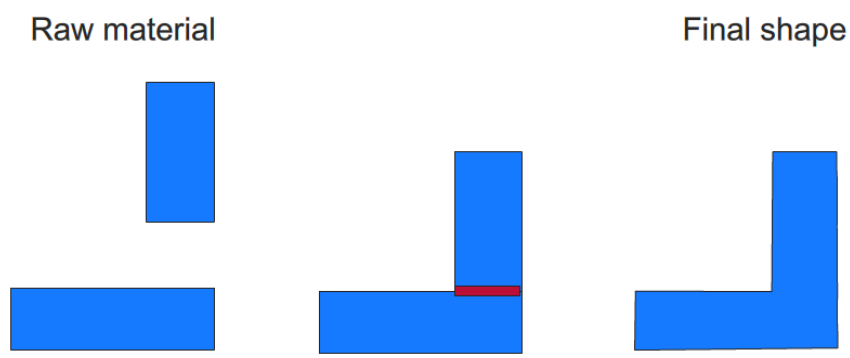
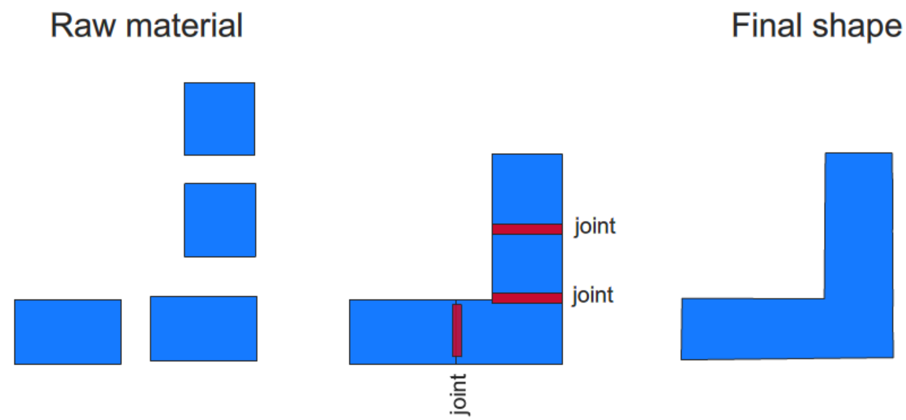
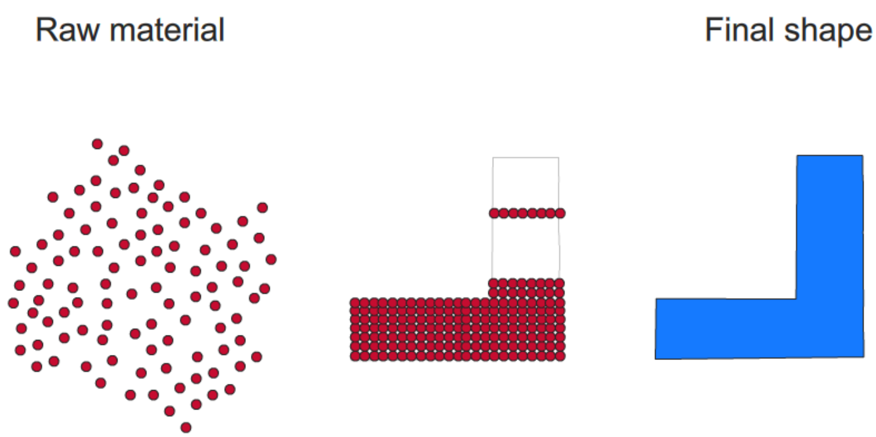
ME2300: Manufacturing Processes
Jan-May 2020

Shaping by joining (Introduction)

Introduction







Can we think of some single component product

Products are usually made up of multiple parts

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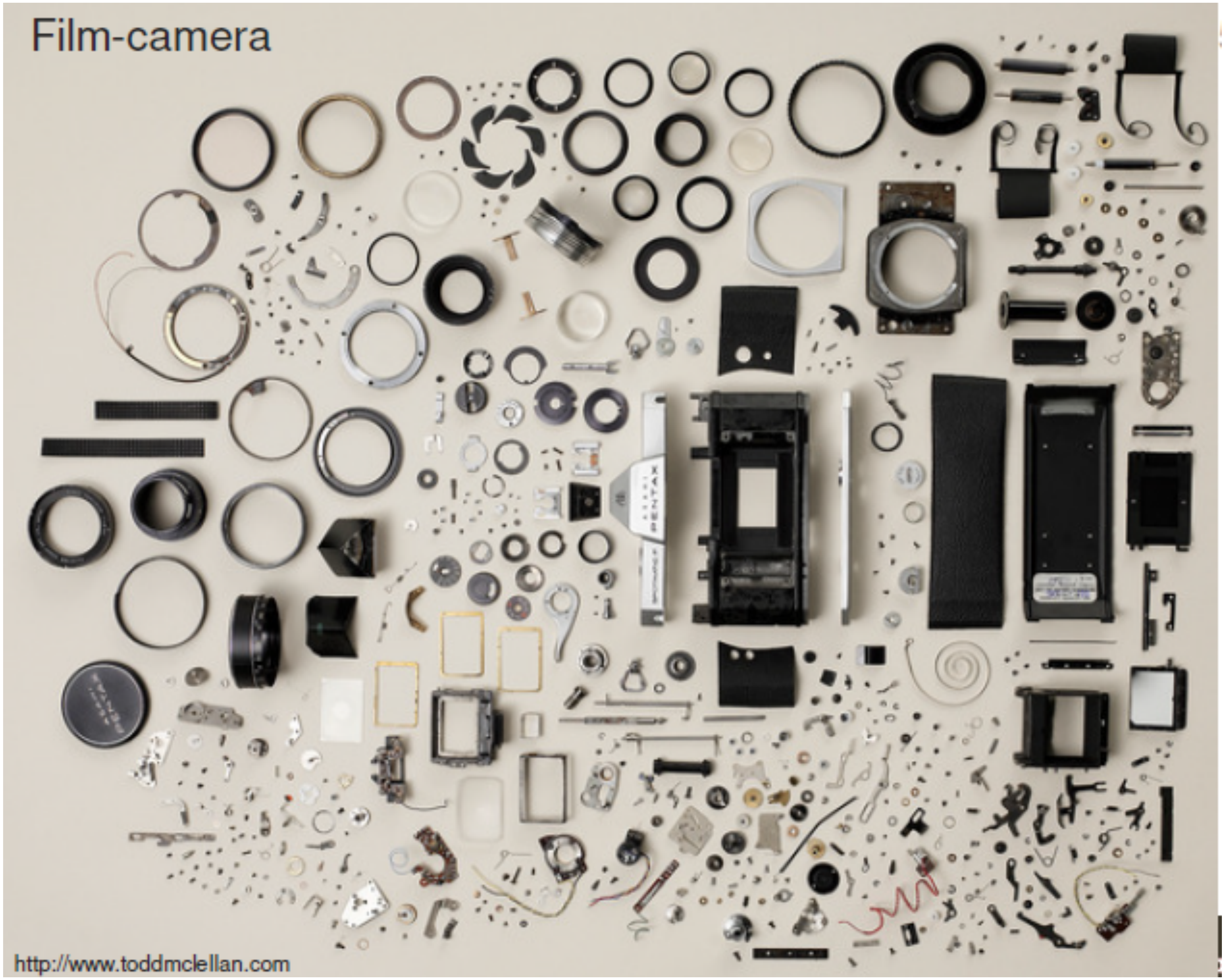


Joining finite shapes

• Make finite shapes separately using primary manufacturing methods (phase change, deformation, mass change etc.) and then join them

• Why do this? Can we not make one comprehensive shape?

– Many times different materials are needed for different functions and applications in the same product

– It may not be possible to make an integral big complex shape

• Joining or assembly of finite shapes may be done

– To completely arrest movement of the joined parts - e.g in all 6 degrees of freedom (DoF)

– To arrest movement in only some DoF while permitting motion in others

-Material specific functions

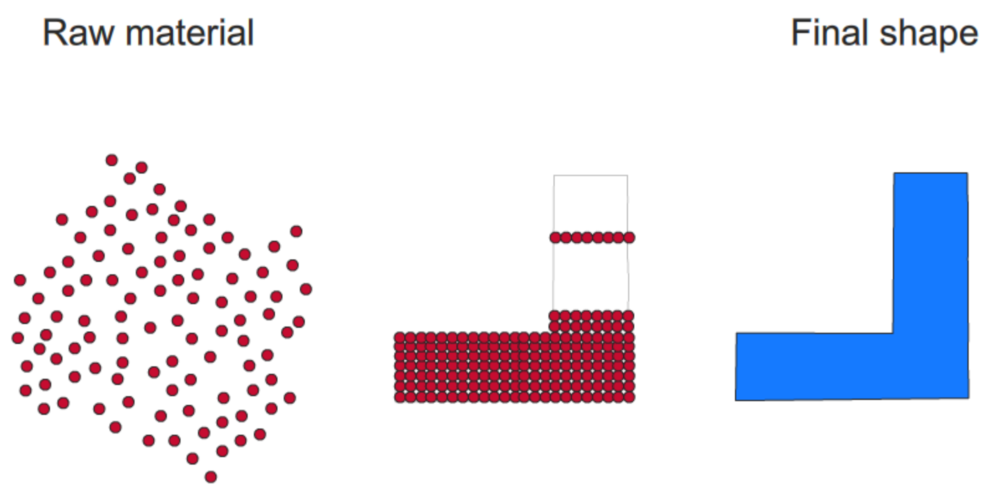
Joining powders

• Powders are tiny (could be mm or µm) random shaped particles

• There are two problems to solve here:

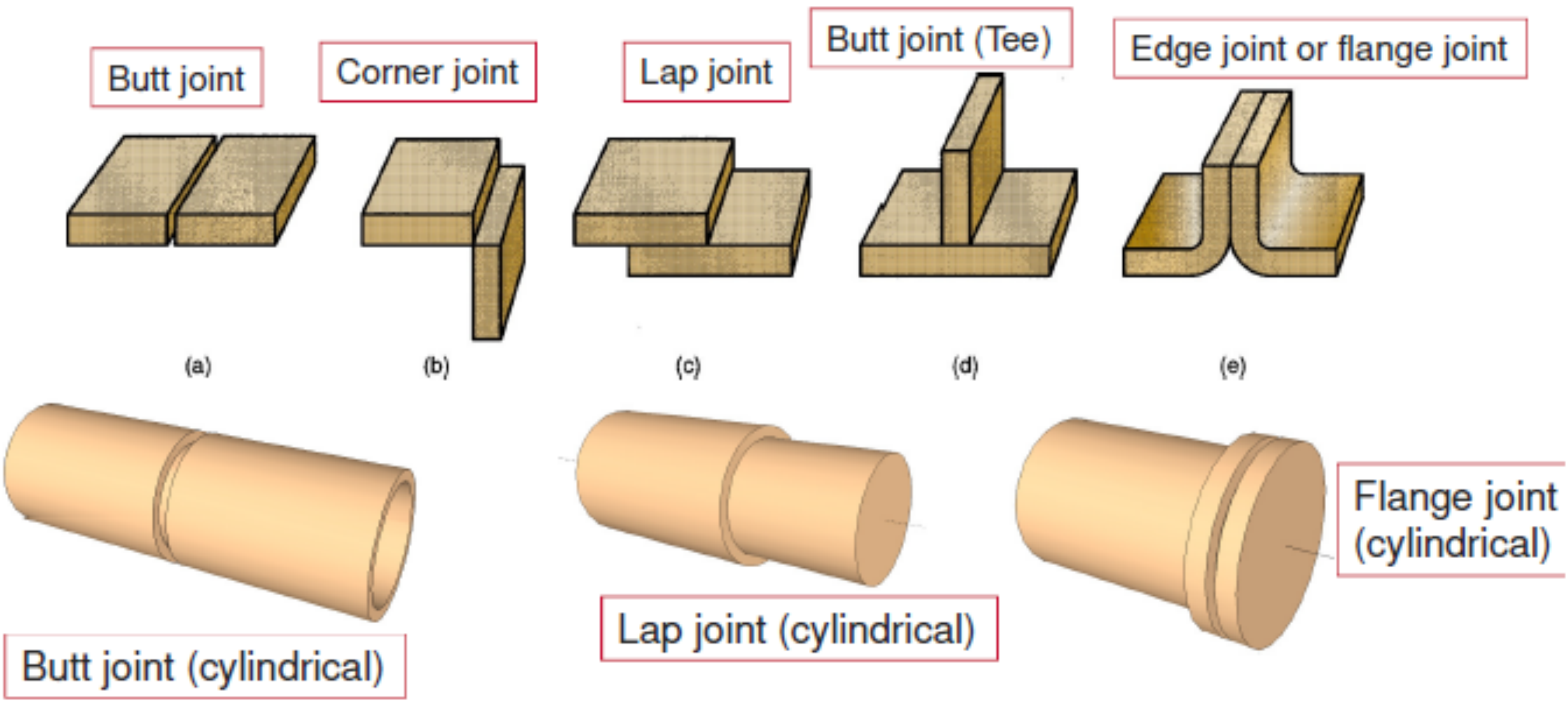
– How to join such teeny-tiny powders together strongly ?

– How to form a macro-sized geometrical shape from such numerous joined powders?



Where to join?

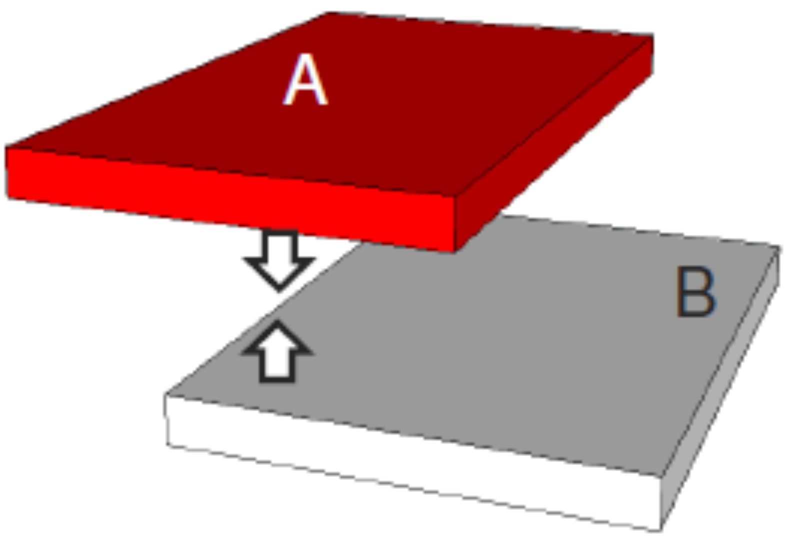
• Two conforming surfaces have to be brought together to effect a joint – many possible joint configurations



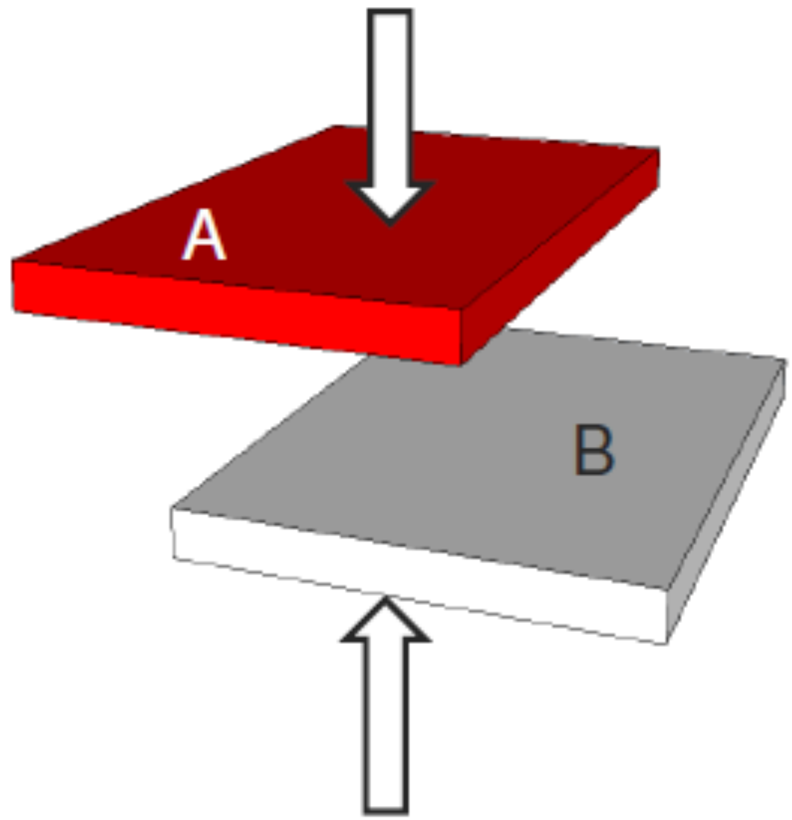
Forces needed to bring and keep two surface together

We have two choices of forces to bring and hold the surface together

We can supply forces from outside



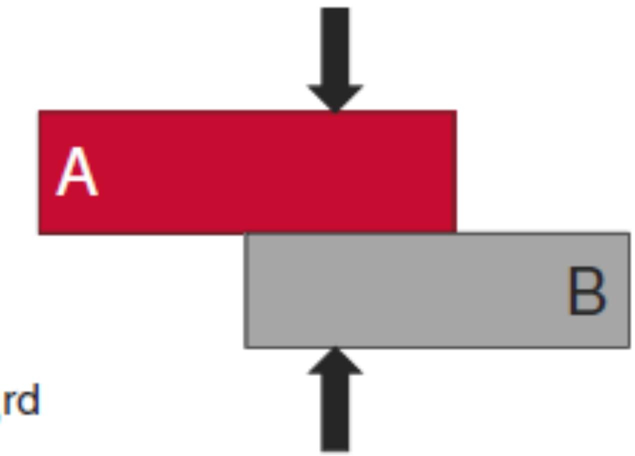
We can induce forces in the inside (within the surfaces)



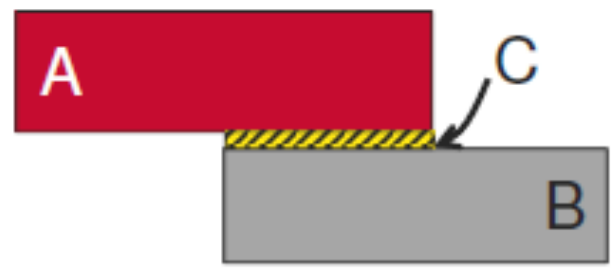
Basically three ways to join materials

Need to join 2 parts ‘A’ and ‘B’:

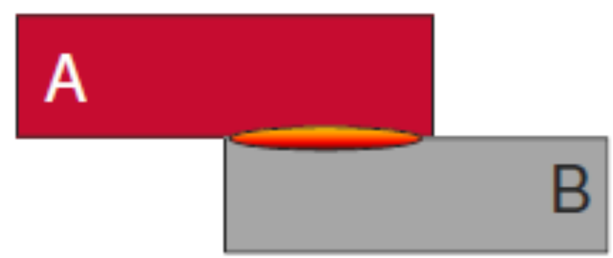
- Use mechanical forces from outside
  - E.g. tie the two parts with a string!
  - E.g use bolts



- Use surface forces – provided by a 3rd material ‘C’ in between the two surfaces
  - A joins to C and C holds on to B; so A joins to B!
  - E.g. adhesive, soldering, brazing



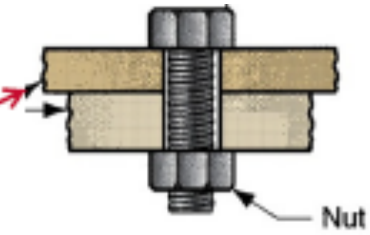
- Use molecular forces
  - Locally (near the surfaces) “mix” material from the 2 objects; they then hold to each other using inter-molecular forces
  - E.g. welding

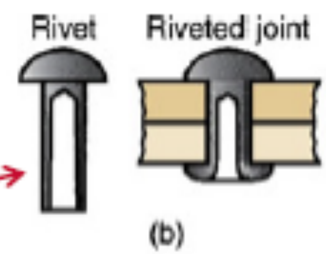


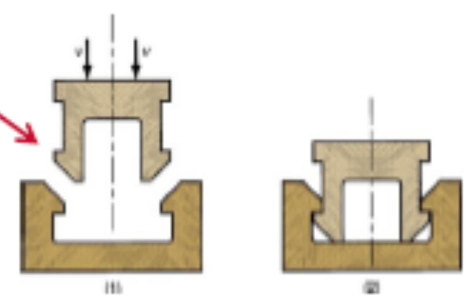
Joining mechanical forces

Mechanical force can be provided by interlocking (physical obstructions). Many interlocking methods are available:

- A: Using threads
- B: Using plastic deformation (e.g. rivets)
- C: Using protrusions (snap fit)
- D: Using microscopic surface interlocks - friction (e.g. shrink fit)



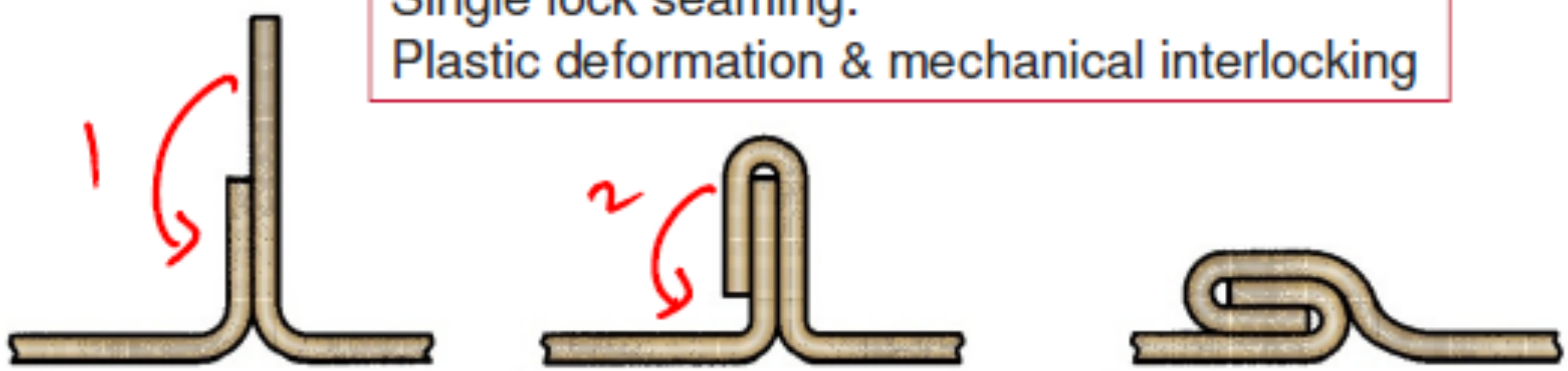




Joining (Plastic deformation)

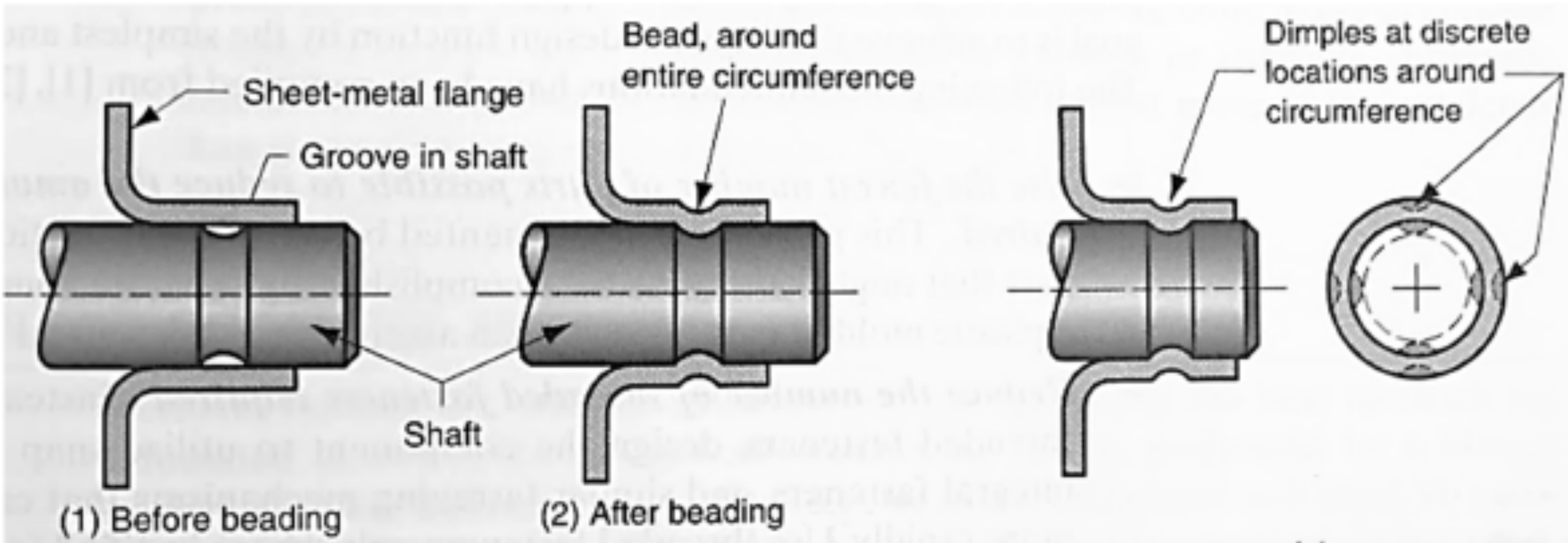
- Combination of the several mechanical forces can also be used to create a rigid joint

Single lock seaming:
Plastic deformation & mechanical interlocking



(1) Bent edges on two parts (2) One edge bent over other (3) Seam is bent down and flattened.

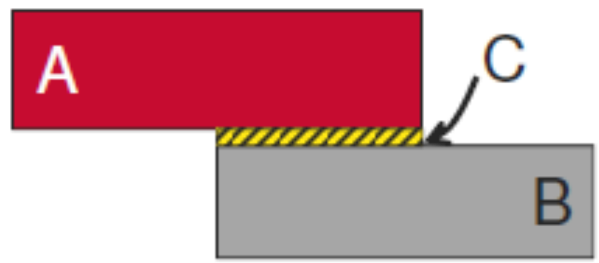
Joining (Plastic deformation)



Joining using surface forces

• Using surface force – provided by a 3rd material ‘C’ in between the two surfaces
– A joins to C and C holds on to B; so A is joined to B!

• Different types of materials available for ‘C’ to create the joint. ‘C’ can be:
– (i): Polymers (adhesive joint)
– (ii): Metallic alloys
• (iii): High-temperature melting alloys (brazing)
• (iv): Low-temperature melting alloys (soldering)



Material “C”

- Adhesive or glue
- Many types
  – Natural
- Starch, soya flour
  – Inorganic
- Sodium Silicate, Magnesium Oxychloride
  – Synthetic
- Most popular
- See table

Adhesive	Description and Applications
Anaerobic	Single-component, thermosetting, acrylic-based. Cures by free radical mechanism at room temperature. Applications: sealant, structural assembly.
Modified acrylics	Two-component thermoset, consisting of acrylic-based resin and initiator/hardener. Cures at room temperature after mixing. Applications: fiberglass in boats, sheet metal in cars and aircraft.
Cyanoacrylate	Single-component, thermosetting, acrylic-based that cures at room temperature on alkaline surfaces. Applications: rubber to plastic, electronic components on circuit boards, plastic and metal cosmetic cases.
Epoxy	Includes a variety of widely used adhesives formulated from epoxy resins, curing agents, and filler/modifiers that harden upon mixing. Some are cured when heated. Applications: aluminum bonding applications and honeycomb panels for aircraft, sheet-metal reinforcements for cars, lamination of wooden beams, seals in electronics.
Hot melt	Single-component, thermoplastic adhesive hardens from molten state after cooling from elevated temperatures. Formulated from thermoplastic polymers including ethylene vinyl acetate, polyethylene, styrene block copolymer, butyl rubber, polyamide, polyurethane, and polyester. Applications: packaging (e.g., cartons, labels), furniture, footwear, bookbinding, carpeting, and assemblies in appliances and cars.
Pressure-sensitive tapes and films	Usually one component in solid form that possesses high tackiness resulting in bonding when pressure is applied. Formed from various polymers of high molecular weight. Can be single-sided or double-sided. Applications: solar panels, electronic assemblies, plastics to wood and metals.
Silicone	One or two components, thermosetting liquid, based on silicon polymers. Curing by room-temperature vulcanization to rubbery solid. Applications: seals in cars (e.g., windshields), electronic seals and insulation, gaskets, bonding of plastics.
Urethane	One or two components, thermosetting, based on urethane polymers. Applications: bonding of fiberglass and plastics.

Adhesive joints: surface preparation

Surface preparation is important.

For adhesive bonding to succeed, part surfaces must be extremely clean

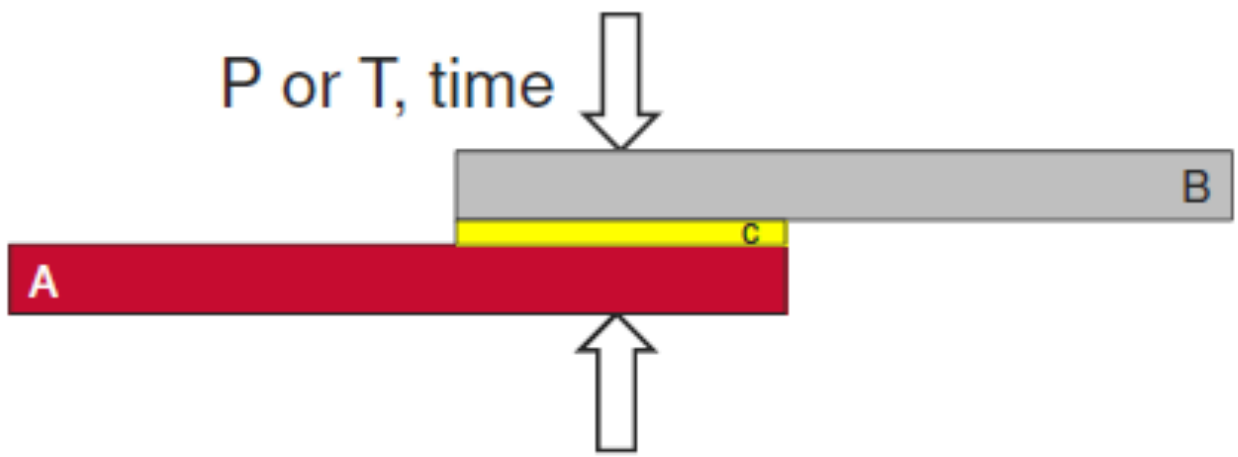
Bond strength depends on adhesion between adhesive (C) and adhered (A or B), which depends on clean surfaces

For metals, solvent wiping often used for cleaning, and sandblasting improves surface adhesion

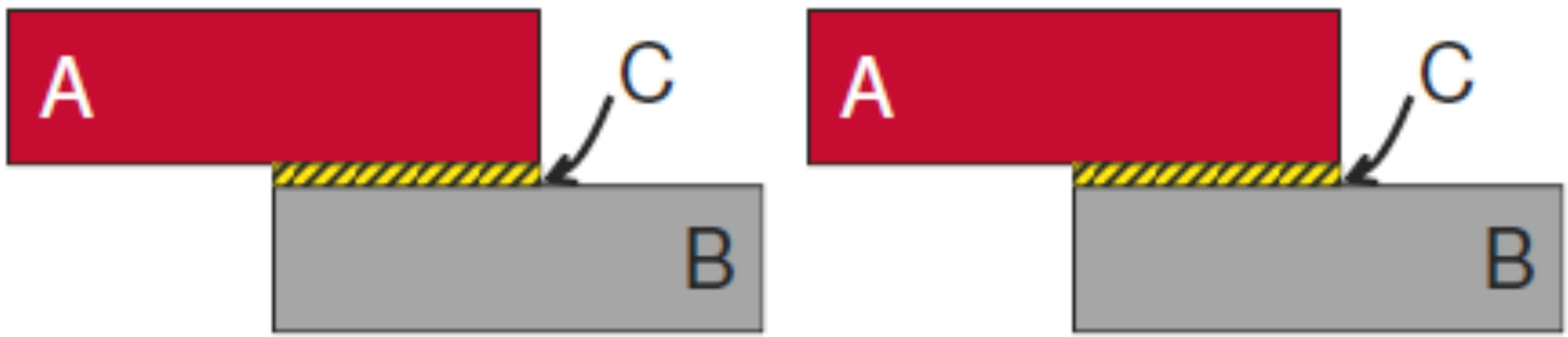
For non-metallic parts, surfaces can be mechanically abraded or chemically etched to increase roughness

Adhesive joints (curing)

- Process by which physical properties of the adhesive are changed from liquid to solid, usually by chemical reaction, to accomplish surface attachment of parts
  - Curing often aided by heat and/or a catalyst
    - If heat is used, temperatures are relatively low
  - Curing takes time - a disadvantage in production
  - Pressure sometimes applied between parts to activate bonding process



Adhesion vs. cohesion



Adhesion vs. cohesion

Cohesion (welding): The joining of two or more pieces of material by means of heat, pressure, or both, with or without a filler metal, to produce bonding through fusion or recrystallization. The force of attraction in the bond is primarily cohesion. A few of the cohesion processes are arc welding, laser welding, diffusion bonding, and forge welding.

Adhesion (gluing): The joining of two or more pieces of material by the forces of attraction between the adhesive and the materials being joined (adherends). Gluing processes depend primarily upon adhesive bonding. It includes processes such as brazing, soldering, and epoxy bonding.

Adhesive joints advantages

- Applicable to a wide variety of materials
- Bonding occurs over entire surface area of joint
- Low temperature curing avoids damage to parts being joined
- Can be used for sealing as well as bonding
- Joint design is often simplified, e.g., two flat surfaces can be joined without providing special part features such as screw holes

Material ‘C’ is a high-melting metallic alloy - BRAZING

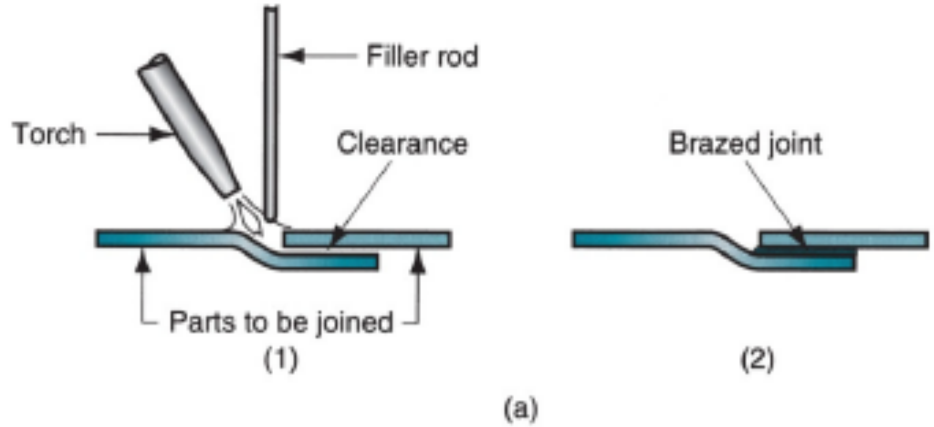
- Process is called Brazing
- Material ‘C’ is also called “filler metal”
- Filler metal has a melting point (liquidus temp) more than 450°C – but smaller than that of A or B

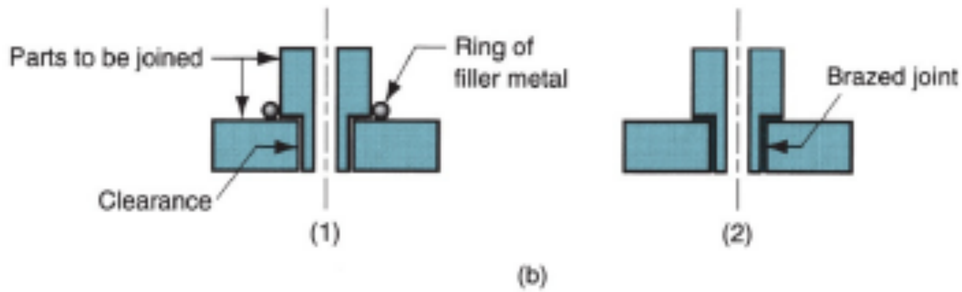
  (why 450 - it is rather arbitrary)
- ‘A’ and ‘B’ themselves do not melt
- Dissimilar metals can be joined using this method
- Joint is typically stronger than the strength of ‘C’ itself

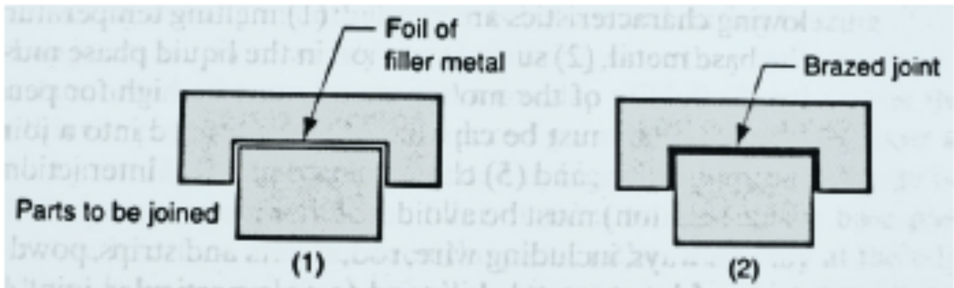
Filler material BRAZING	Melting temp
Al & Si	600 °C
Cu & P	850 °C
Ag, Cu, Zn Cd	730 °C
Cu and Zn	925 °C
Au and Ag	950 °C
Ni, Cr, etc	1120 °C

Brazing

- 'C' can be in the form of powder/paste, solid bulk form (wire, rod, sheet/foil, preformed shape)
- Heat sources (to melt 'C'):
  - – Torch (flame)
  - – Furnace
  - – Induction heating
  - – Resistance heating
  - – Dip in molten salt or molten metal bath
  - – Infrared heating
- "Flux" material is added to the joint during melting to prevent oxidation of the molten metal

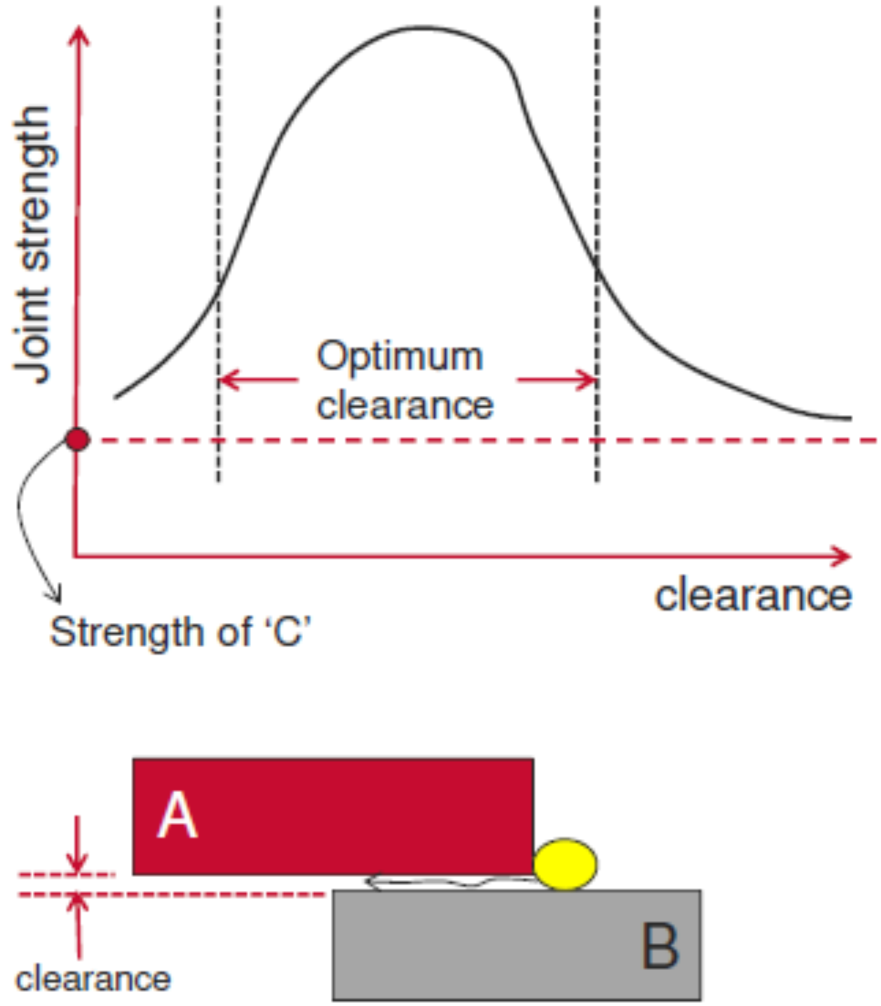






Brazing: clearance and capillary action

- 'C' melts and flows into the joint by capillary action in the thin clearance area between 'A' and 'B'
- If clearance is too small – 'C' cannot flow into joint area
- If clearance is too large – capillary action will fail and result in a poor joint
- Typical clearance ranges from 0.025 mm to 0.25 mm
- Surfaces must be cleaned properly to promote wetting and capillary attraction



Material 'C' is a low-melting metallic alloy - SOLDERING

- Process is called Soldering
- Material 'C' is also called "filler metal"
- Filler metal has a melting point (liquidus temp) less than 450°C – and smaller than that of 'A' or 'B'
- Otherwise the process is similar to brazing.
- So, again 'A' and 'B' do not melt
- 'A' and 'B' surfaces are kept apart at a small clearance; material 'C' is placed near this clearance and melted; it flows into the clearance to form a joint
- Flux is also needed here

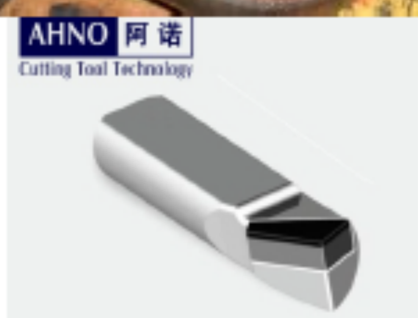
Filler material SOLDERING	Melting temp
Lead-Silver	305 °C
Tin-Antimony	238 °C
Tin-Lead	183-207 °C
Tin-Silver	221 °C
Tin-Zinc	199 °C
Tin-Silver-Copper	217 °C

Brazing/soldering applications

Brazing

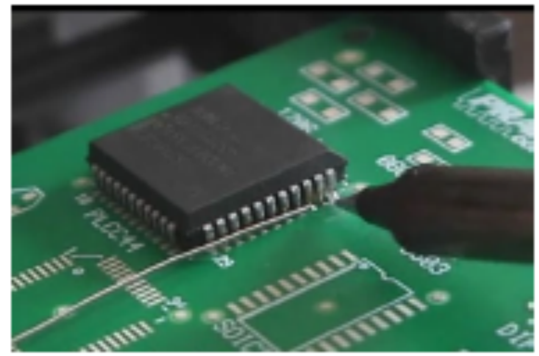
jewelry

pipes

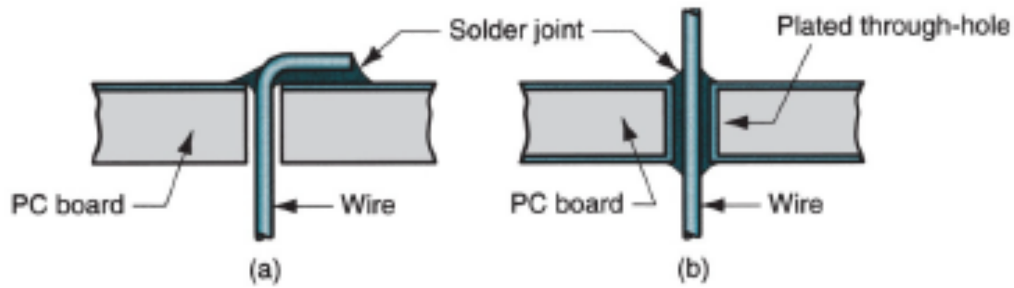


cutting tools

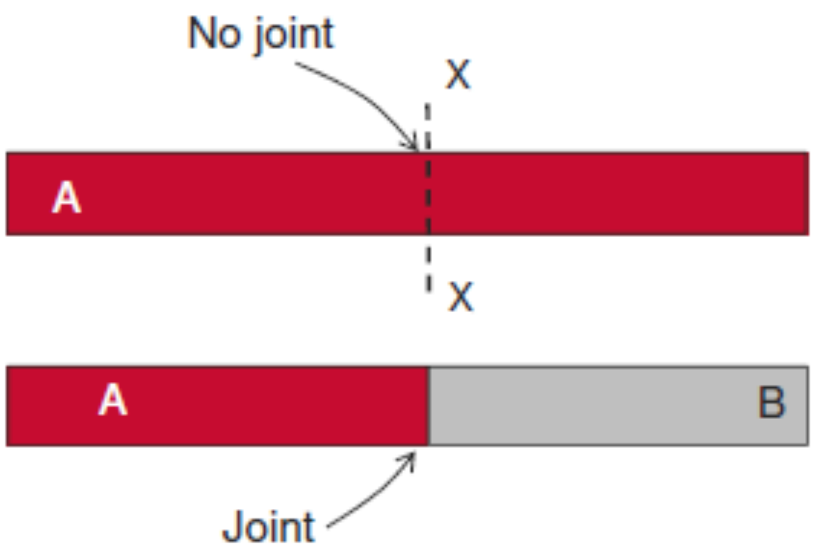
Soldering



electronics



Joining by direct molecular forces



What holds the material that is on either side of the imaginary section X-X?

How can we get similar forces to develop at the joint surfaces between A and B?

- One way to join these two surfaces is by creating atomic bonds directly between A and B without introducing any 3rd material in between
- How to do this? (assume A and B are similar materials)
- There are two ways to do this
  - In the solid state
  - By going into the liquid state

Welding process

Welding is a process in which materials of the same fundamental type or class are brought together and cause to join by heating them to the melting temperature with or without the application of pressure and filler metal.

Welding processes based on state of base material

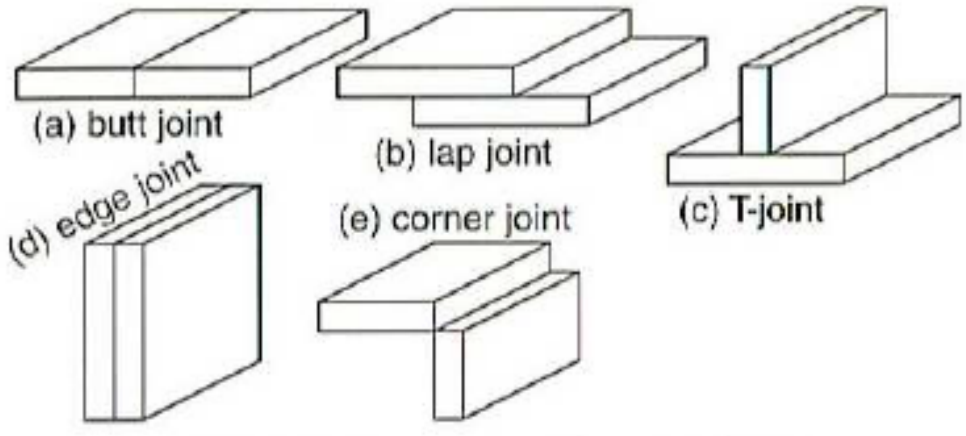
Liquid state welding (Fusion welding)

- Oxyacetylene welding
- Arc welding
- Resistance welding

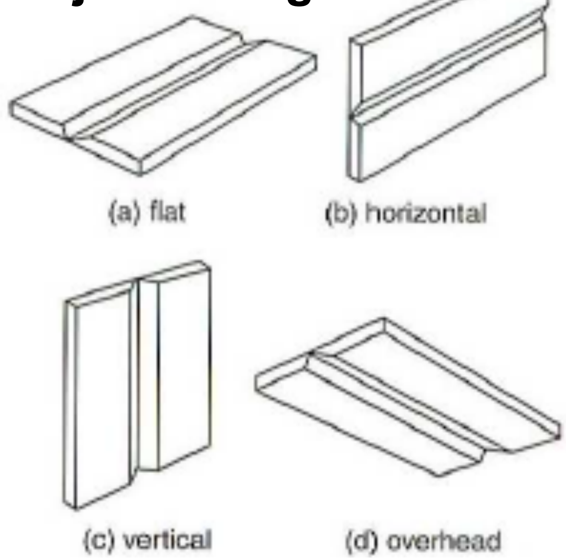
Solid state welding

- Diffusion welding
- Friction welding

Types of joints and welding positions

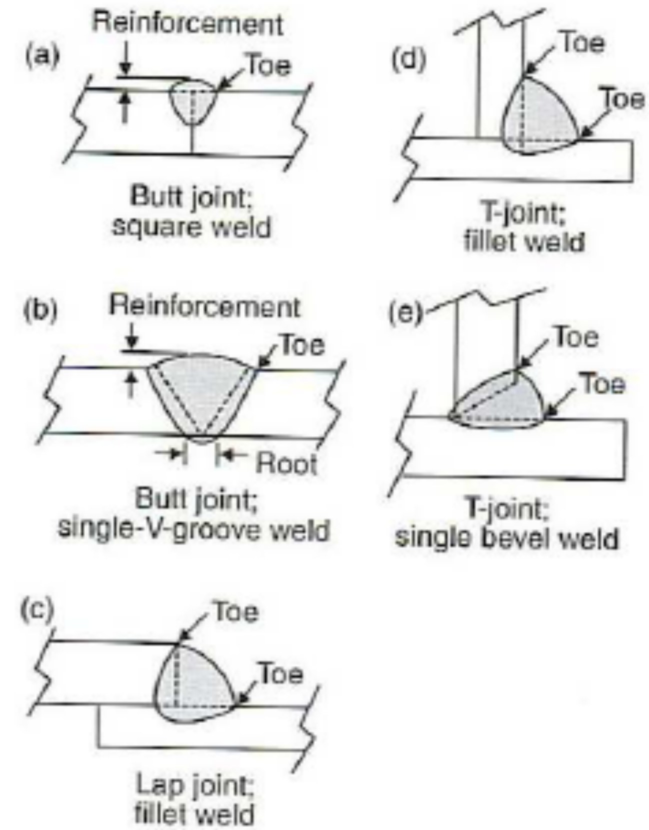


Weld joint designs



Welding positions

Weld-joint variations



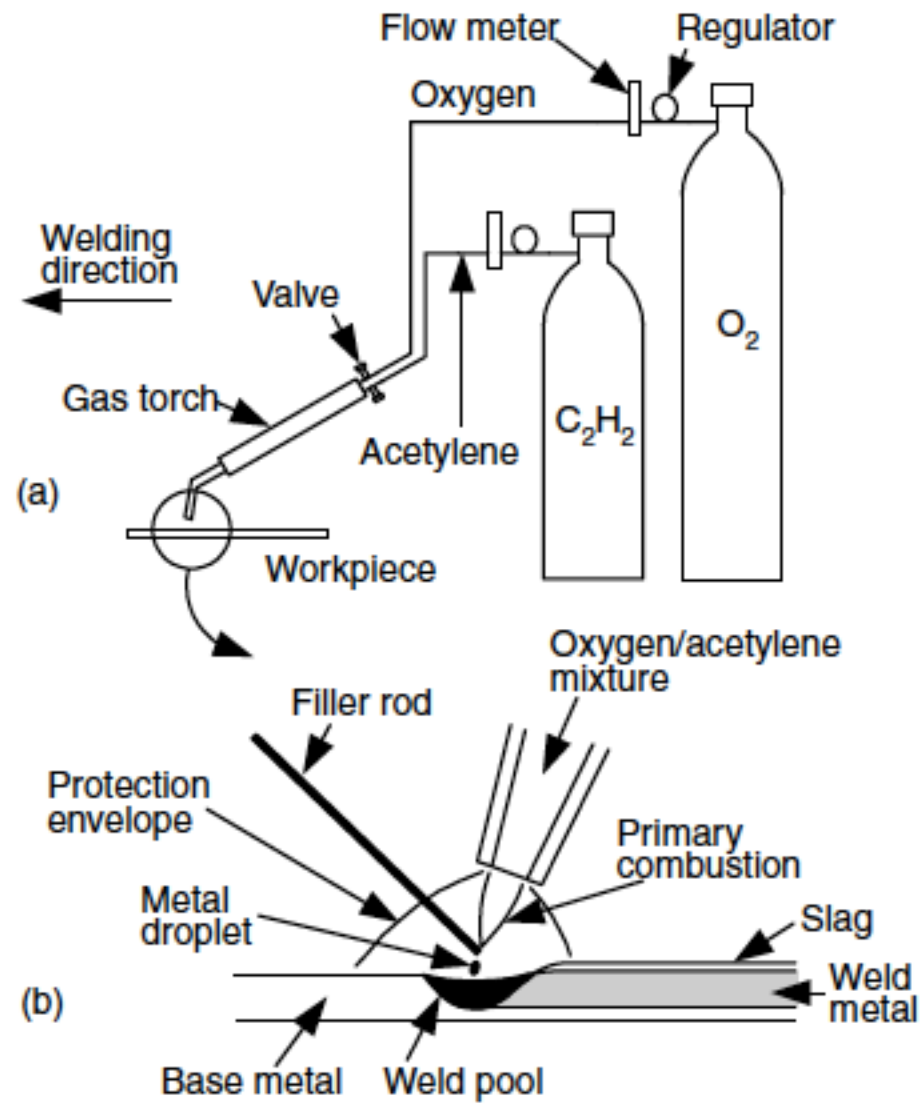
- The surface of the weld is called the face.
- The two junctions between the face and the workpiece surface are called the toes.
- The portion of the weld beyond the workpiece surface is called the reinforcement.

Gas welding

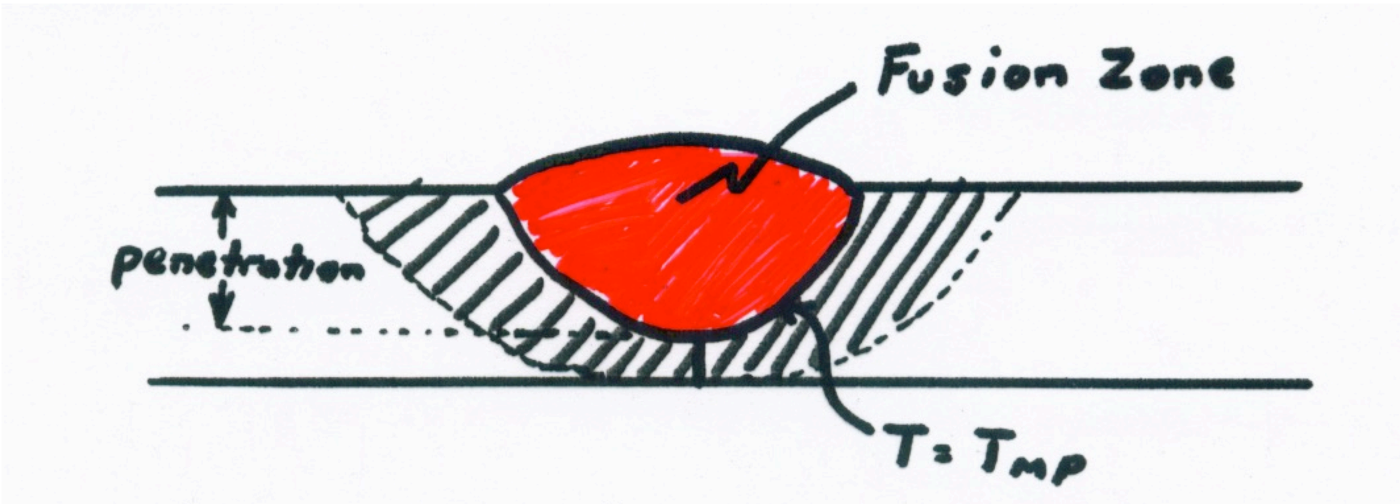
•Gas welding is a welding process that melts and joints metals by heating them with a flame caused by a reaction of fuel gas and oxygen.

•The most commonly used method is oxyacetylene welding, due to its high flame temperature.

•The flux melts, solidifies and forms a slag skin on the resultant weld metal.



Gas welding



Fusion Zone

Material that was molten during the welding process

Heat-Affected Zone (HAZ)

Heating above some critical temperature will almost always induce some undesirable changes in structure and properties of the materials

The zone is usually described by its width

Typically want to minimize

Often hard to control

Unaffected base material

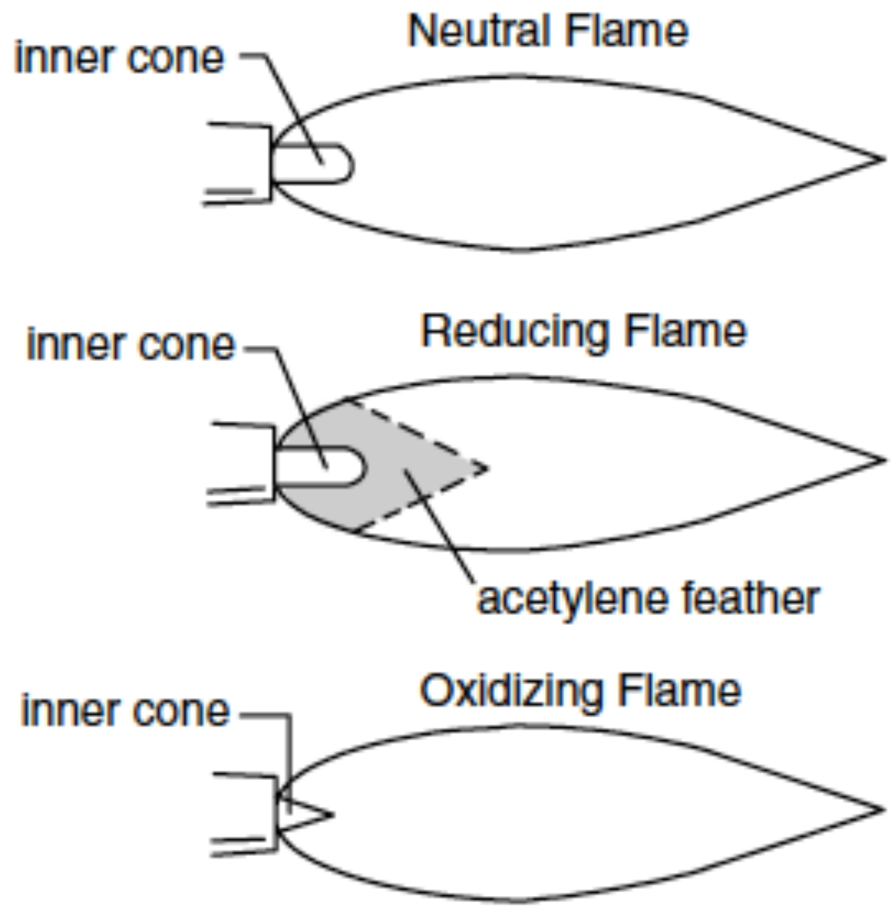
The region where the temperature did not reach the critical

Oxyacetylene welding (types of flames)

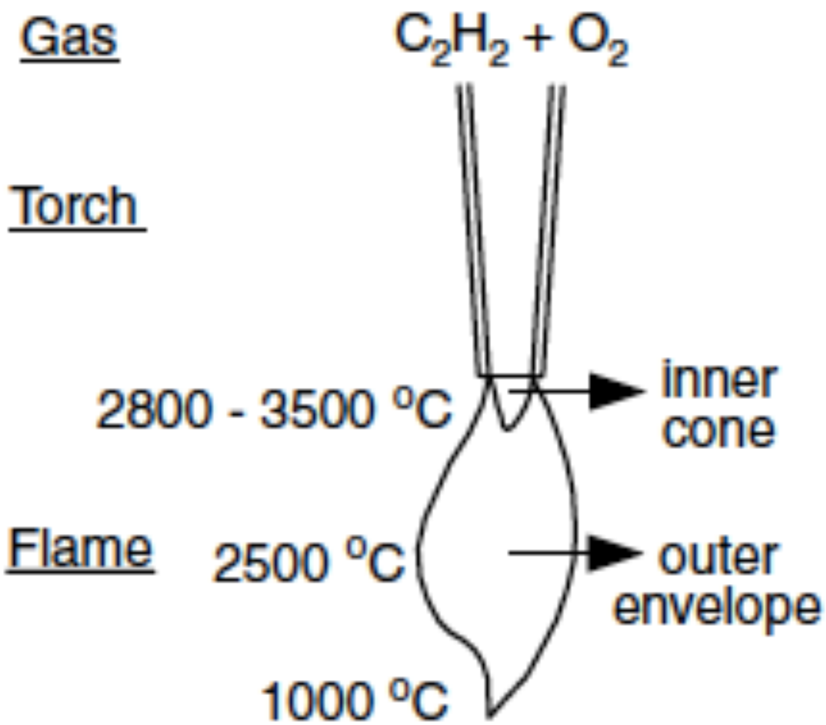
Neutral flame: Acetylene (C_2H_2) and O_2 are mixed in equal amounts and burn at the tip of the welding torch. The inner cone gives 2/3 of heat whereas the outer envelope provides 1/3 of the energy.

Reducing flame: The excess amount of acetylene is used, giving a reducing flame. The combustion of acetylene is incomplete (greenish) between the inner cone and the outer envelope. Good for welding aluminium alloys, high carbon steels.

Oxidizing flame: The excess amount of O_2 is used, giving an oxidizing flame. Good for welding brass.



Oxyacetylene welding



Primary combustion in inner cone (2/3 total heat) :

$2C_2H_2 + 2O_2$ (from cylinder)

$\longrightarrow 4CO + 2H_2$

Secondary combustion in outer envelope (1/3 total heat) :

$4CO + 2O_2$ (from air) $\longrightarrow 4CO_2$

$2H_2 + O_2$ (from air) $\longrightarrow 2H_2O$

The secondary combustion is also called the protection envelope since CO and H_2 here consume the O_2 entering from surrounding air, thereby protecting the weld from oxidation.

Oxyacetylene welding

Advantages

- Simple equipment
- Portable
- Inexpensive
- Easy for maintenance and repair

Disadvantages

- Limited power density
- Very low welding speed
- High total heat input per unit length
- Large heat affected zone
- Severe distortion
- Not recommended for welding reactive metals such as titanium and zirconium.

Pressure gas welding

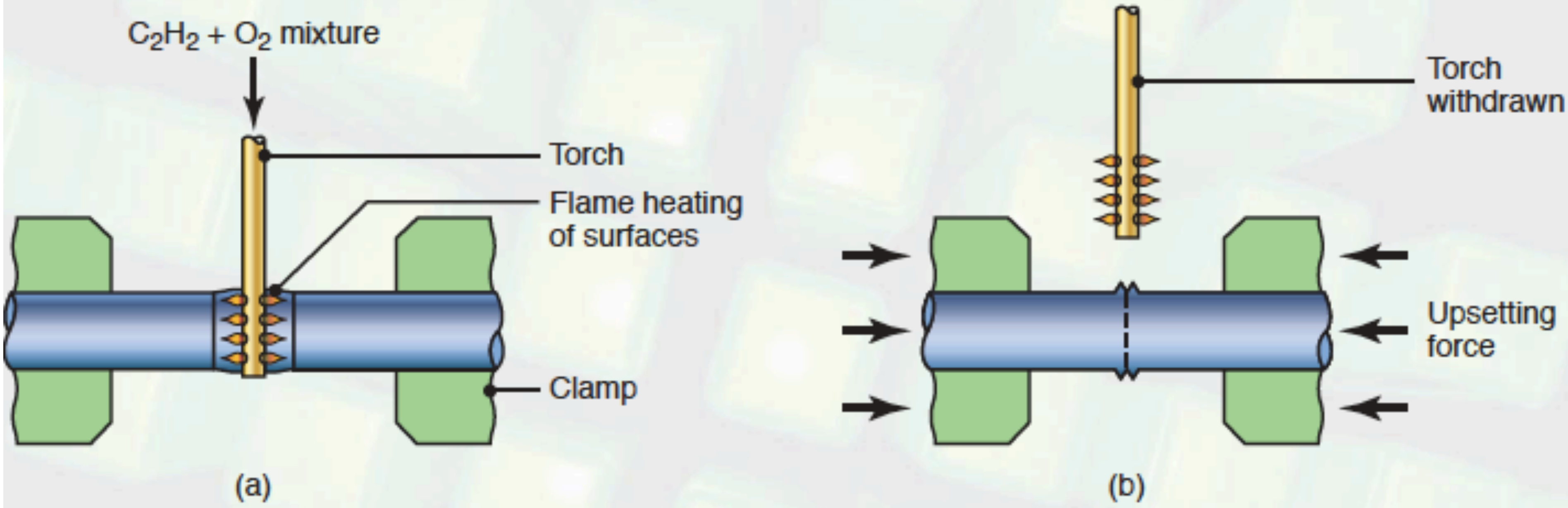


FIGURE 12.3 Schematic illustration of the pressure gas welding process; (a) before, and (b) after. Note the formation of a flash at the joint, which can later be trimmed off.

Heat transfer in welding

Material	Specific Energy, u J/mm^3	BTU/in^3
Aluminum and its alloys	2.9	41
Cast irons	7.8	112
Copper	6.1	87
Bronze (90Cu-10Sn)	4.2	59
Magnesium	2.9	42
Nickel	9.8	142
Steels	9.1-10.3	128-146
Stainless steels	9.3-9.6	133-137
Titanium	14.3	204

TABLE 12.3 Approximate specific energy required to melt a unit volume of commonly welded materials.

Heat input

$$\frac{H}{l} = e\frac{VI}{v}$$

Welding speed

$$v = e\frac{VI}{uA}$$

Heat transfer in welding

$$\frac{H}{l} = e\frac{VI}{v}$$

$$H = u(volume) = uAl$$

$$v = e\frac{VI}{uA}$$

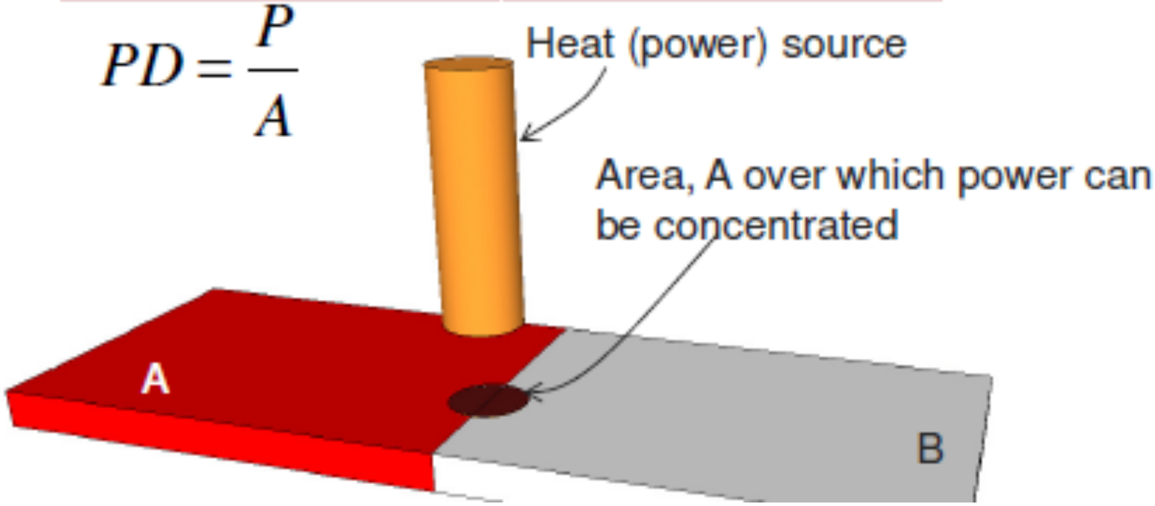
H is the heat input in J
l is the weld length
V is voltage applied
I is the current in amperes
v is the welding speed
e is the efficiency

u is the specific energy required for melting

Fusion welding: heat sources

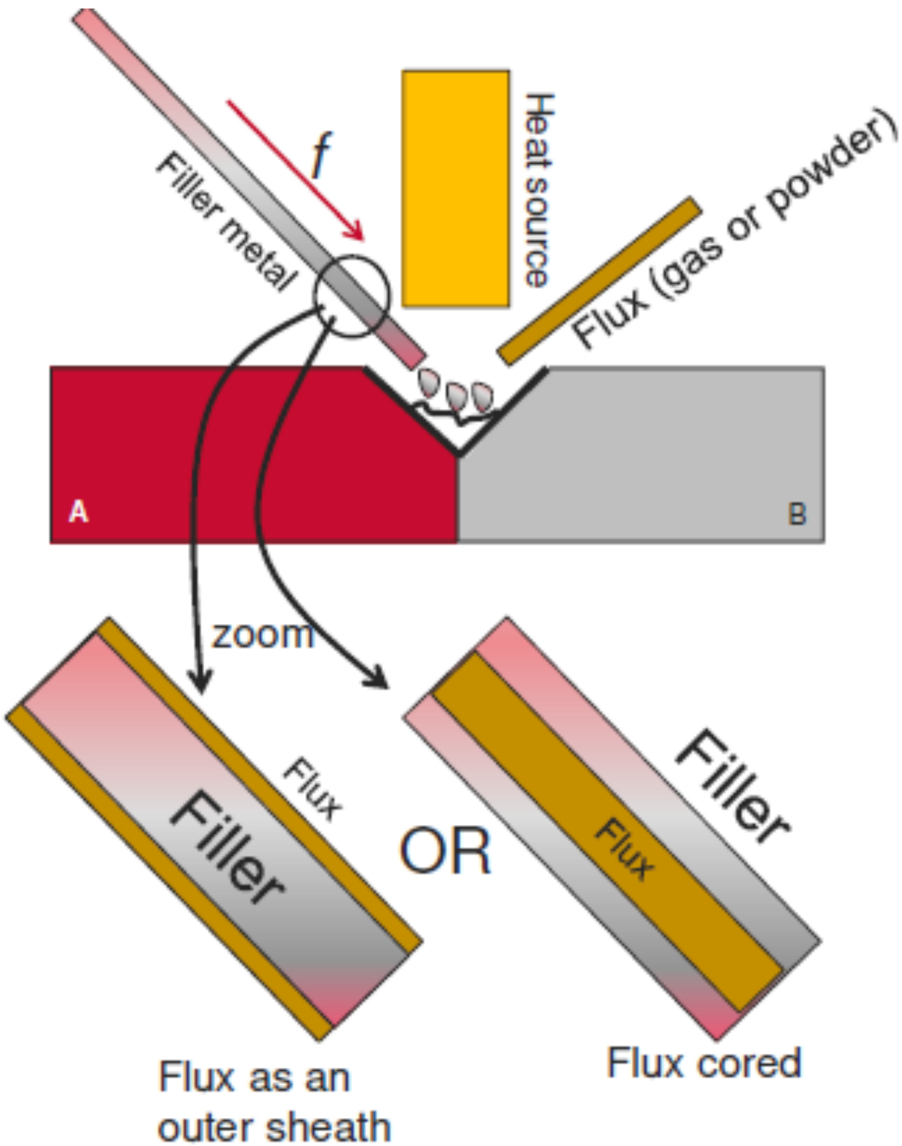
Heat source	Power Density
A. Oxyfuel torch	10 W/mm^2
B. Electric Arc	50 W/mm^2
C. Interface electrical resistance heating	1000 W/mm^2
D. Laser beam	9000 W/mm^2
E. Electron beam	10,000 W/mm^2

$$PD = \frac{P}{A}$$



- *PD*: Power transferred to work per unit surface area, W/mm^2 (Btu/sec-in^2)
  - If power density is too low, heat is conducted into work, so melting never occurs
  - If power density too high, localized temperatures vaporize metal in affected region
  - There is a practical range of values for heat density within which welding can be performed

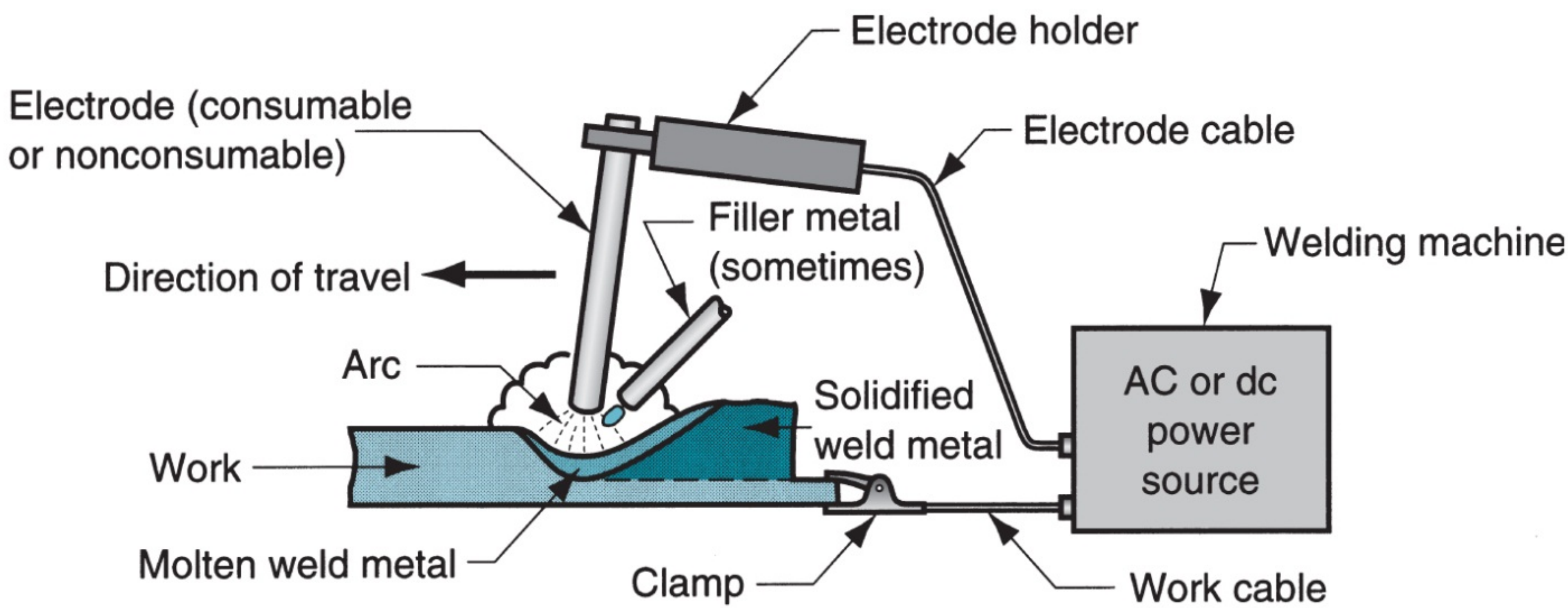
Fusion welding: flux and its application



- We saw flux earlier in brazing/soldering
- Fusion welding involves melting; molten metal can react with the environment – can form oxides (these are very hard and undesirable in the weld).
- Flux helps in preventing oxygen to react with the metal
- Flux can be applied separately as a powder or gas or along with the filler rod (as outside sheath or in the core)
- After welding, flux comes out (floats on weld pool) as slag on top of the weld – it can be broken and taken off (it is brittle); if flux is gas – then there is no slag

Arc Welding: The most common fusion welding

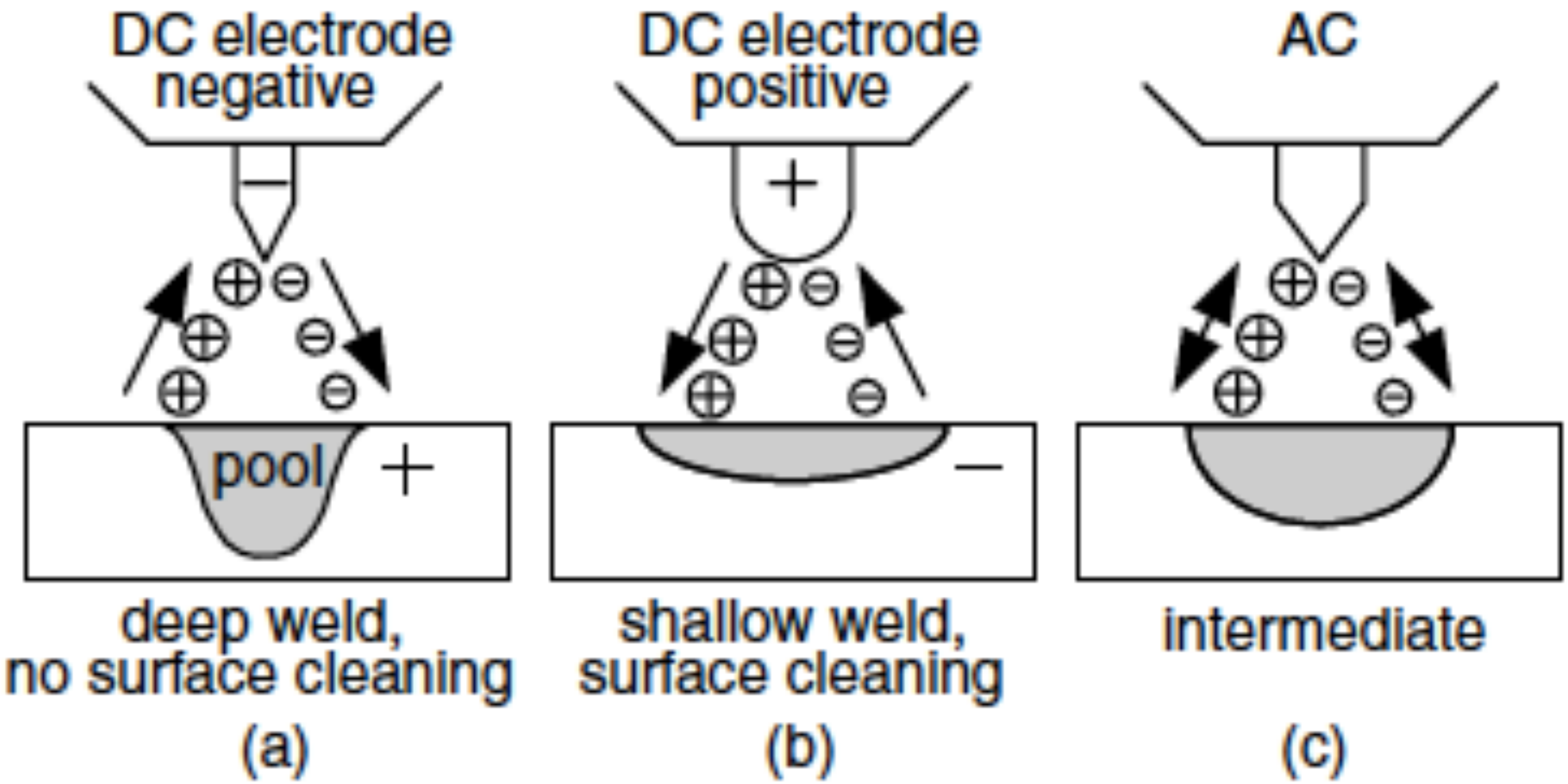
- A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake



Functions of Electrode Covering

- **Protection:** It provides a gaseous shield to protect the molten metal from air.
- **Deoxidation:** It provides deoxidizers and fluxing agents to deoxidize and cleanse the weld metal. The solid slag formed also protects the already solidified but still hot weld metal from oxidation.
- **Arc Stabilization:** It provides arc stabilizers to help maintain a stable arc. The arc is an ionic gas (a plasma) that conducts the electric current.
- **Metal Addition:** It provides alloying elements and/or metal powder to the weld pool.

Polarity (arc welding)



a. Direct-Current Electrode Negative (DCEN)
b. Direct-Current Electrode Positive (DCEP)
c. Alternating Current (AC)

Two Basic Types of Arc Welding Electrodes

- Consumable – consumed during welding process
  - Source of filler metal in arc welding
- Non-consumable – not consumed during welding process (e.g. Tungsten)
  - Filler metal must be added separately if it is added

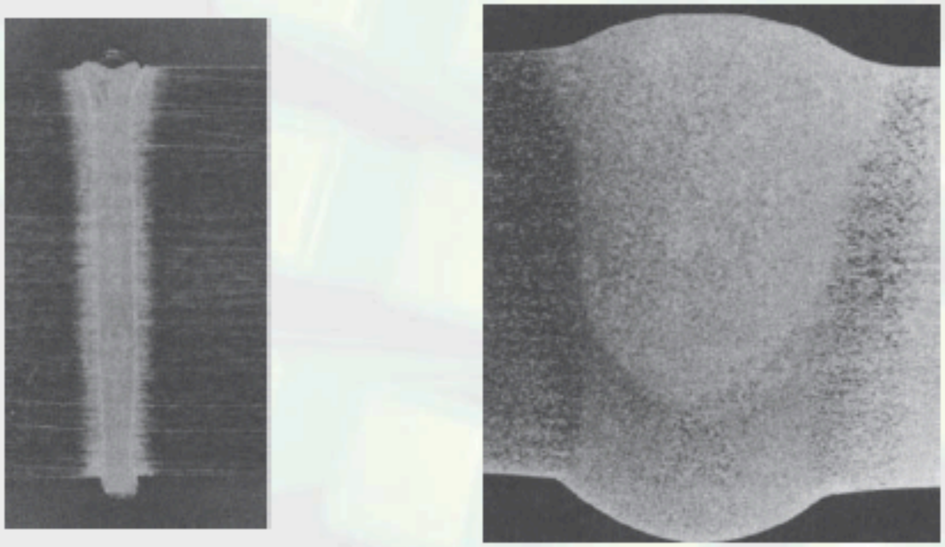
Consumable Electrode Arc Welding Processes

- Shielded Metal Arc Welding (SMAW)
- Gas Metal Arc Welding (GMAW)
- Flux-Cored Arc Welding (FCAW)
- Submerged Arc Welding (SAW)

Arc welding

Process	Filler	Electrode	Flux	Heat source
SMAW	Filler rod is also the electrode		Coated on OD of filler	Arc
FCAW	Filler rod is also the electrode; fed continuously		Flux is in the core of filler rod; Gas also may be applied	Arc
GMAW	Filler rod is also the electrode; fed continuously		Gas is supplied via nozzle	Arc
SAW	Filler rod is also the electrode; fed continuously		Flux applied as powder/granules	Arc
GTAW	In rod shape; fed continuously	Electrode made of Tungsten (Separate from filler)	Gas is supplied via nozzle	Arc

Weld bead comparisons



(a) (b)

FIGURE 12.13 Comparison of the size of weld beads in (a) electron-beam or laser-beam welding with that in (b) conventional (tungsten arc) welding. *Source:* American Welding Society, *Welding Handbook*, 8th ed., 1991.

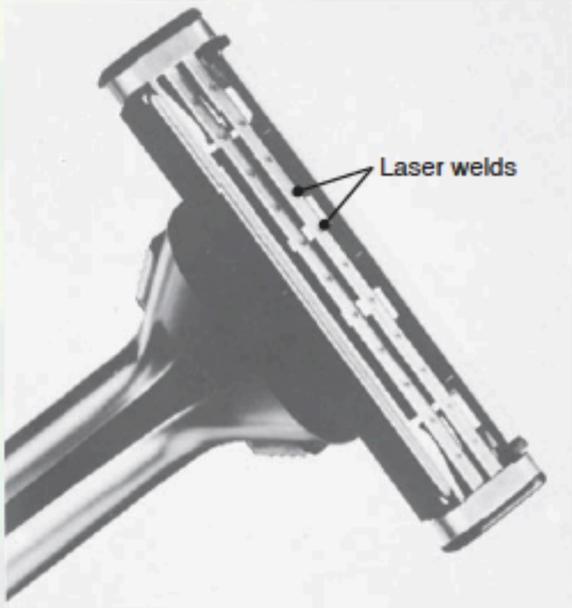


FIGURE 12.14 Gillette Sensor razor cartridge, with laser-beam welds.

Fusion Weld Characteristics

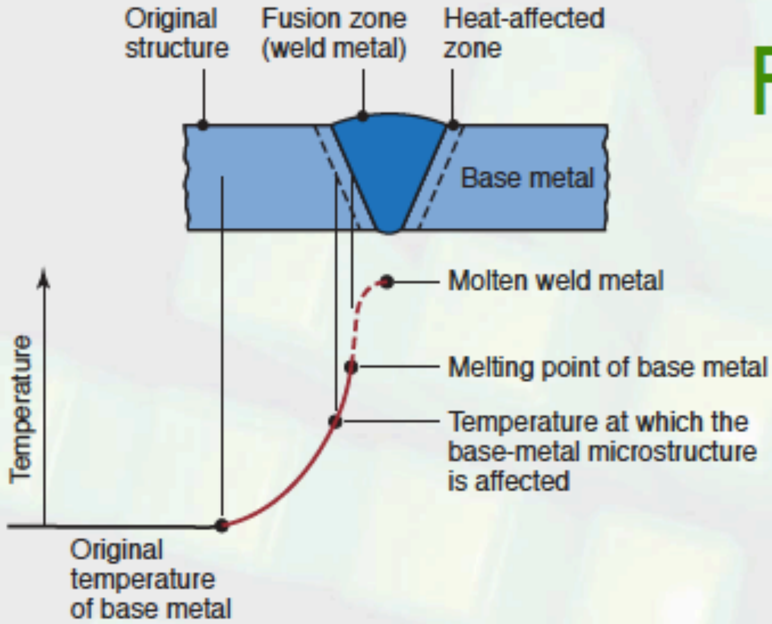


FIGURE 12.15 Characteristics of a typical fusion weld zone in oxyfuel gas welding and arc welding processes.

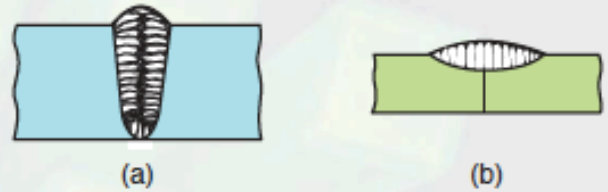


FIGURE 12.16 Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal.

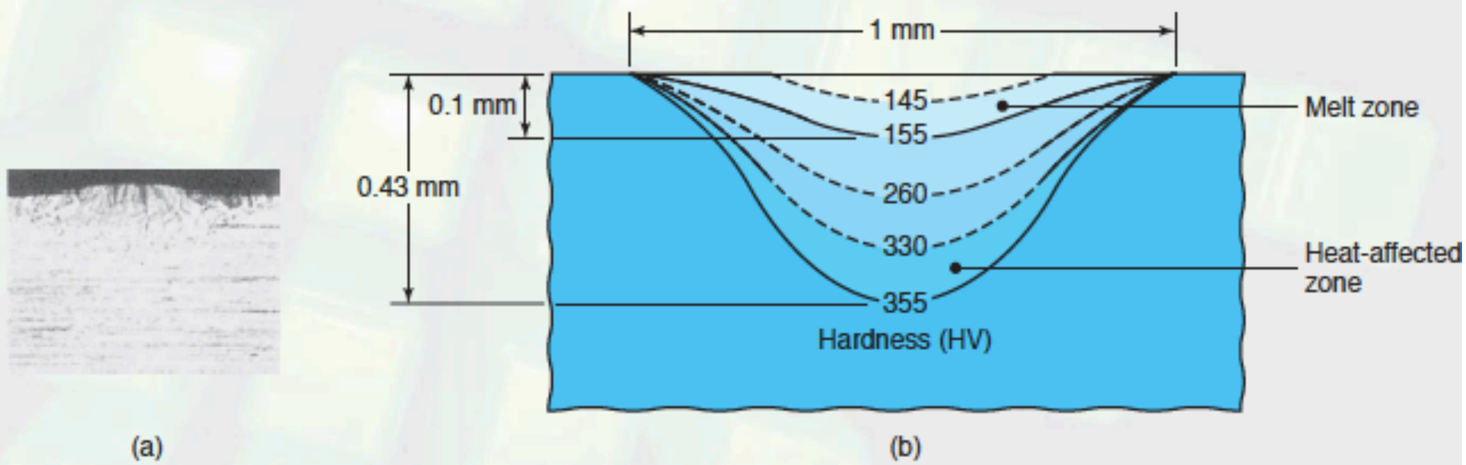
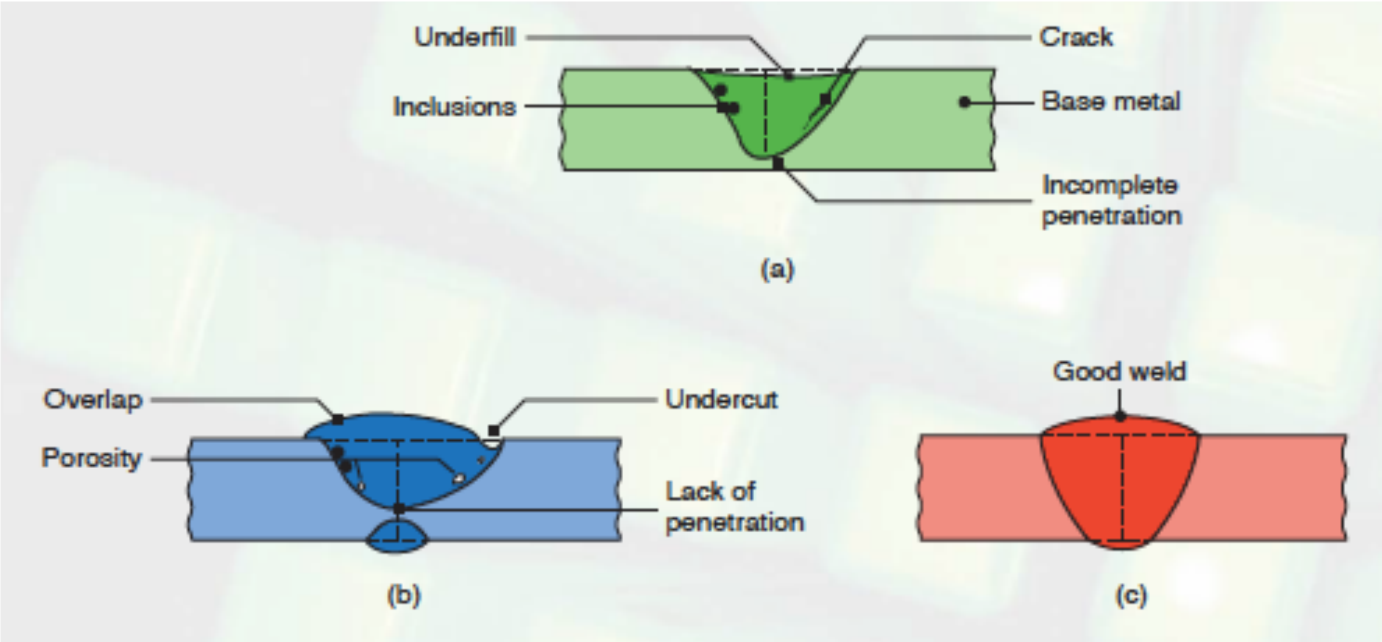
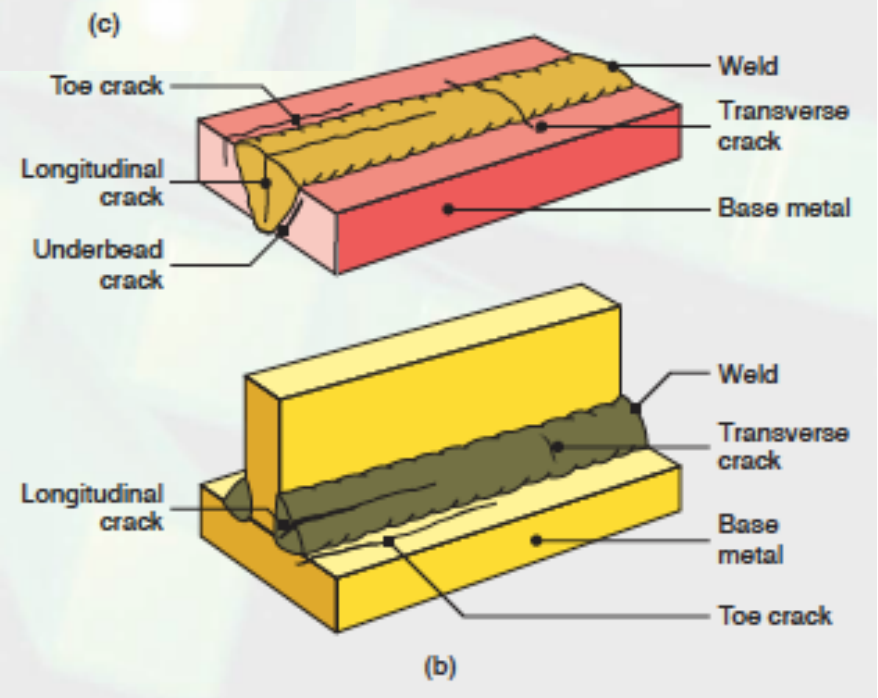


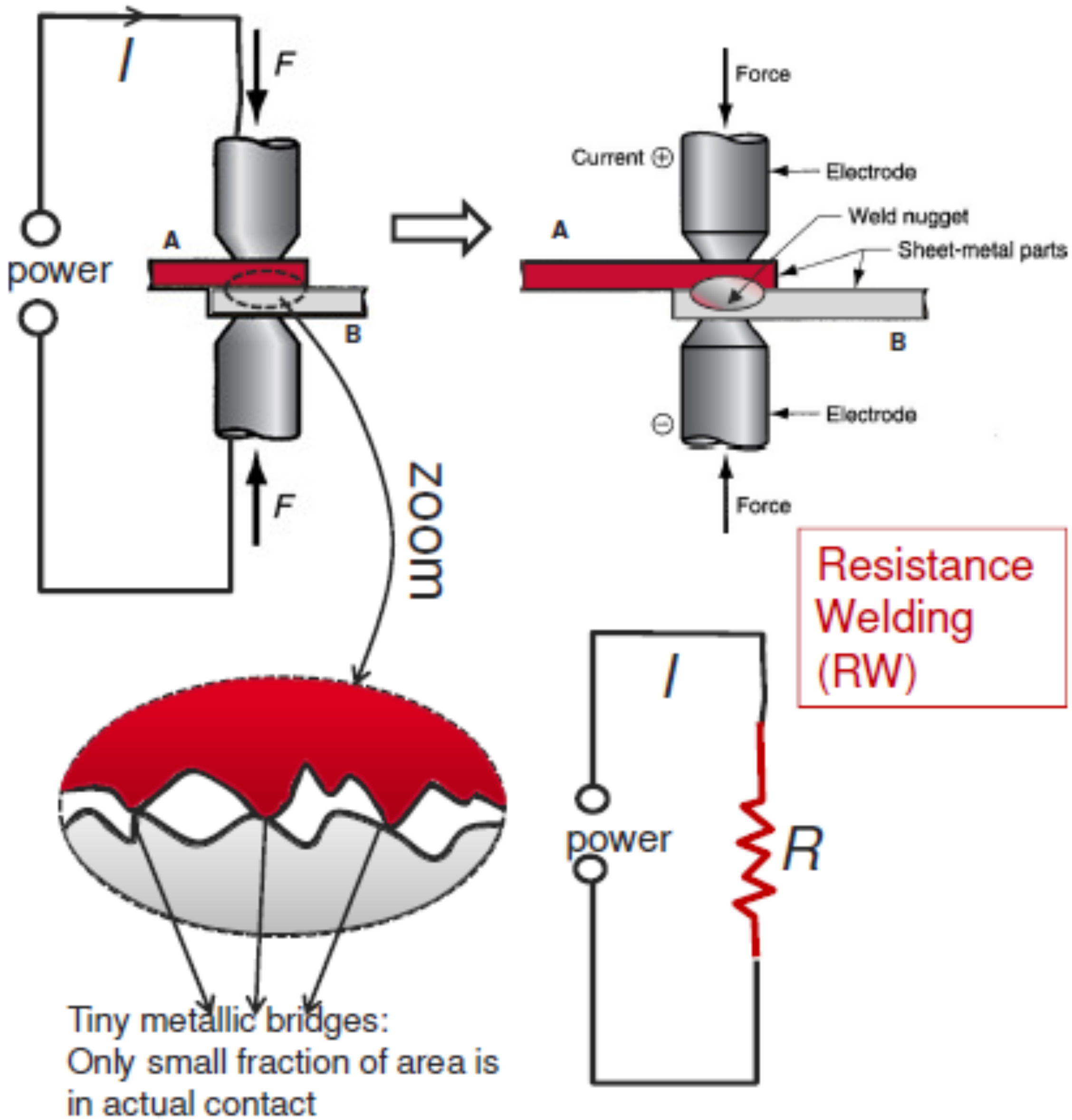
FIGURE 12.17 (a) Weld bead on a cold-rolled nickel strip produced by a laser beam. (b) Microhardness profile across the weld bead. Note the lower hardness of the weld bead as compared with the base metal. *Source:* IIT Research Institute.

Defects in welded joints



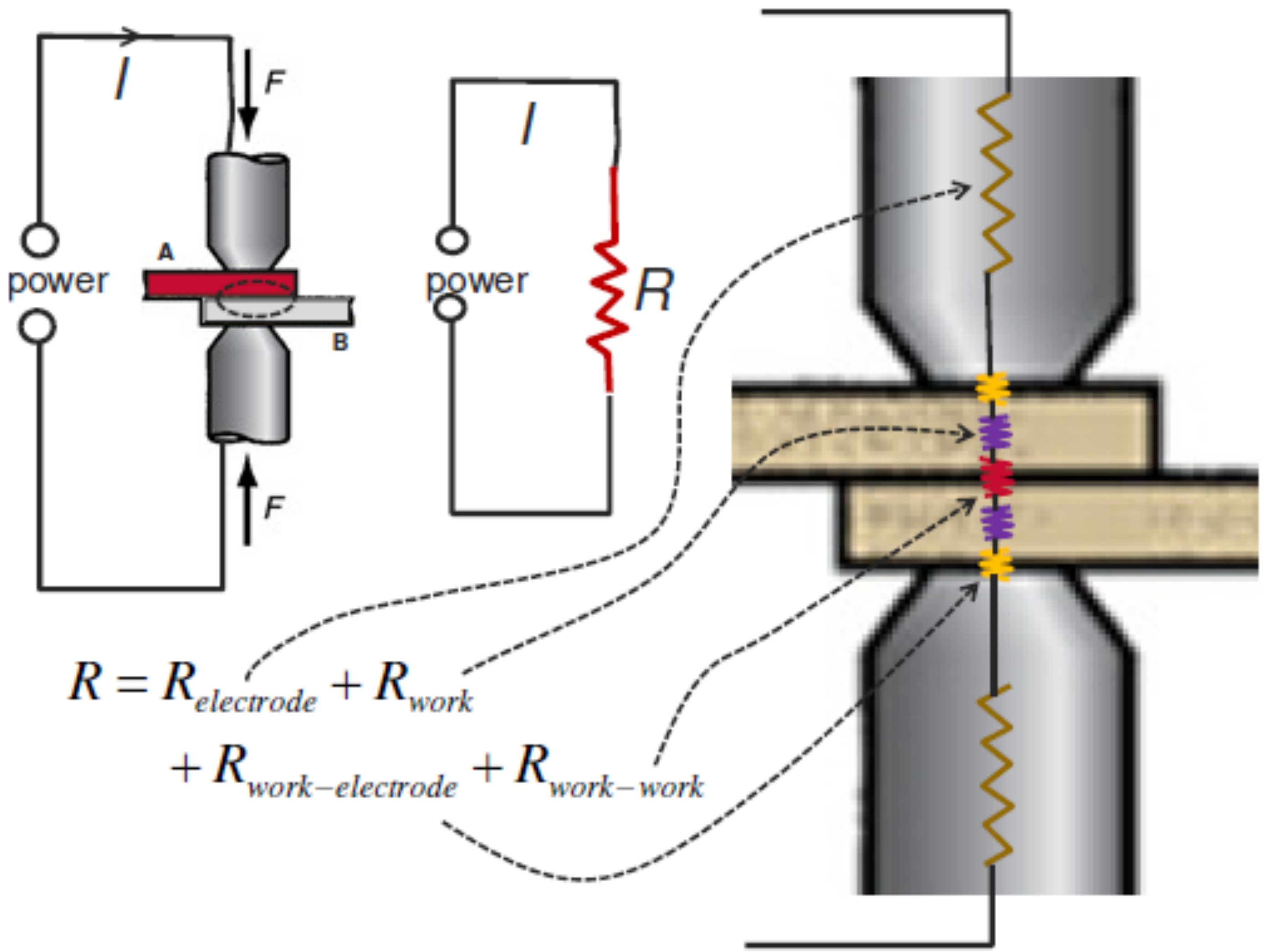


Fusion welding: electrical



- Two surface to be joined are kept in contact and large electrical current (5000-20,000 A) made to flow
- Since actual area of contact is much small – current flow is constricted to tiny metallic bridges – this causes resistance to flow
- Resistance – causes heating at the junction
- Local melting occurs and fusion welding happens
- No filler is used

Resistance welding

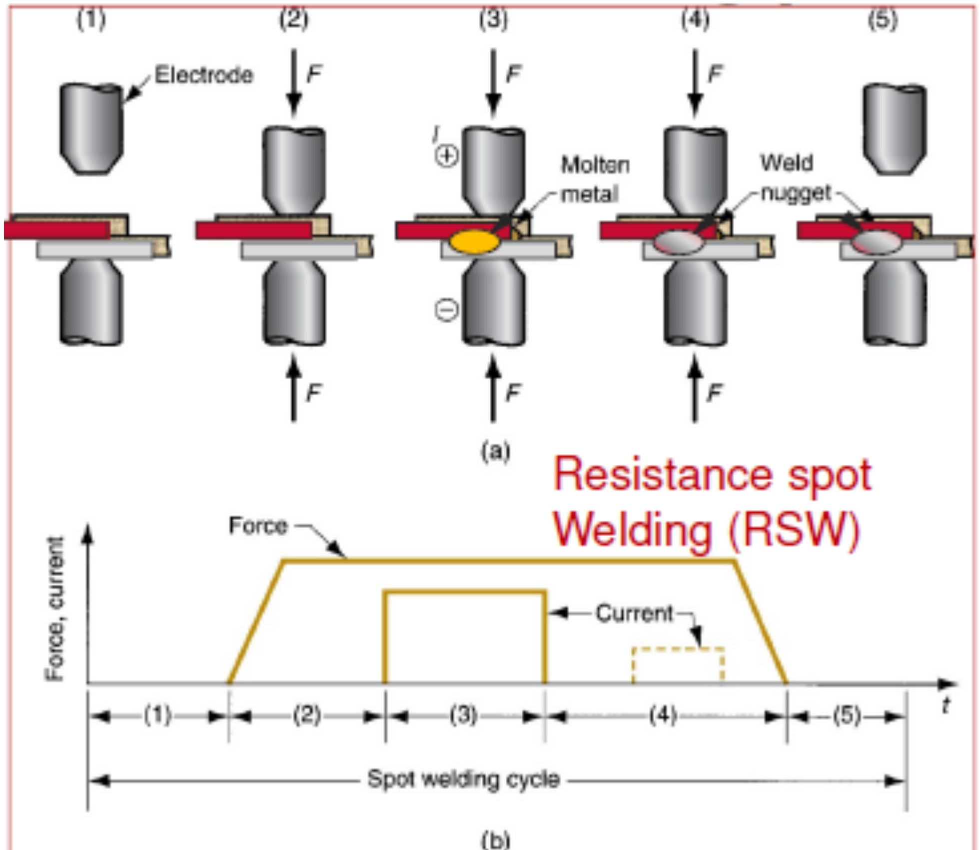


$$R = R_{electrode} + R_{work} + R_{work-electrode} + R_{work-work}$$

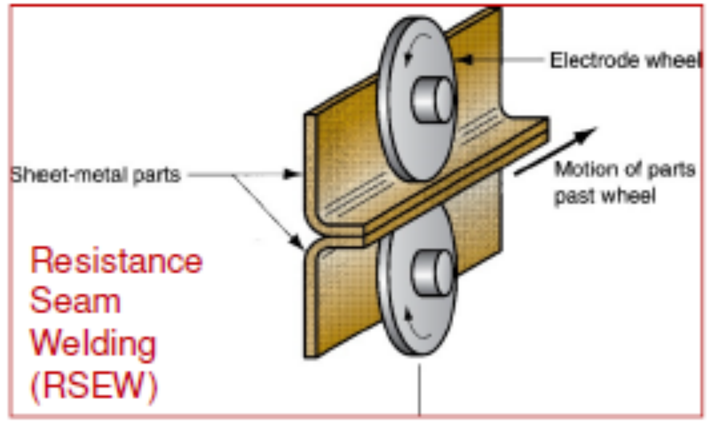
R is usually very small ~ $10^{-4}\ \Omega$; so current has to be high to cause sufficient heating

R has several components; we try to minimize all components except for $R_{work\text{-}work}$

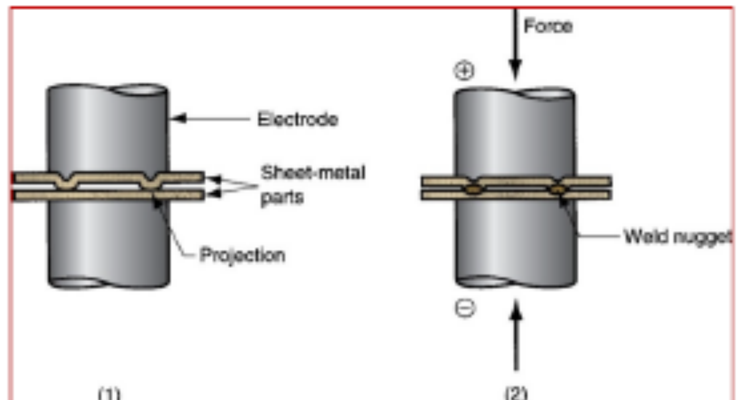
Resistance welding processes

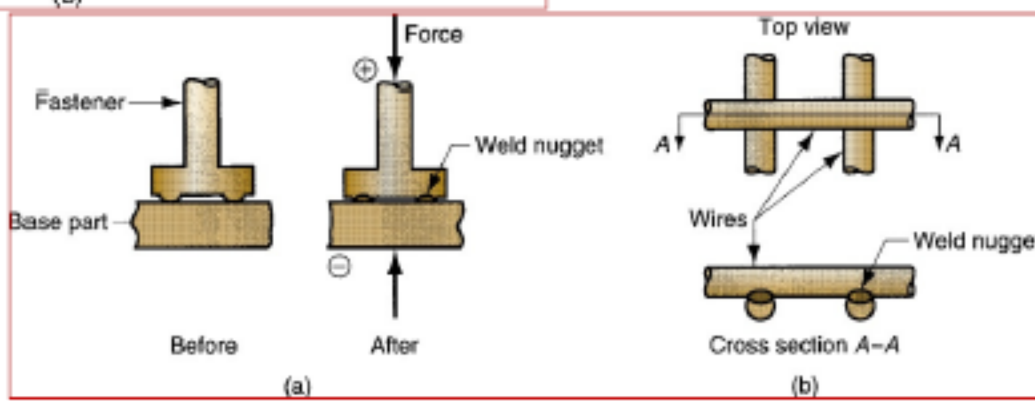


Resistance spot Welding (RSW)



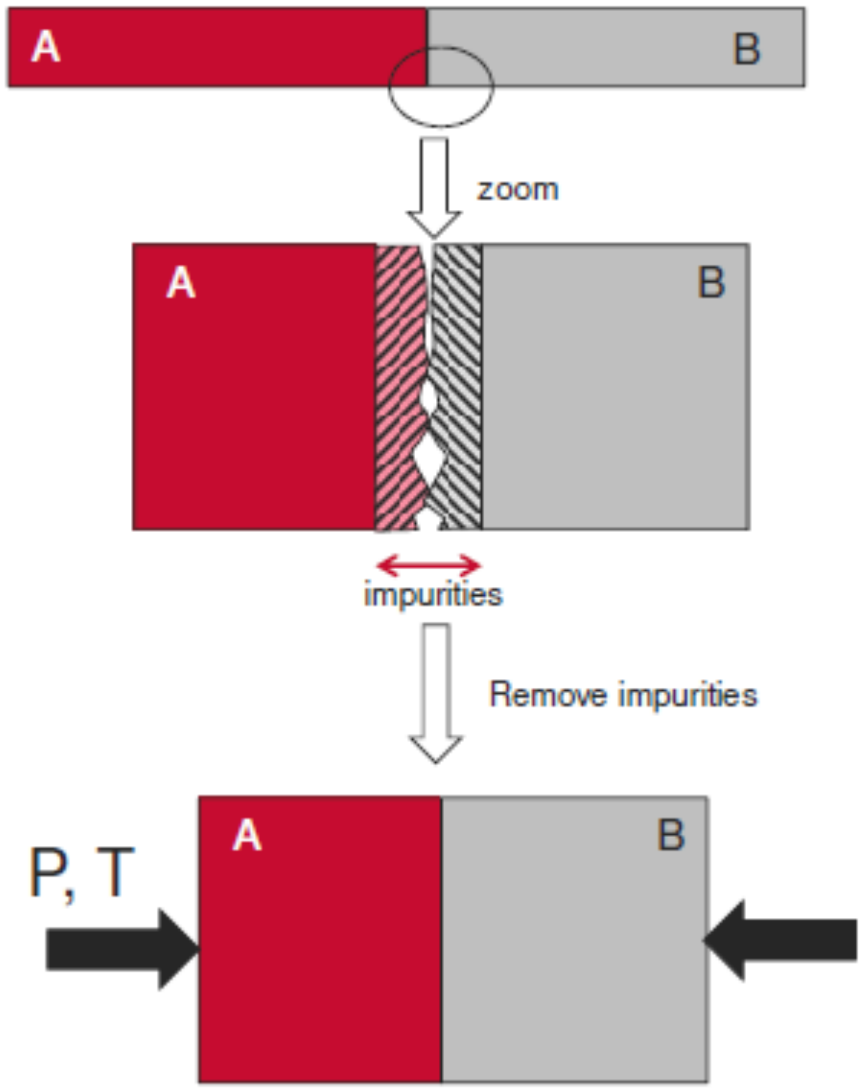
Resistance Seam Welding (RSEW)





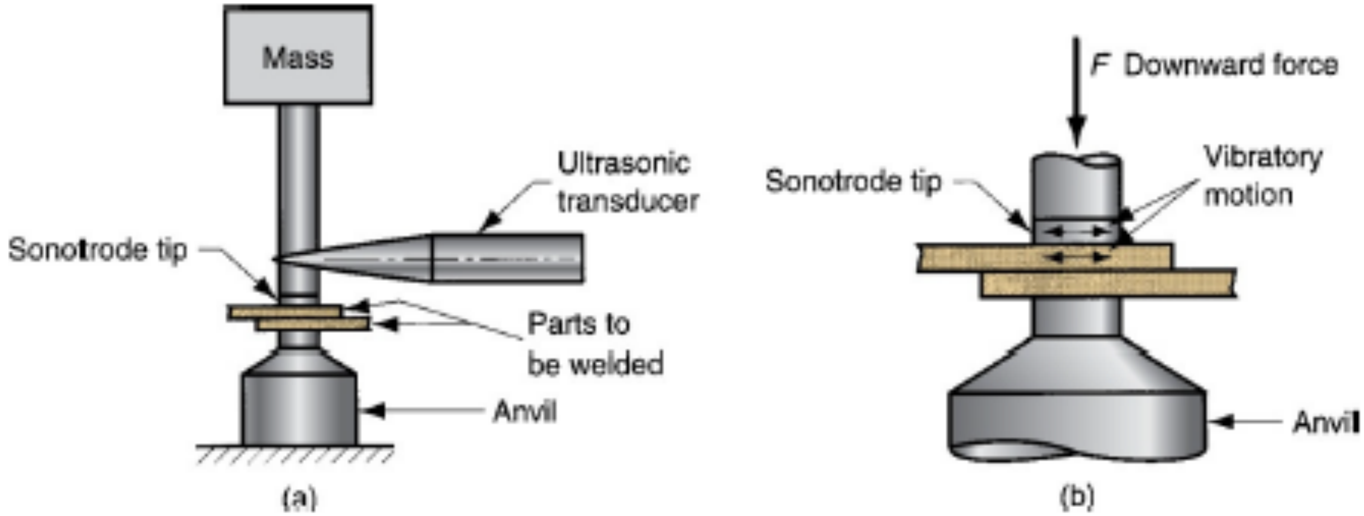
Resistance Projection Welding (RPW)

Solid state welding (SSW)



- Normally surfaces have oxide films and impurities etc on them
- If we can break these films and bring the *nascent* surfaces into contact – then the atoms on the surface will bond naturally
- Bonding can be aided by pressure (P) and/or temperature (T)
- Called SOLID STATE WELDING:
  - Diffusion welding
  - Friction welding
  - Ultrasonic welding

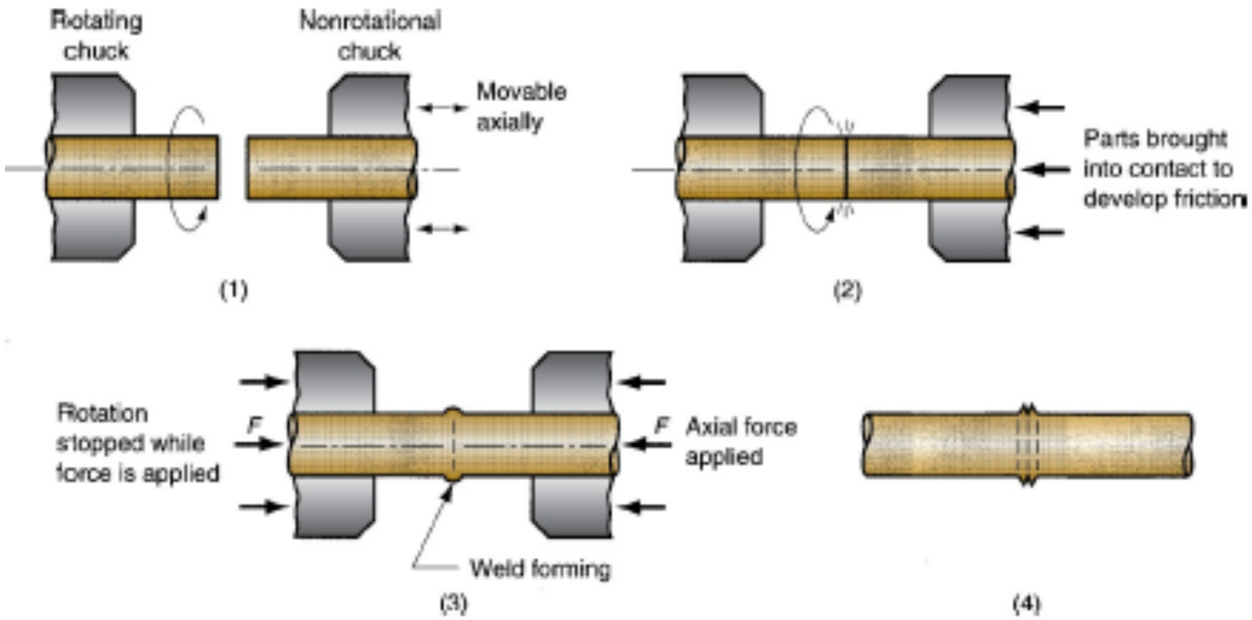
Ultrasonic welding

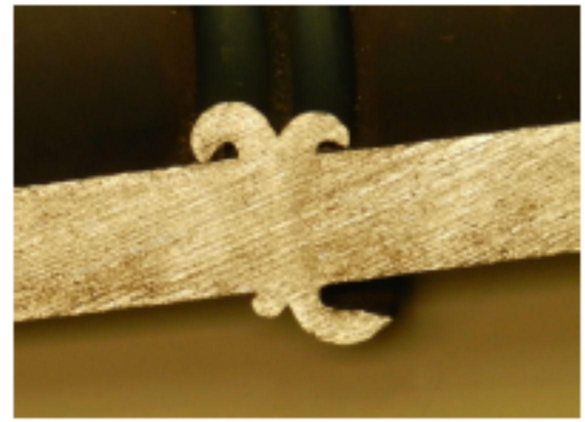


ULTRASONIC WELDING

- Two components are held together, and oscillatory shear stresses of ultrasonic frequency (15-75 kHz) are applied to interface to cause coalescence
  - Oscillatory motion breaks down any surface films to allow intimate contact and strong metallurgical bonding between surfaces
  - Temperatures are well below T_m
  - No filler metals, fluxes, or shielding gases

Friction welding



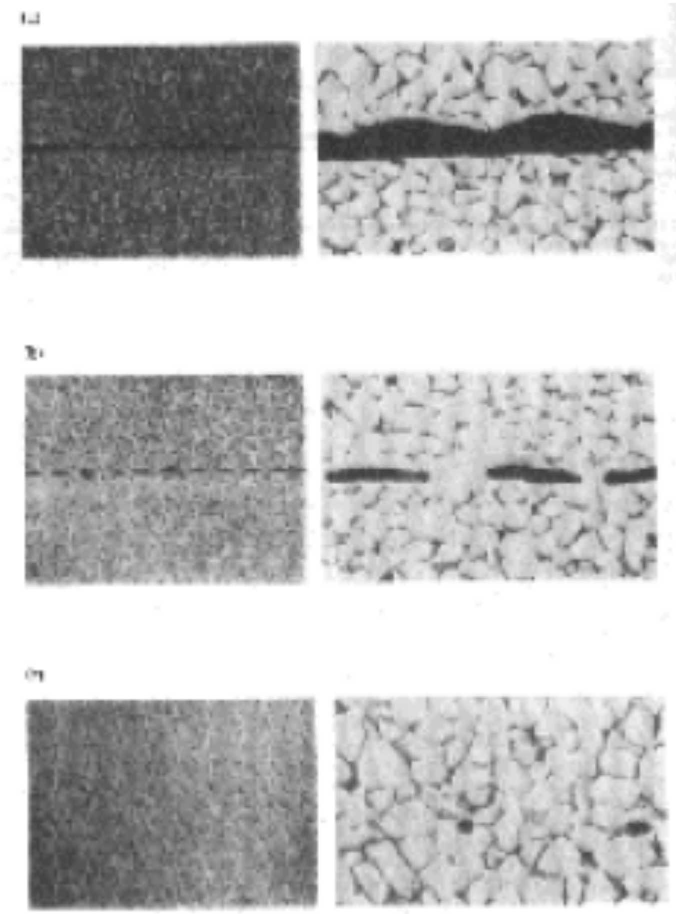


- SSW process in which coalescence is achieved by frictional heat combined with pressure
  - When properly carried out, no melting occurs at faying surfaces
  - No filler metal, flux, or shielding gases normally used
  - Can be used to join dissimilar metals
  - Widely used commercial process, amenable to automation and mass production

Diffusion bonding

DIFFUSION BONDING

- A SSW process that uses heat and pressure, usually in a controlled atmosphere, with sufficient time for diffusion and coalescence to occur
  - Temperatures $\leq 0.5\ T_m$
  - Plastic deformation at surfaces is minimal
  - Primary coalescence mechanism is solid state diffusion
  - Limitation: time required for diffusion can range from seconds to hours



(Diffusion bonding of Ti alloy)