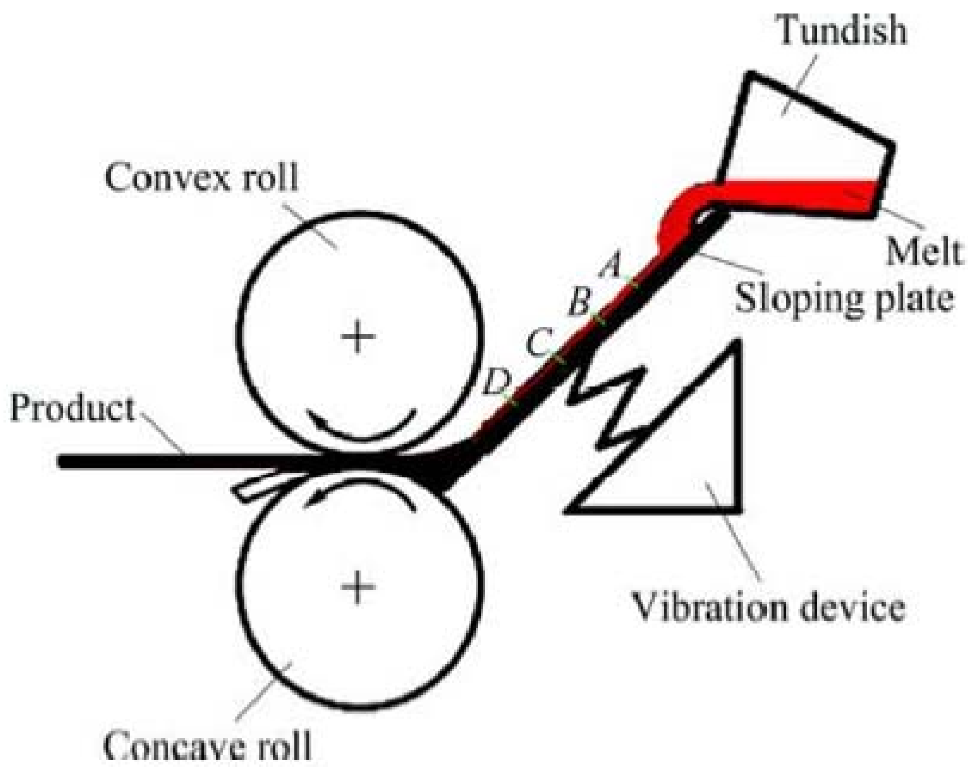
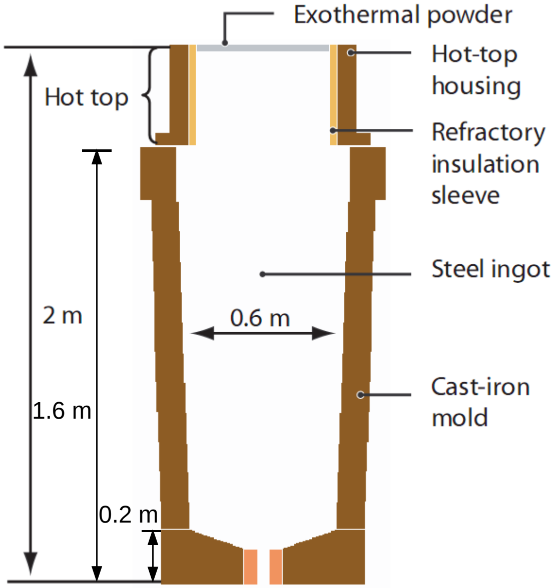
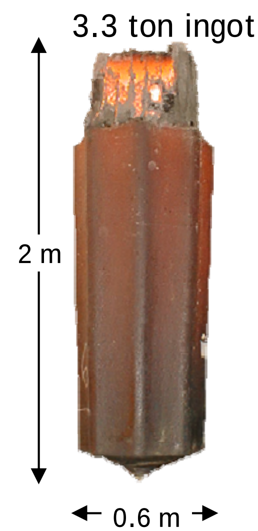
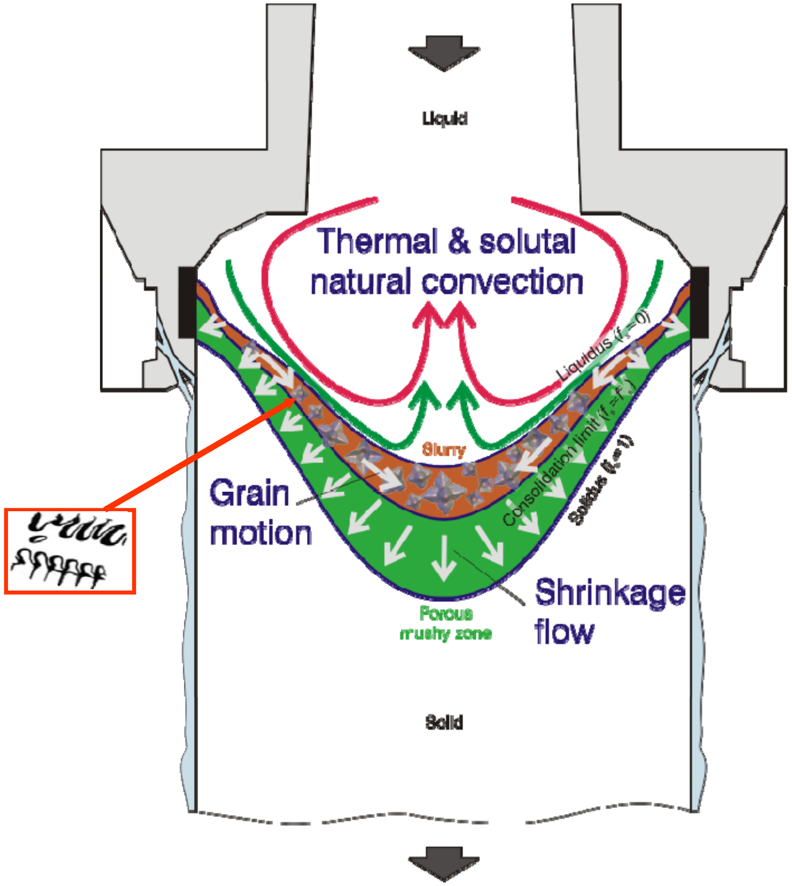
Semisolid rheo-rolling process



Ingot Casting







The physical phenomena

One need to account for

- Various transport mechanisms
- Inoculant particles (nuclei) distribution by different class
- Transport of nuclei by the fluid flow
- Heterogeneous nucleation on the inoculant particles
- Grain growth - development of grain morphology

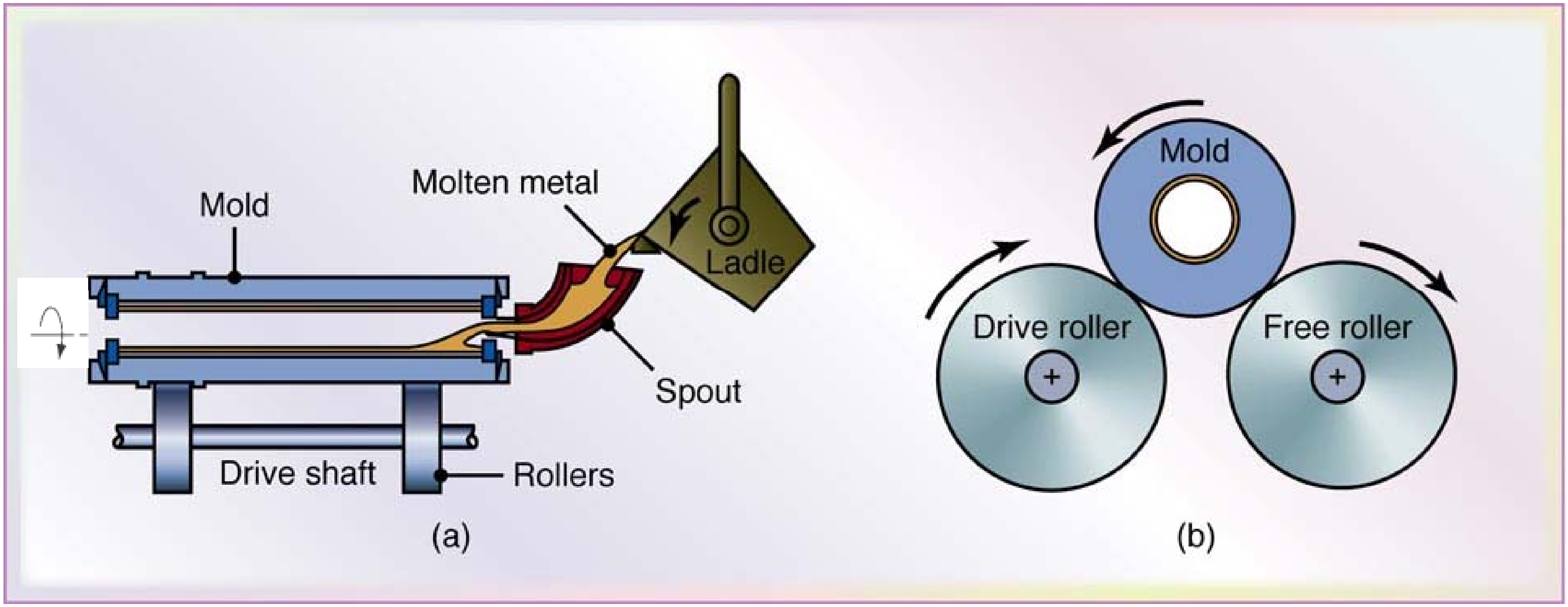
Lecture 12

ME 361A

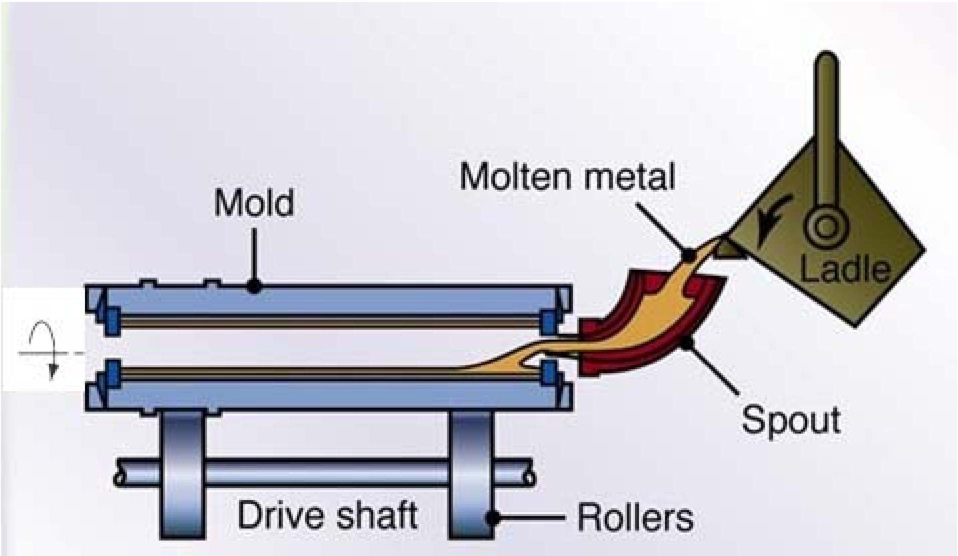
Various Casting Processes…contd.

Critical assessment

Centrifugal casting process



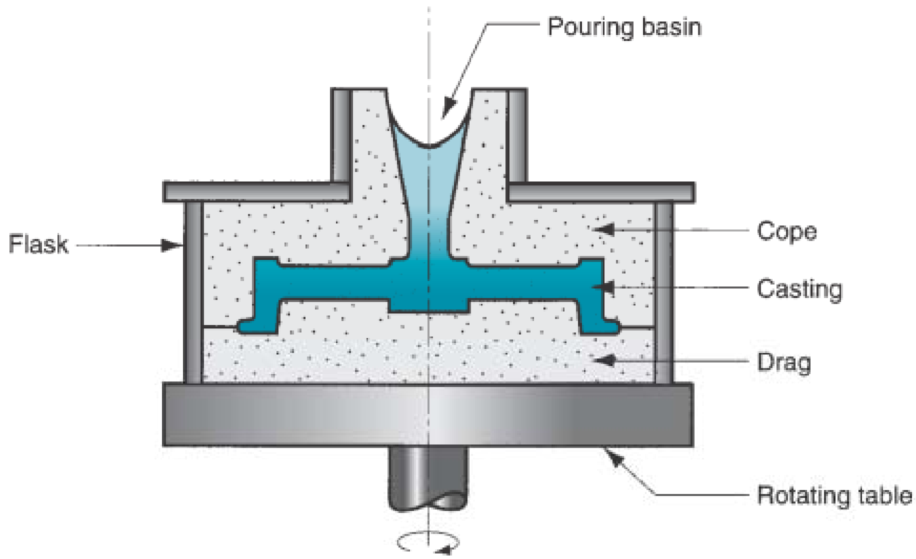
(a) Schematic illustration of the centrifugal-casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process. (b) Side view of the machine



- In true centrifugal casting, molten metal is poured into a rotating mold to produce a tubular part. Examples of parts made by this process include pipes, tubes, bushings, and rings.

- The high-speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. Thus, the outside shape of the casting can be round, octagonal, hexagonal, and so on. However, the inside shape of the casting is (theoretically) perfectly round, due to the radially symmetric forces at work. Orientation of the axis of mold rotation can be either horizontal or vertical, the former being more common.

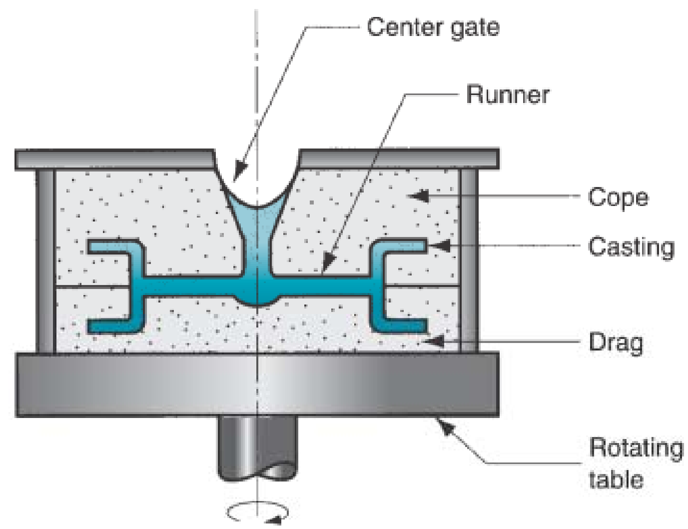
- Castings made by true centrifugal casting are characterized by high density, especially in the outer regions of the part where Force is greatest. Solidification shrinkage at the exterior of the cast tube is not a factor, because the centrifugal force continually reallocates molten metal toward the mold wall during freezing. Any impurities in the casting tend to be on the inner wall and can be removed by machining if necessary.



Semicentrifugal Casting

- In this method, centrifugal force is used to produce solid Castings rather than tubular parts. The molds are designed with risers at the center to supply feed metal.

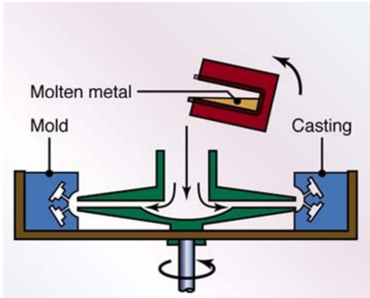
- Density of metal in the final casting is greater in the outer sections than at the center of rotation. The process is often used on parts in which the center of the casting is machined away, thus eliminating the portion of the casting where the quality is lowest. Wheels and pulleys are examples of castings that can be made by this process.



Centrifuge Casting

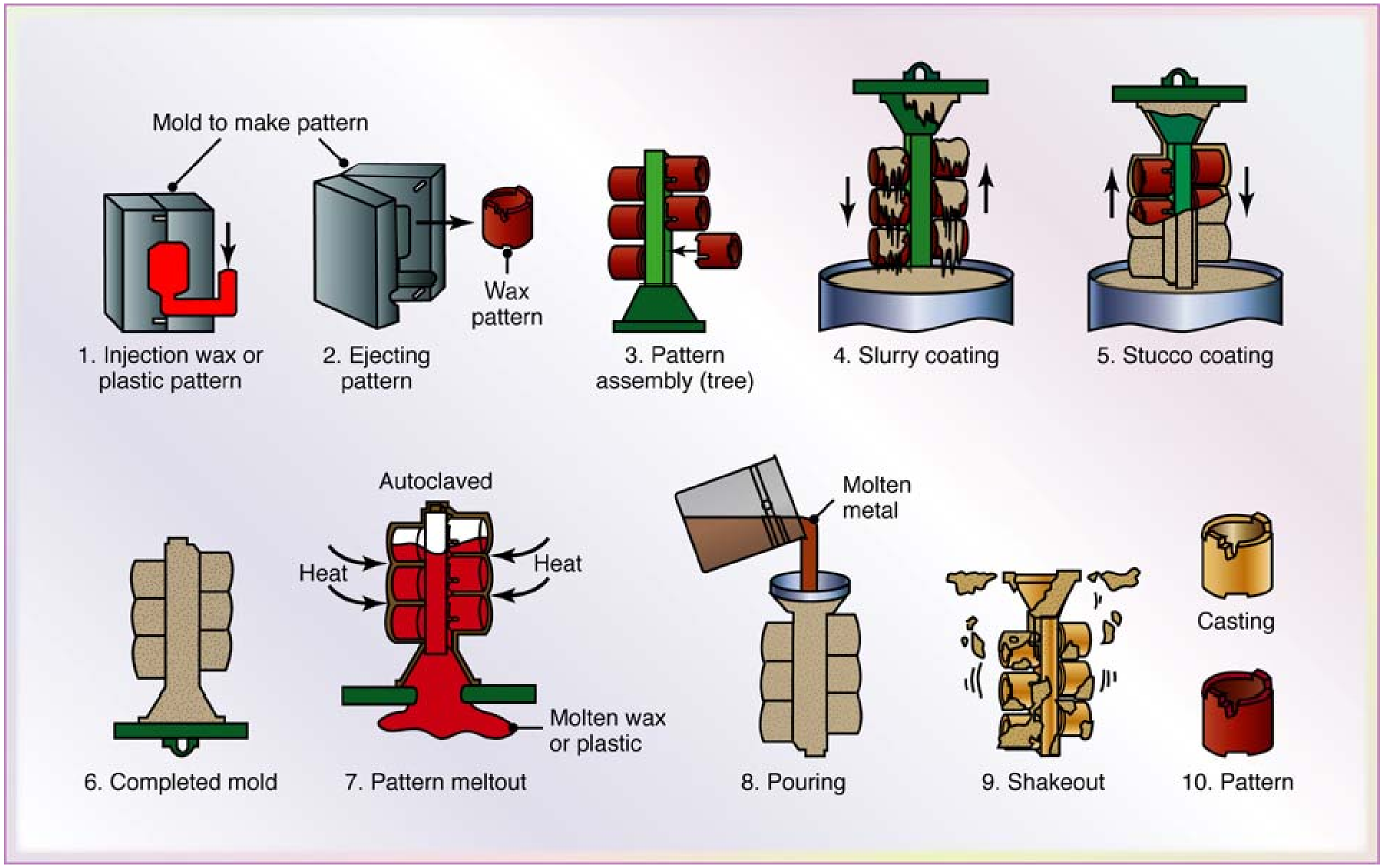
- In centrifuge casting the mold is designed with part cavities located away from the axis of rotation, so that the molten metal poured into the mold is distributed to these cavities by centrifugal force.

- The process is used for smaller parts, and radial symmetry of the part is not a requirement as it is for the other two centrifugal casting methods.



Investment casting (lost wax casting)

Widely known as lost wax casting, because of the use of wax patterns which are coated with a refractory (i.e. the patterns are invested in alternate layers of slurry and stucco), with the wax patterns subsequently melted out to leave a hollow shell into which the metal is cast.



Sequence of steps used in the investment (lost-wax) casting technique. These include wax injection and solidification in a prefabricated die, formation of a "tree" or "cluster" of wax patterns on a wax sprue, repeated immersion in a fine ceramic slurry, and a dry "stucco" coat. This is followed by melting the wax out, firing the shell, and pouring.

Schematic illustration of investment casting (e.g., lost-wax) process. Castings by this method can be made with very fine detail and from a variety of metals

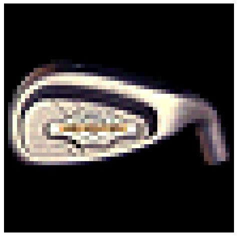
stucco

Advantages:

- most materials
- intricate shapes, mass production
- high accuracy
- very good surface finish

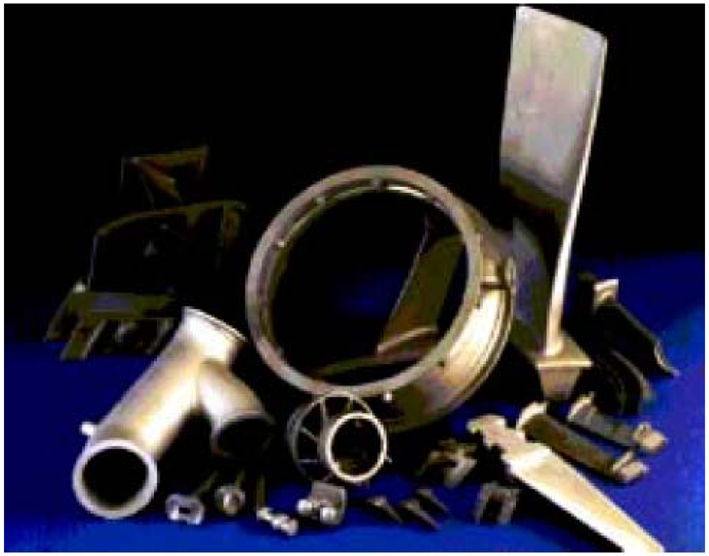
Problems:

- lengthy process
- costly process
- not suitable for very large parts



Golf club

Investment cast exhaust manifold for a Chrysler car made from an SLS wax pattern



Characteristics of investment casting

- Investment casting is used to make turbine blades for aircraft engines, fuel system components, combustor chamber parts, turbine vanes, prosthetic devices, air frame parts, precision machine tools, dental implants, jewelry and sculpture, and a wide variety of other industrial and consumer items from ferrous and nonferrous alloys.

- Parts with complex geometry and thin sections (typically 0.015 inch) with tight dimensional tolerances (0.005 to 0.010 inch per inch) and excellent surface finish are routinely produced with this process.

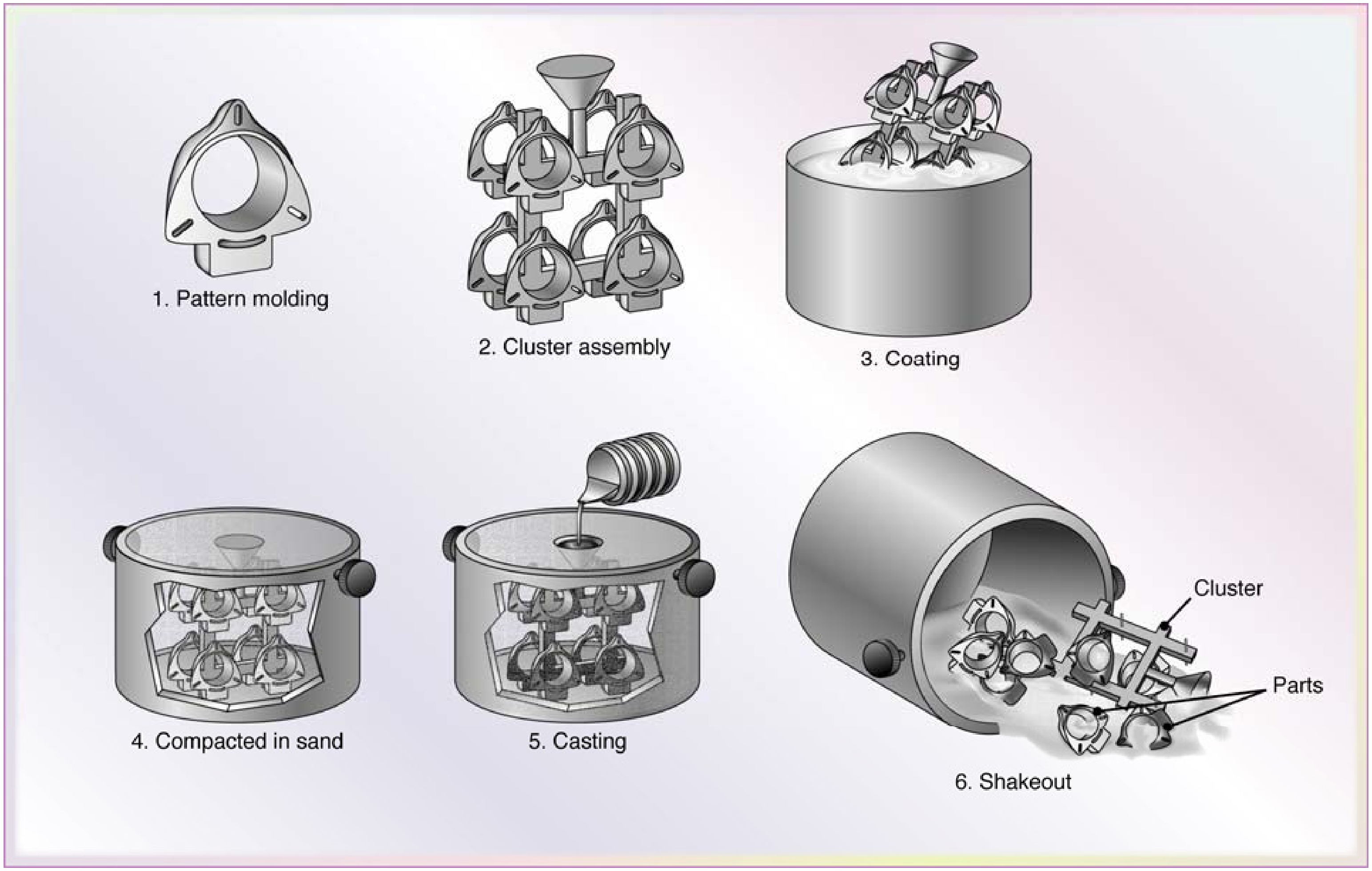
- Investment casting is a near-net-shape fabrication process applicable to a wide range of alloys (Al, Cu, steel, Co, Ti, and Ni-base superalloys).

- The process is good for difficult-to-machine alloys such as Ni-base superalloys used in aircraft engine parts. The high design flexibility of investment casting and its ability to cast complex parts to near-net shape reduces the fabrication and assembly costs.

- It is an extremely slow process. The production of a wax pattern might take only 1 or 2 minutes but most ceramic shell moulds require between 7 and 14 coats and take at least 24 hours and sometimes as long as several days to complete. However, it is now normal practice to make several hundred moulds automatically in one batch and, of course, each mould may comprise several dozen or over a hundred small components.

Expendable-pattern casting process

or lost-foam or evaporative casting



Schematic illustration of the expandable-pattern casting process

Characteristics of lost-foam casting

• The lost-foam casting process uses expendable polystyrene patterns.

• A thin coat of a fine ceramic is applied via immersion in a slurry to cover all the surfaces of the foam pattern. The coating improves the casting surface finish by acting as a barrier between the supporting sand and the foam.

• After the coating has dried, the coated pattern assembly is either buried in loose, free-flowing sand or covered in lightly packed green sand. The metal is poured, allowing the pattern to volatilize and progressively create the mold cavity to be continuously filled by the incoming metal. Pouring is usually assisted with a vacuum that removes gases from the burnt foam through the semi-permeable coating, thus enabling uninterrupted metal filling.

• After solidification, the casting is readily extracted from loose sand by robots, thus eliminating shakeout.

• The casting yield in the lost-foam casting is usually less than 70%. The lost-foam casting is applicable both to alloys and metal-matrix composites and has been widely used by automotive manufacturers in making engine parts such as intake manifolds.

Stages in investment (low wax) casting

- Make wax pattern in die
- Assemble patterns onto 'tree'
- Build up ceramic shell mould
- Dewax and fire shell
- Pour metal and allow to solidify
- Remove shell
- Separate castings from runner system and fettle

Stages in the 'lost foam' process

- Produce expanded polystyrene pattern
- Assemble patterns onto runner system
- Coat with ceramic slurry and dry
- Embed in sand and vibrate to consolidate
- Pour metal
- Remove from sand
- Clean and fettle castings

THE LOST FOAM CASTING PROCESS

• First, a pattern is made from polystyrene foam. Pre-made pouring basins, runners, and risers can be hot glued to the pattern to finish it.

• Next, the foam cluster is coated with ceramic investment, also known as the refractory coating, via dipping, brushing, spraying or flow coating. This coating creates a barrier between the smooth foam surface and the coarse sand surface. Secondly it controls permeability, which allows the gas created by the vaporized foam pattern to escape through the coating and into the sand. Controlling permeability is a crucial step to avoid sand erosion. Finally, it forms a barrier so that molten metal does not penetrate or cause sand erosion during pouring.

Coating

• After the coating dries, the cluster is placed into a flask and backed up with un-bonded sand. The sand is then compacted using a vibration table. Once compacted, the mold is ready to be poured.

• There is no bake-out phase, as for lost-wax. The melt is poured directly into the foam-filled mould, burning out the foam as it pours. As the foam is of low density, the waste gas produced by this is relatively small and can escape through mould permeability.

• So the purpose of applying ceramic coating is for gas escape and for avoiding direct contact of metal and sand.

• Purpose of compacting in sand:

- The foam pattern are very light weight (as opposed to wax pattern). Since this process is used for near-net-shape castings, these molds will certainly contain thin and fine sections, undercuts etc that is needed to be filled properly without any damage during pouring process. Without providing any external rigidity support and strength by sand compacting the fine details of the mold can be damaged during the pouring process. So compacting by sand just serves this purpose.

- In lost wax process since the weight of the wax+weight of several layers of coating is much larger than that weight of foam pattern+weight of just few layer of coating in lost foam process, no sand compacting is needed.

- The casting process that you performed in your TA lab is done with thermocoal, which still can offer some rigidity to the mold than by a foam pattern. Additionally that casting was just for demonstration of the process and may not has fine details which can be damaged during the pouring.

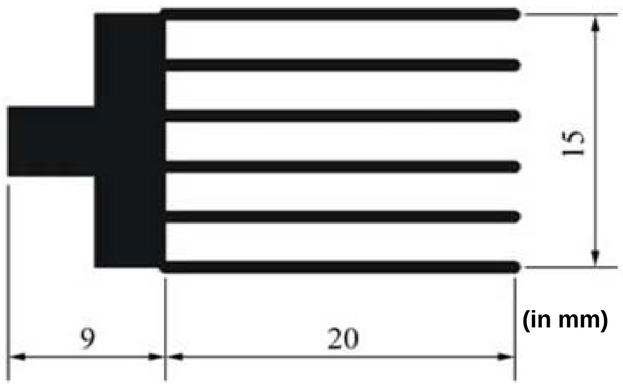
Compaction

- Cluster is delivered to the pouring line by conveyor.
- Cluster is placed into flask and held in position by a fixture

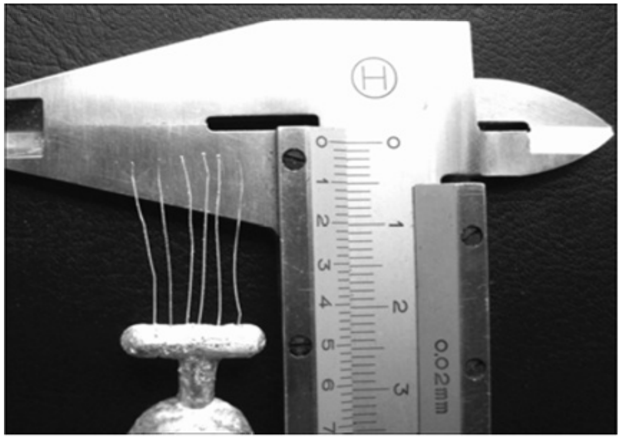
- Sand is rained into flask from overhead bin.

Microcasting

Microcasting: small structures in the micrometer range or larger parts carrying micro-sized structures (e.g., metallic micro parts with high aspect ratio (ratio of flow length to diameter)). Molten metal is cast into a microstructured mold



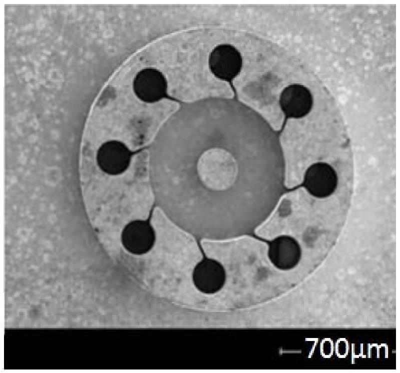
(a)



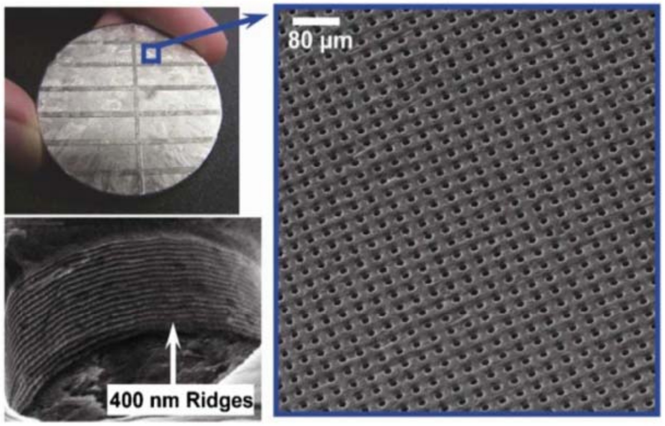
(b)

(a) A microcasting part containing microwires, (b) Sample microcasting part containing 100 μm metal wires

Examples of microcast parts



(a)



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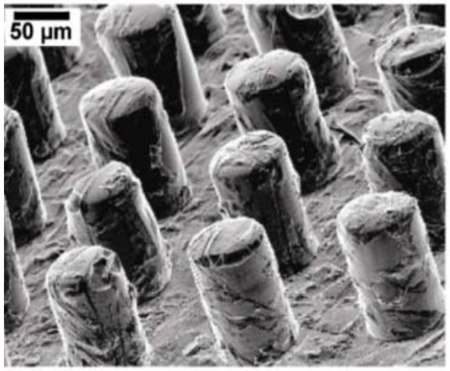
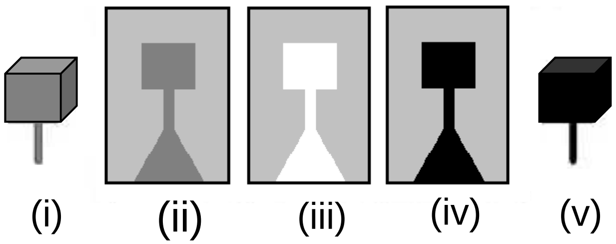


(c)

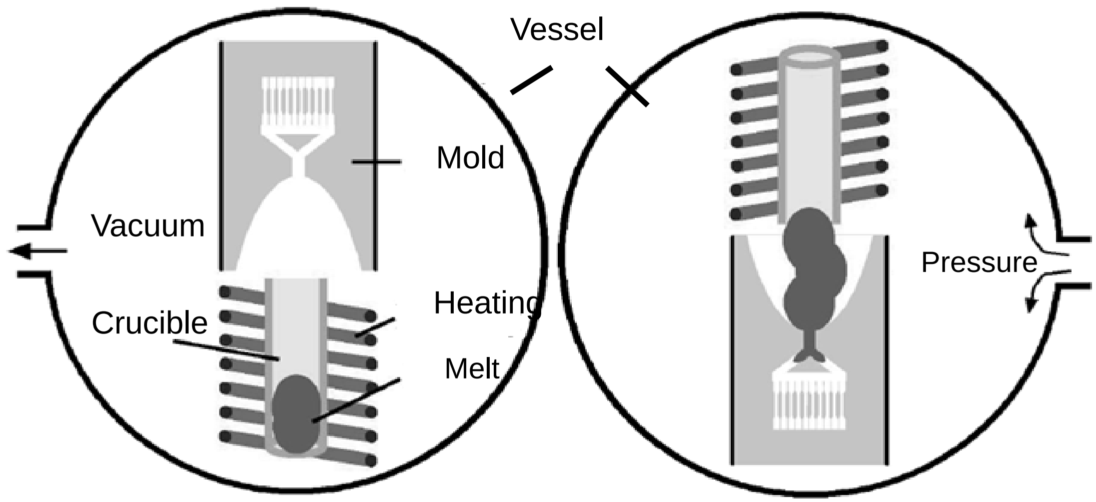
Miniaturized demonstrative microcasting parts (a) nozzle plate with 1.9 mm diameter and 25 µm channel width made of gold base alloy (b) Metal with 10 µm diameter holes 15 µm deep. 400 nm ridges are viewable in the picture showing a single 25 µm diameter hole; (c) Metal pillars with 50 µm diameter and 100 µm tall

- Micro components are widely used in manufacturing, biotechnology and information technology applications
- They can be manufactured by various microsystem technologies-
  - micro powder injection molding
  - micro electrical discharge machining
  - electroplating
  - laser ablation and micro milling
- These days microcasting techniques based on permanent mold and investment casting are being used to manufacture micro parts in large quantities
- The microcasting technique: versatile, very complicated structures, scalable, economically efficient for mass production, and needs minimal subsequent machining

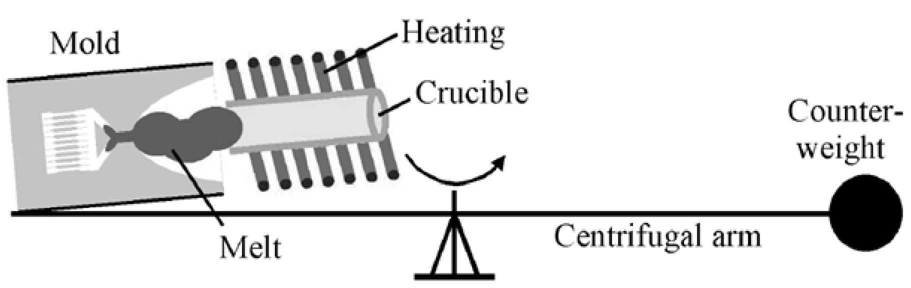


Schematic of micro investment casting process: (i) plastic pattern, (ii) embedded in ceramic slip, (iii) hollow form, (iv) molten metal filled mold, (v) cast part consisting a micro structure

Other microcasting methods to manufacture micro parts: vacuum casting method, centrifugal casting



Vacuum pressure casting process. Left: vacuum condition with mold atop the heating chamber; Right: pressure condition with melt discharged into the mold by gravity



Centrifugal microcasting process

Challenges

- Due to decrease in the dimensions of casting part, some challenges like complete mold filling, suitable operational pressure and other parameters become important in microcasting technique
- Materials to be microcast must have sufficient castability
- This embraces properties such as flowability and form filling ability, little contraction and shrinkage, reduced segregation, low porosity, high surface quality.
- The form filling ability and flowability of the melt are influenced by the viscosity of the melt, the wetting behaviour of the form, the reaction with the mold and the atmosphere and, of course, by the solidification behaviour
- Fast solidification in the small structures due to very high cooling rate hinders form filling much more than in macrostructures
- Further, the occurrence of turbulent flow needs to be taken into account due to higher surface to volume ratio in microchannels and the distinct influence of surface roughness

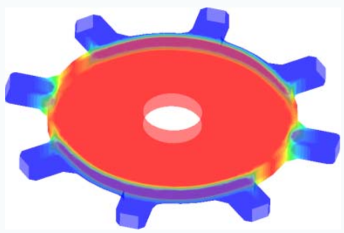
Micro casting

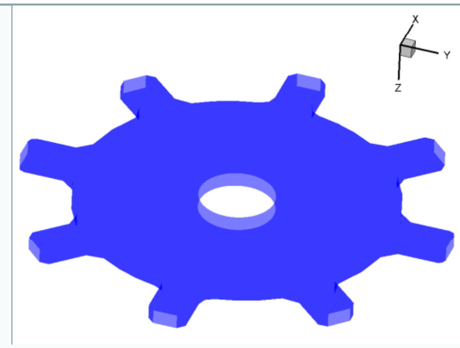
Applications: Surgical and dental devices, Miniaturized mechanical devices, Jewellery

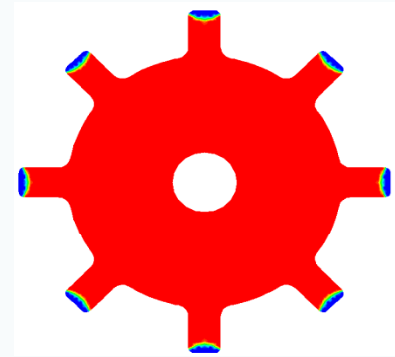
Challenges in Microcasting

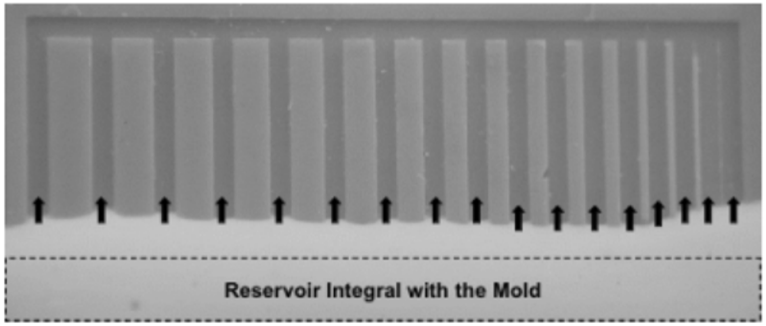
- Capillary action during filling
- Incomplete mold filling
- Rapid solidification

$$p = \frac{2\sigma \cos\theta}{r}$$

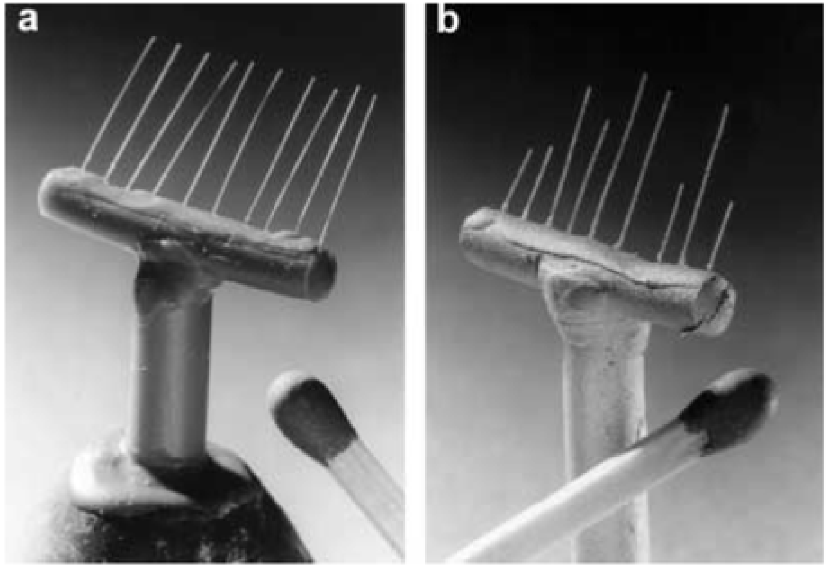








Microcasting is a potential fabrication method for metal parts in microdimensions. Since this technique is at developmental stage, many works are needed for this technology for suitability in industrial production



Lecture 13

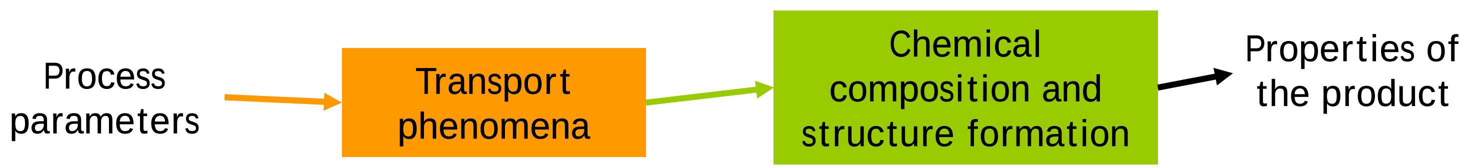
ME 361A

Solidification and melting principles

in other scientific applications

Solidification transport phenomena can be used to study/ to predict/ to explore means to control the **defects, chemical heterogeneities and microstructure** in a solidification process (say various casting processes or even other solidification processing (e.g., welding) which we will see in subsequent lectures)

Principal application: solidification processes

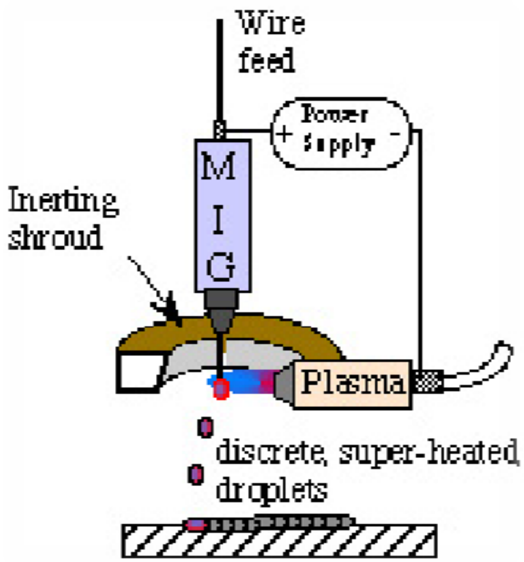


Applications of solidification and melting

Great deal of interdisciplinary research – Manufacturing, Materials, Thermal

1. **Manufacturing** – casting, welding, and other solidification processing for materials such as, steel, Al, Mg, Superalloys, MMCs, ceramics, plastics,
    - Lightweight materials – Al, Mg etc
    - Microgravity – Reduced gravity processing of materials
    - Electromagnetic processing of materials (EPM)
    - Levitation materials processing
    - Jewellery, watch design – joining and welding at micro scale
    - Other industrial processes……casting and rolling simultaneously
    - Solidification of polymers and plastics – injection molding
    - Microcasting - solidification of Miniature devices for MEMS and NEMS
2. **Surface Engineering** – To enhance surface properties by providing thin coating (thermal spray coating process)
3. **Energy** – phase change latent thermal energy systems, Air-conditioning, refrigeration, cooling, solar energy, energy efficient building construction
4. **Electronics** – Semiconductor's growth for electronic devices, solidification in printed circuit board, thin film deposition
5. **Earth science** – ocean iceberg formation, mantle convection and pattern formation in rock
6. **Food processing** - Chocolate, ice cream solidification, food storage using ice,
7. **Nuclear and industrial application** - nuclear safety – interaction of radioactive nuclear core debris and coolant, freezing the radioactive nuclear waste, industrial waste for disposal
8. **Medicine and biomedical engineering** – medicine tablets production, cancer tumour treatment, cryosurgery

Shape Deposition Manufacturing (SDM) droplet based manufacturing



small droplets of materials are directly deposited onto a substrate continuously, they solidified and take the shape

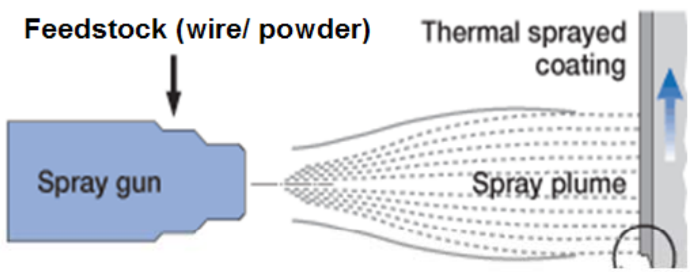
There are number of physical variables

- Cooling rate
- Substrate remelting which determines the metallurgical bonding
- Proper substrate temperature control, coupled with droplet temperature control
- Droplet deposition rate, droplet size and free-falling distance

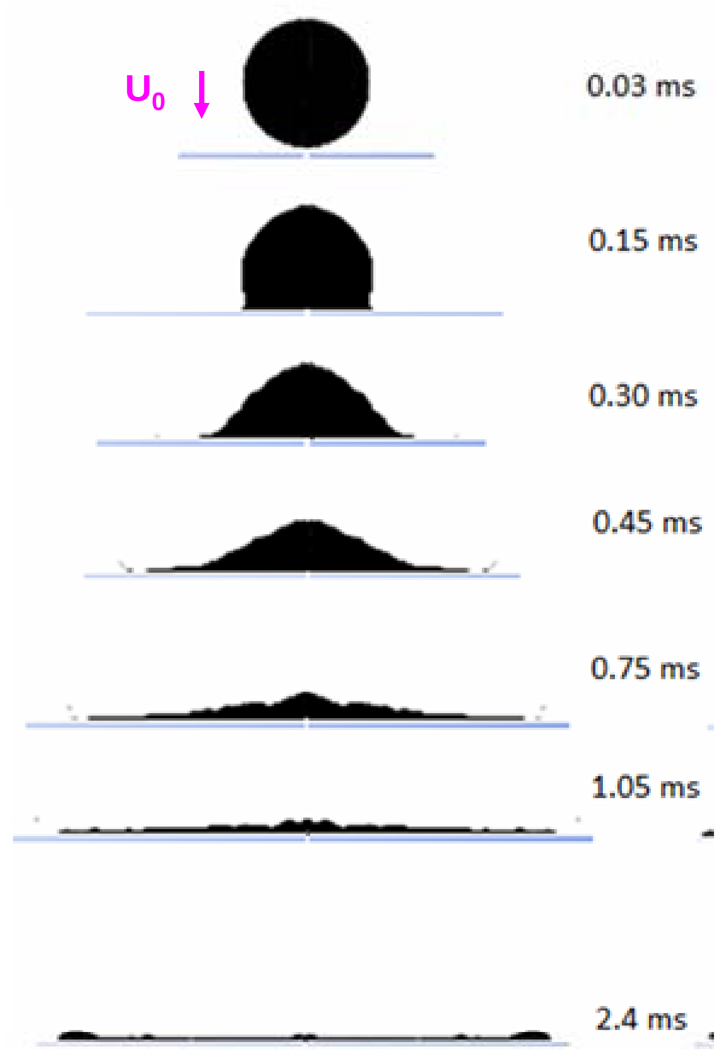
Thermal Spray Coating

❖ Droplet impact on a solid surface – spray coating, ink-jet printing, solder deposition on circuit boards etc.

❖ Thermal spray coating — melt powder particles are projected onto substrates to produce protective coating after impact, flattening and solidification on the substrate.



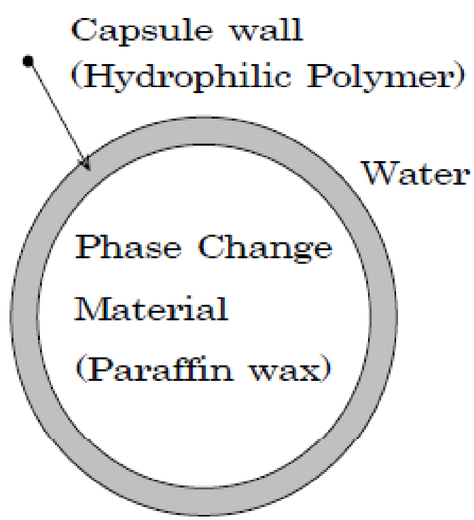
Fluid flow and heat transfer during droplet impact involves free surfaces undergoing large deformations, moving liquid–solid–gas contact lines and solidification



Phase change thermal energy systems

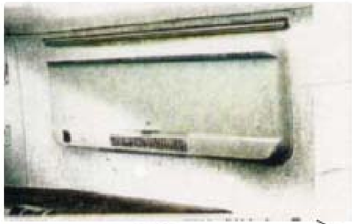
(1) Ice slurry (water, water solution): Cooling, Refrigeration

(2) PCM microcapsule slurry (phase change material, paraffin wax etc.): Air conditioning, solar energy storage

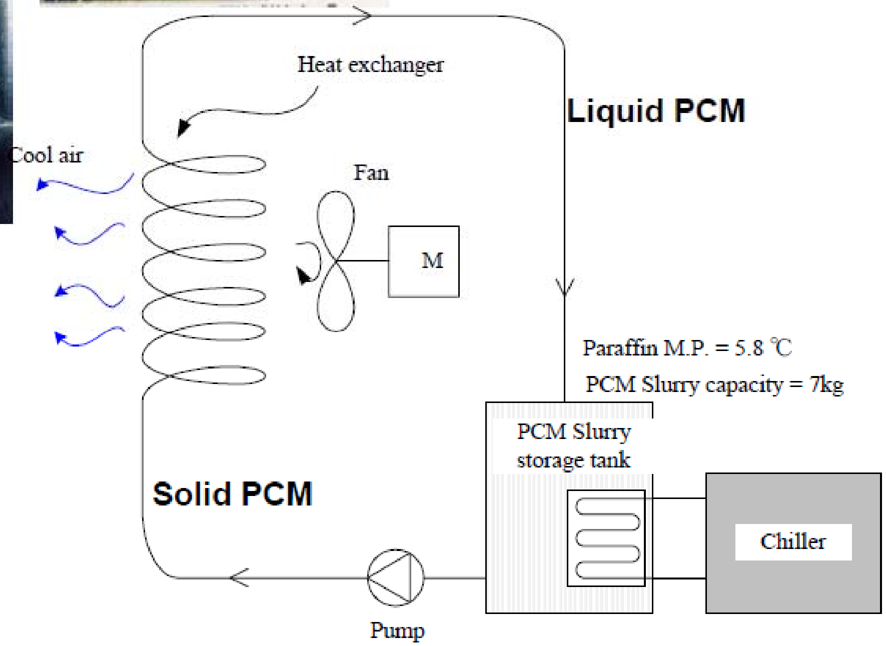


Single Film Layer Capsule

Air conditioning in vehicle cabin by PCM emulsion slurry



Cooling unit by PCM microemulsion slurry behind the vehicle cabin



PCM: Tetradecane paraffin, Melting point of 5.8 ℃

Concentration of PCM: 40% in the slurry

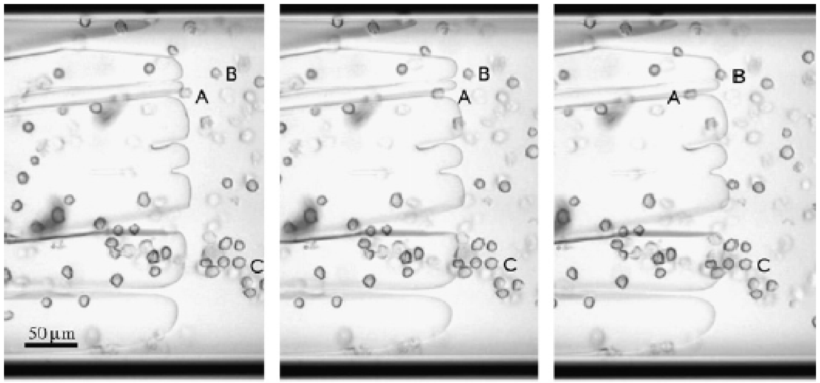
Total mass : 7 kg, operation time period : 4 hours (during stopping engine)

Heat Transfer with Phase Transformation in Biological Science

• Modelling heat and mass transfer during freezing of biological tissues

• Modelling solidification of ice from biological solutions; thermo-fluid interactions of ice with solidifying interfaces having planar and widely varied morphologies (ice/cell interactions) using directional solidification and its response to local environment (changing microstructure of the solidifying interfaces)

Towards developing an understanding of the effects of freezing, bioheat transfer and local fluid flow on cell survival and living organisms.



Fat Crystal Growth and Microstructural Evolution in Industrial Milk Chocolate

Freezing in Food processing - ice fouling

Ice cream solidification

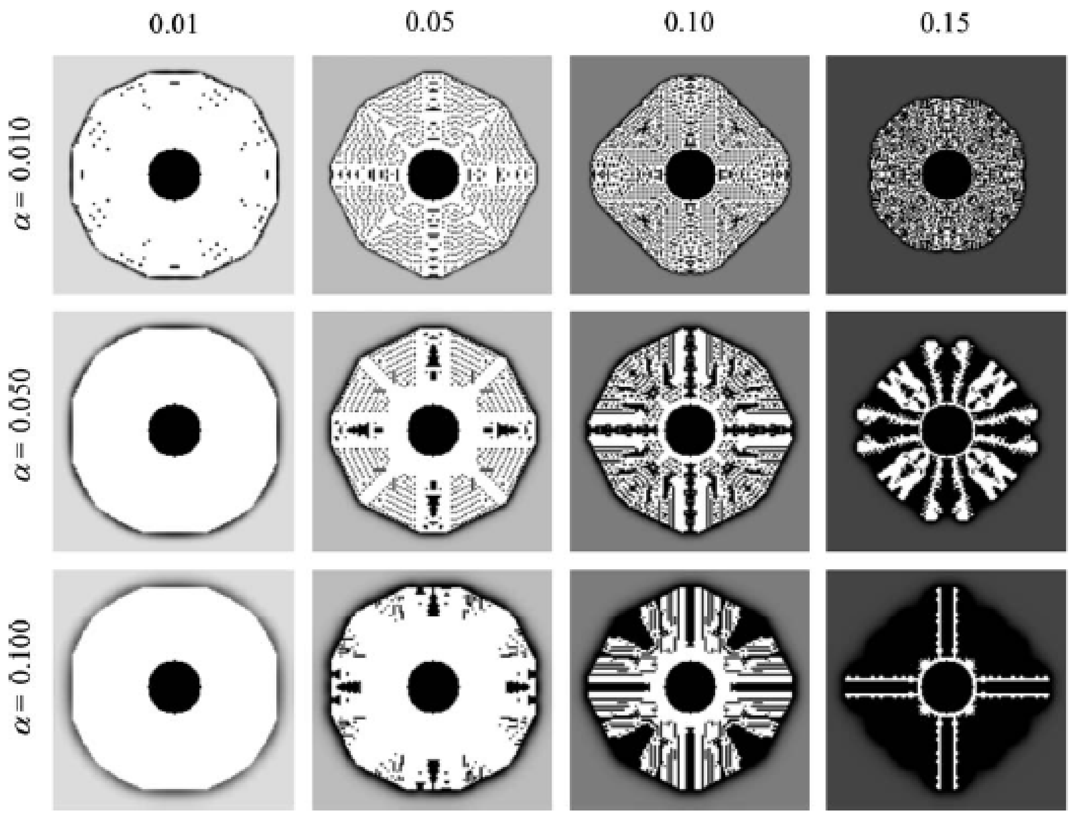


Fig. 9. 2D sections of microstructures simulated using different values for the initial sugar concentration and of α. The matrix colour ranges from white (no sugar concentration) to black (sugar concentration equal to the saturation). The oversaturated matrix is also shown in black.

Freezing the industrial waste

Soil contamination:

Solidification for the Treatment of Contaminated Soil; Solidification - involves the addition of reagents to a contaminated material to impart physical/dimensional stability to contain contaminants in a solid product and reduce access by external agents (e.g. air, rainfall).

Solidification in electronics packaging:

In electronic packaging, solidification is commonly associated with solder materials used to bond components together such as microchips onto a printed circuit board. A number of defects may occur during the bonding process such as flux entrapment, void formation, and cracking of the joints. The consideration for a cleaner environment may also mean solder

Magma chamber solidification and convection:

phase change and convection in melts due to sedimentary crystal flux from above

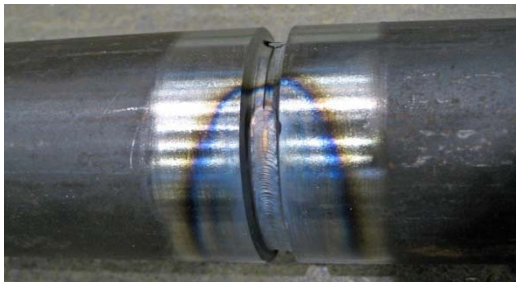
Problem of Volcanic Ash for Aircraft

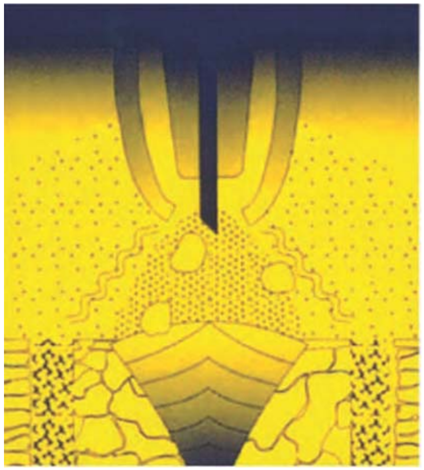
Volcanic ash are sucked in the turbine system and melt by the high temperature in the system. Form a pasty type materials and stick to the turbine blades, hampers the operation of the turbine and also cause abrasion

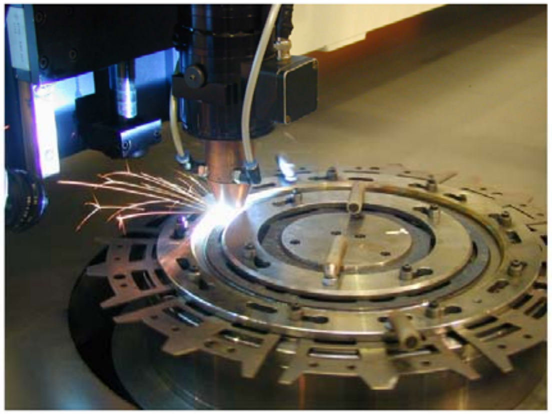
Lecture 14

ME 361A

Joining Processes







Welding and Joining Processes

(A) Joining and welding process

(B) Physics of joining

- **Solidification transport phenomena** involved in a welding process
- Defects analysis-causes and remedies. Understanding the **role of solidification transport phenomena and heat transfer** in the formation of these defects

Welding and Joining Processes

(A) Joining processes - Overview

Joining and Assembly Distinguished

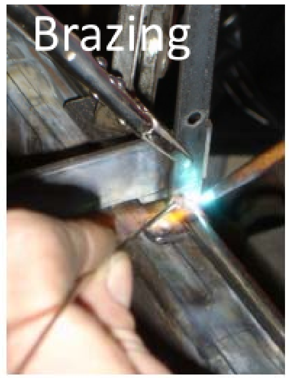
Joining – welding and adhesive bonding

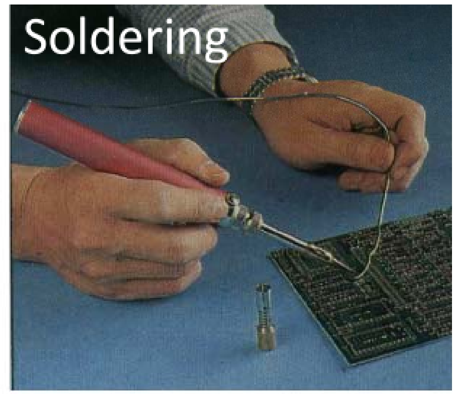
- These processes form a permanent joint between parts

Assembly - mechanical methods (usually) of fastening parts together

- Some of these methods allow for easy disassembly, while others do not

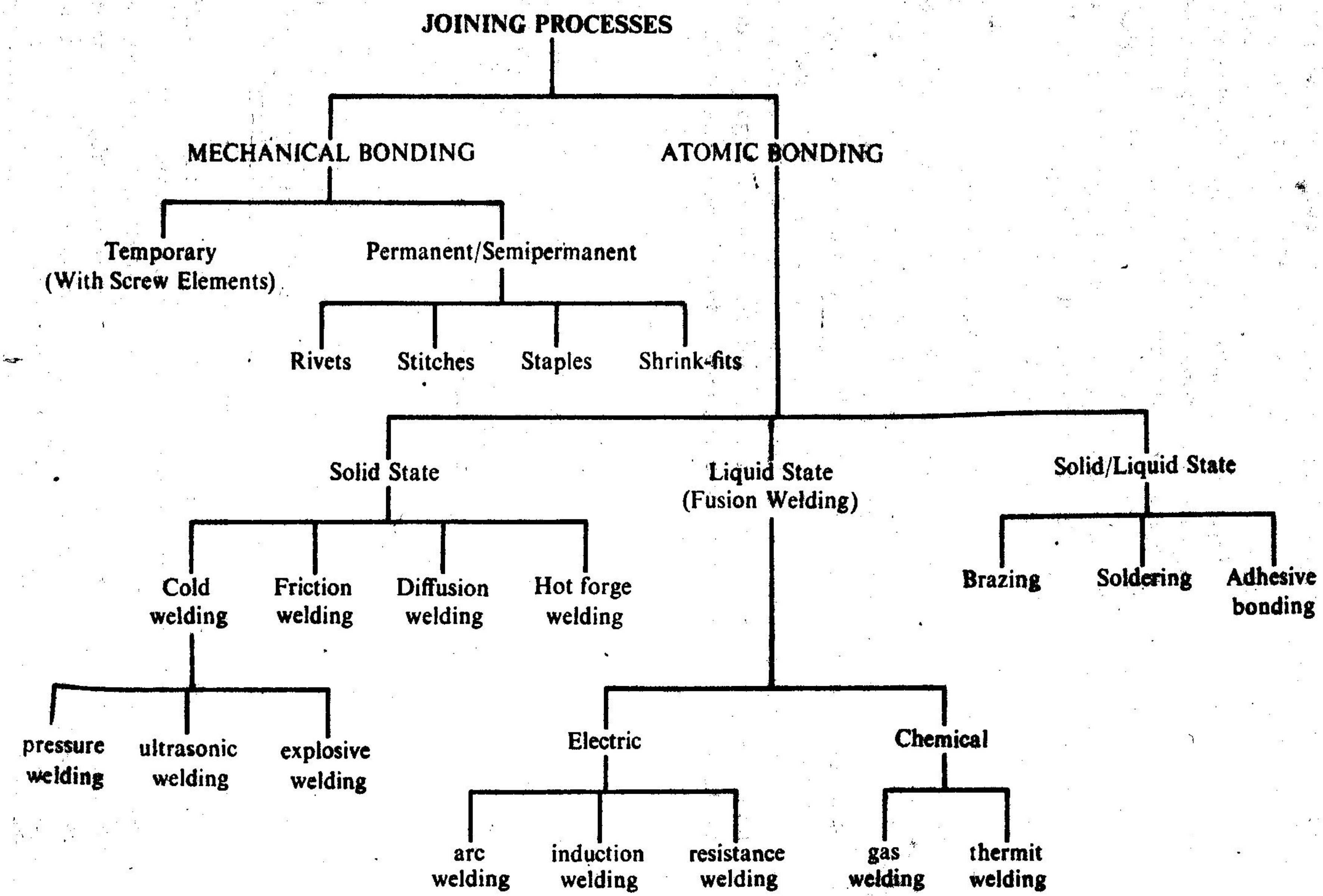
Joining Processes





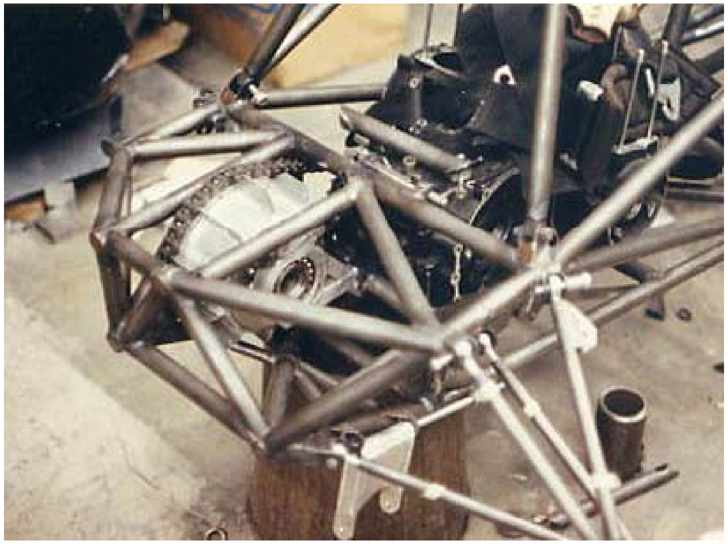
Classification

- Welding
  - Fusion
  - Solid-state
- Brazing and Soldering
- Adhesive bonding
- Mechanical fastening


JOINING PROCESSES
MECHANICAL BONDING
ATOMIC BONDING
Temporary (With Screw Elements)
Permanent/Semipermanent
Rivets
Stitches
Staples
Shrink-fits
Solid State
Liquid State (Fusion Welding)
Solid/Liquid State
Cold welding
Friction welding
Diffusion welding
Hot forge welding
pressure welding
ultrasonic welding
explosive welding
Electric
Chemical
arc welding
induction welding
resistance welding
gas welding
thermit welding
Brazing
Soldering
Adhesive bonding

Joining Processes: Welding, Brazing, Soldering

1. Brazing and Soldering: Melting of filler rod only
   - Brazing: higher temperature - brass filler, strong
   - Soldering: lower temperature - tin-lead filler, weak
2. Welding: Melting of filler rod (if any) and base metals both
3. Both 1 and 2: Join parts to form complex product



Principles of solid/ liquid state joining

- Brazing, soldering, and adhesive bonding are grouped under solid/ liquid state welding
- **Bulk material is not melted**. Also, a **molten filler material is used to provide the joint**

Soldering and brazing

- **Filler material has to have a melting point much lower than that of the parent bodies**.
- **Filler material is copper alloy (Cu-Zn and Cu-Silver) - BRAZING**
- **Filler material is lead-tin alloy - SOLDERNG**
- **The most common heat source for these processes is electrical resistance heating**

Two distinct advantages of this kind of joining processes are obvious:

- Heating of the parent materials is negligible to cause any change in their structure or properties
- Can join two materials which are insoluble in each other

Soldering and Brazing

- To produce a perfect joint, the entire gap between the parent bodies must be filled up by the filler material
- This is achieved essentially through a capillary action
- Thus, the **spreading and the wetting capacities of the filler liquid play a predominant role in producing a satisfactory joint**
- Now, for a liquid drop in contact with a solid surface having contact angle α, we see that

  $\gamma_{s/v} = \gamma_{s/l} + \gamma_{l/v} \cos\alpha$

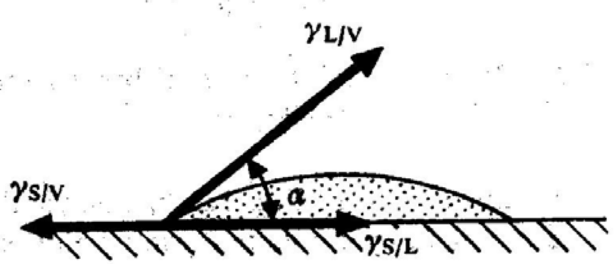
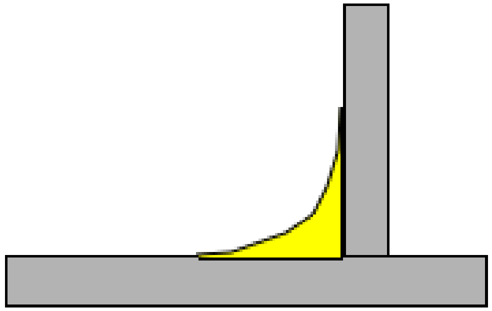


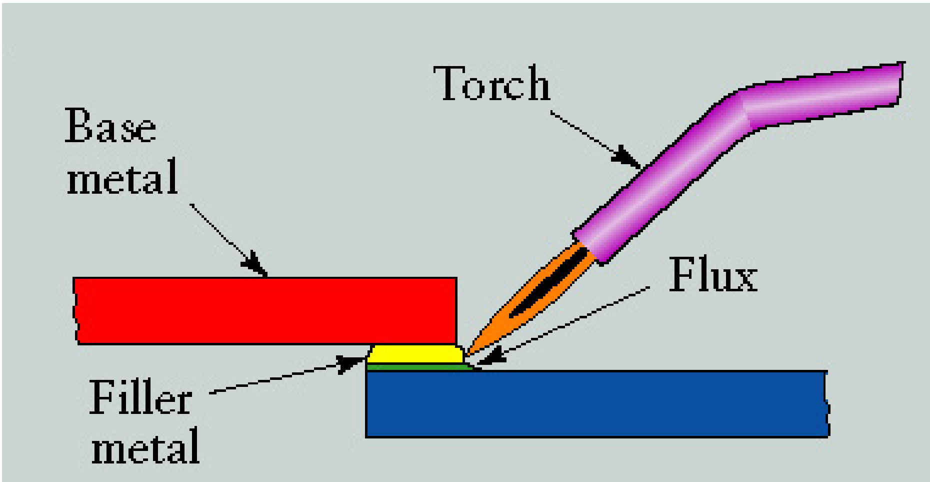
Fig. 5.20 Liquid drop in contact with solid surface.

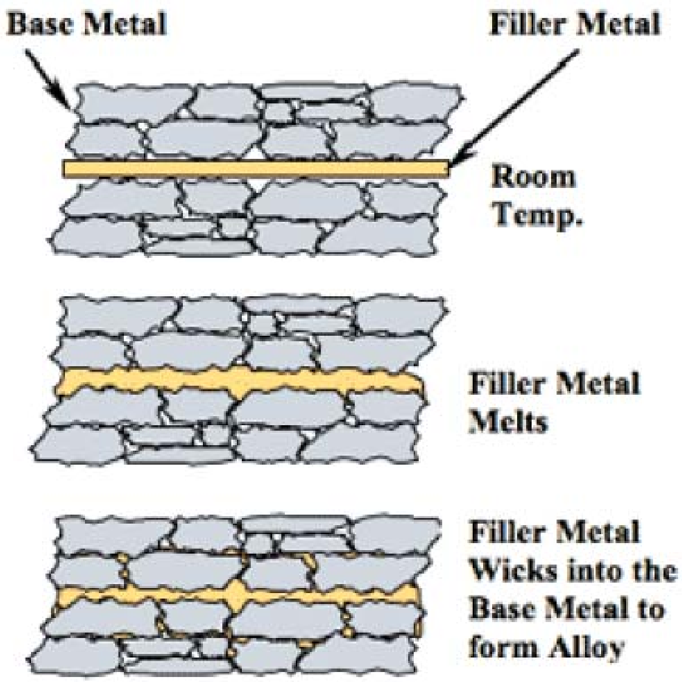
Difficulty of soldering or brazing of grey cast iron whose surface is contaminated with graphite having very low surface energy and hence high contact angle

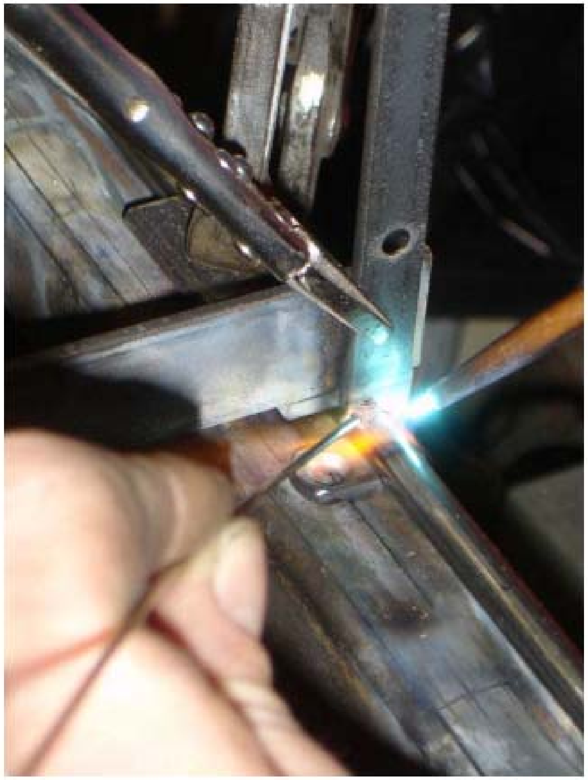
Brazing

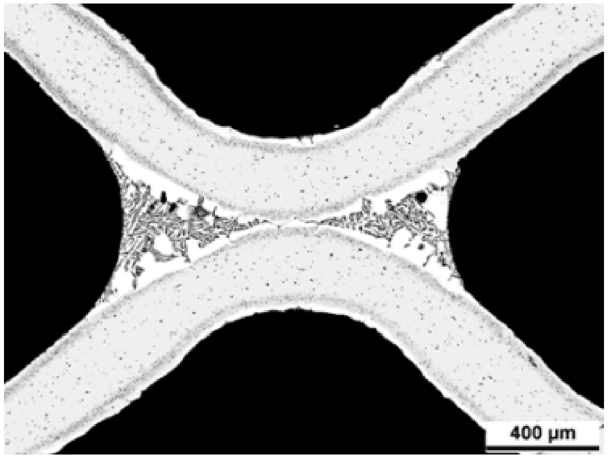
- Steel base metal + Brass filler rod is common
- Lower temp than welding: retains heat treatment (if present), minimizes grain growth.
- Strong but slow (careful preparation, cleanup)

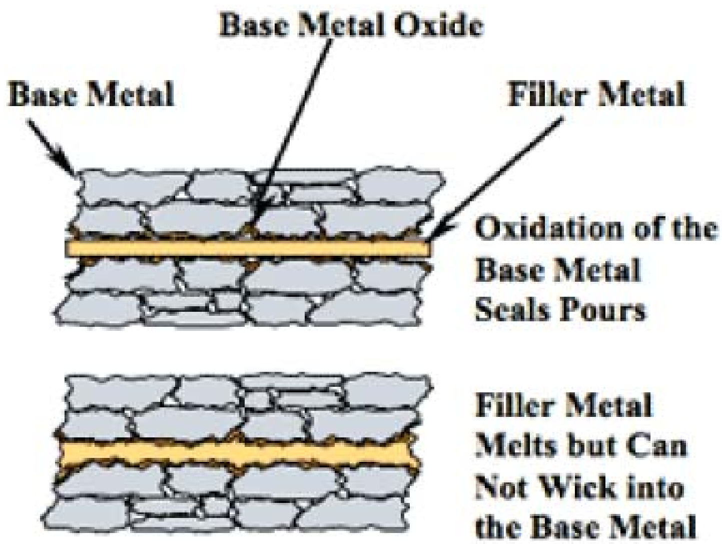


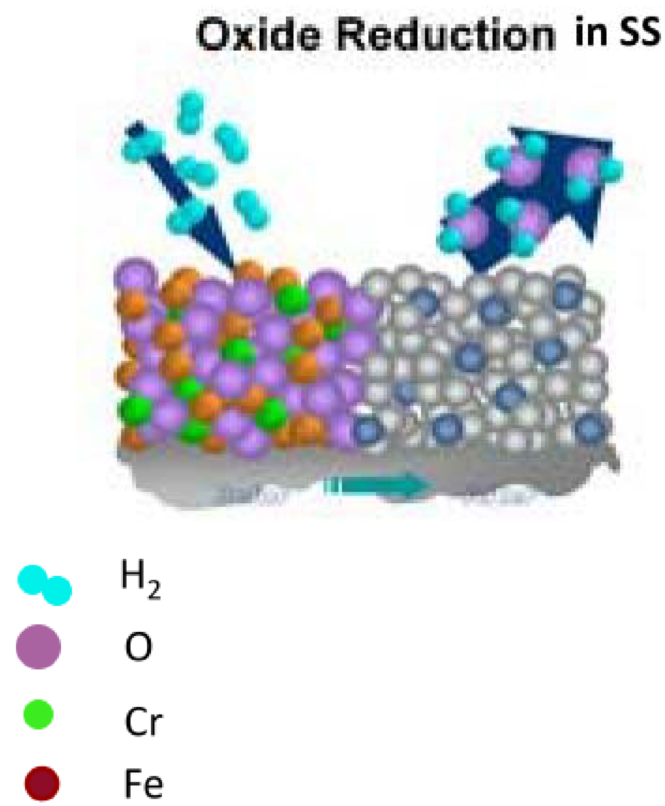



Base Metal
Filler Metal
Room Temp.
Filler Metal Melts
Filler Metal Wicks into the Base Metal to form Alloy



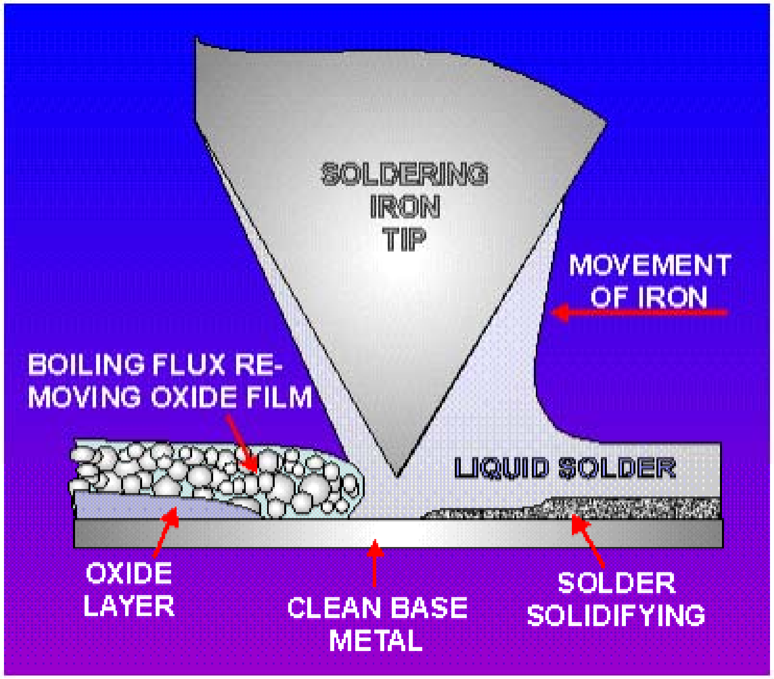

400 µm

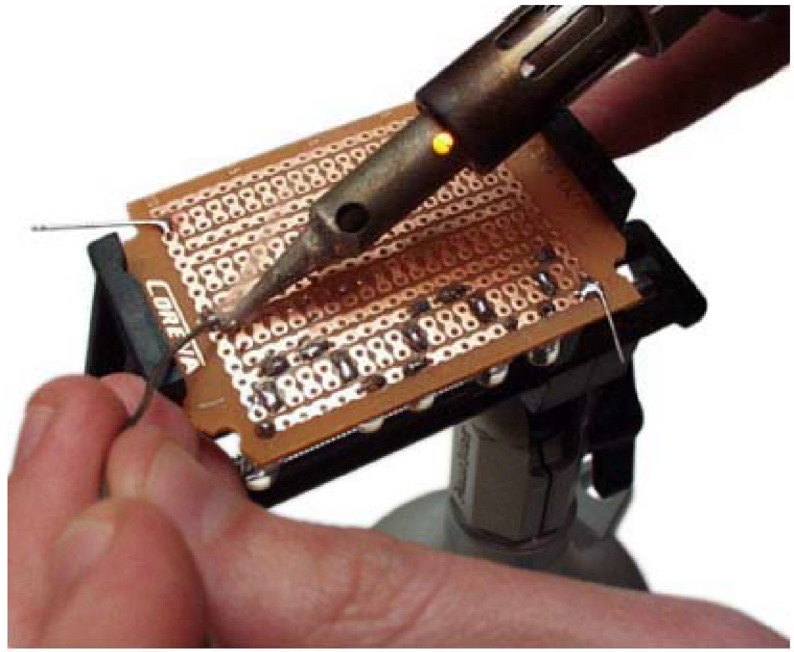




The key is surface preparation before brazing

Soldering



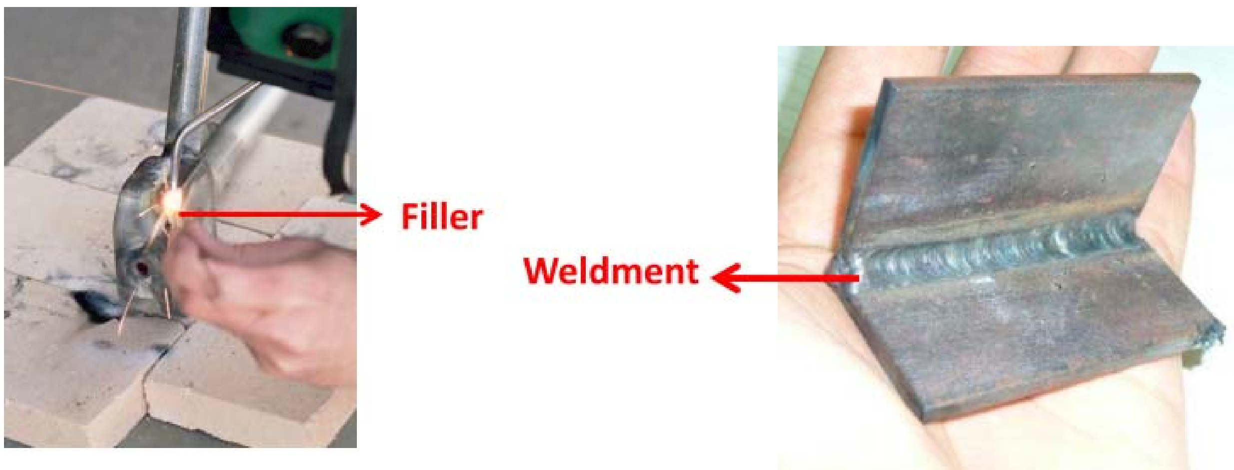


The key is surface preparation before soldering

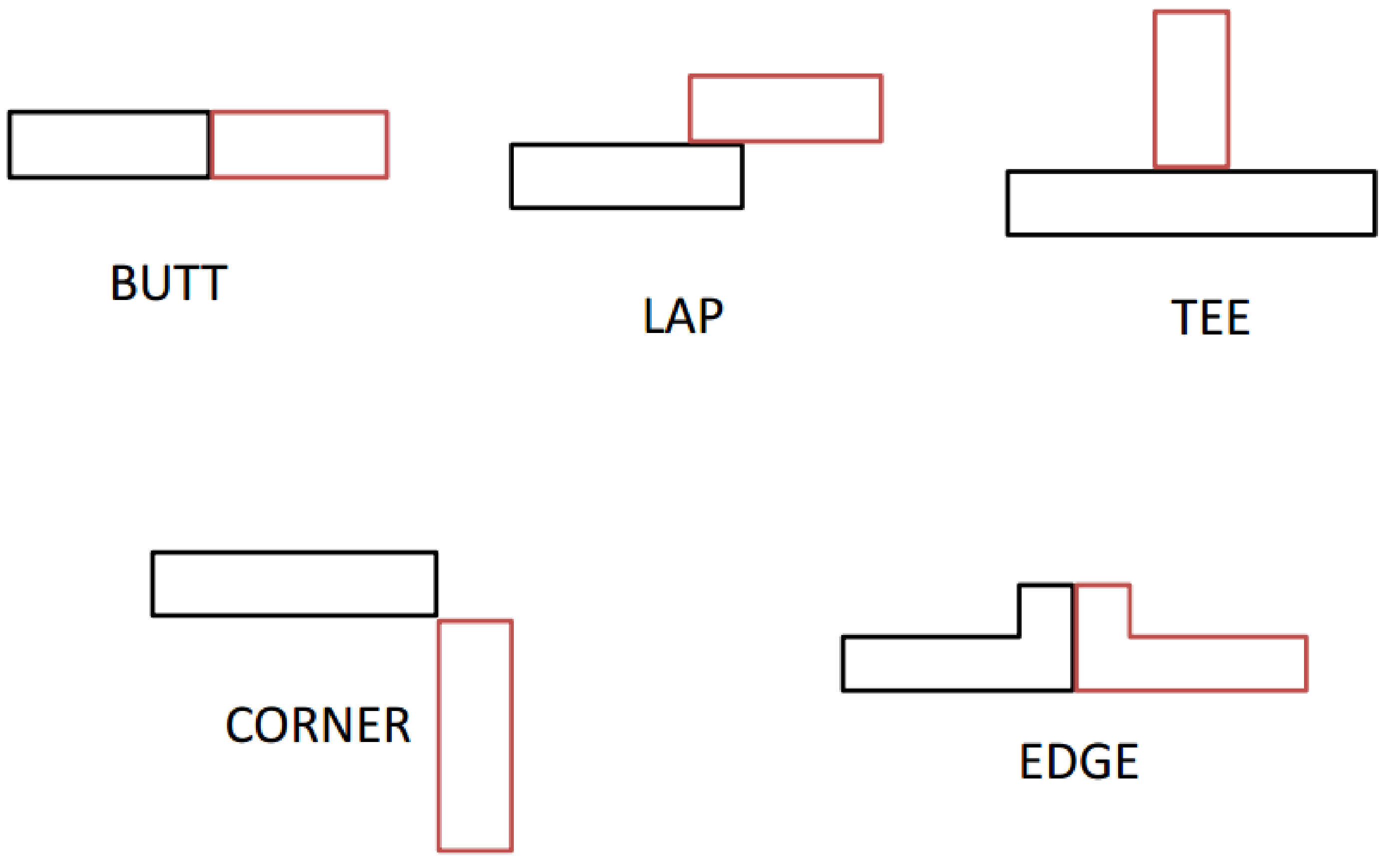
Welding

Joining process in which two (or more) parts are joined at their contacting surfaces by application of heat and/or pressure

- In some welding processes a *filler* material is added to facilitate coalescence



Five basic joint designs



Comparison of Casting and Welding Solidification

- Heat is continually being added to the weld pool as it travels, whereas no heat is added to a casting after the pour, except for possibly modest heating of the mold.

- The practical result of this is that the temperature of the casting is relatively uniform. In contrast, a very large temperature gradient develops in a weld.

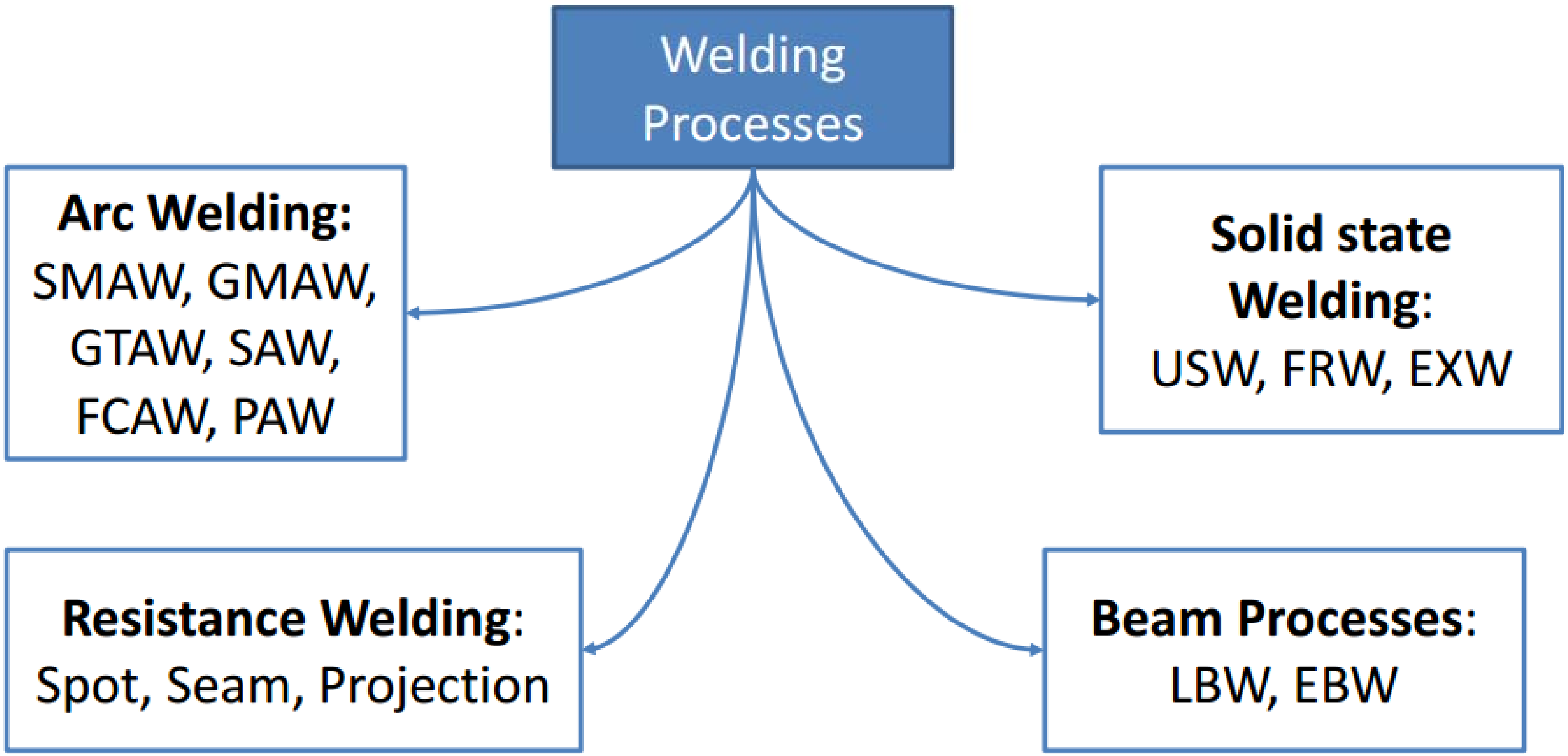
- The generally larger volume of a casting, relative to that of a weld, and the poorer heat transfer makes the cooling rate and the solidification rate much lower for castings than for welds. Microcasting ???

- Welding duration is much lower than casting.

- As a casting solidifies, the volume of the remaining liquid decreases. Thus, the shape of the molten pool is continually changing. In a weld, the weld pool shape is generally kept constant as it travels (if the heat input and section geometry are constant).

- Because of the stirring action of the arc and the action of Marongoni surface tension gradient induced convection forces, there is good mixing of the molten weld pool. In contrast, there is comparatively little mixing of the molten material of a casting. Forced convection as in electromagnetic stirring ???

Different Welding Processes



Welding Processes

- SMAW : Shielded (Manual) Metal Arc Welding
- GMAW: Gas Metal Arc (MIG) Welding
- GTAW: Gas Tungsten Arc (TIG) Welding
- PAW: Plasma Arc Welding
- SAW: Submerged Arc Welding
- EBW: Electron Beam Welding
- LBW: Laser Beam Welding

Types of Welding Processes

- Some 50 different types of welding processes have been catalogued by the American Welding Society (AWS)
- Welding processes can be divided into two major categories:
  - Fusion welding
  - Solid state welding

Fusion Welding

Joining processes that melt the base metals. Heat input from a heat source

- In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and added strength to the welded joint

Heat source

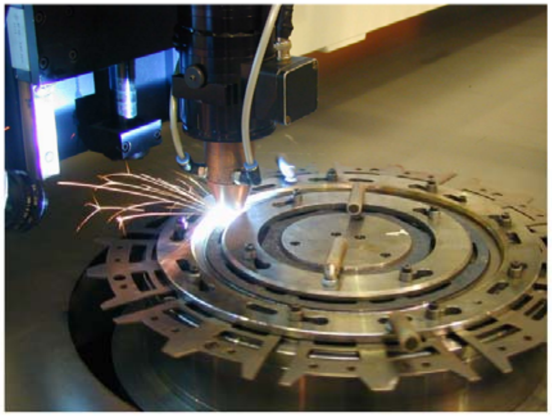
– Chemical, as in gas welding/oxyfuel welding

– Electrical, as in arc welding, resistance welding

Some Fusion Welding Processes

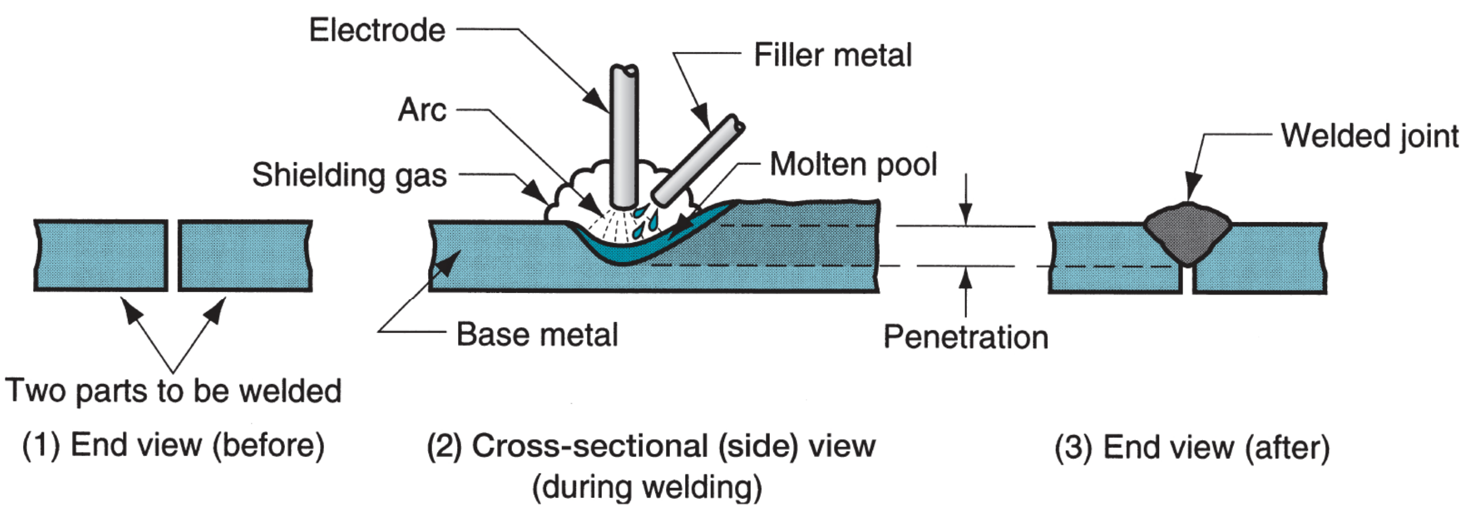
- Arc welding (AW) – melting of the metals is accomplished by an electric arc
- Resistance welding (RW) - melting is accomplished by heat from resistance to an electrical current between surfaces held together under pressure
- Oxyfuel gas welding (OFW) - melting is accomplished by an oxyfuel gas such as acetylene
- Many more, such as

Laser Welding



Arc Welding

- Basics of arc welding: (1) before the weld; (2) during the weld, the base metal is melted and filler metal is added to molten pool; and (3) the completed weldment



Solid State Welding

Joining processes in which coalescence results from application of pressure alone or a combination of heat and pressure

- If heat is used, temperature is below melting point of metals being welded
- No filler metal is added in solid state welding

Some solid state welding processes

- Diffusion welding (DFW) - coalescence is by solid state fusion between two surfaces held together under pressure at elevated temperature
- Friction welding (FRW) - coalescence by heat of friction between two surfaces
- Ultrasonic welding (USW) - coalescence by ultrasonic oscillating motion in a direction parallel to contacting surfaces of two parts held together under pressure

Physics of Welding

Next class: heat transfer and fluid flow

Lecture 15

ME361

Physics of welding

Heat transfer and fluid flow

Physics of welding

- Fusion is most common means of achieving coalescence in welding
- To accomplish fusion, a source of high density heat energy must be supplied to the welded surfaces
  - Resulting temperatures cause localized melting of base metals (and filler metal, if used)

Principles of fusion (liquid State) welding

The most important factors governing a fusion welding process are

- The **characteristics of the heat source**
- The **nature of deposition of the filler material in the fusion zone**, known as the **weld pool**
- The **heat transfer in the weld pool**
- The **cooling of the fusion zone with the associated contraction, residual stresses, and metallurgical changes**

Heat Source

A heat source, suitable for welding, **should release the heat in a sharply defined, isolated zone.** Moreover, the **heat should be produced at a high temperature at a high rate**.

Common heat sources
- The **electric arc** (as in various **arc welding)**
- The **chemical flame** (as in **gas welding**)
- An **exothermic chemical reaction** (as **in thermite welding**)
- An **electric resistance heating** (as in **electroslag and other resistance welding processes**)

Power density

Power transferred to work per unit surface area, W/mm^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

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

where *PD* = power density, W/mm^2; *P* = power entering surface, W; and *A* = surface area over which energy is entering, mm^2

Power densities for welding processes

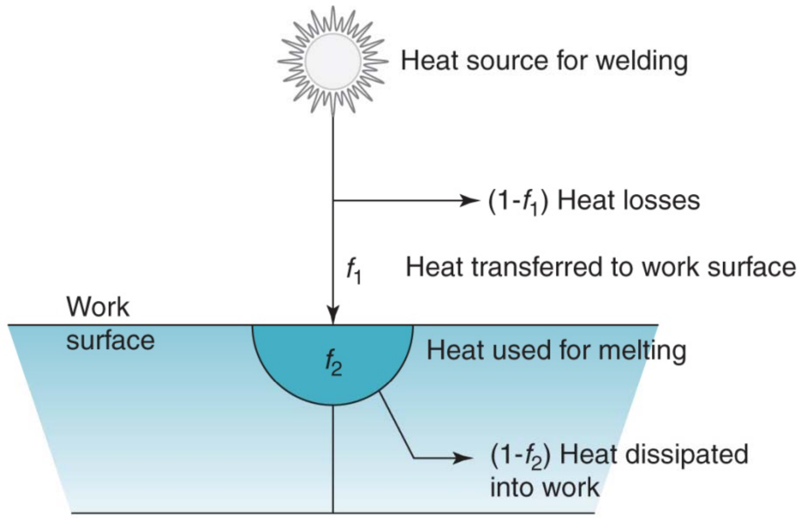
Welding process	W/mm^2
Oxyfuel	10
Arc	50
Resistance	1,000
Laser beam	9,000
Electron beam	10,000

Energy for melting

Quantity of heat required to melt a unit volume of metal (U_m)

- U_m is the sum of:
  - Heat to raise temperature of solid metal to melting point
    - Depends on volumetric specific heat
  - Heat to transform metal from solid to liquid phase at melting point
    - Depends on heat of fusion

Heat energy balance in Welding



Heat Transfer Efficiency f_1

Proportion of heat received at work surface relative to total heat generated at source

- Depends on welding process and capacity to convert power source (e.g., electrical energy) into usable heat at work surface
  - Oxyfuel gas welding processes are relatively inefficient
  - Arc welding processes are relatively efficient

Melting Efficiency f_2

Proportion of heat received at work surface used for melting; the rest is conducted into the work

- Depends on welding process but also thermal properties of metal, joint shape, and work thickness
  - Metals with high thermal conductivity, such as aluminum and copper, present a problem in welding because of the rapid dissipation of heat away from the heat contact area

Not all of the input energy is used to melt the weld metal

1. Heat transfer efficiency f_1 - actual heat received by workpiece divided by total heat generated at source
2. Melting efficiency f_2 - proportion of heat received at work surface used for melting
    - The rest is conducted into work metal

Heat Available for Welding

$$H_w = f_1 f_2 H$$

where H_w = net heat available for welding; f_1 = heat transfer efficiency; f_2 = melting efficiency; and H = total heat generated by welding process

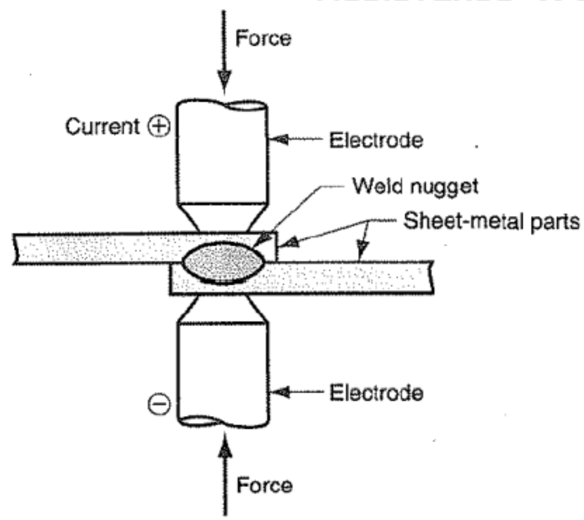
- Net heat energy into welding operation equals heat energy required to melt the volume of metal welded

$$H_w = = f_1 f_2 H = U_m V$$ Energy balance

where H_w = net heat energy delivered to operation, J ; U_m = unit energy required to melt the metal, J/mm^3 ; and V = volume of metal melted, mm^3

Example

Resistance Welding



H = I^{2}Rt

H: Heat generated
I: Current
R: Resistance
T: Time

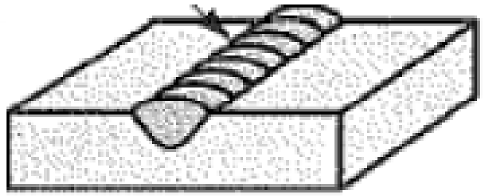
Heat + Pressure :

Joining by fusion due to electrical resistance to the current flow at the junction to be welded

25

Rate balance

$HR_w = f_1 f_2 HR = U_m Av$



HR = Heat generated per unit time (J/s)

HR_w = Rate of heat delivered to the weld (J/s)

Av = Volume rate of metal welded (mm^3/s)

v = Travel speed of arc or flame (mm/s)

A = Area of the weld (mm^2)

Example

HR = V I (in W or J/s) ($P = VI = I^2R$)

V = voltage (volt)

I = current (amp)

Physical processes

- Heat transfer
- Fluid flow
- Mass transfer
- Species transport
- Phase transformations
- Stress effects

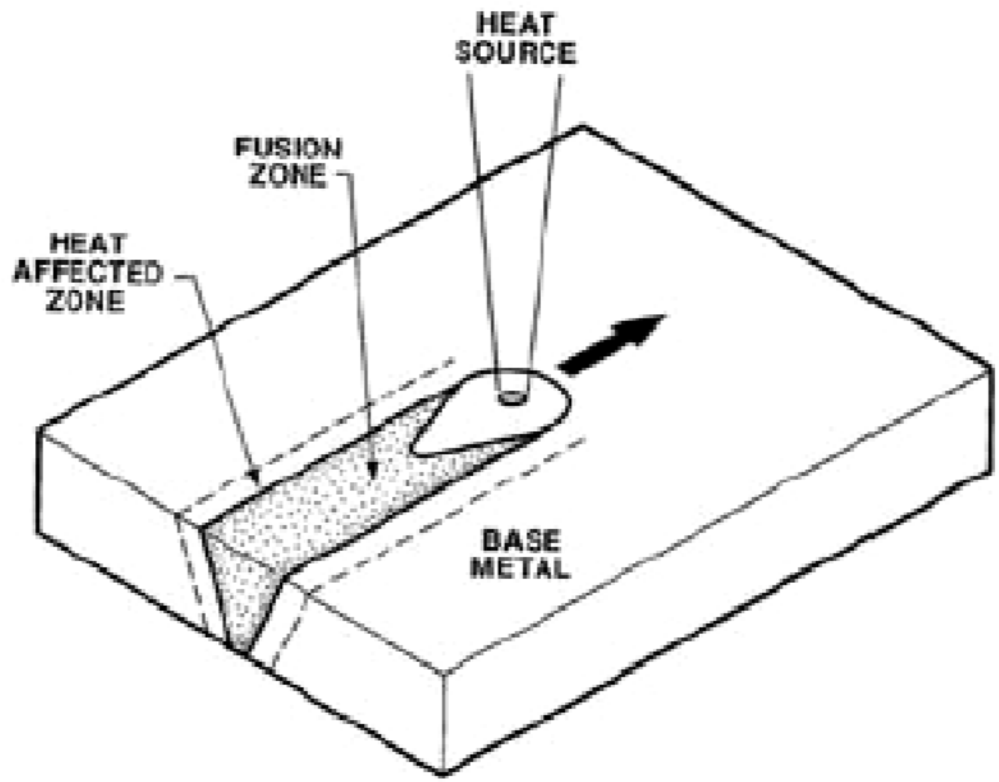
Heat transfer

- Heating of base metal
- Melting
- Possible vaporization
- Solidification
- Cooling to ambient temperature

- Heat gain from welding source
- Heat loss from external heat sinks
- Heat loss by convective mode
- Heat loss by radiation
- Heat loss by conduction in the base metal
- Enhanced heat extraction through water cooled backing setup
- Formation of compounds through exothermic reaction

Characteristics of a heat source

- Nature of distribution : surface or volumetric
- Power distribution : spatial variation
- Absorption efficiency : dependency on material, temperature etc.
- Temporal changes : pulsing effects
- Traverse rate : velocity of heat source
- Path : raster or arc oscillation



In welding, as the heat source interacts with the material, the severity of thermal excursions experienced by the material varies from region to region, resulting in three distinct regions in the weldment. These are the fusion zone (FZ) also known as the weld metal, the heat-affected zone (HAZ), and the unaffected base metal (BM). The FZ experiences melting and solidification, microstructural changes.

General boundary conditions

Gaussian heat flux

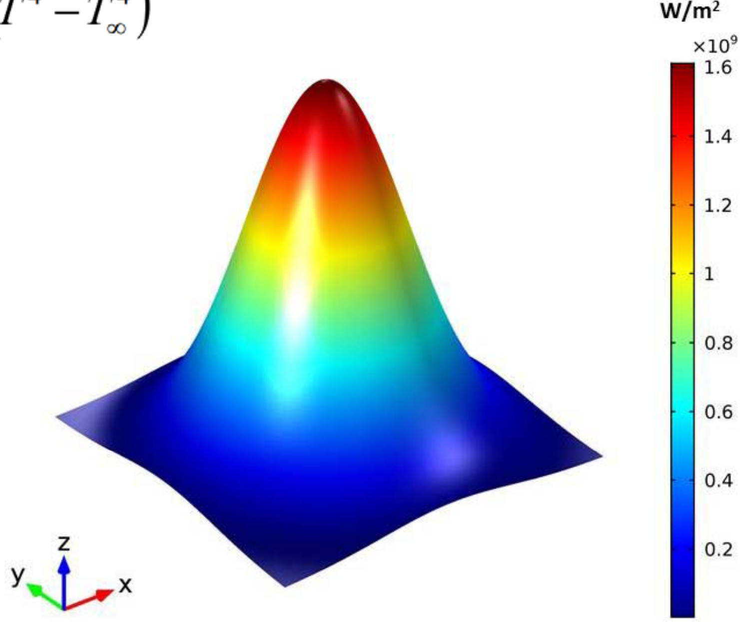
$$q = \frac{Q}{\pi r^2} \exp\left\{ -\frac{(x-x_0)^2 + (y-y_0)^2}{r^2} \right\}$$

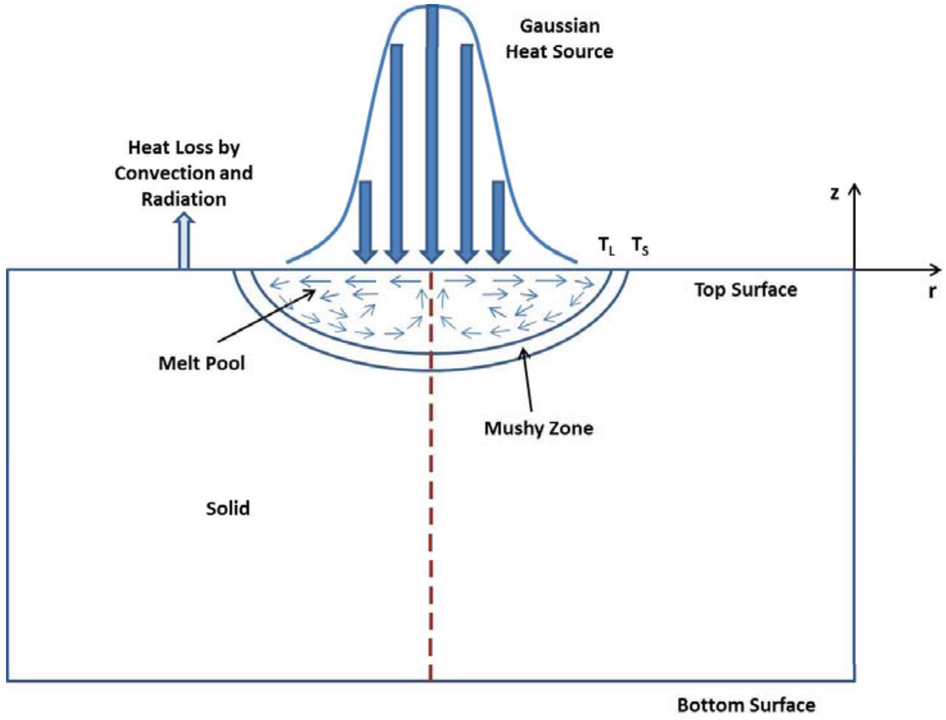
Convective loss

$$h(T - T_\infty)$$

Radiative loss

$$\varepsilon\sigma(T^4 - T_\infty^4)$$





Weld pool shape

Govern by various convective forces

- Buoyancy - Surface tension - Electromagnetic - Impinging

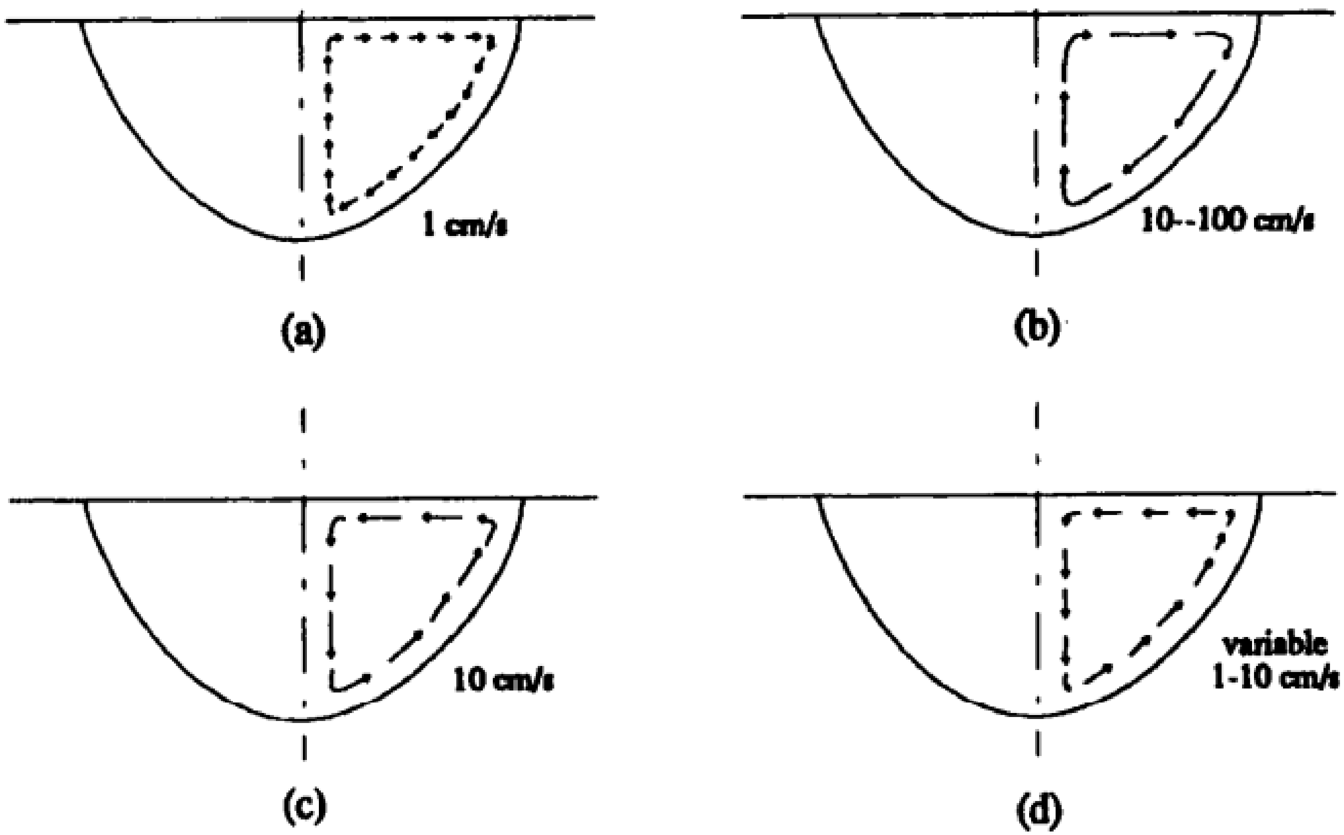


Figure 10.2 Schematic of the circulation or convection pattern induced by (a) only a buoyancy (or gravity) force; (b) only a surface tension gradient force or Marangoni force; (c) only an electromagnetic force (EMF) or Lorentz force; or (d) only an impinging force. The arrows shown direction, as well as relative velocity by their lengths.

Buoyancy or Gravity Force $$\mathbf{F}_b = -\rho B g(T - T_0)$$

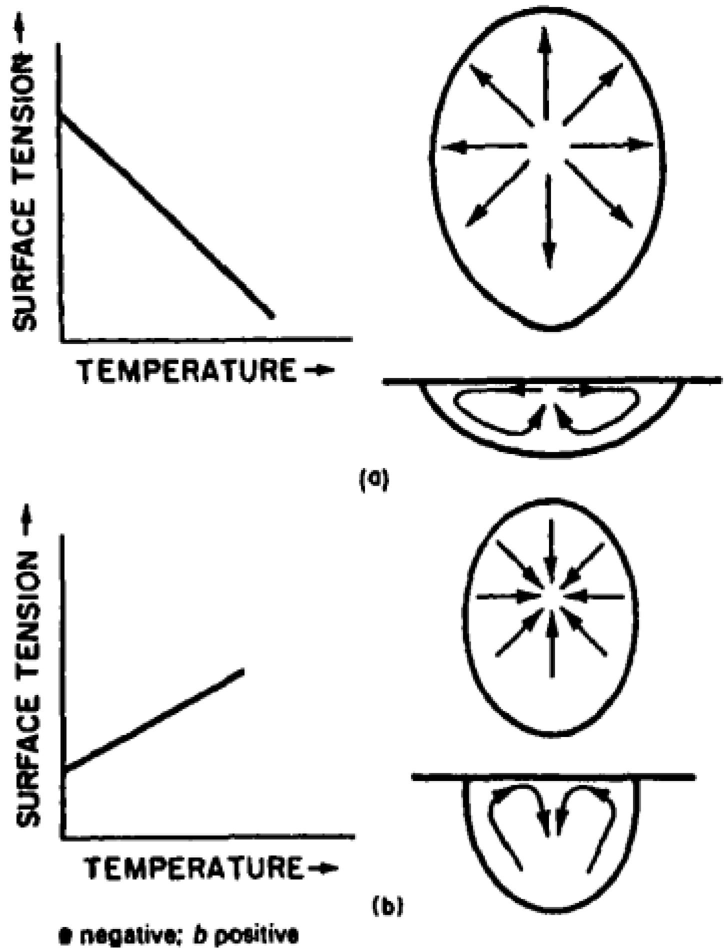
Surface Gradient Force or Marangoni Convection $$\mathbf{F}_\gamma = -\frac{d\gamma}{dT}\nabla T$$

where γ is the surface tension of the molten metal, T is the temperature, and ∇T is the temperature gradient at the weld pool surface

Thus, whenever a temperature gradient exists in a liquid, so too does a gradient in surface tension. This gradient exerts a force

Surface Gradient Force or Marangoni Convection

$$F_\gamma = -\frac{d\gamma}{dT}\nabla T$$



Different convective flow patterns produced by different temperature coefficients of surface tension.

In (a), the pattern of convective flow without a surface-active agent; in (b) the effect of adding a surface-active agent

Impurities in weld metal often alter the surface tension of the molten metal through their surface activity.

The surface tension gradient at the weld pool surface could be changed by the addition of surface-activating agents such as O, S, Se, and Te.

Electromotive Force or Lorentz Force $\mathbf{F}_{em} = \mathbf{J} \times \mathbf{B}$

where J is the vector of current density (with a direction the same as the current, positive to negative) and B is the vector of magnetic flux (with a direction the same as the flux lines).

Obviously, electromagnetic or Lorentz forces are present only for processes using an electric energy source, namely

- arc, resistance, microwave, or electron beam processes, and
- are totally absent for gas and laser beam welding.

Impinging or Friction Force

The impinging force is the result of momentum transfer through friction between impinging particles and metal atoms in the molten weld pool.

Thus, the magnitude of the impinging force depends on the process, but the flow pattern is always from edge-to-center of the weld pool, as shown in Figure 10.2d. This is because more energy is deposited at the center of weld pools than near their edges as a result of the normal (Gaussian) distribution of energy in most sources

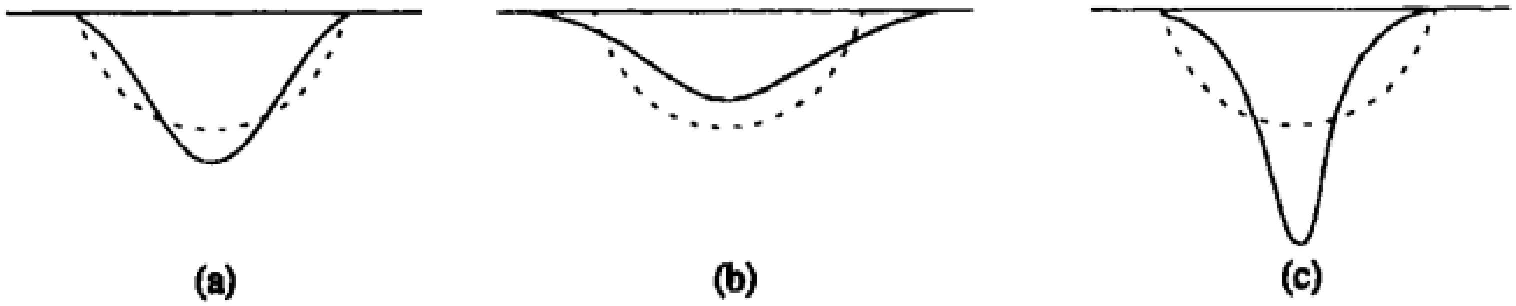
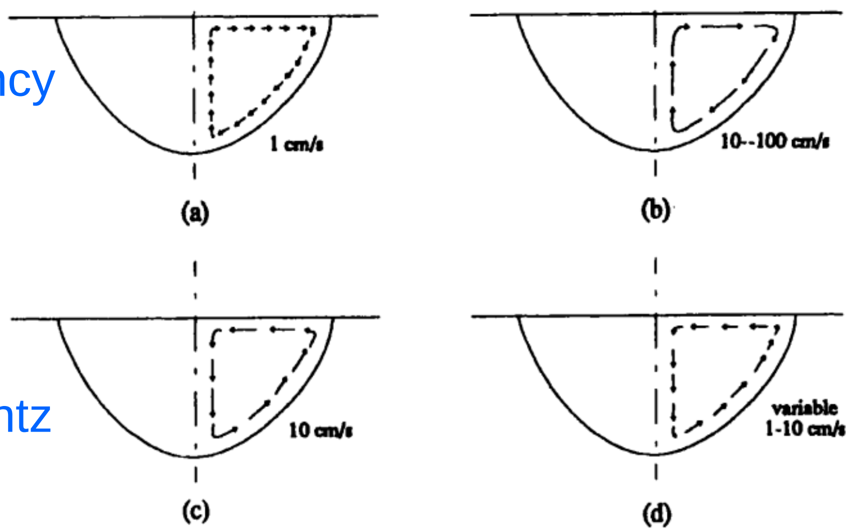


Figure 10.9 Schematic showing the effects of particular dominant driving forces for convection on weld pool shape, including (a) greater penetration at the bottom-center of a weld pool due to convection enhanced by a dominant electromagnetic (Lorentz) force, (b) shallower but wider penetration due to convection dominated by either a buoyancy or surface tension gradient force (or both together), and (c) pronounced deepening at the weld pool bottom due to convection enhanced by a dominant impinging force. A theoretical, semicircular cross section is shown by a dashed line for comparison.

Buoyancy

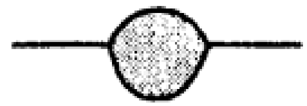
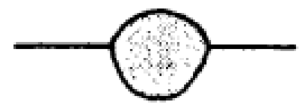
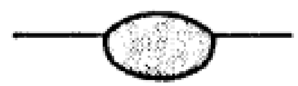
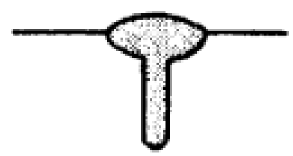
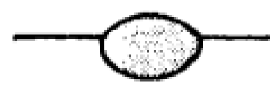
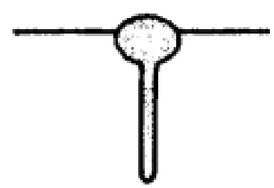
Surface tension



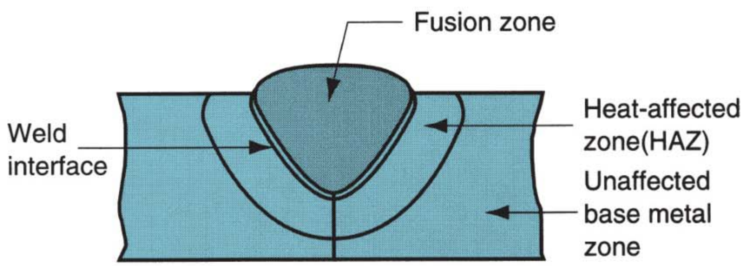
Impinging

Lorentz

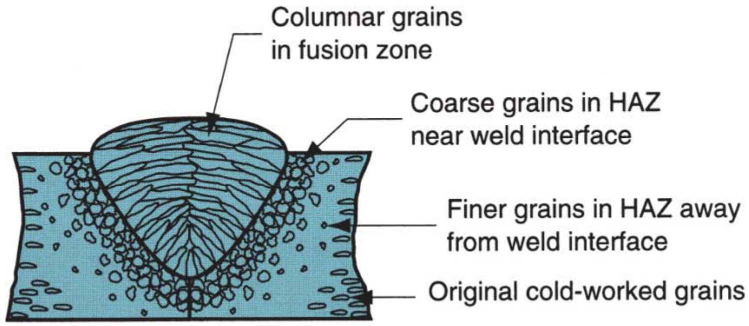
TABLE 5.2 Typical Values of Energy Density and the Type of Penetration for Various Sources Used in Welding

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	

Typical Fusion Welded Joint



(a)



(b)

principal zones in the joint

typical grain structure