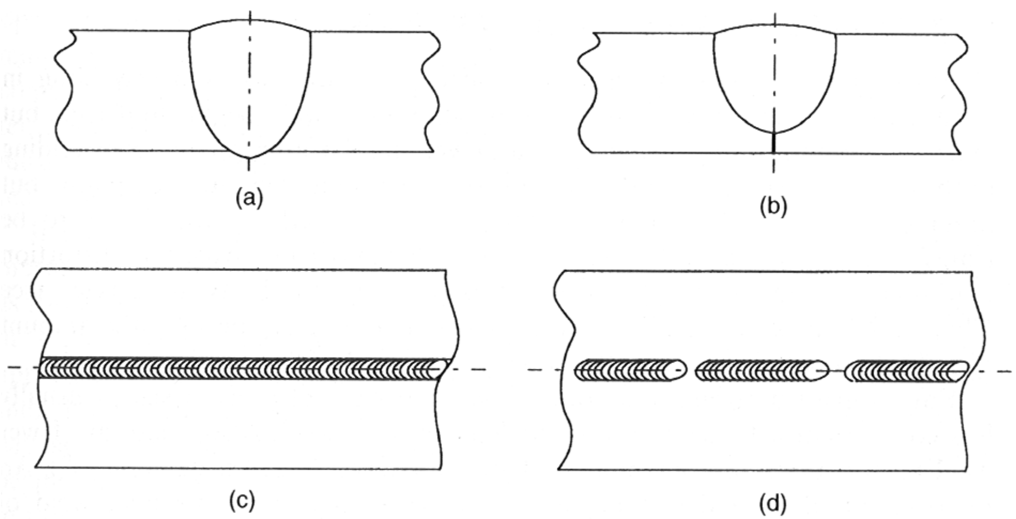
Some typical weld joint variations.

Weld Joint Configuration



(a) Single V, (b) double V, (c) single U, (d) double U joints. Require filler metal.

(a) Full penetration, (b) partial penetration, (c) continuous, (d) intermittent welds.



Weld Joint Configuration

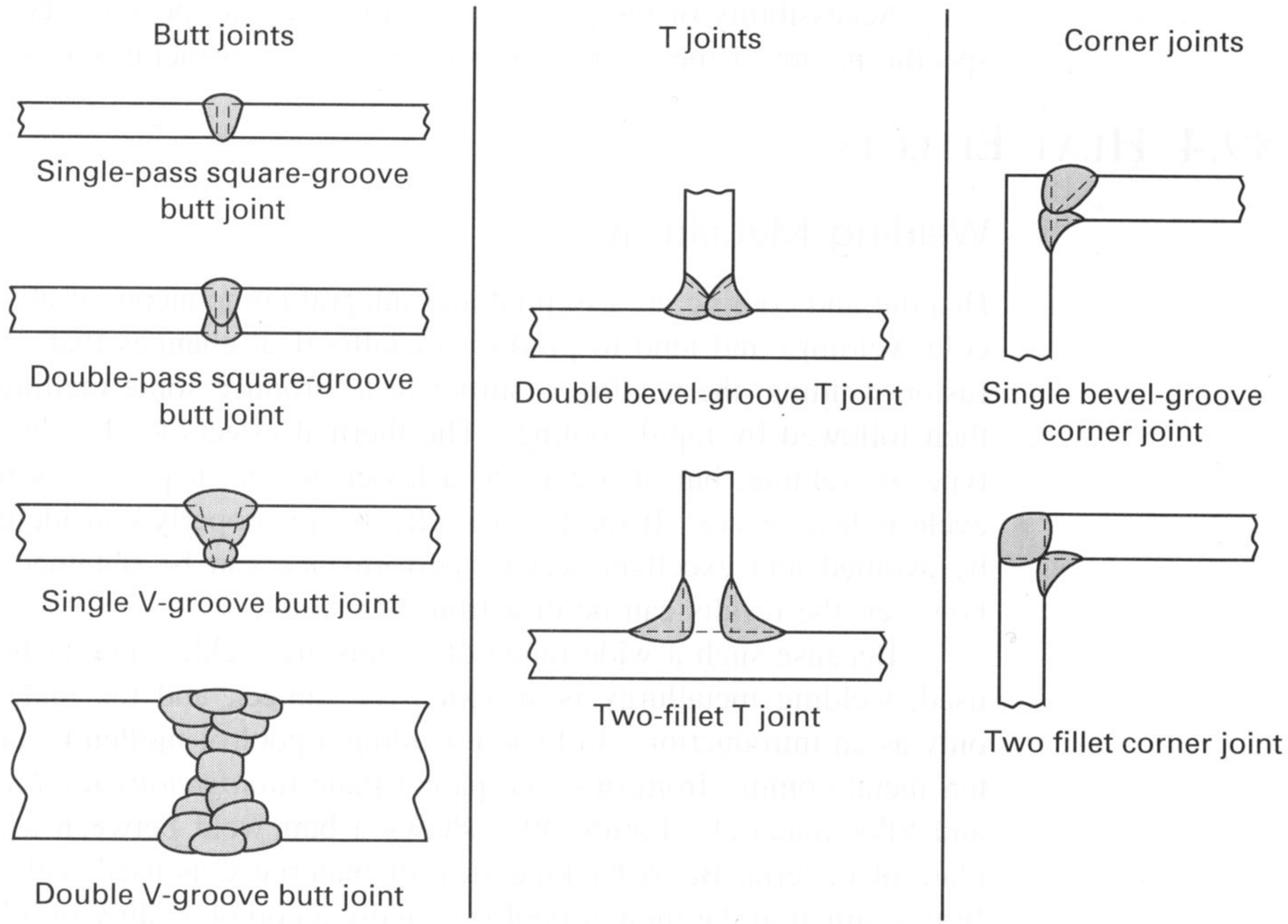


FIGURE 39-5 Various weld procedures used to form several common joints. *(Courtesy of Republic Steel Corporation.)*

Weld Joint Configuration

- Straight butt joints do not require filler metal as long as faces abut tightly (gaps less than 1.5 mm) usually requires machined surface (not sawn) – GTAW, PAW, LBW, EBW .
- Other joint configurations (V, double V, J, U etc) require filler metal and preparation is made by cutting, machining etc. – SMAW, FCAW, GMAW, SAW.
- Likewise with corner and edge joints. Some can be done without preparation, others require machining.

Weld Design Considerations

- Welding is a unique process producing monolithic structures (one-piece from 2 or more pieces welded together)
- If pieces joined together, and if there is a crack in one, it does not propagate to other piece normally.

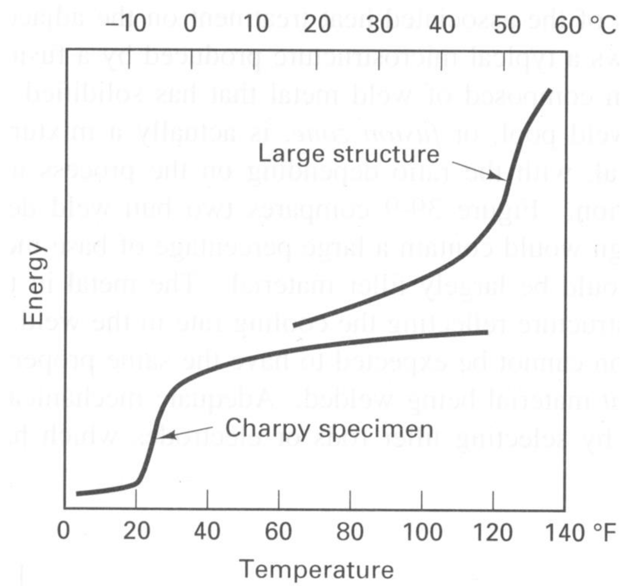


FIGURE 39-6 Effect of size on the transition temperature and energy-absorbing ability of a certain steel.

- In case of welding, since it becomes single piece, crack can propagate through to other piece. (The crack can initiate in the weld or otherwise). - reflects the monolithic nature of welding process.
- Another consideration is small pieces may behave differently compared to larger pieces of steel (shown in figure)

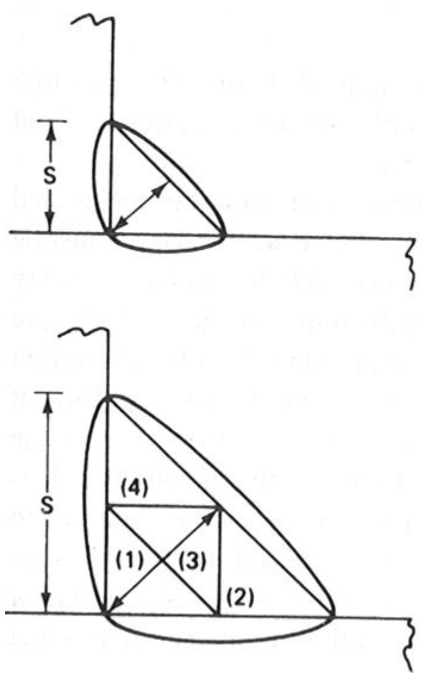
Weld Design Considerations

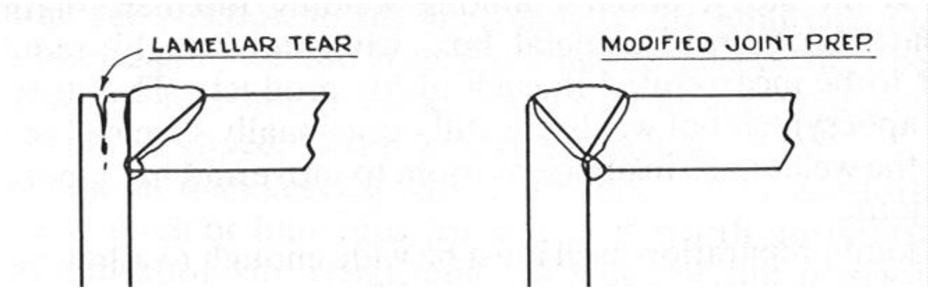
- Joint designed primarily for load-carrying ability.
- Variable in design and layout can affect costs, distortion, reliability, inspection, corrosion, type of defects.
- Select design that requires least amount of weld metal. (minimizes distortion, residual stresses).

1. Where possible use square grooves (cheaper) and partial penetration (helps maintain dimensions – unmelted metal in contact) except where stress raisers cannot be tolerated (fatigue).
2. Use lap and fillet (instead of groove) welds where fatigue is not a problem (cheaper).

Weld Design Considerations

3. Use double-V double-U (instead of single-V or –U) for thick plates (reduces weld metal vol.; controls distortion & balances heat input).
4. For corner joints in thick plates where fillet welds are inadequate, bevel both plates to reduce tendency for lamellar tearing.
5. Design so weld can be accessed and inspected.
6. Over designing is a common problem in welding that should be avoided (causes excessive weight and costs – as a fillet weld side increases x2 the weld metal increases by x4





Weld Metallurgy

- Remember(?)
- **HEAT TREATMENT** and how various microstructures + properties can be obtained by different cooling rates.
- **CASTING** - liquids shrink on solidifying, type of grain structures, segregation, etc.
- **WELDING -** combines both usually:
  - Melting + solidifying of weld pool
  - Varying heating/cooling rates

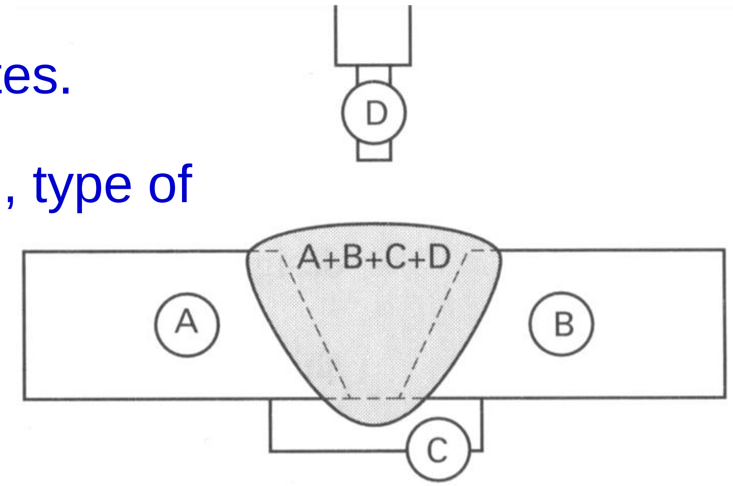


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

Weld Metallurgy

- Figure shows a welding where Metals A and B are welded with Metal C as a backing plate and Metal D as a filler
- Molten pool is a complex alloy of ABCD held in place by metal mould (formed by solids)
- Fusion welding can be viewed as a casting with small amount of molten metal
- Resultant structure can be understood if it is analyzed as casting and subsequent heat treating

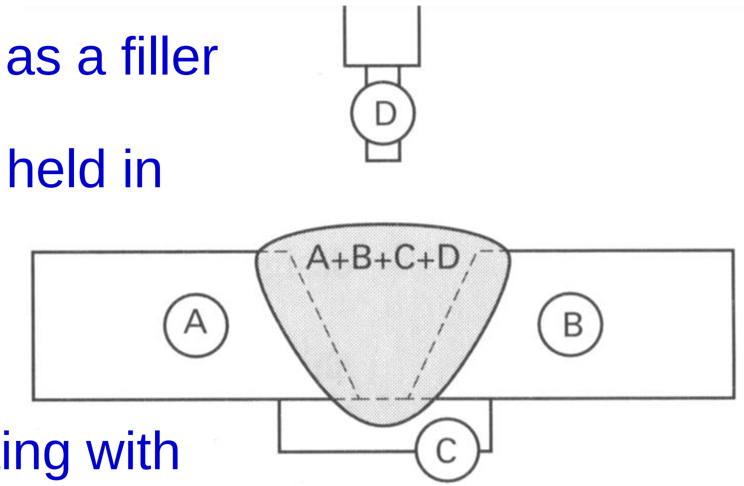


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

Weld Fusion Zone

- The composition of the material in the weld pool depends on the joint design
- Upper design has more base and lower one has more filler metal
- Microstructure in this zone depends purely on the cooling rate of the metal as in casting
- This region cannot have properties similar to that of the wrought parent metal
- Mainly because casting is inferior to wrought products and metal in the fusion zone has solidified from molten state as in casting

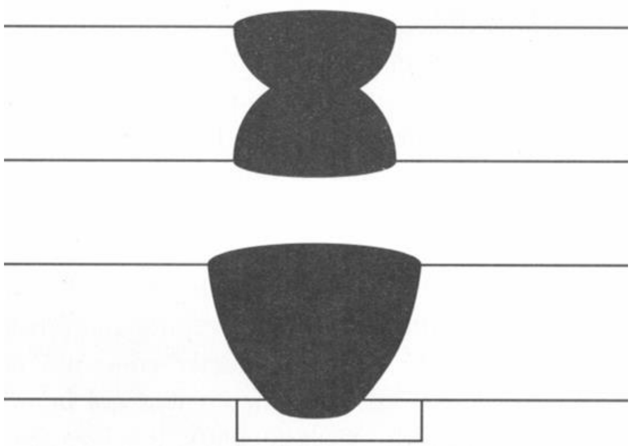
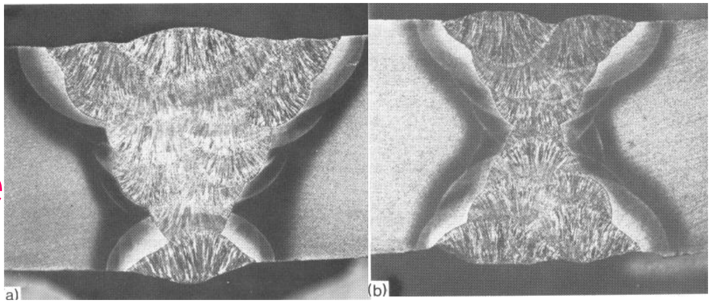


FIGURE 39-9 Comparison of two butt-weld designs. In the top weld, a large percentage of the weld pool is base metal. In the bottom weld, most of the weld pool is filler metal.

Weld Fusion Zone

- All of these can affect microstructure
  - Heating up to welding temperature
  - Cooling down from welding temperature
  - Holding at temperature during welding
  - Formation of molten metal
  - Solidification of molten metal



Manual arc multi-pass welds of (a) single vee-butt and (b) double vee-butt weld. Plate is 180mm (7”) thick!

- As weld can be considered as a mini-“casting”:
  - cast metal is always inferior to **same** alloy in wrought condition.
  - Good mechanical properties can be attained only if the filler metal has properties (in as deposited condition) superior to or equal to that of parent wrought metal

Weld Fusion Zone

- So may use filler metal/electrode of slightly different composition.
- Structure is changed (due to melting and solidification in short time due to low volume of molten metal).
- Fusion zone is "casting". Cooling rates influence grain structure
- Variation in grain structure, gas porosity, shrinkage, cracks and similar to that of casting
- Contributing factors include: impurities, base metal dilution of filler, turbulence & mixing, "casting" and "mould" interact, large temperature gradients, dynamic (moving) process etc.

Weld Fusion Zone

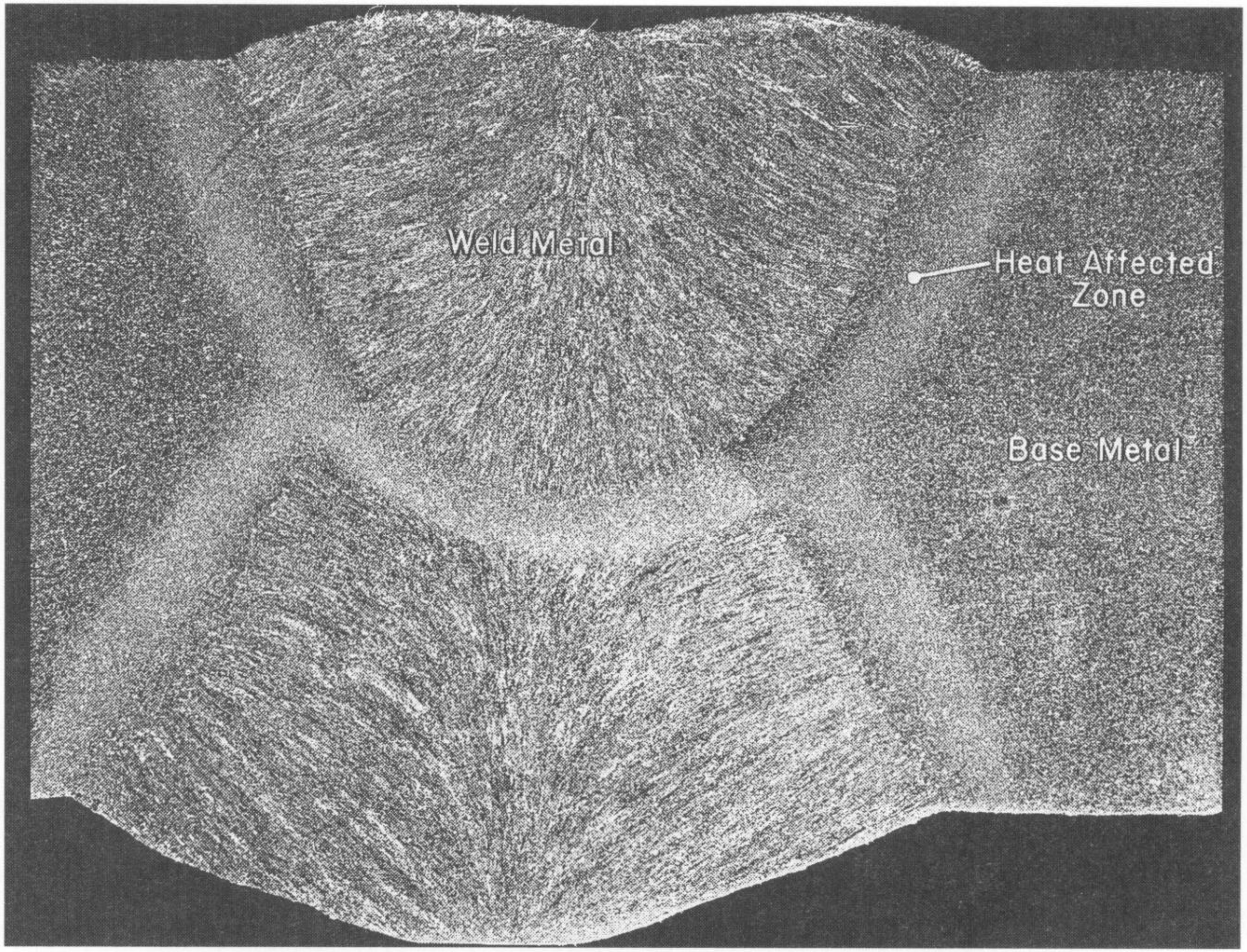


FIGURE 39-8 Grain structure and various zones in a fusion weld.

Heat Affected Zone - HAZ

- Adjacent to Fusion zone is region where temperature is not sufficient to cause melting but is often high enough to change the microstructure. (an abnormal, widely varying heat treatment).
  - Phase transformations
  - recrystallisation
  - grain growth
  - precipitation/coarsening
  - Embrittlement, cracking
- Steels can get anywhere from brittle martensite to coarse pearlite.
- Usually HAZ is weakest region in material (especially if base material is cold-worked or precipitation hardened).

Heat Affected Zone - HAZ

- Altered structure – so no longer have positives of parent metal
- Not molten – cannot assume properties of solidified weld metal
- Making this the weakest zone in the weld

If there are no obvious defects like cracks in the weld zone, normally the weld starts to fail in HAZ

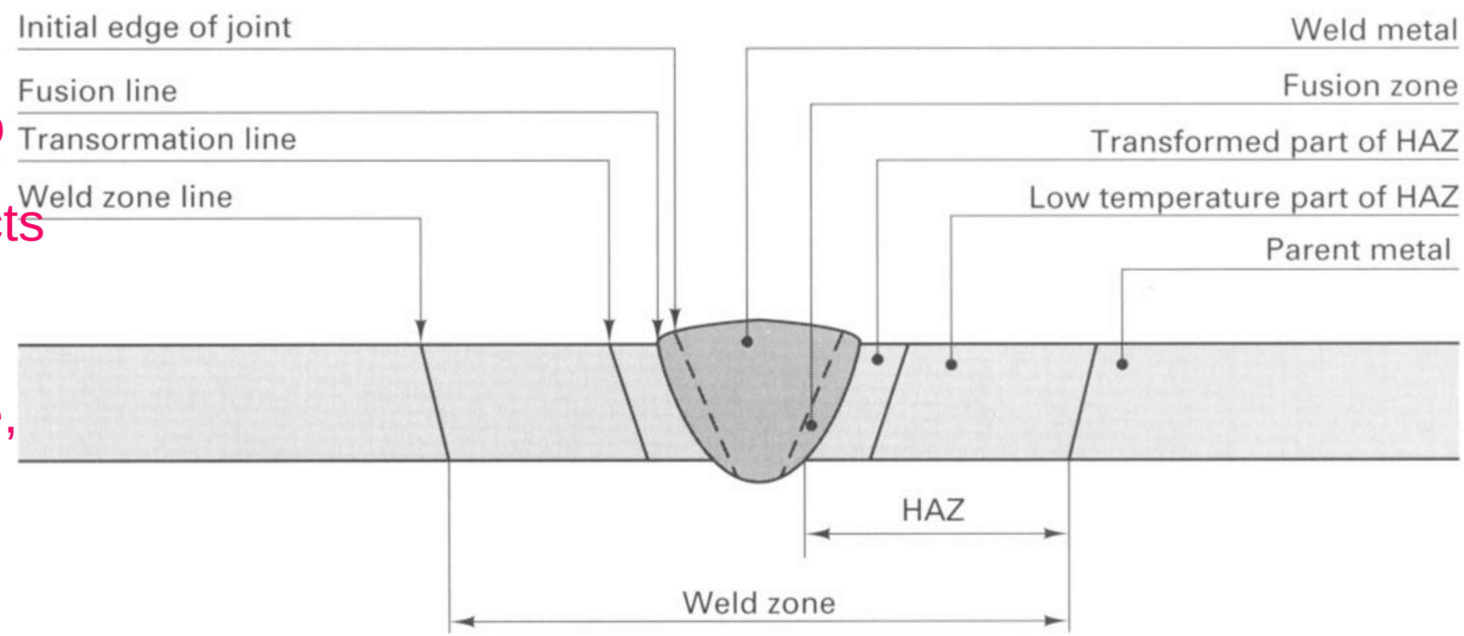


FIGURE 39-10 Schematic of a fusion weld in steel, presenting proper terminology for the various regions and interfaces. Part of the heat-affected zone has been heated above the transformation temperature. *(Courtesy of Sandvik AB.)*