MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Introduction

Lecture 1

Contact Details

Instructor: Dr. Sivakumar Narayanswamy

Office: EV Building

Room: 004 –124

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Office Hours: _ _ _ _ F 10:00 – 12:00

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Course Web Site: http://users.encs.concordia.ca/~nrskumar/

Outline of the Course

Week		Chapter*	Lecture Topics
1	11th Sep '12	Degarmo Chp. 11	Introduction; Fundamentals of casting processes
2	18th Sep '12	Degarmo Chp. 11	Solidification of liquid metals; Patterns, Castings Design
3	25th Sep '12	Degarmo Chp. 12	Expendable mould casting
4	2nd Oct '12	Degarmo Chp. 13	Multi-Use mould casting; Casting alloys
5	9th Oct '12	Degarmo Chp. 4	Phase Diagrams; Phase changes (Callister Chp. 9 & 10)
6	16th Oct '12	Degarmo Chp. 5, 35	Heat treatments; Surface treatment (Callister Chp. 11)
7	23rd Oct '12	Degarmo Chp. 30	Fundamentals of Joining Processes
8	30th Oct '12	Degarmo Chp. 30	Fundamentals of welding/brazing/soldering processes
9	6th Nov '12	Degarmo Chp. 31	Gas welding; Arc welding
10	13th Nov '12	Degarmo Chp. 32	Resistance welding; Other welding processes
11	20th Nov '12	Degarmo Chp. 33, 34	Brazing & soldering; Weld effects/defects, joint design
12	27th Nov '12	Degarmo Chp. 10	Non-Destructive Testing (NDT)
13	4th Dec '12		Review

There will be 2 midterm exams during the tutorial period of Weeks 5 and 10

*Chapter #s are from 10th Edition

About the Course

- The course is about learning different manufacturing processes that add value to material, like casting, welding, heat treating, NDT
  - 13 lectures of all - one is a review lecture
  - 2 Midterm tests
  - 3 assignments
  - 1 Project / Presentation
  - Lab experiment report (Interim and Final)
  - Final exam
- http://users.encs.concordia.ca/~nrskumar

Text book and other reference

TEXTBOOK

- **Materials and Processes in Manufacturing, E. Degarmo, J.T. Black and R.A. Kohser, Prentice-Hall, 11th Edition. (earlier editions will be fine)**
- **Material Science and Engineering, W.D. Callister, 5th Edition, Wiley, 1999 (or similar)**

REFERENCES (not exhaustive)

1. ASM Metals Handbook; Volumes 4 (Heat-Treating), 6 (Welding, Brazing and Soldering) and 15 (Casting).
2. Modern welding by Andrew D. Althouse, and Carl H. Turnquist, and William A. Bowditch.

Midterm test

- You will write 2 optional midterm tests on Oct 4th and Nov 8th, 2013 during the tutorial period starting at 4.15pm
- Duration of the test will be 50 minutes
- Write the midterm test – this is a good measurement means for your performance

Final Test

- The final test may have a number of multiple choice, short answer and comprehensive questions that will require answer.
- Duration of the test: 3 Hrs.
- Write the final exam with confidence that you will do very well

Assignments

- Three assignments that will require significant effort must be completed during the term
- The timetable of the assignments is below. Late submissions (regardless of reason) not allowed
  - Sep 27th 2.45pm Assignment #1
  - Oct 25th 2.45pm Assignment #2
  - Nov 22nd 2.45pm Assignment #3
- Work must be submitted DIRECTLY to the TUTOR or IN CLASS. Tutor Coordinates available in the outline and in course webpage.
- Good presentation, including legibility, spelling and grammar, is expected for all work

The Laboratory

- There is a laboratory component to this course.
- The aim is to illustrate the effects of various welding and heat treatment on the mechanical properties of bare and welded metals.
- Mr. Peter Sakaris will be supervising this in the Materials Laboratory (H 1058/59) and will be assisted by Mr. Ehsan Rezabeigi.
- This section involves experiments and report writing.
- Lab Manual is available for purchase from the COPY CENTER
- Note: Safety is of utmost importance. Wearing a lab coat and covered shoes during the session is **mandatory**

Project / Presentation

- Each student/group will select a topic related to this course and will prepare a 20 minute presentation giving an overview of the subject, major advantages/disadvantages, applications etc.
- Time will be set aside in the tutorial(s) for each student/group to make their presentation to the rest of the class. Each talk will be followed by a short question period. Each student/group will submit an hard and soft copy of the presentation/report.
- Marks will be awarded for:
  - Presentation style (audibility, structure, clarity, quality etc.).
  - Technical content (understanding of subject,, explanation etc.).

Grading Scheme

Grade composition:	Option A	Option B
Final:	50%	65%
Midterm:	15%	0%
Assignments (4):	15%	15%
Lab (Heat Treating):	10%	10%
Presentation (topic to be discussed):	10%	10%

- To pass the course you have to
  - Pass the final
  - Submit your assignments and lab and project report on or before due date
  - Option A is if your midterm grades are very good and option B is if your midterm grades are not better than the final or you did not take midterm

Coursework–Certificate of Originality

- In keeping with the faculty policy, all coursework submitted as part of this course must have the certificate of originality form filled-in appropriately and attached as the cover page.

- The form is available on the following website:

  http://www.encs.concordia.ca/scs/Forms/expectations.pdf

Content of the Lecture 1

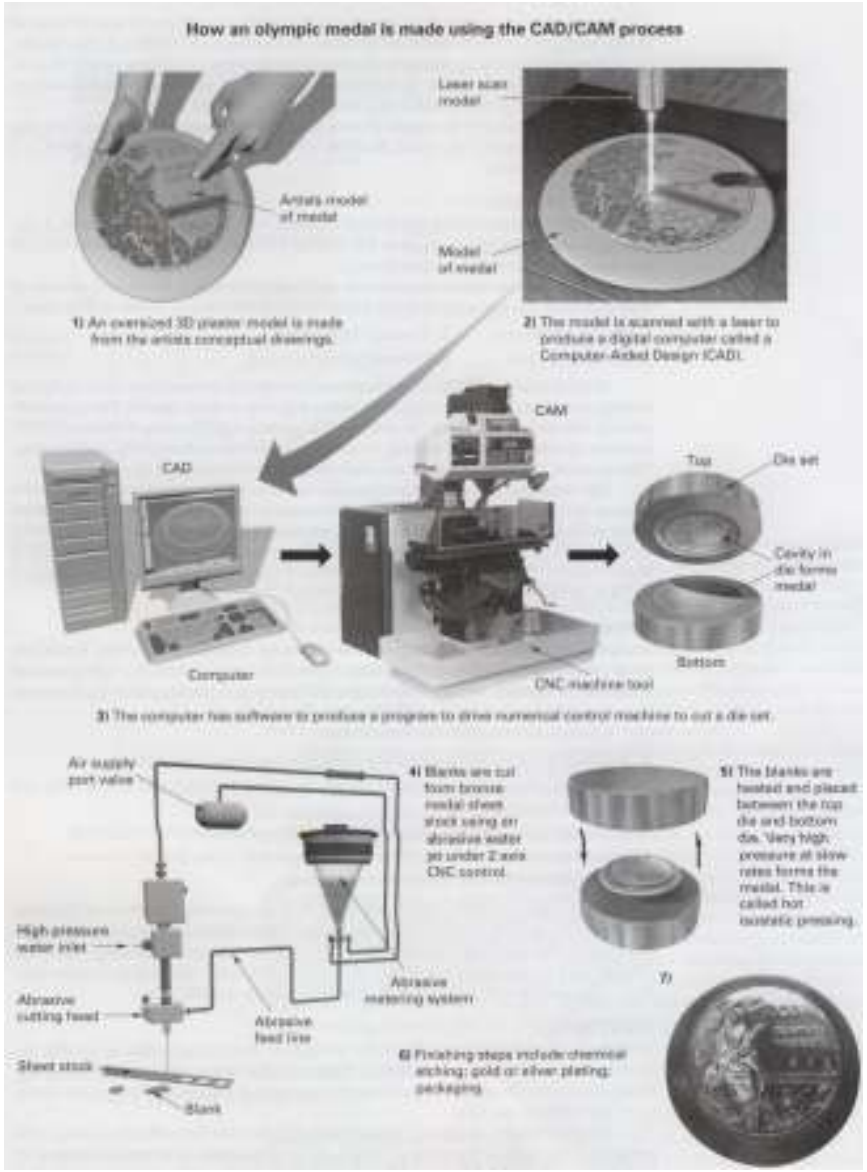
- Fundamentals of Casting Processes
- Introduction to Materials Processing
- Introduction to Casting
- Casting Terminology

Basic Manufacturing Processes

- Casting or moulding (liquid to solid with new shape)
- Forming (deformation of solid into new shape)
- Machining (material removal to make new shape)
- Joining and assembly (making new shape from smaller shapes)
- Surface treatments (changing or adding to surface)
- Heat treating (changing properties without changing shape)
- Other (vapour deposition, dissolution etc)

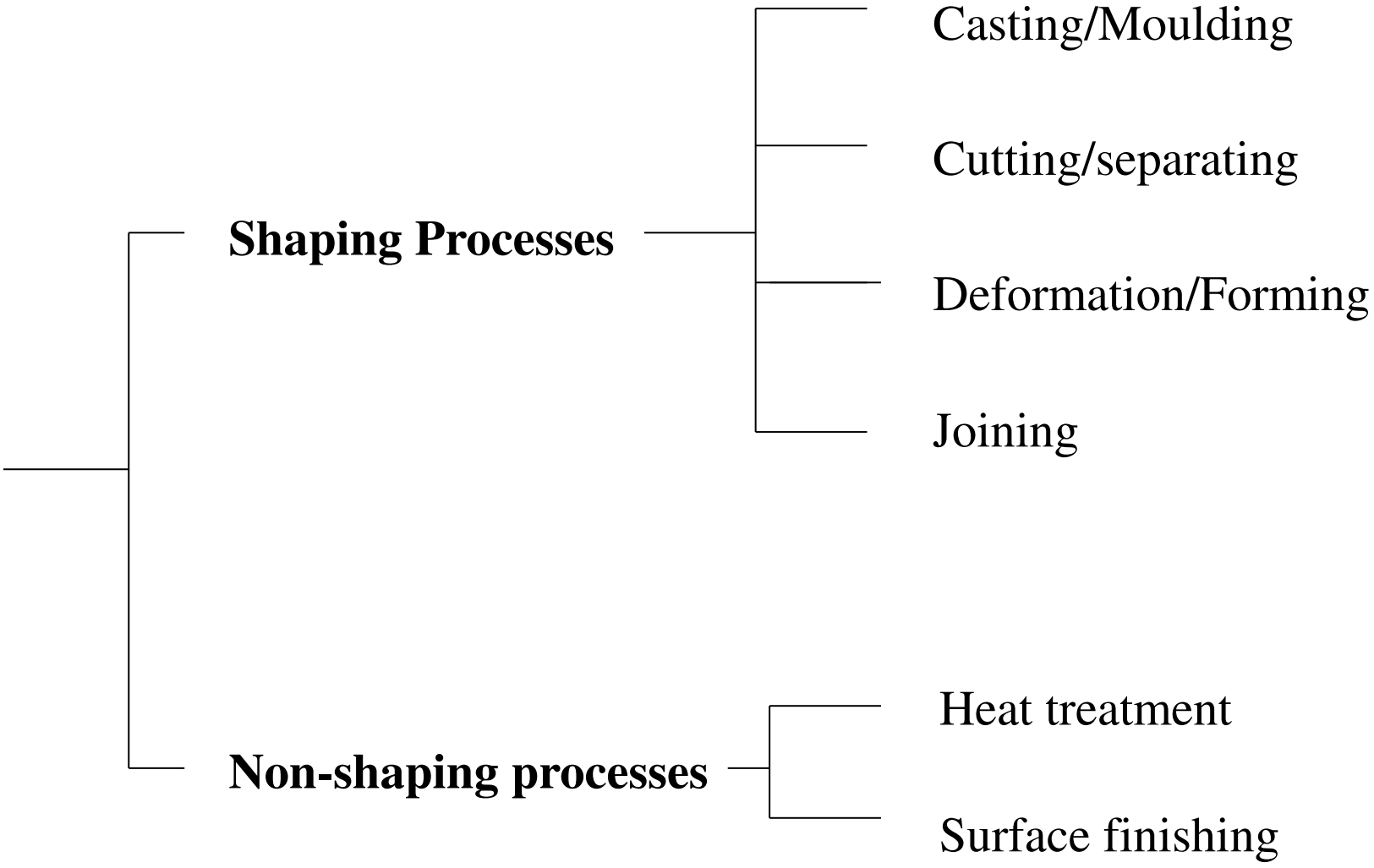
Often more than one process will be involved; e.g. casting, heat treating, machining, surface treatment.

Basic Manufacturing Processes



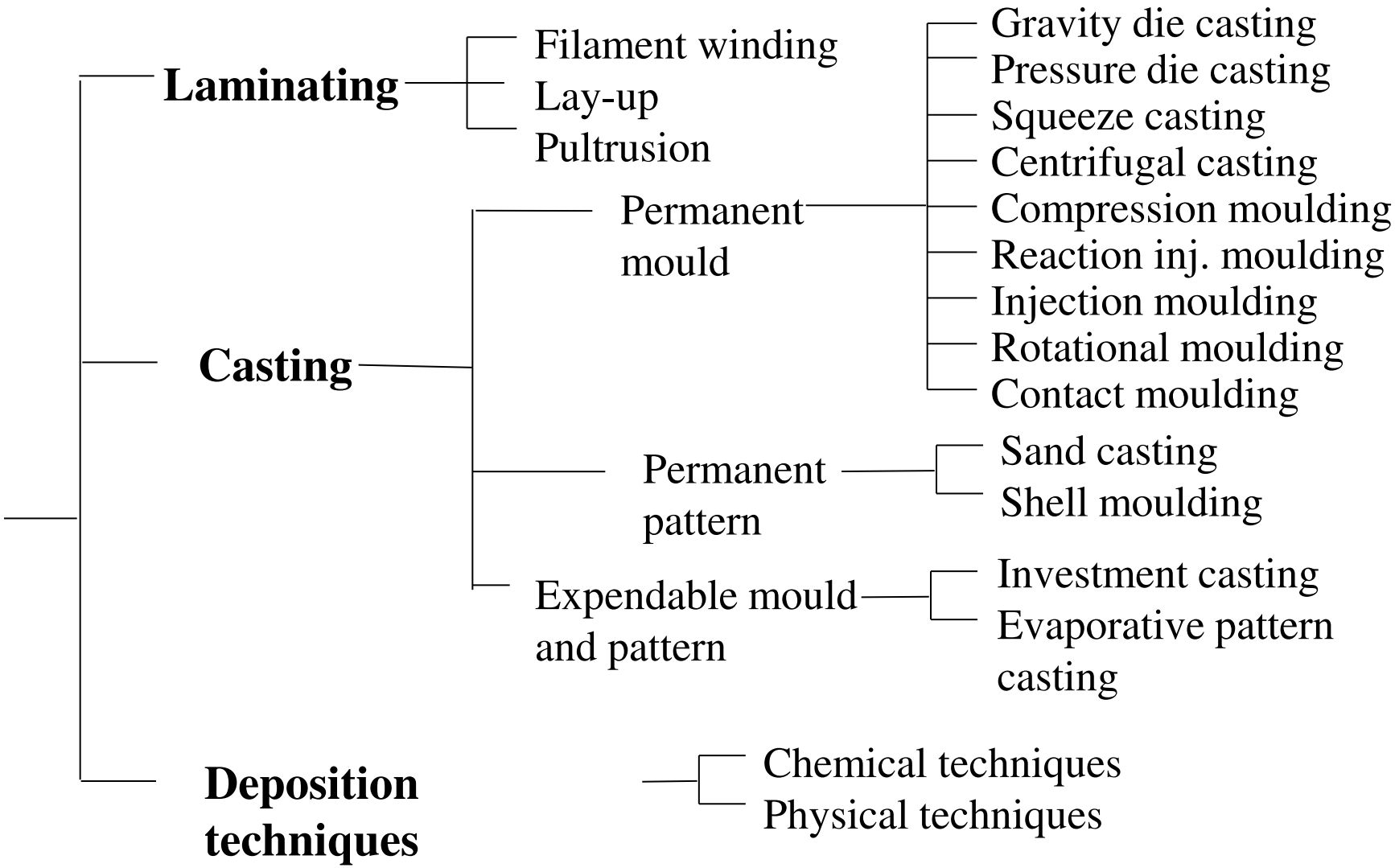
- A 3D model is made with artist impression on a plaster
- The model is then digitized
- The digitized model is used to cut die
- Bronze metal strip is used and abrasive jet is used to cut circular Blanks
- The blanks are placed into the die and heat and pressure is supplied to get the medal
- Final finishing and coating is done with gold, silver, bronze to get the model

Basic Manufacturing Processes

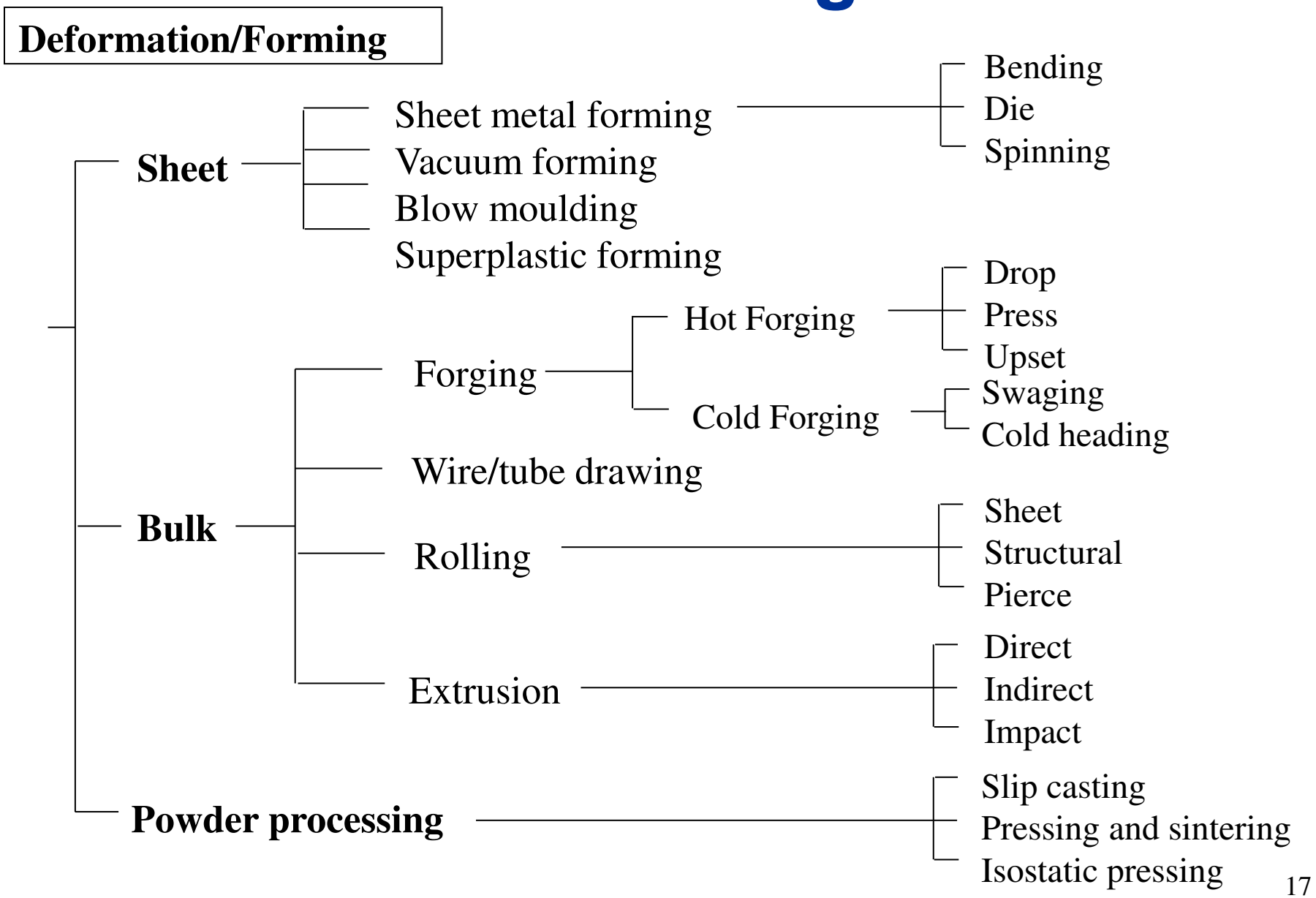


Basic Manufacturing Processes

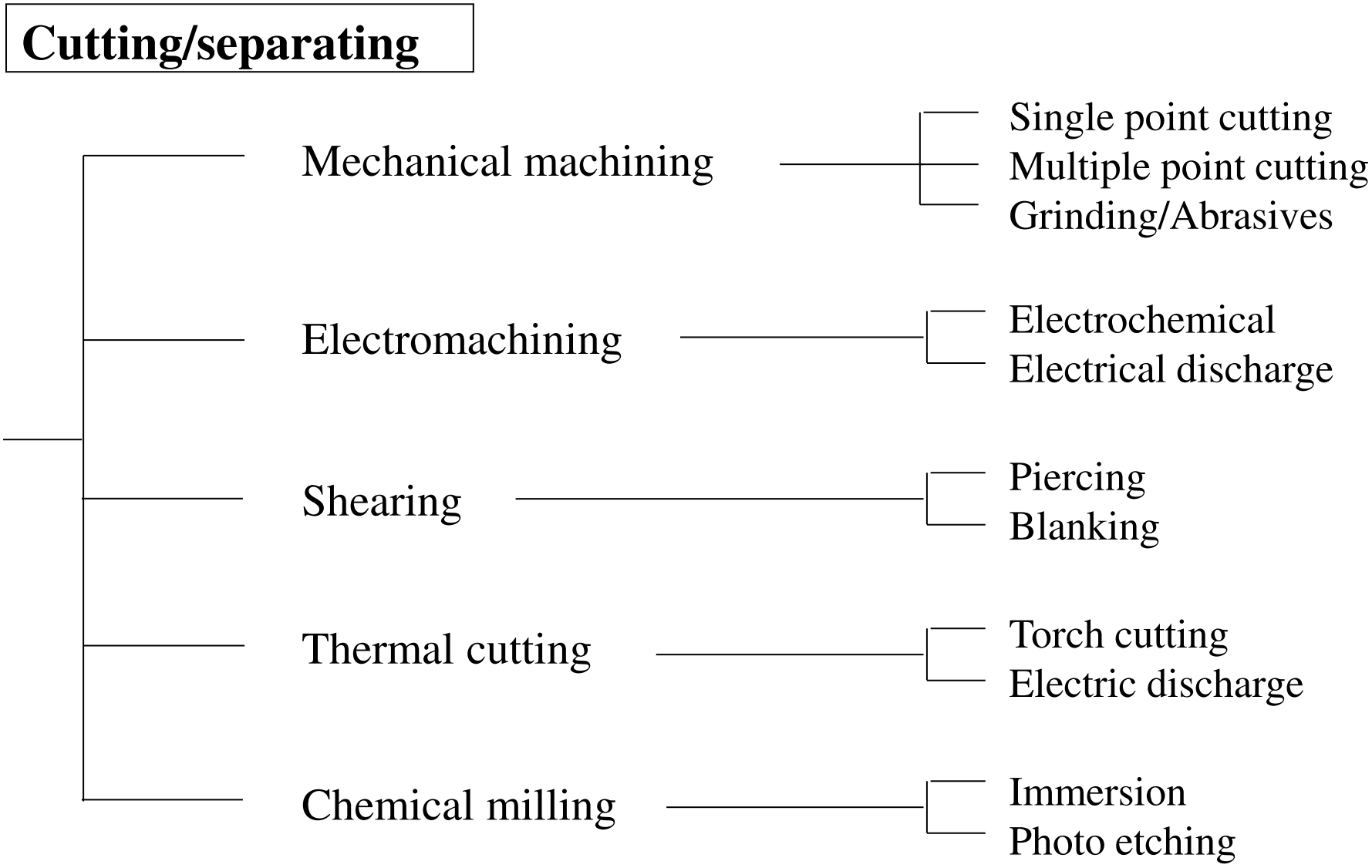
Consolidation/casting



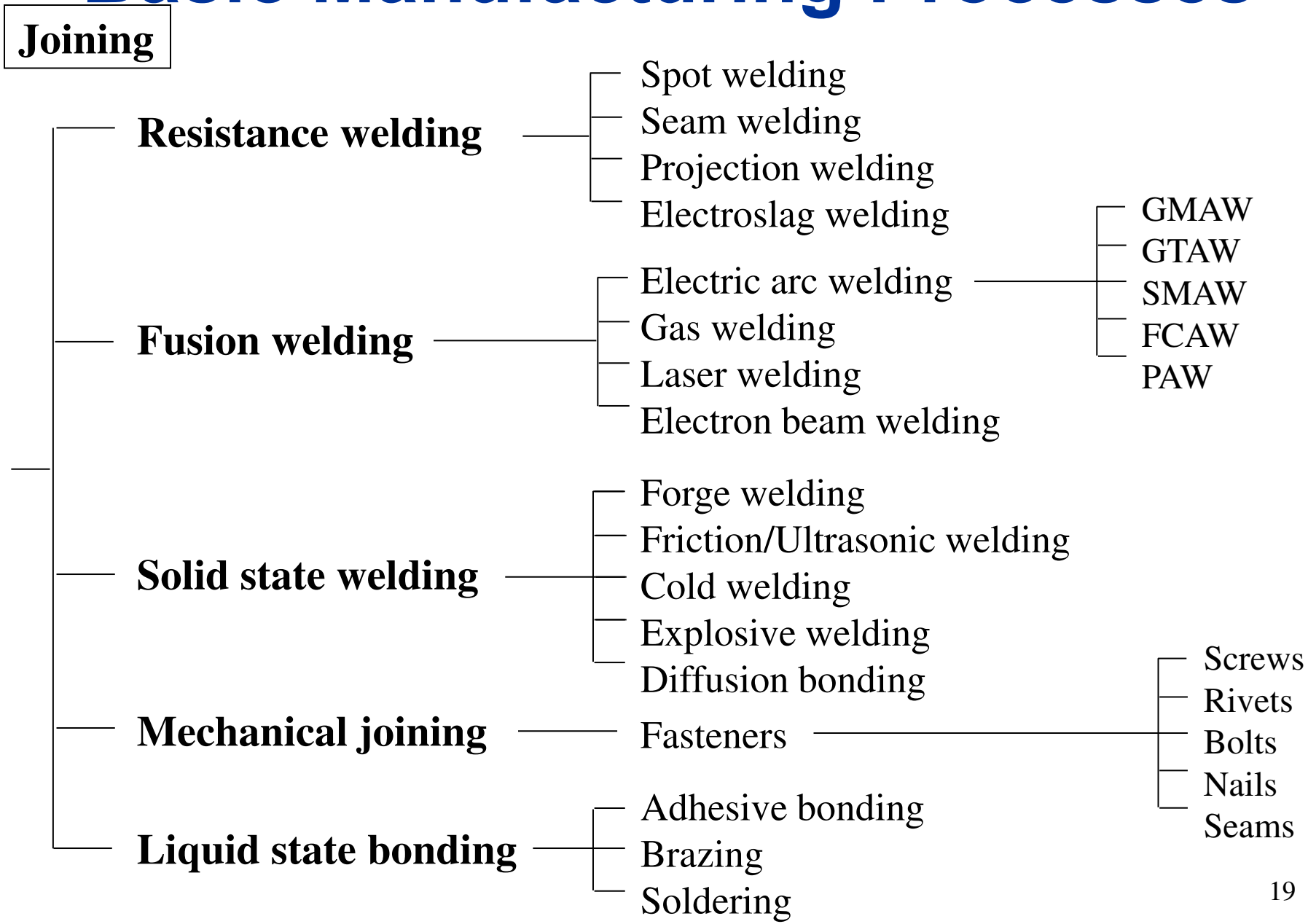
Basic Manufacturing Processes



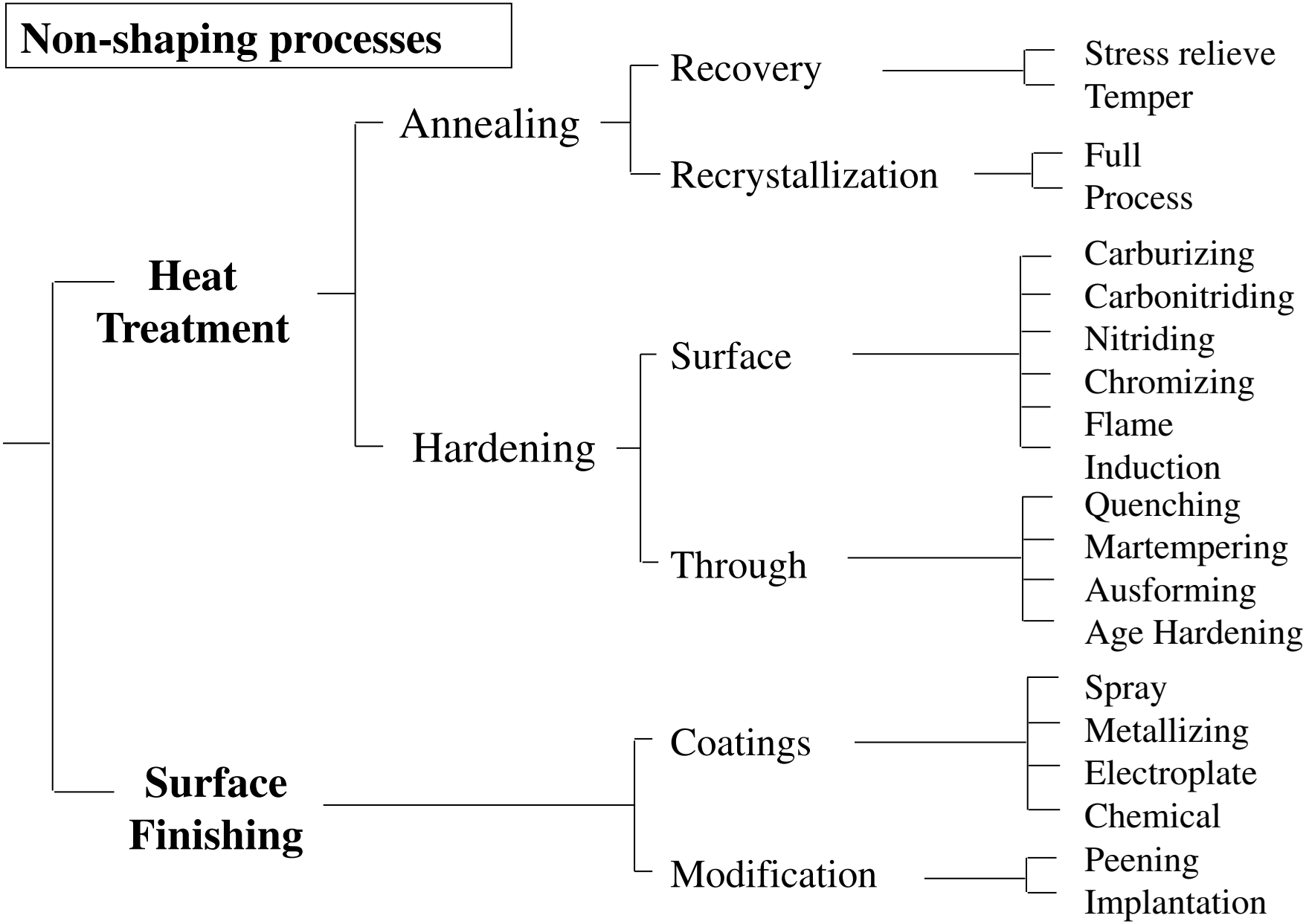
Basic Manufacturing Processes



Basic Manufacturing Processes



Basic Manufacturing Processes



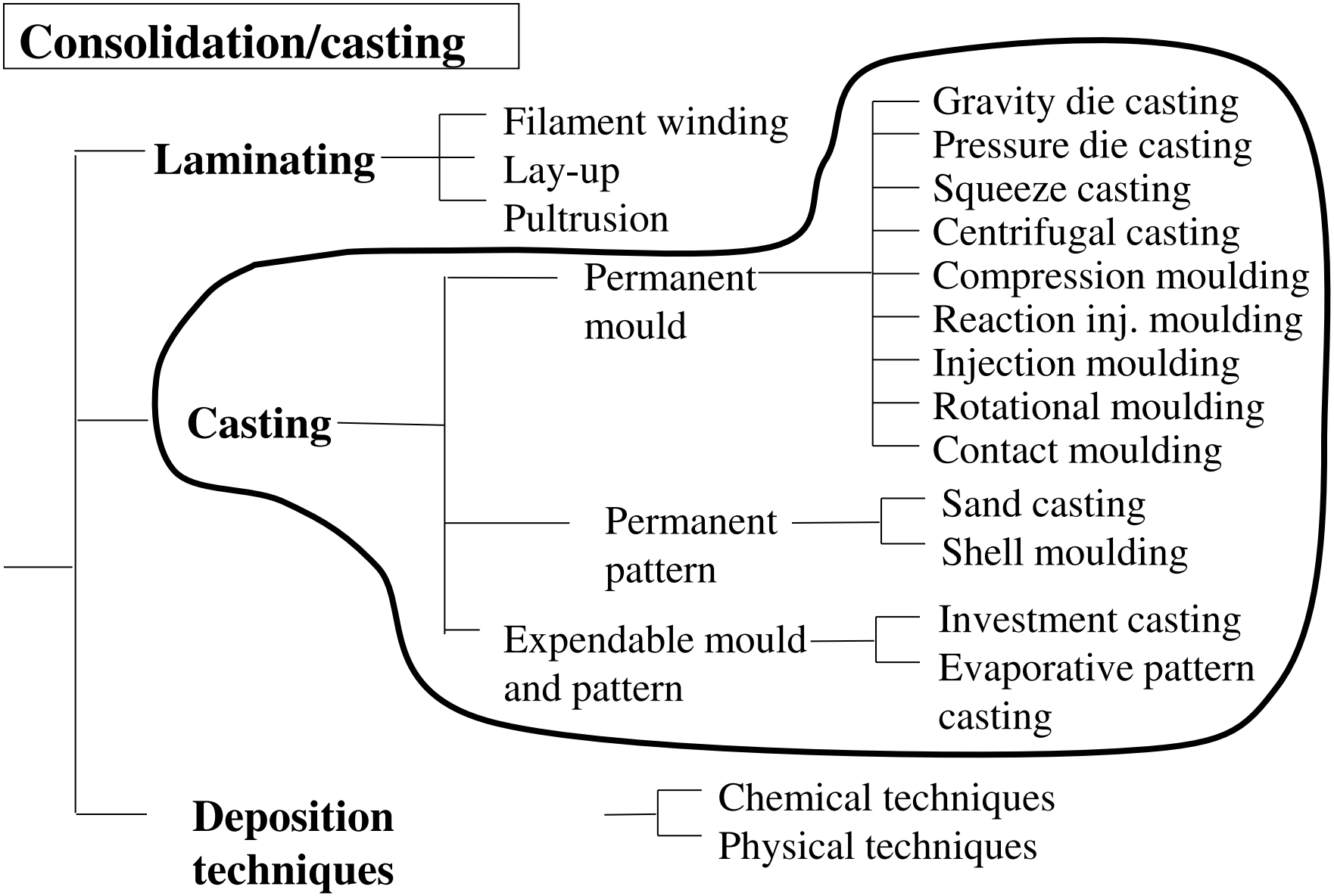
Processing and Property

- A fabricating process can change the properties of a material as well as the shape.
- This can be advantageous:
  - Deformation (forging) changes the shape and internal structure of the grains (crystals) in a metal which can increase strength and fatigue resistance.
- Or it can be deleterious:
  - Casting may produce large columnar grains that result in lower strength and toughness.
- It is important to understand the effects that a process has on the structure and properties of a material.

Processing and Property

- There is a interrelationship between
  - the designed component and its function
  - the chosen material and
  - the chosen processing route
- A component is usually designed for its “purpose” or final use. However it should also be “designed for manufacture.”
- One should not select any of the above without due consideration to the remaining two factors.

Introduction to Casting



Introduction to Casting

- Casting is a process where molten material is poured into a mould of the required shape and then allowed to solidify.
- Moulding is a similar process used for plastic materials.
- The mould should be shaped so that molten material flows to all parts of the mould.

Introduction to Casting

- Advantages
  - This process is widely used as a primary forming process and suitable for bulk shaping of a material.
- Disadvantages
  - The shape of the finished casting may be different to the shape of the mould because metals shrink as they cool.

Introduction to Casting

Considerations when selecting a method of casting

- The type of casting process most suitable for a particular application is dictated by a number of factors.
  - The number of castings
  - The cost per casting
  - The material being cast
  - The surface finish and tolerances of the finished casting
  - The size of the casting

Fundamentals of Casting

CASTING – Pouring liquid into cavity & solidifying material

1. Design and production of mould or die system
2. Melting of solid work material
3. Introduction of molten metal into die cavity or mould
4. Solidification of shaped molten metal
5. Removal of solidified component from mould or die
6. Cleaning and finishing

Fundamentals of Casting

1. Design and production of mould or die system

- Desired shape and size
- Due allowance for shrinkage of solidifying material.
- Any feature desired in the final casting must exist in the cavity.
- Able to reproduce the desired detail and have a refractory character to prevent impurities in casting
- Single-use Molds or Multiple-use Molds

Fundamentals of Casting

2. Melting of solid work material

- Process must be capable of providing molten material not only at the proper temperature, but also in the desired quantity, with acceptable quality, and at a reasonable cost

3. Introduction of Molten Material

- Pouring technique - devised to introduce molten metal into mold.
- Provision should be made for the escape of all air or gases present in the cavity prior to pouring, as well as those generated by the introduction of the hot metal.
- The molten material is then free to fill the cavity, producing a high-quality casting that is fully dense and free of defects.

Fundamentals of Casting

4. Solidification

- Process should be properly designed and controlled
- Castings should be designed so that solidification and solidification shrinkage can occur without producing internal porosity or voids.
- Molds should not provide excessive restraint to the shrinkage that accompanies cooling.
- If they do, the casting may crack when it is still hot and its strength is low.

Fundamentals of Casting

5. Removal of cast from the die

- It must be possible to remove the casting from the mold
- With single-use molds that are broken apart and destroyed after each casting, mold removal presents no serious difficulty.
- With multiple-use molds, however, the removal of a complex-shaped casting may be a major design problem.

6. Cleaning, Finishing and Inspection

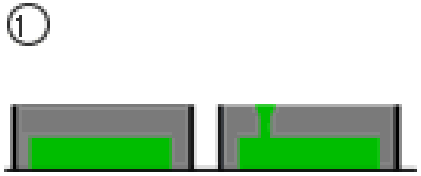
- Extraneous material is usually attached where the metal entered the cavity
- Excess material may be present along mold parting lines, and mold material often adheres to the casting surface
- All of these must be removed from the finished casting

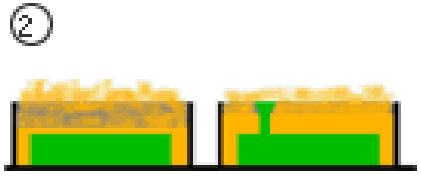
Fundamentals of Casting

Casting variations:

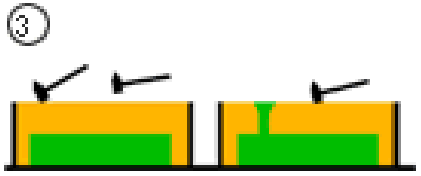
- Mould type (container that imparts shape to liquid metal):
  1. Permanent mould or die (re-used)
  2. Non-permanent mould (used once)
- Pattern type (produces shaped cavity in mould):
  1. Permanent (re-used for next mould)
  2. Non-permanent (used once - expended)
- Pouring principle
  1. Pressure (high or low)
  2. Gravity

Fundamentals of Casting

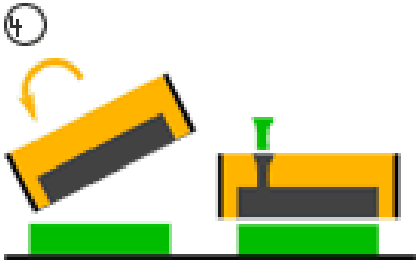




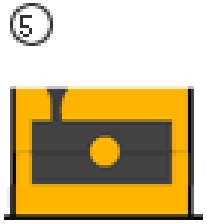
The pattern is formed in foundry sand.



The sand is compacted.

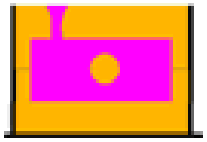


The pattern is removed.

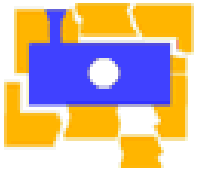


The sand mold is assembled and the cores inserted.

Molten metal is poured into the mold.



The casting solidifies.



The sand mold is destroyed to remove the casting.

Casting Terminology

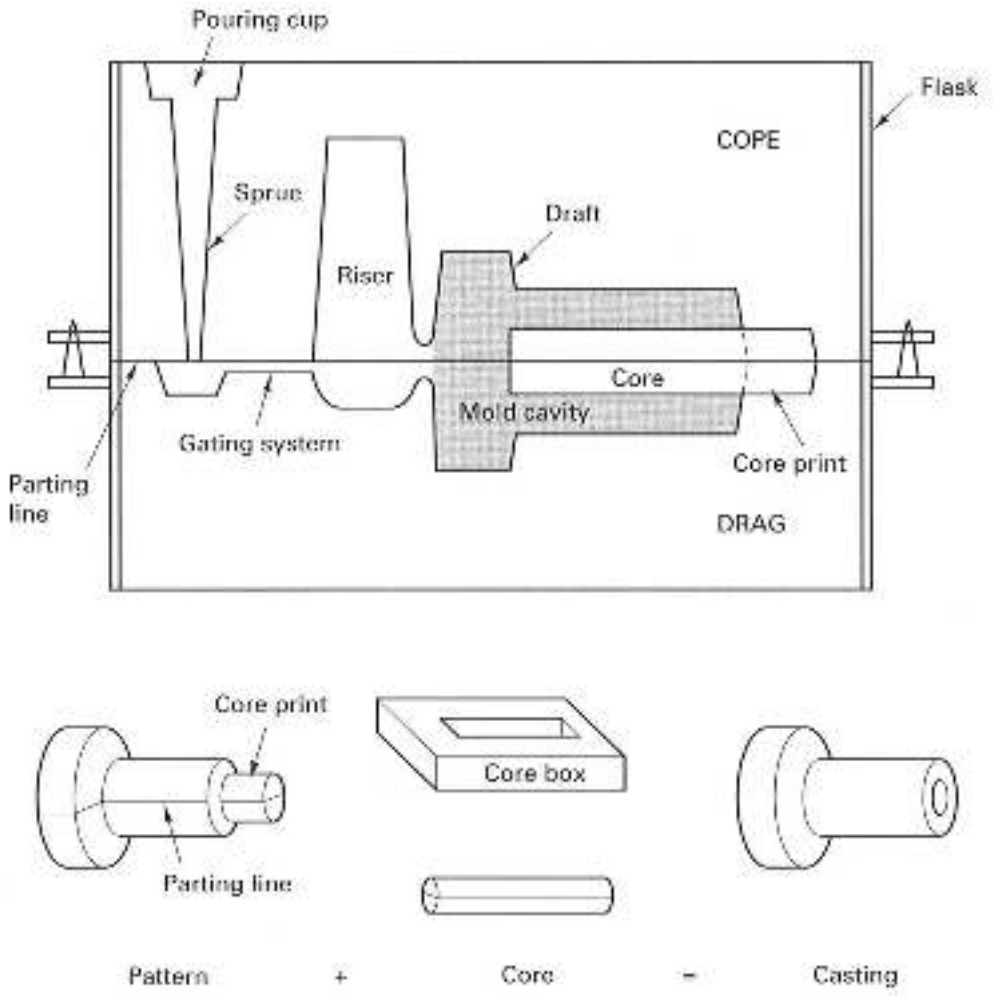


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- Construction of a **pattern** - duplicate of final casting.
- **Molding material** packed around the pattern and the pattern is removed.
- **Flask** is the rigid metal or wood frame that holds the molding aggregate.
- **Cope** is the name given to the top half of the pattern, flask, mold, or core.
- **Drag** refers to the bottom half

Casting Terminology

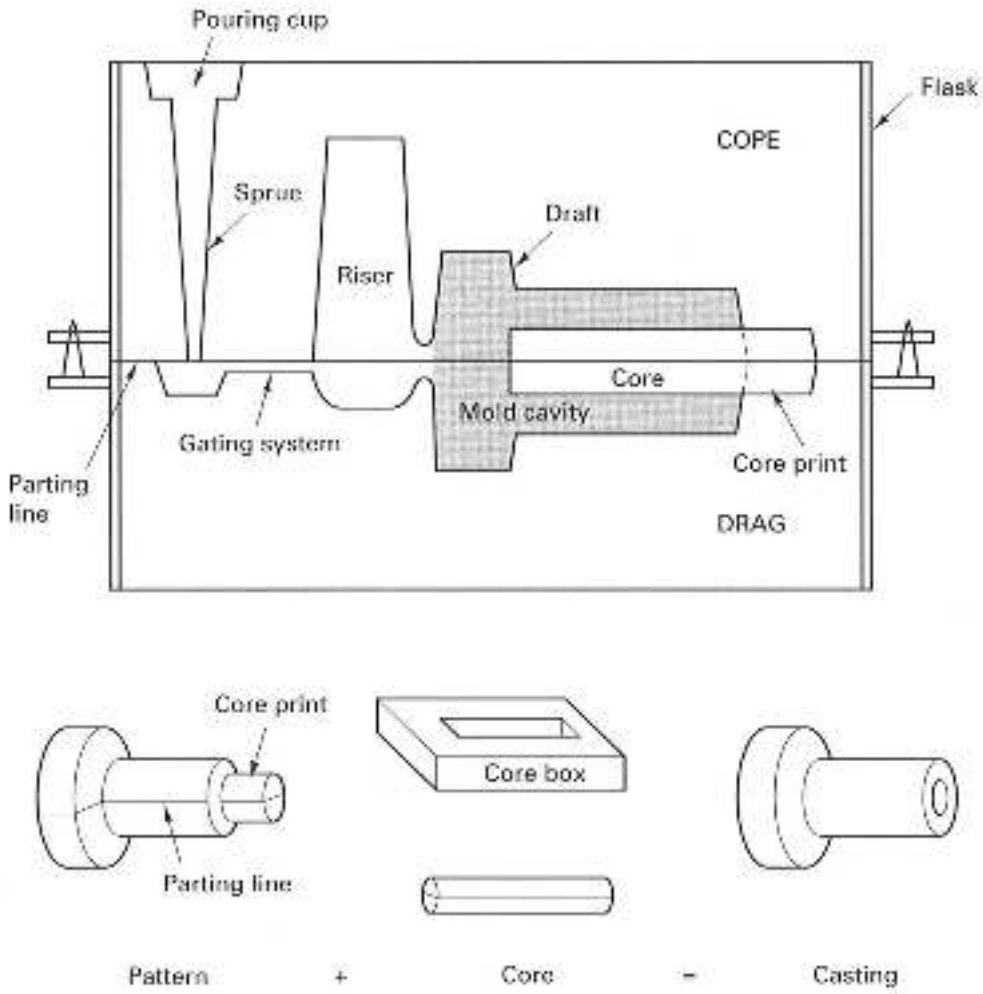


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- **Core** is a sand (or metal) shape that is inserted into a mold to produce the internal features of a casting
- **Core print** is a region that is added to the pattern, or mold to locate and support the core within the mold.
- The mold material and the core produce the **Mold cavity,** to produce the desired casting.

Casting Terminology

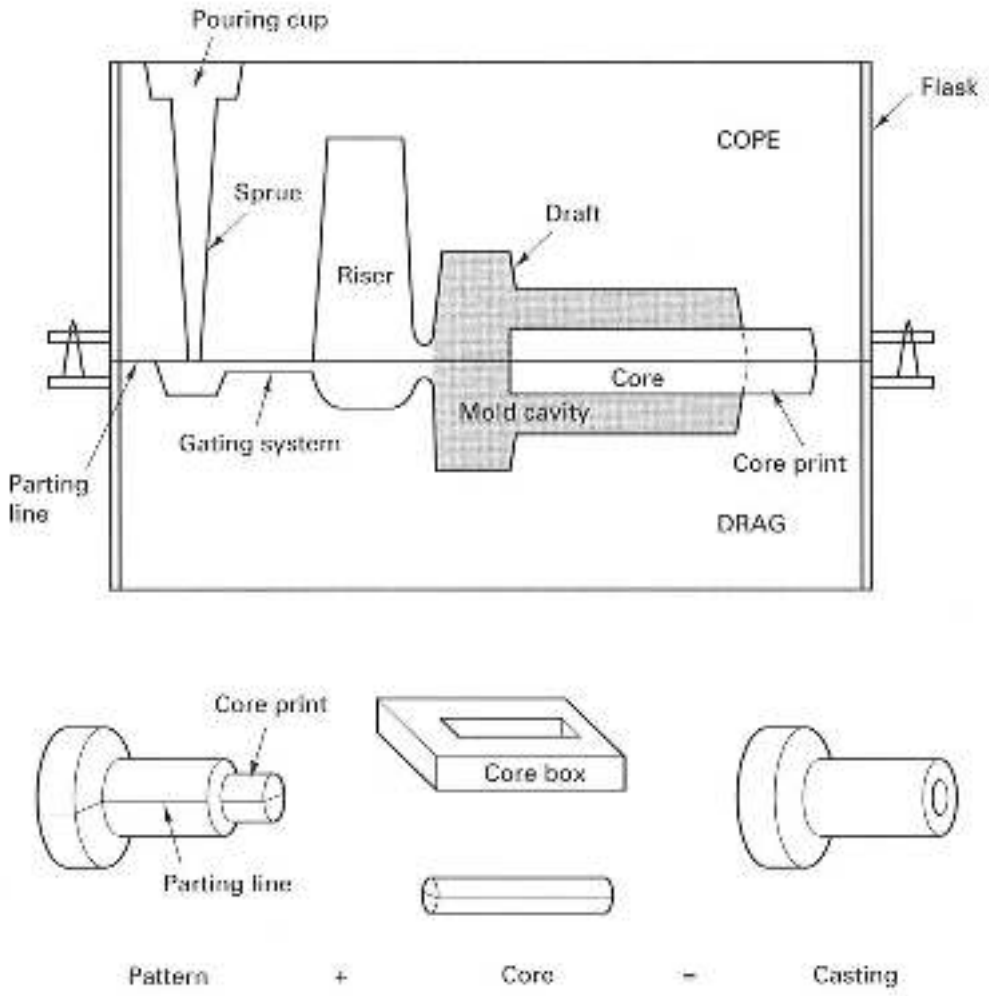


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- **Riser** is an extra void created in the mold
- It provides a reservoir to compensate for shrinkage occurring during solidification.
- If the riser contains the last material to solidify, shrinkage voids should be located in the riser and not the final casting.

Casting Terminology

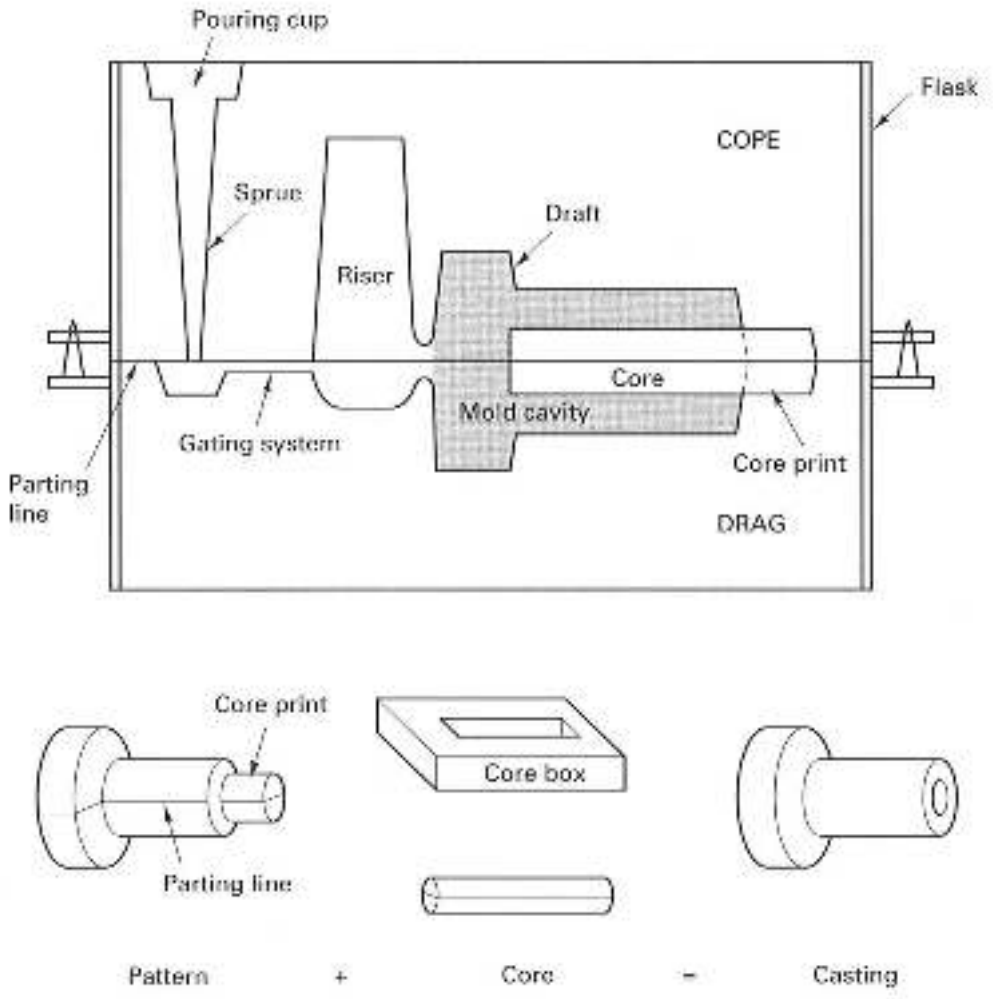


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- **Gating system** is the network of channels used to deliver molten metal to the mold cavity.
- **Pouring cup** receives the molten metal.
- Metal travels down a **sprue**, then along horizontal channels, called **runners**, and finally through controlled entrances, or **gates**, into the mold cavity.

Casting Terminology

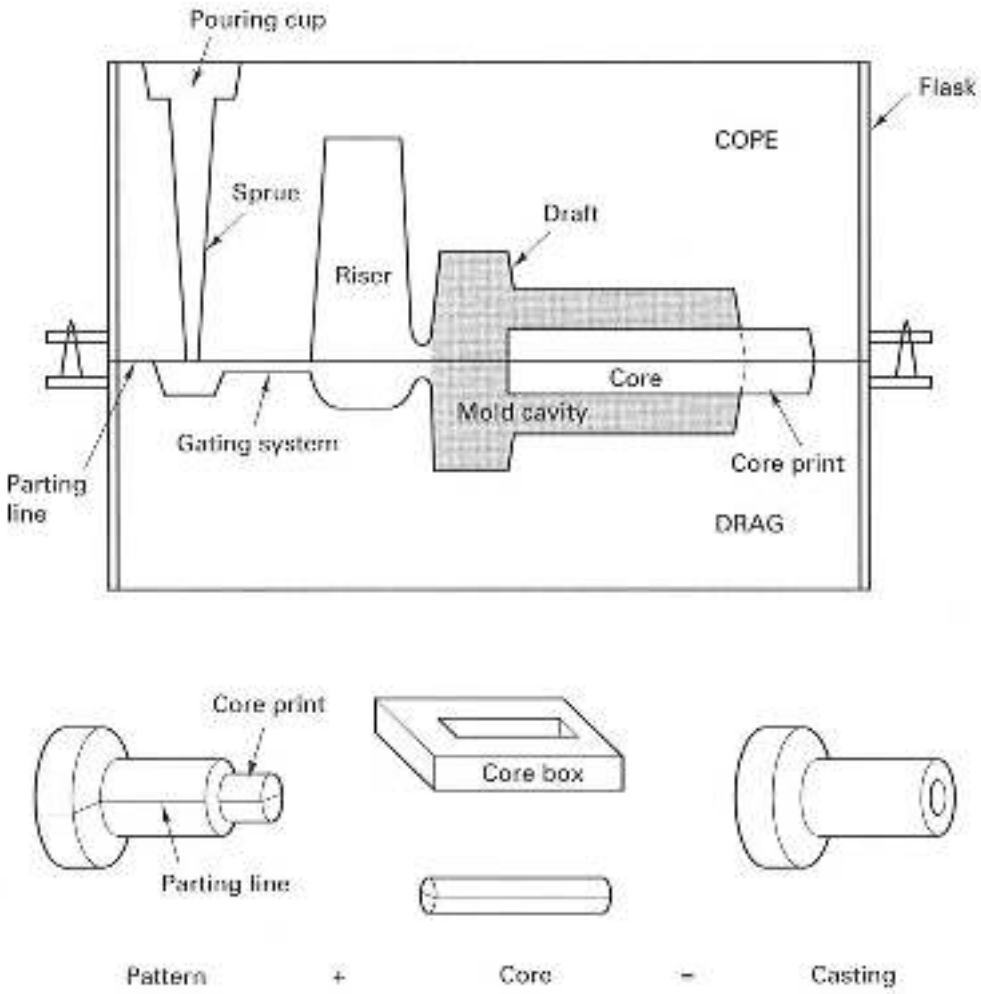


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- **Parting line** is the interface between cope and drag.
- **Draft** is the taper that permits withdrawal.
- **Core box** is the mold or die used to produce cores.
- The term **casting** is used to describe both the process and the product when molten metal is poured and solidified in a mold.

Table 3 Major markets for metal castings

Ranked in order of tonnage shipped. In some cases, the total of "Other major markets" is larger as a whole than the individual markets listed.

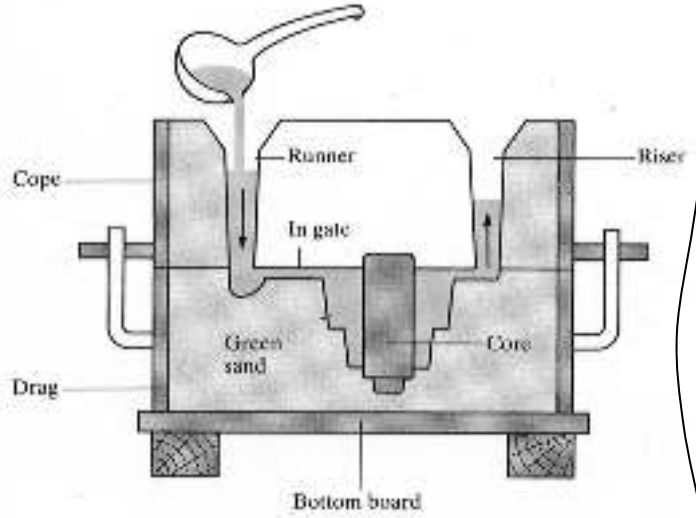
Ferrous castings		Nonferrous castings	
Gray iron	**Ductile iron**	**Aluminum**	**Copper-base**
Ingot molds	Pressure pipe	Auto and light truck	Valves and fittings
Construction castings	Motor vehicles	Aircraft and aerospace	Plumbing brass goods
Motor vehicles	Farm machinery	Other transportation	Electrical equipment
Farm equipment	Engines	Engines	Pumps and compressors
Engines	Pumps and compressors	Household appliances	Power transmission equipment
Refrigeration and heating	Valves and fittings	Office machinery	General machinery
Construction machinery	Metalworking machinery	Power tools	Transportation equipment
Valves	Construction machinery	Refrigeration, heating, and air conditioning	
Soil pipe			
Pumps and compressors			
Pressure pipe			
Other major markets include machine tools, mechanical power transmission equipment, hardware, home appliances, and mining machinery, oil and natural gas pumping and processing equipment	Other major markets include textile machinery, wood working and paper machinery, mechanical power and transmission equipment, motors and generators, refrigeration and heating equipment, air conditioning	Other major markets include machine tools, construction equipment, mining equipment, farm machinery, electronic and communication equipment, power systems, motors and generators	Other major markets include chemical processing, utilities, desalination, petroleum refining
Malleable iron	**Steel**	**Magnesium**	**Zinc**
Motor vehicles	Railroad equipment	Power tools	Automotive
Valves and fittings	Construction equipment	Sporting goods	Building hardware
Construction machinery	Mining machinery	Anodes	Electrical components
Railroad equipment	Valves and fittings	Automotive	Machinery
Engines	General and special industrial machinery		Household appliances
Mining equipment	Motor vehicles		
Hardware	Metalworking machinery		
Other major markets include heating and refrigeration, motors and generators, fasteners, ordnance, chains, machine tools, general industrial machinery	Other major markets include steel manufacturing, spring goods, heating and air conditioning, recreation equipment, industrial material handling equipment, ships and boats, aircraft and aerospace	Other major markets include office machinery, health care, aircraft and aerospace	Other major markets include scientific instruments, medical equipment, radio and television equipment, audio components, toys, sporting goods

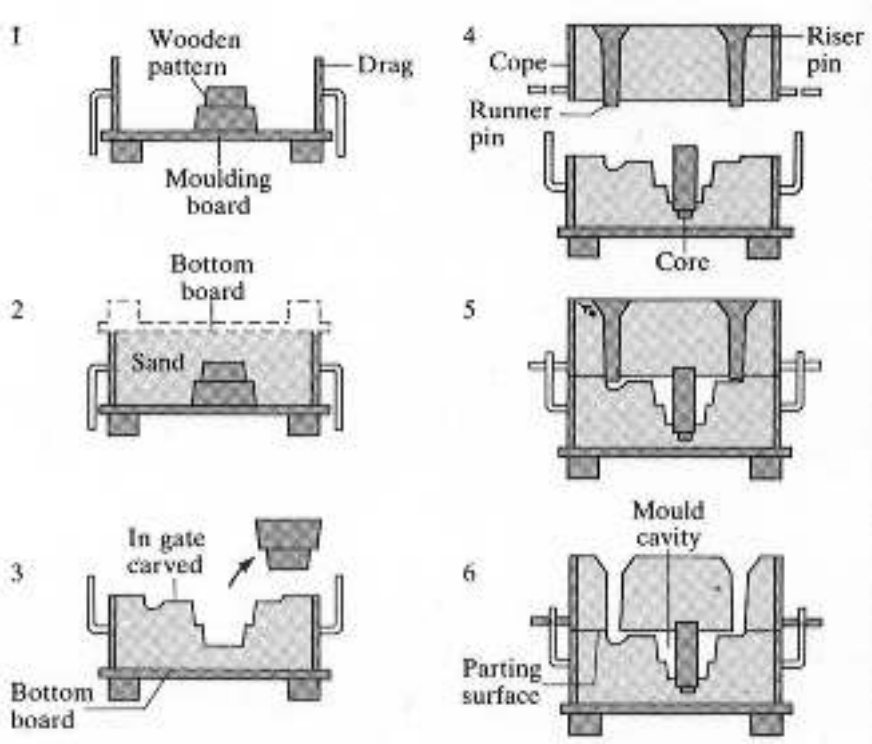
Casting Quality

- Casting Quality - at least two types of defects
- Porosity (“holes” or “bubbles” in the solid)
- Inclusions (unwanted particles)
- Can be minimised by:
- using good foundry practice (such as pouring metal without creating turbulence and placing filter in mould)
- use advanced techniques (e.g. applying vacuum over liquid or squeeze casting).
- Certain casting techniques produce better quality castings than others but are usually more expensive

Fig. 4 Compressor case for a jet engine that was converted from a multiple-component weldment into a two-part cast component by a major jet engine manufacturer. The company converted all of its formerly welded cases to castings; this reduced by 27 000 the number of parts in one of its newest engines.

Sand Casting





Repeat process for top half – with runner and riser pins

Casting Quality

- PROCESS - Sand moulds are produced around a permanent pattern which is withdrawn to leave a cavity. Molten metal is poured into the mould and solidifies. Mould (and core) is broken up to retrieve the casting.
- SHAPE - Mainly solid components but complex internal shapes produced using friable cores. Very large & small castings possible but thin sections difficult.
- MATERIALS - All metals excluding refractory and reactive alloys (e.g. Ti).

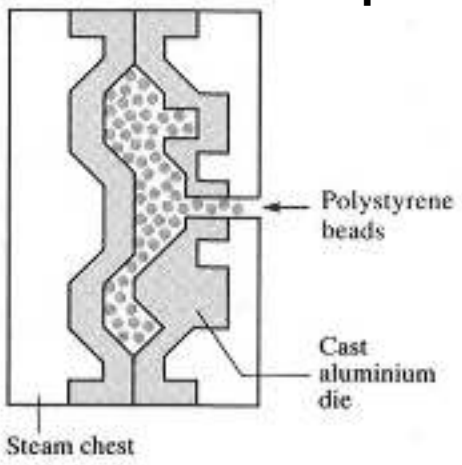
CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Usually long as limited by rate of heat transfer out of the casting. Use of multiple moulds increases production rate.	Surface texture poor. Porosity endemic. Nonmetallic inclusions difficult to control.	Patterns cheap and easy to make.	Up to 50% of casting in runners and risers. Both mould and scrap metal can be directly recycled.	Very low as pattern costs are low and mould making is relatively easy.
RATING 2	RATING 1	RATING 5	RATING 2	RATING 5

(1 = Poor , 5 = Excellent)

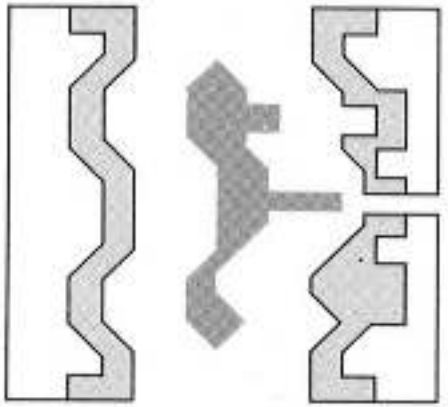
Full Mould Casting

Evaporative pattern (EPS) Casting

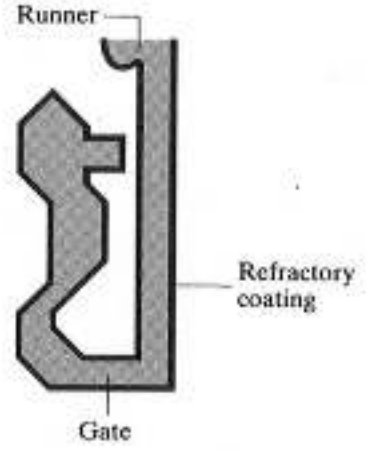
Expanded Poly-Styrene



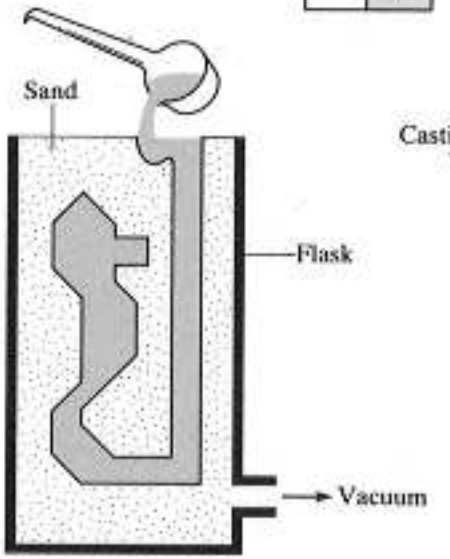
1. Inject polystyrene beads into a heated aluminium die. Pass steam through mould to fuse and expand polystyrene beads to form solid pattern.

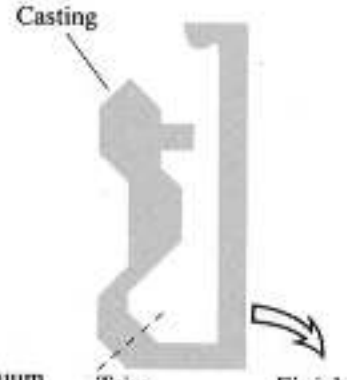


2. Cool die, open to eject pattern.



3. Glue on additional runners and risers where necessary. Cover pattern with refractory slurry and dry to form a refractory coating.





4. Place pattern in a 'flask' of loose dry unbonded sand and consolidate by vibration. Apply vacuum to flask and pour metal. Cool, remove casting and recycle sand.

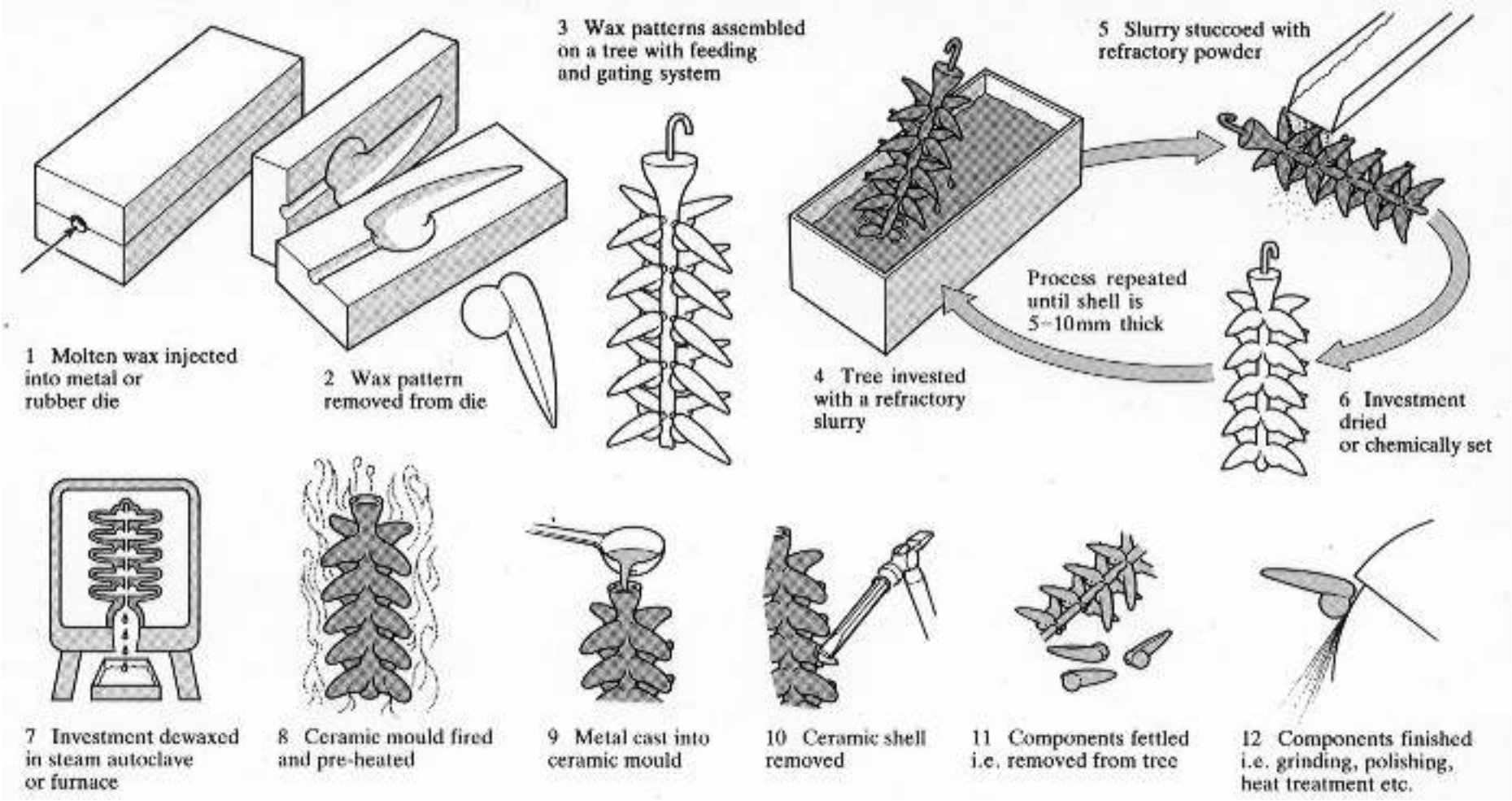
Full Mould Casting

- PROCESS (Expendable mould and pattern) - A refractory coating is applied to a volatile or combustible pattern which is used in a sand mould. The pattern is destroyed by the molten metal.
- SHAPE - Very complex 3D shapes possible.
- MATERIALS - Non-refractory metals with casting temperatures high enough to vaporize the pattern.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Long due to process complexity. Multiple moulds increase production rate.	Normal sand casting defects. Surface texture similar to that of pattern.	Ideal for the manufacture of one-offs.	Pattern material entirely wasted. Metal usage poor due to runners etc.	All equipment involved is rudimentary and process is very cheap to operate.
RATING 1	RATING 2	RATING 5	RATING 2	RATING 4

(1 = Poor , 5 = Excellent)

Investment (Lost Wax) Casting



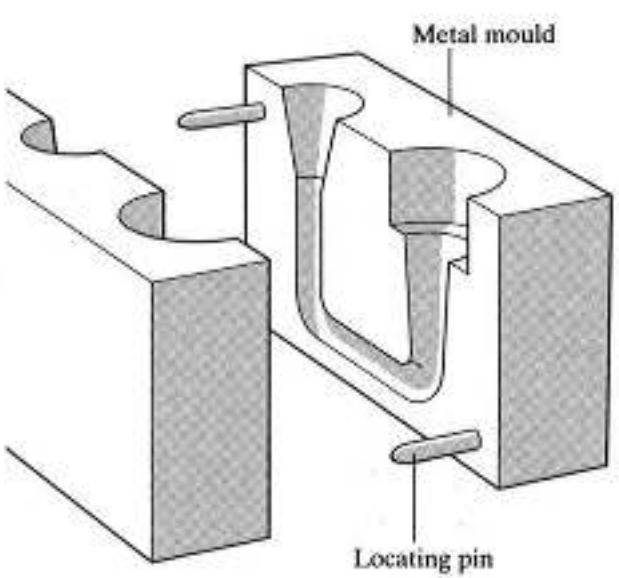
Investment (Lost Wax) Casting

- PROCESS (Expendable mould and pattern) - A ceramic shell (investment) is slip cast around a wax pattern. Wax is melted and molten metal cast into the investment which is broken up to remove the casting.
- SHAPE - Best for relatively small, complex 3D components. Re-entrant angles possible.
- MATERIALS - Suitable for most metals. Reactive metals can be cast under vacuum.

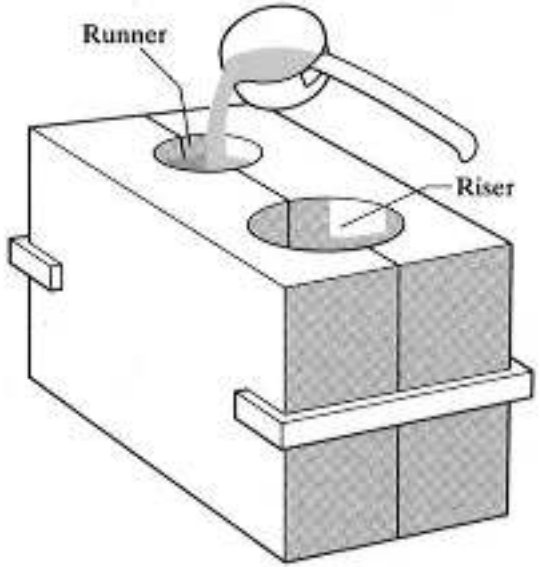
CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by rate of heat transfer out of the casting. Production rates low because of process complexity. Increased by using multiple moulds and patterns.	Surface texture good. Higher mould temperatures decrease porosity but produce coarse microstructures.	Moderately high because of the ease of production of patterns.	Near net shape process with little material contained in feeding systems. Wax recycled, investment lost.	Equipment costs can be high especially where reactive alloys are concerned. Labour costs are high due to the many stages in the process.
RATING 2	RATING 4	RATING 4	RATING 4	RATING 3

(1 = Poor , 5 = Excellent)

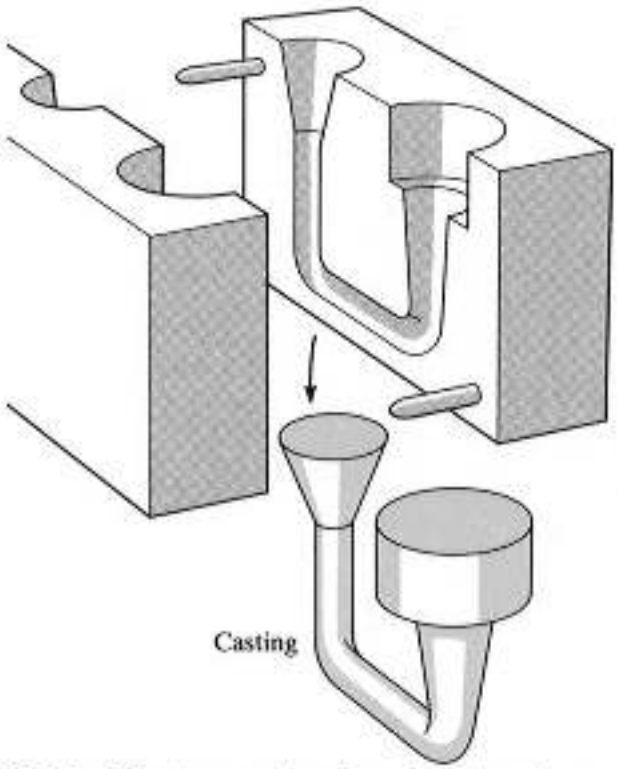
Gravity Die Casting



1. Mould and cores (where applicable) sprayed with coating. Mould heated using gas burners and lubricant sprayed on.



2. Mould parts assembled and clamped. Metal poured into runner.



3. Mould set opened and casting ejected, finished and heat treated (when necessary).

Gravity Die Casting

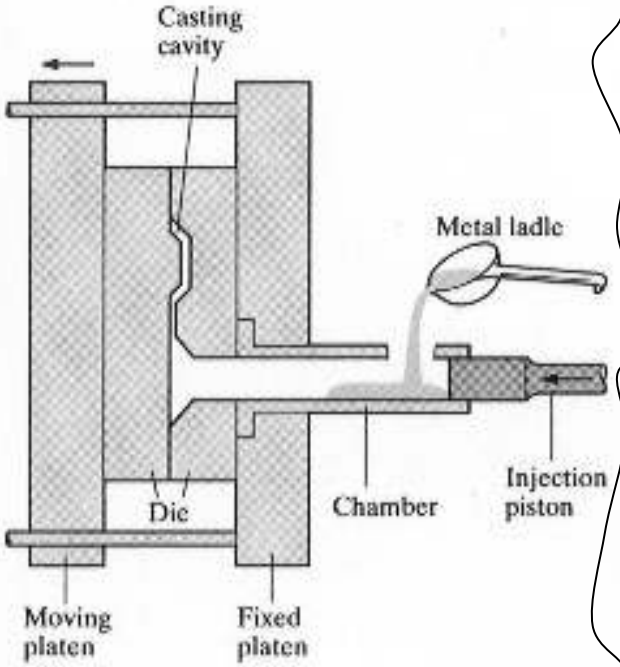
- PROCESS (Permanent mould) - Molten metal is poured into a metallic mould where it solidifies.
- SHAPE - Mostly used for small, simple shapes with only simple coring.
- MATERIALS - Mainly used for light alloys. Steels and cast irons also possible.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by rate of heat transfer across the interface. Production rates can be increased by using multiple moulds or multiple cavities.	Surface texture is good. Porosity unavoidable but can be minimized by slower mould filling to reduce turbulence.	Negligible setting up time for manual operation. Mould making relatively difficult.	Rarely better than 60% utilization. Scrap in the runners and risers can be directly recycled.	Equipment cost can be limited to mould and melt preparation apparatus.
RATING 4	RATING 3	RATING 2	RATING 2	RATING 2

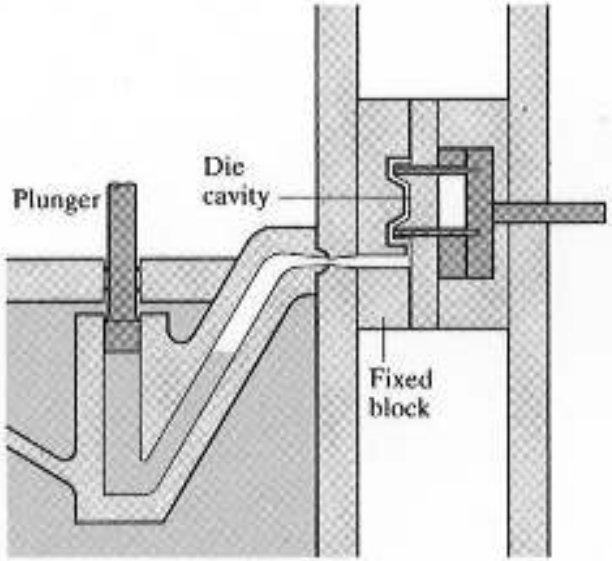
(1 = Poor , 5 = Excellent)

Pressure Die Casting

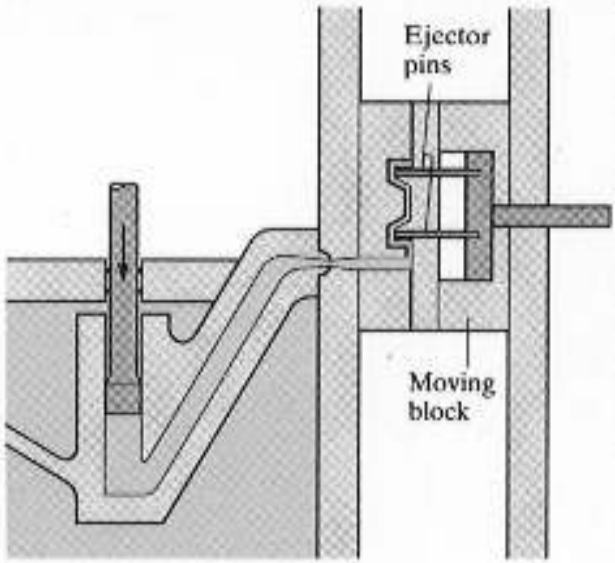
High or Low Pressure

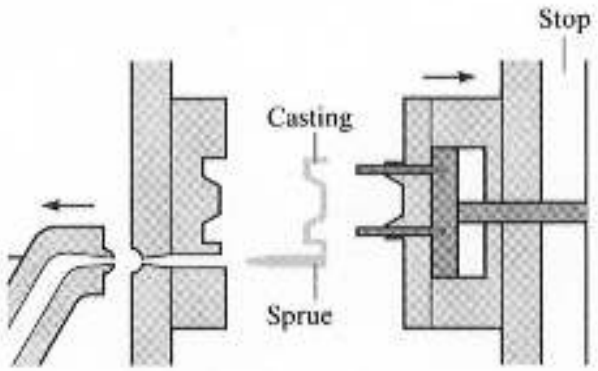


Cold-chamber high pressure die casting
Molten metal is poured into a cold shot chamber. A high pressure plunger forces metal into the single or multi-die cavity.



Hot chamber high pressure die casting
A gooseneck hot chamber is submerged in a pot of molten metal. Metal is injected directly from the pot via the gooseneck.





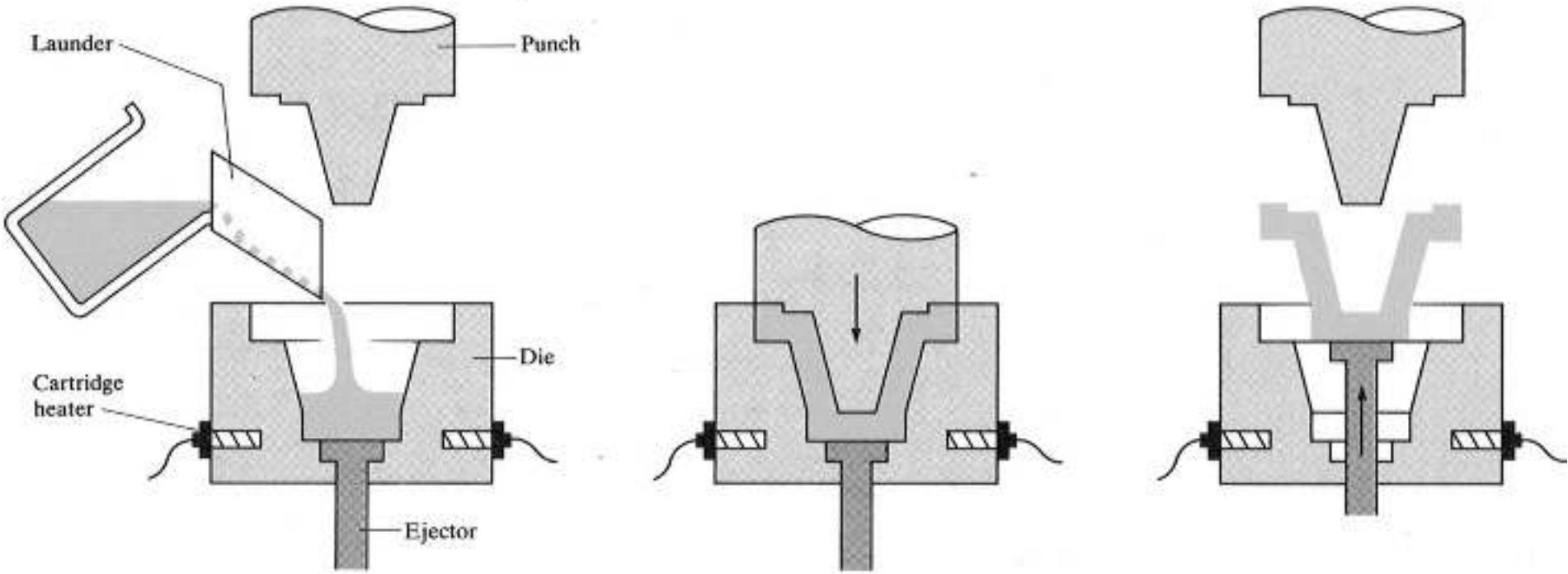
Pressure Die Casting

- PROCESS (Permanent mould) - Molten metal is forced into a water-cooled metal mould (die) through a system of sprues and runners. The metal solidifies rapidly and the casting is removed with its sprues and runners.
- SHAPE - Used for complex shapes and thin sections. Cores must be simple and retractable.
- MATERIALS - High fluidity requirement means low melting temperature eutectics usually used (e.g. Al-Si). Hot chamber method restricted to very low melting temperature alloys (e.g. Mg and Zn).

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Solidification time is typically < 1 s so cycle is controlled by time taken to fill mould and remove casting.	Good surface texture but turbulent mould filling produces high degree of internal porosity.	Tooling dedicated so limited by machine setting up time.	Near net shape process but some scrap in sprues, runners and flash which can be directly recycled.	High, since machine and moulds are expensive.
RATING 5	RATING 2	RATING 1	RATING 4	RATING 1

(1 = Poor , 5 = Excellent)

Squeeze Casting



Stage 1
Preheated mould set is positioned on hydraulic press and coated with a releasing agent such as graphite. Liquid metal is accurately metered into the mould cavity via a launder.

Stage 3
Press actuated to bring two parts of the mould together. Metal displaced to fill mould cavity and pressure held until solidification is complete.

Stage 2
Press withdrawn, mould set separated and component ejected.

A ceramic fibre/particle preform may be placed in the mould prior to pouring to fabricate MMC's

Squeeze Casting

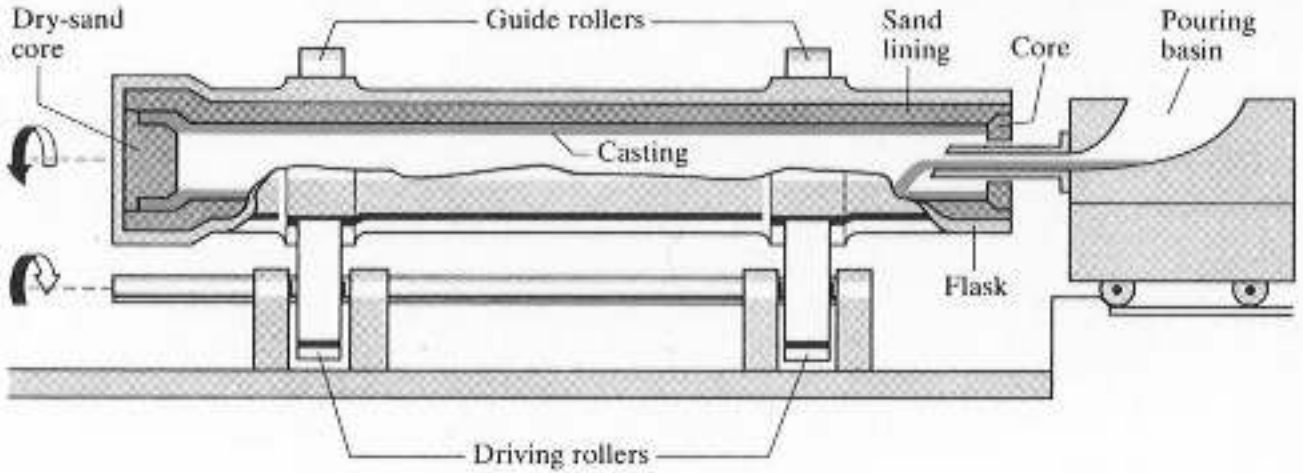
- PROCESS (Permanent mould) - Accurately metered quantity of molten metal is poured into preheated mould. The mould is then closed and pressure applied until solidification is complete.
- SHAPE - Retractable and disposable cores used to create complex internal and re-entrant features.
- MATERIALS - Principally used for light alloys (temperatures) but can be used for most non-refractory metals.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Solidification times short but long cycle times needed to ensure adequate process control.	Low levels of porosity and fine microstructures due to imposed pressure and rapid rate of solidification. Surface texture good.	Restricted by dedicated tooling and long setting up times.	Accurate metering of liquid metal leads to approx. 100% material utilization.	Costs are extremely high because of the complex tooling and the accuracy of process control required.
RATING 3	RATING 4	RATING 1	RATING 5	RATING 1

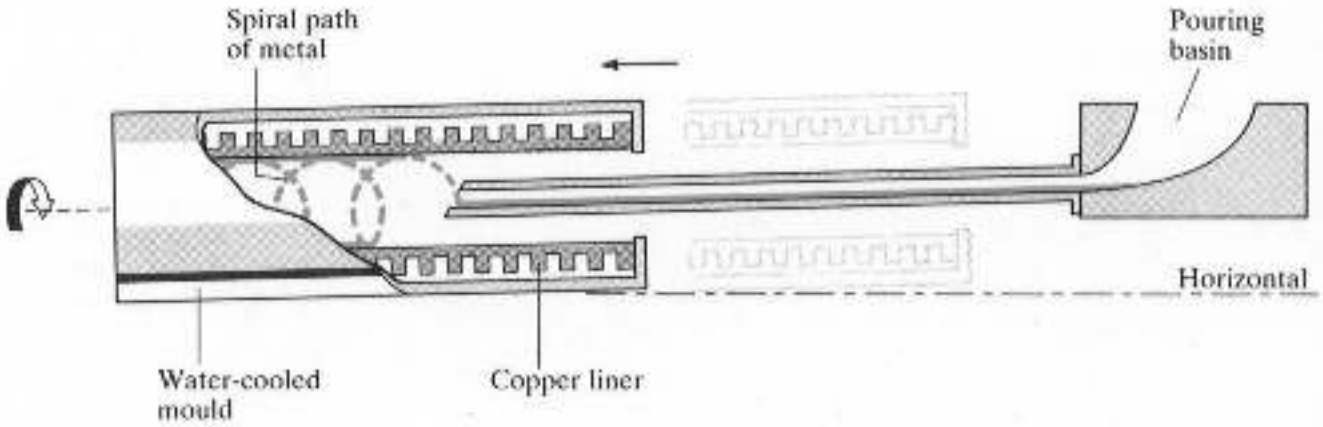
(1 = Poor , 5 = Excellent)

Centrifugal Casting

Sand mould casting



Metal mould casting



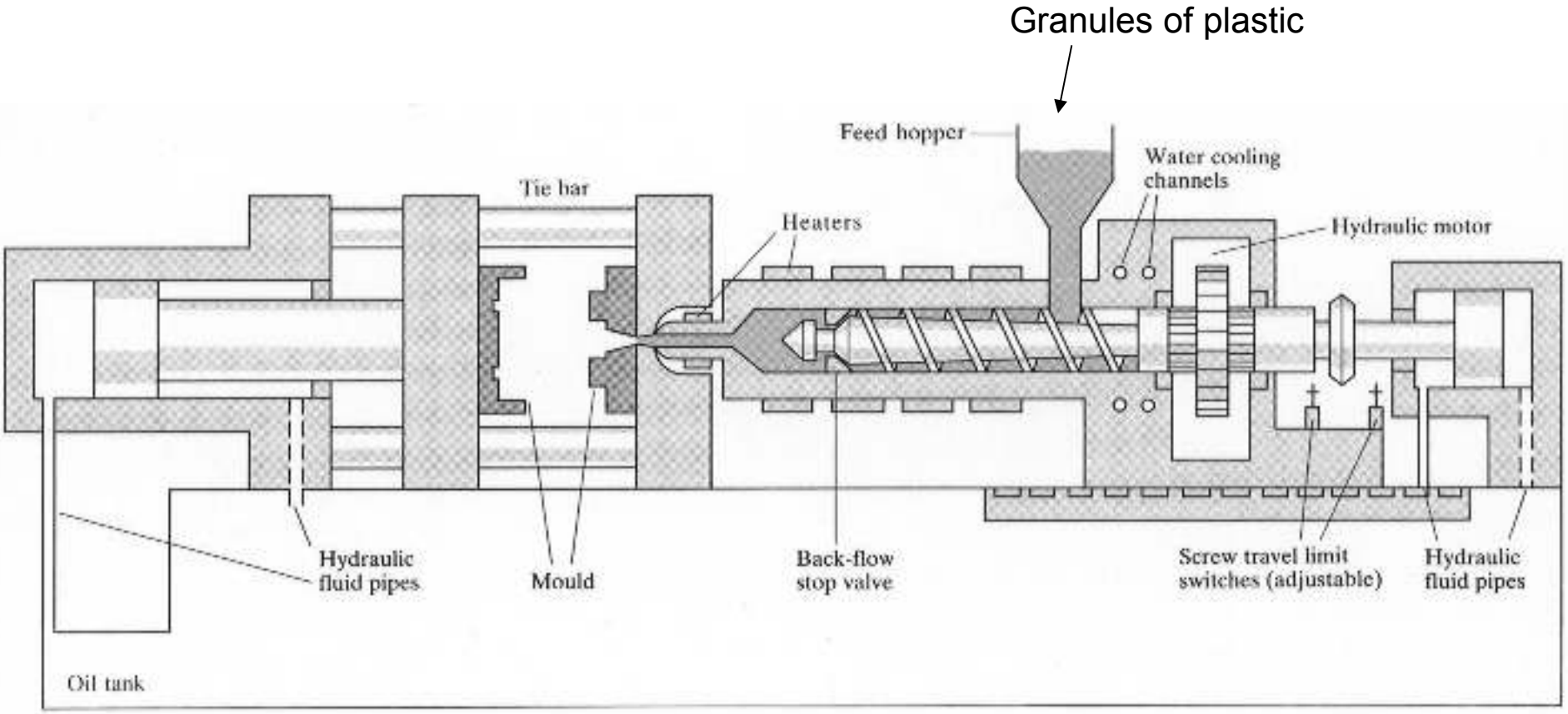
Centrifugal Casting

- PROCESS (Permanent mould) - Molten metal is introduced into a sand- or copper-lined, cylindrical steel mould which is rotated about its long axis, distributing the metal over its inner surface.
- SHAPE - Technique used to produce relatively long, hollow objects (e.g. pipes) without the need for cores.
- MATERIALS - Metals excluding refractory and reactive metals.

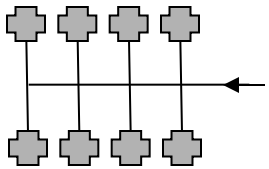
CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Determined by the rate of introduction of metal into the mould and the rate of solidification of the metal. The latter is lower for sand-lined moulds.	Porosity and nonmetallic inclusions migrate towards the inner surface because of their lower density, giving a high quality outer surface.	Setting up times are relatively short.	Absence of runners and risers leads to near 100% use of material.	Equipment is relatively simple and can cost little. Increased complexity of water-cooled copper-lined moulds more costly.
RATING 2	RATING 3	RATING 3	RATING 5	RATING 3

(1 = Poor , 5 = Excellent)

Injection Moulding



For small parts, mould cavity has many cavities connected by runners



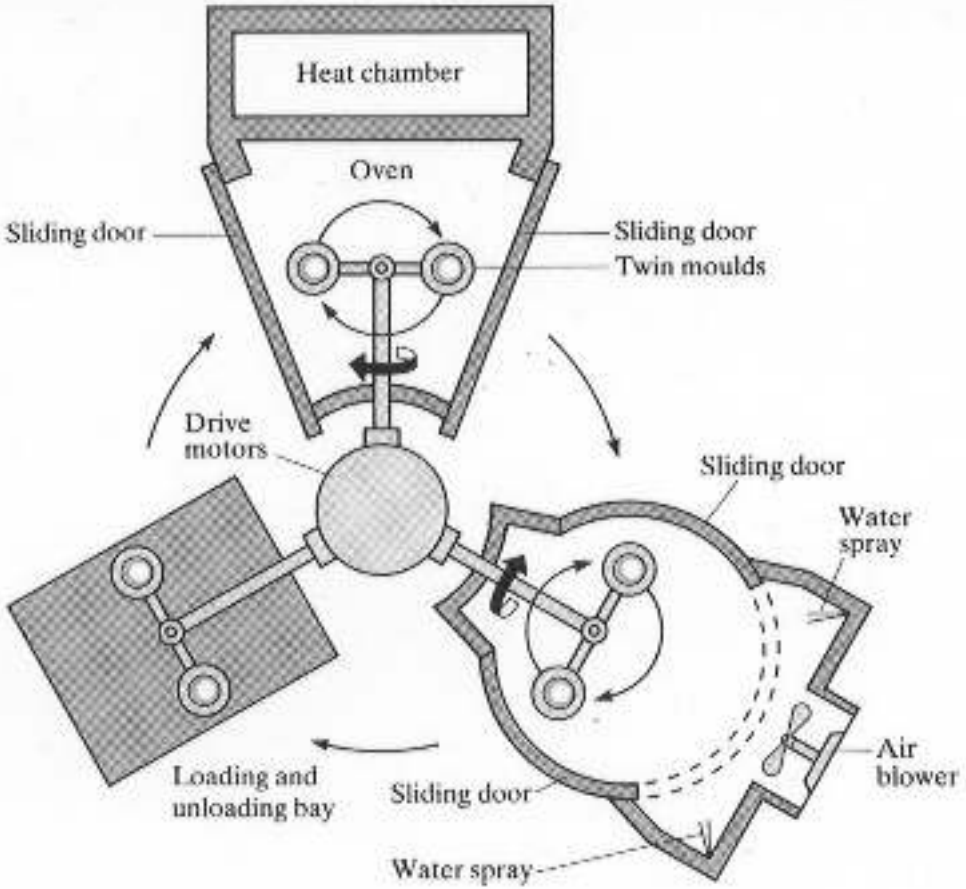
Injection Moulding

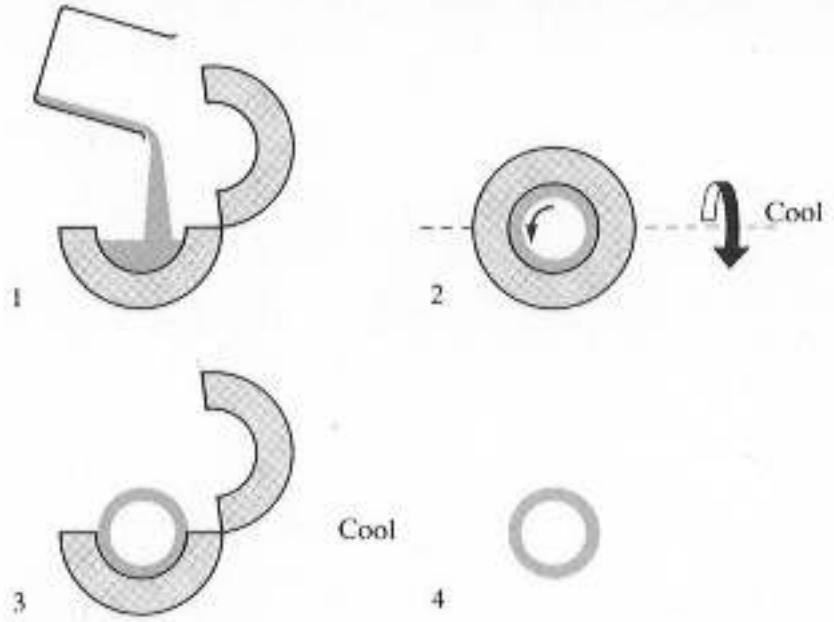
- PROCESS (Permanent mould) - Permanent mould Molten polymer is forced at high pressure into a cool metal mould. The polymer solidifies under pressure and the moulding is removed.
- SHAPE - Complex shapes although thick sections are problematical. Small re-entrant angles possible if material flexible. Screw threads possible.
- MATERIALS - Mainly thermoplastics, also rubbers, thermosets and composites.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by solidification time and demoulding time.	Can be reasonable but normally compromised in the pursuit of high production rates.	Restricted by mould changeover and machine setting up time.	Scrap in sprues and runners. Thermoplastics can be recycled with some degradation of properties.	High due to cost of machines and moulds.
RATING 4	RATING 3	RATING 1	RATING 4	RATING 1

(1 = Poor , 5 = Excellent)

Rotational Moulding





1. Add measured amount of polymer to mould
2. Close mould and rotate around two or more axes in a heated chamber.
3. Cool mould and open
4. Remove product.

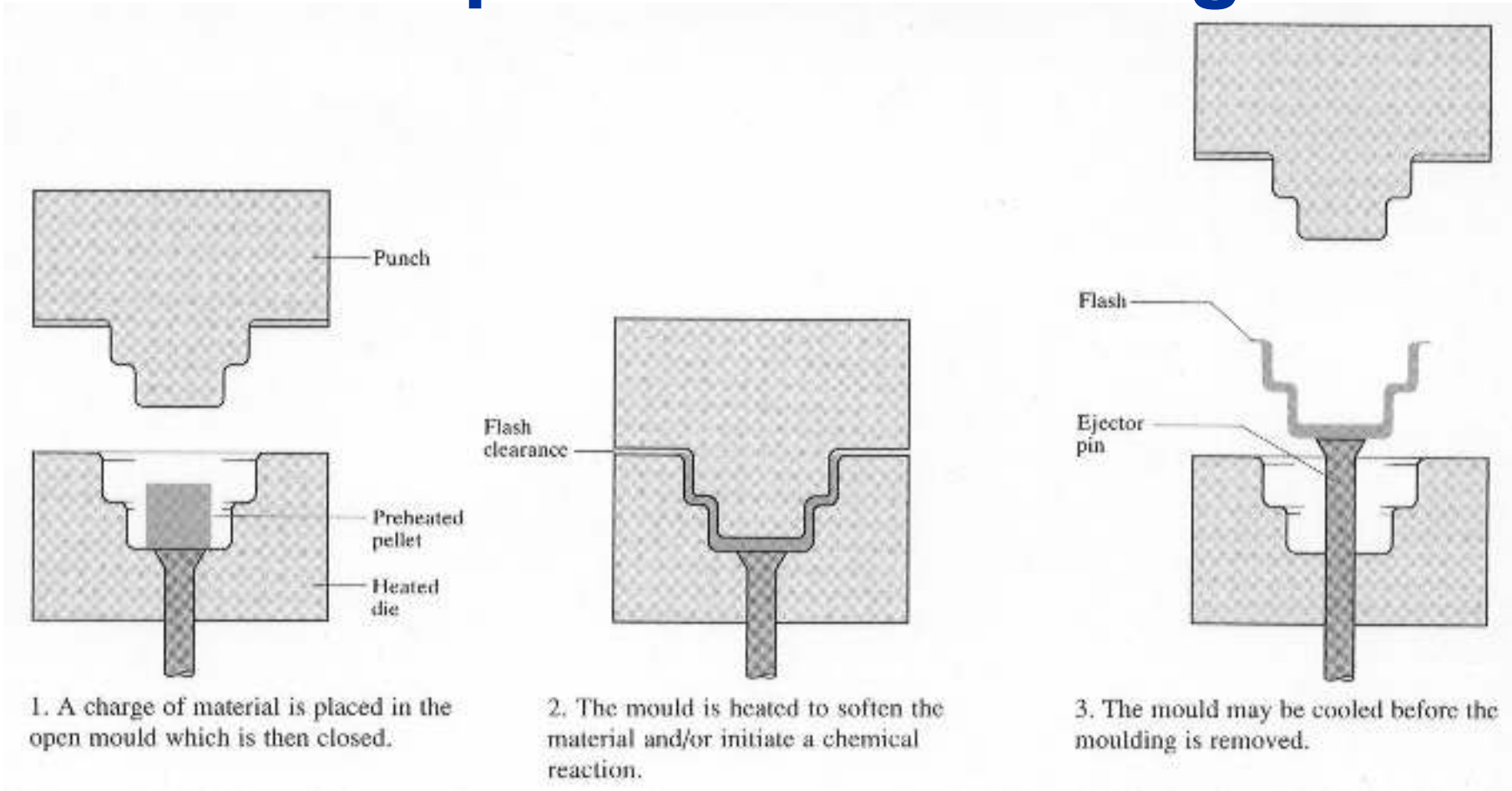
Rotational Moulding

- PROCESS (Permanent mould) - Polymer is introduced, as powder or slurry, into a closed mould. Mould is heated, to melt the material, then cooled to solidify it, whilst being rotated about two orthogonal axes.
- SHAPE - Principally used to produce containers and similar hollow articles with uniform, thin sections (e.g. buoys, kayaks)
- MATERIALS - Mainly thermoplastics.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by heat transfer into and out of the material so cycle times increase dramatically with wall thickness.	Isotropic properties as little molecular orientation. Low molecular mass materials used have poor mechanical properties.	Tooling dedicated, but moulds relatively cheap.	100% of material in mould is incorporated into the product.	Mould and equipment costs can be low.
RATING 2	RATING 2	RATING 4	RATING 5	RATING 4

(1 = Poor , 5 = Excellent)

Compression Moulding



1. A charge of material is placed in the open mould which is then closed.

2. The mould is heated to soften the material and/or initiate a chemical reaction.

3. The mould may be cooled before the moulding is removed.

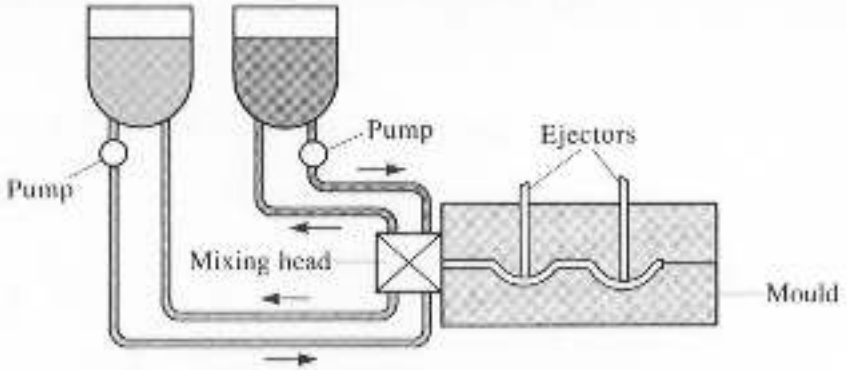
Compression Moulding

- PROCESS (Permanent mould) - Closed mould process where mould is heated to soften the material and/or initiate a chemical reaction. The charge may be preheated before loading into the mould.
- SHAPE - Limited to relatively simple shapes because of short flow lengths. Re-entrant angles possible in materials which are flexible at demoulding temperatures.
- MATERIALS - Very widely used for thermosets but more recently developed for thermoplastics and composites.

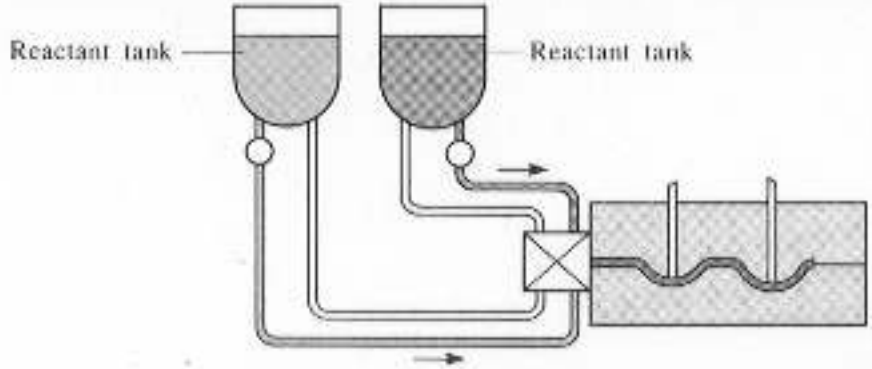
CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by rate of heat transfer and, for thermosets, the rate of reaction of the polymer. Multiple cavity moulds increase production rate.	Highly operator dependent. Problems include premature chemical reaction, air entrapment and inadequate filling of the cavity.	Process uses dedicated tooling. Mould changing is fast and changeover time is dictated by the heating up time.	Scrap consists of flash alone (no sprues or runners). This is not recyclable in the case of thermosets.	Machine and tooling costs low compared to most other permanent mould casting processes.
RATING 3	RATING 2	RATING 4	RATING 4	RATING 3

(1 = Poor , 5 = Excellent)

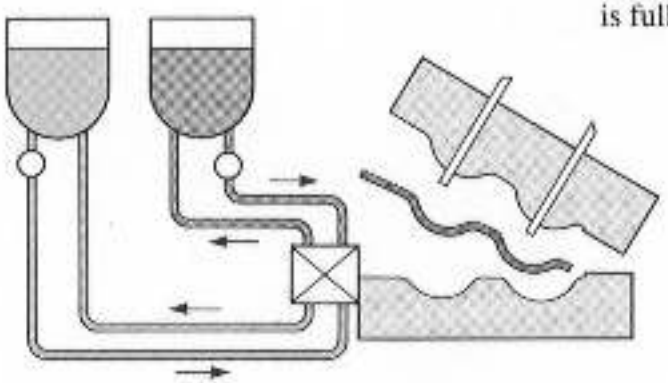
Reaction Injection Moulding



In steady state, valves in mixing head allow reactants to circulate without mixing.



Mixing head opens and reactants mix as they enter the mould at high speed. Mixing head closes again when mould is full.



After curing time mould is opened and component ejected.

Reaction Injection Moulding

- PROCESS (Permanent mould) - Two streams of preheated, low molecular mass reactants are mixed and injected at high speed into a closed mould. Polymerization produces high molecular mass casting which is removed from the mould.
- SHAPE - Use of low modulus materials allows slight re-entrant angles to be accommodated.
- MATERIALS - Polymer & polymer matrix composites A wide range of chemically reactive systems possible. Mostly used for polyurethanes, polyamides and composites incorporating glass

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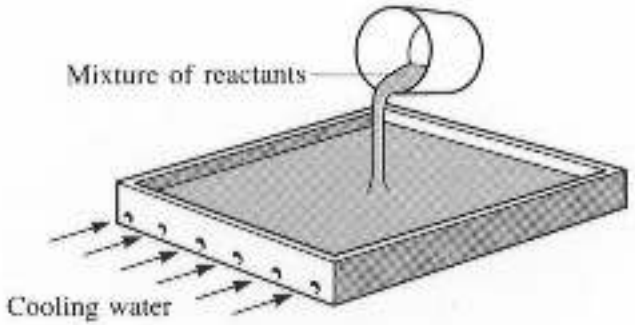
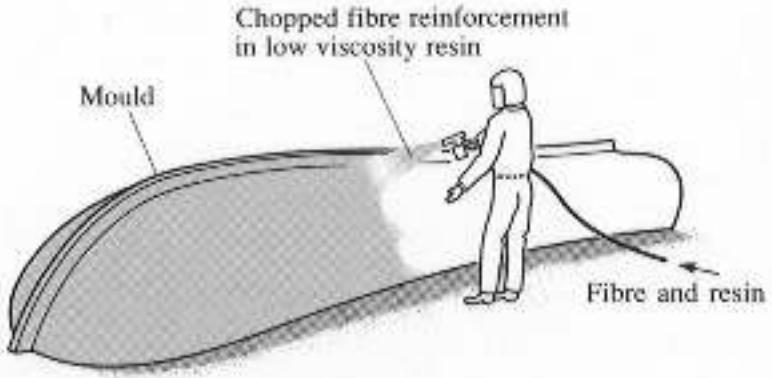
CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Limited by reaction rate of the polymer and time taken to remove casting from mould.	Surface texture can be variable. Flaws created by premature reaction of the polymer result in poor mould surface reproduction.	Tooling dedicated. Mould changing relatively easy but process is complex to set up.	Moulds do not need runners. Some scrap, which cannot be recycled, at start-up.	Equipment is expensive although moulds are relatively cheap.
RATING 3	RATING 2	RATING 2	RATING 4	RATING 2

(1 = Poor , 5 = Excellent)

Monomer Casting /Contact Moulding



Monomer casting
Reactive chemicals mixed and cast into water-cooled moulds. Used to produce high molecular mass polymer sheet for certain thermoforming applications.



Contact moulding
Mixtures of fibre reinforcement and reactive chemicals applied to mould either by hand or automatically using spraying techniques.

Monomer Casting /Contact Moulding

- PROCESS (Permanent mould) - Low molecular mass polymer is mixed with catalysts and introduced into the mould. Fibre or particulate reinforcement may be incorporated.
- SHAPE - Mostly used for simple shapes. Re-entrant angles can be produced by using flexible moulds.
- MATERIALS - Used for all polymers that will polymerize at low temperatures and at atmospheric pressure.

CYCLE TIME	QUALITY	FLEXIBILITY	MATERIALS UTILIZATION	OPERATING COST
Controlled by the reaction rate of the polymer which is designed to be slow to allow time to mix and apply the material.	Highly operator dependent. Problems include inadequate mixing, air entrapment and gas evolution.	Moulds are cheap and easy to produce. Setting up times are short.	Some excess material is normally produced, since accurate metering is rarely employed.	Costs can be very low.
RATING 1	RATING 2	RATING 4	RATING 4	RATING 4

(1 = Poor , 5 = Excellent)

Casting-Comparisons

Casting Processes	Advantages	Limitations
Sand casting	• Almost any metal can be cast. • No limit on size and shape. • Low equipment cost. • Economical for low-volume production.	• Coarse finish. • Dimensional accuracy not so good. • Finishing required. • Low production rate.
Investment casting	• Almost any metal can be cast. • Good surface finish. • Good dimensional accuracy. • Fairly high production rate. • Intricate shapes can be cast. • Low finishing cost.	• Limitation on part size. • Expensive pattern and mould. • High labour cost.
Permanent mould casting	• Good surface finish. • Good dimensional accuracy. • High production rate.	• High mould cost. • Suitable for high volume production. • Suitable for casting of simple shapes. • Suitable for low-melting-point metals.
Die casting	• Excellent surface finish. • Excellent dimensional accuracy. • High production rate. • Complex shapes can be cast. • Little or no finishing cost.	• Limitation on part size. • High cost of die. • Generally limited to casting of non-ferrous metals.
Centrifugal casting	• High production rate. • Good dimensional accuracy and surface finish.	• Expensive set-up. • Good for production of cylindrical parts only.

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Introduction

Lecture 2

Solidification/Freezing

- Casting is a process where molten material is allowed to freeze and take the final shape
- Final product property that depend of structural features are formed during solidification

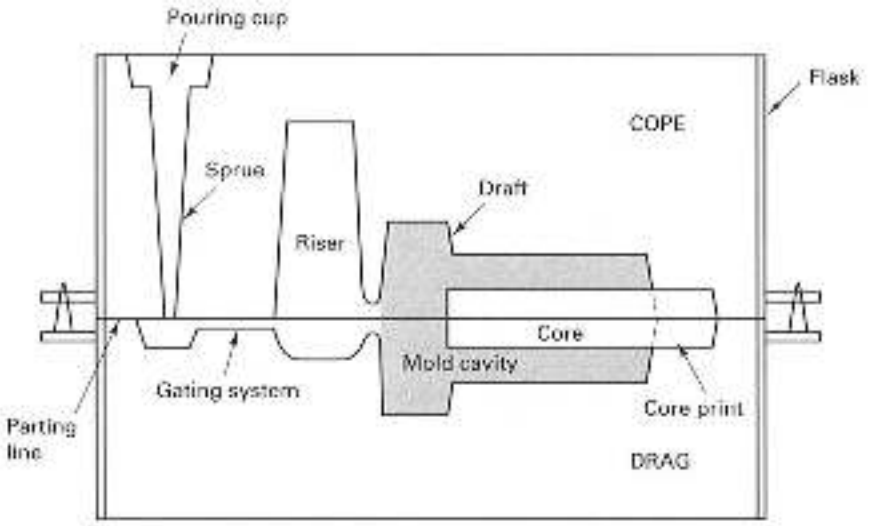


FIGURE 13-2 Cross section of a typical two-part sand mold, indicating various mold components and terminology.

- Many defects gas porosity and shrinkage also happen this time
- These defects can be reduced by controlling the solidification
- Refinement of grain size is also possible by controlling solidification

Solidification/Freezing

- **Nucleation**:- formation of stable particle of solid material within the molten liquid.
- **Growth**:- growth of solid particles to convert remaining liquid to solid.
- **Nucleation –** while material changes state, internal energy reduces as at low temperature solid phase is stable than liquid
- New surfaces are created at the interface between solid and liquid which requires energy
- There is balance between the energy levels

Solidification/Freezing

- Due to this balance in energy, nucleation occurs at temperatures below the melting point
- The temperature difference between the melting point and the actual temperature at which nucleation starts is called super or undercooling

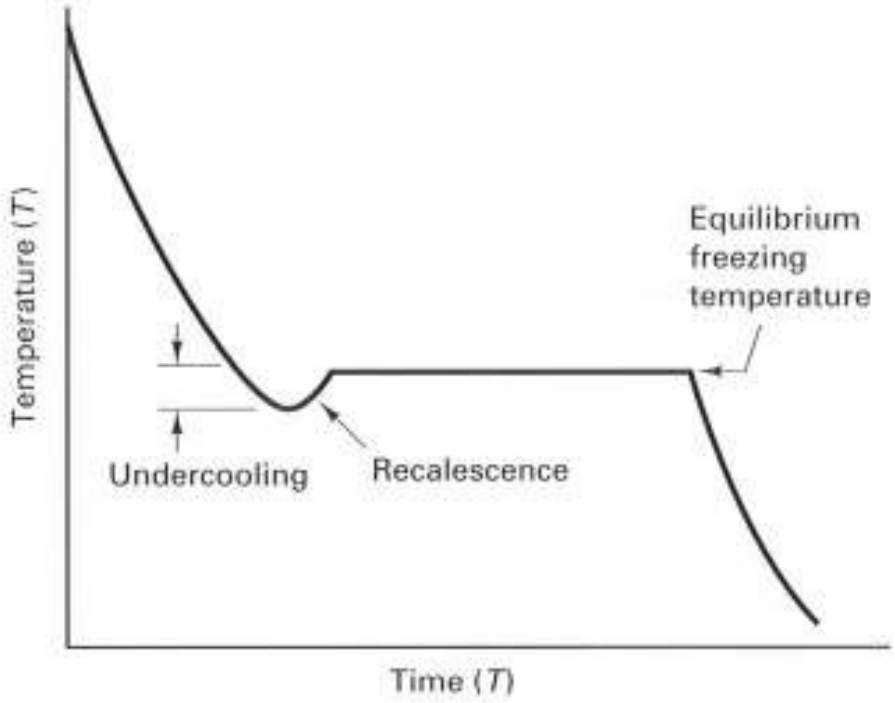


FIGURE 13-5 Cooling curve depicting undercooling and subsequent recalescence.

Solidification/Freezing

- Homogeneous nucleation takes place inside liquid metal when atoms bond together to form large enough particle that does not remelt (latent heat of fusion). Rare in industry.
- Heterogeneous nucleation takes place at foreign bodies e.g., mould walls, impurities etc. Most common type industrially

Solidification/Freezing

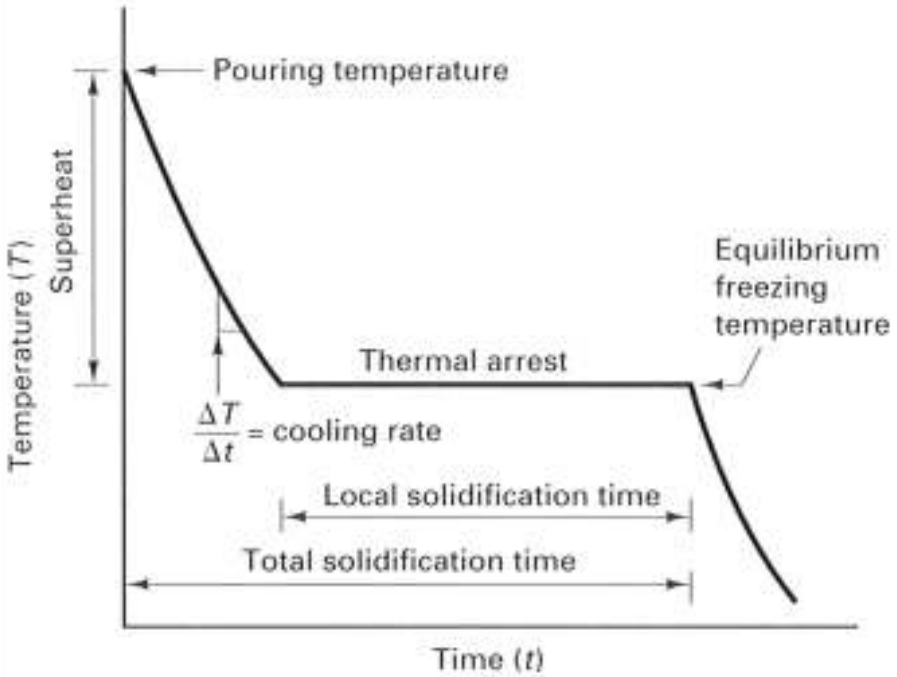
- Each nuclei grows to form grain (crystal) so in given volume, more nuclei means smaller final grain size
- Products with smaller grains have better mechanical properties generally (except creep).
- Innoculation - Deliberate addition of small impurity particles (that do not melt) to provide many sites for nucleation and give grain refinement.

Solidification/Freezing

- Growth - as mould extracts heat, liquid cools, nuclei grow in size (+ more formed) and eventually consume all liquid metal to form solid
- Direction, rate and type of growth can be controlled by the way heat is removed
- Faster cooling tends to give less time for growth (more nucleation) and so gives finer grains usually.

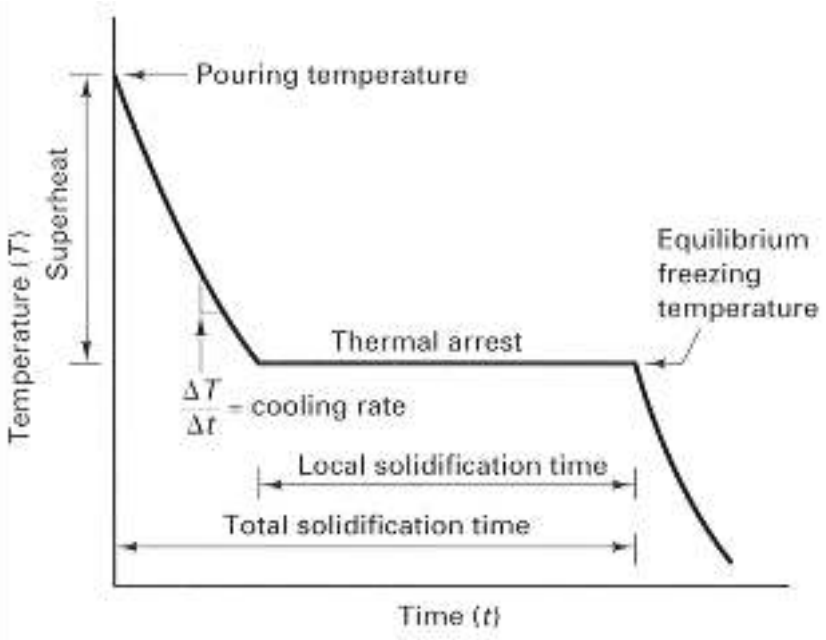
Cooling Curves

- Study temperature of cooling metal:- thermal analysis
- Insert thermocouples into casting and study the temperature vs time
- Superheat is the heat above melting point
- More the superheat, more time for metal to flow into difficult places before freezing



Cooling Curves

- Cooling rate is the rate at which liquid solidifies. It is the slope of the cooling curve at a given point $\Delta T/ \Delta t$
- At thermal arrest heat is being removed from the mould comes from latent heat due to solidification
- Pure metals & eutectics show thermal arrest at T_m (plateau)
- From pouring to solidification is the total solidification time
- From start to end of solidification is local solidification time



Cooling Curves

- Alloys (non-eutectic) usually have freezing range; change in slope of $\Delta T/\Delta t$.
- Now the solidification appears as a slope in the curve

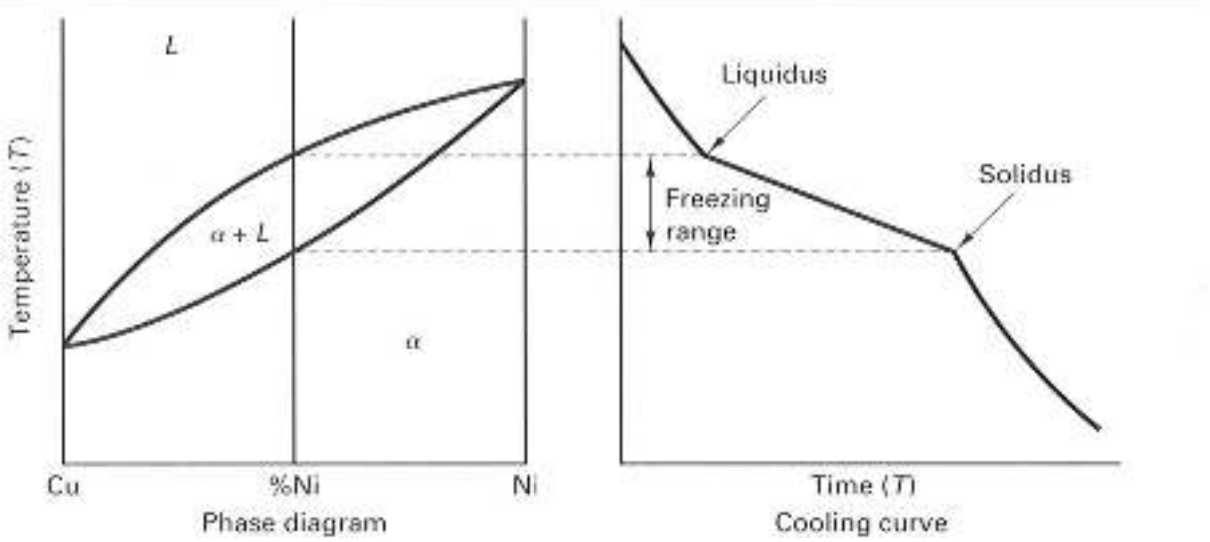


FIGURE 13-4 Cooling curve of an alloy that has a freezing range. Slope changes indicate the onset and termination of solidification.

Cooling Curves

- If undercooling required for nucleation, heat of fusion increases the temperature back to melting point this is recalescence
- Specific form of cooling curve depends on the material poured, type of nucleation, and rate and means of heat removal from mould
- Faster cooling rates and short solidification times lead to materials with finer grains and better mechanical properties

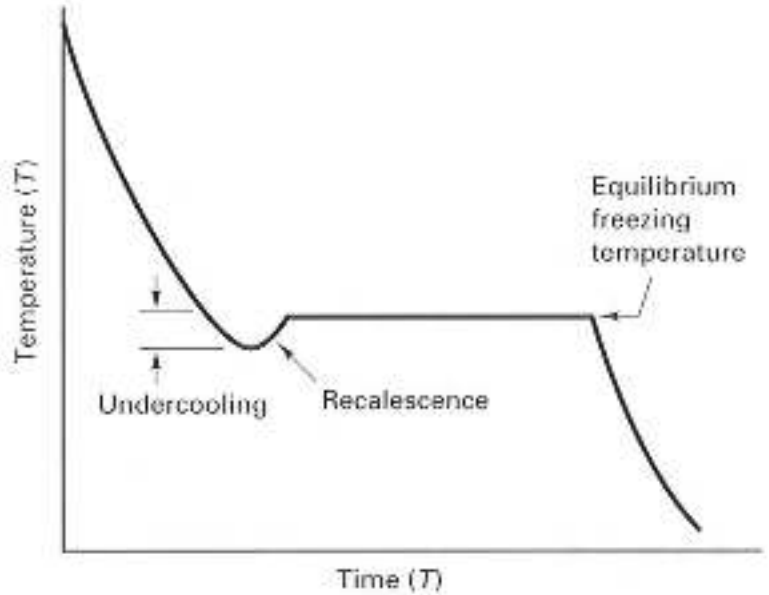


FIGURE 13-5 Cooling curve depicting undercooling and subsequent recalescence.

Solidification Time: Chvorinov's Rule

- Amount of heat that must be removed from a casting for solidification depends on the amount of superheat on the pouring metal and volume of metal in the casting.
- The ability to remove that heat depends on the exposed surface area through heat can be extracted and the surrounding environment to the molten metal.
- Taking these into account, chvorinov came out with a prediction for solidification time

Solidification Time: Chvorinov's Rule

t_s = total solidification time

n = constant (1.5 - 2.0)

V = volume of casting

A = surface area of casting

$$t_s = B\left(\frac{V}{A}\right)^n$$

B = mould constant (dependent on metal, mould material etc - density, heat capacity, thermal conductivity etc).

- Establish B by casting test specimens for a given mould material under particular conditions

Solidification Time: Chvorinov's Rule

- This value can be used for computing T_s of other castings under similar conditions
- Since riser and casting are of same metal and in same condition, use the rule to compare solidification time for riser and casting
- then use rule to design casting so that casting solidifies before riser
- This is a must as the riser will then feed the solidifying casting

Cast Structure

- Structure depends on metal/alloy, cooling rate, additions etc.
- **Chill zone** - Narrow band randomly oriented along surface (touching mould) due to rapid cooling due to nucleation
- As heat removed, grains grow inwards, process slows down
- Preferred growth of grains with fast growth direction oriented with heat flow.

FIGURE 13.6 Cross-sectional structure of a cast metal bar showing the chill zone at the periphery, columnar grains growing toward the center, and central shrinkage cavity.

Cast Structure

- **Columnar zone** – at the end of chill zone as the rate of heat extraction reduces, By selection processes grains growing in other directions are stopped, only favorably oriented ones grow
- Grains grow longer and towards the center
- Not very desirable (anisotropic properties, large grains).

Cast Structure

- **Equiaxed zone** – in many materials nucleation takes place inside the casting and this can grow to form spherical randomly oriented crystals.
- low superheat, alloying, inoculation can promote this
- This produces structures with isotropic (uniform in all directions) properties
- Preferable structure

Molten Metal Problems

- Liquid metals tend to be REACTIVE. (Atmosphere, crucible, mould etc) could produce defects in castings
- Metal + Oxygen $\rightarrow$ Metal Oxide which is knows as dross or slag can be trapped inside casting, and affect
  - surface finish
  - machinability
  - mechanical properties (strength, fatigue life etc.)
- Material from sand, furnace lining, pouring ladle contribute to dross or slag

Molten Metal Problems

- Dross or slag can be controlled by good foundry practice
- Use FLUXES to cover surface and prevent reactions.
- Melt under VACUUM (some alloy steel), or INERT ATMOSPHERE (titanium).
- Let oxides float on surface; take liquid metal from below so that the oxide stays back and does not go into the casting. (figure 13.7)
- Use ceramic filters to trap particles.
- Gating system designed to trap particles as well

Molten Metal Problems

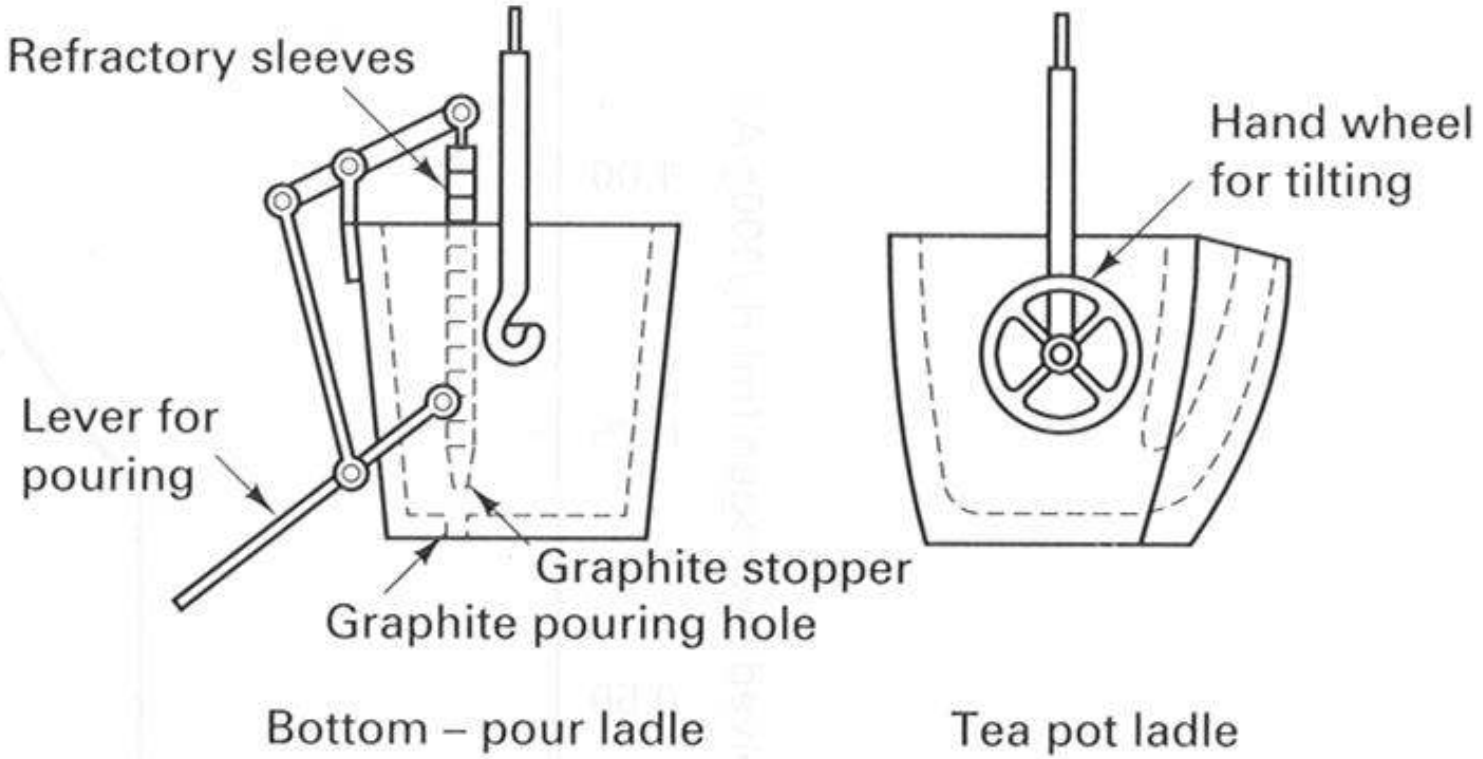


FIGURE 13.7 Two types of ladles used in the pouring of castings. Note how each avoids pouring the impure material from the top of the molten pool.

Molten Metal Problems

- **Gas Porosity** – liquid metals contain dissolved gas. more gas (hydrogen, oxygen, etc.) can dissolve in liquid metal than solid
- When metal solidifies, gas comes out of solution to form bubbles – gas porosity
- Bad for mechanical properties, gas tightness, surface finish after machining etc.

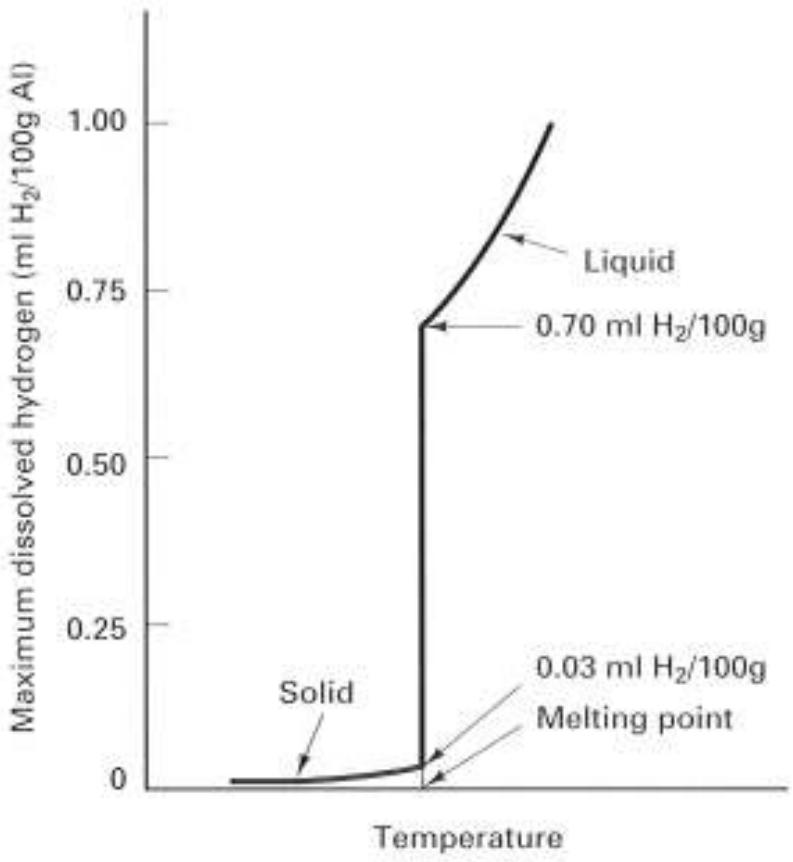
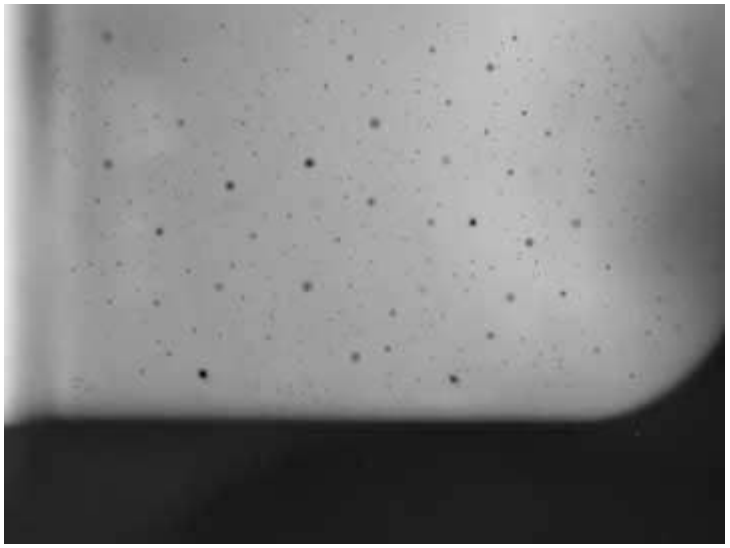


FIGURE 13-8 Maximum solubility of hydrogen in aluminum as a function of temperature.

Molten Metal Problems



- Prevention of gas porosity can be done using different techniques
  - Prevent gas entering liquid metal
    - Melt under vacuum.
    - Melt in inert gas or under flux coating to prevent atmospheric contact
    - Minimize superheat to minimize gas solubility
    - Reduce turbulence, splashing etc during pouring. Streamline the flow

Molten Metal Problems

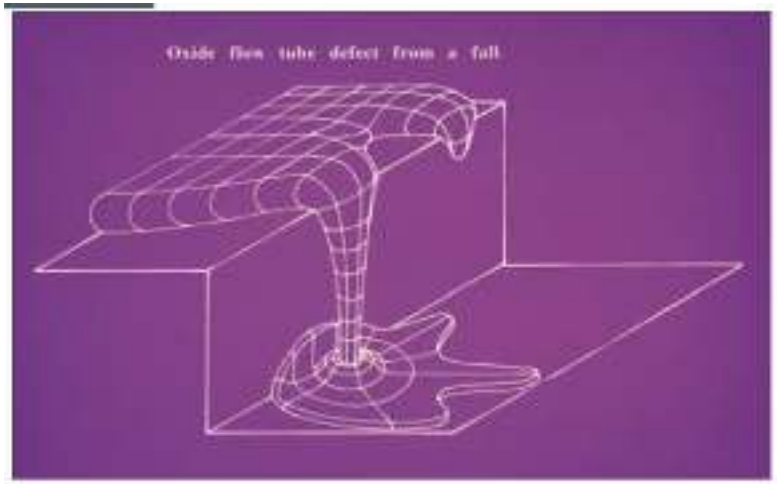
- Remove dissolved gas from molten metal before pouring.
  - Vacuum degassing - spray molten metal through low pressure environment
  - Gas flushing – passing small bubbles of inert or reactive gas (nitrogen, argon, chlorine in Al). Dissolved gas enters this flushing gas and is carried away.
  - React with gas to form low density solid (slag/dross) e.g. Al or Si to deoxidize steel, Phosphorous in copper to remove oxygen. The oxides stay on top of the molten metal and can be removed by skimming

Surface Films

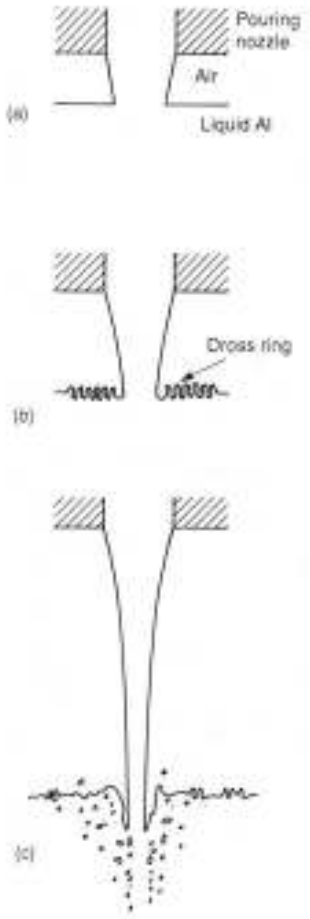
- Some gases enter liquid and diffuse into bulk (hydrogen in al) but some react to form surface films.
  - Usually from reaction with oxygen, moisture, hydrocarbons.
- Tin, gold, platinum usually free of films
- Lead - forms pbo on surface. Interferes with soldered joints (“dry” joint - non-wetting) use fluxes/pre-tinning/non-lead solders.
- Ductile cast iron - more difficult than gray cast iron due to Mg.
- High Temp. alloys (many elements which can form oxides Al etc.)

Surface Films

- POURING -This should be carried out to minimize turbulence.
  - Prevent entrainment of oxide film
  - Prevent further reaction/oxidation/gas entrainment.
- Low pouring height.
- Use filters.
- Casting rate must not be:
  - too slow; laps, folded surface films.
  - too fast; jetting, surface turbulence.



Surface Films



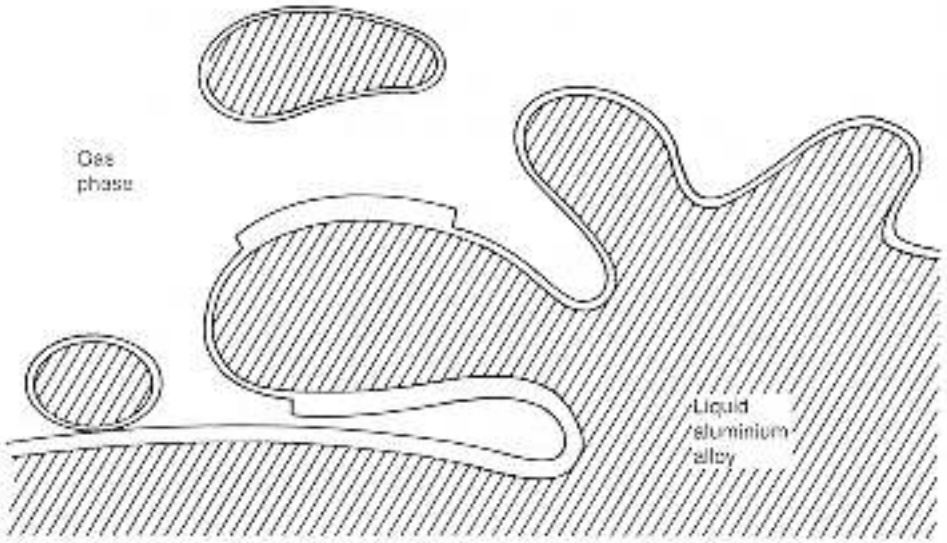


Figure 1.12 *A schematic view of a splash of molten aluminium showing the formation of a folded (double) film which might consist of thick old film, or new thin film, or both, all likely to occlude air in the folds.*

Figure 1.11 The effect of increasing height on a falling stream of liquid illustrating: (a) the oxide film remaining intact; (b) the oxide film being detached and accumulating to form a dross ring; and (c) the oxide film and air being entrained in the bulk melt.

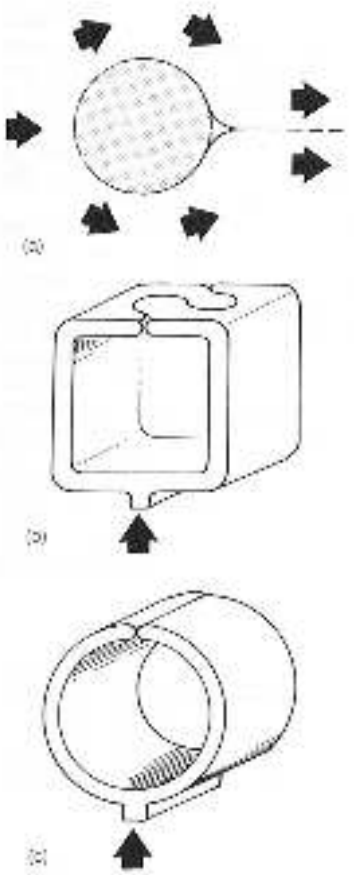


Figure 1.14 Confluence geometries: (a) at the side of a **round core; (b) randomly irregular join on the top of** a **bottom-gated box; and** (c) a **straight and reproducible join on the top of** a **bottom-gated round pipe** (**Campbell, 1988)** .

Effect of Surface Films

- Machining - Oxide particles in Al alloys and steels drag out and leave grooves.
  - Tool tip is blunted

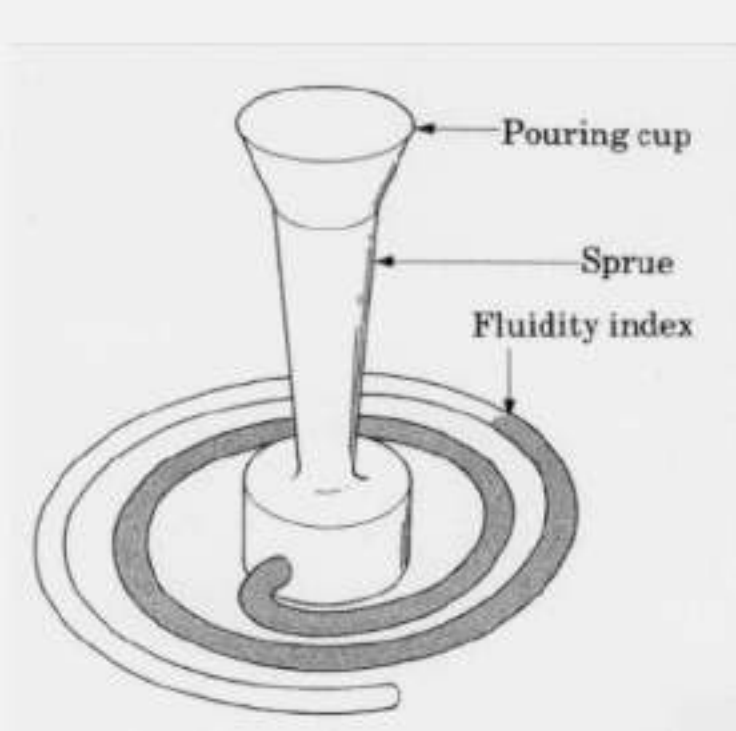
- Defects - Entrapped folded oxide films are “cracks” in the liquid and carried into casting.
- Leak-tightness - leaking through walls of thin casting is due to collections of defects such as entrapped films. Reduces pressure-tightness of casting (eg. Cylinder heads etc).

Effect of Surface Films

- Mechanical Properties
  - increases scatter in property values, reduced fatigue resistance.
- Fluidity
  - “Cleaner” melts are more fluid and can be cast at lower temps.
  - Repeated remelting/stirring of melt can cause problems if oxide not removed.

Fluidity

- require good flow of molten metal to all parts of the mould and freeze in required shape - in proper sequence
- If freezing before filling defects (misruns & cold shuts) occur
- Ability of the metal to flow is fluidity and this affects the minimum section thickness of cast, length and fine details
- Measure of fluidity by standard castings



Pouring Temperature

- Fluidity depends on composition, melting point and freezing range and surface tension of oxide films
- Pouring temperature affects fluidity (superheat)
  - high enough for good filling
  - too high - penetration into mould wall (sand mould)
- affects interactions
  - between metal and mould
  - between metal and atmosphere

Gating Systems

- Gating system distributes molten metal to all parts of cavity
- Speed of filling is important
  - Slow – misruns and cold shuts (material solidifies before filling)
  - Fast – erosion of gating or mould cavity and entrapment of mould material in the casting
- CSA of various channels can regulate flow shape and length can control heat loss (short channels with round CSA work well)
- Attached to heaviest section of casting to avoid shrinkage and to the bottom to avoid turbulence and splashing

Gating Systems

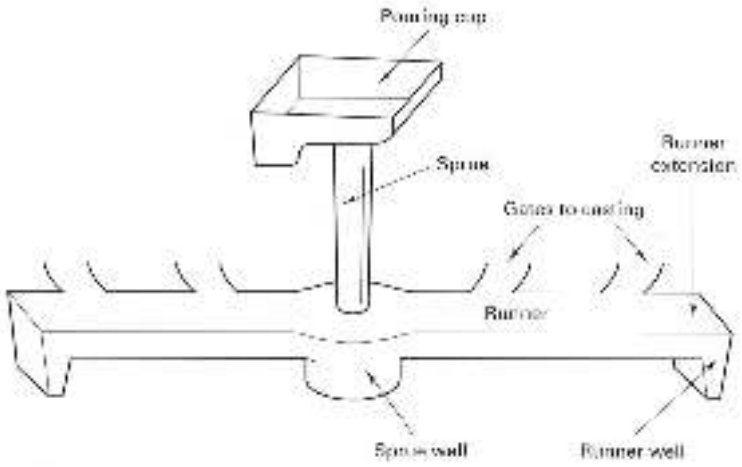


FIGURE 13-9 Typical gating system for a horizontal parting plane mold, showing key components involved in controlling the flow of metal into the mold cavity.

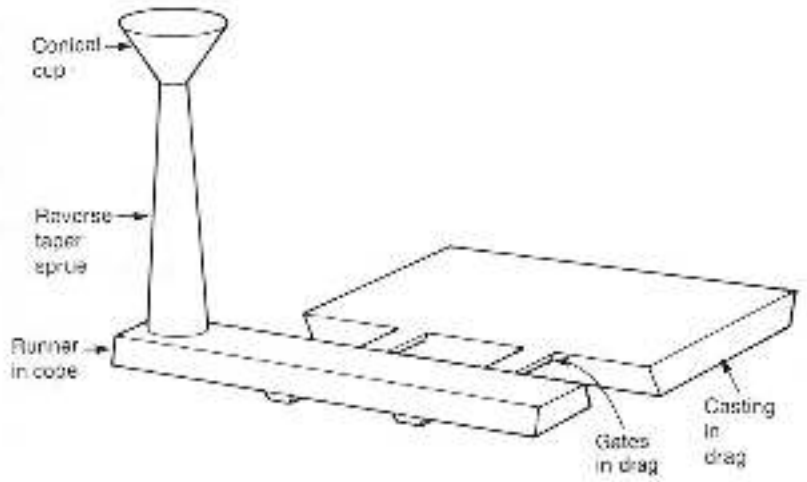


Figure 2.3 *A poor running system.*

- Short sprues – reduce kinetic energy, avoid splashing
- Rectangular cups – prevent vortex or turbulence while pouring
- Sprue well – dissipate energy and prevent splashing
- Choke – smallest CSA in the sprue to regulate metal flow rate, if it is above, the metal enters the runner without control (turbulence)

Gating Systems

- Choke – located near the base, flow through runner is smooth, and smaller CSA allows easier removal from casting
- Gating can also prevent dross from entering the cavity. Long flat runners with more time for dross to raise will do it, but material will cool faster
- Generally first metal contains dross and it can be trapped in well
- Ceramic filters can be added to trap dross and other foreign bodies from entering the mould cavity as well

Gating Systems

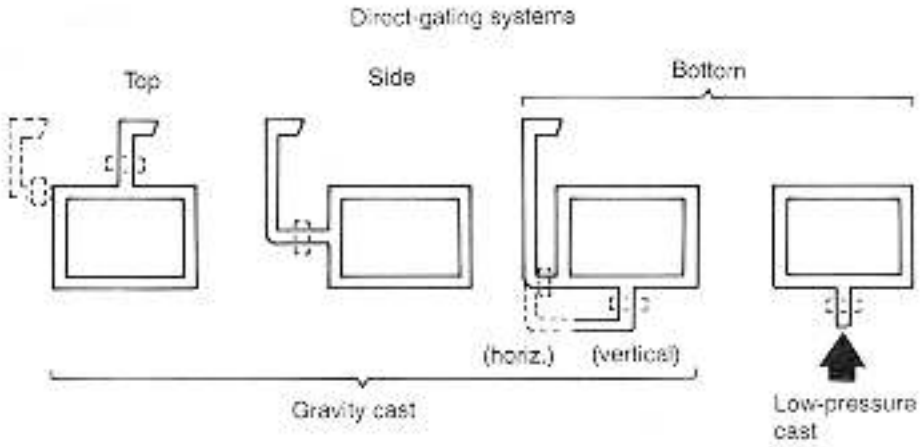


Figure 2.5 *Various direct gating systems applied to a box-shaped casting. Possible filter positions are shown as dashed outlines. (Note that all of the gravity systems shown here are poor: the sprue base connects directly with the ingate into the casting. All need a well, runner, and gate system, which is omitted for clarity.)*

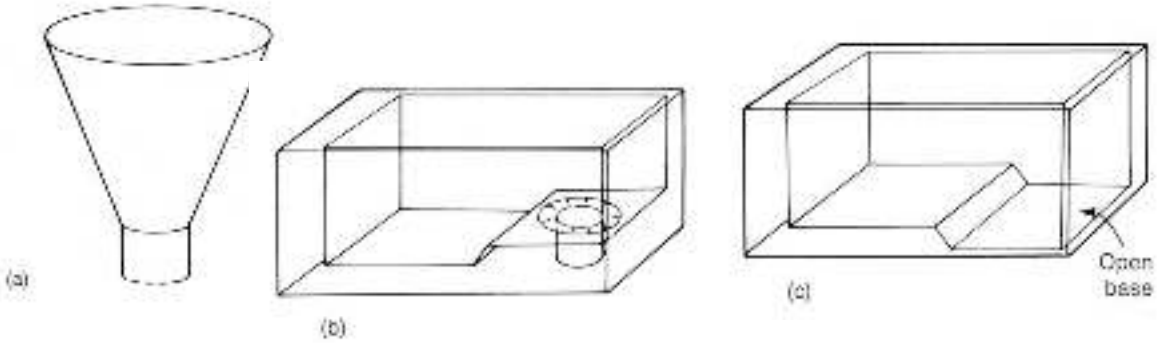


Figure 2.8 (a) A simple funnel pouring cup, not recommended in general; (b) a weir bush of excellent design, whose upward circulation will assist in the separation of slag and dross, but which would need to be carefully matched to the entrance diameter of the sprue in the cope; and (c) an offset bush with an open base recommended for general use.

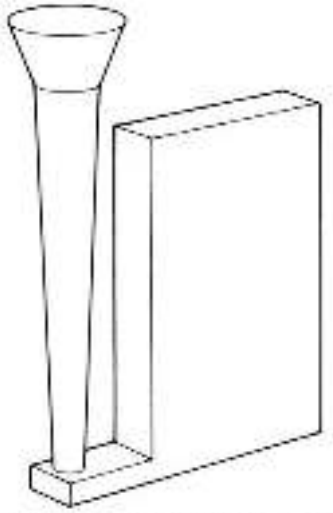


Figure 2.6 *A poor bottom-gated system.*

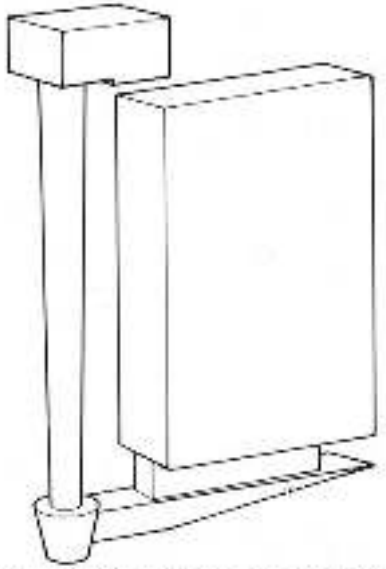


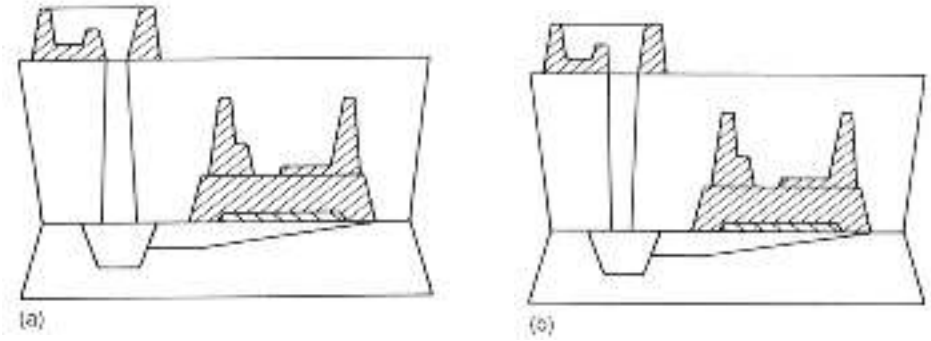
Figure 2.7 *An improved bottom-gated system.*

Gating Systems

Figure 2.13 A cross-section of a self-moulding sprue

a) formed integrally with the pattern, - requires 'draw' negative taper. Bad design

b) A properly tapered sprue, pattern needs to be detachable, and be withdrawn from the back



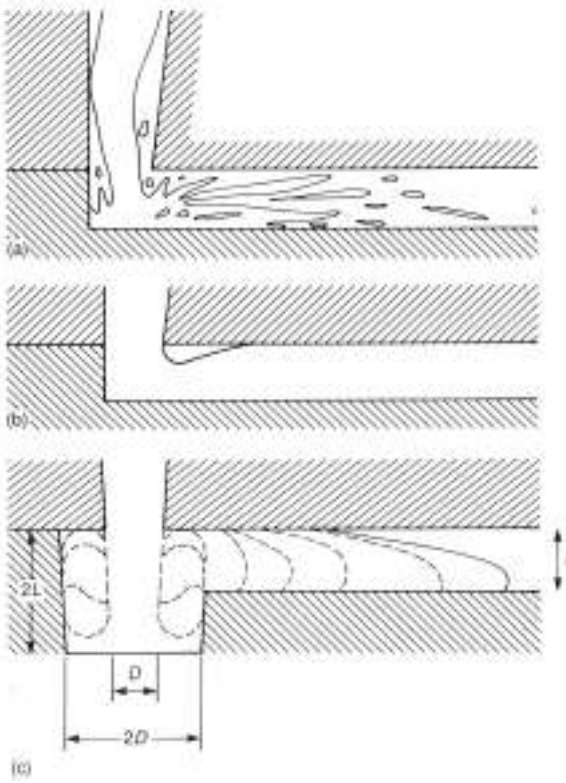


Figure 2.14 Various sprue base designs

a) the first splash problem - direct linking of sprue to runner;

b) steady-state vena contracta problem which cause air to enter the stream

c) a well base, avoiding the worst effects of the first splash and the vena contracta problems.

Gating Systems

- Liquid metal should flow into cavity smoothly
- Different gate designs depending on shape
- Gates can trap dross and slag
- Turbulent sensitive metals (Al & Mg) and low mp metals use systems to prevent turbulence
- Turbulent insensitive metals (cast irons, some copper alloys) and high mp metals use short systems for quick filling

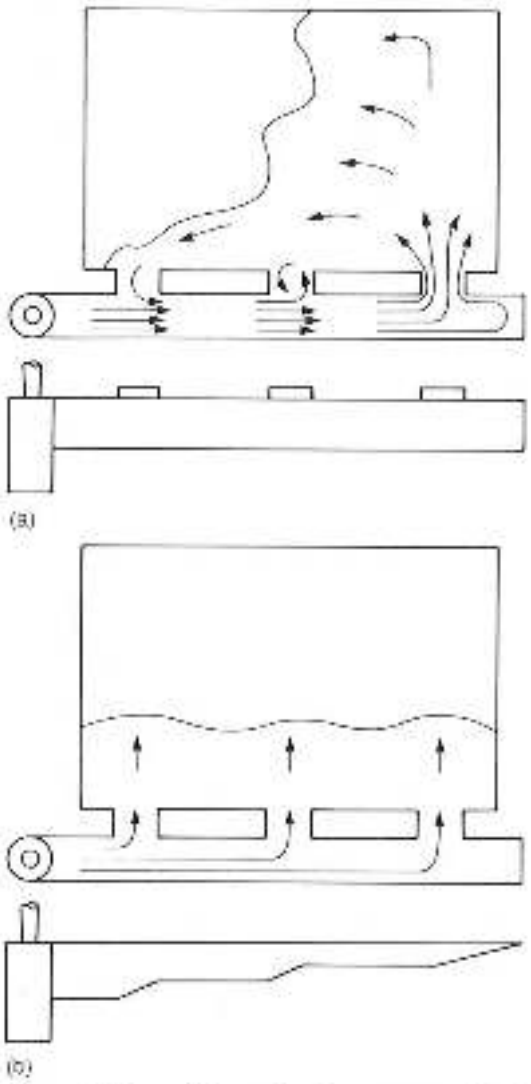


Figure 2.15 *An unbalanced gating system resulting from (a) an incorrect runner design and (b) a tolerably balanced system.*

Gating Systems & Filters

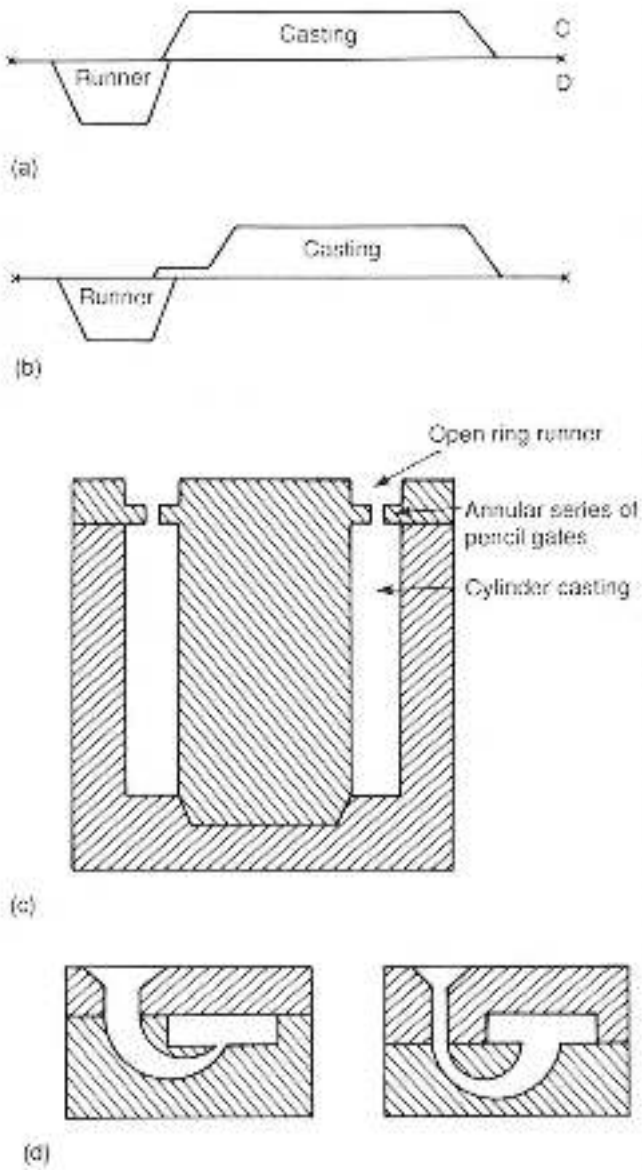


Figure 2.19 *The touch gate (a), knife gate (b), pencil gate (c), and normal and reversed horn gates (d).*

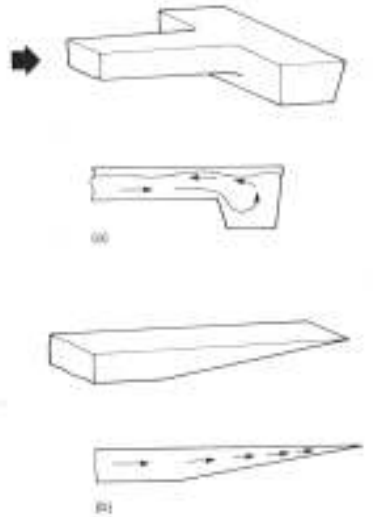


Figure 2.26 *A dross trap of traditional design showing: (a) the backward eddy which defeats the purpose of the trap; and (b) a more effective wedge trap.*

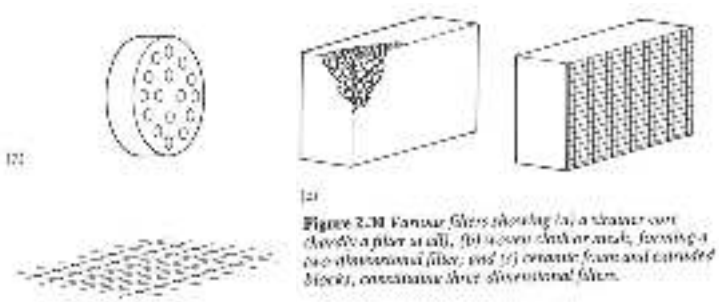


Figure 2.30 *Various filters showing (a) a strainer core (needle a filter at all), (b) woven cloth or mesh, forming a two-dimensional filter; and (c) ceramic foam and extruded blocks, constituting three-dimensional filters.*

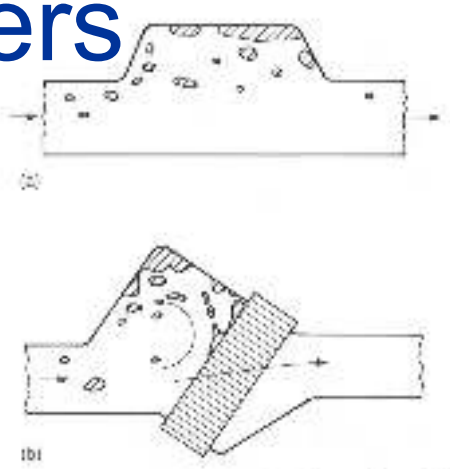


Figure 2.33 *(a) A slag pocket, (b) a slag pocket sited just upstream of a block filter.*

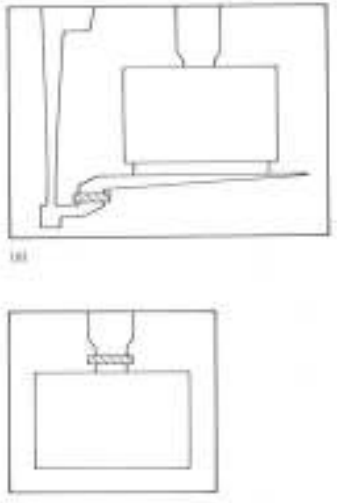


Figure 2.32 *Sizing of block filters in: (a) a classical running system in which filling will be good but feeding will be less efficient, and (b) a direct top pouring system. The direct top filling may be tolerable in some cases, since the inferior filling may be countered to some extent by the superior feeding.*

Gating System Design

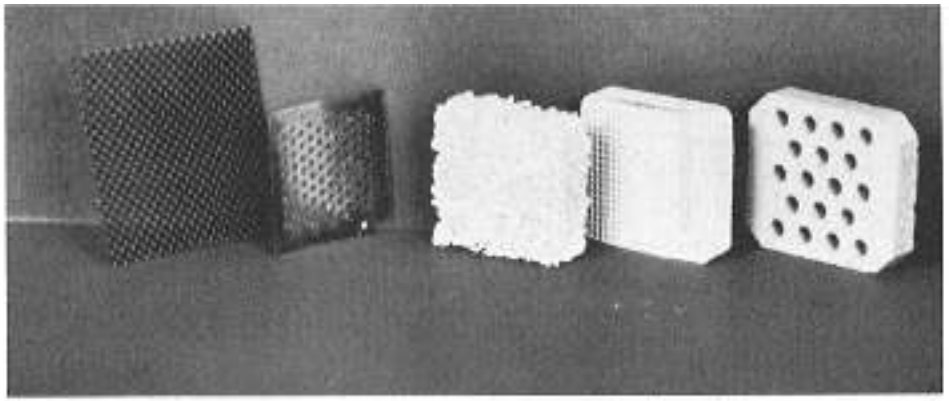


Fig. 14 Several common filtration and flow modification devices (from left to right): strainer core, extruded ceramic filter, ceramic foam filter, mica screen, and woven fabric screen. The two types of ceramic filters are by far the most widely used.

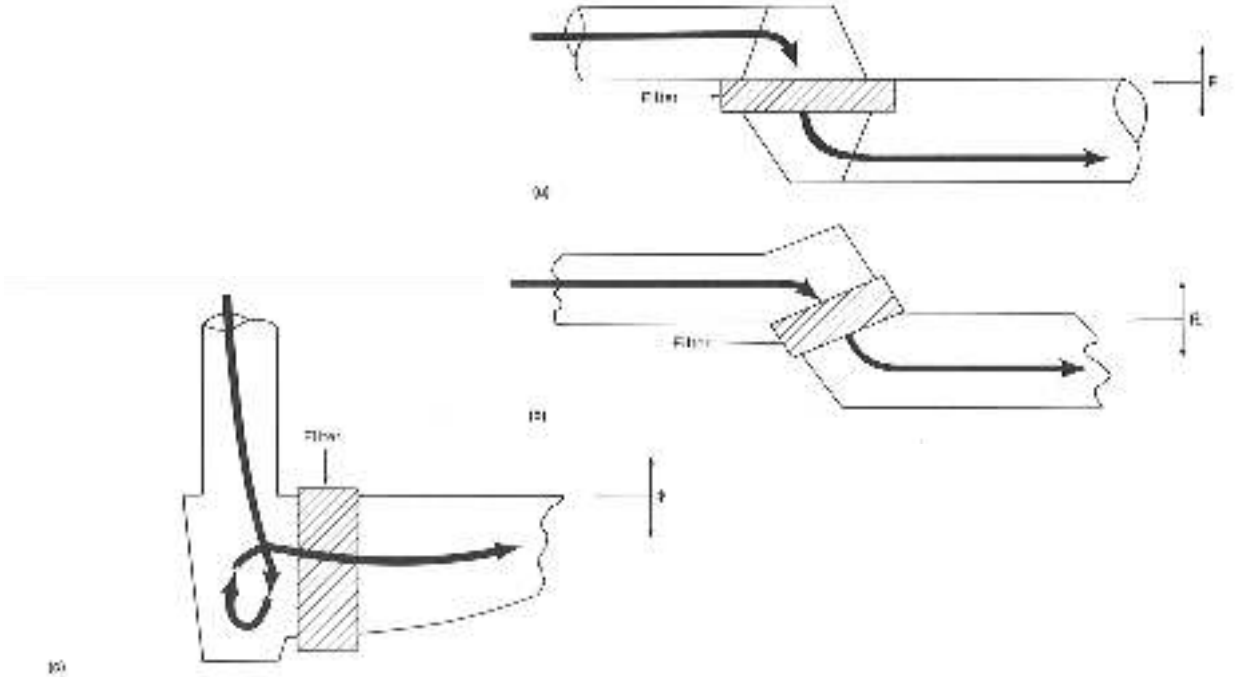


Fig. 16 Common methods of filter placement in horizontally parted molds: (a) Parallel to parting line; (b) Between 0 and 90° to parting line; (c) 90° to parting line. Arrows indicate the direction of metal flow.

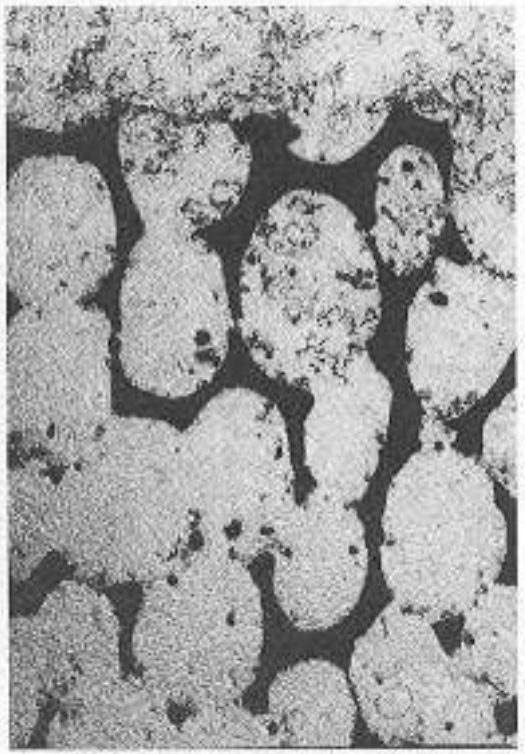
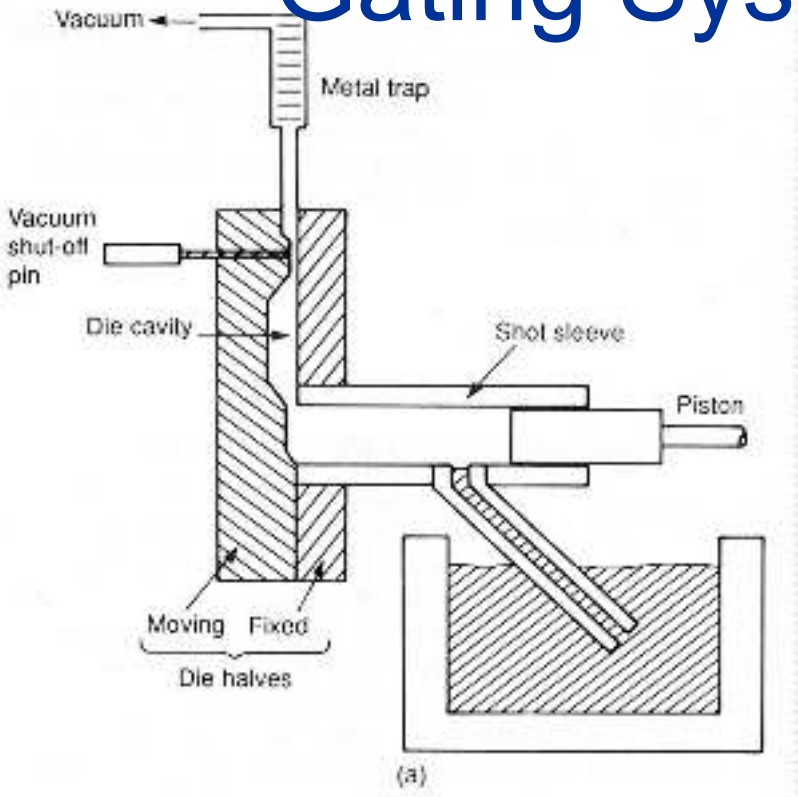


Fig. 15 Cross section through a runner bar containing a ceramic foam filter. Particle capture occurs at the front face (top) and inside the filter. The alloy is aluminum-base LM25.

Gating Systems - Pressure



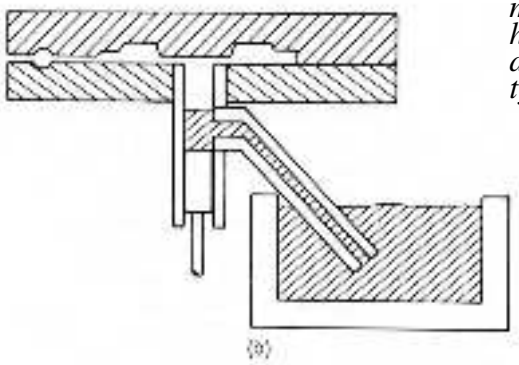
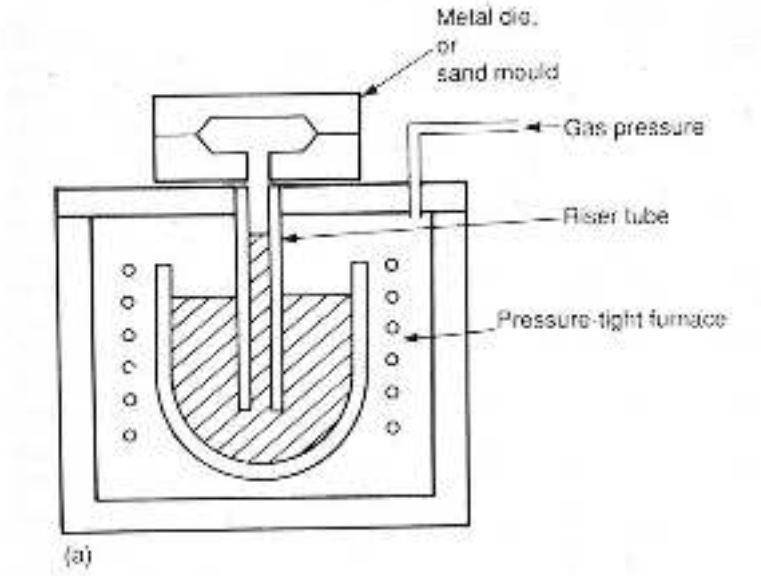


Figure 2.39 *Vacuum delivery systems to pressure die-casting machines for (a) a horizontal cold chamber; and (b) a vertical injection type.*



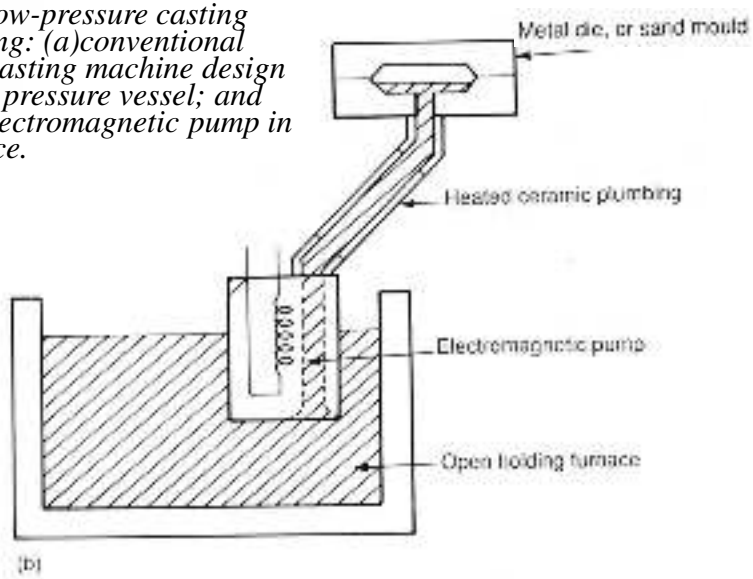


Figure 2.40 *Low-pressure casting systems showing: (a)conventional low-pressure casting machine design using a sealed pressure vessel; and (b) using an electromagnetic pump in an open furnace.*

Gating Systems - Gravity

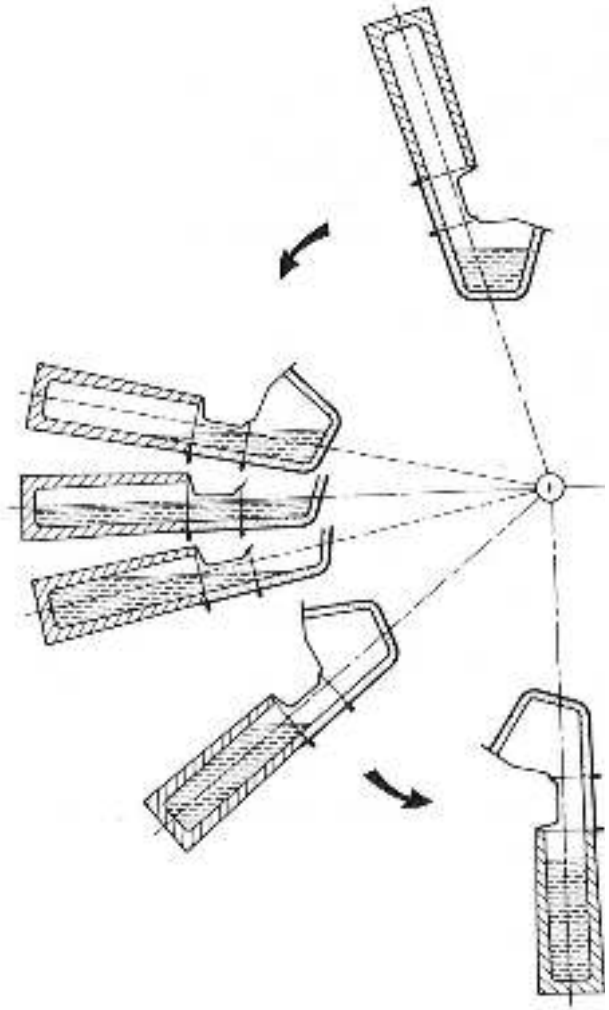
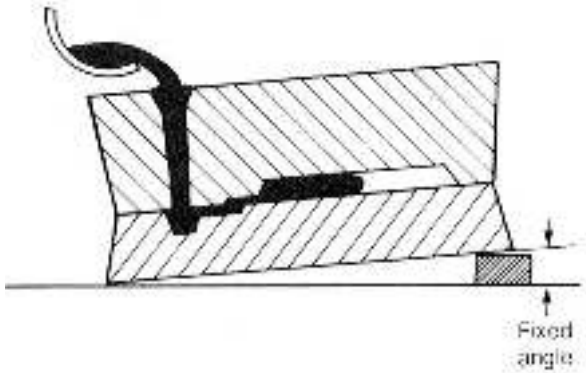


Figure 2.43 *Stages of casting using the Durville process. From Genders and Bailey (1934).*



igure 2.42 *Bottom-gated inclined plate.*

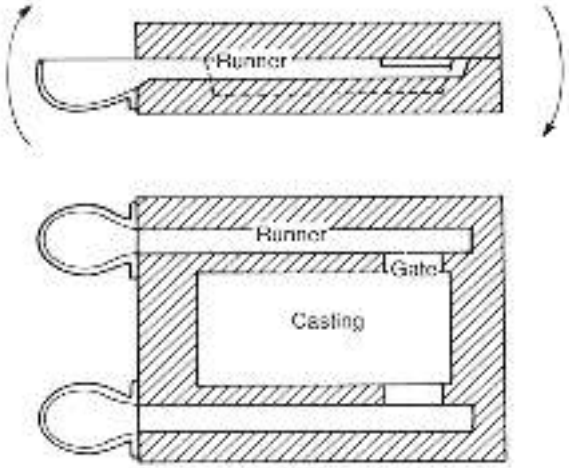


Figure 2.44 *Stahl tilt-pour system (an improved arrangement would have the mould cavity mainly in the upper die half if vents for the remaining entrapped air can be provided).*

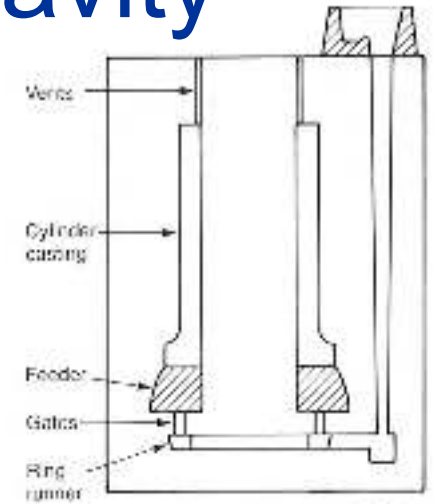


Figure 2.45 *Cylinder casting arranged for inversion casting. Adapted from Batty (1935), with mould and core assembly details omitted for clarity.*

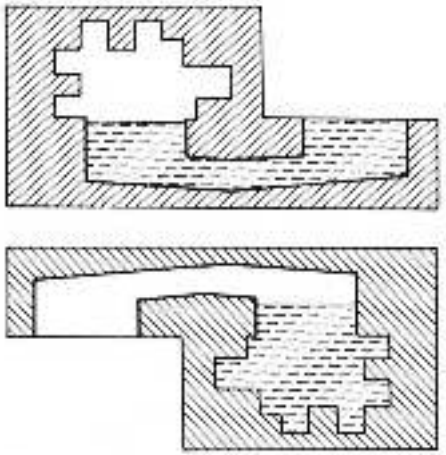


Figure 2.46 *Inversion casting of a gravity die, showing the start and finish stages. A thicker insulating wash over the running areas reduces heat loss from the liquid metal. After Butler (1980).*

Solidification Shrinkage

- Three stages of shrinkage (volumetric contraction)
  - Shrinkage of the Liquid (not usually a problem)
  - Solidification Shrinkage as liquid turns to solid
  - Shrinkage of the solid as it contracts while cooling to room temperature
- Depends on co-eff of thermal contraction and superheat
- Liquid contraction can be compensated by liquid in the gating system
- While material changes from liquidus to solidus state, shrinkage can occur, depends on the metal or alloy (not all metals shrink)

Solidification Shrinkage

Solidification Shrinkages (%) of some common engg. metals

Aluminum	6.6
Copper	4.9
Magnesium	4.0
Zinc	3.7
Low-carbon steel	2.5-3.0
High-carbon steel	4.0
White cast iron	4.0-5.5
Gray cast iron	-1.9

- Need to control shrinkage void
- Short freezing range metals and alloys tend to form large cavities or pipes (Al ingots)
  - design these to have void in riser (feeder)
- Alloys with long freezing ranges have mushy zone. Difficult to feed new liquid into cavity. Dispersed porosity results, poor properties
- Patterns need to compensate for shrinkage when solid gets to room temperature

Solidification Shrinkage

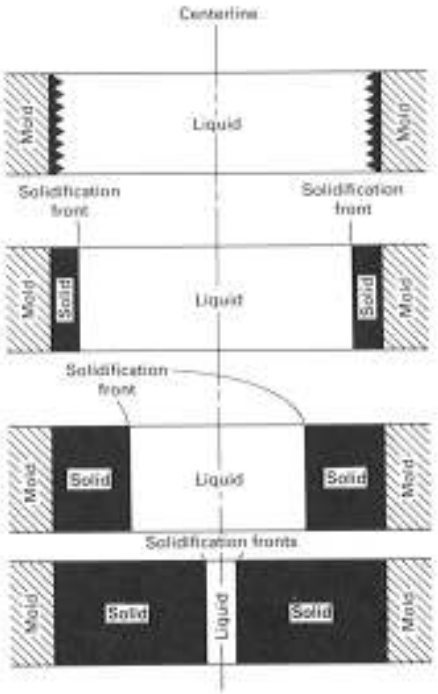


Fig. 5 Schematic of mode of freezing in pure metals. Crystallization begins at the mold wall and advances into the casting interior as a plane solidification front. Source: Ref 11

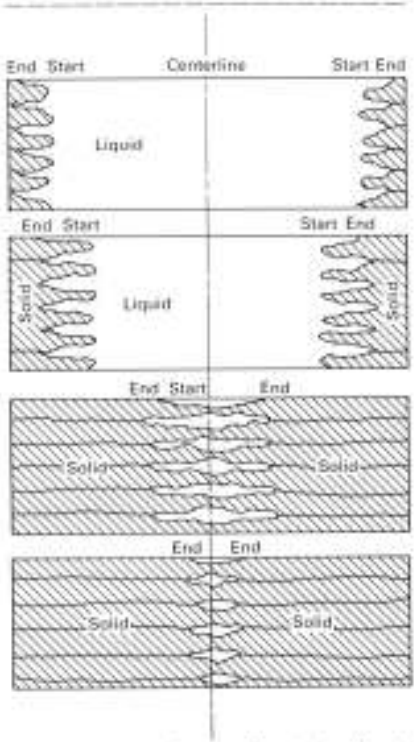


Fig. 6 Diagram of mode of freezing in alloys having a short freezing range

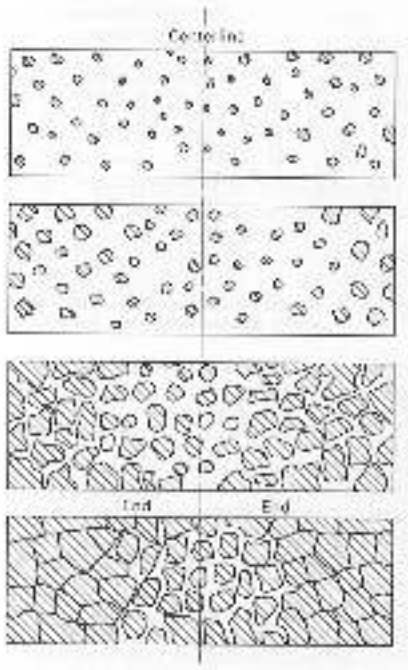


Fig. 7 Schematic of mode of freezing in alloys having a long freezing range

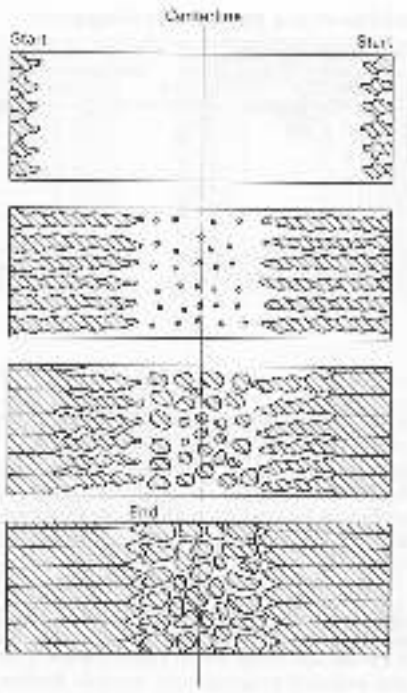


Fig. 8 Schematic of intermediate mode of freezing in alloys having a moderate freezing range

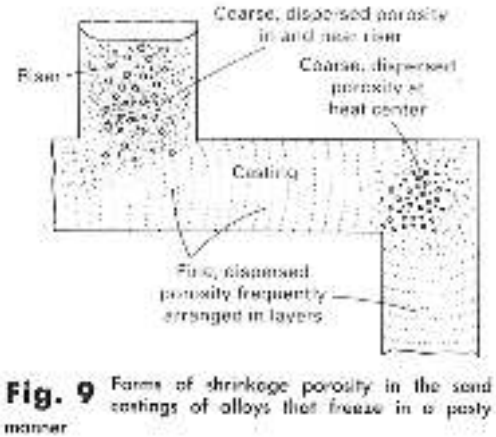


Fig. 9 Forms of shrinkage porosity in the sand castings of alloys that freeze in a pasty manner

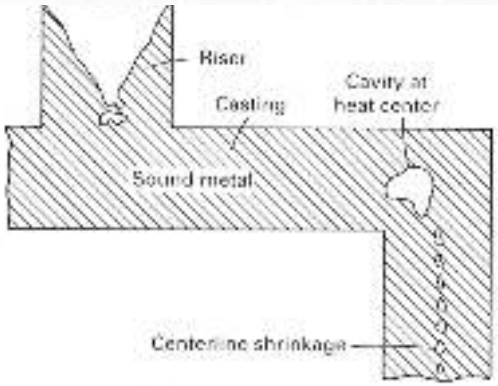


Fig. 10 Shrinkage cavities produced by skin formation in alloys

Solidification Shrinkage

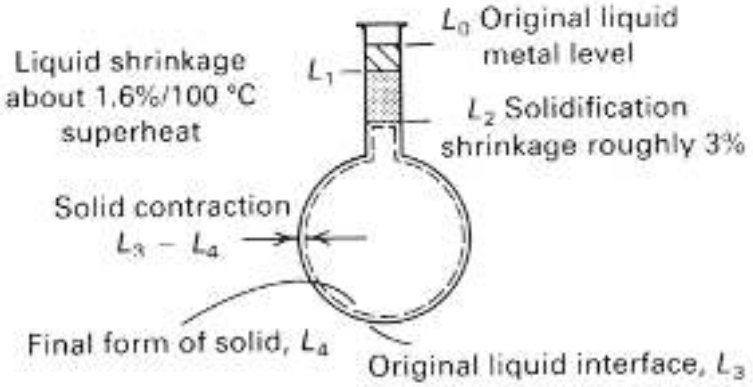


Fig. 1 Schematic of the shrinkage of low-carbon steel. The contribution of each one of the three distinct stages of volume contraction is shown: liquid shrinkage, solidification shrinkage, and solid contraction. Source: Ref 1

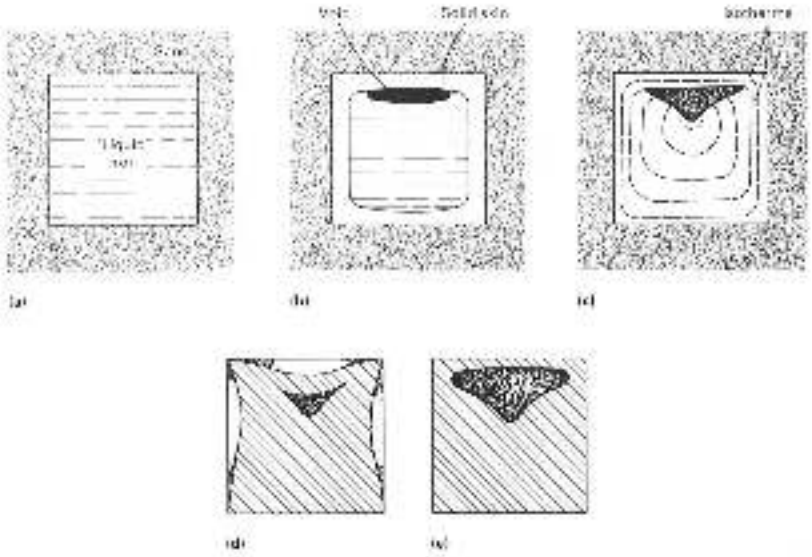


Fig. 2 Schematic of sequence of solid-liquid shrinkage in an iron alloy. (a) Initial liquid metal. (b) Solid skin and formation of shrinkage void. (c) Internal shrinkage. (d) Internal shrinkage plus skin. (e) Surface pipe

- Eject casting immediately in die casting to avoid cracking ?

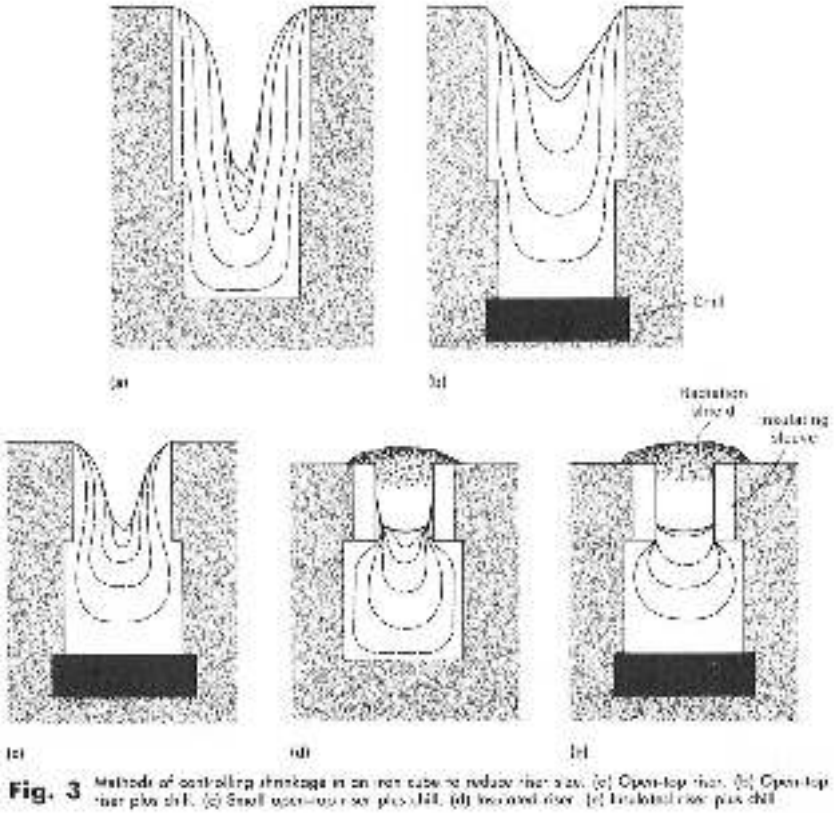


Fig. 3 Methods of controlling shrinkage in an iron casting to reduce riser size. (a) Open-top riser. (b) Open-top riser plus chill. (c) Small open-top riser plus chill. (d) Insulated riser. (e) Insulated riser plus chill

Risers and Riser Design

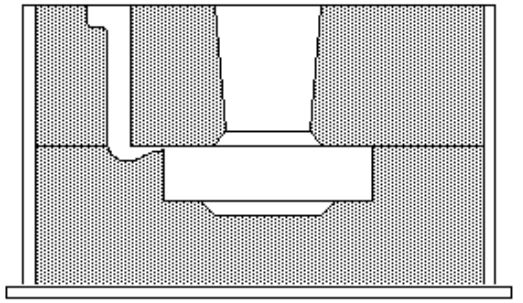
- Added reservoirs to feed liquid metal to solidifying casting.
- Aim to reduce solidification shrinkage & porosity.
- Filling & Feeding are different - Filling is quick, Feeding is slower
- Rules:

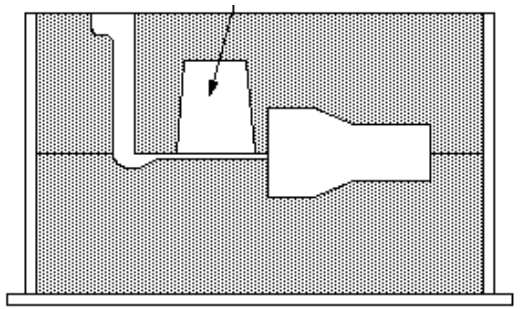
1. Feeder must NOT solidify before casting
2. Feeder must contain enough liquid to meet volume contraction requirements
3. Junction of feeder & casting should not form a “hot-spot”
4. There must be a path for liquid to reach required regions
5. Sufficient pressure differential to feed liquid in right direction

Risers and Riser Design

- Design casting to solidify directionally from extremities towards riser (sometimes multiple risers required).
- Design riser to feed properly WITH minimum metal (scrap) - sprue+gate+runner+riser+casting = total liquid metal required.
- Sphere is best theoretical shape (vol/S.Area is high) but impractical for casting. Cylindrical shape is common.
- Make modulus (V/A) of feeder > modulus of casting.
- Thickest sections are usually last to freeze so attach riser to them

Risers and Riser Design





- Top Riser - sits on top of casting (short feeding distance)
- Side Riser - sits next to casting
- Blind Riser - contained within mould (must be vented)
- Open Riser - top of riser open to atmosphere
- Live (hot) Riser - receives last hot metal poured (metal in mould already may have started to cool) – smaller than dead riser (part of gating system)
- Dead (cold) Riser - filled before or concurrent with cavity by metal that has flown through the mould. (top riser – dead riser)

Risers and Riser Design

$$t_s = B\left(\frac{V}{A}\right)^n$$

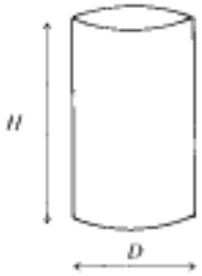
- Use Chvorinov's Rule.
- Mould constant, B is the same, Assume n = 2.
- Make riser take 25% longer to freeze, i.e.; $t_{riser} = 1.25t_{casting}$

$$\left(\frac{V_{riser}}{A_{riser}}\right)^2 = 1.25\left(\frac{V_{casting}}{A_{casting}}\right)^2$$

- Insert modulus of casting and then calculate riser size.
- Note: Only use riser areas that allow heat loss - discount common surfaces.
- Other methods exist.

Risers and Riser Design

Table 5.2 Moduli of some common shapes

Shape		*Modulus*			
		100% Cooled area		*Base uncooled*	
Sphere		$\frac{D}{6}$	$0.167D$	—	—
Cube		$\frac{D}{6}$	$0.167D$	$\frac{D}{5}$	$0.200D$
Cylinder	*H/D*				
	 1.0	$\frac{D}{6}$	$0.167D$	$\frac{D}{5}$	$0.200D$
	1.5	$\frac{3D}{16}$	$0.188D$	$\frac{3D}{14}$	$0.214D$
	2.0	$\frac{D}{5}$	$0.200D$	$\frac{2D}{9}$	$0.222D$
Infinite cylinder	∞	$\frac{D}{4}$	$0.250D$	–	–
Infinite plate		$\frac{D}{2}$	$500D$	–	–

- Modulus of common shapes
- Design should take into account if there is un-cooled based where the riser and casting share a surface
- Small - to reduce scrap and low modulus to solidify last

Risers and Riser Design

- Riser has to be removed from casting (as well as runner/gate)
- Make connection small - easier to cut off
- But if too small link freezes before feeding.
- Use short connections placing riser close to casting.

  Note: Risers are not always required. For alloys with large freezing ranges feeding does not work well - fine dispersed porosity is common.

- Die-casting, pressure casting, centrifugal casting pressure provides feeding action to compensate for freezing.

Risering Aids

- Methods developed for risers to perform their job
  - Promote directional solidification
  - Reduce the number and size of riser to increase yield
- Generally done by
  - Chills – speeding solidification of casting
  - Sleeves or Toppings – retard the solidification in riser

Risering Aids

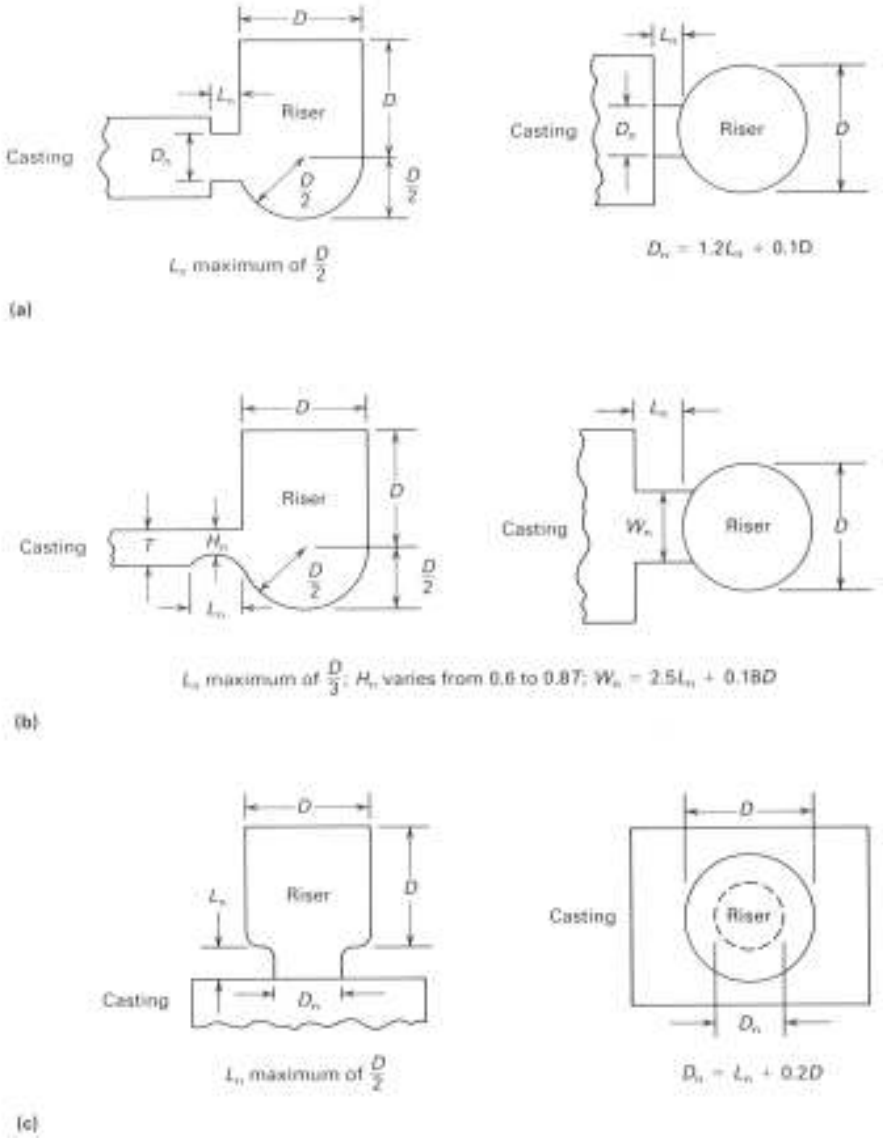
- CHILLS - External and Internal
- Aim to speed (directional) solidification of casting
- External Chills - chunk of high-heat-capacity, high thermal conductivity, material placed in mould wall next to casting to accelerate cooling and promote directional solidification. (Made from steel, graphite, copper) - reduce shrinkage defects.
- Internal Chills - Pieces of metal placed IN mould cavity to absorb heat and promote rapid solidification. Becomes part of casting ∴ same metal as casting.

Risering Aids

- To slow cooling of a riser:
  - Switch from Blind to Open riser
  - Place insulating sleeves and toppings on risers
  - Place exothermic material around feeder to add heat only around the riser

Risers and Riser Design

- General design rules for riser necks used in iron castings;
  a. general riser
  b. side riser for plates
  c. top round riser



Gating System Design

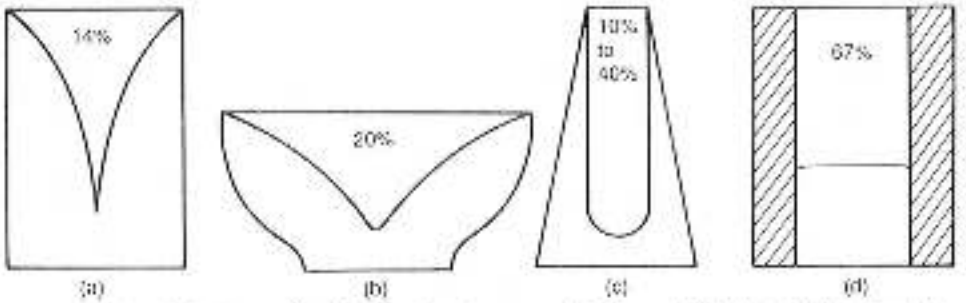


Figure 5.5 *Metal utilization of feeders of various forms moulded in sand. The (a) cylindrical and (b) hemispherical heads have been treated with normal feeding compounds; (c) the efficiency of the reverse taper heads depends on detailed geometry (Heine, 1982, 1983); (d) shows an exothermic sleeve (Beeley, 1972).*

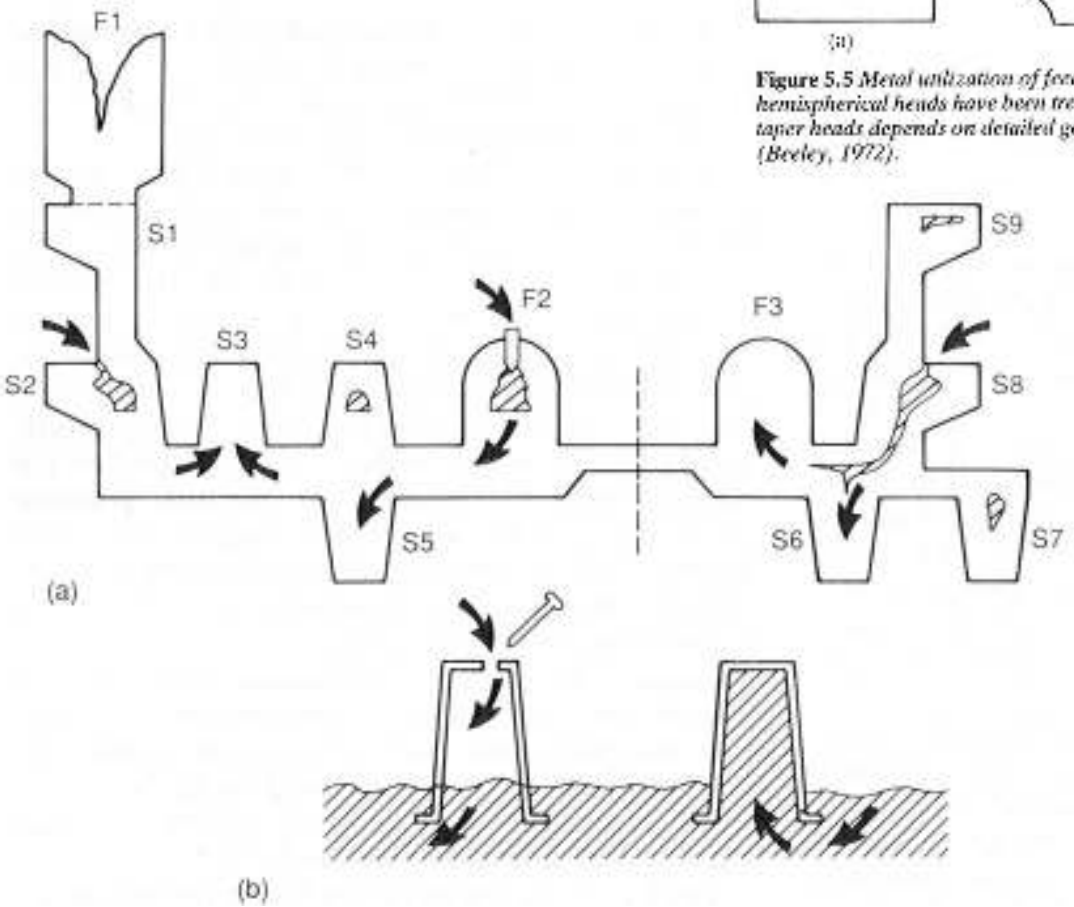
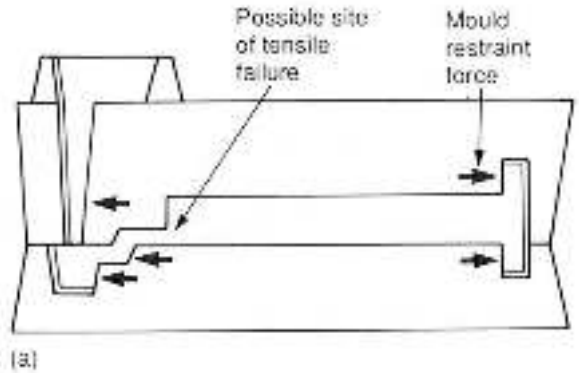


Figure 5.10 *(a) Castings with blind feeders, F2 is correctly vented but has mixed results on sections* S3 *and S4. Feeder F3 is not vented and therefore does not feed at all. The unfavourable pressure gradient draws liquid from a fortuitous skin puncture in section S8. The text contains more details of the effects. (b) The plastic coffee cup analogue: the water is held up in the upturned cup and cannot be released until air is admitted via a puncture. The liquid it contains is then immediately released.*

Gating System Design



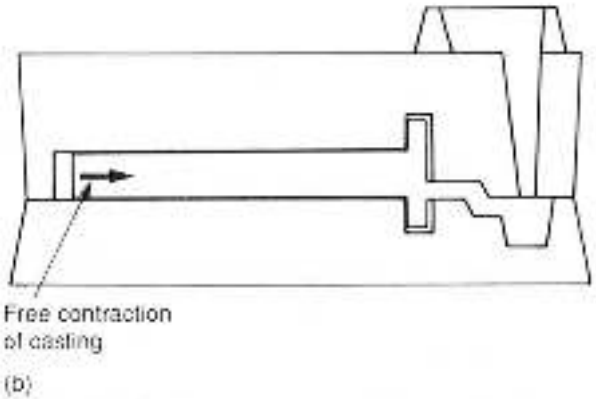


Figure 6.8 *(a) The effect of the running and feeding systems imposing constraint on the contraction of the casting. (b) Applying the running and feeding to the opposite end of the casting removes the problem.*

Figure 6.7 *The distortion of an open-sided box casting during cooling as a result of uneven mould constraint.*

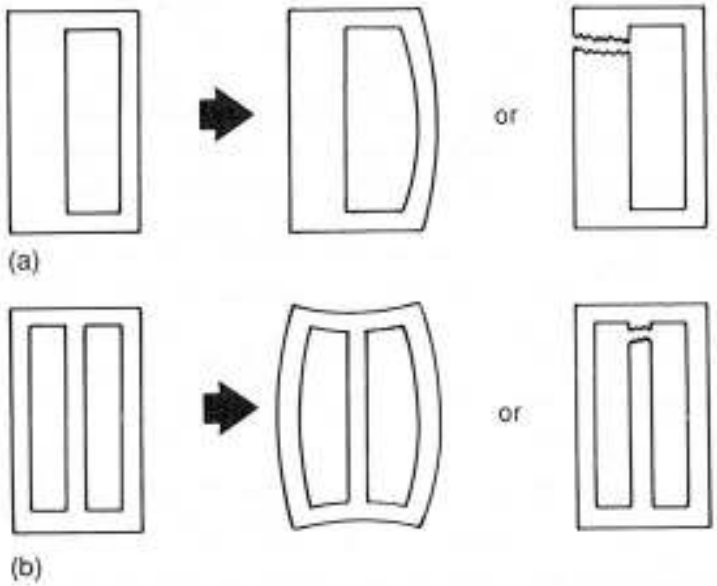


Figure 6.9 *(a) A thick/thin-section casting showing tensile stress in the thick section; (b) an even-walled casting showing internal tensile stress.*

Gating System Design

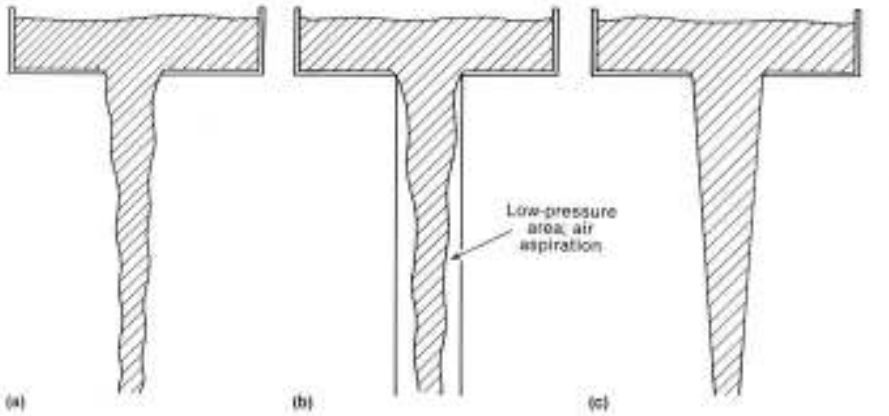


Fig. 3 Schematic showing the advantages of a tapered sprue over a straight-sided sprue. (a) Natural flow of a free-falling liquid. (b) Air aspiration induced by liquid flow in a straight-sided sprue. (c) Liquid flow in a tapered sprue

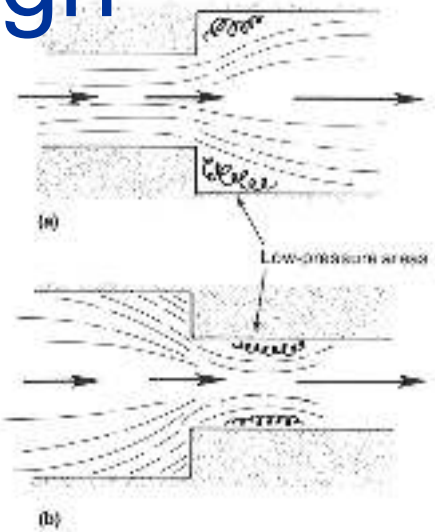


Fig. 6 Schematic showing the formation of low-pressure areas due to abrupt changes in the cross section of a flow channel. (a) Sudden enlargement of the channel. (b) Sudden reduction of the channel

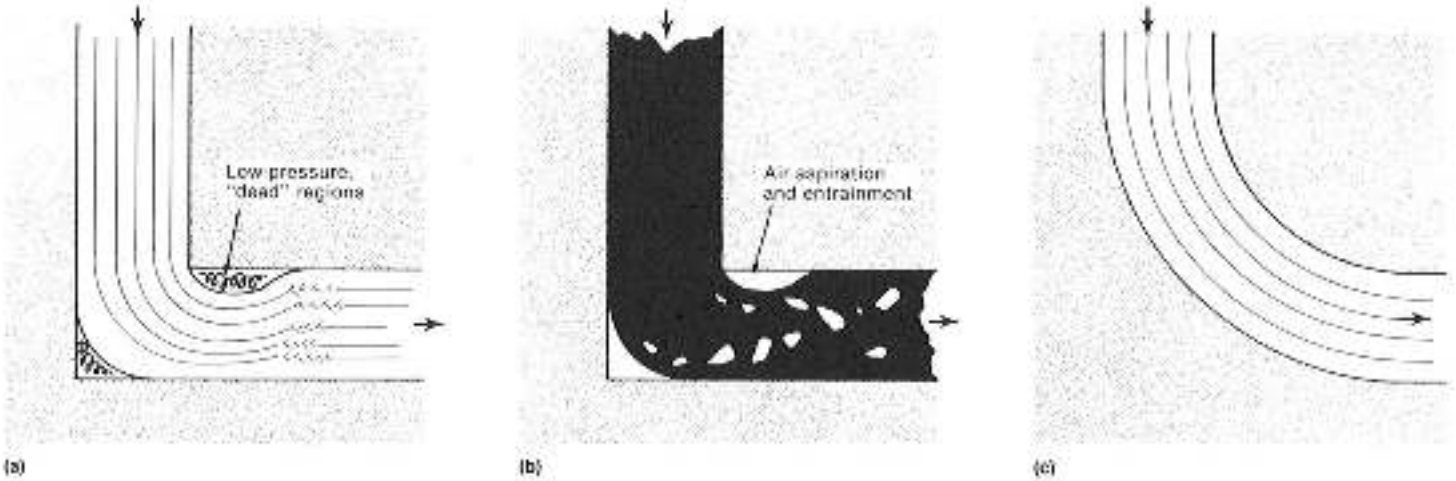


Fig. 7 Schematic illustrating fluid flow around right-angle and curved bends in a gating system. (a) Turbulence resulting from a sharp corner. (b) Metal damage resulting from a sharp corner. (c) Streamlined corner that minimizes turbulence and metal damage

Gating System Design

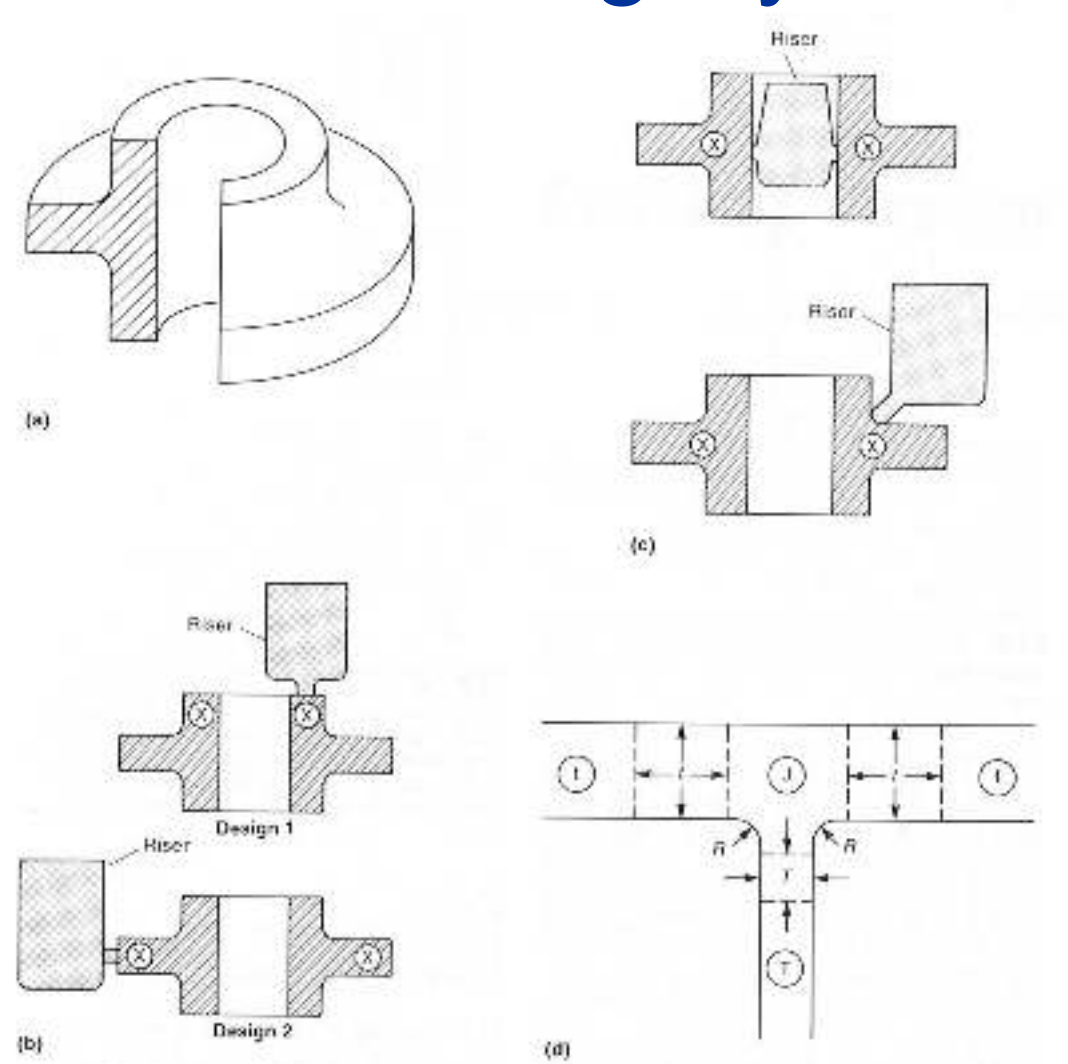


Fig. 4 Cross section (a) of a hub casting showing that it is actually a T-section revolved around an axis. (b) and (c) Possible riser placements, X indicates the last portion of the casting to solidify. See text for discussion. (d) Principal design dimensions of T-section and component sections; see text for discussion.

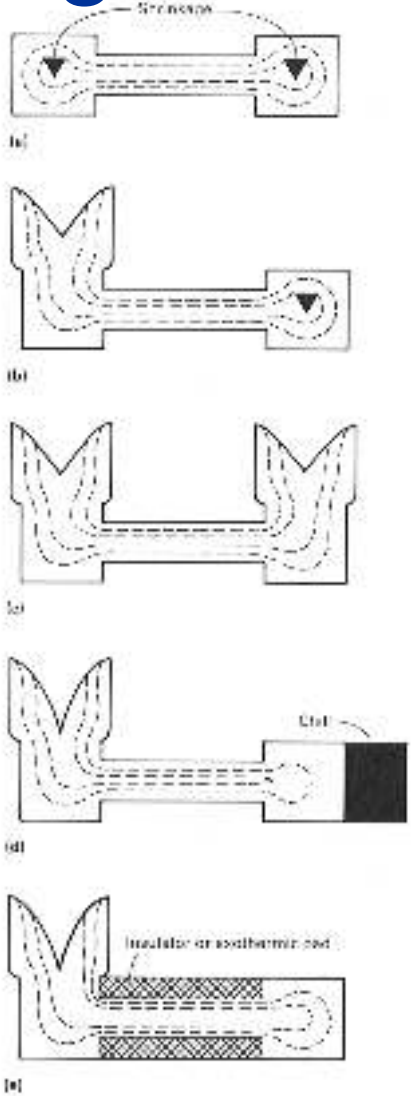
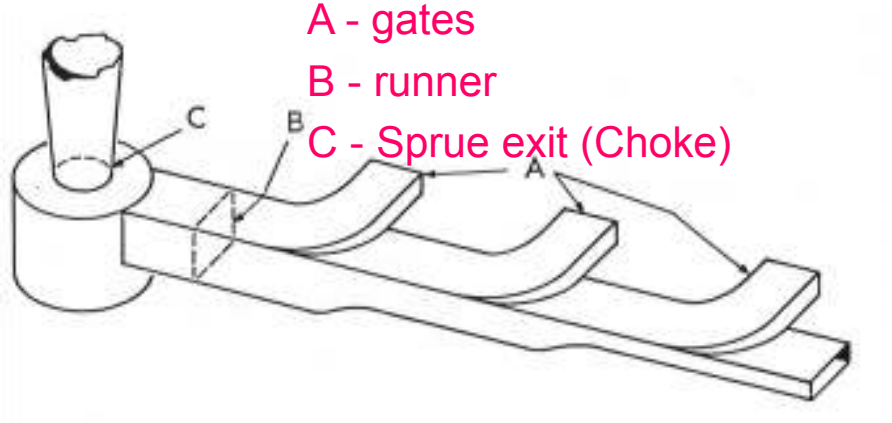


Fig. 16 Riser

Gating System Design



- Un-pressurized system reduces metal velocity and turbulence
- Pressurized systems usually reduce size and weight of gating system (pressure at constriction (gate) causes metal to completely fill runner more quickly)

- System is often designed to follow ratio of (CSA) 1:2:2, or 1:4:4 WRT:
- Sprue exit CSA C : total runner CSA B: total gate CSA A
- Gating system is un-pressurized if area is increasing (e.g. 1:4:4) or pressurized if there is a constriction (4:8:3).

Surface Films

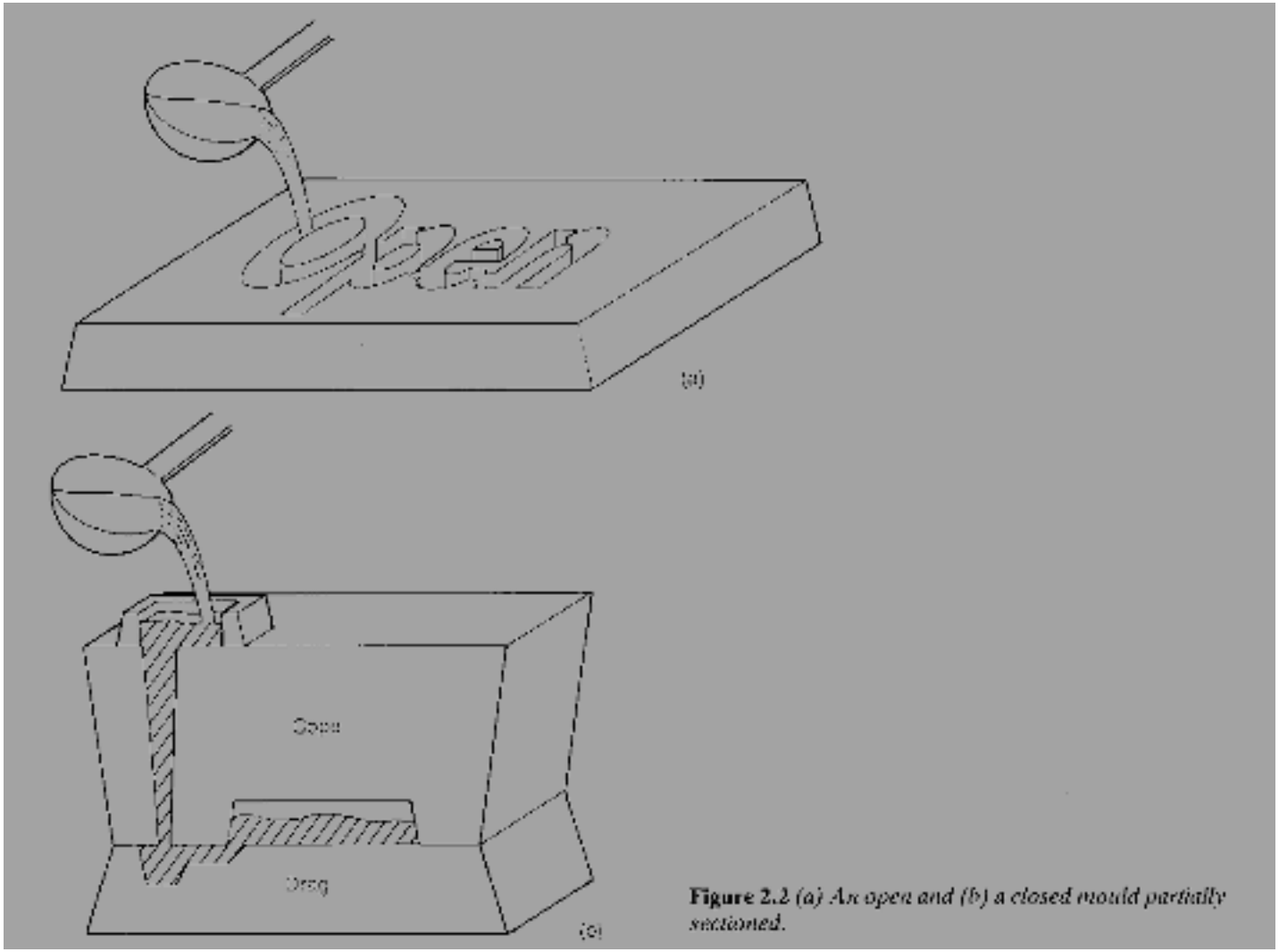
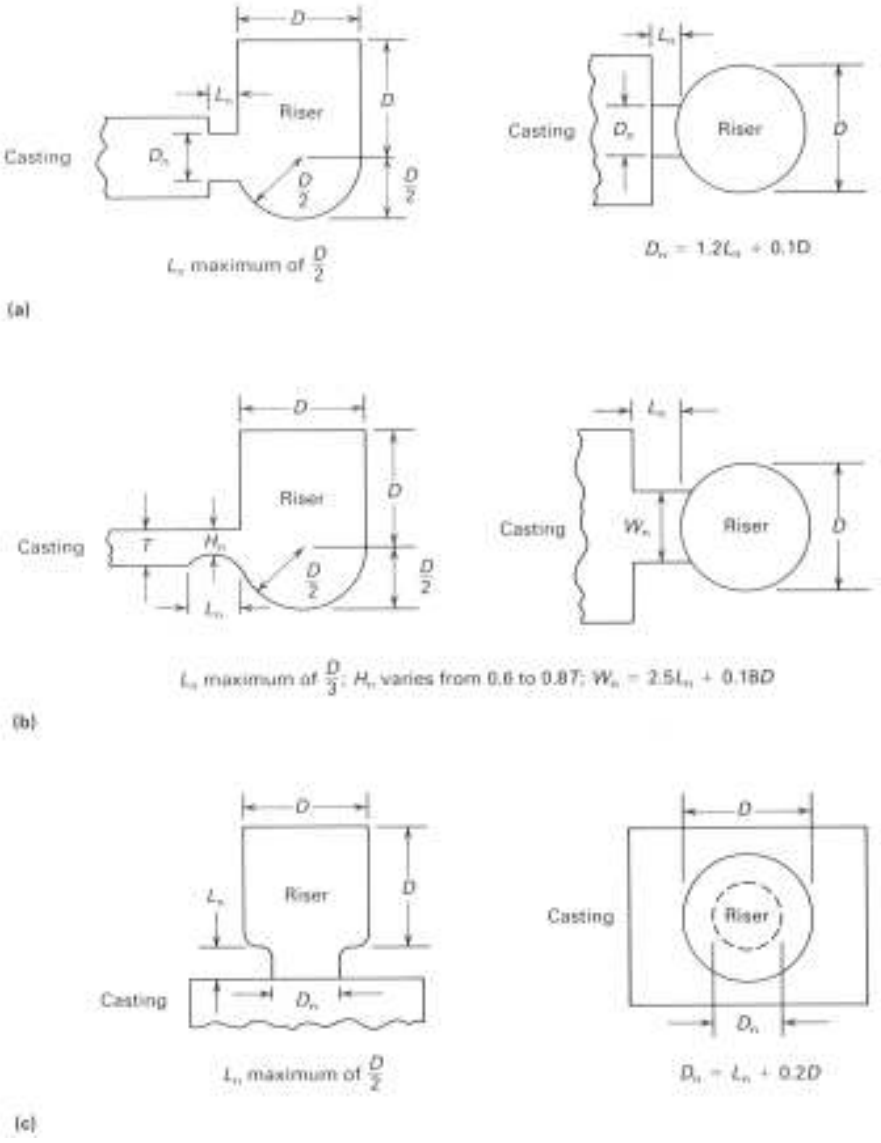


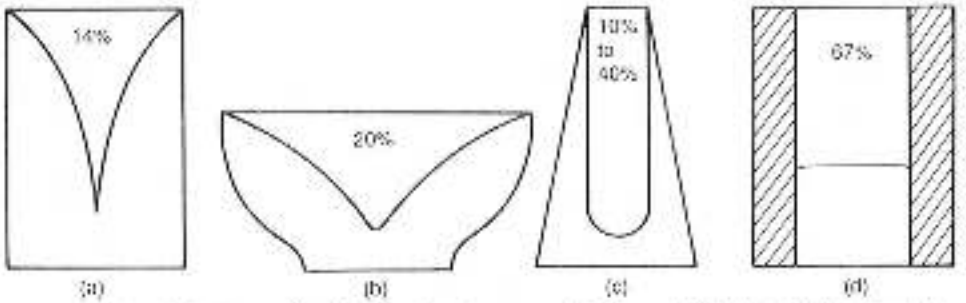
Figure 2.2 *(a) An open and (b) a closed mould partially sectioned.*

Risers and Riser Design

- General design rules for riser necks used in iron castings;
  a. general riser
  b. side riser for plates
  c. top round riser



Gating System Design



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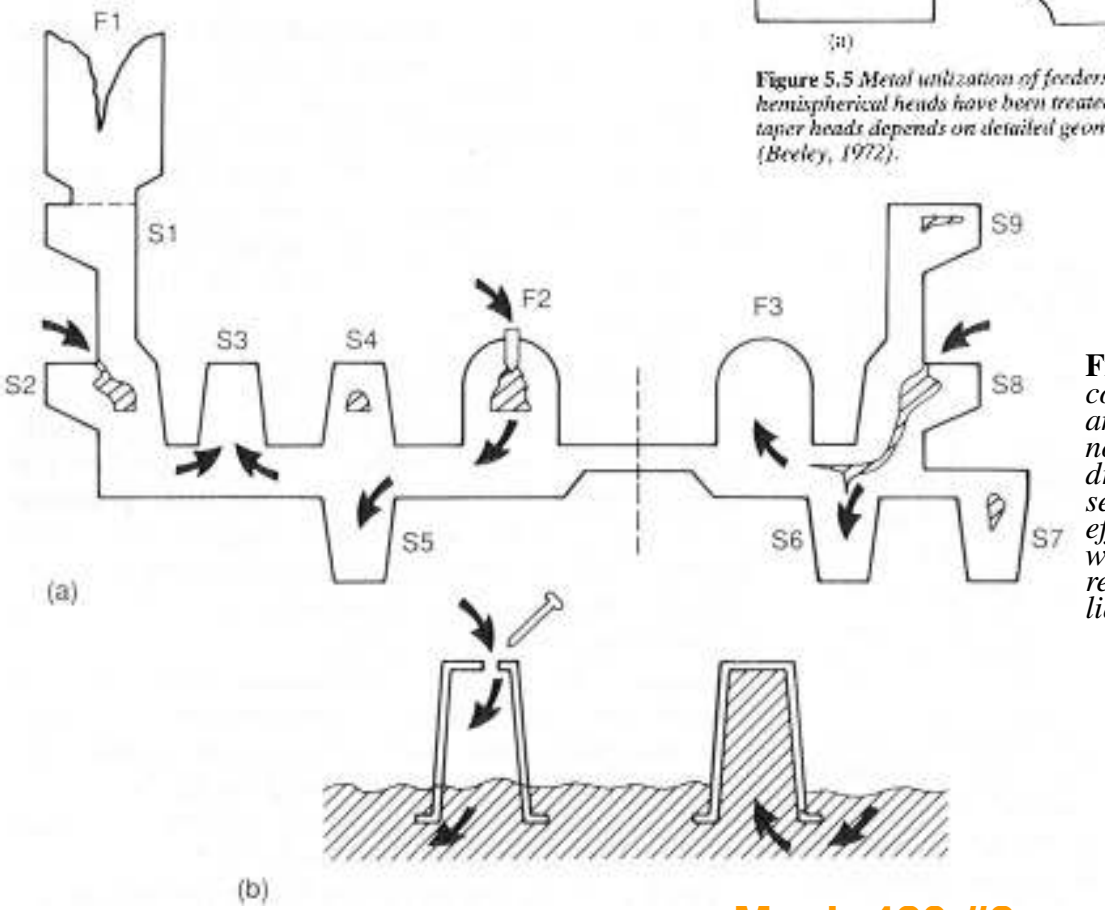
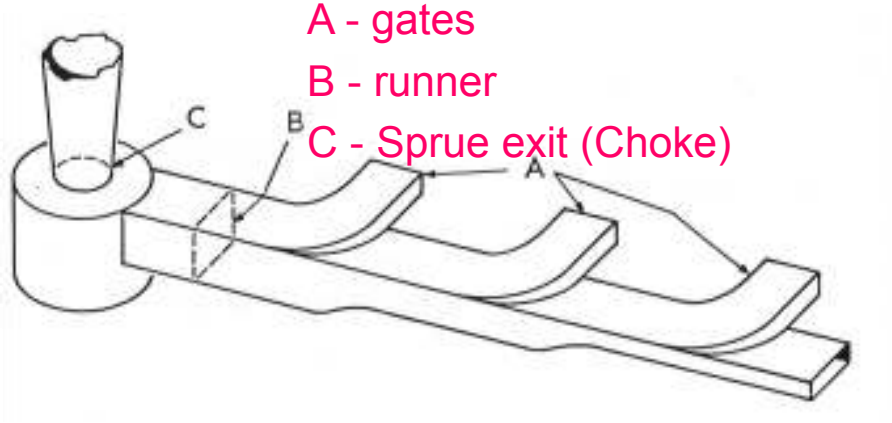


Figure 5.10 *(a) Castings with blind feeders, F2 is correctly vented but has mixed results on sections* S3 *and S4. Feeder F3 is not vented and therefore does not feed at all. The unfavourable pressure gradient draws liquid from a fortuitous skin puncture in section S8. The text contains more details of the effects. (b) The plastic coffee cup analogue: the water is held up in the upturned cup and cannot be released until air is admitted via a puncture. The liquid it contains is then immediately released.*

Gating System Design



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- Pressurized systems usually reduce size and weight of gating system (pressure at constriction (gate) causes metal to completely fill runner more quickly)

- System is often designed to follow ratio of (CSA) 1:2:2, or 1:4:4 WRT:
- Sprue exit CSA C : total runner CSA B: total gate CSA A
- Gating system is un-pressurized if area is increasing (e.g. 1:4:4) or pressurized if there is a constriction (4:8:3).

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Expendable Mould Casting

Lecture 3

Patterns – Shrink Allowance

- 2 types of Casting Process - Expendable & Reusable Mould
- Expendable mould requires pattern
  - Similar to final product
  - Modified in dimension based on material and process
  - Shrinkage allowance (pattern to be larger than part at room temp)
  - Done by using shrink rules which take into account the shrinkage allowance (1' will be 1' 3/16'' in a shrink rule for brass)

Cast iron	0.8–1.0%	($\frac{1}{10}$ – $\frac{1}{8}$ in./ft.)
Steel	1.5–2.0%	($\frac{3}{16}$ – $\frac{1}{4}$ in./ft.)
Aluminum	1.0–1.3%	($\frac{1}{8}$ – $\frac{5}{32}$ in./ft.)
Magnesium	1.0–1.3%	($\frac{1}{8}$ – $\frac{5}{32}$ in./ft.)
Brass	1.5%	($\frac{3}{16}$ in./ft.)

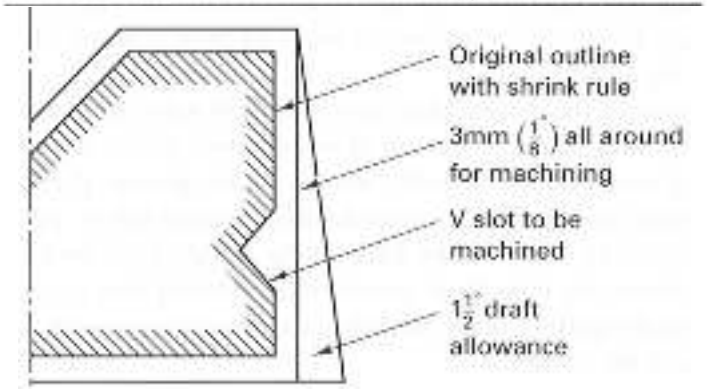


FIGURE 13-12 Various allowances incorporated into a casting pattern.

Patterns – Draft

- Facilitate withdrawal from mould, patterns may be split at parting line
- Location of parting line important - the plane at which 1 section of the mould mates with other section(s)

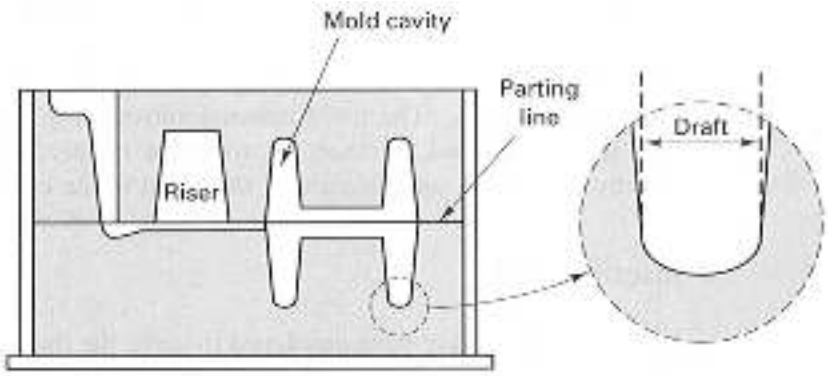
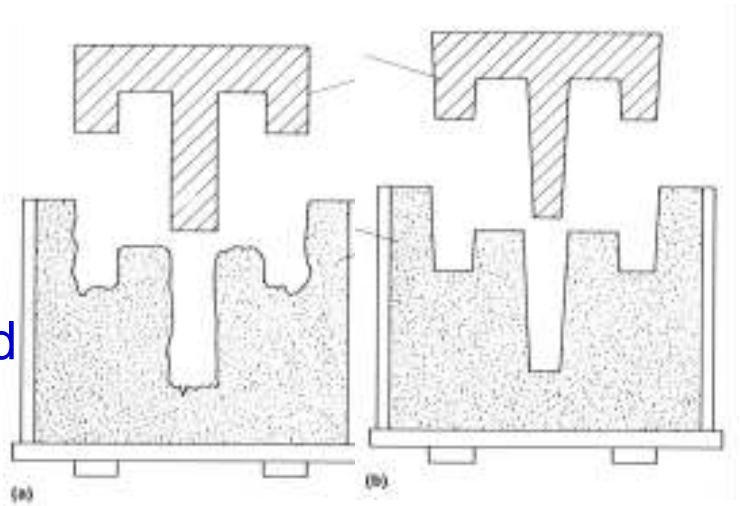


FIGURE 13-11 Two-part mold showing the parting line and the incorporation of a draft allowance on vertical surfaces.

- Flat line is preferred, but casting design and mould may require complex parting lines
- To effect withdrawal Draft is given
- Depends on mould material and procedure
- $1/8^{th}$ to $1/16^{th}$ of an inch per feet is standard
- Can be reduced by increasing mould strength and automatic withdrawal



Patterns – Parting Line

- Good castings require good design.
- Simple, simple, simple!
- Communicate with foundry.
- Location of Parting Plane - effect:
  - number of cores
  - use of effective gating
  - weight of final casting
  - method of supporting cores
  - final dimensional accuracy
  - ease of moulding.
- Minimize cores if possible.

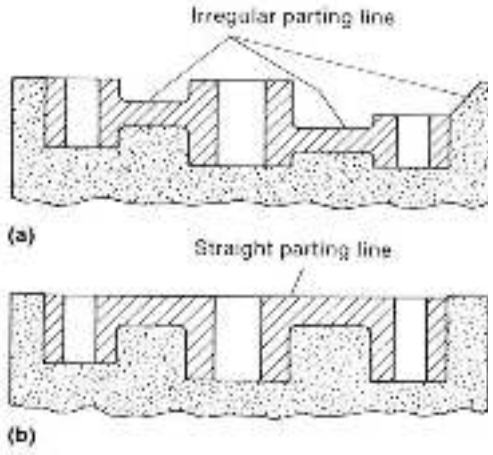


Fig. 28 Designing for a straight parting line reduce pattern and casting costs. (a) regular parting line is a costly design. (b) Straight par line is less expensive.

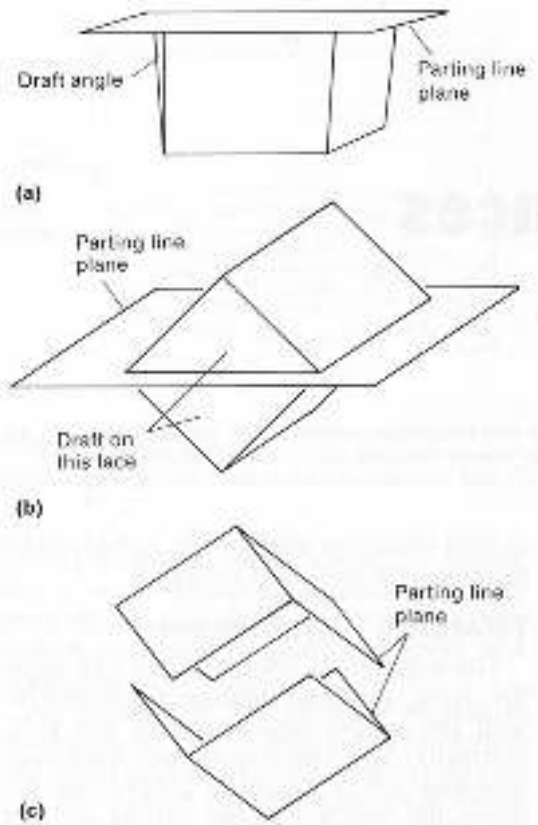


Fig. 29 Parting line options for a cube that must have as many sides as possible parallel and at 90° to each other. (a) Cube parted with four drafted sides is the least expensive option but does not meet design requirements. (b) Parting along the diagonal is a moderate-cost solution that results in four faces in compliance with design requirements. (c) Irregular parting is the most costly option, but is the only one that allows all sides to be parallel and at 90° to each other.

Patterns – Allowance

- Machining Allowance is given on pattern for final finishing operations in casting
- Depends on the mould process and material
- Sand castings rougher than shell castings
- Die, investment castings are smooth, no machining required
- Designer needs to look into these before deciding the final machining allowance required
- Sometimes draft can serve to act as part or whole of machining allowance

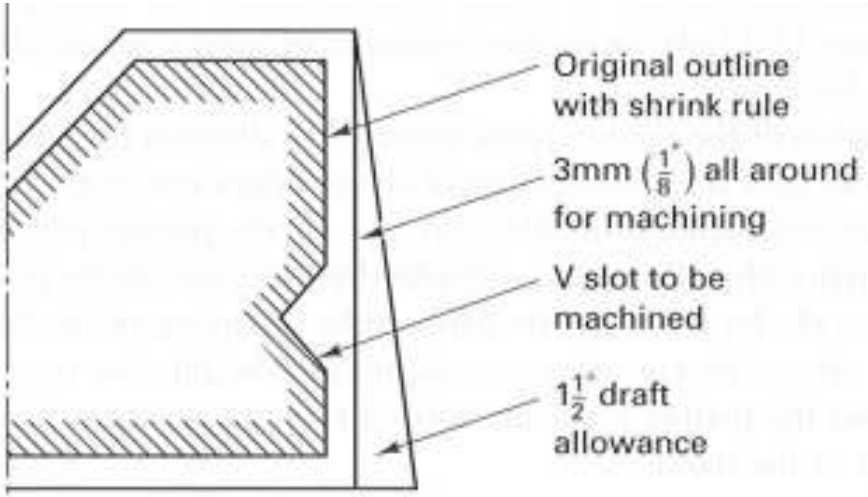


FIGURE 13-12 Various allowances incorporated into a casting pattern.

Patterns – Cores

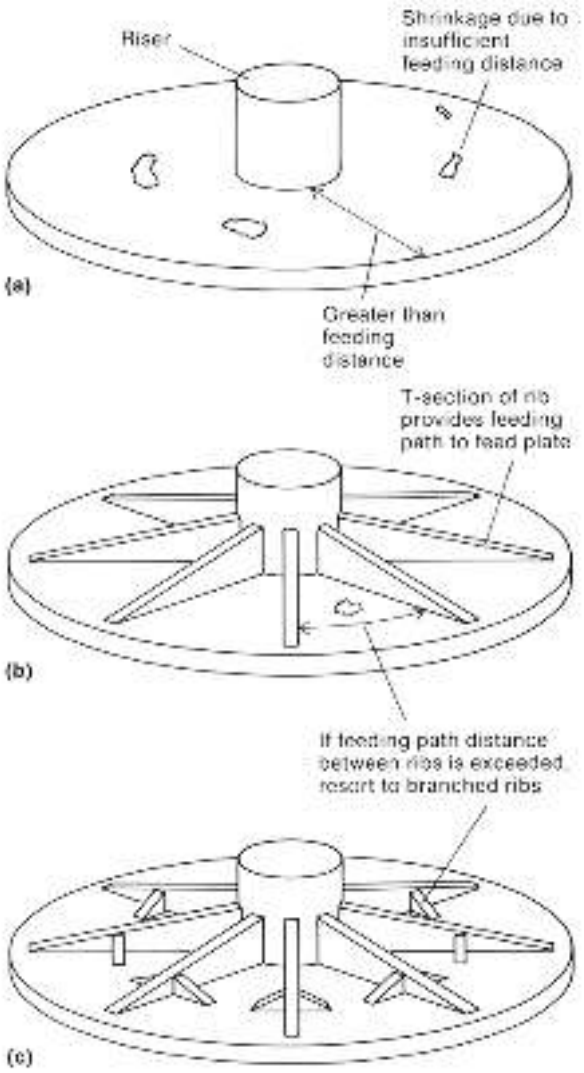


Fig. 16 Feeding path design considerations. (a) Circular flat plate with a single riser. (b) Addition of wedge-shaped ribs to ensure proper solidification. (c) Branched ribs to overcome feeding problems at the circumference of the plate

- Cores to be big to compensate for shrinkage
- Core prints to be added in pattern
- Machining allowance to be reduced from core Size – machining increases hole size

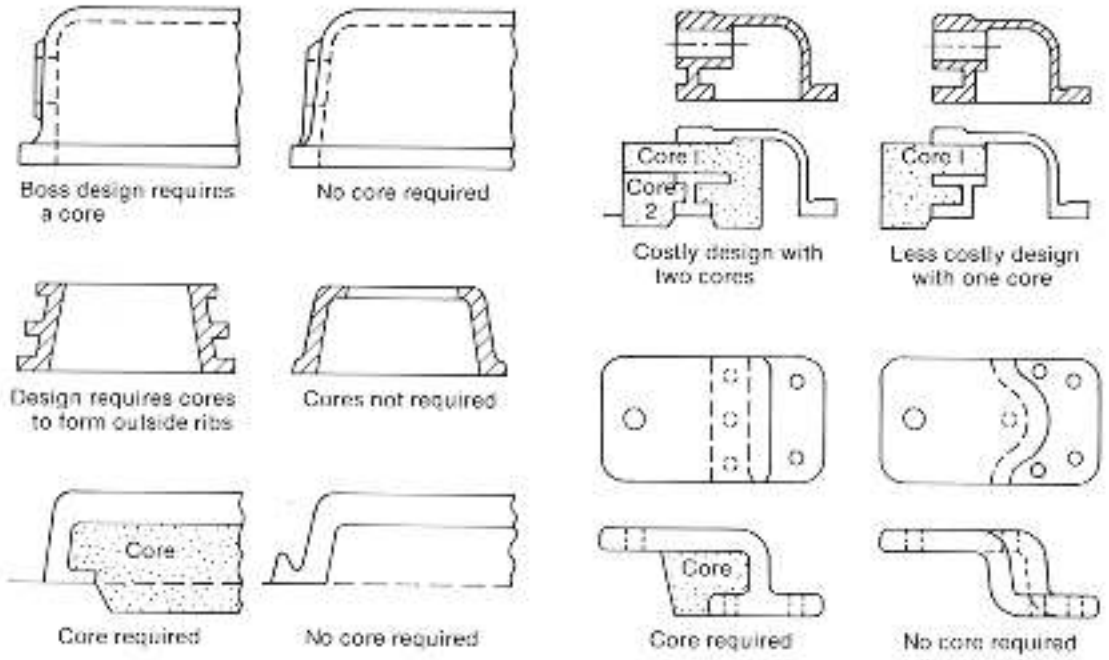


Fig. 27 Restrictions to pattern removal, and some potential solutions

Patterns – Allowances

- Distortion allowance
- U shape castings will distort by bending outside
- To prevent this patterns to be made with an inward angle
- Long horizontal pieces sag in the centre if adequate support not given

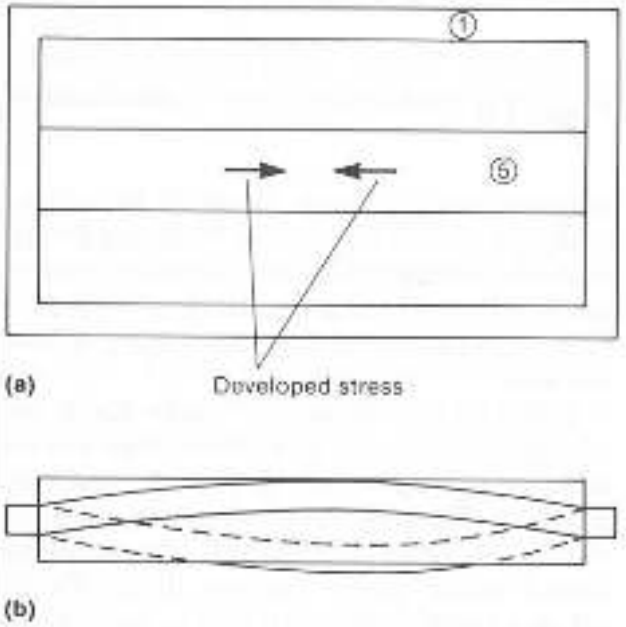
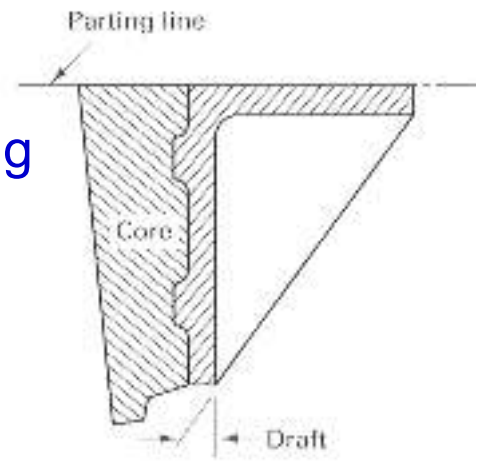


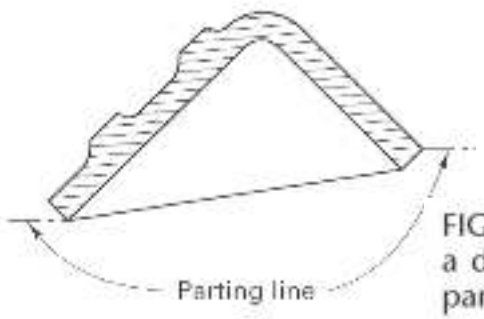
Fig. 1 The effects of design on distortion of castings. (a) Top view of casting; numbers indicate moduli of the two sections. (b) Distortion caused by solidification stresses

- If casting is done directly from reusable mould, all these allowances should go into the mould cavity
- In addition, heating of metal moulds and its expansion while in operation should be taken into account before deciding the final size

Design Consideration in Castings

- Good quality at lowest possible cost.
- Attention to common requirements
- Changes in design to simplify casting example - Location of Parting Plane can affect:
  - number of cores
  - use of effective gating
  - weight of final casting
  - method of supporting cores
  - final dimensional accuracy
  - ease of moulding.
- Minimize cores if possible.





13-13 Elimination of core by changing parting line. Also eliminates draft which reduces weight

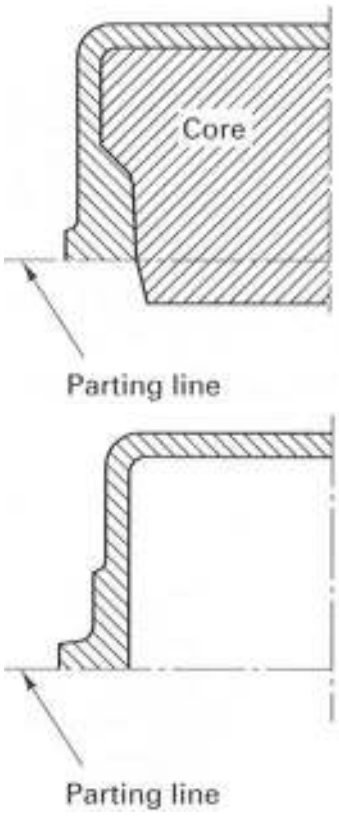


FIGURE 13-14 Elimination of a dry-sand core by change in part design.

Design Consideration in Castings

- Cores can also be eliminated by design change
- Design dictates location of patterning plane - cannot be on the plane of round edges
- Draft also can determine the parting plane – giving it as a note provides more options in foundry

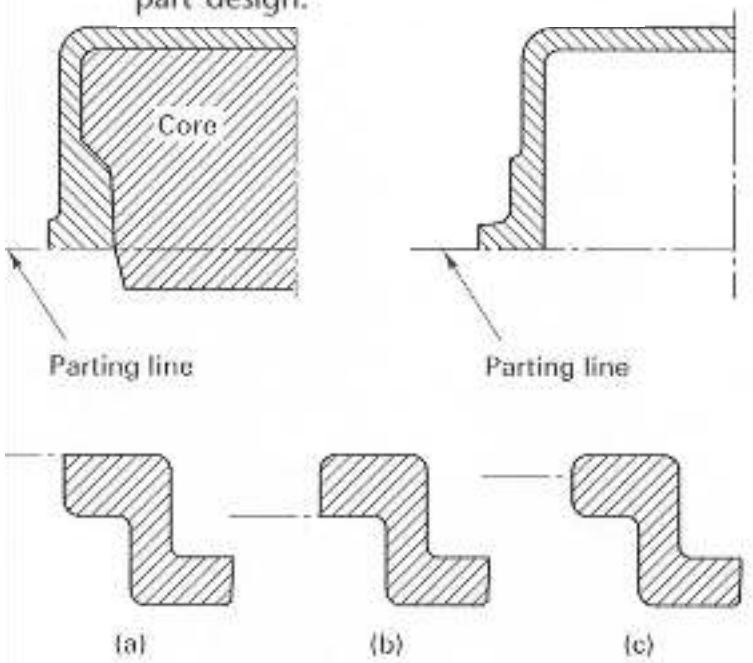
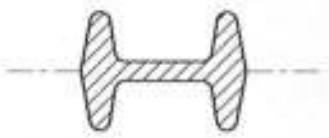
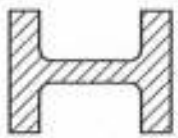


FIGURE 13-14 Elimination of a dry-sand core by change in part design.

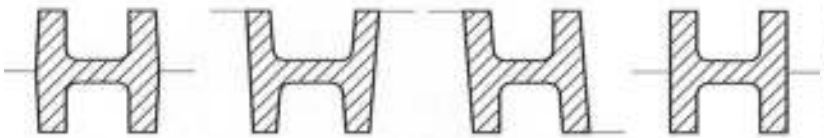
FIGURE 13-15 Parting planes should not intersect rounded edges. Three alternative designs are presented.



As shown on drawing



As shown on drawing, with draft permitted by note

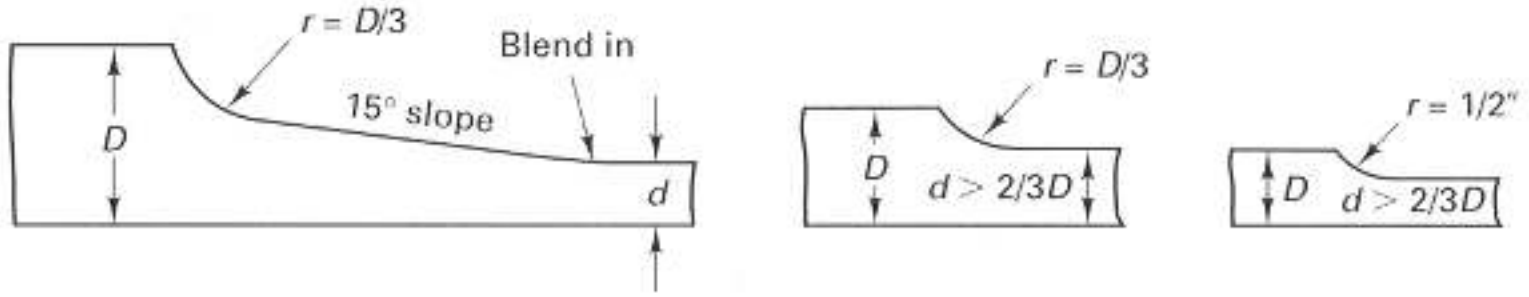


Optional results, with and without draft (exaggerated)

FIGURE 13-16 (*Top left*) Design where the location of the parting plane is specified by the draft. (*Top right*) Part with draft unspecified. (*Bottom*) Various options in producing that part, including a no-draft design.

Design Consideration in Castings

- Sections with high area to volume ratio will cool faster.
- Heavier sections cool slower - more potential for void formation on solidification, and large grains.
- Try for uniform wall thicknesses.
- If not possible use gradual changes in section



If $D > 1.5''$ and $d < 2D/3$ then $r = D/3$ with a 15° slope between the two parts

If $D > 1.5''$ and $d > 2/3\,D$ then $r = D/3$

If $D < 1.5''$ and $d > 2/3\,D$ then $r = 1/2''$

FIGURE 13-17 Guidelines for section changes in castings.

Design Consideration in Castings

- Where walls/sections intersect - problems.
  - Stress concentrations (use fillets)
  - Hot spots. Localized thick section at intersection (especially if fillets too big!). These regions cool slower and often contain voids.
- Try to avoid hot spots and voids in castings.
  - Sometimes use cores to make deliberate, controlled “voids” in heavy sections.
  - Place risers to feed heavy sections/hot spots.
  - Stagger ribs on plates to avoid high stresses/cracking.

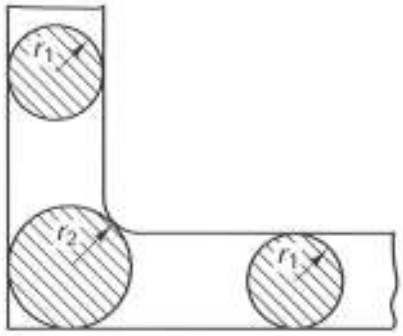
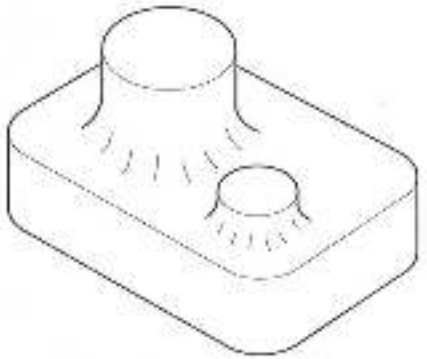


FIGURE 13-18 "Hot spot" at section r_3 caused by intersecting sections.



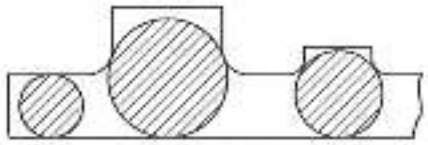


FIGURE 13-19 Hot spots resulting from intersecting sections of various thickness.

Design Consideration in Castings

- Use risers near heavy sections.
  - Adjacent riser feeds these sections
  - Shrinkage will be in the riser that will be cut off rather than in the casting
- Intersecting Sections crack.
  - When ribs are placed, due to shrinkage, material cracks at the intersection
  - Possible solution is to use staggered ribs arrangement.

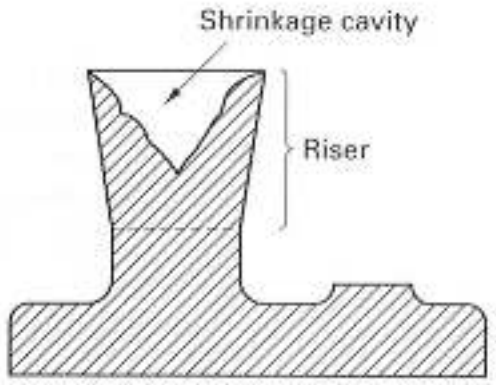
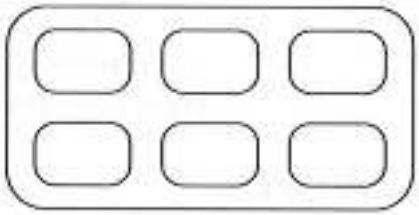


FIGURE 13-21 Use of a riser to keep the shrinkage cavity out of a casting.



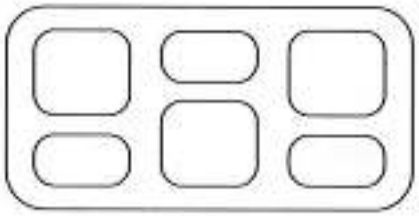


FIGURE 13-22 Method of using staggered ribs to prevent cracking during cooling.

Design Consideration in Castings

TABLE 13-2. Recommended Minimum Section Thicknesses for Various Engineering Metals and Casting Processes

Material	Minimum		Desirable		Casting Process
	mm	in.	mm	in.	
Steel	4.76	$\frac{3}{16}$	6.35	$\frac{1}{4}$	Sand
Gray iron	3.18	$\frac{1}{8}$	4.76	$\frac{3}{16}$	Sand
Malleable iron	3.18	$\frac{1}{8}$	4.76	$\frac{3}{16}$	Sand
Aluminum	3.18	$\frac{1}{8}$	4.76	$\frac{3}{16}$	Sand
Magnesium	4.76	$\frac{3}{16}$	6.35	$\frac{1}{4}$	Sand
Zinc alloys	0.51	0.020	0.76	0.030	Die
Aluminum alloys	1.27	0.050	1.52	0.060	Die
Magnesium alloys	1.27	0.050	1.52	0.060	Die

- Avoid large, unsupported areas - tend to warp on cooling disrupts smooth surface (especially if reflective)
- Consider location of parting line
  - Flash often appears at parting line
  - Locate parting line at corners/edge rather in middle
- Consider minimum thickness. Use common sense and ask advice

Expendable Mould Casting

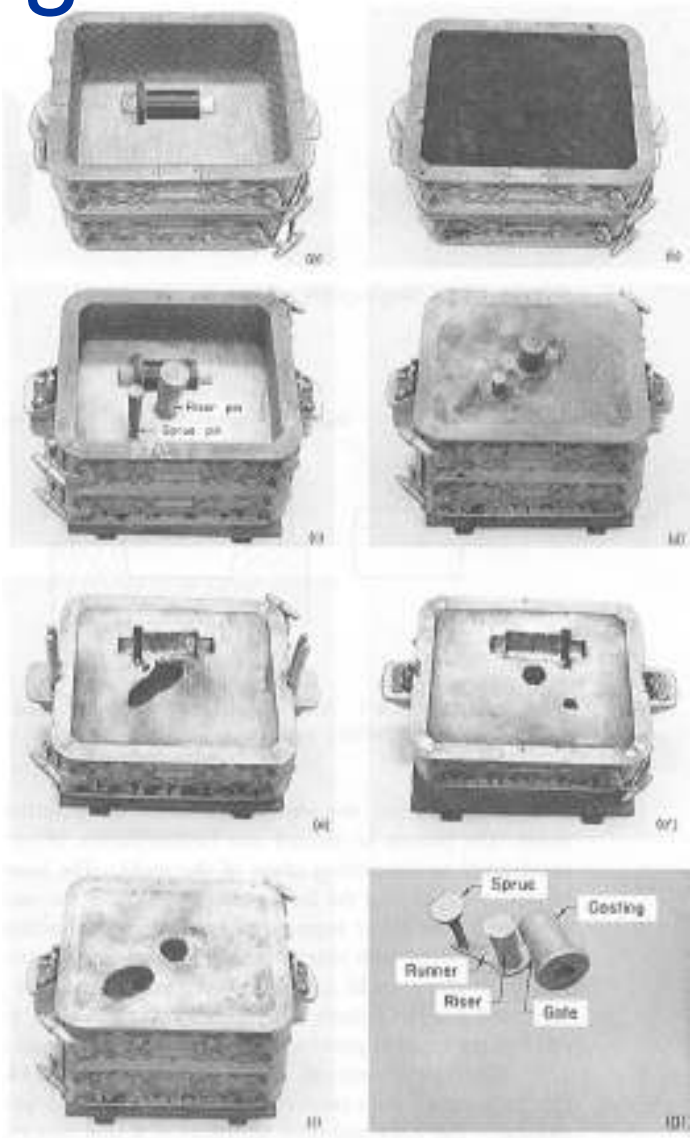
Introduction

1. Single use moulds made from the same pattern (multiple-use pattern)
2. Single use moulds made from single-use patterns (one-off).

- These two are called expendable mould casting processes
- Mould material usually made from sand, plaster, ceramic powder mixed with binder.
- Metals often cast this way are: iron, steel, aluminum, brass, bronze, magnesium, some zinc alloys, nickel-based alloys.
- Cast iron and aluminium are most common:
  - Cheap, good fluidity
  - low shrinkage, good rigidity,
  - Good compressive strength and hardness

Sand Casting

- Most common casting technique
- Sand (mixture of sand + clay + water) is packed around pattern.
- Pattern removed to give cavity, sprue, runners added
- Mould closed, metal poured in.
- After solidification, sand broken out and casting removed. Casting fettled.
- New mould required for next casting (Expendable moulding).



Patterns and Pattern Materials

- For most expendable mould casting techniques a pattern is required
- Material depends on No. of castings to be made, metal being cast, process being used, size and shape, dimensional precision required
- Multiple - Use Patterns
  - **Wood -** Cheap, easily machined but prone to warping, swelling (moisture), unstable, wears. Used for small runs.
  - **Metal -** more expensive but stable, accurate, durable. Typically aluminium, cast iron or steel. Either cast then machined or machined directly (e.g. NC-machining). Large runs and elevated pressure and/or temperature moulding process

Patterns and Pattern Materials

- **Plastic -** Epoxy and Polyurethane. More common now. Easy preparation, stable and durable relative to wood. Cast & machined, easily repaired, can be reinforced/backed

- Expendable (single-use) patterns:
  - **Wax -** used for investment casting. Wax formulated for melting point, viscosity, ash residue etc. Melted out (mostly) before casting
  - **EPS -** Expanded PolyStyrene. Pre-expanded beads blown into mould, heated (steam) to completely fill mould and bond beads. Pattern is burnt out by molten metal. Carbon film possible.

Types of Pattern

- Type of pattern depends on number of castings and complexity.
- **One Piece (Solid) Patterns -** simplest, cheapest, slowest moulding. For simple, low number of castings.
- Only allowances and core prints

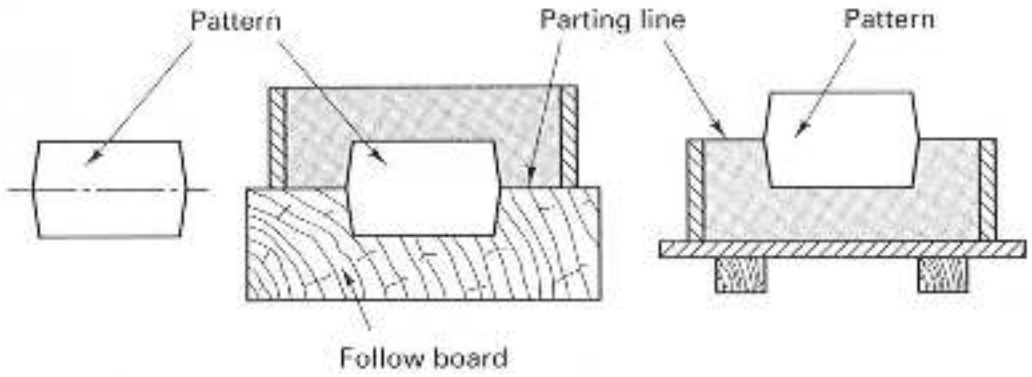
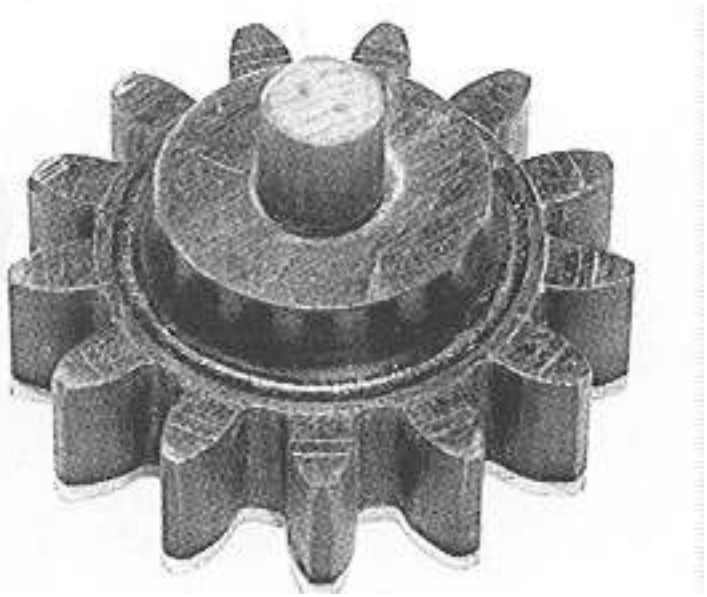


FIGURE 14-3 Method of using a follow board to position a pattern and locate a parting surface.

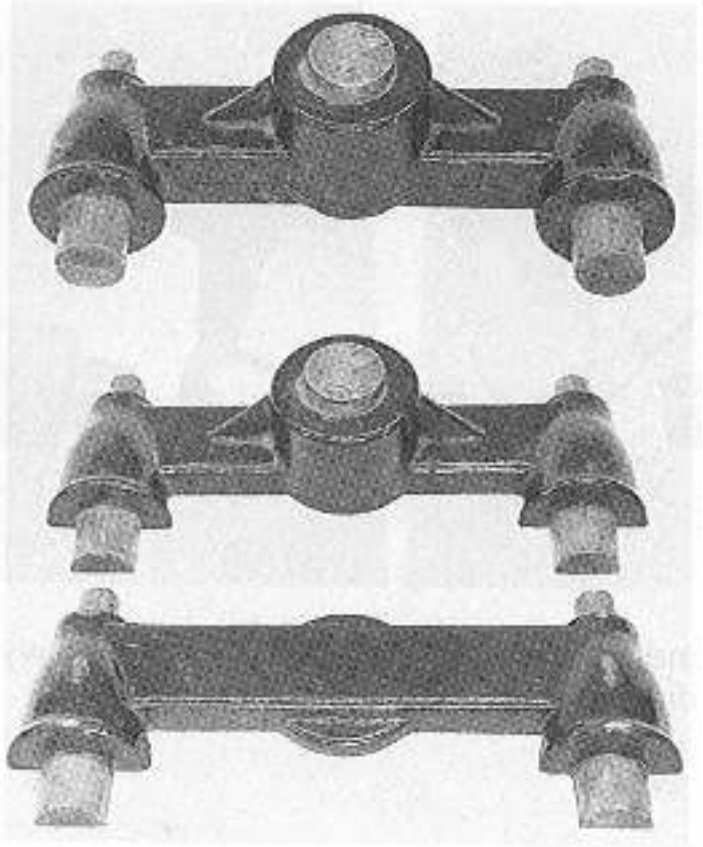
FIGURE 14-2 Single-piece pattern for a pinion gear.



Types of Pattern

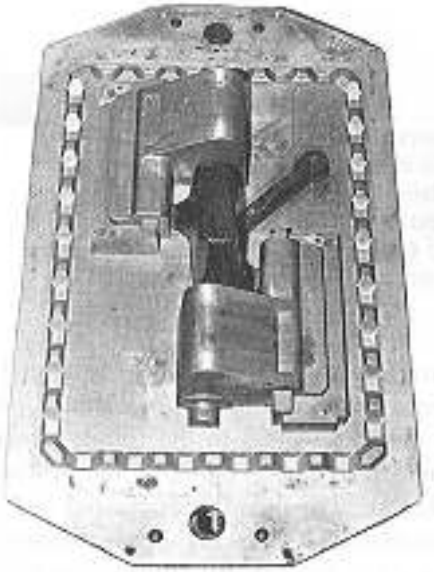
- **Split Patterns -** splits into two parts where parting line will be.
- Mould drag first with bottom part of pattern, invert, add top half of pattern (locating pins) then mould cope.
- Remove pattern, close, cut runner, riser etc and ready to pour.
- OR each part of the mould (Cope & Drag) can be moulded separately then joined
- High volume and large castings

FIGURE 14-4 Split pattern, showing the two sections together and separated. Light-colored portions are core prints.



Types of Pattern

- **Match-Plate Patterns -** a plate with the cope pattern on one side and the drag pattern on the other side (with locating pins and holes respectively).
- Can include runners and gates. Made from wood and joined or machined/cast from metal. (higher volumes, small to medium size castings).



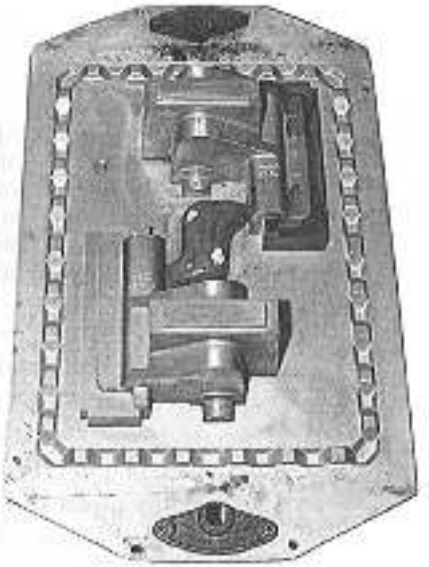


FIGURE 14-5 Match-plate pattern to produce two identical parts in a single flask. (*Left*) Cope side; (*right*) drag side.

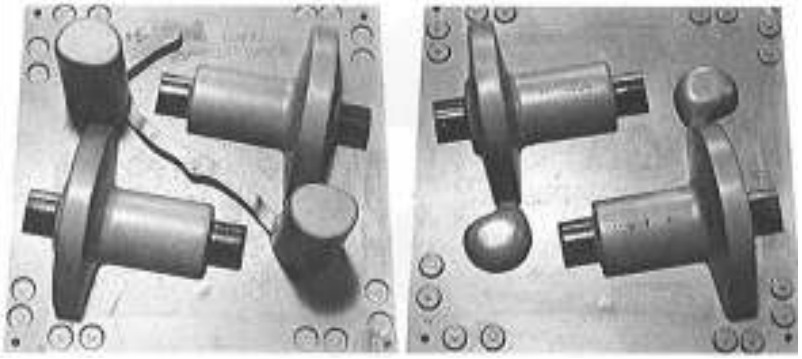


FIGURE 14-6 Cope-and-drag pattern for molding two heavy parts. (*Left*) Cope section; (*right*) drag section.

Types of Pattern

- **Loose Piece Patterns -** Special patterns can be made for very complex shapes. Pattern is assembled from different pieces held together with pins. Pieces are withdrawn sequentially after pin removed. Expensive.
- All patterns should have a small radius on internal corners to prevent stress concentrations in the casting, avoid shrinkage cracking and make pattern easier to remove without mould damage (3-7mm is good). Machined in for NC patterns; added to patterns using wax, plastic strips.

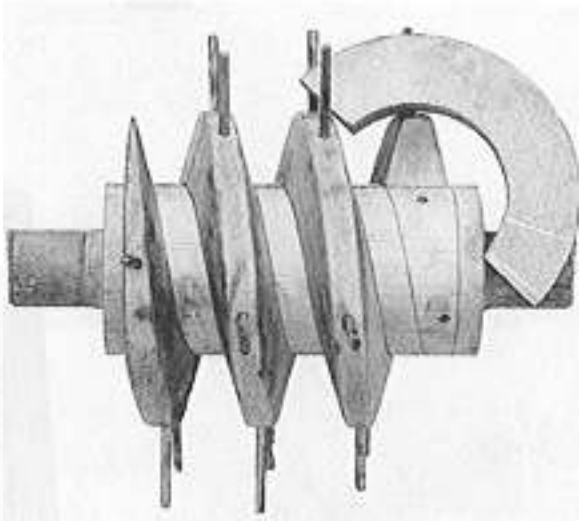


FIGURE 14-7 Loose piece pattern for molding a large worm. After sufficient sand is packed around the pattern halves to hold the pieces in position, the wooden pins are withdrawn. The mold is completed and the pieces of the pattern are removed in sequence.

Sand and Sand Conditioning

- SAND - very important part of sand-casting. Require following properties.
- Refractoriness - ability to withstand high temperatures.
  - Silica ("sand")- cheap, lower temps (Al, Mg possibly cast iron).
  - Zircon ($ZrO_2.SiO_2$) - more expensive, higher temps. Steels. Investment casting.
  - Others
- Cohesiveness - how well the sand bonds together to give shape.
  - Controlled by adding binder, clays (bentonite, kaolinite) + water.

Sand and Sand Conditioning

- Permeability - ability to allow gas to pass through/escape as metal fills cavity. Denser packing - stronger, better surface finish but less permeability.
  - Depends on size and shape of sand particle, amount of clay and water, compacting pressure.
- Collapsibility - ability to permit metal to shrink after solidification and also to disintegrate during “knock-out”.

- Usually trade-off in properties: more clay means stronger bond but less permeability and refractoriness etc.
- 88% Silica, 9% clay, 3% water; typical for green-sand cast.
- Blended and mixed; uniform, flows easily into mould (Fig 14-8)
- Tested for grain size, moisture content, permeability, strength etc.

Sand Testing

- Grain Size – tested by shaking in 11 sieves of decreasing mesh size and the weight in each of them gives an idea of grain size.
- Moisture – electrical conductivity, or weigh 50g sample of sand after heating for sometime at 110°C for water to evaporate
- Clay – wash 50g of sample sand with alkaline water (NaOH) to remove clay, dry the sand and weighed to find the clay content
- Permiability – measure of escape gases – done by standard ramming of sand and passing air through it at known pressure. Pressure loss between orifice and sand gives permiability (12-9)
- Compressive Strength – also mould strength. Use the prepared sample and compressively load it find when it fails
- Hardness – Resistance of sand to spring loaded steel ball (12-10)
- Compactibility – 45% is good. Amount of height change from loose sand to application of standard load

Sand Properties and Defects

- Round grains - better permeability, minimize clay required.
- Angular grains - better strength due to interlocking.

TABLE 14-1. Desirable Properties of a Sand-Based Molding Material

1. Is inexpensive in bulk quantities
2. Retains properties through transportation and storage
3. Uniformly fills a flask or container
4. Can be compacted or set by simple methods
5. Has sufficient elasticity to remain undamaged during pattern withdrawal
6. Can withstand high temperatures and maintains its dimensions until the metal has solidified
7. Is sufficiently permeable to allow the escape of gases
8. Is sufficiently dense to prevent metal penetration
9. Is sufficiently cohesive to prevent wash-out of mold material into the pour steam
10. Is chemically inert to the metal being cast
11. Can yield to solidification and thermal shrinkage, thereby preventing hot tears and cracks
12. Has good collapsibility to permit easy removal and separation of the casting
13. Can be recycled

- Large grains - better permeability, better high temps.
- Smaller grains - better surface finish.
- Uniform particle size - better permeability.
- Wide PSD - better strength & surface finish.
- Sand expands on heating; (also phase transformation in silica). Expands next to cavity but not elsewhere, sometimes get sand expansion defects especially on long flat surfaces.

Sand Properties and Defects

- Sand expands on heating; (also phase transformation in silica). Expands next to cavity but not elsewhere, sometimes get sand expansion defects especially on long flat surfaces.
- Voids can be formed if gas cannot escape ahead of molten metal (short run). Either low permeability or too much gas produced (volatiles/steam). May need vent passages.
- Penetration if sand too coarse, fluidity too high.
- Hot tears or cracks can occur in long freezing range alloys especially if casting is restrained by mould/cores during cooling (poor collapsibility) Add cellulose.

Making Sand Moulds

- Hand ramming. For small number of castings. Pneumatic hand rammer as well.
- **Moulding Machines**
- Jolting - sand on pattern then drop flask several times to pack sand.
- Squeezing - platen/piston squeezes sand against pattern. Non-uniform sand density.
- Combined Jolt & Squeezing - Uniform density.

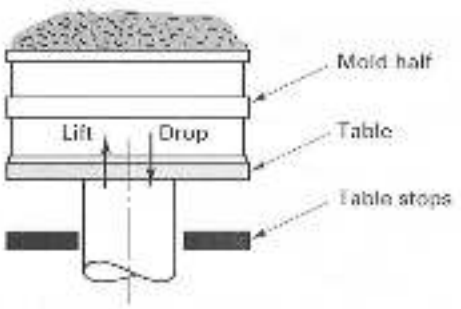


FIGURE 14-12 Jolting a mold half.

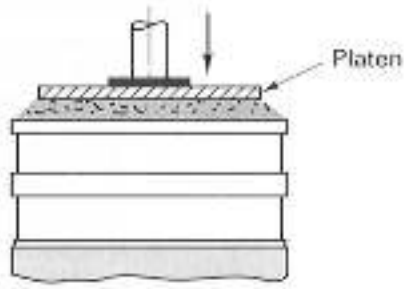


FIGURE 14-13 Squeezing operation

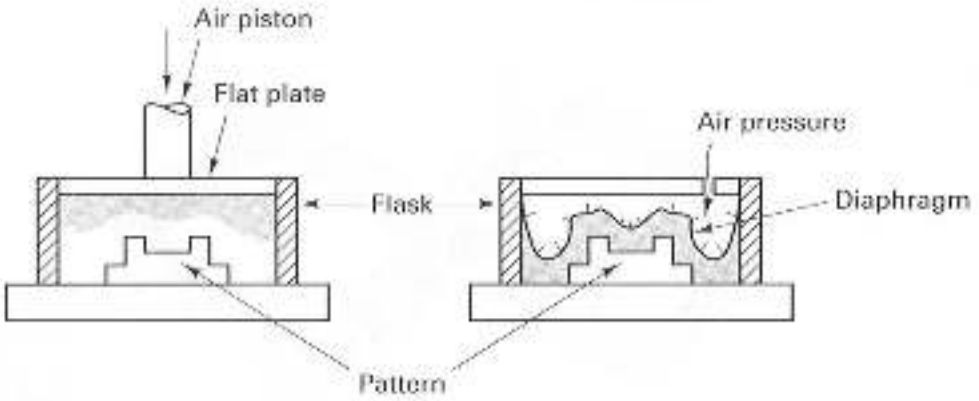
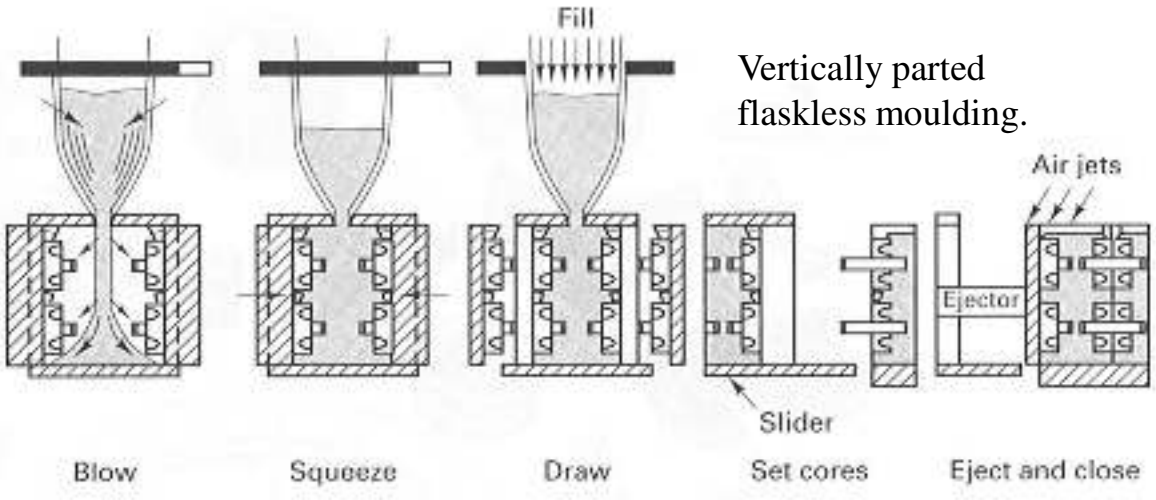
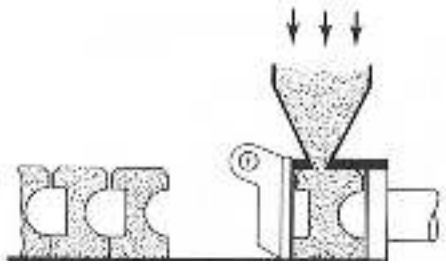


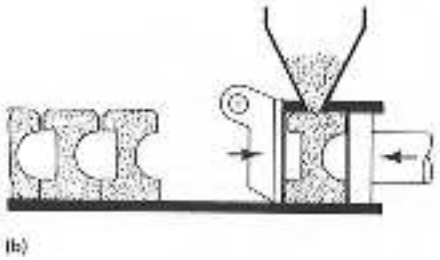
FIGURE 14-14 Schematic diagram showing relative sand densities obtained by flat-plate squeezing (*left*) and by flexible-diaphragm squeezing (*right*).

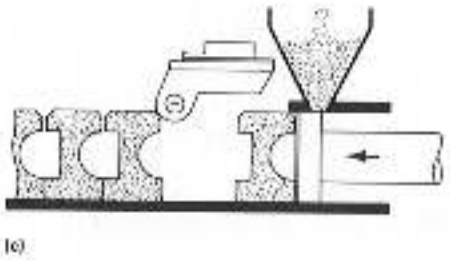
Making Sand Moulds



Vertically parted flaskless moulding.







- Automatic mold making (eg. Disamatic Process)
- Vertically parted, flaskless moulding machine. Block of sand is pressed with RHS of casting pattern on the left side and LHS of pattern/casting on the RHS. Stacked in a line to give multiple moulds (refer back to H-process). Good for mass production

Blow-fill pressure squeeze molding machine making vertically parted molds. (a) Molding chamber filled with sand. (b) Sand compacted by squeeze pressure. (c) Finished sand mold pushed out of molding chamber

Sand Cast Parts-Examples

FIGURE 14-16 Some aluminum products produced by conventional sand casting. *(Courtesy of Bodine Aluminum Inc.)*

Sand Moulds

TABLE 14-2. Green-Sand Casting

Process:	Sand, bonded with clay and water, is packed around a wood or metal pattern. The pattern is removed and molten metal is poured into the cavity. When the metal has solidified, the mold is broken and the casting is removed.
Advantages:	Almost no limit on size, shape, weight or complexity; low cost; almost any metal can be cast.
Limitations:	Tolerances and surface finish are poorer than in other casting processes; some machining is often required; relatively slow production rate.
Common metals:	Cast iron, steel, stainless steel, and casting alloys of aluminum, copper, magnesium, and nickel
Size limits:	1 oz to 6000lb
Thickness limits	As thin as $\frac{3}{32}$ in., with no maximum
Typical tolerances:	$\frac{1}{32}$ in. for first 6 in., 0.003 in. for each additional inch; additional increment for dimensions across the parting line
Draft allowance:	1–3°
Surface finish:	100-1000 μin. rms

- Dry sand moulds are durable
- Long time required for drying and increased cost of operation
- Compromise is skin dried mould
  - Commonly used for large castings
  - Binders (linseed oil etc) added in the sand face to improve the strength of the skin

- Disadvantages of green sand can be reduced.
- Improved surface and casting by drying mould before casting.
  - Bake mould (150°C) - expensive, time consuming.
  - Skin-dried mould - just dry area near to cavity e.g. using gas torch.

Sand Moulds

- Sodium Silicate - CO_2 molding
  - Sand mixed with 3-4% liquid sodium silicate to add strength.
  - Soft and mouldable until exposed to flow of CO_2 gas
  - Has poor Collapsibility (difficult to remove by shakeout)
  - Heating (due to metal pour) makes it more stronger
  - Additives that burn during pour increases collapsibility
  - Can use this material close to cavity upto 1” thickness and then back-filed with regular moulding sand
  - If CO_2 is introduced only sand close to mould is hardened without affecting the mould

Sand Moulds

- No-Bake, Air-Set or Chemically-bonded sands.
  - Alternative to sodium silicate
  - Use organic resin binders that cure at room temperature.
  - Binders mixed with sand just before moulding and curing begins immediately
  - Limited working time before curing – operation to be fast
  - After some time (depending on binder) the sand cures and pattern can be withdrawn. After some more time to cure, metal can be poured
  - Offers high dimensional accuracy, good strength and high resistance to mould related casting defects
  - Patterns can have thinner section with deeper draws
  - Easy to shakeout as they decompose after metal pour

Shell Moulding

- Becoming increasingly popular; Better surface finish and dimensional accuracy, higher production rate and reduced labour costs. Possible to mechanize for mass production.
- Make shell of sand+binder on hot metal pattern, bake, strip and clamp.
- Less fettling as resin binder burns out due to heat from molten metal

TABLE 14-3. Shell-Mold Casting

Process:	Sand coated with a thermosetting plastic resin is dropped onto a heated metal pattern, which cures the resin. The shell segments are stripped from the pattern and assembled. When the poured metal solidifies, the shell is broken away from the finished casting.
Advantages:	Faster production rate than sand molding; high dimensional accuracy with smooth surfaces.
Limitations:	Requires expensive metal patterns. Plastic resin adds to cost; part size is limited.
Common metals:	Cast irons and casting alloys of aluminum and copper
Size limits:	1 oz minimum; usually less than 25 lb; mold area usually less than 500 in^2
Thickness limits:	Minimums range from $\frac{1}{16}$ to $\frac{1}{4}$ in., depending on material
Typical tolerances:	Approximately 0.005 in./in.
Draft allowance:	$\frac{1}{4}-\frac{1}{2}°$
Surface finish:	50–150 µin. rms

Shell Moulding

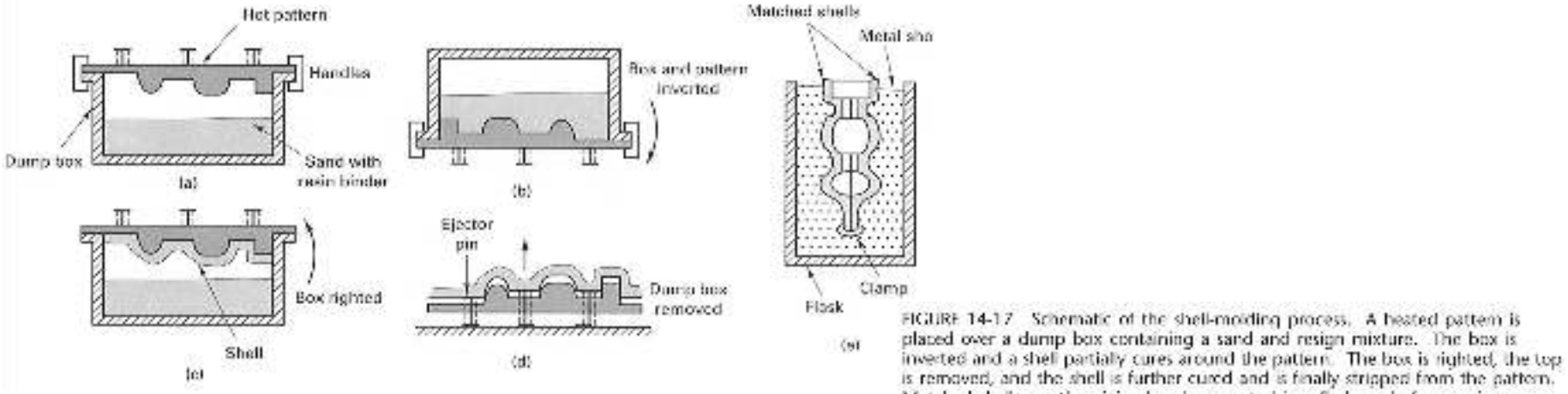
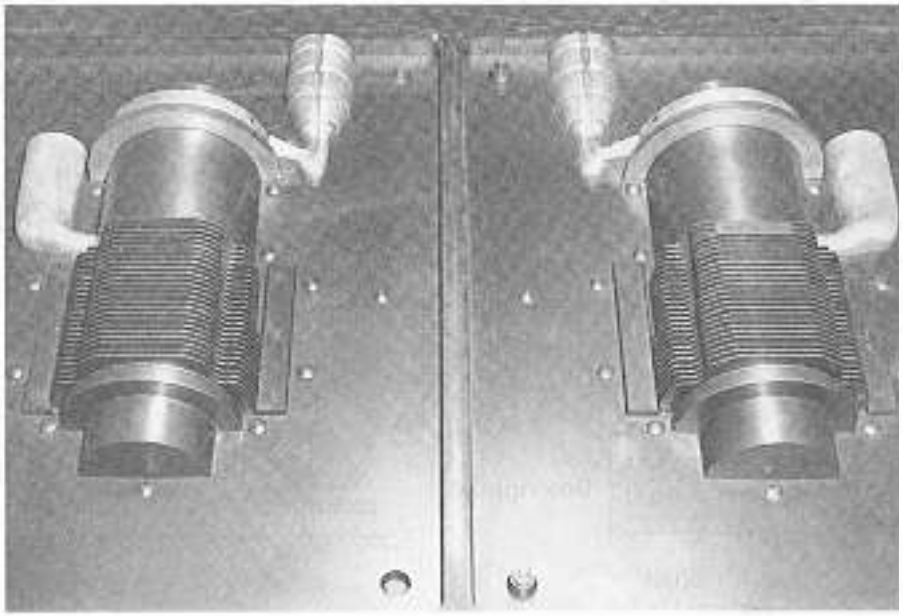


FIGURE 14-17 Schematic of the shell-molding process. A heated pattern is placed over a dump box containing a sand and resign mixture. The box is inverted and a shell partially cures around the pattern. The box is righted, the top is removed, and the shell is further cured and is finally stripped from the pattern. Matched shells are then joined and supported in a flask ready for pouring.

- Use of metal pattern and finer sand (with smooth resin) gives smoother surface and high dimensional accuracy (0.08 - 0.13mm).
- More consistent casting. Thin shell increases permeability but gas evolution is less due to less moisture in sand
- Metal pattern (including runner & gates) cost is high & cost of binder, BUT only thin shell produced (5-10mm).
- High productivity etc economical for many cases (small to medium)

Shell Moulding



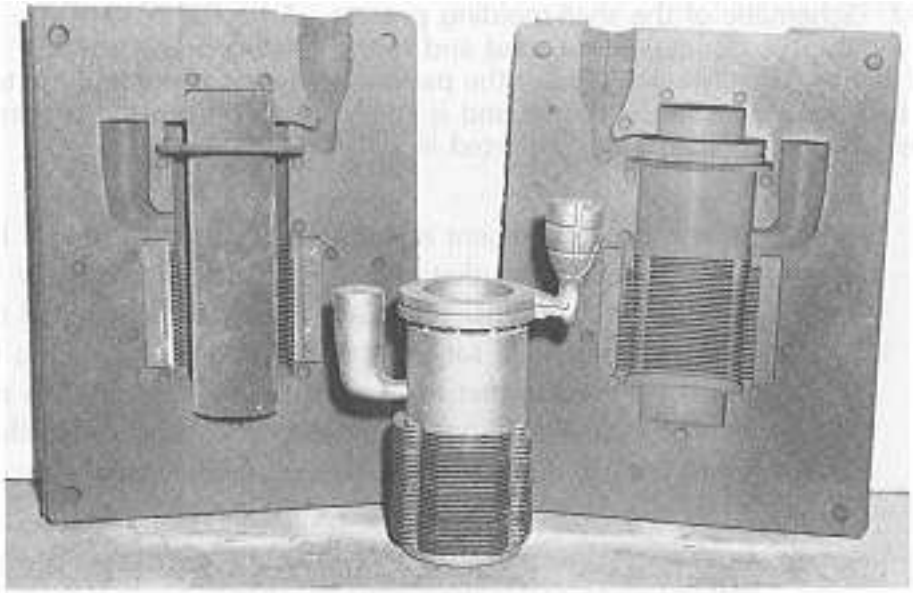


FIGURE 14-18 (*Top*) Two halves of a shell-mold pattern. (*Bottom*) The two shells before clamping, and the final shell-mold casting. *(Courtesy of Shalco Systems, an Acme-Cleveland Company.)*

Other Sand Moulding Processes

- Processes proposed to overcome limitations of traditional methods
- V-process or vacuum molding - Draping a thin sheet of heat-softened plastic over a special vented plastic pattern
- The sheet is then drawn tightly to the pattern surface by a vacuum
- A vacuum flask is then placed over the pattern, filled with sand, a sprue and pouring cup are formed, and a second sheet of plastic is placed over the mold
- Vacuum is used to compact the sand
- The pattern vacuum is released, and the pattern is withdrawn.

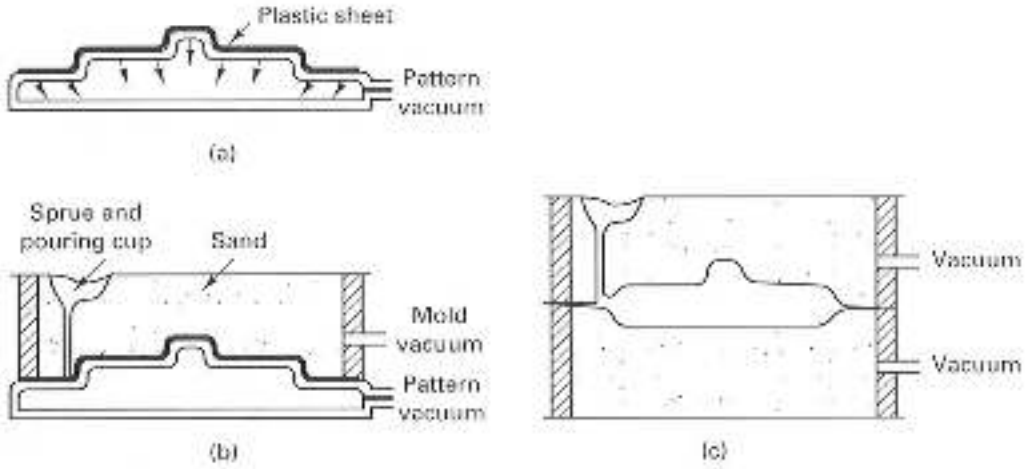


FIGURE 14-19 Schematic of the V-process or vacuum molding. A) A vacuum is pulled on a pattern, drawing a plastic sheet tightly against it. B) A vacuum flask is placed over the pattern, filled with sand, a second sheet placed on top, and a mold vacuum is drawn. C) The pattern vacuum is then broken and the pattern is withdrawn. The mold halves are then assembled, and the molten metal is poured.

Other Sand Moulding Processes

- Repeat for other segment, and the two mold halves are assembled.
- Metal is poured while maintaining vacuum. Plastic film vaporizes instantaneously. Vacuum is still sufficient to hold the sand in shape until metal cools.
- When the vacuum is released, the sand reverts to a loose, unbonded state, and falls away from the casting.
- No moisture-related defects. No binder cost. Dry sand is reusable.
- Better surface finish since there is no clay, water, or other binder to impair permeability, finer sands can be used,
- Excellent Shakeout characteristics, since the mold collapses when the vacuum is released.
- Unfortunately, the process is relatively slow because of the steps required

http://www.mccannsales.com/book/vprocess.pdf#search=%22v-process%20moulding%22

Cores and Core Making

- For making internal cavities or reentrant sections (undercuts)
- Increase moulding cost but reduce machining cost, wastage, allow design versatility
- 14 -21 shows 4 methods of making the pulley
- Machining out the hole, making as 2 piece pattern (also called green sand cores)
- Green sand cores have low strength and difficult to do long or complex sections

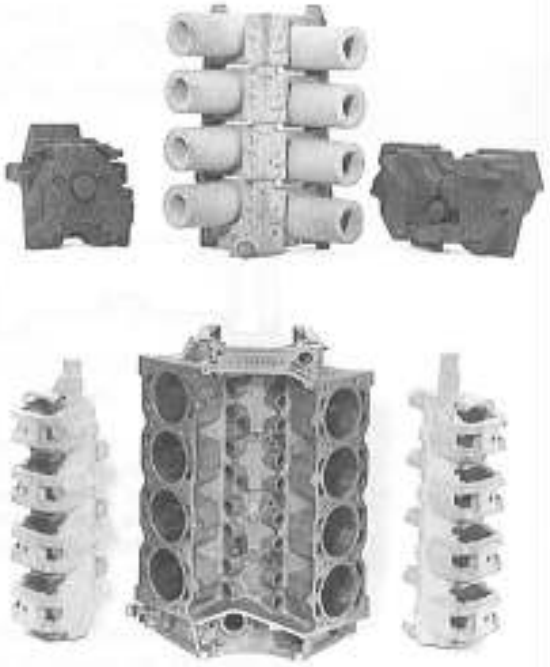


FIGURE 14-20 V-8 engine block (*bottom center*) and the five dry-sand cores that are used in its construction. *(Courtesy of Central Foundry Division of General Motors Corporation.)*

This part cannot be cast without use of cores

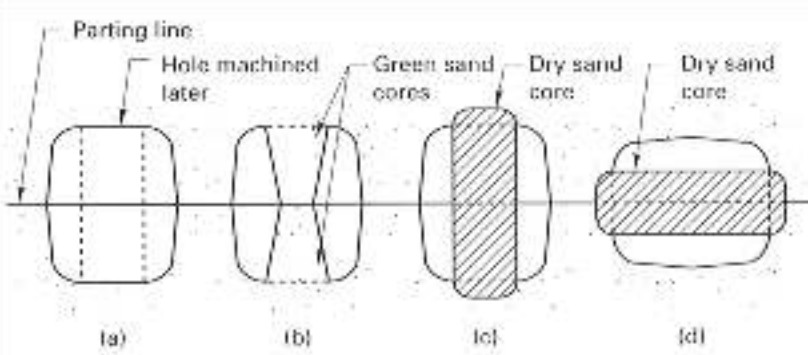


FIGURE 14-21 Four methods of making a hole in a cast pulley.

Cores and Core Making

- Dry-sand cores – independent to mould cavity. Make sand block that fits inside cavity (resting in core-prints). Cast around core. Remove core as crumbled sand. 14-21 C & D
- Dump core box approach -
  - Mould sand + binder in core-box, baked and removed. Joined with hot melt glue and fettled if necessary.
  - Coated with heat resistant material and to get smooth surface (graphite, silica etc)
  - Simple cores can be pressed or extruded.
  - Complex cores can be done in core making machines similar to injection moulding

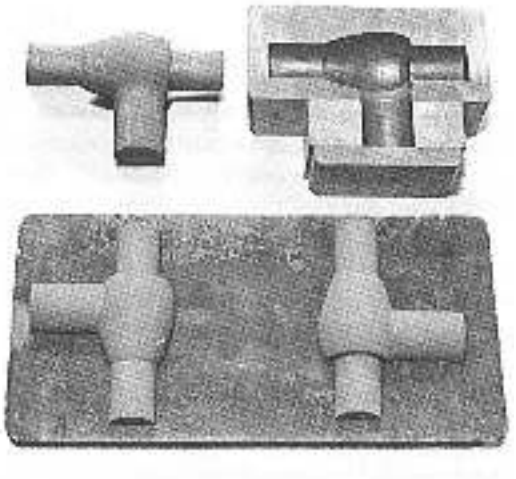


FIGURE 14-22 (*Clockwise from upper right*) Core box, two core halves ready for baking, and the completed core made by gluing the two halves together.

Cores and Core Making

- Cores are fragile and the core making process should provide the required strength for the cores.
  - Hot-Box method - A liquid thermosetting binder is added to sand and blown into hot (230°C) core-box. Cures quickly (10-30s) & removed.
  - Cold-Box method - Binder + sand blown into core-box and gas (e.g. SO2) passed through to cure resin without heat. (gases are toxic).
  - Air-set and no-bake sands (cold curing binder) and shell process can also be used to make cores.
    - The advantages of these approaches include curing in room temperature and in shell moulding hollow cores can be formed

Cores and Core Making

- Cores require:
  - Sufficient strength before hardening for handling
  - Sufficient hardness and strength after hardening to withstand handling and molten metal. (wires may be added) 100-500psi
  - Good permeability to gases. (charcoal centre or venting)
  - Collapsibility. After pouring, core must be weak enough to allow shrinkage, and also be easily removed on knock-out. (increase this by using straw centre)
  - Adequate refractoriness. Usually surrounded by hot metals.
  - Smooth surface.
  - Minimum gas generation during pour.

Cores and Core Making

- Cores located/supported by:
  - Core prints in cavity (from pattern)
  - Extra supports (Chaplets) can be added. Like internal chills these will become part of casting (possible cause of defects - to be avoided).
  - Large enough to prevent full melting, and small enough for surface to melt and fuse

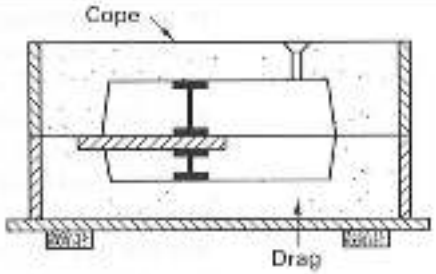


FIGURE 14-24 (*Top*) Typical chaplets. (*Bottom*) Method of supporting cores by use of chaplets (relative size of the chaplets is exaggerated).

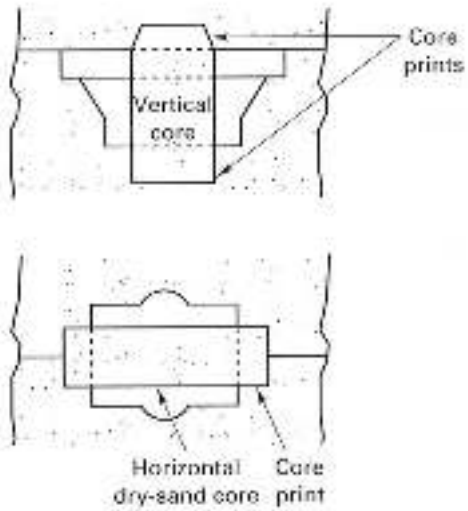
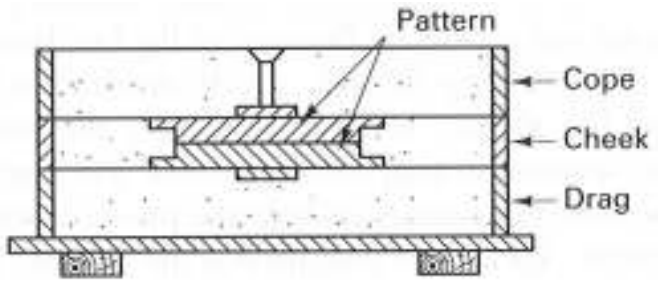


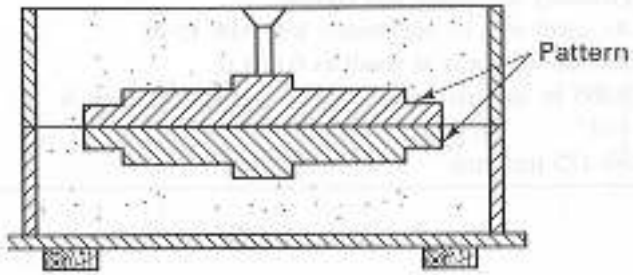
FIGURE 14-23 Molds cavities containing core prints to hold and position cores. (*Left*) Vertical core; (*right*) horizontal core.

Cores and Core Making

- A pulley with recess on sides has reentrant angles and can be made by two approaches:
  - 14-25 use of 3 piece process. Adding an additional parting line enables use of withdrawable patterns
  - No cores (green sand cores) – good for small runs
  - 14-26 use of cores. Use simple green sand mould together with ring shaped cores
  - Reduced moulding time – good for large runs

FIGURE 14-25 Method of making a reentrant angle using a three-piece flask.





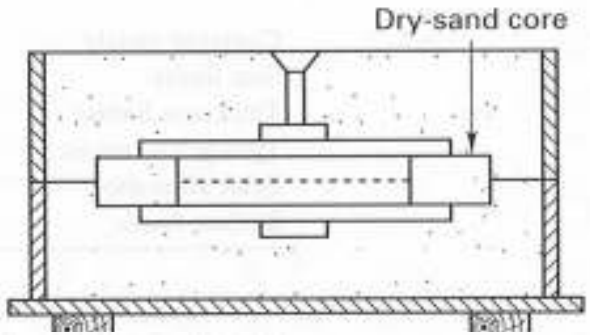


FIGURE 14-26 Molding a reentrant section using a dry-sand core.

Other Processes – Multi use patterns

- Plaster Mould Process – also known as Plaster of Paris is the mold mat'l
- Mixed with additives

Process:	A slurry of plaster, water, and various additives is poured over a pattern and allowed to set. The pattern is removed and the mold is baked to remove excess water. After pouring and solidification, the mold is broken and the casting is removed.
Advantages:	High dimensional accuracy and smooth surface finish; can reproduce thin sections and intricate detail to make net- or near-net-shaped parts.
Limitations:	Lower-temperature nonferrous metals only; long molding time restricts production volume or requires multiple patterns; mold material is not reusable; maximum size is limited.
Common metals:	Primarily aluminum and copper
Size limits:	As small as 1 oz but usually less than 15 lb.
Thickness limits:	Section thickness as small as 0.025 in.
Typical tolerances:	0.005 in. on first 2 in., 0.002 in. per additional inch
Draft allowance:	$\frac{1}{2}$–1°
Surface finish:	50–125 μin. rms

  - Talc (MgO_2) is added to prevent cracking, lime controls expansion, glass fibers add strength and sand is used as filler.
- Mould material added with water and additives poured over pattern and allowed to cure. Mould is then removed from metal pattern (complex patterns can be rubber too for easy removal)
- Advantage - Good surface finish. Limitation – Low MP metals/alloys

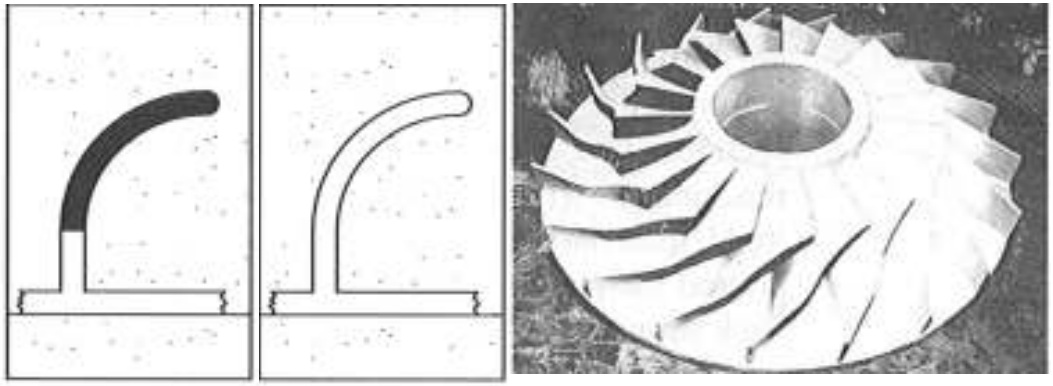
Other Processes – Multi use patterns

Process:	Stable ceramic powders are combined with binders and gelling agents to produce the mold material.
Advantages:	Intricate detail, close tolerances, and smooth finishes.
Limitations:	Mold material is costly and not reusable
Common metals:	Ferrous and high-temperature nonferrous metals are most common; can also be used with alloys of aluminum, copper, magnesium, titanium, and zinc.
Size limits:	Several ounces to several tons
Thickness limits:	As thin as 0.050 in.; no maximum
Typical tolerances:	0.005 in. on the first inch, 0.003 in. per each additional inch
Draft allowance:	1° preferred.
Surface finish:	75–150 μin. rms

- Ceramic Mould Process – similar to plaster but can withstand higher temp good for casting high MP metals/alloys
- Cope and drag moulds are formed using ceramic slurry as mould
- Thin sections can be done and good surface finish possible
- Mould material is expensive. Can use a thin layer of ceramic material backed with sand for large castings to reduce cost.

Other Processes – Multi use patterns

FIGURE 14-28 Method of combining ceramic mold casting and wax pattern casting to produce the complex vanes of an impeller. A wax pattern is added to a metal pattern. After the metal pattern is withdrawn *(**Left**)*, the wax pattern is melted out, leaving a cavity as shown *(**Center**), to produce the casting (**Right**).*



- Expendable graphite moulds - for metals like titanium (reactive when hot) graphite mixed binder is used around the pattern and cured at 1000°C. The pattern is removed and after casting, mould is broken.
- Rubber-mould casting - artificial elastomers are cast around pattern. Stripped from pattern (semi-rigid) to form mould. Good for low melting point materials and metals (<260°C) and for small castings.

Expendable Mould and Pattern

1. Investment casting - Produce a master pattern. (metal, wood, plastic).
2. From master pattern, produce a master die. (low-MP metal, steel, wood). If low-MP metal or rubber molds are used, the die can be cast from the master pattern. Steel dies may be machined without step 1
3. Produce wax patterns. Injecting molten wax into the master die. Cores can be made with soluble wax and removed before ceramic coating.
4. Assemble the wax patterns onto a common wax sprue to produce a pattern cluster, or tree to get better re entrant angles.
5. Coat the cluster with a thin layer of investment material. (dipping into a watery slurry of finely ground refractory).

Investment Casting

6. Produce the final investment around the coated cluster. (cluster is re-dipped, but wet ceramic is coated with a layer of sand - process repeated until desired thickness reached, or the single-coated cluster can be placed upside down in a flask and liquid investment material poured around it)
   - Vibrate the flask to remove entrapped air and settle the investment material around the cluster. (performed when the investment material is poured around the cluster)
7. Allow the investment to harden.
8. Melt or dissolve the wax pattern to remove it from the mold. (place molds upside down in an oven - wax melts and runs out, any residue subsequently vaporizes.

Investment Casting

9. Preheat the mold in preparation for pouring. Heating to 1000 to 2000°F (550 to 1100°C) complete removal of wax, cures the mold to give added strength, and allows the molten metal to retain its heat and flow more readily to all thin sections. It also gives better dimensional control because the mold and the metal will shrink together during cooling.
10. Pour the molten metal. Various methods, beyond simple pouring, can be used to ensure complete filling of the mold, especially when complex, thin sections are involved. Among these methods are the use of positive air pressure, evacuation of the air from the mold, and a centrifugal process.
11. Remove casting from mould

Investment Flask Casting

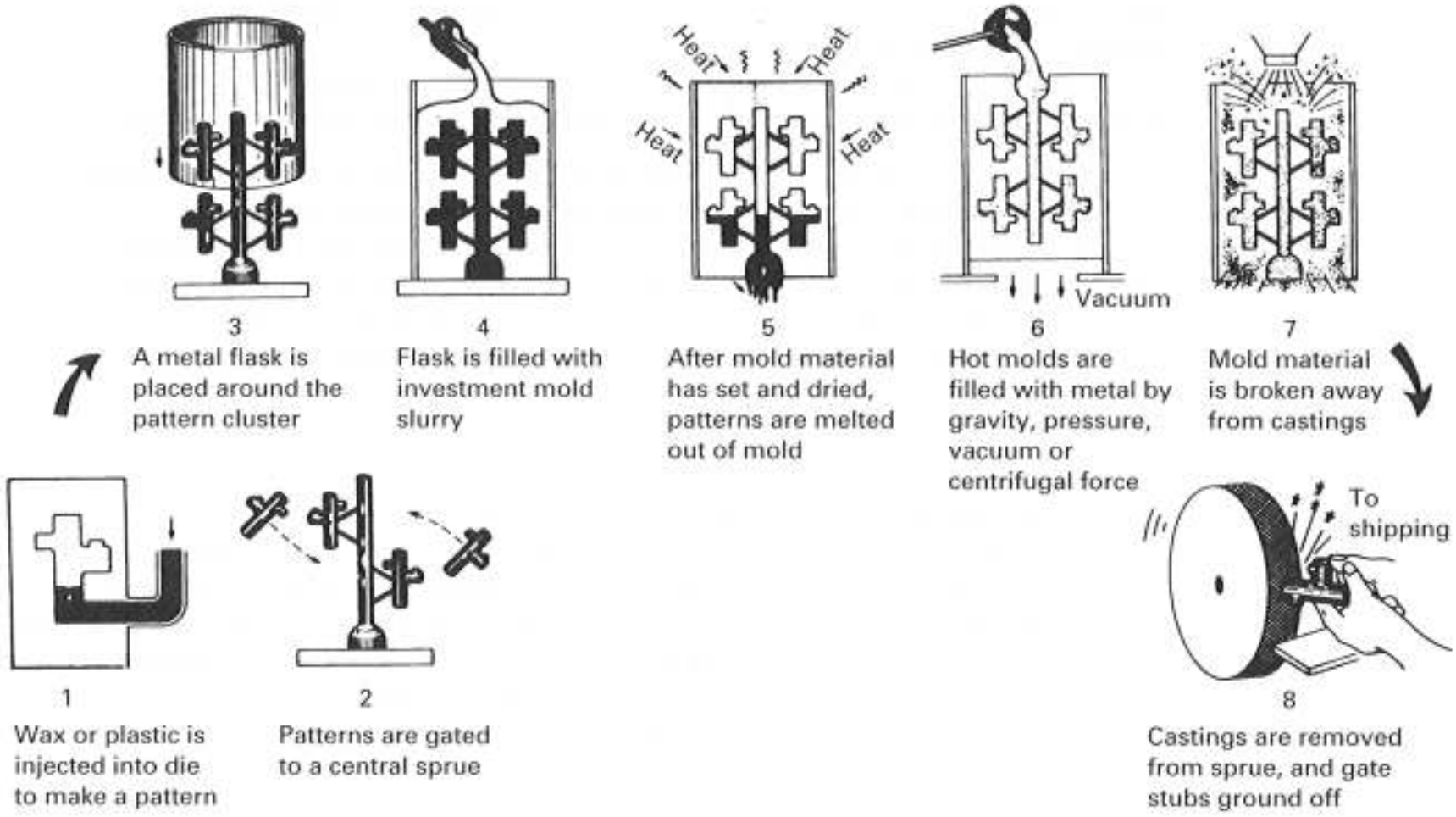


FIGURE 14-29 Investment flask-casting procedure. *(Courtesy of Investment Casting Institute, Dallas, Texas.)*

Investment Shell Casting

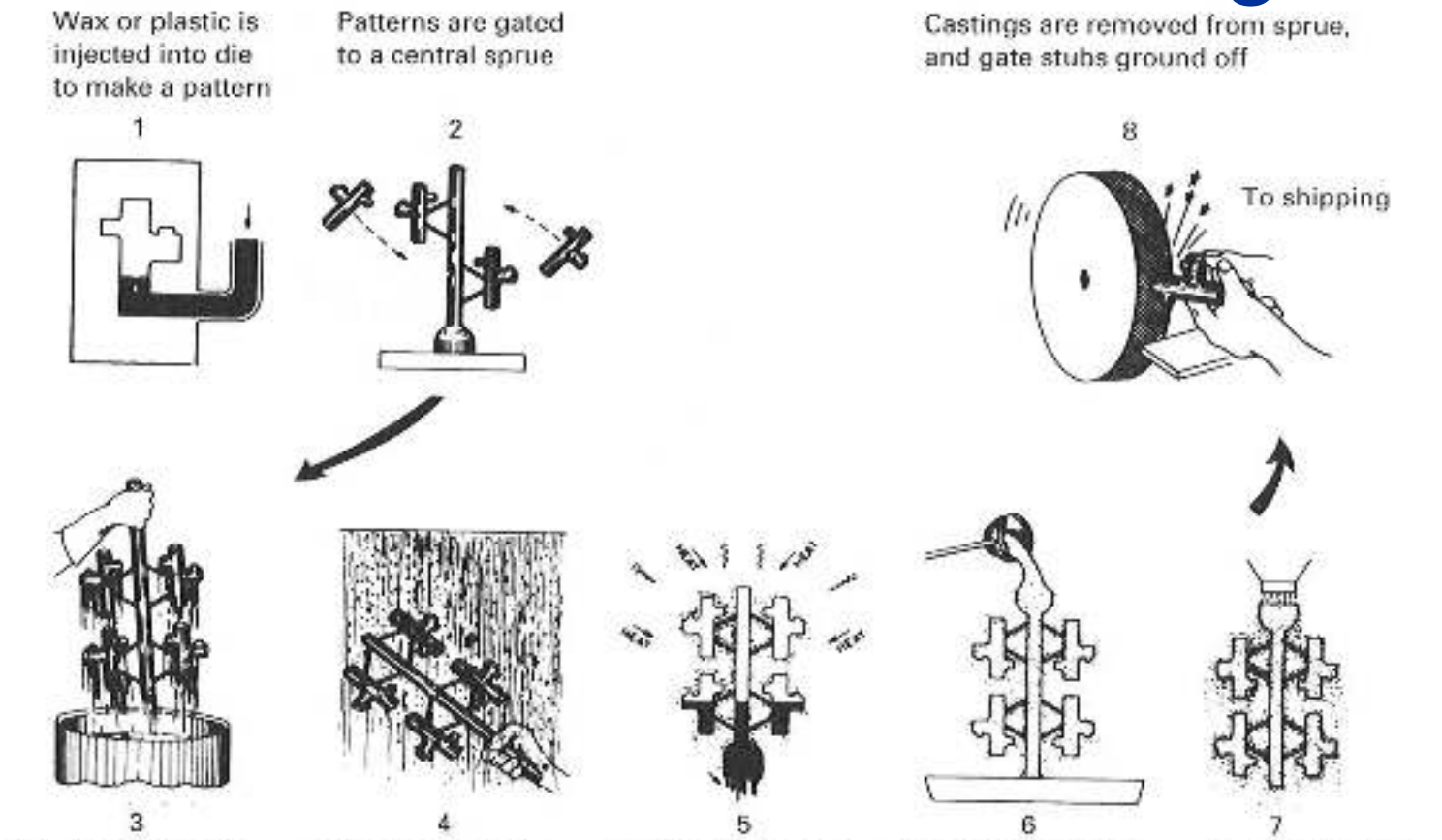


FIGURE 14-30 Investment shell-casting procedure. *(Courtesy of Investment Casting Institute, Dallas, Texas.)*

Investment Casting

TABLE 14-6. Investment Casting

Process:	A refractory slurry is formed around a wax or plastic pattern and allowed to harden. The pattern is then melted out and the mold is baked. Molten metal is poured into the mold and solidifies. The mold is then broken away from the casting.
Advantages:	Excellent surface finish; high dimensional accuracy; almost unlimited intricacy; almost any metal can be cast; no flash or parting line concerns.
Limitations:	Costly patterns and molds; labor costs can be high; limited size.
Common metals:	Aluminum, copper, and steel dominate; also performed with stainless steel, nickel, magnesium, and the precious metals.
Size limits:	As small as $\frac{1}{10}$ oz but usually less than 10 lb
Thickness limits:	As thin as 0.025 in., but less than 3.0 in.
Typical tolerances:	0.005 in. for the first inch and 0.002 in. for each additional inch.
Draft allowance:	None required
Surface finish:	50 to 125 μin. rms

FIGURE 14-31 Typical parts produced by investment casting. (Courtesy of Haynes Stellite Company.)

Evaporative Pattern Casting

1. EPS casting - Produce a pattern made of expanded polystyrene. For small quantities, pattern can be cut by heated wires. Runners and risers can be added by glue.
2. If large quantities are required, a metal mould is used to do single use pattern. Beads of PS injected into the mould cavity and heated where the expanded PS bonds together to form a complex bond. For more complex patterns can be made in multiple sections and glued
3. After patterning and gating attached, mould is done by
   - Full Mould method – green sand with chemical additives 14-32
   - Lost Foam Method – dipping in water based ceramic and powder 14-33

Evaporative Pattern Casting

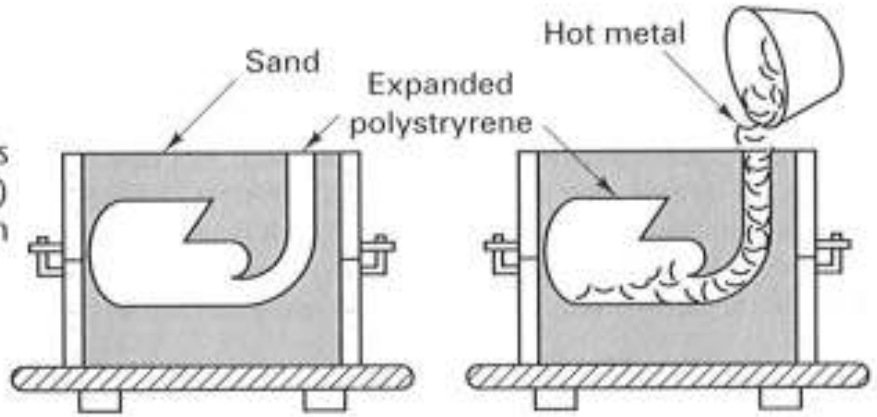
4. Mould metal poured inside the cavity without removing the pattern. During the pour the metal vaporizes and replaces the EPS pattern.
5. After cooling the sand is dumped and the casting is taken out for finishing.
6. Can make complex castings of both ferrous or non-ferrous metal economically. No draft is required as well.

TABLE 14-7. Full-Mold Casting

Process:	A Pattern containing a sprue, runners, and risers is made from single or multiple pieces of foamed plastic, such as polystyrene. It is dipped in a ceramic material, dried, and positioned in a flask, where it is surrounded by loose sand. Molten metal is poured directly onto the pattern, which vaporizes and is vented through the sand.
Advantages:	Almost no limits on shape and size; most metals can be cast; no draft is required and no flash is present (no parting lines).
Limitations:	Pattern cost can be high for small quantities; patterns are easily damaged or distorted because of their low strength.
Common metals:	Aluminum, iron, steel, and nickel alloys; also performed with copper and stainless steel.
Size limits:	1 lb to several tons
Thickness limits:	As small as 0.1 in. with no upper limit
Typical tolerances:	$\frac{1}{32}$ in./ft or less
Draft allowance:	None required
Surface finish:	100–1000 μin. rms

Evaporative Pattern Casting

FIGURE 14-32 Schematic of the full-mold process. (*Left*) Uncoated polystyrene pattern is in a bonded sand mold. (*Right*) Hot metal vaporizes the pattern and fills the resulting cavity.



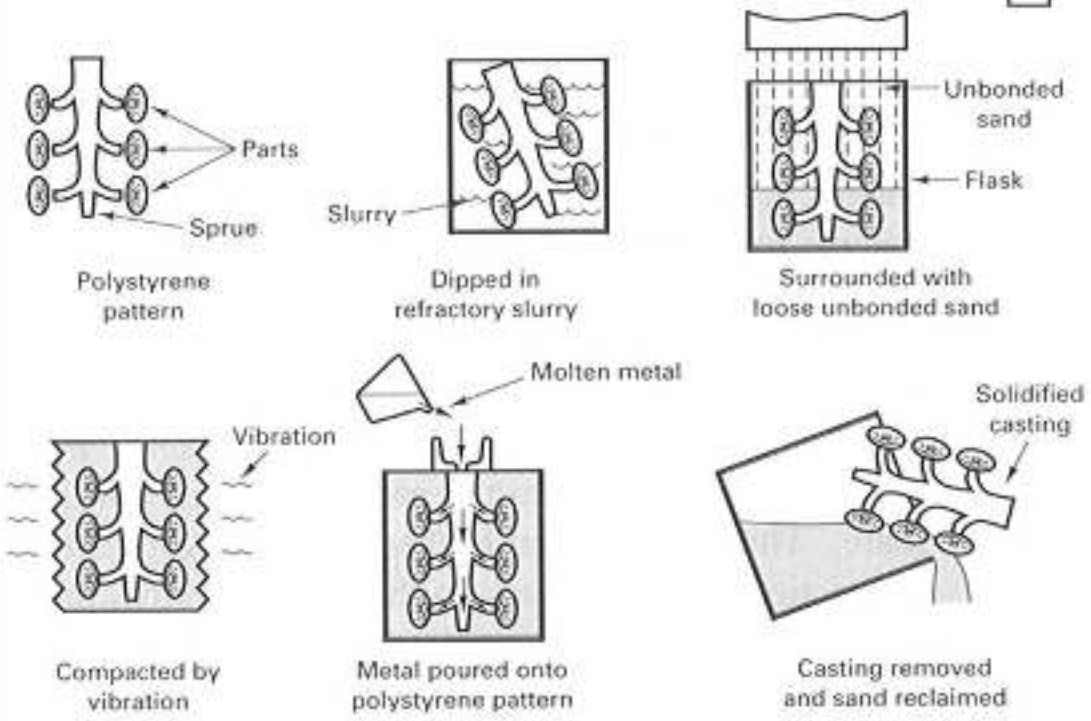


FIGURE 14-33 Schematic of the lost-foam casting process. In this process, the polystyrene pattern is dipped in a ceramic slurry, and the coated pattern is surrounded with loose, unbonded sand.

Evaporative Pattern Casting

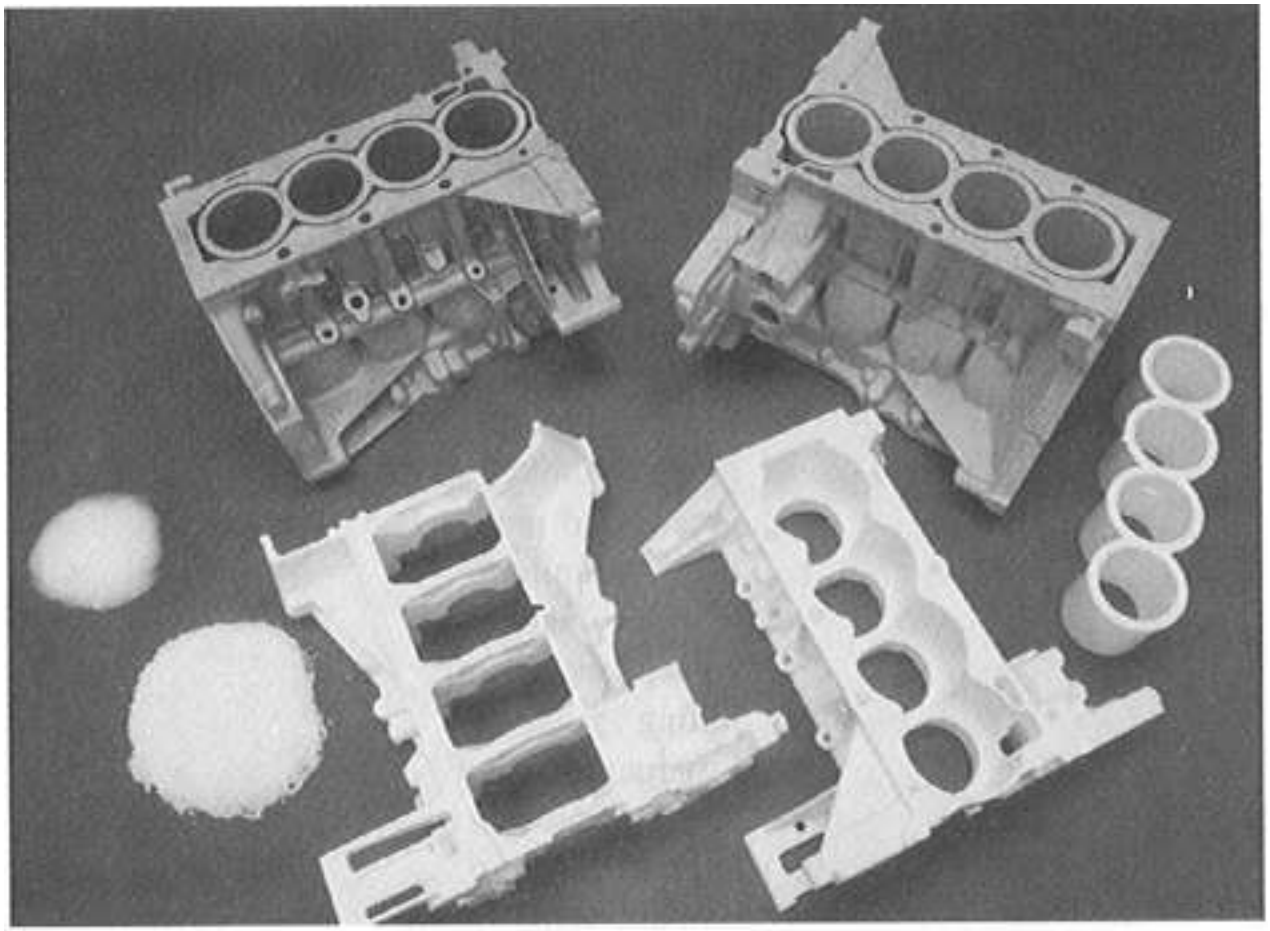


FIGURE 14-34 The stages of full-mold casting, counterclockwise from the left: polystyrene beads, expanded polystyrene pellets, foam pattern segments, assembled and dipped polystyrene pattern, and the finished metal casting. *(Courtesy of Saturn Corporation, Spring Hill, TN.)*

Shakeout, Cleaning and Finishing

- Final operation in casting is to separate casting from mould.
- Shakeout is designed to do
  - Separate the moulds and remove casting from mould
  - Remove sand from flask and cores from cast
- Punch out or vibratory machines are available for this task
- Blast cleaning is done to remove adhering sand from casting, or remove oxide scale and parting line burs.
- Final finishing operations include Grinding, Turning or any forms of machining

Types of Pattern

Table 5–2. Types of molds/dies, mold materials, patterns, and pouring principles classified in four basic process groups

Grouping	Type of mold	Mold material	Pouring principle	Pattern material	Process name
Sand casting	Nonpermanent (single-purpose)	Sand (green)	Gravity	Wood, metal, plastics	Green sand, dry sand, core sand casting
Permanent (metallic) mold casting	Permanent	Alloy steels	High pressure	—	Die casting
		Graphite, steel, cast iron	Low pressure	—	Low pressure (permanent mold casting)
		Cast iron, steel	Gravity		Nonpressure gravity permanent mold casting
Precision casting	Nonpermanent (single-purpose)	Nonmetallic (sand, plaster, ceramics, etc.)	Gravity (low pressure)	Metal	Shell mold casting
Investment or precision casting				Wax, plastic, (rubber, metal)	Plaster mold casting
Investment or precision casting				Wax, plastic, (rubber, metal)	Ceramic shell mold casting
Investment or precision casting				Wax, plastic, (rubber, metal)	"Lost wax" casting (investment casting)
Centrifugal casting	Nonpermanent/ permanent	Nonmetallic/ metallic	Centrifugal forces	—	Centrifugal casting

Shakeout, Cleaning and Finishing

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Investment or precision casting				Wax, plastic, (rubber, metal)	Plaster mold casting
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Centrifugal casting	Nonpermanent/ permanent	Nonmetallic/ metallic	Centrifugal forces	—	Centrifugal casting

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Multiple Mould Casting

Lecture 4

Multiple Use Mould Casting

- Use the same mould many times rather than make a new one for each casting.
  - high production rates,
  - more consistent castings (not necessarily better!)
  - different problems
  - limited to lower melting point metals
  - small to medium size castings
  - dies/moulds expensive to make

Permanent Mould Casting

Also known as Gravity Die Casting

- Machine (milling, EDM - spark erosion etc) a cavity in metal die. Gray cast iron, steel, bronze, graphite etc.
- Hinged or pinned to co-locate rapidly.
- Pre-heat die the first time (molten metal must get all the way through the mould before solidifying). Heat from previous casting is usually sufficient for subsequent castings.
- Directional solidification promoted by heating/cooling specific parts of the mould.
- Sound, relatively defect-free castings
- Multiple cavities in one die.

Permanent Mould Casting

- Expendable sand core or retractable metal cores can be used.
- Faster cooling rates than sand casting mean smaller grain size

  - better mechanical properties and surface finish, usually.

Process:	Mold cavities are machined into mating metal die blocks, which are then preheated and clamped together. Molten metal is then poured into the mold and enters the cavity by gravity flow. After solidification, the mold is opened and the casting is removed.
Advantages:	Good surface finish and dimensional accuracy; metal mold gives rapid cooling and fine-grain structure; multiple-use molds (up to 25,000 uses).
Limitations:	High initial mold cost; shape, size, and complexity are limited; yield rate rarely exceeds 60%, but runners and risers can be directly recycled; mold life is very limited with high-melting-point metals such as steel.
Common metals:	Alloys of aluminum, magnesium, and copper are most frequently cast; irons and steels can be cast into graphite molds; alloys of lead, tin, and zinc are also cast.
Size limits:	Several ounces to about 150 lb
Thickness limits:	Minimum depends on material but generally greater than $\frac{1}{8}$ in.; maximum thickness about 2.0 in.
Typical tolerances:	0.015 in. for the first inch and 0.002 in. for each additional inch; 0.01 in. added if the dimension crosses a parting line
Draft allowance:	2–3°
Surface finish:	100 to 250 μin. rms

Permanent Mould Casting

Limitations

- Limited to lower melting point metals usually but life still limited from 10,000 to 120,000 cycles. Mould life depends on:
  - Alloy being cast - higher the T_m (mp), the shorter the life.
  - Mould material - Gray cast iron best thermal fatigue resistance, easily machined.
  - Pouring temperature - higher temps mean reduced life, higher shrinkages and longer cycle times.
  - Mould temperature - too low, get misruns; too high long cycle times and erosion.
  - Mould configuration - difference in section sizes produce temperature variations through mould - reduce life.

Permanent Mould Casting

- No collapsibility so die opened as soon as solidification occurs.
- Refractory washes or graphite coatings used to prevent sticking & extend mould life.
- When casting iron, carbon deposited on walls with acetylene torch
- Moulds are non permeable. Special provision for venting. Cracks between die halves or special vent holes.
- Under gravity feed only so risers/feeders still necessary to compensate for solidification shrinkage. (yields < 60%)
- Sand and retractable metal cores used to increase complexity
- High volume production can justify die cost. Process mostly automated

Permanent Mould Casting

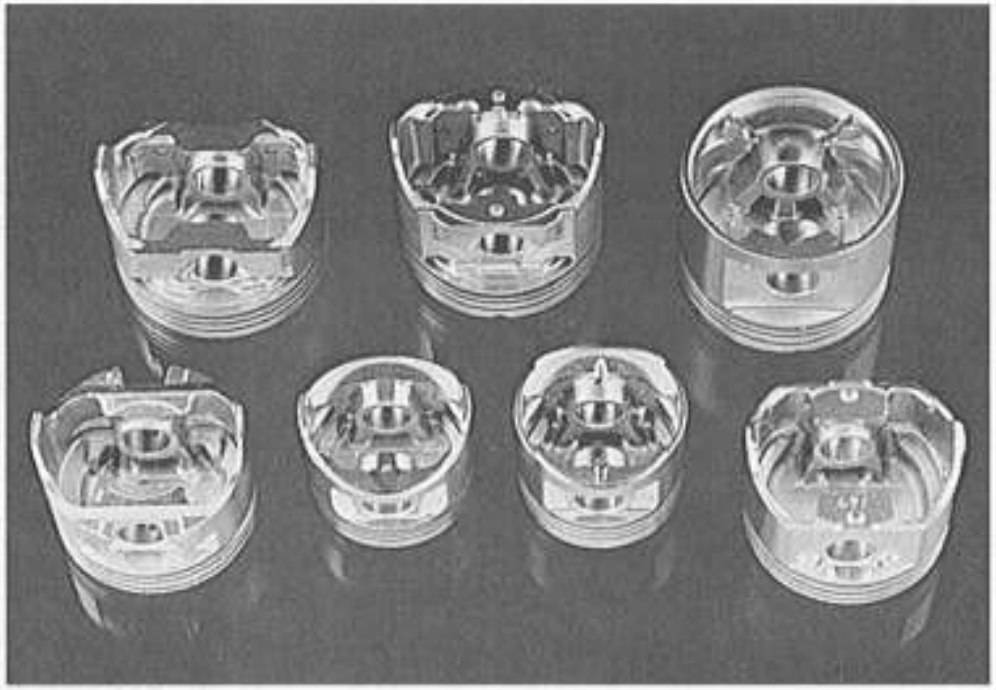


FIGURE 15-1 Truck and car pistons, mass-produced by the millions using permanent mold casting. *(Courtesy of Central Foundry Division of General Motors Corporation.)*

- Slush casting - permanent mould for hollow castings.
- Metal poured into die and allowed to cool
- Once shell of metal solidifies against die, mould is inverted excess metal poured out.
- Variable wall thickness, good outer surface - poor inner surface.

- Casting ornamental objects, candlesticks, lamp bases from low MP metals

Low Pressure Permanent Mould Casting

- Low pressures (5-15 psi) used to force molten metal up tube into mould. (common for Al or Mg)
- Clean metal from centre of bath fed directly into mould.
  - Dross floats up or sinks down, clean in the middle.
  - No sprues, gates runners, risers etc
  - Minimal oxidation
  - minimal turbulence

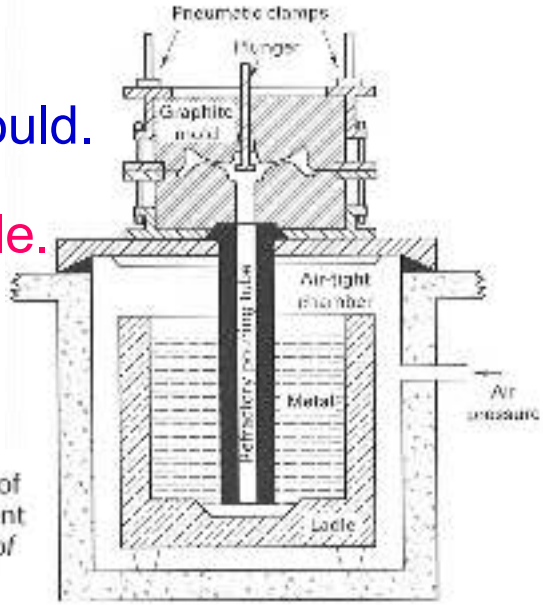


FIGURE 15-2 Schematic of the low-pressure permanent mold process. *(Courtesy of Amsted Industries.)*

- Mould solidifies directionally - tube can keep feeding liquid during solidification.
- Unused liquid drops back tube. Yields > 85%.
- Better mechanical properties than gravity die casting but slightly longer cycle times.

Vacuum Permanent Mould Casting

- Another variation of permanent mould casting
- Use vacuum to suck metal up into die.,
- Vacuum helps reduce surface oxidation and removes dissolved gases.
- Advantages of LPM are retained including clean metal from center
- Cleaner than LPM process
- Properties 10 to 15% better than conventional processes

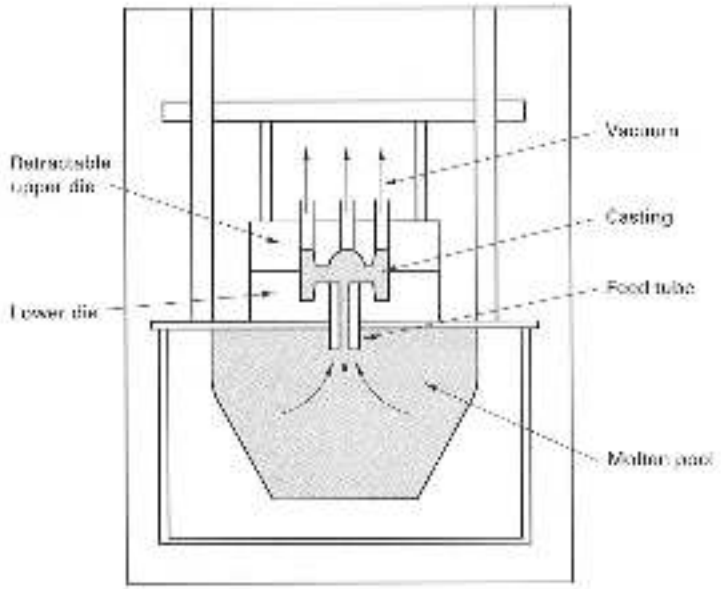
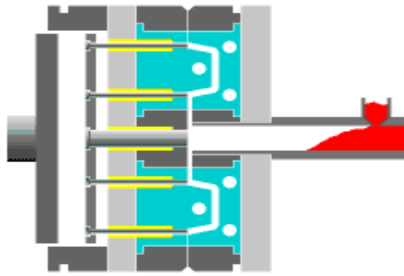


FIGURE 15-3 Schematic illustration of vacuum permanent mold casting.

Die Casting – High Pressure

- Metal forced into mould at high pressures (1,500 - 25,000 psi)
- Usually non-ferrous metals.
- Fine sections and excellent surface detail
- Need hardened hot-worked tool steels to withstand heat pressure - expensive. ($7500 - 15000)



- Complex parts - complex moulds. At least in 2 sections for removal
- Often water cooling passages, retractable cores, knock-out pins.

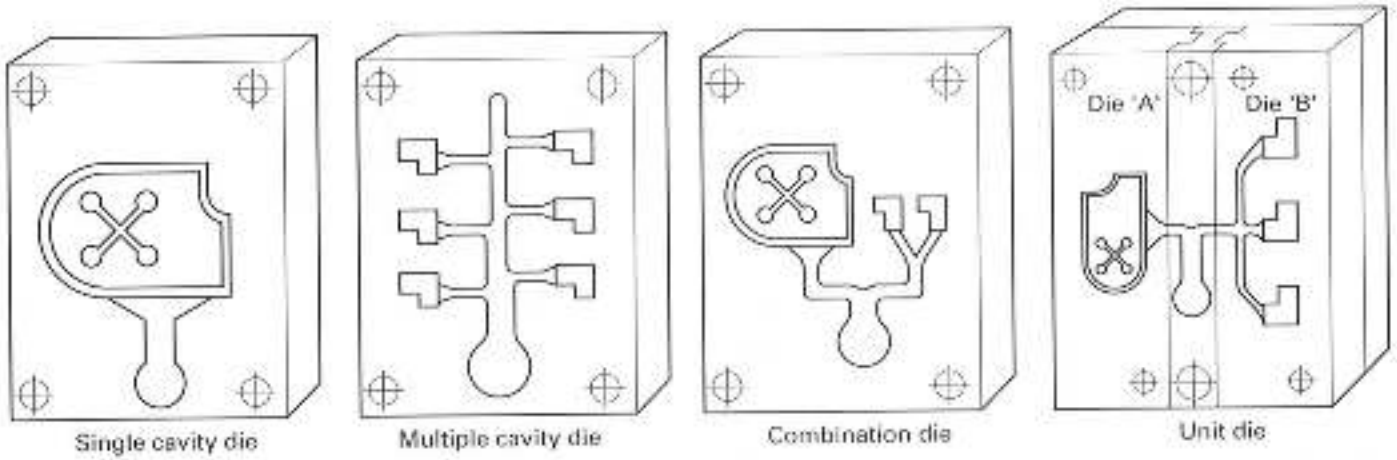


FIGURE 15-4 Some common die-casting designs. *(Courtesy of American Die Casting Institute, Inc., Des Plaines, Illinois.)*

Die Casting – High Pressure

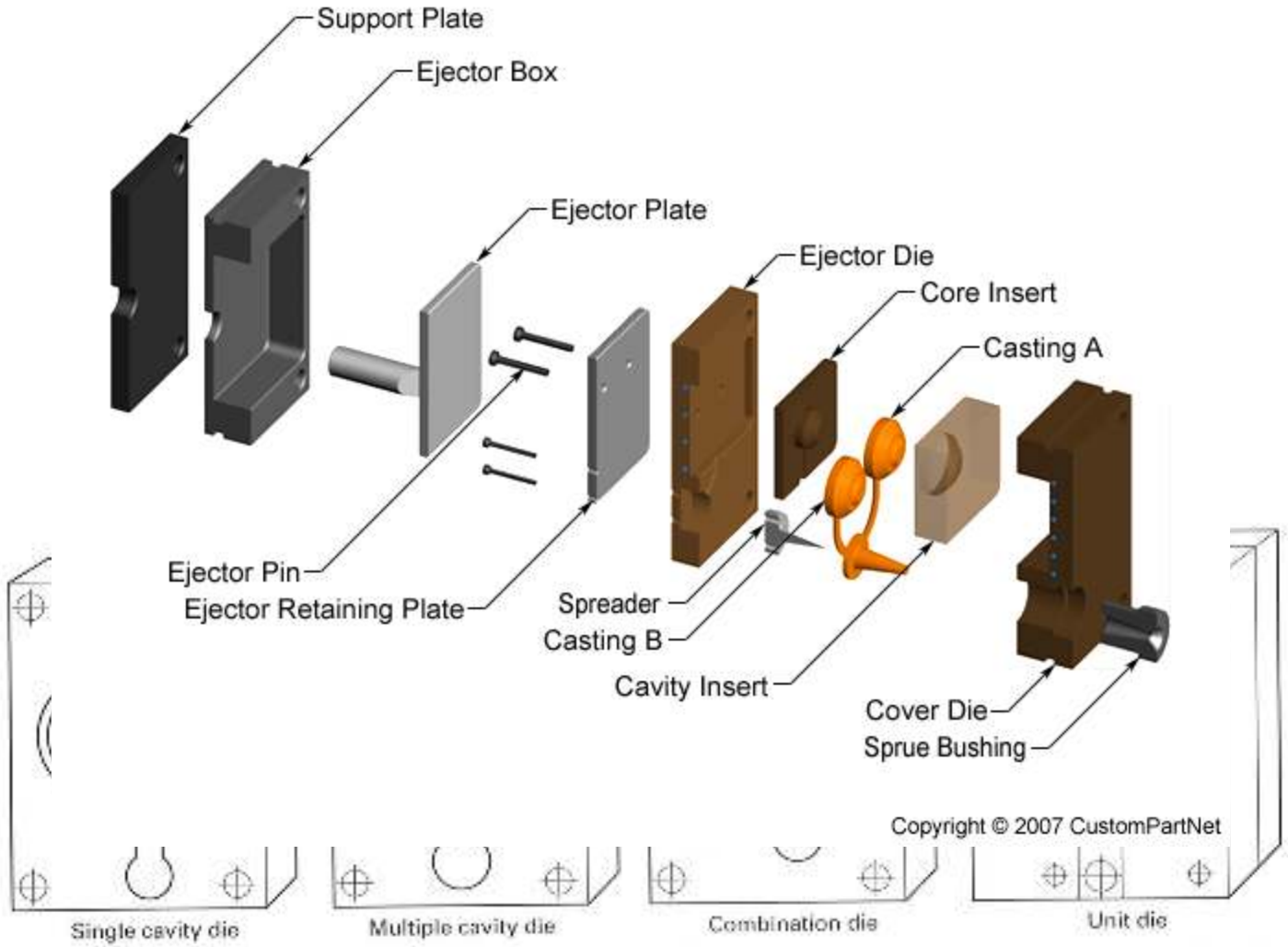


FIGURE 15-4 Some common die-casting designs. *(Courtesy of American Die Casting Institute, Inc., Des Plaines, Illinois.)*

Die Casting – High Pressure

- Die life limited by wear & erosion, and thermal fatigue.
- Die lubricated before closing.
- High injection pressures/ velocities cause turbulence - move to using larger gates and controlled filling - reduce porosity and entrained oxide. There are 2 types of Die Casting
- **Hot-chamber machines (gooseneck design)**
  - fast cycle times (up to 15 per minute)
  - same melting & holding chamber (no transfer required) (Al picks up iron from chamber, hence not good for Al)
  - lower mpt metals (zinc, tin, lead-based alloys)

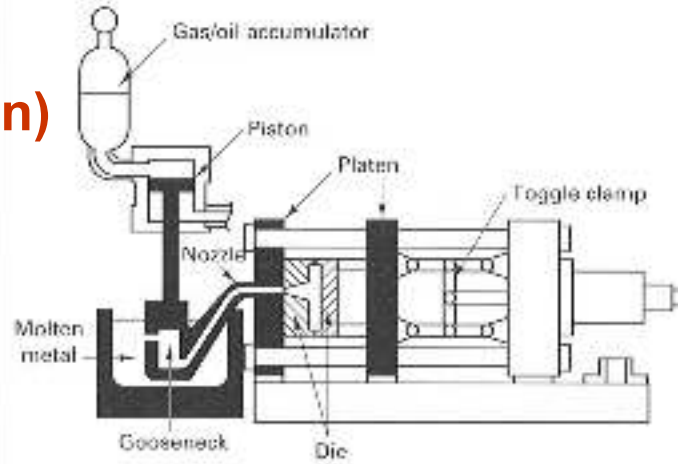
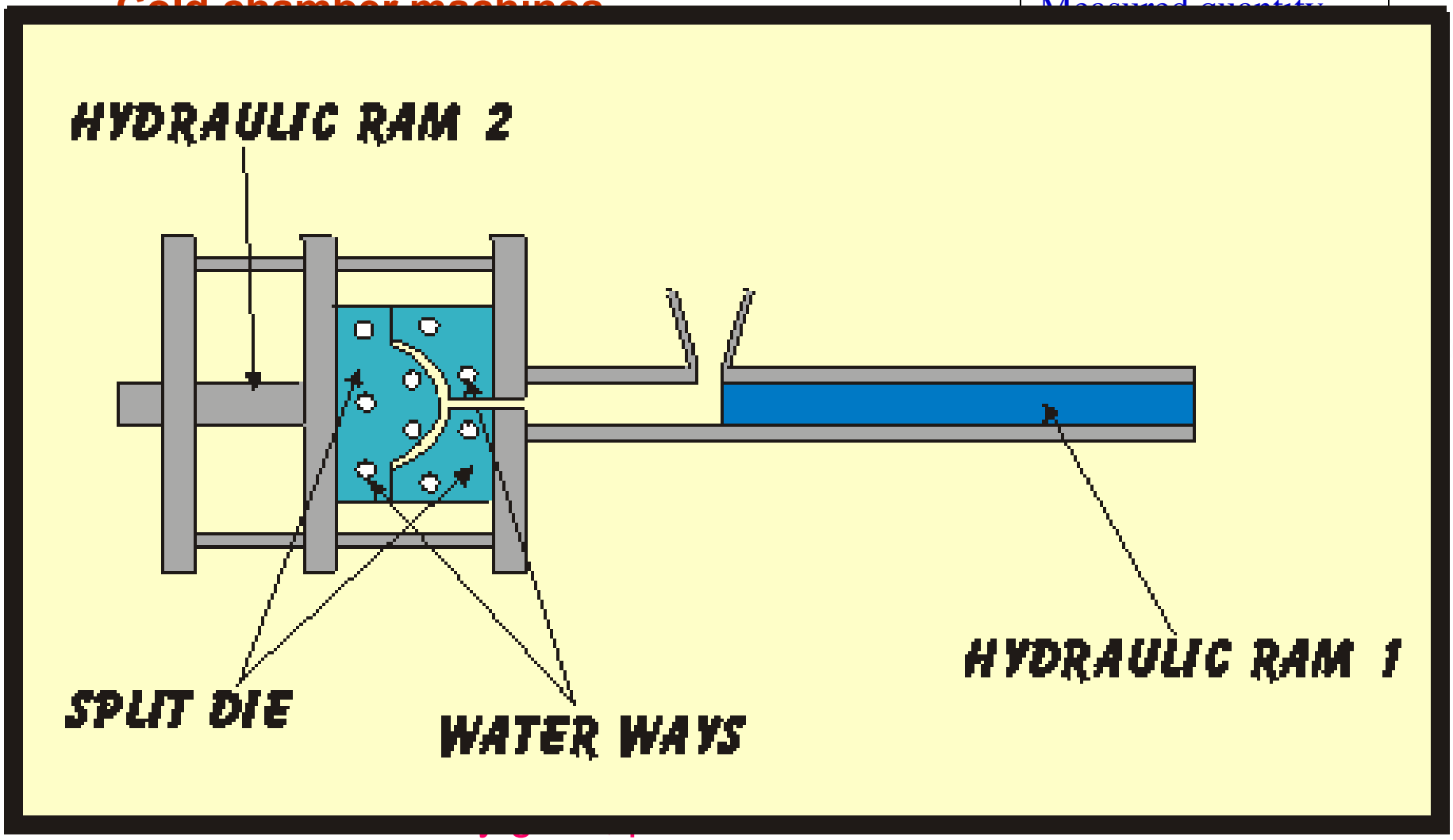


FIGURE 15-5 Principal components of a hot-chamber die-casting machine. *(Courtesy of Noranda Sales Corp. Ltd.)*

Die Casting – High Pressure



Die Casting – High Pressure

- No risers, pressure can fill for shrinkage. But trapped air can cause porosity in the center
- Pore-free casting
  - oxygen introduced into cavity to react with metal to form **small** oxide particles (eliminates gas porosity). Increase mechanical properties. Applied commonly in Al, Zn, Pb.
- Sand cores cannot be used (due to high pressure used). Retractable metal cores needed.
- Inserts may be placed in cavity for inclusion into casting; threaded bosses, heating elements, bearing surfaces can be placed in die before casting low MP metals/alloys.

Die Casting – High Pressure

Metal	Minimum Section	Minimum Draft
Aluminum alloys	0.035 in. (0.89 mm)	1:100 (0.010 in./in.)
Brass and bronze	0.050 in. (1.27 mm)	1:80 (0.015 in./in.)
Magnesium alloys	0.050 in. (1.27 mm)	1:100 (0.010 in./in.)
Zinc alloys	0.025 in. (0.63 mm)	1:200 (0.005 in./in.)

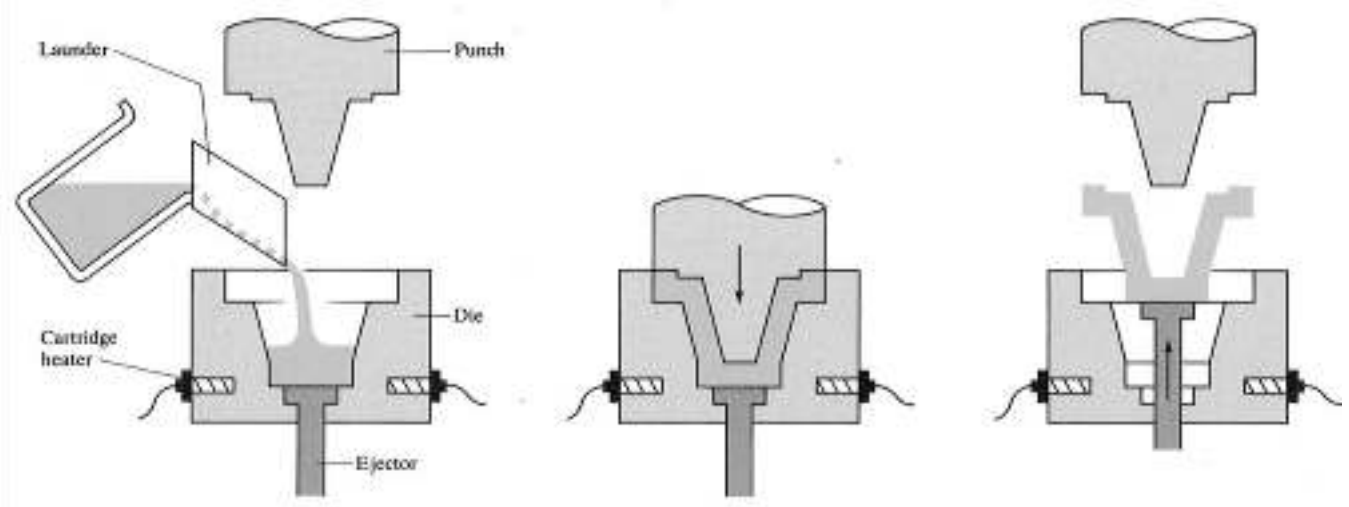
- No machining required due high tolerances and lesser draft

TABLE 15.2 Die Casting

Process:	Molten metal is injected into closed metal dies under pressures ranging from 1500 to 25,000 psi. Pressure is maintained during solidification, after which the dies separate and the casting is ejected along with its attached sprues and runners. Cores must be simple and retractable and take the form of moving metal segments
Advantages:	Extremely smooth surfaces and excellent dimensional accuracy; rapid production rate.
Limitations:	High initial die cost; limited to high-fluidity nonferrous metals; part size is limited; porosity may be a problem; some scrap in sprues, runners, and flash, but this can be directly recycled
Common metals:	Alloys of aluminum, zinc, magnesium, and lead; also possible with alloys of copper and tin
Size limits:	Less than 1 oz up through about 15 lb most common
Thickness limits:	As thin as 0.03 in., but generally less than $\frac{1}{2}$ in.
Typical tolerances:	Varies with metal being cast; typically 0.005 in. for the first inch and 0.002 in. for each additional inch
Draft allowances:	2°
Surface finish:	40–100 μin. rms.

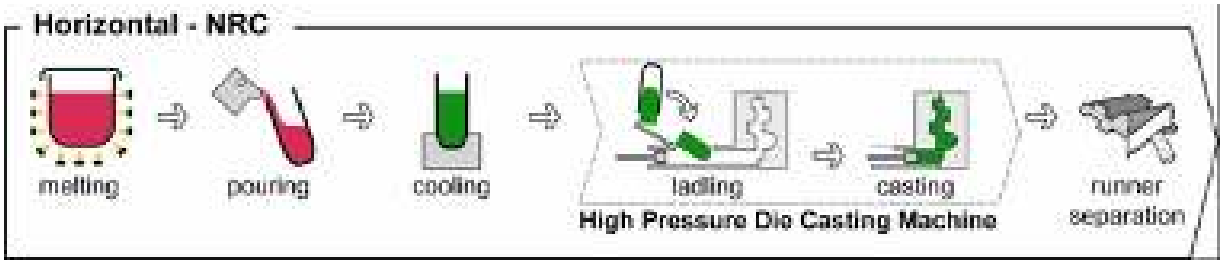
Squeeze Casting & Semi-Solid Casting

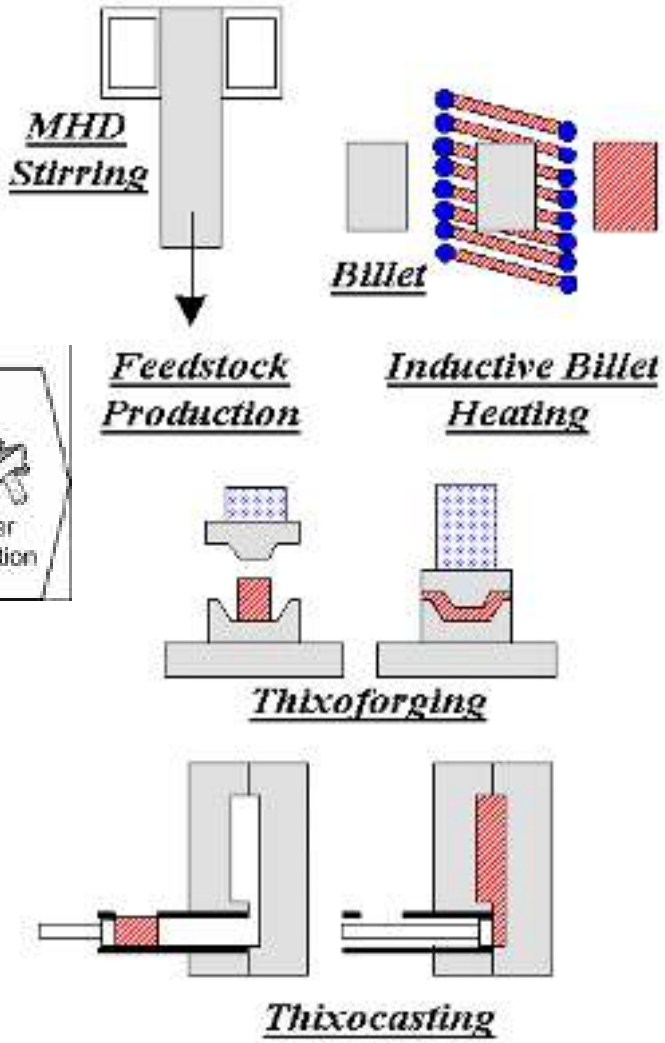
- Cast metal into die bottom, allow partial solidification then squeeze with die top.
- Use of large gates reduce velocity and turbulence
- Core can be used. Gas and shrinkage porosity are minimal.
- Reinforcement inserts can be used (Metal Matrix Composites)



Squeeze Casting & Semi-Solid Casting

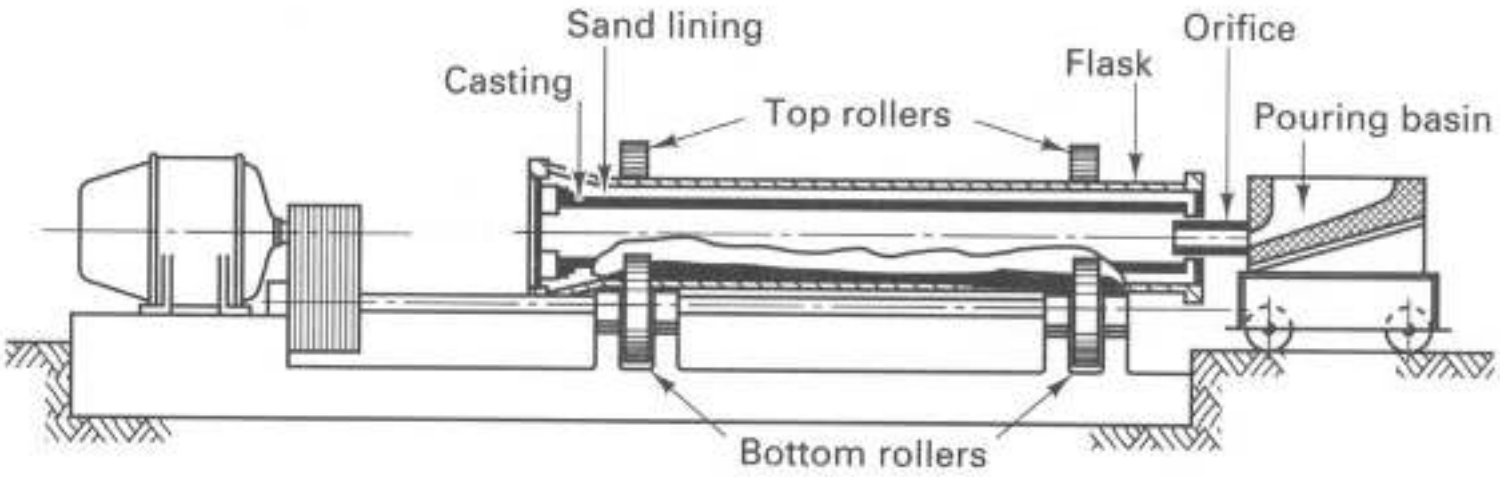
- Material in the form of semi solid (thixo tropic material) can be cast with this
- Less gas entrapment, high quality finish





Centrifugal Casting

- Inertial forces of rotation distribute molten metal in cavity (300-3000rpm) against mould walls to form hollow product; pipes, gun barrels etc



Horizontal centrifugal casting

Centrifugal Casting

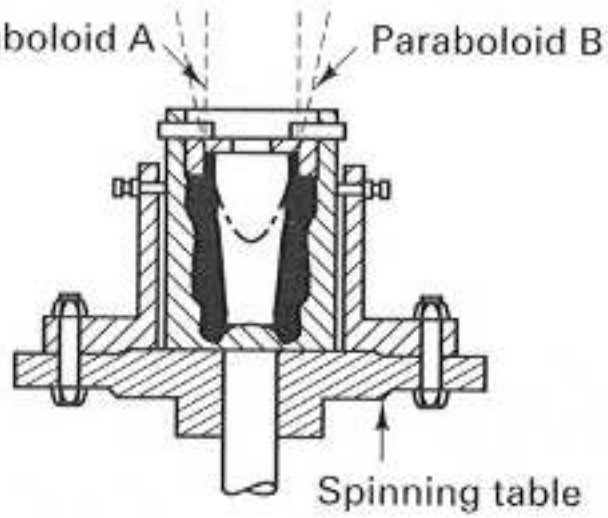


FIGURE 15-9 Vertical centrifugal casting, showing the effect of rotational speed on the shape of the inner surface. Paraboloid A results from fast spinning, paraboloid B from slow spinning.

TABLE 15.3 Centrifugal Casting

Process:	Molten metal is introduced into a rotating sand, metal, or graphite mold, and held against the mold wall by centrifugal force until it is solidified
Advantages:	Can produce a wide range of cylindrical parts, including ones of large size; good dimensional accuracy, soundness, and cleanliness
Limitations:	Shape is limited; spinning equipment can be expensive
Common metals:	Iron, steel, stainless steel, and alloys of aluminum, copper, and nickel
Size limits:	Up to 10 ft in diameter and 50 ft in length
Thickness limits:	Wall thickness 0.1–5 in.
Typical tolerances:	O.D. to within 0.1 in.; I.D. to about 0.15 in.
Draft allowance:	$\frac{1}{8}$ in./ft.
Surface finish:	100–500 μin. rms.

Centrifugal Casting

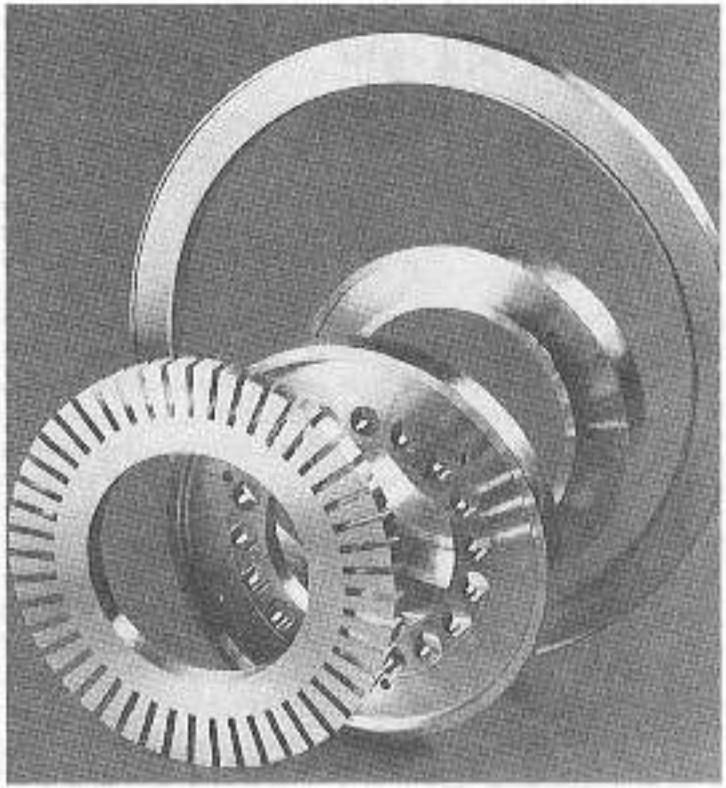


FIGURE 15-10 Electrical products (collector rings, slip rings, and rotor end rings) that have been centrifugally cast from aluminum and copper. *(Courtesy of The Electric Materials Company.)*

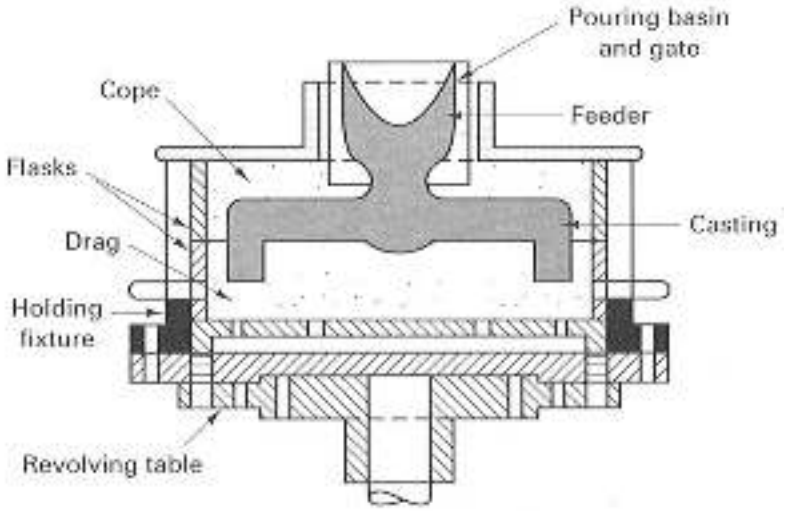


FIGURE 15-11 Semicentrifugal casting process.

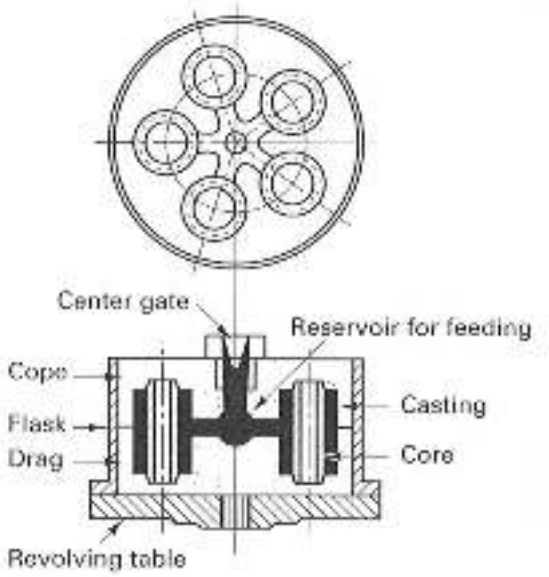


FIGURE 15-12 Method of casting by the centrifuging process. Metal is poured into the central pouring sprue and spun into the various mold cavities. *(Courtesy of American Cast Iron Pipe Company.)*

Continous Casting

- Used to produce:
  - basic shapes for subsequent hot/cold working.
  - Long lengths of uniform cross section product.
- Direct chill - long ingots (semi-continuous casting)

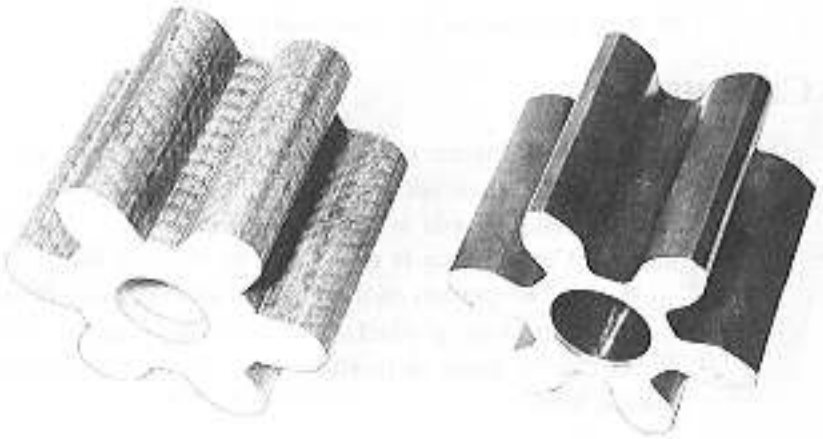


FIGURE 15-13 Gear produced by continuous casting. (*Left*) As-cast material; (*right*) after machining. (*Courtesy of American Smelting and Refining Company.*)

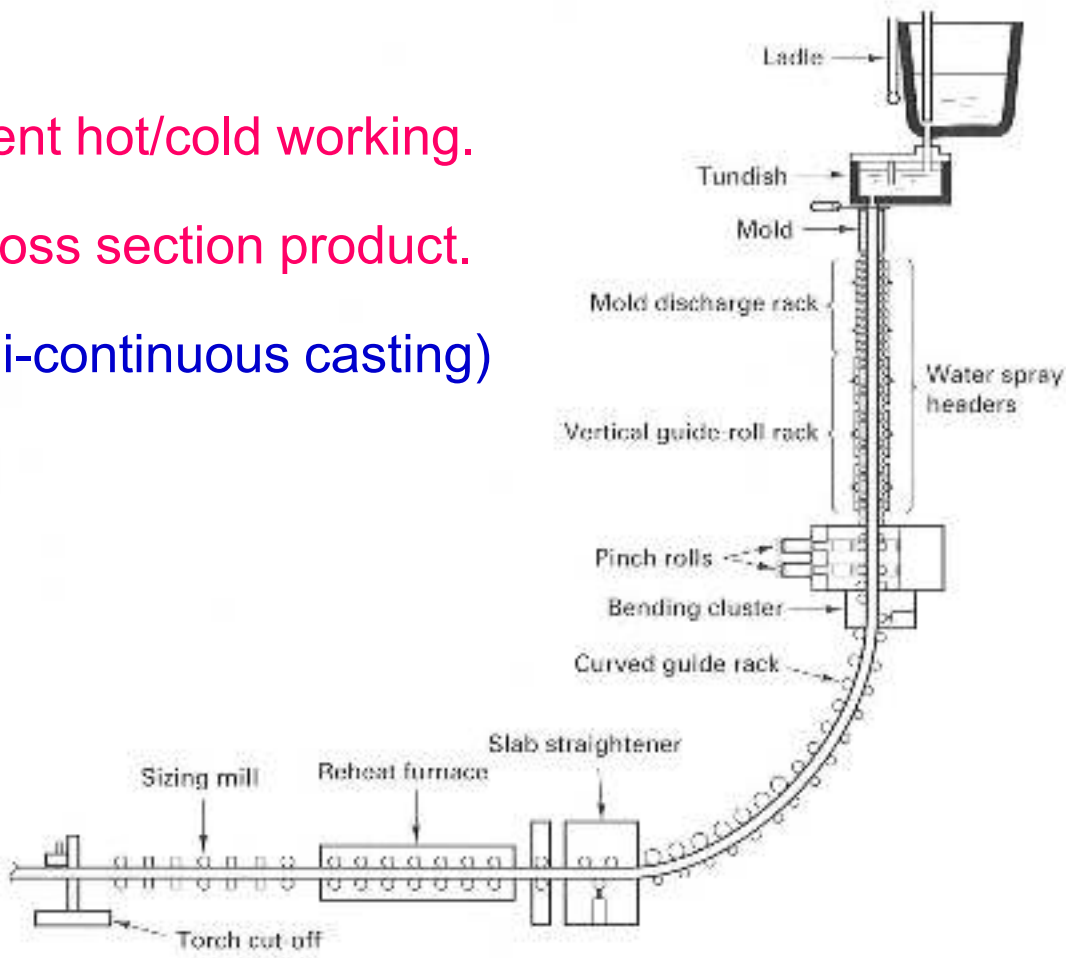


FIGURE 6-6 Schematic representation of the continuous casting process for producing billets, slabs, and bars. (*Courtesy of Materials Engineering.*)

Melting and Pouring

- System needs to produce molten metal:
  - at right temperature
  - with desired chemistry (not gaining or losing elements)
  - minimum contamination
  - long holding times without deterioration of quality
  - economical
  - environmentally friendly

Melting Procedure

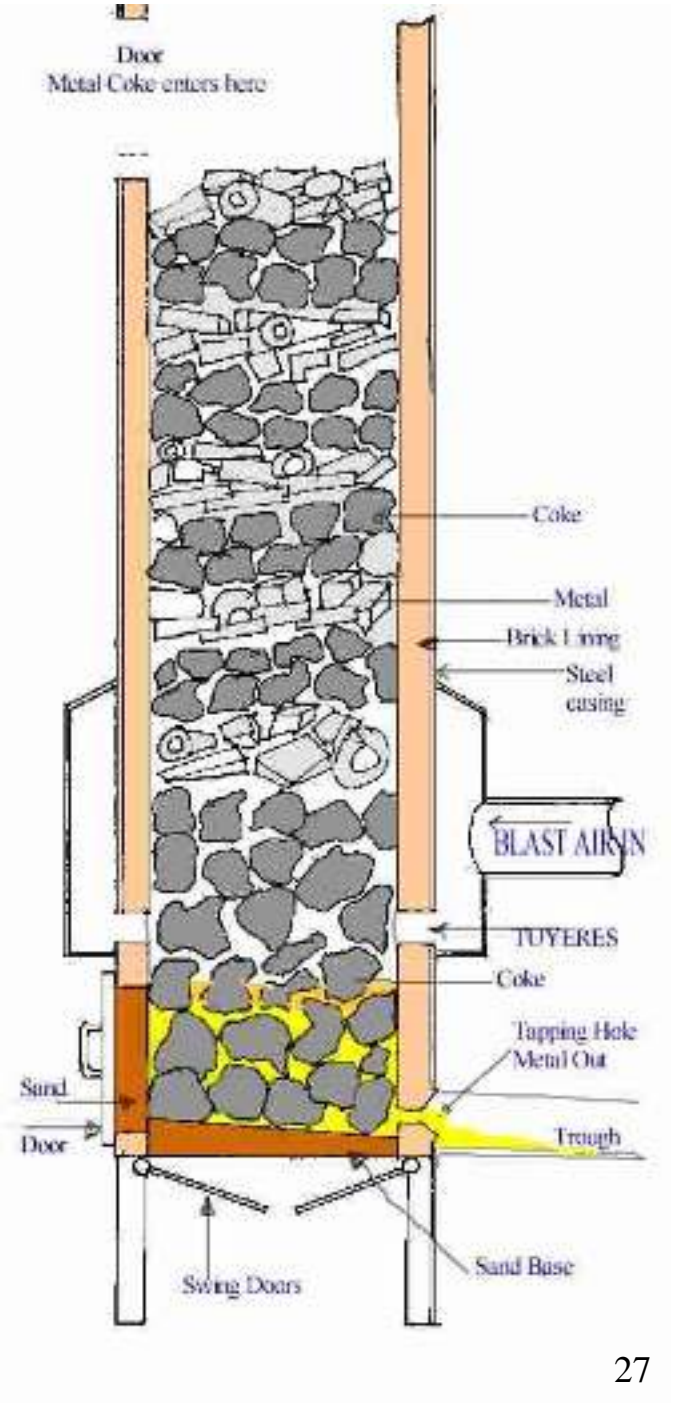
- Furnace/melting procedure depends on:
- temperatures required (including superheat)
- alloy being melted (and additions required)
- melting rate required
- metal quality (cleanliness)
- fuel costs
- variety of metals to be melted
- batch or continuous
- emission levels
- capital and operating systems

Melting Procedure

- Feedstock varies:
  - pre-alloyed ingot,
  - primary metal ingots + alloying elements (pure or master alloys),
  - commercial scrap.
- Often pre-heated. Increases melting rate by 30%

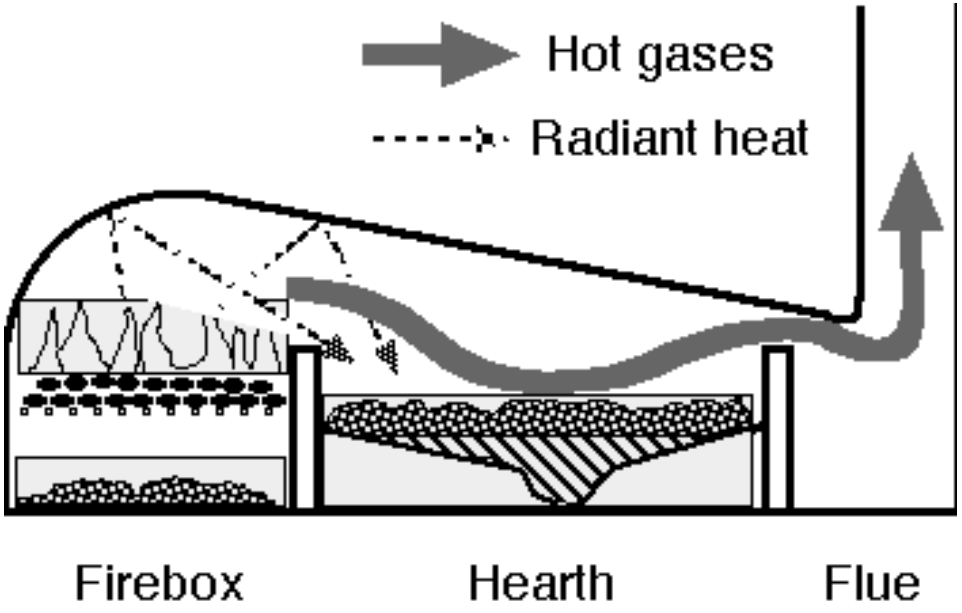
Furnaces

- Cupola - old-fashioned method of heating cast irons
  - Vertical, refractory lined shell with layers of coke, pig iron/scrap, limestone/flux, additions. Melted under forced air draft (like blast furnace). Molten metal collects at bottom, tapped off as needed.
  - Chemistry and temperature difficult to control



Furnaces

- Indirect Fuel Fired Furnaces
  - small batches of non-ferrous metals, Crucible is heated on outside by flame
- Direct Fuel Fired Furnaces
  - Surface of metal heated directly by burning fuel, larger than crucible, non-ferrous or cast iron holding furnace



Furnaces

- Arc Furnaces
  - Uses electrodes to pass electric arc to charge and back.
  - Rapid heating. Good for holding molten metal
  - Easier for pollution control

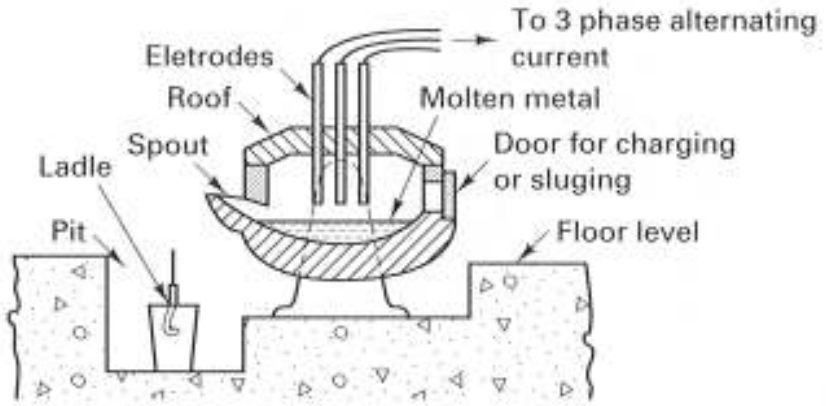


FIGURE 15-16 Schematic diagram of a three-phase electric arc furnace.

Furnaces

- Arc Furnaces
  - Open top, put charge in, replace top, lower electrodes to create arc.
  - Fluxes are added to protect molten metal (up to 200 tons, up to 25 tons more common).
  - Often used for steel, stainless steel. Good mixing, noisy, high consumables cost

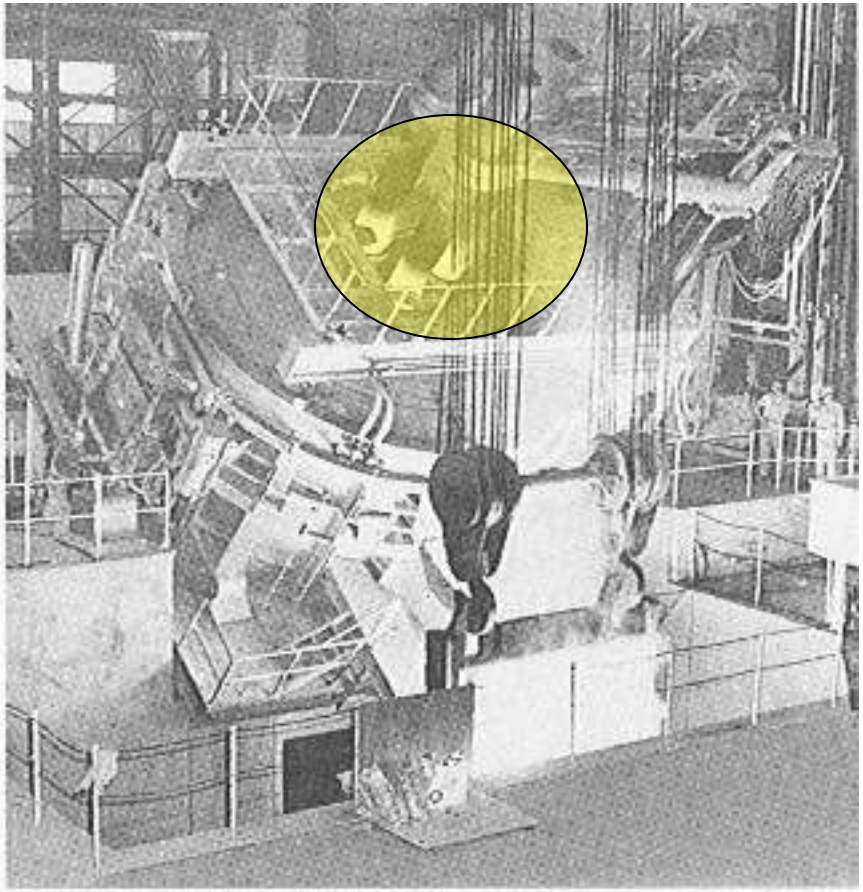


FIGURE 15-17 Electric arc furnace, tilted for pouring. *(Courtesy of Pittsburgh Lectromelt Furnace Corporation.)*

Furnaces

- Induction Furnaces
  - Electric induction. Rapid melting rates
  - Easier pollution control. Popular
- High-Frequency/coreless Units
  - crucible is surrounded by water cooled copper coil carrying high frequency electrical current. Creates alternating magnetic field which induces secondary currents in metal causing rapid heating.
  - All common alloys. Max temp. limited only by crucible lining
  - good temperature and compositional control
  - Up to 65 tons capacity, no contamination from heat source, pure

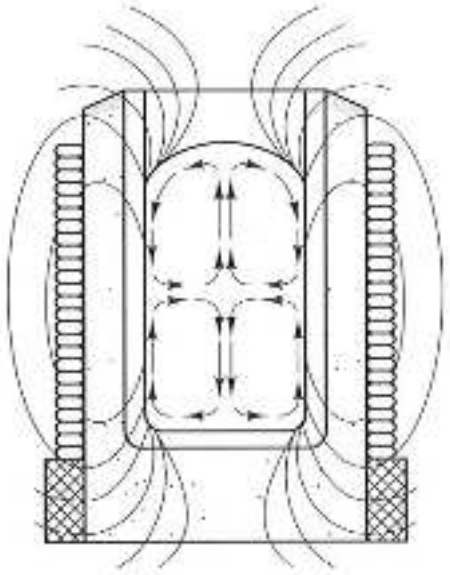


FIGURE 15-18 Schematic showing the basic principle of a coreless induction furnace.

Furnaces

- Low frequency/channel-type units
  - Primary coil surrounds a small channel through which molten metal flows to form secondary coil. Metal circulates through channel to be heated.

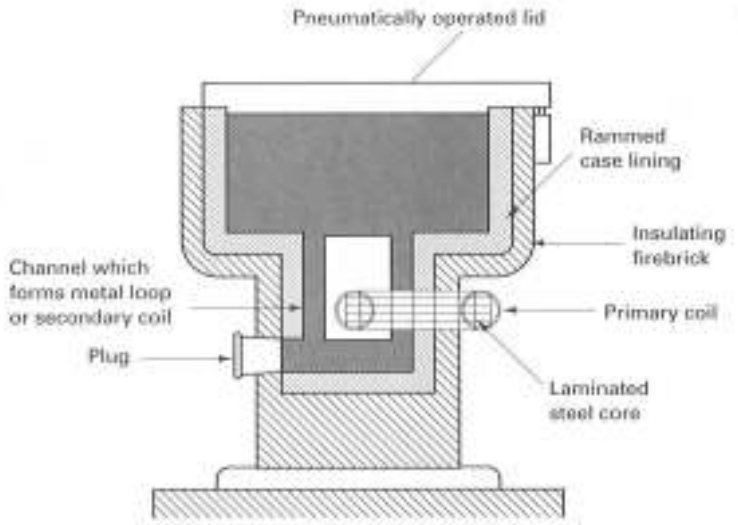


FIGURE 15-19 Cross section showing the principle of the low-frequency or channel-type induction furnace.

  - Accurate control, rapid heating
  - Must charge initially with enough molten metal to fill secondary coil.
  - Remaining metal can be any form
  - Often used as holding furnace, to maintain temperature for extended time. Capacities up to 250 tons

Pouring Practice

- Pouring device (LADLE) usually used to transfer molten metal from furnace to mould.
  - Maintain metal at appropriate temperature
  - deliver only high quality metal to mould (I.e. no dross/slag etc.)

- hand-held for small foundries/castings
- machine held, bottom pour ladles in larger foundries/castings

Melting and Pouring

- Automatic pouring machines in mass-production foundries.
  - Molten metal transferred from main melting furnace to holding furnace
  - Measured quantity transferred to pouring ladles
  - And into corresponding moulds as they move in pouring station
  - Laser based position control

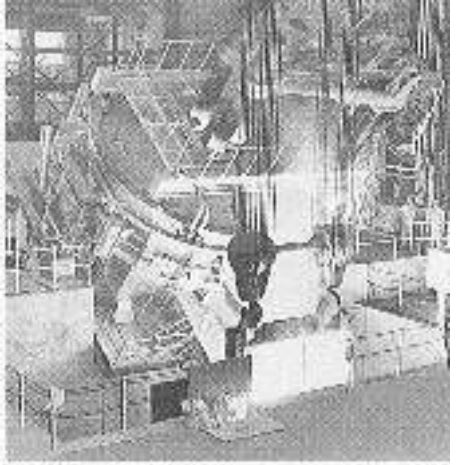


FIGURE 13-17 Electric arc furnace, tilted for pouring. (Courtesy of Pittsburgh Lectromelt Furnace Corporation.)

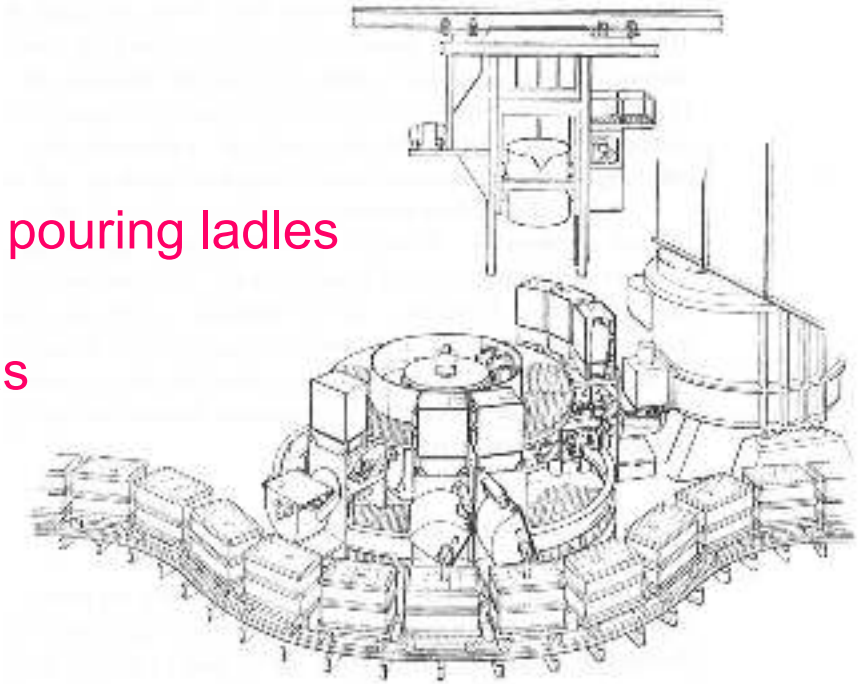


FIGURE 15-21 Machine for automatic pouring of molds on a conveyor line. (Courtesy of Roberts Corporation.)

Cleaning & Finishing

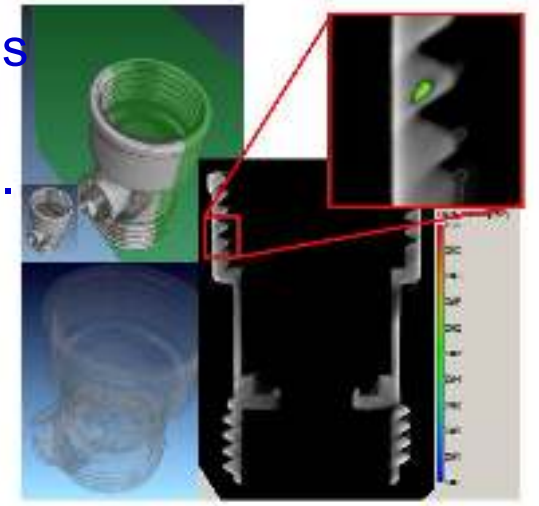
- Once removed from mould, most casting castings require some cleaning and/or finishing. E.g.
  - Removing cores (shaking, chemical dissolving of binder).
  - Removing gates, risers (small castings - knocked off, larger castings - cut off - cut-off wheel, hacksaw, plasma/gas cutter)
  - Remove fins, flash, rough spots (tumbling with metal shot, sand blasting, manual cutting, dressing for large castings)
  - Cleaning the surface (as above)
  - Repairing large castings (small castings remelted but large castings often cheaper to repair - grind/chip defect out then weld (or cast a patch). Pores can be filled with resin for some applications.

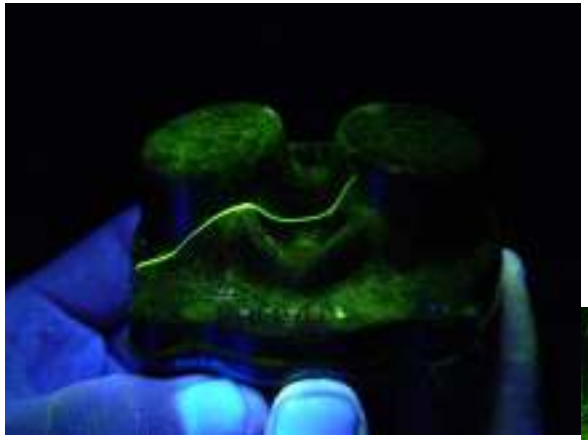
Heat Treating & Inspection

- Heat Treatment - main way of changing properties without affecting shape
- Steel castings annealed to reduce brittleness of rapidly cooled thin sections and for stress relief
- Quench & temper treatments possible on most ferrous alloys
- Age-hardening treatments possible on some alloys

Heat Treating & Inspection

- Non destructive testing often carried out on castings to check for defects; cracks, pores, internal defects.
  - X-ray radiography
  - neutron radiography
  - liquid penetrant
  - magnetic particle





Process Selection

- Some factors independent of casting method (metal & energy cost) but others are dependent (mould, pattern, machining, & labor costs)
- Pattern & Mould costs (sand casting – cheap, die casting – expensive)
- But as quantities of castings increase:
  - sand casting still needs new mould per casting, price per unit not strongly affected.
  - Die-casting can use same mould so price per unit comes down.

Process Selection

- Each casting process has its own benefits/ disadvantages:
  - Costs, batch sizes,
  - Quality, mass production
  - Alloys, complexity
  - compositional control
  - surface finish

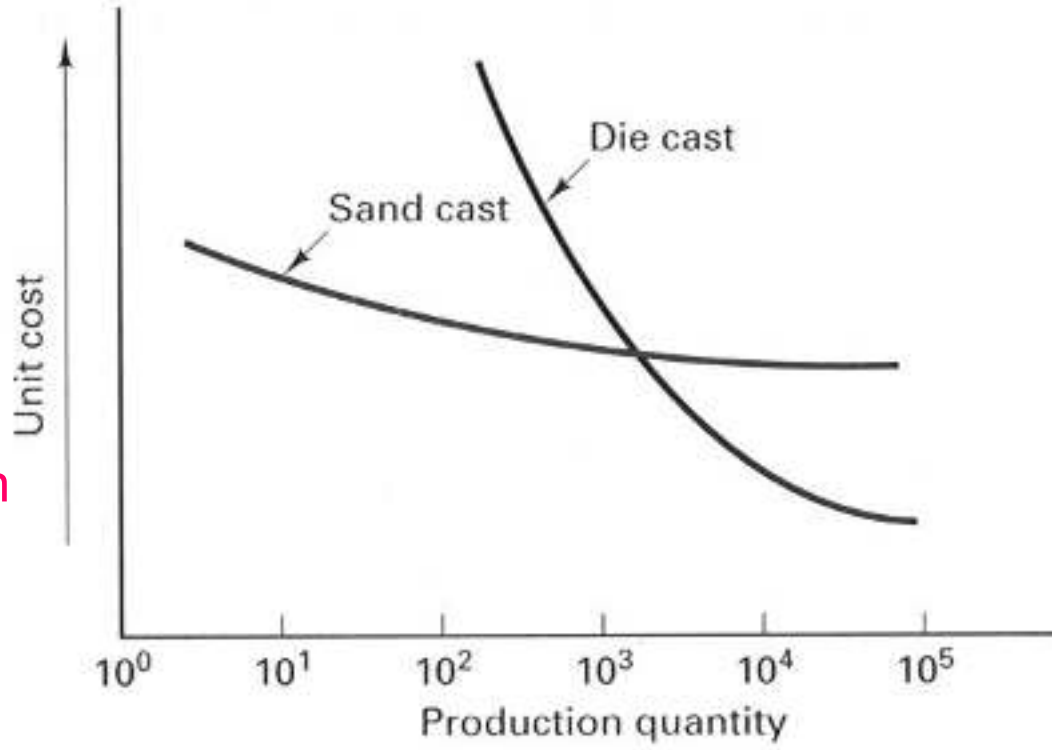


FIGURE 15-22 Typical unit cost of castings for both sand casting and die casting.

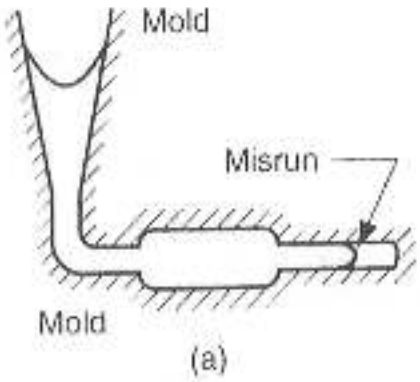
Casting Defects

- Some defects are common to all casting processes.

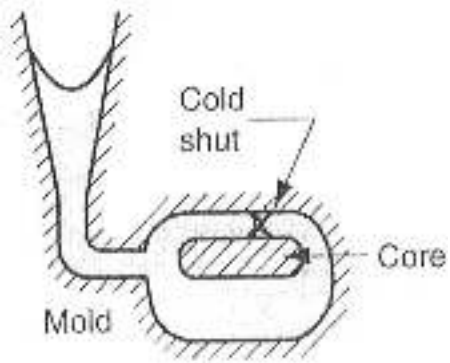
a. Misruns: casting solidifies before complete filling of cavity. Due to: (1) low fluidity (2) low pouring temperature, (3) slow pouring and/or (4) thin cross section of the mold cavity.

b. Cold shut: lack of fusion between two portions of the metal flow due to premature freezing. Causes are similar to those of a misrun.

c. Cold shots: solid globules of metal are formed that become entrapped in the casting due to splattering during pouring.



(a)



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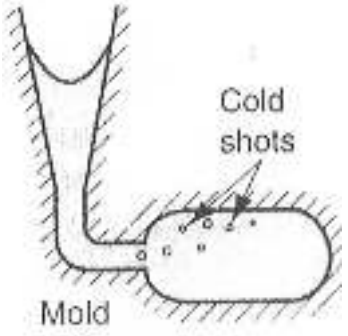

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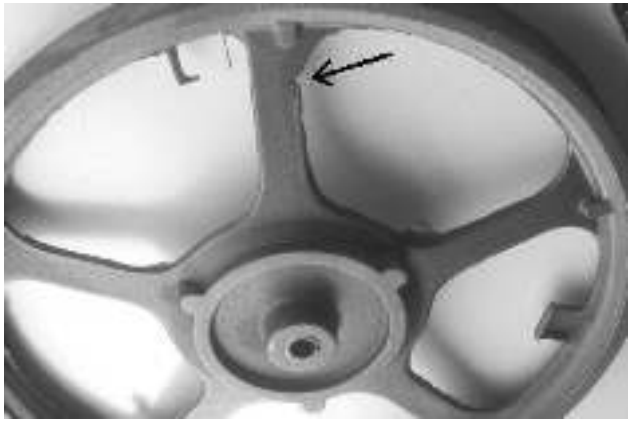


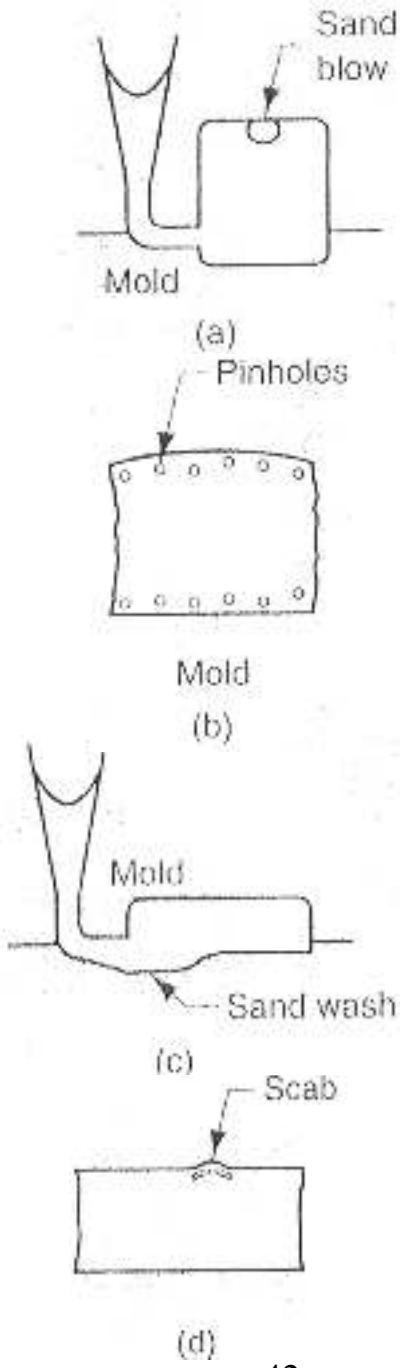
Sand Casting Defects

a. Sand blow – a balloon-shaped gas cavity caused by release of mold gases during pouring. At or below the casting surface near the casting top. Low permeability; poor venting, and high moisture contents in sand mold are the usual causes.

b. Pinhole - similar to a sand blow - formation of many small gas cavities at or slightly below the casting surface

c. Sand wash –irregularity in the casting surface that results from erosion of sand mold during pouring

d. Scab - rough area on the casting surface due to encrustations of sand and metal. Caused by mold surface flaking off and embedding in the casting surface.



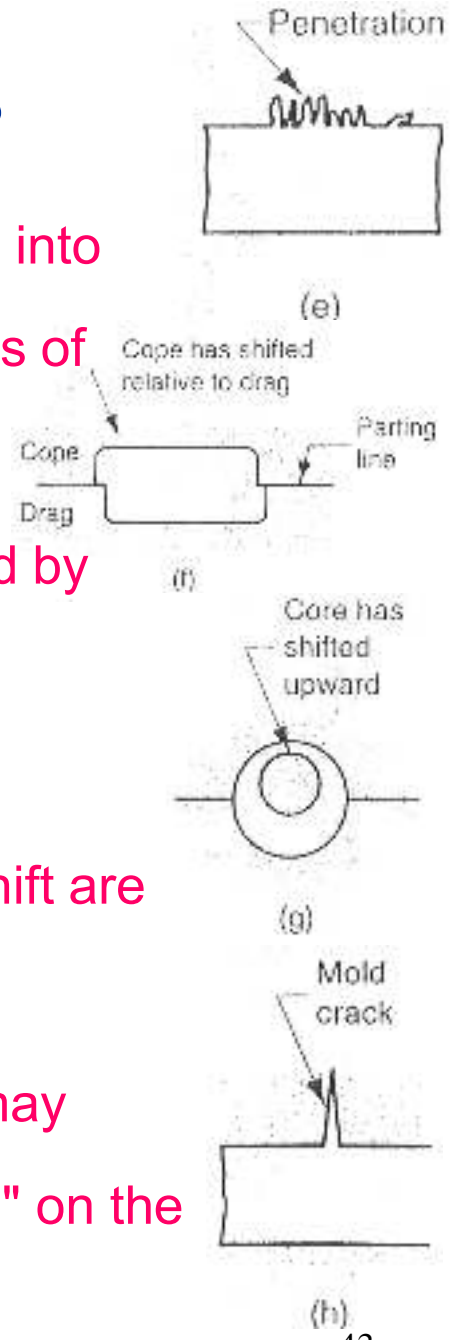
Sand Casting Defects

e. Penetration- fluidity of the liquid is too high, penetrates into the sand mold or sand core. Surface of casting consists of sand grains and metal. Harder packing reduces this

f. Mold shift -step in the casting at the parting line caused by shift of cope/drag.

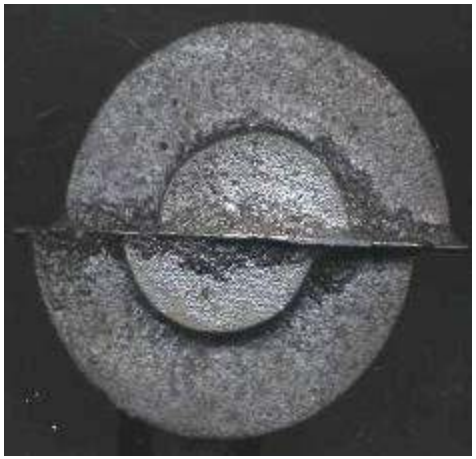
g. Core shift -similar thing happens with the core, but the displacement is usually vertical. Core shift and mold shift are caused by buoyancy of the molten metal.

h. Mold crack – If mould strength is insufficient, a crack may develop, into which liquid metal can seep to form a "fin" on the final casting.



Sand & Slag Inclusions

Blowhole



MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Phase Diagrams

Lecture 5

Casting Alloy Systems

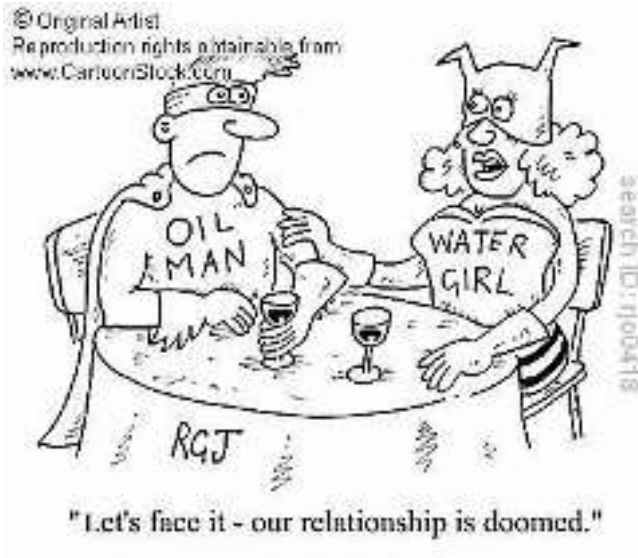
- Most metals originally cast from liquid to form ingots. Many go through subsequent hot/cold working;
  - homogenization of composition
  - healing of defects, pores/cracks
  - recrystallisation, annealing.
- For Final castings (i.e. to finished or semi-finished shape) the alloy selection is more specific:
  - high fluidity
  - lower melting points (eutectic compositions)
  - short freezing ranges
  - low shrinkage
  - strength that doesn't rely on cold working
    - eutectic
    - solid solution strengthening
    - precipitation hardening
    - fine grain size

What is a Phase?

- Sand and Salt
- Coffee and Sugar
- Water and Alcohol

How many phases in each?

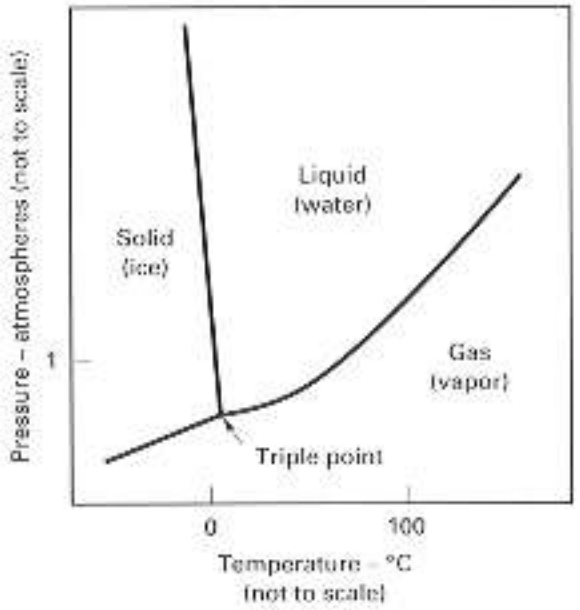
- A phase is a homogenous, physically distinct and mechanically separable portion of the material with a given chemical composition and structure.
- For solids: Chemically and structurally distinct
- For liquids: Miscibility
- For gases: Always 1 phase



Equilibrium Phase Diagram

- Graphic mapping of material under different conditions assuming equilibrium has been attained
- Simplest P-T diagram for fixed composition mat'l
- 4.1 gives the P-T diagram of water
- @1 atm: water is solid < 0° and gas > 100°
- At normal pressure find a temperature at which water is liquid
- Reduce the temperature until it becomes solid
- At that temperature reduce pressure and at one point, the solid directly goes to gas, without going to liquid phase – sublimation (process is called as freeze drying)
- If we have phase diagram, we can calculate the conditions required

FIGURE 4.1 Pressure–temperature diagram for water



Here's how freeze drying works.

1. Fresh or cooked foods are flash frozen, then placed in a vacuum chamber.

2. About 98% of the food's moisture is drawn off by evaporating the ice, at temperatures as low as -50° F.

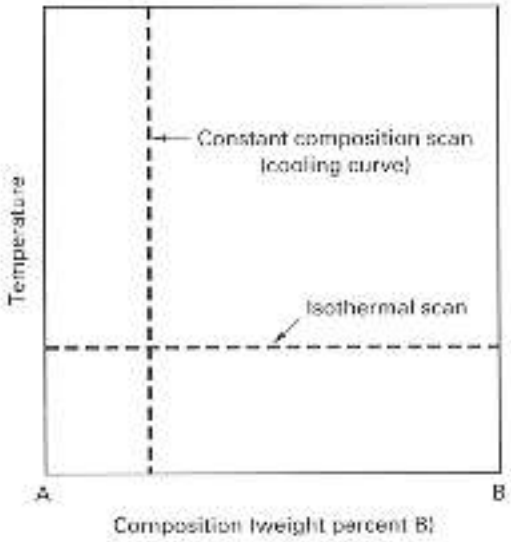
3. The freeze-dried food is sealed in moisture-and-oxygen proof packaging, to ensure freshness until opened.

4. When the water is replaced, the food regains its original fresh flavor, aroma, texture, and appearance.

Temperature Composition Diagram

- Generally engineering processes are done at constant pressure (mostly atmospheric)
- Variations will be in temperature and composition
- 4.2 gives the temperature composition diagram
- A and B at the ends are pure metals
- In between is the composition percentage of B in A

FIGURE 4.2 Mapping for a temperature–composition equilibrium phase diagram.



- Constant composition at various temperatures give the cooling curve
- Constant temperature at various compositions give isothermal scan
- Cooling curves are the ones that we will be interested in for various alloy compositions
- Example, salt added to water, reduces the freezing point, and used commonly in winter

Solubility

- If we move away from pure metals, we have one metal dispersed over the other
- If it is partially soluble Tin and Lead shown in 4-5
- Three single phase regions (α - solid solution of Tin in Lead matrix, β = solid solution of Pb in Sn marix, L - liquid)
- Three two-phase regions (α + L, β +L, α +β)
- Solvus line separates one solid solution from a mixture of solid solutions.
- The Solvus line shows limit of solubility
- 4-6 shows copper nickel diagram, which is completely soluble

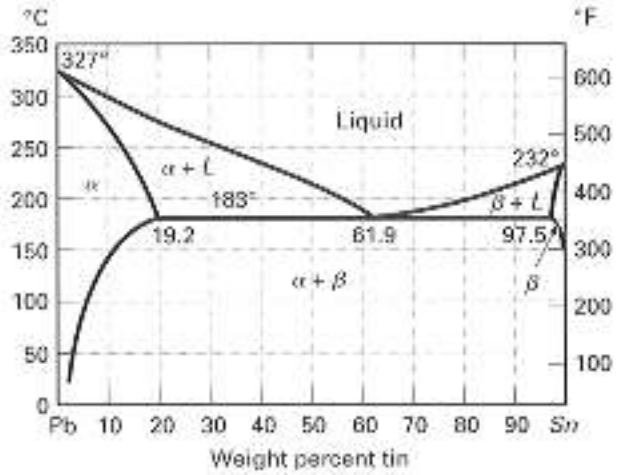


FIGURE 4.5 Lead–tin equilibrium diagram.

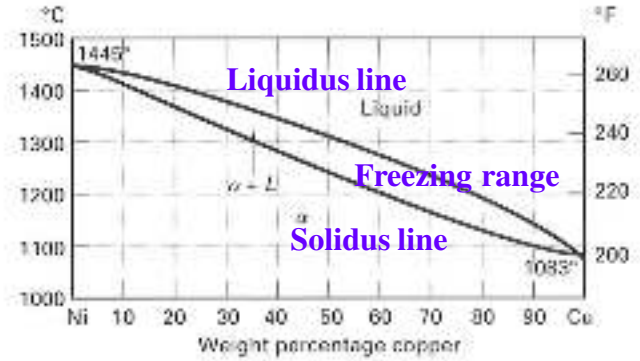
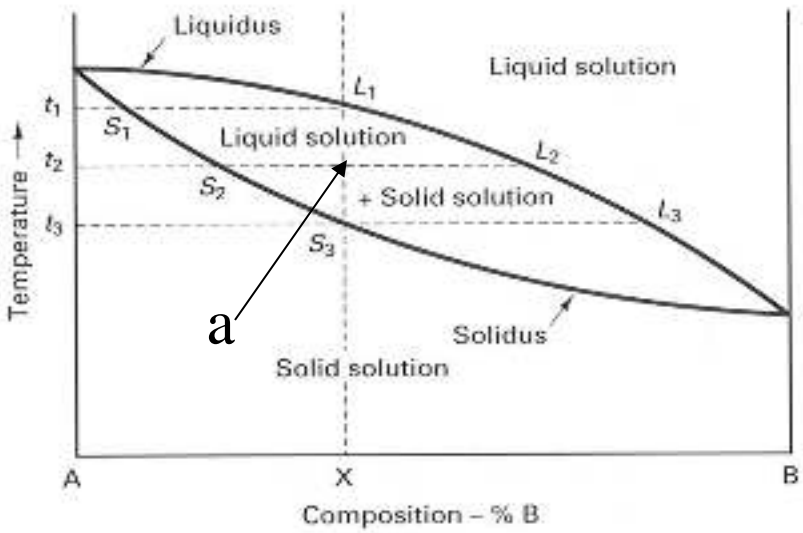


FIGURE 4.6 Copper nickel equilibrium diagram, showing complete solubility in both liquid and solid states.

Solidification

- Each temperature and composition gives 3 different pieces of info
- For composition X we have above L_1, below S_3 and in between
- For temperature t_2, we have below S_2 above L_2 and in between

FIGURE 4.8 Equilibrium diagram showing the changes that occur during the cooling of alloy X.



- At point a, the tie line runs from S_2 to L_2 and the solid at this 2 phase mixture will have composition of S_2 and the liquid will have that of L_2
- For alloy X, t_1 is the temperature at which first amount solid starts forming with chemistry of S_1
- As t reduces, more solid forms and chemistries follow the tie line point
- At t_3, the alloy is completely solidified to give a single phase alloy X

Intermetallic Compounds

- Suffix *ic* tells one of the phase is liquid and *oid* tells all phases are solid
- Eutectic reaction – transition between liquid and two solid phases mixture at eutectic concentration – e.g. $L \leftrightarrow \alpha + \beta$
- A peritectic reaction - solid and liquid phase will form a second solid phase at particular t & c - e.g. $L + \alpha \leftrightarrow \beta$
- A Monotectic reaction - liquid phase will form a second liquid and solid phase at particular t & c - e.g. $L_1 \leftrightarrow L_2 + \alpha$

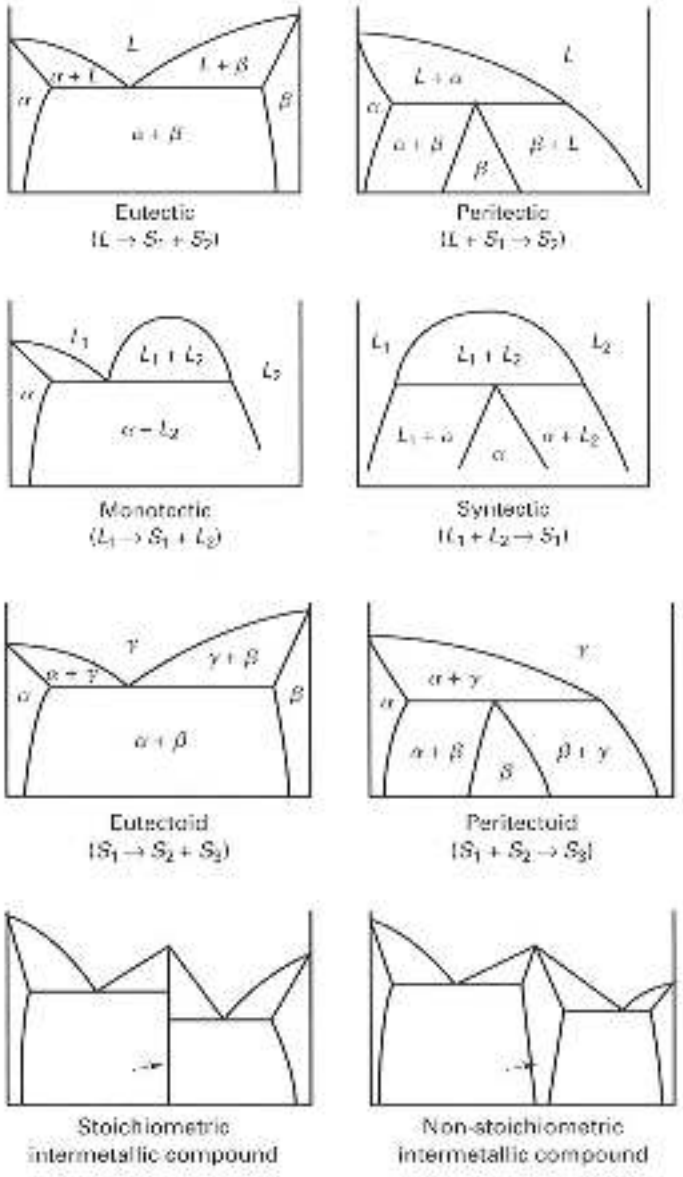
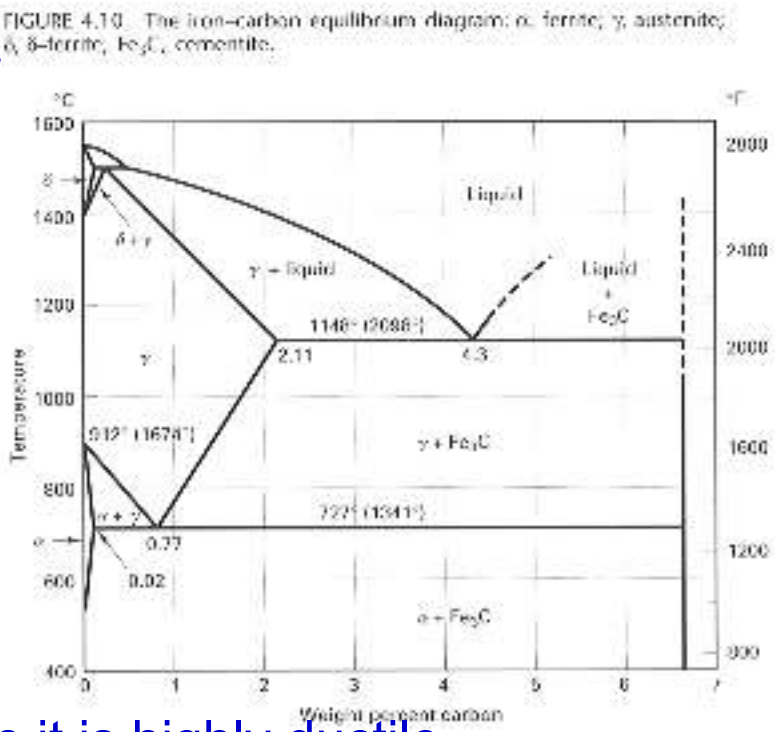


FIGURE 4.9 Schematic summary of three-phase reactions and intermetallic compounds.

Iron-Carbon Diagrams

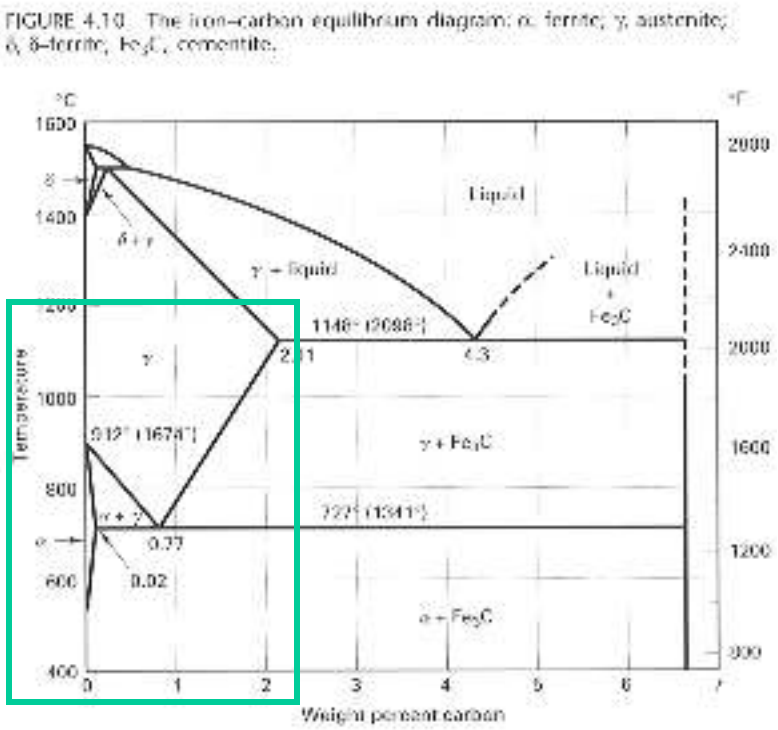
- Steel is an iron carbon compound and of great engineering importance
- Fe_3C is used which caps C at 6.67 %
- Pure iron forms delta ferrite at 1394° upon cooling which has BCC structure – not much engineering importance
- 1394-912° FCC structure, austenite - good formability & good solubility of C



- Austenite is used for hot forming because it is highly ductile
- Below 912° ferrite or alpha-ferrite is formed (more stable BCC). But cannot take more than .02% of C without forming 2 phase structure
- Below 770° (curie point) changes from non-magnetic to magnetic. No phase change, so not seen

Iron-Carbon Diagrams

- 4th single phase is Fe_3C iron carbide
- Also called as cementite - quite hard and brittle
- Exact mp of Fe_3C is unknown and hence the liquidus line is not clear at high c %
- 3 distinct phase reactions @ 1495° peritectic reaction for low C alloys
- High temperature and single phase austenite below it, no significance



- @ 1148° Eutectic reaction with 4.3% carbon. All alloys having more than 2.11% C go thro eutectic reaction and are called Cast Iron
- @ 727° we have the eutectoid reaction of 0.77%C. all alloys with less than 2.11%C go though 2 phase mixture upon cooling (AKA steels)

Cast Iron

- Iron with more than 2.11% C is cast Iron, excellent fluidity, inexpensive and easy to cast. Lot of applications
- Generally contain significant silicon%
- Typical values are 2-4% C, 0.5 – 3% Si less than 1% mn, less than 0.2% S
- Adding Si promotes graphite formation and 2 distinct stages of eutectics
- Ferrite + Austenite & Ferrite + Graphite
- Different cast irons (various composition)
  - Gray Cast Iron
  - White Cast Iron
  - Ductile Iron
  - Malleable Iron

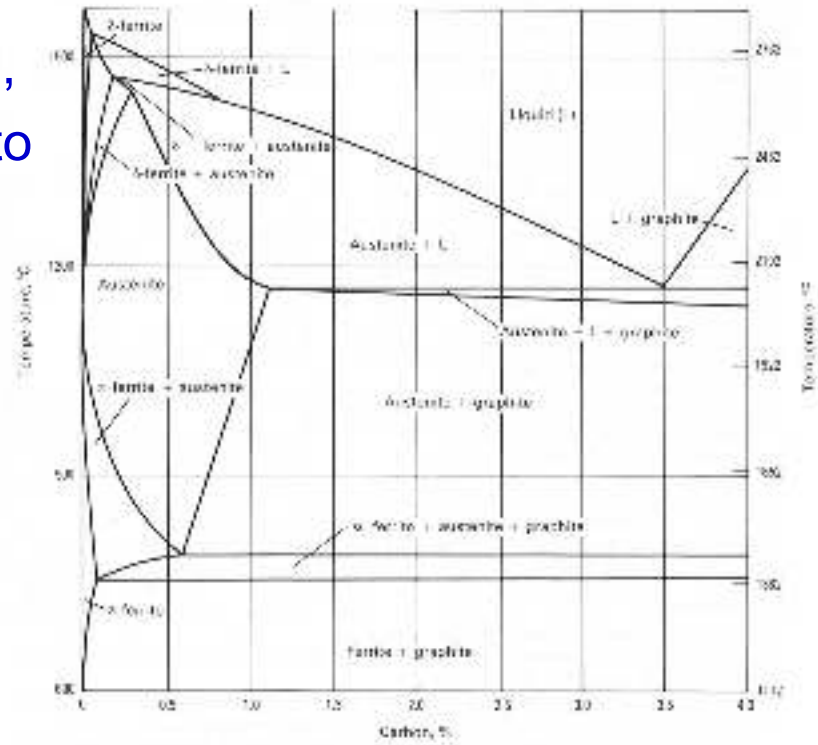
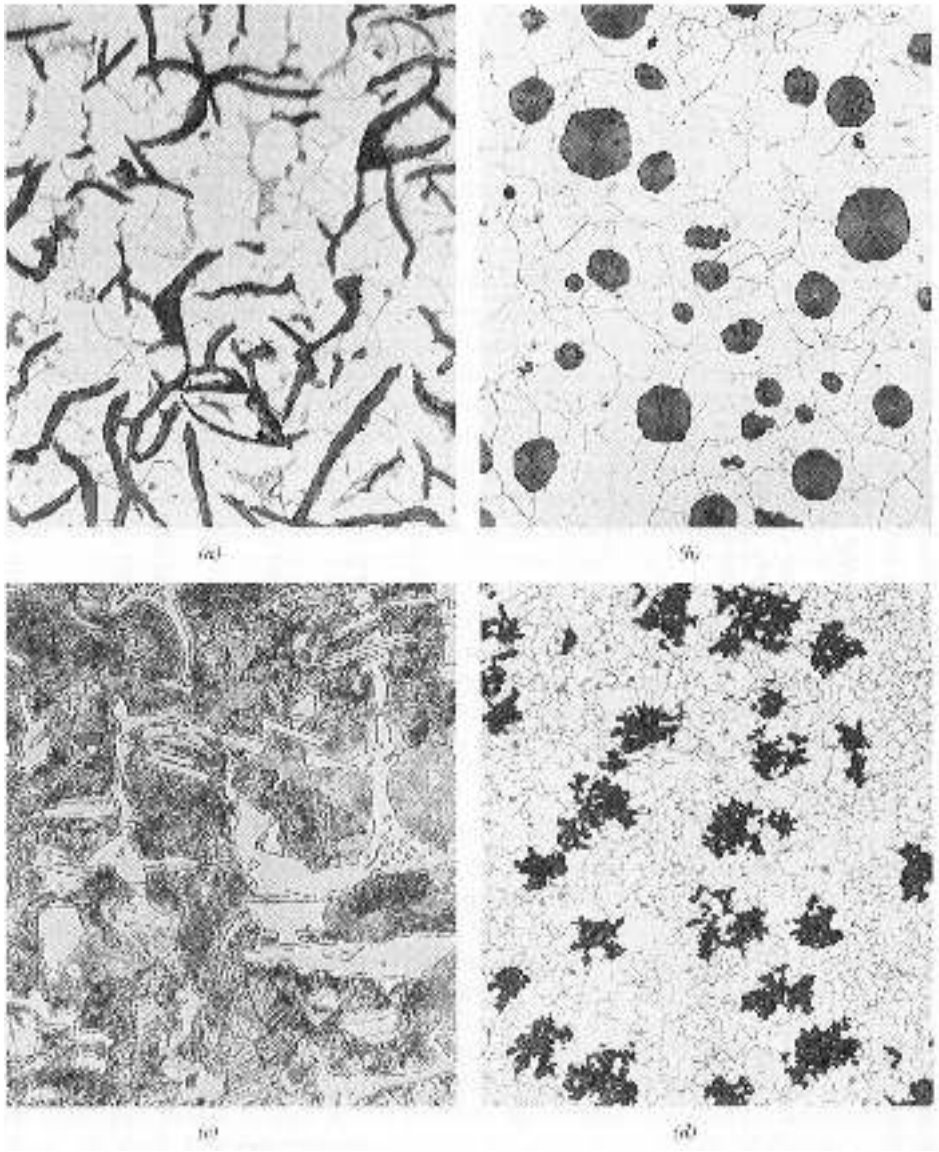


Fig. 1 Iron-carbon phase diagram at 2.5% Si. Source: Ref 1

Type of iron	Total carbon, %	Silicon, %
Class 20	3.40–3.60	2.30–2.50
Class 30	3.10–3.30	2.10–2.30
Class 40	2.95–3.15	1.70–2.00
Class 50	2.70–3.00	1.70–2.00
Class 60	2.50–2.85	1.90–2.10

Cast Iron



- Optical micrographs of various cast irons.

(a) Gray iron: the dark graphite flakes are embedded in an α-ferrite matrix. 500x.

(b) Nodular (ductile) iron: the dark graphite nodules are surrounded by an α-ferrite matrix. 200x.

(c) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite-cementite layered structure. 400x.

(d) Malleable iron: dark graphite rosettes (temper carbon) in an α - ferrite matrix. l50x.

Grey Cast Iron

- 2.5 - 4% C; 1 – 3% Si; 0.4 – 1% mn; Least expensive and promote graphite formation. Large 3d graphite flakes
- Common in high carbon equivalent irons and heavy-section castings
- Desirable properties such as damping capacity, dimensional stability, resistance to thermal shock, and ease of machining.
- Higher tensile strength and modulus of elasticity values
- Smooth machined surfaces are obtainable with irons having small flakes which are promoted by low carbon equivalents and faster cooling rates
- Sold in class (increasing strength)

Class	Tensile strength		Torsional shear strength		Compressive strength		Reversed bending fatigue limit		Transverse load on test bar		Hardness,
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	kgf	lbf	HB
20	152	22	179	26	572	83	69	10	839	1850	156
25	179	26	220	32	669	97	79	11.5	987	2175	174
30	214	31	276	40	752	109	97	14	1145	2525	210
35	252	36.5	334	48.5	855	124	110	16	1293	2850	212
40	293	42.5	393	57	965	140	128	18.5	1440	3175	235
50	362	52.5	503	73	1130	164	148	21.5	1633	3600	262
60	431	62.5	610	88.5	1293	187.5	169	24.5	1678	3700	302

Grey Cast Iron

Table 6 Typical pouring temperatures for some classes of gray iron

Class	Approximate liquidus temperature		Pouring temperature							
			Small castings				Large castings			
			Thin sections		Thick sections		Thin sections		Thick sections	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
30	1150	2100	1400	2550	1370	2500	1345	2450	1315	2400
35	1175	2150	1425	2600	1400	2550	1370	2500	1345	2450
40	1200	2190	1450	2640	1420	2590	1395	2540	1365	2490
45	1220	2230	1470	2680	1445	2630	1415	2580	1390	2530

- Refinement and stabilization of structures result in an increase in hardness, tensile strength, and wear resistance.
- In addition to composition (particularly carbon equivalent) and section size, factors such as alloy additions, heat treatment, thermal properties of the mold, and casting geometry affect the microstructure and therefore the properties of the iron.

Grey Cast Iron

Table 9 Typical applications for gray iron castings

Specification	Grade or class	Typical applications
ASTM A 48	20, 25	Small or thin-sectioned castings requiring good appearance, good machinability, and close dimensional tolerances
	30, 35	General machinery, municipal and waterworks, light compressors, automotive applications
	40, 45	Machine tools, medium-duty gear blanks, heavy compressors, heavy motor blocks
	50, 55, 60	Dies, crankshafts, high-pressure cylinders, heavy-duty machine tool parts, large gears, press frames
ASTM A 159, SAE J431	G1800	Miscellaneous soft iron castings in which strength is the primary consideration; exhaust manifolds
	G2500	Small cylinder blocks and heads, air-cooled cylinders, pistons, clutch plates, oil pump bodies, transmission cases, gear boxes, light-duty brake drums
	G2500a	Brake drums and clutch plates for moderate service where high carbon is desirable to minimize heat checking
	G3000	Cylinder blocks, heads, liners, flywheels, pistons, clutch plates
	G3500	Truck cylinder blocks and heads, heavy flywheels, differential carriers
	G3500b	Brake drums and clutch plates for heavy-duty service that require heat resistance and high strength
	G4000	Truck and tractor cylinder blocks and heads, heavy flywheels, tractor transmission cases, differential carriers, heavy gear boxes
	G3500c	Extraheavy-duty brake drums
	G4000d	Alloyed automotive engine camshafts
	G4900	Diesel engine castings, liners, cylinders, and pistons; heavy-duty parts for general industry
ASTM A 278	40, 50, 60, 70, 80	Valve bodies, paper mill dryer rollers, chemical process equipment, pressure vessel castings
ASTM A 319	I, II, III	Stoker and firebox parts, grate bars, process furnace parts, ingot molds, glass molds, caustic pots, metal melting pots
ASTM A 823		Automobile, truck, appliance, and machinery castings in quantity
ASTM A 436	1	Valve guides, insecticide pumps, flood gates, piston ring bands
	1b	Seawater valve and pump bodies, pump suction belts
	2	Fertilizer applicator parts, pump impellers, pump casings, plug valves
	2b	Caustic pump casings, valves, pump impellers
	3	Turbocharger housings, pumps and liners, stove tops, steam piston valve rings, caustic pumps and valves
	4	Range tops
	5	Glass rolls and molds, machine tools, gages, optical parts requiring minimal expansion and good damping qualities, solder rolls and pots
	6	Valves

White Cast Iron

- 1.8 – 3.6% C; 0.5 – 1.9% Si; 0.25 – 0.8% mn; Carbon content is from Fe_3C. Promotes cementite instead of graphite and rapid cooling
- Hard and brittle, used in application where abrasion resistance is needed

Table 1 Composition and mechanical requirements of abrasion-resistant cast irons per ASTM A 532

Class	Type	Designation	Composition					
			C	Mn	Si	Ni	Cr	Mo
I	A	Ni-Cr-HC	3.0–3.6	1.3 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max(a)
I	B	Ni-Cr-LC	2.5–3.0	1.3 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max(a)
I	C	Ni-Cr-GB	2.9–3.7	1.3 max	0.8 max	2.7–4.0	1.1–1.5	1.0 max(a)
I	D	Ni-Hi Cr	2.5–3.6	1.3 max	1.0–2.2	5.0–7.0	7.0–11.0	1.0 max(b)
II	A	12% Cr	2.4–2.8	0.5–1.5	1.0 max	0.5 max	11.0–14.0	0.5–1.0(c)
II	B	15% Cr-Mo-LC	2.4–2.8	0.5–1.5	1.0 max	0.5 max	14.0–18.0	1.0–3.0(c)
II	C	15% Cr-Mo-HC	2.8–3.6	0.5–1.5	1.0 max	0.5 max	14.0–18.0	2.3–3.5(c)
II	D	20% Cr-Mo-LC	2.0–2.6	0.5–1.5	1.0 max	1.5 max	18.0–23.0	1.5 max(c)
II	E	20% Cr-Mo-HC	2.6–3.2	0.5–1.5	1.0 max	1.5 max	18.0–23.0	1.0–2.0(c)
III	A	25% Cr	2.3–3.0	0.5–1.5	1.0 max	1.5 max	23.0–28.0	1.5 max(c)

Class	Type	Designation	Mechanical requirements					
			Hardness, HB				Typical section thickness, max	
			Sand cast, min	Chill cast, min	Hardened, min	Softened, max	in.	mm
I	A	Ni-Cr-HC	550	600	...	...	8	200
I	B	Ni-Cr-LC	550	600	...	...	8	200
I	C	Ni-Cr-GB	550	600	...	...	3 diam ball	75 diam ball
I	D	Ni-Hi Cr	550	500	600	400	12	300
II	A	12% Cr	550	...	600	400	1 diam ball	25 diam ball
II	B	15% Cr-Mo-LC	450	...	600	400	4	100
II	C	15% Cr-Mo-HC	550	...	600	400	3	75
II	D	20% Cr-Mo-LC	450	...	600	400	8	200
II	E	20% Cr-Mo-HC	450	...	600	400	12	300
III	A	25% Cr	450	...	600	400	8	200

(a) Maximum: 0.30% P, 0.15% S. (b) Maximum: 0.10% P, 0.15% S. (c) Maximum: 0.10% P, 0.06% S, 1.2% Cu

Ni-Cr White Cast Iron

- Low cost, Ni-Cr white irons are consumed in large tonnages in mining operations as grinding balls.
- Class I type A castings are used in applications requiring maximum abrasion resistance, such as ash pipes, slurry pumps, roll heads, muller tires, augers, coke-crusher segments, classifier shoes, brick molds, pipe elbows carrying abrasive slurries.
- Type B is recommended for applications requiring more strength and exerting moderate impact, such as crusher plates, crusher concaves, and pulverizer pegs.

Fig. 1 Typical microstructure of class I type A nickel-chromium white cast iron. 340×

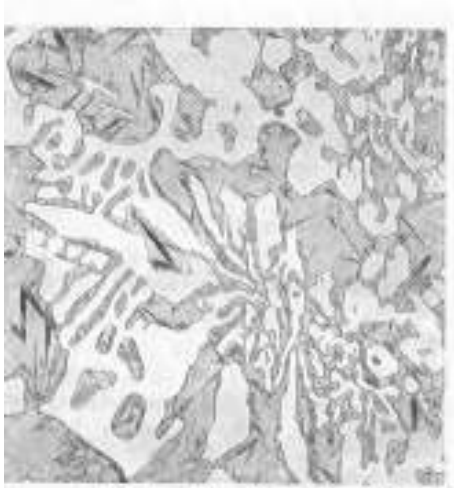


Fig. 2 Typical microstructure of class I type D nickel-chromium white cast iron. 340×

Ni-Cr White Cast Iron

- Class I type D, (Ni-Hard type 4), has a higher level of strength and toughness and is therefore used for the more severe applications that justify its added alloy costs. It is commonly used for pump volutes handling abrasive slurries and coal pulverizer table segments and tires.
- The class I type C alloy (Ni-Hard 3) is specifically designed for the production of grinding balls. This grade is both sand cast and chill cast. Chill casting has the advantage of lower alloy cost, and, more important, provides a 15 to 30% improvement in life. All grinding balls require tempering for 8 h at 260 to 315°C (500 to 600°F) to develop adequate impact toughness.

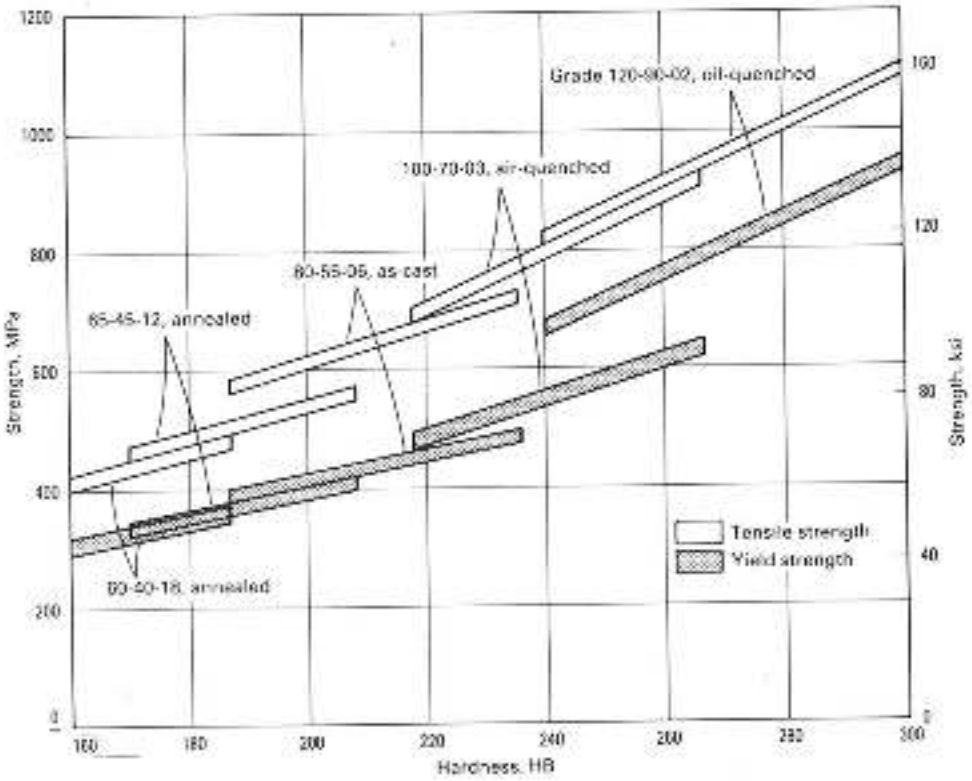
High Cr White Cast Iron

- Applications of High Cr White Cast Irons
- The high-chromium white irons are superior in abrasion resistance and are used effectively in impellers and volutes in slurry pumps, classifier wear shoes, brick molds, impeller blades and liners for shot blasting equipment, and refiner disks in pulp refiners.
- In many applications they withstand heavy impact loading, such as from impact hammers, roller segments and ring segments in coal-grinding mills, feed-end lifter bars and mill liners in ball mills for hard- rock mining, pulverizer rolls, and rolling mill rolls.

Ductile Iron

- Ductile iron replace gray iron because of its superior properties
- Examples - crankshafts, piston rings, exhaust manifolds, and cylinder liners.
- ductile iron provides increased strength and reduces weight
- In agricultural and earth-moving applications, brackets, couplings, rollers, hydraulic valves, sprocket wheels, and track components of improved strength and toughness are made of ductile iron.

Grade	Composition C	Si	Mn	P	S
3.1	3.5–4.6	<3.0	<0.1	<0.08	0.03 max
3.2	3.5–4.6	<4.0	<0.1–0.4	<0.08	0.03 max



Ductile Iron

- General engineering applications include hydraulic cylinders, mandrels, machine frames, switch gear , rolling mill rolls, tunnel segments, low-cost rolls, bar stock, rubber molds, street furniture such as covers and frames, and railway rail- clip supports. For these applications, ductile iron has provided increased performance or weight savings.
- Ductile iron gears have performed well in noncritical engineering and agricultural applications, but austempered (heat treatment) ductile iron offers a combination of strength, fatigue properties, and wear resistance that makes it of great interest for heavy engineering and automotive gears-applications
- However, many new engineering components are likely to be amenable to design with ductile iron

Ductile Iron

Table 5 Some mechanical properties expected in ductile iron grades covered by UK standard B52789

Grade	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %	Yield strength in compression MPa	Yield strength in compression ksi	Shear strength MPa	Shear strength ksi	Torsional strength MPa	Torsional strength ksi	Modulus of elasticity (E) GPa	Modulus of elasticity (E) 10^6 psi	Modulus of rigidity (G) GPa	Modulus of rigidity (G) 10^6 psi	Poisson's ratio, ν	Hardness, HB	Fatigue limit(a) Notched MPa	Fatigue limit(a) Notched ksi	Fatigue limit(a) Unnotched MPa	Fatigue limit(a) Unnotched ksi
Ferritic grades																					
350/22; 350/22L40	350	51	215	31	22	229	33	315	46	315	46	169	24.5	65.9	9.6	0.275	107–130	114	17	180	26
400/18; 400/18L20	400	58	259	38	18	273	40	360	52	360	52	169	24.5	65.9	9.6	0.275	120–140	122	18	195	28
420/12	420	61	278	40	12	292	42	378	55	378	55	169	24.5	65.9	9.6	0.275	140–155	124	18	201	29
Intermediate grades																					
450/10	450	65	305	44	10	319	46	405	59	405	59	169	24.5	65.9	9.6	0.275	150–172	128	19	210	30
500/7	500	73	339	49	7	351	57	450	65	450	65	169	24.5	65.9	9.6	0.275	172–216	134	20	224	32
600/3	600	87	372	54	3	382	55	540	78	540	78	174	25.2	67.9	9.8	0.275	216–247	149	22	248	36
Pearlitic as-cast and normalized																					
700/2	700	102	416	60	2	425	62	630	91	630	91	176	25.5	68.6	9.9	0.275	247–265	168	41	280	41
800/2	800	116	471	68	2	480	70	720	104	720	104	176	25.5	68.6	9.9	0.275	>265	182	44	304	44
900/2	900	131	526	76	2	535	78	810	117	810	117	176	25.5	68.6	9.9	0.275	>265	190	46	317	46
Hardened-and-tempered grades																					
700/2	700	102	550	80	2	559	81	630	91	630	91	172	24.9	67.1	9.7	0.275	232–259	168	41	280	41
800/2	800	116	630	91	2	639	93	720	104	720	104	172	24.9	67.1	9.7	0.275	>259	182	44	304	44
900/2	900	131	710	103	2	719	104	810	117	810	117	172	24.9	67.1	9.7	0.275	>259	190	46	317	46

(a) Wöhler specimen 10.6 mm (0.42 in.) in diameter unnotched; 10.6 mm (0.042 in.) in diameter at root of notch in notched tests. Circumferential 45° V-notch with 25 mm (1 in.) root radius and notch depth of 3.6 mm (0.14 in.). Source: Ref 9

Malleable Iron

- Malleable Iron is a cast metal produced as white cast iron and heat treated to convert the carbon-containing phase from Fe_3C to a nodular form of graphite called temper carbon.

Table 1 Chemical composition of malleable iron

Element	Composition, %
Carbon	2.16–2.90
Silicon	0.90–1.90
Manganese	0.15–1.25
Sulfur	0.02–0.20
Phosphorus	0.02–0.15

- There are two types of ferritic malleable iron: blackheart and whiteheart. Only the blackheart type is produced in the United States. This material has a matrix of ferrite with interspersed nodules of temper carbon.
- Malleable iron, like ductile iron, possesses considerable ductility and toughness because of its combination of nodular graphite and low-carbon metallic matrix. Because of the way in which graphite is formed in malleable iron, however, the nodules are not truly spherical as they are in ductile iron but are irregularly shaped aggregates.

Malleable Iron

- Malleable iron and ductile iron are used for some of the same applications in which ductility and toughness are important. In many cases, the choice between malleable and ductile iron is based on economy or availability rather than on properties. In certain applications, however, malleable iron has a distinct advantage. It is preferred for thin-section castings; for parts that are to be pierced, coined, or cold formed; for parts requiring maximum machinability; for parts that must retain good impact resistance at low temperatures; and for some parts requiring wear resistance (martensitic malleable iron only).
- Ductile iron has a clear advantage where low solidification shrinkage is needed to avoid hot tears or where the section is too thick to permit solidification as white iron. (Solidification as white iron throughout a section is essential to the production of malleable iron.) Malleable iron castings are produced in section thicknesses ranging from about 1.5 to 100 mm and in weights from less than 0.03 to 180 kg or more.

Malleable Iron

Table 3 Properties of malleable iron castings

Microstructures and typical applications are given in Table 2.

Specification No.	Class or grade	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Hardness, HB	Elongation(a), %
Ferritic							
ASTM A47 and A338, ANSI G48.1, FED QQ-I-666c	32510	345	50	224	32	156 max	10
	35018	365	53	241	35	156 max	18
ASTM A197	...	276	40	207	30	156 max	5
Pearlitic and martensitic							
ASTM A220, ANSI G48.2, MIL-I-11444B	40010	414	60	276	40	149–197	10
	45008	448	65	310	45	156–197	8
	45006	448	65	310	45	156–207	6
	50005	483	70	345	50	179–229	5
	60004	552	80	414	60	197–241	4
	70003	586	85	483	70	217–269	3
	80002	655	95	552	80	241–285	2
	90001	724	105	621	90	269–321	1
Automotive							
ASTM A602, SAE J158	M3210(b)	345	50	224	32	156 max	10
	M4504(c)	448	65	310	45	163–217	4
	M5003(c)	517	75	345	50	187–241	3
	M5503(d)	517	75	379	55	187–241	3
	M7002(d)	621	90	483	70	229–269	2
	M8501(d)	724	105	586	85	269–302	1

(a) Minimum in 50 mm (2 in.). (b) Annealed. (c) Air quenched and tempered. (d) Liquid quenched and tempered

Malleable Iron

- The requirement that any iron produced for conversion to malleable iron must solidify white places definite section thickness limitations on the malleable iron industry .
- High-production foundries are usually reluctant to produce castings more than about 40 mm thick. Some foundries, however, routinely produce castings as thick as 100 mm (4 in.).
- Automotive and associated applications of ferritic and pearlitic malleable irons include many essential parts in vehicle power trains, frames, suspensions, and wheels.
- Ferritic and pearlitic malleable irons are also used in the railroad industry and in agricultural equipment.

Malleable Iron

- Malleable iron castings are often selected because the material has excellent machinability in addition to significant ductility.
- In other applications, malleable iron is chosen because it combines castability with good toughness and machinability.
- Malleable iron is often chosen because of shock resistance alone.

Table 2 Applications of malleable iron castings

Mechanical properties are given in Table 3.

Specification No.	Class or grade	Microstructure	Typical applications
Ferritic			
ASTM A47, ANSI G48.1, FED QQ-I-666c	32510 35018	Temper carbon and ferrite	General engineering service at normal and elevated temperatures for good machinability and excellent shock resistance
ASTM A338	32510 35018	Temper carbon and ferrite	Flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty service to 345 °C (650 °F)
ASTM A197, ANSI G49.1	...	Free of primary graphite	Pipe fittings and valve parts for pressure service
Pearlitic and martensitic			
ASTM A220, ANSI G48.2, MIL-I-11444B	40010 45008 45006 50005 60004 70003 80002 90001	Temper carbon in necessary matrix without primary cementite or graphite	General engineering service at normal and elevated temperatures. Dimensional tolerance range for castings is stipulated
Automotive			
ASTM A602, SAE J158	M3210	Ferritic	For low-stress parts requiring good machinability: steering-gear housings, carriers, and mounting brackets
	M4504	Ferrite and tempered pearlite(a)	Compressor crankshafts and hubs
	M5003	Ferrite and tempered pearlite(a)	For selective hardening: planet carriers, transmission gears, and differential cases
	M5503	Tempered martensite	For machinability and improved response to induction hardening
	M7002	Tempered martensite	For high-strength parts: connecting rods and universal-joint yokes
	M8501	Tempered martensite	For high strength plus good wear resistance: certain gears

(a) May be all tempered martensite for some applications

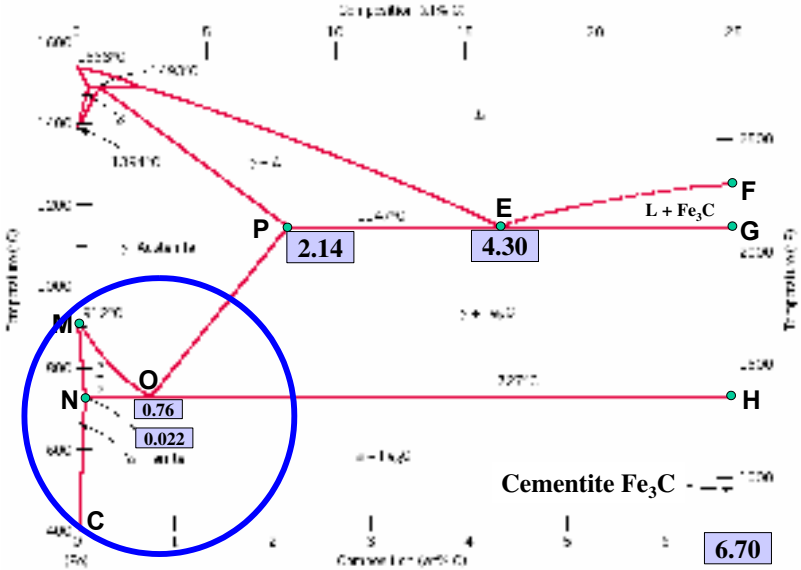
Steel Castings

Plain Carbon Steels (≤ 1%Mn)

Low carbon (≤ 0.20%C)

Medium Carbon (0.2 – 0.5%C)

High Carbon (≥ 0.5%C)



- Two methods of identifying grades of cast steels are extensively used in the United States. AISI designations for wrought steels are examples of the first method -first two digits indicate the alloy type, and the second two digits represent the carbon content. For example, a 1010 steel represents a carbon steel with 0.10% C, while a 1320 steel represents a manganese steel with 0.20% C. This system does not include mechanical properties or heat treatment. Accordingly, a cast 1040 steel (0.40% C) can exhibit a yield strength of 330 MPa (48 ksi) or of 496 MPa (72 ksi), depending on the choice of heat treatment.

Steel Castings

Plain Carbon Steels (≤ 1%Mn)

Low carbon (≤ 0.20%C)

Medium Carbon (0.2 – 0.5%C)

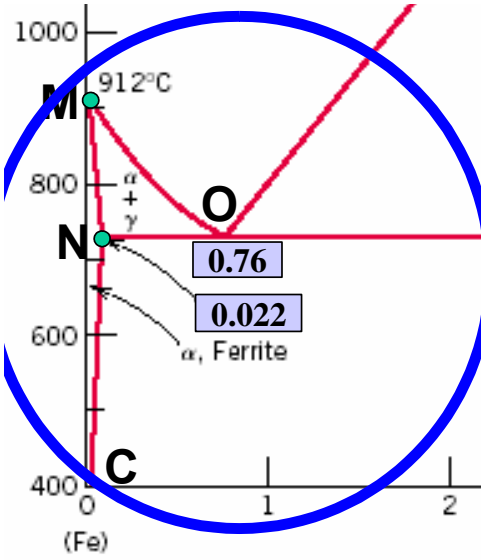
High Carbon (≥ 0.5%C)

- In the second method, letters and numbers are arbitrarily assigned to steels with well-defined compositions, which index the heat treatment as well as the mechanical properties. There are usually many steel grade designations that represent a single type of steel. For example, there are four ASTM specifications that together include 16 grades of chromium-molybdenum steels. These 16 grades, however, are made up of only three different steels. Although such a system may appear confusing because of the redundancy of designations, the system does offer the advantage of characterizing the cast steel end product as thoroughly as is needed for its end use.

Steel Castings

- Low-carbon cast steels (less than 0.20% C) are mainly produced for electrical and magnetic equipment and are normally given a full anneal heat treatment.
- Some castings for the railroad industry are produced from low-carbon cast steel. Castings for the automotive industry are also produced from this class of steel, as are annealing boxes and hot metal ladles.
- Steel castings in this class are also produced for case carburizing, by which process the castings are given a hard wear-resistant exterior and a tough, ductile core.
- The magnetic properties of cast low-carbon steels make them useful in the manufacture of electrical equipment.

Steel Castings



- The medium-carbon cast steels (0.20 to 0.50%C) represents bulk of steel casting production. Mostly heat treated by normalizing, which consists of cooling the castings in air from approximately 50°C above the upper critical temperature. A stress-relief treatment can be used to relieve stresses set up in the casting by cooling conditions or welding operations and to soften the HAZ resulting from welding.

- used in a wide variety of ways, including applications in the railroad and other transportation industries, machinery and tools, equipment for rolling mills, mining and construction equipment, and many other miscellaneous applications.

Steel Castings

- High-Carbon Cast Steels. (more than 0.50% C) Because of their high carbon contents, these grades are the most hardenable of the plain carbon cast steels. They are therefore used in applications that require relatively high strength levels.
- In addition to Plain carbon steels, there are steels with alloying elements
- Low Alloy Steels (< 8% alloying elements)

Cast steel designation	Nearest wrought equivalent	Alloying elements
1300	1300	Manganese
8000, 8400....	8000, 8400	Manganese, molybdenum
80B00	80B00	Manganese, molybdenum, boron
2300	2300	Nickel
8600, 4300....	8600, 4300	Nickel, chromium, molybdenum
9500	9500	Manganese, nickel, chromium, molybdenum
4100	4100	Chromium, molybdenum

- High–Alloy Steel Castings (including stainless steel castings)
- Widely used for corrosion resistance, and for high temperature service in hot gases, liquids.

Steel Castings

Table 1 Properties of various classes of cast carbon and low-alloy steels

Class(a)	Heat treatment(b)	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Reduction in area, %	Elongation, %	Hardness, HB	Fatigue endurance limit MPa	Fatigue endurance limit ksi	Ratio of endurance limit to tensile strength
Carbon steels											
60	A	434	63	241	35	54	30	131	207	30	0.48
65	N	469	68	262	38	48	28	131	207	30	0.44
70	N	517	75	290	42	45	27	143	241	35	0.47
80	NT	565	82	331	48	40	23	163	255	37	0.45
85	NT	621	90	379	55	38	20	179	269	39	0.43
100	QT	724	205	517	75	41	19	212	310	45	0.47
Low-alloy steels(c)											
65	NT	469	68	262	38	55	32	137	221	32	0.47
70	NT	510	74	303	44	50	28	143	241	35	0.47
80	NT	593	86	372	54	46	24	170	269	39	0.45
90	NT	655	95	441	64	44	20	192	290	42	0.44
105	NT	758	110	627	91	48	21	217	365	53	0.48
120	QT	883	128	772	112	38	16	262	427	62	0.48
150	QT	1089	158	979	142	30	13	311	510	74	0.47
175	QT	1234	179	1103	160	25	11	352	579	84	0.47
200	QT	1413	205	1172	170	21	8	401	607	88	0.43

(a) Class of steel based on tensile strength (ksi). (b) A, annealed; N, normalized; NT, normalized and tempered; QT, quenched and tempered. (c) Below 8% total alloy content

Steel Castings

Table 1 Compositions and microstructures of corrosion-resistant high-alloy cast steels

Alloy	Wrought alloy type(s)	Most common end-use microstructure	Composition, % (b) Cr	Ni	Mo	Si	Mn	P	S	C	Others
Chromium steels											
CA-15	410	Martensite	11.5–14.0	1.00	0.50	1.50	1.00	0.04	0.04	0.15	...
CA-15M	...	Martensite	11.5–14.0	1.00	0.15–1.0	0.65	1.00	0.04	0.04	0.15	...
CA-40	420	Martensite	11.5–14.0	1.00	0.5	1.50	1.00	0.04	0.04	0.20–0.40	...
CB-30	431,442	Ferrite + carbides	18.0–21.0	2.00	...	1.50	1.00	0.04	0.04	0.30	...
CC-50	446	Ferrite + carbides	26.0–30.0	4.00	...	1.50	1.00	0.04	0.04	0.50	...
Chromium-nickel steels											
CA-6NM	...	Martensite	11.5–14.0	3.5–4.5	0.40–1.0	1.00	1.00	0.04	0.03	0.06	...
CB-7Cu	17-4PH	Martensite-age hardenable	15.5–17.0	3.6–4.6	...	1.50	1.00	0.04	0.04	0.07	2.3–3.3 Cu
CD-4MCu	...	Austenite in ferrite-age hardenable	25.0–26.5	4.75–6.0	1.75–2.25	1.00	1.00	0.04	0.04	0.04	2.75–3.25 Cu
CE-30	...	Ferrite in austenite	26.0–30.0	8.0–11.0	...	2.00	1.50	0.04	0.04	0.30	...
CF-3	304L	Ferrite in austenite	17.0–21.0	8.0–12.0	...	2.00	1.50	0.04	0.04	0.03	...
CF-8	304	Ferrite in austenite	18.0–21.0	8.0–11.0	...	2.00	1.50	0.04	0.04	0.08	...
CF-20	302	Austenite	18.0–21.0	8.0–11.0	...	2.00	1.50	0.04	0.04	0.20	...
CF-3M	316L	Ferrite in austenite	17.0–21.0	9.0–13.0	2.0–3.0	1.50	1.50	0.04	0.04	0.03	...
CF-8M	316	Ferrite in austenite	18.0–21.0	9.0–12.0	2.0–3.0	1.50	1.50	0.04	0.04	0.08	...
CF-12M	...	Ferrite in austenite or austenite	18.0–21.0	9.0–12.0	2.0–3.0	2.00	1.50	0.04	0.04	0.12	...
CF-8C	347	Ferrite in austenite	18.0–21.0	9.0–12.0	...	2.00	1.50	0.04	0.04	0.08	Nb = 8 × C, 1.0 max
CF-16F	303	Austenite	18.0–21.0	9.0–12.0	1.50	2.00	1.50	0.17	0.04	0.16	0.20–0.35 Se
CG-8M	317	Ferrite in austenite	18.0–21.0	9.0–13.0	3.0–4.0	1.50	1.50	0.04	0.04	0.08	...
CH-20	309	Austenite	22.0–26.0	12.0–15.0	...	2.00	1.50	0.04	0.04	0.20	...
CK-20	310	Austenite	23.0–27.0	19.0–22.0	...	1.75	1.50	0.04	0.04	0.20	...
Nickel-chromium steel											
CN-7M	320	Austenite	19.0–22.0	27.5–30.5	2.0–3.0	1.50	1.50	0.04	0.04	0.07	3.0–4.0 Cu

(a) Wrought alloy type numbers are AISI designations for grades most closely corresponding to casting alloys. Wrought alloy type numbers are given only as a guide for determining corresponding cast and wrought grades. Buyers should use cast alloy designations when specifying castings. (b) Maximum unless range is given. All compositions contain balance of iron.

Aluminum and Aluminum Alloys

- 1xx.x: Controlled unalloyed compositions
- 2xx.x: Al alloys containing copper as the major alloying element
- 3xx.x: Al-Si alloys also containing magnesium and/or copper
- 4xx.x: Binary Al-Si alloys .
- 5xx.x: Al alloys containing magnesium as major alloying element
- 6xx.x: Currently unused
- 7xx.x: Al alloys containing zinc as the major alloying element, usually also containing additions of either copper, magnesium, chromium, manganese, or combinations of these elements
- 8xx.x: Al alloys containing tin as the major alloying element
- 9xx.x: Currently unused

Aluminum and Aluminum Alloys

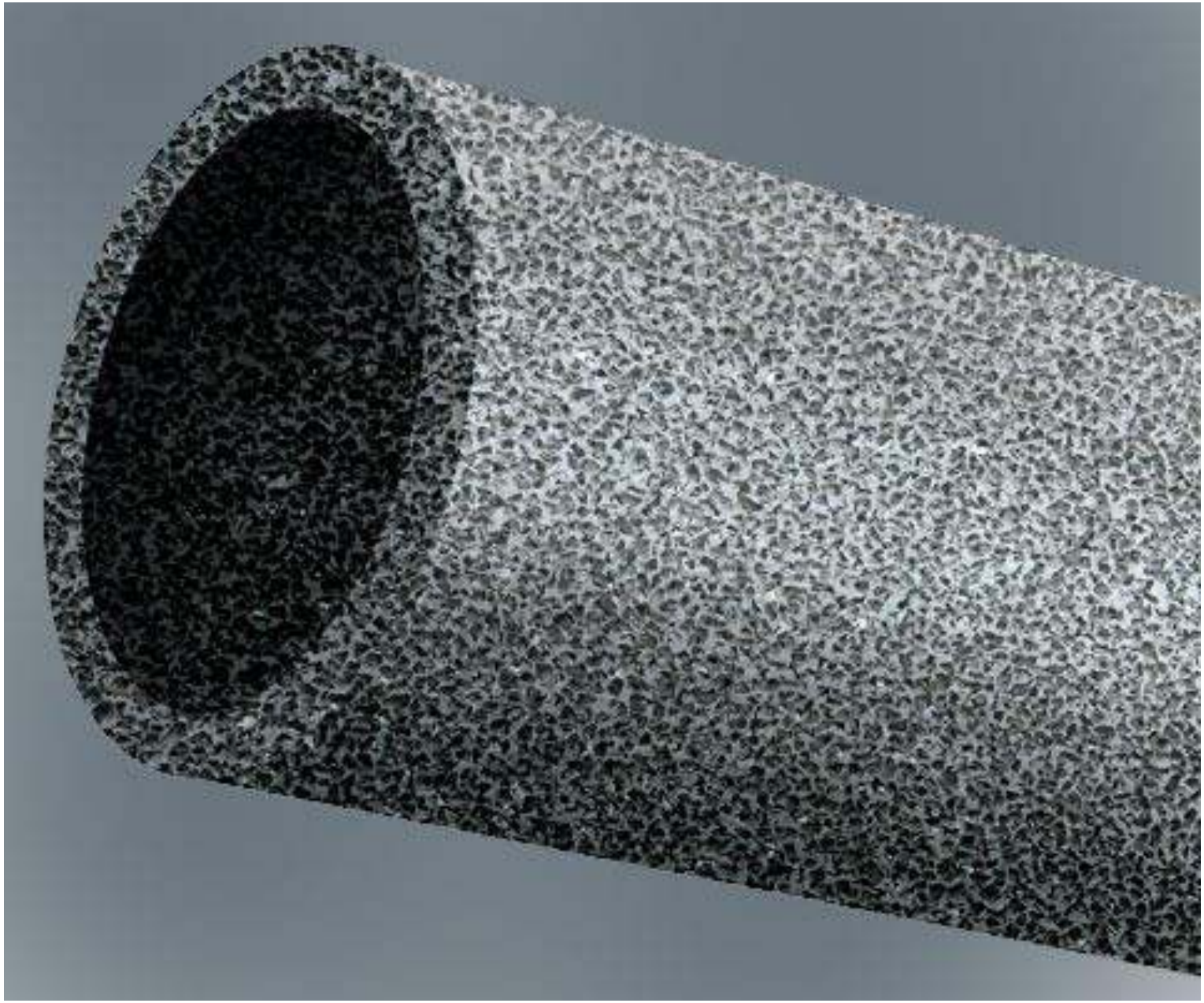
Table 1 Compositions of registered aluminum casting alloys used to cast shapes

Compositions of alloys used to cast primary ingots are not shown.

Alloy	Production	Composition, %(a)										
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Sn	Ti	Others: Each	Others: Total
201.1	S	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	...	...	...	...	0.15–0.35	0.05(c)	0.10
A201.0	S	0.05	0.10	4.0–5.0	0.20–0.40	0.15–0.35	...	...	...	...	0.15–0.35	0.03(c)	0.10
B201.0	S	0.05	0.05	4.5–5.0	0.20–0.50	0.25–0.35	...	...	...	...	0.15–0.35	0.05(d)	0.15
202.0	S	0.10	0.15	4.6–5.2	0.20–0.8	0.15–0.55	0.20–0.6	...	...	...	0.15–0.35	0.05(c)	0.10
203.0	S	0.30	0.50	4.5–5.5	0.20–0.30	0.10	...	1.3–1.7	0.10	...	0.15–0.25(e)	0.05(f)	0.20
204.0	S, P	0.20	0.35	4.2–5.0	0.10	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	0.15
206.0	S, P	0.10	0.15	4.2–5.0	0.20–0.50	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	0.15
A206.0	S, P	0.05	0.10	4.2–5.0	0.20–0.50	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	0.15
208.0	S, P	2.5–3.5	1.2	3.5–4.5	0.50	0.10	...	0.35	1.0	...	0.25	...	0.50
213.0	S, P	1.0–3.0	1.2	6.0–8.0	0.6	0.10	...	0.35	2.5	...	0.25	...	0.50
222.0	S, P	2.0	1.5	9.2–10.7	0.50	0.15–0.35	...	0.50	0.8	...	0.25	...	0.35
224.0	S, P	0.06	0.10	4.5–5.5	0.20–0.50	...	...	...	...	...	0.35	0.03(g)	0.10
238.0	P	3.5–4.5	1.5	9.0–11.0	0.6	0.15–0.35	...	1.0	1.5	...	0.25	...	0.50
240.0	S	0.50	0.50	7.0–9.0	0.30–0.7	5.5–6.5	...	0.30–0.7	0.10	...	0.20	0.05	0.15
242.0	S, P	0.7	1.0	3.5–4.5	0.35	1.2–1.8	0.25	1.7–2.3	0.35	...	0.25	0.05	0.15
A242.0	S	0.6	0.8	3.7–4.5	0.10	1.2–1.7	0.15–0.25	1.8–2.3	0.10	...	0.07–0.20	0.05	0.15
243.0	S	0.35	0.40	3.5–4.5	0.15–0.45	1.8–2.3	0.20–0.40	1.9–2.3	0.05	...	0.06–0.20	0.05(h)	0.15
249.0	P	0.05	0.10	3.8–4.6	0.25–0.50	0.25–0.50	...	...	2.5–3.5	...	0.02–0.35	0.03	0.10
295.0	S	0.7–1.5	1.0	4.0–5.0	0.35	0.03	...	...	0.35	...	0.25	0.05	0.15
296.0	P	2.0–3.0	1.2	4.0–5.0	0.35	0.05	...	0.35	0.50	...	0.25	...	0.35
305.0	S, P	4.5–5.5	0.6	1.0–1.5	0.50	0.10	0.25	...	0.35	...	0.25	0.05	0.15
A305.0	S, P	4.5–5.5	0.20	1.0–1.5	0.10	0.10	...	...	0.10	...	0.20	0.05	0.15
308.0	S, P	5.0–6.0	1.0	4.0–5.0	0.50	0.10	...	...	1.0	...	0.25	...	0.50
319.0	S, P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	...	0.35	1.0	...	0.25	...	0.50
A319.0	S, P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	...	0.35	3.0	...	0.25	...	0.50
B319.0	S, P	5.5–6.5	1.2	3.0–4.0	0.8	0.10–0.50	...	0.50	1.0	...	0.25	...	0.50
320.0	S, P	5.0–8.0	1.2	2.0–4.0	0.8	0.05–0.6	...	0.35	3.0	...	0.25	...	0.50
324.0	P	7.0–8.0	1.2	0.40–0.6	0.50	0.40–0.7	...	0.30	1.0	...	0.20	0.15	0.20
328.0	S	7.5–8.5	1.0	1.0–2.0	0.20–0.6	0.20–0.6	0.35	0.25	1.5	...	0.25	...	0.50
332.0	P	8.5–10.5	1.2	2.0–4.0	0.50	0.50–1.5	...	0.50	1.0	...	0.25	...	0.50
333.0	P	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	...	0.50	1.0	...	0.25	...	0.50
A333.0	P	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	...	0.50	3.0	...	0.25	...	0.50
336.0	P	11.0–13.0	1.2	0.50–1.5	0.35	0.7–1.3	...	2.0–3.0	0.35	...	0.25	0.05	...
339.0	P	11.0–13.0	1.2	1.5–3.0	0.50	0.50–1.5	...	0.50–1.5	1.0	...	0.25	...	0.50
341.0	D	6.7–7.7	1.2	0.50–0.9	0.50	0.10	0.10	...	1.7–2.0	0.50	...	0.10	0.35
354.0	P	8.6–9.4	0.20	1.6–2.0	0.10	0.40–0.6	...	...	0.10	...	0.20	0.05	0.15
355.0	S, P	4.5–5.5	0.6(i)	1.0–1.5	0.50(i)	0.40–0.6	0.25	...	0.35	...	0.25	0.05	0.15
A355.0	S, P	4.5–5.5	0.09	1.0–1.5	0.05	0.45–0.6	...	...	0.05	...	0.04–0.20	0.05	0.15
C355.0	S, P	4.5–5.5	0.20	1.0–1.5	0.10	0.40–0.6	...	...	0.10	...	0.20	0.05	0.15
356.0	S, P	6.5–7.5	0.6(i)	0.25	0.35(i)	0.20–0.45	...	...	0.35	...	0.25	0.05	0.15
A356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.25–0.45	...	...	0.10	...	0.20	0.05	0.15
B356.0	S, P	6.5–7.5	0.09	0.05	0.05	0.25–0.45	...	...	0.05	...	0.04–0.20	0.05	0.15
C356.0	S, P	6.5–7.5	0.07	0.05	0.05	0.25–0.45	...	...	0.05	...	0.04–0.20	0.05	0.15
F356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.17–0.25	...	...	0.10	...	0.04–0.20	0.05	0.15
357.0	S, P	6.5–7.5	0.15	0.05	0.03	0.45–0.6	...	...	0.05	...	0.20	0.05	0.15
A357.0	S, P	6.5–7.5	0.20	0.20	0.10	0.40–0.7	...	...	0.10	...	0.04–0.20	0.05(j)	0.15
B357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.40–0.6	...	...	0.05	...	0.04–0.20	0.05	0.15
C357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.45–0.7	...	...	0.05	...	0.04–0.20	0.05(j)	0.15
D357.0	S	6.5–7.5	0.20	...	0.10	0.55–0.6	...	...	...	...	0.10–0.20	0.05(j)	0.15
358.0	S, P	7.6–8.6	0.30	0.20	0.20	0.40–0.6	0.20	...	0.20	...	0.10–0.20	0.05(k)	0.15
359.0	S, P	8.5–9.5	0.20	0.20	0.10	0.50–0.7	...	...	0.10	...	0.20	0.05	0.15
360.0	D	9.0–10.0	2.0	0.6	0.35	0.40–0.6	...	0.50	0.50	0.15	...	...	0.25

(continued)

(a) D, die casting; P, permanent mold; S, sand. Other products may pertain to the compositions but are not listed. (b) Weight percent; maximum unless range is given or otherwise indicated. All compositions contain balance of aluminum. (c) 0.40–1.0 Ag. (d) 0.50–1.0 Ag. (e) 0.70 max Ti + Zr. (f) 0.20–0.30 Sb; 0.20–0.30 Cu; 0.10–0.30 Zr. (g) 0.05–0.15 V; 0.10–0.25 Zr. (h) 0.06–0.20 V. (i) If iron exceeds 0.45%, manganese content shall not be less than one-half of iron content. (j) 0.04–0.07 Be. (k) 0.30–0.38 Be. (l) 0.8 max Mn + Cr. (m) 0.25 max Pb. (n) 0.02–0.04 Be. (o) 0.08–0.15 V. (p) 0.10 max Pb. (q) 0.003–0.007 Be, 0.005 max B. Source: Ref 1



Aluminum and Aluminum Alloys

Table 1 (continued)

Alloy	Product(a)	Composition, %(b)											
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Sn	Ti	Others, Each	Others, Total
A360.0	D	9.0–10.0	1.3	0.6	0.35	0.40–0.6	...	0.50	0.50	0.15	...	...	0.25
361.0	D	9.5–10.5	1.1	0.50	0.25	0.40–0.6	0.20–0.30	0.20–0.30	0.50	0.30	0.20	0.05	0.15
363.0	S, P	4.5–6.0	1.1	2.5–3.5	(l)	0.15–0.40	(l)	0.25	3.0–4.5	0.25	0.20	(m)	0.30
364.0	D	7.5–9.5	1.5	0.20	0.10	0.20–0.40	0.25–0.50	0.15	0.15	0.25	...	0.05(n)	0.15
369.0	D	11.0–12.0	1.3	0.50	0.35	0.25–0.45	0.30–0.40	0.05	1.0	0.10	...	0.05	0.15
380.0	D	7.5–9.5	2.0	3.0–4.0	0.50	0.10	...	0.50	3.0	0.35	...	...	0.50
A380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	...	0.50	3.0	0.35	...	...	0.50
B380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	...	0.50	3.0	0.35	...	...	0.50
383.0	D	9.5–11.5	1.3	2.0–3.0	0.50	0.10	...	0.30	3.0	0.15	...	...	0.50
384.0	D	10.5–12.0	1.3	3.0–4.5	0.50	0.10	...	0.50	3.0	0.35	...	...	0.50
A384.0	D	10.5–12.0	1.3	3.0–4.5	0.50	0.10	...	0.50	1.0	0.35	...	...	0.50
385.0	D	11.0–13.0	2.0	2.0–4.0	0.50	0.30	...	0.50	3.0	0.30	...	...	0.50
390.0	D	16.0–18.0	1.3	4.0–5.0	0.10	0.45–0.65	...	...	0.10	...	0.20	0.10	0.20
A390.0	S, P	16.0–18.0	0.50	4.0–5.0	0.10	0.45–0.65	...	...	0.10	...	0.20	0.10	0.20
B390.0	D	16.0–18.0	1.3	4.0–5.0	0.50	0.45–0.65	...	0.10	1.5	...	0.20	0.10	0.20
392.0	D	18.0–20.0	1.5	0.40–0.8	0.20–0.6	0.8–1.2	...	0.50	0.50	0.30	0.20	0.15	0.50
393.0	S, P, D	21.0–23.0	1.3	0.7–1.1	0.10	0.7–1.3	...	2.0–2.5	0.10	...	0.10–0.20	0.05(o)	0.15
413.0	D	11.0–13.0	2.0	1.0	0.35	0.10	...	0.50	0.50	0.15	...	...	0.25
A413.0	D	11.0–13.0	1.3	1.0	0.35	0.10	...	0.50	0.50	0.15	...	...	0.25
B413.0	S, P	11.0–13.0	0.50	0.10	0.35	0.05	...	0.05	0.10	...	0.25	0.05	0.20
443.0	S, P	4.5–6.0	0.8	0.6	0.50	0.05	0.25	...	0.50	...	0.25	...	0.35
A443.0	S	4.5–6.0	0.8	0.30	0.50	0.05	0.25	...	0.50	...	0.25	...	0.35
B443.0	S, P	4.5–6.0	0.8	0.15	0.35	0.05	...	...	0.35	...	0.25	0.05	0.15
C443.0	D	4.5–6.0	2.0	0.6	0.35	0.10	...	0.50	0.50	0.15	...	...	0.25
444.0	S, P	6.5–7.5	0.6	0.25	0.35	0.10	...	...	0.35	...	0.25	0.05	0.15
A444.0	P	6.5–7.5	0.20	0.10	0.10	0.05	...	...	0.10	...	0.20	0.05	0.15
511.0	S	0.30–0.7	0.50	0.15	0.35	3.5–4.5	...	...	0.15	...	0.25	0.05	0.15
512.0	S	1.4–2.2	0.6	0.35	0.8	3.5–4.5	0.25	...	0.35	...	0.25	0.05	0.15
513.0	P	0.30	0.40	0.10	0.30	3.5–4.5	...	...	1.4–2.2	...	0.20	0.05	0.15
514.0	S	0.35	0.50	0.15	0.35	3.5–4.5	...	...	0.15	...	0.25	0.05	0.15
515.0	D	0.50–1.0	1.3	0.20	0.40–0.6	2.5–4.0	...	...	0.10	...	...	0.05	0.15
516.0	D	0.30–1.5	0.35–1.0	0.30	0.15–0.40	2.5–4.5	...	0.25–0.04	0.20	0.10	0.10–0.20	0.05(p)	...
518.0	D	0.35	1.8	0.25	0.35	7.5–8.5	...	0.15	0.15	0.15	...	...	0.25
520.0	S	0.25	0.30	0.25	0.15	9.5–10.6	...	...	0.15	...	0.25	0.05	0.15
535.0	S	0.15	0.15	0.05	0.10–0.25	6.2–7.5	...	...	...	...	0.10–0.25	0.05(q)	0.15
A535.0	S	0.20	0.20	0.10	0.10–0.25	6.5–7.5	...	...	...	...	0.25	0.05	0.15
B535.0	S	0.15	0.15	0.10	0.05	6.5–7.5	...	...	...	...	0.10–0.25	0.05	0.15
705.0	S, P	0.20	0.8	0.20	0.40–0.6	1.4–1.8	0.20–0.40	...	2.7–3.3	...	0.25	0.05	0.15
707.0	S, P	0.20	0.8	0.20	0.40–0.6	1.8–2.4	0.20–0.40	...	4.0–4.5	...	0.25	0.05	0.15
710.0	S	0.15	0.50	0.35–0.65	0.05	0.6–0.8	...	...	6.0–7.0	...	0.25	0.05	0.15
711.0	P	0.30	0.7–1.4	0.35–0.65	0.05	0.25–0.45	...	...	6.0–7.0	...	0.20	0.05	0.15
712.0	S	0.30	0.50	0.25	0.10	0.50–0.65	0.40–0.6	...	5.0–6.5	...	0.15–0.25	0.05	0.20
713.0	S, P	0.25	1.1	0.40–1.0	0.6	0.20–0.50	0.35	0.15	7.0–8.0	...	0.25	0.10	0.25
771.0	S	0.15	0.15	0.10	0.10	0.8–1.0	0.06–0.20	...	6.5–7.5	...	0.10–0.20	0.05	0.15
772.0	S	0.15	0.15	0.10	0.10	0.6–0.8	0.06–0.20	...	6.0–7.0	...	0.10–0.20	0.05	0.15
850.0	S, P	0.7	0.7	0.7–1.3	0.10	0.10	...	0.7–1.3	...	5.5–7.0	0.20	...	0.30
851.0	S, P	2.0–3.0	0.7	0.7–1.3	0.10	0.10	...	0.30–0.7	...	5.5–7.0	0.20	...	0.30
852.0	S, P	0.40	0.7	1.7–2.3	0.10	0.6–0.9	...	0.9–1.5	...	5.5–7.0	0.20	...	0.30
853.0	S, P	5.5–6.5	0.7	3.0–4.0	0.50	...	...	...	...	5.5–7.0	0.20	...	0.30

(a) D, die casting; P, permanent mold; S, sand. Other products may pertain to the composition but are not listed. (b) Weight percent; maximum unless range is given or otherwise indicated. All compositions contain balance of aluminum. (c) 0.40–1.0 Ag. (d) 0.50 max Ti + Zr. (e) 0.20–0.30 Sb, 0.20–0.30 Co, 0.10–0.30 Zr. (g) 0.06–0.15 V, 0.10–0.25 Zr. (h) 0.06–0.20 V. (i) If iron exceeds 0.45%, manganese content shall not be less than one-half of iron content. (j) 0.04–0.07 Be. (k) 0.10–0.30 Be. (l) 0.8 max Mn + Cr. (m) 0.25 max Pb. (n) 0.07–0.04 Be. (o) 0.08–0.15 V. (p) 0.10 max Pb. (q) 0.003–0.007 Be, 0.005 max Ti. Source: Ref 1

Aluminum and Aluminum Alloys

Table 8 Representative applications for aluminum casting alloys

Alloy	Representative applications
100.0	Electrical rotors larger than 152 mm (6 in.) in diameter
201.0	Structural members; cylinder heads and pistons; gear, pump, and aerospace housings
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads
238.0	Sole plates for electric hand irons
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings
B295.0	Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts
332.0	Automotive and heavy-duty pistons; pulleys, sheaves
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings
354.0	Premium-strength castings for the aerospace industry
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts
357.0	Corrosion-resistant and pressure-tight applications
359.0	High-strength castings for the aerospace industry
360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges
380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
A380.0	Applications requiring strength at elevated temperature
384.0	Pistons and other severe service applications; automatic transmissions
390.0	Internal combustion engine pistons, blocks, manifolds, and cylinder heads
413.0	Architectural, ornamental, marine, and food and dairy equipment applications
A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
514.0	Fittings for chemical and sewage use; dairy and food handling equipment; tire molds
A514.0	Permanent mold casting of architectural fittings and ornamental hardware
518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
520.0	Aircraft fittings; railway passenger car frames; truck and bus frame sections
535.0	Instrument parts and other applications where dimensional stability is important
A712.0	General-purpose castings that require subsequent brazing
713.0	Automotive parts; pumps; trailer parts; mining equipment
850.0	Bushings and journal bearings for railroads
A850.0	Rolling mill bearings and similar applications

Source: Compiled from *Aluminum Casting Technology*, American Foundrymen's Society, 1986

Aluminum and Aluminum Alloys

Table 7 Typical mechanical properties of aluminum casting alloys

Alloy	Temper	Ultimate tensile strength, MPa	ksi	0.2% offset yield strength, MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HBW
Sand casting alloys							
201.0	T43	414	60	295	43	13.0	...
	T6	448	65	379	55	8.0	130
	T7	467	68	414	60	5.5	...
A206.0	T4	359	52	250	36	7.0	...
208.0	F	145	21	97	14	2.5	55
213.0	F	262	38	103	15	1.5	70
222.0	O	186	27	138	20	1.0	80
	T61	290	42	228	33	<0.5	105
	T62	421	61	331	48	1.0	...
224.0	T72	380	55	276	40	3.0	125
240.0	F	235	34	200	29	1.0	80
242.0	F	214	31	207	30	0.5	...
	O	186	27	124	18	1.0	70
	T571	221	32	207	30	0.5	85
	T77	227	33	159	23	2.0	75
A242.0	T75	310	45	...	...	2.0	...
295.0	T4	221	32	110	16	8.5	60
	T6	234	34	165	24	5.0	75
	T62	283	41	221	32	2.0	90
319.0	F	186	27	124	18	2.0	70
	O	207	30	159	23	3.5	80
	T6	234	34	165	24	2.0	90
355.0	F	179	26	83	12	3.0	...
	T51	193	28	159	23	1.5	65
	T6	241	35	172	25	3.0	80
	T61	269	39	241	35	1.0	90
	T7	264	38	234	34	2.5	80
	T71	241	35	186	27	1.5	75
C355.0	T6	265	39	220	32	3.0	85
356.0	F	165	24	124	18	3.0	...
	T51	172	25	138	20	2.0	60
	T6	228	33	164	24	3.5	70
	T7	234	34	207	30	2.0	75
	T71	193	28	145	21	3.5	60
A356.0	F	158	23	83	12	6.0	...
	T51	152	22	124	18	2.0	...
	T6	228	33	165	24	3.5	70
	T61	262	38	207	30	6.0	75
	T71	207	30	138	20	5.0	...
359.0	F	172	25	90	13	5.0	...
	T61	179	26	117	17	2.0	...
	T6	345	50	255	37	2.0	90
	T7	228	33	214	31	3.0	90
A357.0	T6	317	46	248	36	3.0	85
A390.0	F	179	26	138	20	<1.0	100
	T5	179	26	138	20	<1.0	100
	T6	276	40	228	33	<1.0	140
	T7	220	32	220	32	<1.0	115
443.0	F	131	19	62	9	8.0	40
A444.0	F	145	21	62	9	28.0	...
	T4	99	14	62	9	16.0	...
511.0	F	145	21	83	12	3.0	90
512.0	F	138	20	90	13	2.0	80
514.0	F	172	25	103	15	9.0	80
520.0	T4	331	48	179	26	16.0	75
A520.0	F	250	36	124	18	9.0	95
535.0	F	241	35	172	25	3.0	75
705.0	F	241	35	172	25	3.0	75
707.0	F	241	35	172	25	3.0	75
710.0	F	241	35	172	25	5.0	75
712.0	T5	234	34	172	25	5.0	80
850.0	T5	186	27	152	22	2.0	85
Permanent mold casting alloys							
201.0	T43	414	60	255	37	17.0	...
	T7	448	65	379	55	8.0	120
	T6	483	70	414	60	5.0	...

Alloy	Temper	Ultimate tensile strength, MPa	ksi	0.2% offset yield strength, MPa	ksi	Elongation in 50 mm (2 in.), %	Hardness, HBW
A206.0	T4	431	62	264	38	15.0	...
	T7	436	63	345	50	11.0	...
213.0	F	207	30	103	15	1.5	85
222.0	T52	241	35	234	34	1.0	100
	T221	290	42	241	35	<1.0	110
	T62	331	48	248	36	<0.5	105
238.0	F	207	30	103	15	1.5	100
242.0	T571	276	40	234	34	1.0	105
	T61	324	47	290	42	0.5	110
243.0	T67	276	40	241	35	6.0	...
	T7	276	40	255	37	9.0	...
254.0	T4	290	42	152	22	9.0	75
	T6	276	40	179	26	3.0	95
	T7	290	42	179	26	4.0	85
308.0	F	193	28	110	16	2.0	70
319.0	F	234	34	131	19	2.5	85
	T6	276	40	186	27	3.0	95
324.0	F	207	30	110	16	4.0	70
	T5	248	36	179	26	3.0	90
	T62	310	45	269	39	3.0	105
332.0	T5	248	36	193	28	1.0	100
333.0	F	234	34	131	19	2.0	90
	T5	234	34	172	25	1.0	100
	T6	262	38	207	30	1.5	105
	T7	255	37	193	28	2.0	90
336.0	T551	248	36	193	28	0.5	105
	T65	324	47	296	43	0.5	125
354.0	F	317	46	228	33	3.0	...
	T51	186	27	96	14	2.0	...
	T6	365	53	296	43	5.0	90
	T62	393	57	324	47	3.0	120
A354.0	T6	365	53	296	43	3.5	120
355.0	T6	276	40	207	30	3.0	80
	T61	290	42	234	34	2.0	90
	T7	255	37	193	28	2.0	80
C355.0	T6	303	44	234	34	3.0	90
A355.0	T61	283	41	207	30	3.0	90
357.0	F	193	28	103	15	5.0	...
	T51	200	29	145	21	4.0	...
	T6	359	52	296	43	3.0	120
A357.0	T6	359	52	290	42	5.0	120
359.0	T62	365	53	290	42	5.5	...
A360.0	F	200	29	200	29	<1.0	110
	T6	200	29	200	29	<1.0	110
	T61	310	45	310	45	<1.0	105
	T7	262	38	165	24	<1.0	100
443.0	F	138	20	62	9	10.0	45
A444.0	F	165	24	55	8	12.0	44
	T4	159	23	69	10	24.0	45
513.0	F	234	34	124	18	7.0	60
514.0	F	241	35	124	18	8.0	75
518.0	T2	259	32	96	14	12.0	45
520.0	T6	345	50	255	37	5.0	75
535.0	F	234	34	131	19	9.0	60
A535.0	F	324	47	159	23	4.0	75
705.0	T5	255	37	207	30	2.0	90
707.0	T5	324	47	234	34	2.0	90
711.0	T1	207	30	152	22	2.0	80
A712.0	F	234	34	131	19	9.0	90
713.0	F	221	32	152	22	3.5	80
771.0	T5	345	50	296	43	5.0	90
850.0	T5	207	30	152	22	6.0	90
851.0	T5	152	22	83	12	6.0	90
852.0	T5	221	32	179	26	2.0	95
Die casting alloys							
360.0	F	324	47	172	25	3.0	75
A360.0	F	317	46	165	24	3.0	75
364.0	F	296	43	179	26	7.5	...
380.0	F	331	48	165	24	3.0	80
A380.0	F	324	47	159	23	4.0	75
384.0	F	324	47	172	25	1.0	...
390.0	F	234	34	234	34	1.0	120
	T5	255	37	207	30	1.0	...
392.0	F	255	37	207	30	<1.0	...
413.0	F	303	44	165	24	3.5	90
A413.0	F	303	44	165	24	3.5	90
443.0	F	228	33	97	14	9.0	90
518.0	F	310	45	186	27	8.0	80

Aluminum and Aluminum Alloys

Table 6 Ratings of castability, corrosion resistance, machinability, and weldability for aluminum casting alloys

1, best; 5, worst. Individual alloys may have different ratings for other casting processes.

Alloy	Resistance to hot cracking(a)	Pressure tightness	Fluidity(b)	Shrinkage tendency	Corrosion resistance(c)	Machinability(d)	Weldability(e)
Sand casting alloys							
201.0	4	3	3	4	4	1	2
208.0	2	2	2	2	4	3	3
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
240.0	4	4	3	4	4	3	4
242.0	4	3	4	4	4	2	3
A242.0	4	4	3	4	4	2	3
295.0	4	4	4	3	3	2	2
319.0	2	2	2	2	3	3	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	1	3	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	3	3	3	3	2	4	2
A443.0	1	1	1	1	2	4	4
444.0	1	1	1	1	2	4	1
511.0	4	5	4	5	1	1	4
512.0	3	4	4	4	1	2	4
514.0	4	5	4	5	1	1	4
520.0	2	5	4	5	1	1	5
535.0	4	5	4	5	1	1	3
A535.0	4	5	4	4	1	1	4
B535.0	4	5	4	4	1	1	4
705.0	5	4	4	4	2	1	4
707.0	5	4	4	4	2	1	4
710.0	5	3	4	4	2	1	4
711.0	5	4	5	4	3	1	3
712.0	4	4	3	3	3	1	4
713.0	4	4	3	4	2	1	3
771.0	4	4	3	3	2	1	...
772.0	4	4	3	3	2	1	...
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Permanent mold casting alloys							
201.0	4	3	3	4	4	1	2
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
238.0	2	3	2	2	4	2	3
240.0	4	4	3	4	4	3	4
296.0	4	3	4	3	4	3	4
308.0	2	2	2	2	4	3	3
319.0	2	2	2	2	3	3	2
332.0	1	2	1	2	3	4	2
333.0	1	1	2	2	3	3	3
336.0	1	2	2	3	3	4	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	2	3	3	2
C355.0	1	1	1	2	3	3	2
356.0	1	1	1	1	2	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
A357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	2	2	2	3	2	4	2
443.0	1	1	2	1	2	5	1
A444.0	1	1	1	1	2	3	1
512.0	3	4	4	4	1	2	4
513.0	4	5	4	4	1	1	5
711.0	5	4	5	4	3	1	3
771.0	4	4	3	3	2	1	...
772.0	4	4	3	3	2	1	...
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Die casting alloys							
360.0	1	1	2	2	3	4	
A360.0	1	1	2	2	3	4	
364.0	2	2	1	3	4	3	
380.0	2	1	2	5	3	4	
A380.0	2	2	2	4	3	4	
384.0	2	2	1	3	3	4	
390.0	2	2	2	2	4	2	
413.0	1	2	1	2	4	4	
C443.0	2	3	3	2	5	4	
515.0	4	5	5	1	2	4	
518.0	5	5	5	1	1	4	

Copper and Copper Alloys

- Group I alloys – that have a narrow freezing range of 50°C
- Group II alloys – that have intermediate freezing range of 50 – 110°C between the liquidus and the solidus.
- Group III alloys –that have wide freezing range over 110°C up to 170°C.

Table 1 Nominal chemical composition and typical mechanical properties for group I alloys

Alloy type	UNS No.	Composition, %										Yield strength(a), 0.5%		Tensile strength(a)		Elongation(a), %
		Cu	Sn	Pb	Zn	Ni	Fe	Al	Mn	Si	Other	MPa	ksi	MPa	ksi	
Copper	C81100	100	...	...	...	...	...	...	...	...	...	28	4	124	18	40
Chrome copper	C81500	99	...	...	...	...	...	...	...	...	1.0 Cr	276	40 (HT)	34	5 (HT)	17 (HT)
Yellow brass	C85200	72	1	3	24	...	...	...	...	...	...	90	13	262	38	35
	C85400	67	1	3	29	...	...	...	...	...	...	83	12	234	34	35
	C85700	61	1	1	37	...	...	...	...	...	...	124	18	345	50	40
	C85800	62	1	1	36	...	...	...	...	...	...	207	30	379	55	15
	C87900	65	...	...	34	...	...	...	...	1	...	241	35	483	70	25
Manganese bronze	C86200	63	...	...	27		3	4	3	...	...	331	48	654	95	20
	C86300	61	...	...	27	...	3	6	3	...	...	476	69	793	115	15
	C86400	58	1	1	38	...	1	5	5	...	...	172	25	448	65	20
	C86500	58	...	...	39	...	1	1	1	...	...	207	30	489	71	30
	C86700	58	1	1	34	...	2	2	2	...	...	290	42	586	85	20
	C86800	55	...	...	36	3	2	1	3	...	...	262	38	565	82	22
Aluminum bronze	C95200	88	...	...	...	...	3	9	...	...	...	186	27	552	80	35
	C95300	89	...	...	...	...	1	10	...	...	...	186–290	27–42 (HT)	517–586	75–85 (HT)	25–18 (HT)
	C95400	86	...	...	...	...	4	10	...	...	...	241–317	35–46 (HT)	586–758	85–110 (HT)	20–12 (HT)
	C95410	84	...	...	...	2	4	10	...	...	...	248–400	36–58 (HT)	662–800	96–116 (HT)	15–10 (HT)
	C95500	81	...	...	...	4	4	11	...	...	...	303–496	44–72 (HT)	717–827	104–120 (HT)	12–6 (HT)
	C95600	91	...	...	...	...	...	7	...	2	...	234	34	517	75	18
	C95700	75	...	...	...	2	3	8	12	...	...	310	45	655	95	26
	C95800	81	...	...	...	4.5	4	9	1.5	...	...	262	38	655	95	25
Nickel bronze	C97300	57	2	9	20	12	...	...	...	...	...	117	17	241	35	30
	C97600	64	4	4	8	20	...	...	...	...	...	165	24	310	45	20
	C97800	66	5	2	2	25	...	...	...	...	...	207	30	379	55	15
White brass	C99700	58	...	2	22	5	...	1	12	...	...	172	25	379	55	25
	C99750	58	...	1	20	...	...	1	20	...	...	221	32	448	65	30

(a) HT, heat treated

Copper and Copper Alloys

Table 2 Nominal chemical composition and typical mechanical properties for group II alloys

Alloy type	UNS No.	Composition, %								Yield strength(b)(c), 0.5%		Tensile strength(b)		
		Cu	Zn	Ni	Fe	Mn	Si	Nb	Other	MPa	ksi	MPa	ksi	Elongation(b), %
Beryllium copper	C81400	99.1	...	...	...	...	...	...	0.6 Be	248	36 (HT)	365	53 (HT)	11 (HT)
									0.8 Cr		...		...	...
	C82000	97	...	...	...	...	...	...	0.5 Be	121	17.6	243	35.2	20
									2.5 Co	517	75 (HT)	689	100 (HT)	3 (HT)
	C82200	98	...	1.5	...	...	...	...	0.5 Be	145	21.1	276	40.1	20
									...	517	75 (HT)	654	95 (HT)	8 (HT)
	C82400	97.8	...	...	...	...	...	...	1.7 Be	179	26.0	349	50.6	20
									0.5 Co	965	140 (HT)	1035	150 (HT)	1 (HT)
	C82500	97.2	...	...	...	...	0.3	...	2.0 Be	218	31.6	387	56.2	20
									0.5 Co		...	1105	160 (HT)	1 (HT)
	C82600	96.8	...	...	...	...	0.3	...	2.4 Be	228	33.0	397	57.6	20
									0.5 Co	1070	155 (HT)	1140	165 (HT)	1 (HT)
	C82800	96.6	...	...	...	...	0.3	...	2.6 Be	267	38.7	470	68.2	20
									0.5 Co	1000	145 (HT)	1140	165 (HT)	1 (HT)
Silicon brass	C87500	82	14	...	...	...	4	...	30	462	67	145	21	...
Silicon bronze	C87300	9.5	...	...	...	1	4	...	25	400	58	241	35	...
	C87600	91	5	...	...	...	4	...	32	455	66	138	20	...
	C87610	92	4	...	...	...	4	...	25	400	58	207	30	...
	C87800(a)	82	14	...	...	...	4	...	50	586	85	172	25	...
Copper-nickel	C96200	87	...	10	1.5	1	...	1	27	345	50	152	22	...
	C96400	66	...	30.5	0.5	1	...	1	27					

Table 3 Nominal chemical composition and typical mechanical properties for group III alloys

Alloy type	UNS No.	Composition, %					Yield strength, 0.5%		Tensile strength, 0.5%		Elongation, %
		Cu	Sn	Pb	Zn	Ni	MPa	ksi	MPa	ksi	
Leaded red brass	C83450	88	2.5	2	6.5	1	103	15	255	37	34
	C83600	85	5	5	5	...	110	16	248	36	32
	C83800	83	4	6	7	...	110	16	241	35	28
Leaded semired brass	C84400	81	3	7	9	...	96	14	234	34	28
	C84800	76	2.5	6.5	15	...	103	15	255	37	29
Tin bronze	C90300	88	8	...	4	...	138	20	310	45	30
	C90500	88	10	...	2	...	152	22	317	46	30
	C90700	89	11	...	...	...	152	22	303	44	20
	C91100	84	16	...	...	...	172	25	241	35	2
	C91300	81	19	...	...	...	241	35	207	30	0.5
Leaded tin bronze	C92200	86	6	1.5	4.5	...	110	16	283	41	45
	C92300	87	8	1	4	...	138	20	290	42	32
	C92600	87	10	1	2	...	138	20	303	44	30
	C92700	88	10	2	...	...	142	21	300	42	20
High-leaded tin bronze	C92900	84	10	2.5	...	3.5	179	26	324	47	20
	C93200	83	7	7	3	...	117	17	262	38	30
	C93400	84	8	8	...	...	110	16	248	36	25
	C93500	85	5	9	1	...	110	16	221	32	20
	C93700	80	10	10	...	...	124	18	276	40	30
	C93800	78	7	15	...	...	110	16	221	32	20
	C94300	70	5	25	...	...	110	16	207	30	18

Copper and Copper Alloys

- Plumbing hardware, pump parts, and valves and fittings – usually red and semi-red brasses. C83300 to C84800.
- Bearings and bushings – Usually phosphor bronzes, Copper-tin-lead, Manganese, silicon, and aluminum bronzes.
- Gears – Tin bronzes, nickel-tin bronzes. C90700, C90800, C91600, C91700, C92900.
- Marine castings – Copper-nickels (high strength) C96200, C96400; Bronzes.
- Electrical components - Pure copper, beryllium-copper, leaded red brasses, bronzes.
- Architectural and ornamental parts - Bronze C87200, Yellow, and leaded yellow brasses.

Copper and Copper Alloys

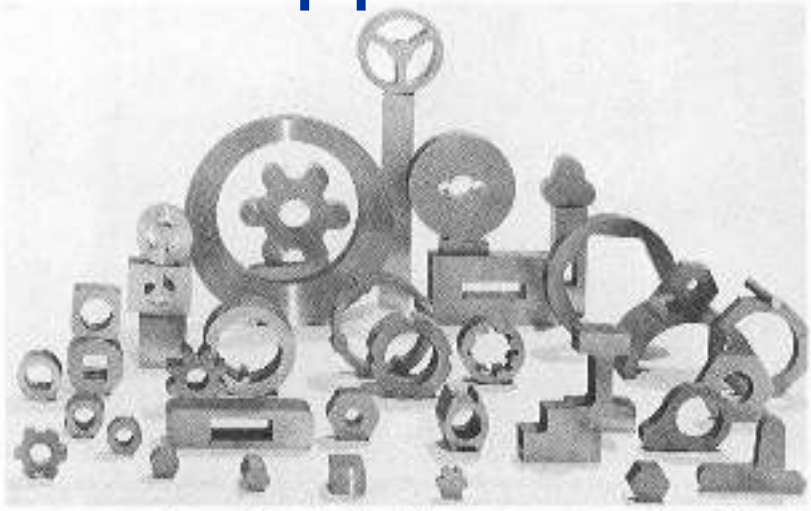


Fig. 22 Variety of intricate shapes and sizes obtained by using continuous casting methods to produce brass and bronze alloy parts. Courtesy of ASARCO, Inc.

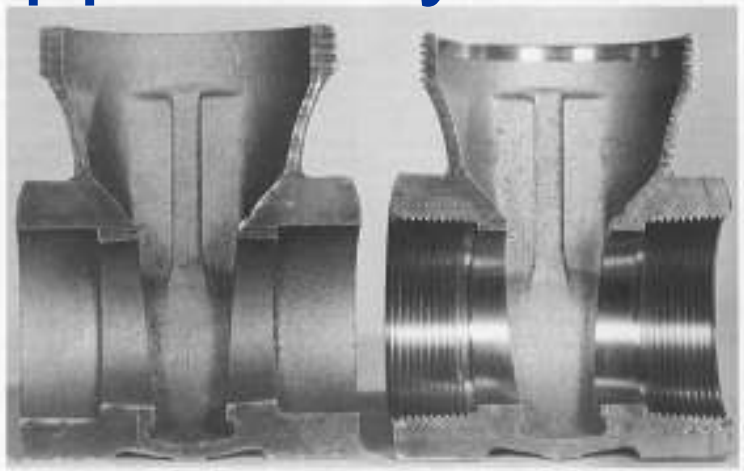


Fig. 23 Cutaway views of an as-cast and finish machined/threaded body of a 50 mm (2 in.) gate valve-union bonnet assembly rated at 1.0 MPa (150 psi). The body section was sand cast of CB360O alloy (Cu-5Sn-5Pb-5Zn composition) and weighs 2.4 kg (5.2 lb). Courtesy of Crane Company

Fig. 26 Propeller for a 114 000 ton tanker measures 7.5 m (24.7 ft) in diameter and weighs 37.52 Mg (82 725 lb). Part was machined and polished from a single 53.75 Mg (118 500 lb) nickel-aluminum bronze casting. Courtesy of Baldwin-Lima-Hamilton Corporation

Fig. 27 Vertical centrifugally cast ship propeller hub for controllable-pitch propeller blades is made of nickel-aluminum bronze, weighs 8.44 Mg (18 600 lb), and measures 1575 mm (62 in.) in diameter and 1270 mm (50 in.) in length. Courtesy of Wisconsin Centrifugal, Inc.

Zinc and Zinc Alloys

Table 1 Compositions of zinc casting alloys

Alloy	Applicable standards	Composition, %(a) Al	Cu	Mg	Fe	Pb	Cd	Sn	Ni	Zn
No. 3 (UNS Z33521)	ASTM B 86	3.5–4.3	0.25	0.02–0.05	0.100 0.100	0.005	0.004	0.003	...	rem
No. 5 (UNS Z35531)	ASTM B 86	3.5–4.3	0.75–1.25	0.03–0.08	0.075	0.005	0.004	0.003	...	rem
No. 7 (UNS Z33522)	ASTM B 86	3.5–4.3	0.25	0.005–0.02	0.10	0.003	0.002	0.001	0.005–0.02	rem
ZA-8 (UNS Z25630)	ASTM B 669	8.0–8.8	0.8–1.3	0.015–0.03	0.075	0.004	0.003	0.002	...	rem
ZA-12 (UNS Z35630)	ASTM B 669	10.5–11.5	0.5–1.25	0.015–0.03	0.10	0.004	0.003	0.002	...	rem
ZA-27 (UNS Z35840)	ASTM B 669	25.0–28.0	2.0–2.5	0.01–0.02	...	0.004	0.003	0.002	...	rem

(a) Maximum unless range is given or otherwise indicated.

Table 2 Comparison of typical mechanical properties of casting alloys

Alloy and product form(a)	Ultimate tensile strength MPa	ksi	0.2% offset yield strength MPa	ksi	Elongation, % in 50 mm (2 in.)	Hardness, HB	Impact strength J	ft · lbf	Fatigue strength MPa	ksi	Young's modulus GPa	Young's modulus ksi × 10^3
Zinc alloys												
No. 3 (D)	283	41	...	...	10	82	58(c)	43	47.6	6.9	...	...
No. 5 (D)	331	48	...	...	7	91	65(c)	48	56.5	8.2	...	...
No. 7 (D)	283	41	...	...	13	80	58(c)	43	...	...	...	...
ZA-8 (S)	248–276	36–40	200	29	1–2	80–90	20(c)	15	...	...	85.5	12.4
ZA-8 (P)	221–255	32–37	207	30	1–2	85–90	...	...	51.8	7.5	85.5	12.4
ZA-8 (D)	372	54	290	42	6–10	95–110	42(c)	31	...	...	...	...
ZA-12 (S)	276–317	40–46	207	30	1–3	90–105	25(c)	19	103.5	15	83.0	12.0
ZA-12 (P)	310–345	45–50	207	30	1–3	90–105	...	...	...	...	83.0	12.0
ZA-12 (D)	400	58	317	46	4–7	95–115	28(c)	21	...	...	...	...
ZA-27 (S)(b)	400–440	58–64	365	53	3–6	110–120	47(c)	35	172.5	25	75.2	10.9
ZA-27 (P)	421–427	61–62	365	53	1	110–120	...	...	...	...	75.2	10.9
ZA-27 (D)	421	61	365	53	1–3	105–125	...	...	...	...	...	...
Aluminum alloys												
319 (S)	185	27	124	18	2	70	5(c)	4	69	10	74.0	10.7
356-T6 (P)	262	38	185	27	5	80	11(c)	8	90	13	72.4	10.5
380 (D)	325	47	159	23	3.5	80–85	4(c)	3	138	20	71.0	10.3
Copper alloys												

Zinc and Zinc Alloys

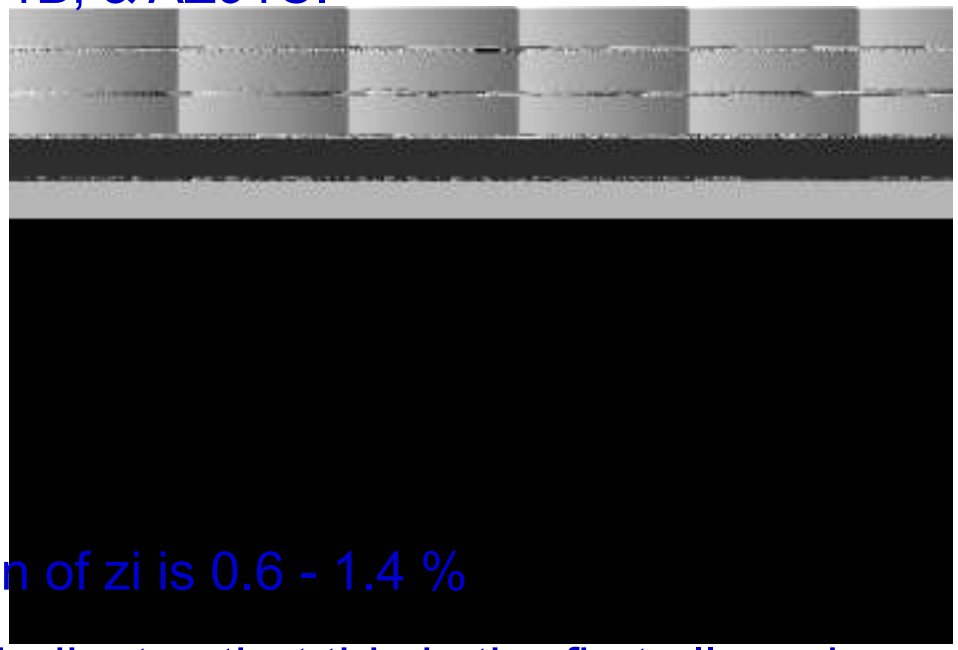
- Applications for Zinc Die Castings
- The automotive industry is the largest user of zinc die castings: carburetor bodies, bodies for fuel pumps, windshield wiper parts, control panels, grilles, horns, and parts for hydraulic brakes. Structural and decorative zinc alloy castings include grilles for radios and radiators, lamp and instrument bezels, steering wheel hubs, interior and exterior hardware, instrument panels, and body moldings.
- Also: electrical, electronic, and appliance industries, business machines and other light machines of all types (including beverage vending machines, and tools. Building hardware, padlocks, and toys and novelties are major areas of application for zinc die castings.

Zinc and Zinc Alloys

- Other Casting Processes for Zinc Alloys
- Sand Casting. The ZA alloys, especially ZA-12 and ZA-27, are being increasingly used in gravity sand casting operations. The use of chills or patterns that promote directional solidification is recommended.
- Permanent mold casting is done using both metallic and machined graphite molds. Cast iron or steel is most commonly used for metallic permanent molds. The use of graphite molds permits as-cast tolerances similar to those obtained in die casting. Machining time is reduced or eliminated, making the graphite process attractive for intermediate production volumes (500 to 20 000 parts per year).
- Squeeze casting - employed to cast MMCs with ZA alloy matrices and SiC or alumina fibres.

Magnesium and Magnesium Alloys

- Consider the 3 alloys AZ91A, AZ91B, & AZ91C.
- A represents Al, the greatest alloying element present
- Z represents Zi, second greatest alloying element
- 9 indicates that the rounded mean of al is 8.6 - 9.4 %



- 1 indicates that the rounded mean of zi is 0.6 - 1.4 %
- Final letter A in the first example indicates that this is the first alloy whose composition qualified assignment of the designation AZ91
- B and C in other examples signify alloys subsequently developed whose specified compositions differ slightly from the first and from one another but do not differ sufficiently to effect a change in the basic designation.

Magnesium and Magnesium Alloys

Table 2 Nominal compositions of magnesium casting alloys for sand, investment, and permanent mold castings

Alloy	Composition, % Al	Zn	Mn	Rare earths	Th	Y	Zr
AM100A	10.0	...	0.1 min	...	...	...	...
AZ63A	6.0	3.0	0.15	...	...	...	...
AZ81A	8.0	0.7	0.13	...	...	...	...
AZ91C	9.0	0.7	0.13	...	...	...	...
AZ91E	9.0	2.0	0.10	...	...	...	...
AZ92A	9.0	2.0	0.10	...	...	...	...
EZ33A	...	2.7	...	3.3	...	...	0.60
HK31A	...	...	...	...	3.3	...	0.70
HZ32A	...	2.1	...	...	3.3	...	0.70
QE22A(a)	...	...	...	2.0	...	...	0.60
EQ21A(a,b)	...	...	...	2.0	...	...	0.60
ZE41A	...	4.2	...	1.2	...	...	0.70
ZE63A	...	5.7	...	2.5	...	...	0.70
ZH62A	...	5.7	...	...	1.8	...	0.70
ZK51A	...	4.6	...	...	...	...	0.70
ZK61A	...	6.0	...	...	...	...	0.70
WE54A	...	...	...	3.50(c)	...	5.25	0.50

(a) These alloys also contain silver, that is, 2.5% in QE22A and 1.5% in EQ21A. (b) EQ21A also contains 0.10% Cu. (c) Comprising 1.75% other heavy rare earths in addition to the 1.75% Nd present

Table 3 Nominal compositions of magnesium casting alloys for die castings

Alloy	Alloying element Mg	Al	Mn	Si	Zn
AM60A	rem	6.0	0.13 min	...	...
AS41A	rem	4.25	0.35	1.0	...
AZ91A	rem	9.0	0.13 min	...	0.7
AZ91B	rem	9.0	0.13 min	...	0.7
AZ91D (HP)(b)	rem	9.0	(a)	...	0.7

(a) Manganese content to be dependent upon iron content. (b) The proposed alloy to have very low limits for iron, nickel, and copper. HP, high purity

Magnesium and Magnesium Alloys

- General Applications
- The most important feature of magnesium castings is their light weight.
- Magnesium castings have found considerable use since World War II in aircraft and aerospace applications
- Due to general requirement for lighter weight automobiles to conserve energy, there has been a growing use of magnesium as die castings
- Magnesium has other important casting advantages over other metals:
  - It is an abundantly available metal
  - It is easier to machine than aluminum.
  - It can be machined much faster than aluminum, preferably dry

Magnesium and Magnesium Alloys

- In die casting, MG can be cast up to four times faster than aluminum. Die lives are considerably longer
- Modern casting methods and the application of protective coatings currently available ensure long life for well-designed components.
- Able to produce complex parts having thin-wall sections. The end product has a high degree of stability as well as being light in weight.
- Mg castings of all types have found use in many applications, where their lightness and rigidity are required, such as for chain saw bodies, computer components, camera bodies, and certain portable tools. Magnesium alloy sand castings are used extensively for aerospace components.

Titanium and Titanium Alloys

- The term castings considered inferior to wrought products.
- This is not true with titanium cast parts.
- They are comparable to wrought products in all respects and superior
- crack propagation and creep resistance can be superior
- So, titanium castings can reliably replace forged/machined parts
  - Allotropic phase transformation at 705 to 1040°C, which is well below the solidification temperature of the alloys.
  - As a result, the cast dendritic structure is wiped out during the solid state cooling stage

Table 2 Comparison of cast titanium alloys

Alloy	Estimated relative usage of castings	Nominal composition, wt %										Special properties(a)
		O	N	H	Al	Fe	V	Cr	Sn	Mo	Zr	
Ti-6Al-4V	90%	0.18	0.015	0.006	6	0.13	4	...	...	...	...	General purpose
Ti-6Al-4V ELI	2%	0.11	0.010	0.006	6	0.10	4	...	...	...	...	Cryogenic toughness
Commercially pure titanium Gr2	5%	0.25	0.015	0.006	...	0.15	...	...	...	...	...	Corrosion resistance
Ti-6Al-2Sn-4Zr-2Mo	2%	0.10	0.010	0.006	6	0.15	...	...	2	2	4	Elevated-temperature creep
Ti-6Al-2Sn-4Zr-6Mo	<1%	0.10	0.010	0.006	6	0.15	...	...	2	6	4	Elevated-temperature strength
Ti-5Al-2.5Sn	<1%	0.16	0.015	0.006	5	0.2	...	...	2.5	...	...	Cryogenic toughness
Ti-3Al-8V-6Cr-4Zr-4Mo	<1%	0.10	0.015	0.006	3.5	0.2	8.5	6	...	4	4	Strength
Ti-15V-3Al-3Cr-3Sn	<1%	0.11	0.015	0.006	3	0.2	15	3	3	...	...	Strength
Total	100%											

(a) Superior, relative to Ti-6Al-4V

Titanium and Titanium Alloys

Table 3 Typical room-temperature tensile properties of titanium alloy castings (bars machined from castings)

Specification minimums are less than these typical properties.

Alloy(a)	Yield strength MPa	Yield strength ksi	Ultimate strength MPa	Ultimate strength ksi	Elongation, %	Reduction of area, %
Commercially pure (Grade 2)	448	65	552	80	18	32
Ti-6Al-4V, annealed	855	124	930	135	12	20
Ti-6Al-4V-ELI	758	110	827	120	13	22
Ti-6Al-2Sn-4Zr-2Mo, annealed	910	132	1006	146	10	21
Ti-6Al-2Sn-4Zr-6Mo, STA	1269	184	1345	195	1	1
Ti-3Al-8V-6Cr-4Zr-4Mo, STA	1241	180	1330	193	7	12
Ti-15V-3Al-3Cr-3Sn, STA	1200	174	1275	185	6	12

(a) Solution-treated and aged (STA) heat treatments may be varied to produce alternate properties.

- Product Applications
- since 1960s, used in corrosion-resistant service in pump and valve parts
- Aerospace use of castings in the early 1970s for aircraft brake torque tubes, missile wings, and hot gas nozzles.
- As the more precise investment casting technology developed and the commercial use of HIP became a reality in the mid-1970s, titanium casting applications quickly expanded into critical airframe and gas turbine engine components.

Titanium and Titanium Alloys

- Today, titanium cast parts are routinely produced for critical structural applications such as space shuttle attachment fittings, complex airframe structures, engine mounts, compressor cases and frames of many types, missile bodies and wings, and hydraulic housings.
- Titanium castings are used for framework for very sensitive optical equipment due to their stiffness and the compatibility of the coefficient of thermal expansion of titanium with that of glass.
- Applications evolving for engine airfoil shapes include individual vanes and integral vane rings for stators, as well as a few rotating parts that would otherwise be made from wrought product.
- Growth will continue as users seek to take advantage of the flexibility of design inherent in the investment casting process and the improvement in economics of net and near-net shapes.

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Heat Treatment

Lecture 6

Heat Treatment

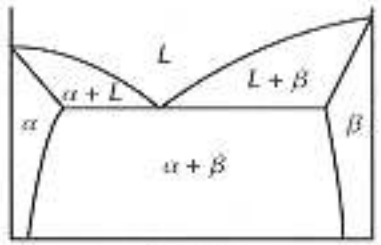
- This is a stupendously amazing concept that can produce some quite amazing changes in certain materials WITHOUT having to change component shape!
  - Softens cold-worked metals (annealing)
  - Strengthens some metals (quench & temper, ppt. harden)
  - Spheroidizes high carbon steels for easier machining.
  - Surfaces can be selectively hardened
  - Phase changes can be utilized for strengthening, shape memory affects etc.
- Requires understanding of PHASE DIAGRAMS!

Phase Diagrams (Review)

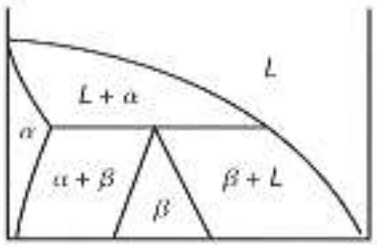
- **Phases** - "physically distinct, chemically homogeneous and mechanically separable portion of a substance"
- **Equilibrium phase diagrams** - variables are temperature, pressure, composition. E.g P-T, T-C.
- T-C phase diagrams determined by cooling curves. (**Liquidus, solidus, freezing range)**
- **Solubility-** solubility limits - non (insoluble), partial or complete solubility.
- Diagrams - give
  - phases present
  - composition of phases
  - amounts of phases present.

Three Phase Reactions

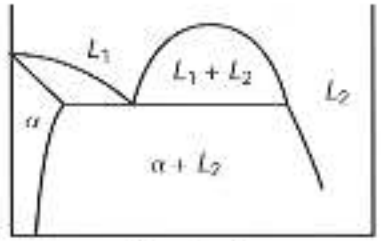
- E.g.
- Eutectic - Liquid $\rightarrow$ solid$_1$ + solid$_2$
- Peritectic - L + $S_1 \rightarrow S_2$
- Eutectoid - $S_1 \rightarrow S_2 + S_3$



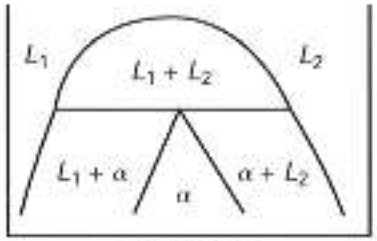
Eutectic
$(L \rightarrow S_1 + S_2)$



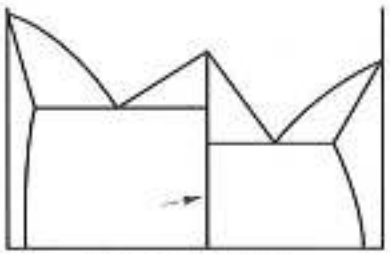
Peritectic
$(L + S_1 \rightarrow S_2)$

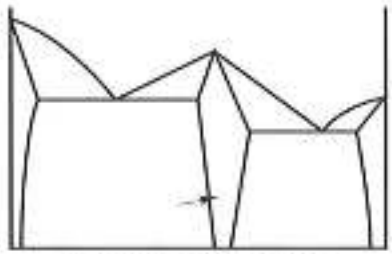


Monotectic
$(L_1 \rightarrow S_1 + L_2)$



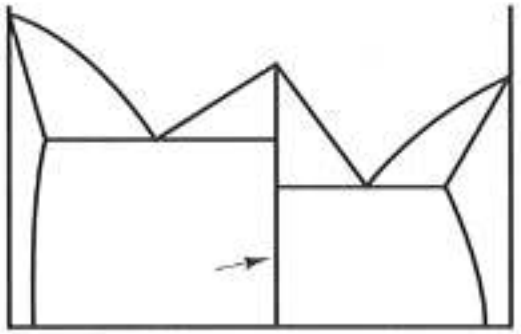
Syntectic
$(L_1 + L_2 \rightarrow S_1)$


Stoichiometric
intermetallic compound

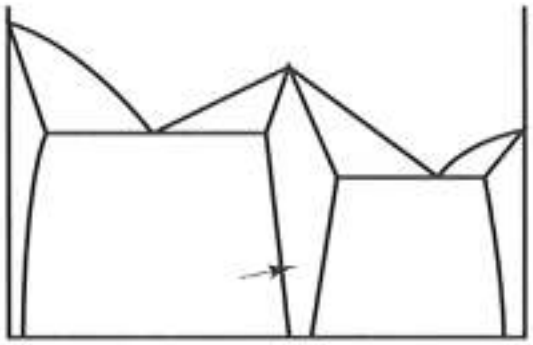

Non-stoichiometric
intermetallic compound

Compounds

- Sometimes formed at particular ratios of two metals or a metal and a non-metal.
- (two metals - Intermetallic compound - Fe_3Al).
- Fixed composition - Stoichiometric E.g. Fe_3C Iron carbide (cementite)
- These Compounds appear as Vertical lines on Phase Diagram.
- Some intermetallic compounds can exist over changes in composition - Non-stoichiometric
- Sometimes known as Intermediate phases
- Eg. Cu - Zn system, Mg - Pb system, Cu – Al system



Stoichiometric intermetallic compound

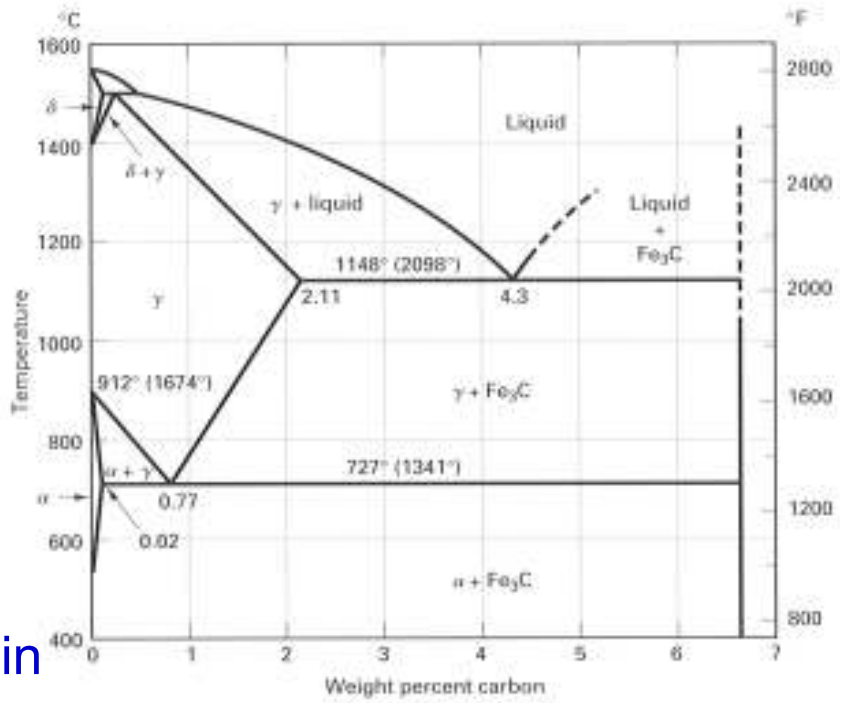


Non-stoichiometric intermetallic compound

Solid Phases in Fe-Fe_3C System

- **α - Ferrite**; Interstitial solid sol^n of C in BCC iron. Max solubility = 0.02%C at 723°C
- **γ - Austenite**; Interstitial solid Sol^n of C in FCC Iron; Max solubility = 2.08% at 1148°C (≈ 0.8 % at 723°C)

FIGURE 4.10 The iron-carbon equilibrium diagram: α, ferrite; γ, austenite; δ, δ-ferrite; Fe_3C, cementite.



- **δ - Ferrite** - Interstitial solid Sol^n of C in BCC iron. (lattice constant "a" is larger than for α - ferrite). Max solubility = 0.09%C at 1485°C.
- **Fe_3C - Cementite** - Iron Carbide (Intermetallic Compound). (3 atoms Fe to 1 atom C) or 93.3 wt% Fe + 6.67 wt% C (Hard + Brittle)

Invariant Points in Fe-Fe_3C System

Lever Rule

- **Peritectic** @ 1495°C

  Liq + δ → γ

  (0.53%C) (0.09%) (0.17%)

- **Eutectic** @ 1148°C

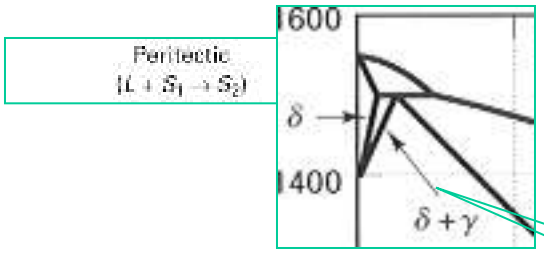
  Liq → γ + Fe_3C (in CI)

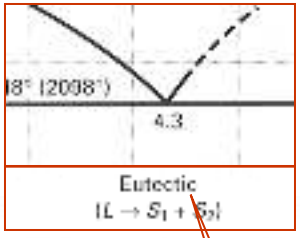
  (4.3%) (2.08%) (6.67%)

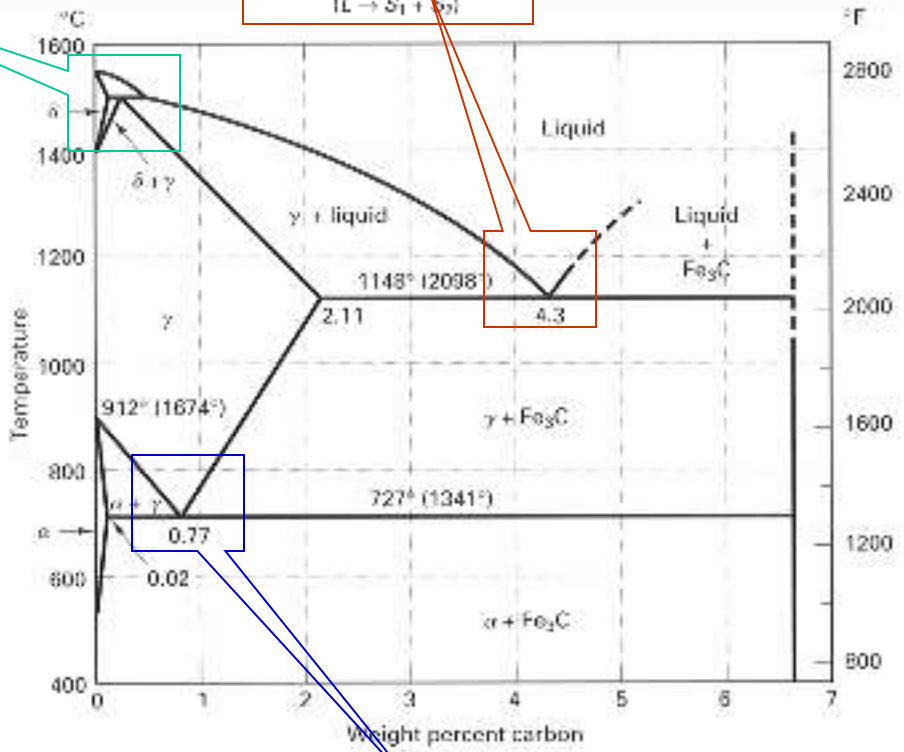
- **Eutectoid** @ 723°C

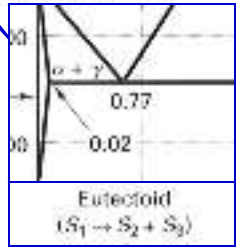
  γ → α + Fe3C (carbon steels)

  (0.77%) (0.022%) (6.67%)







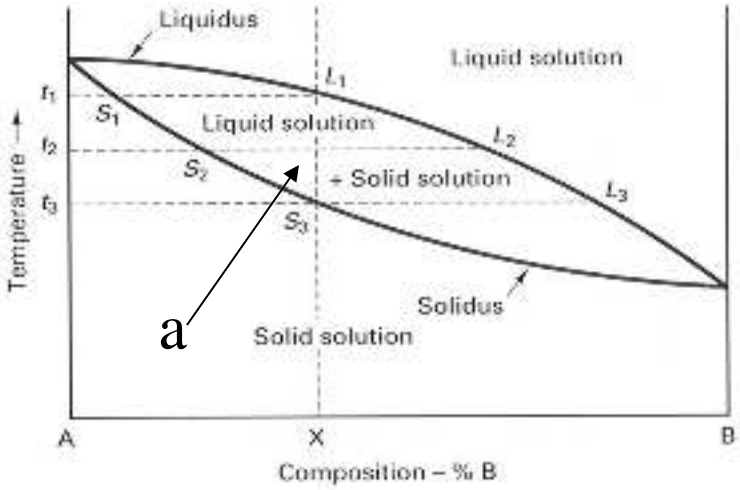


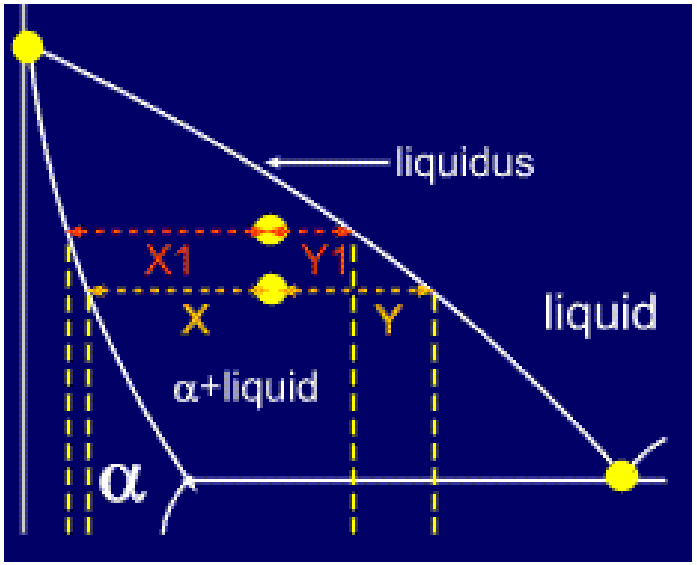
Lever Rule

- > t_1 the alloy X is liquid and < t_3 it is solid
- At t_1 the tie line runs from S_1 to L_1 and is to left of composition X
- At t_3 the tie line runs from S_3 to L_3 and is to right of composition X
- At t_2, it can be proved that the line to the left of point a gives the proportion of liquid and the line to the right gives the proportion of solid
- At t_2 the proportion can be calculated by

$$\frac{a - S_2}{L_2 - S_2} X100\%$$

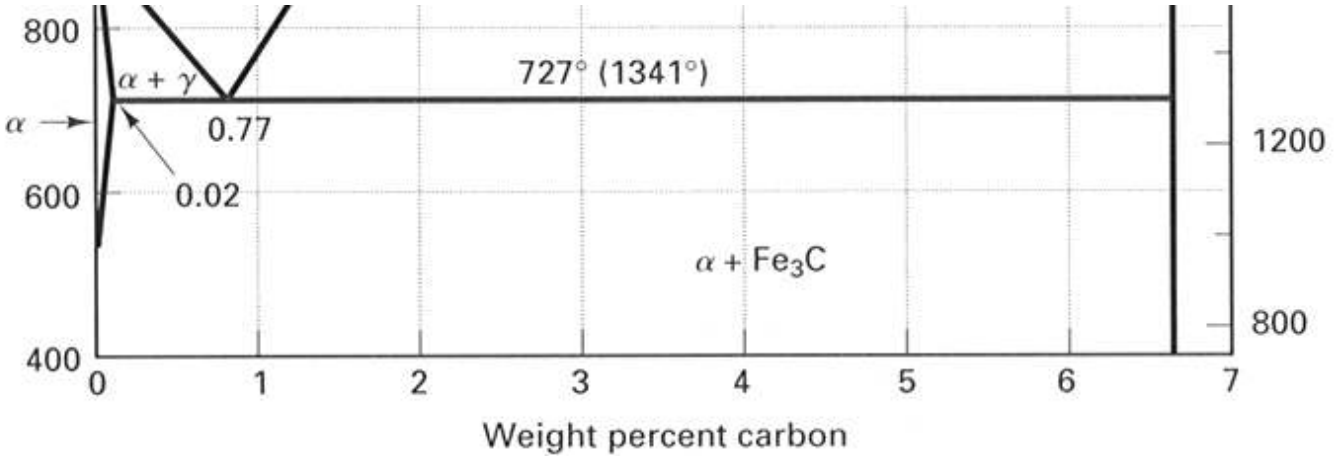
FIGURE 4.8 Equilibrium diagram showing the changes that occur during the cooling of alloy X.





The Eutectoid Reaction

- This particular combination of phases formed through this reaction is known as **Pearlite** (particular mixture of these two phases (α+Fe_3C) formed through the eutectoid reaction)
- As Eutectoid Reaction - (like eutectic) lamellar structure formed)
- So **Pearlite** (α + Fe_3C) formed by the Eutectoid Reaction is



$$\gamma\,(0.77\ wt\ \%\,C) \underset{heating}{\overset{cooling}{\rightleftharpoons}} \alpha\,(0.02\ \ wt\ \%\,C) + Fe_3C\,(6.7\,wt\ \%\,C)$$

The Eutectoid Reaction

- This particular combination of phases formed through this reaction is known as **Pearlite** (particular mixture of these two phases (α+Fe_3C) formed through the eutectoid reaction)
- As Eutectoid Reaction - (like eutectic) lamellar structure formed)
- So **Pearlite** (α + Fe_3C) formed by the Eutectoid Reaction is

$$\gamma(0.77\ wt\ \%C) \underset{heating}{\overset{cooling}{\rightleftharpoons}} \alpha(0.02\ \ wt\ \%C) + Fe_3C(6.7\ wt\ \%C)$$

$$\%\alpha = \frac{6.67 - 0.77}{6.67 - 0.0218} x100 = 88.7\%$$

$$\%Fe_3C = \frac{0.77 - 0.0218}{6.67 - 0.0218} x100 = 11.3\%$$

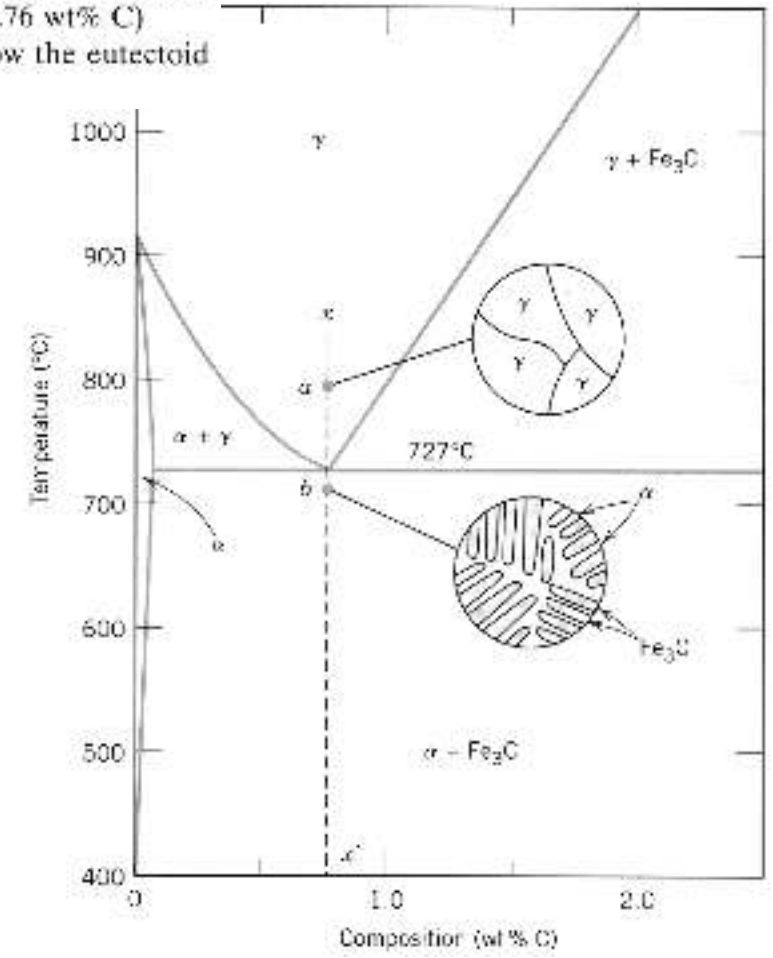
Microstructure Development in Fe-C

- 0.77wt%c **Eutectoid** Steel
- < 0.77wt%c **Hypo**eutectoid
- >0.77wt%c **Hyper**eutectoid

- Slow Cooling of Eutectoid Steel
- A eutectoid steel heated into the γ region (austenitized) and then slow cooled below 727°C will go through the eutectoid reaction:

$$\gamma \rightarrow \alpha + \mathbf{Fe_3C}$$ (form 100% pearlite)

Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.



Microstructure Development in Fe-C

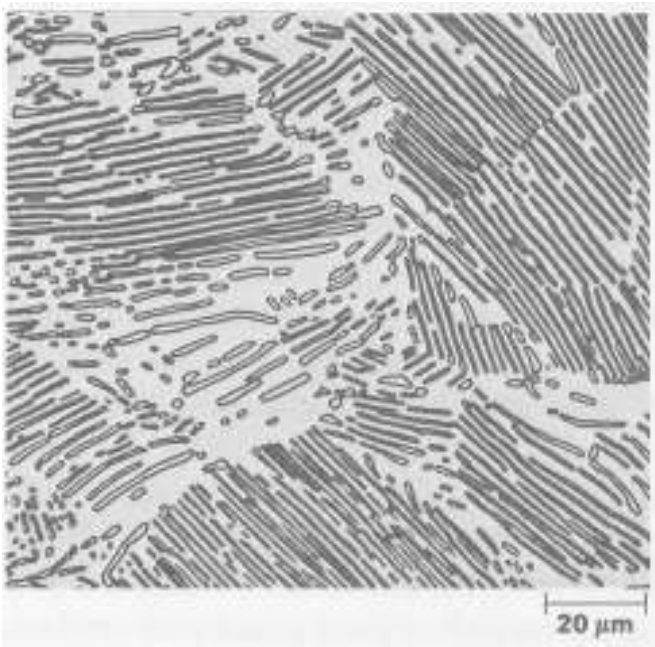


FIGURE 9.25 Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 500×.

- Pearlite is lamellar structure with alternate layers of Ferrite and cementite

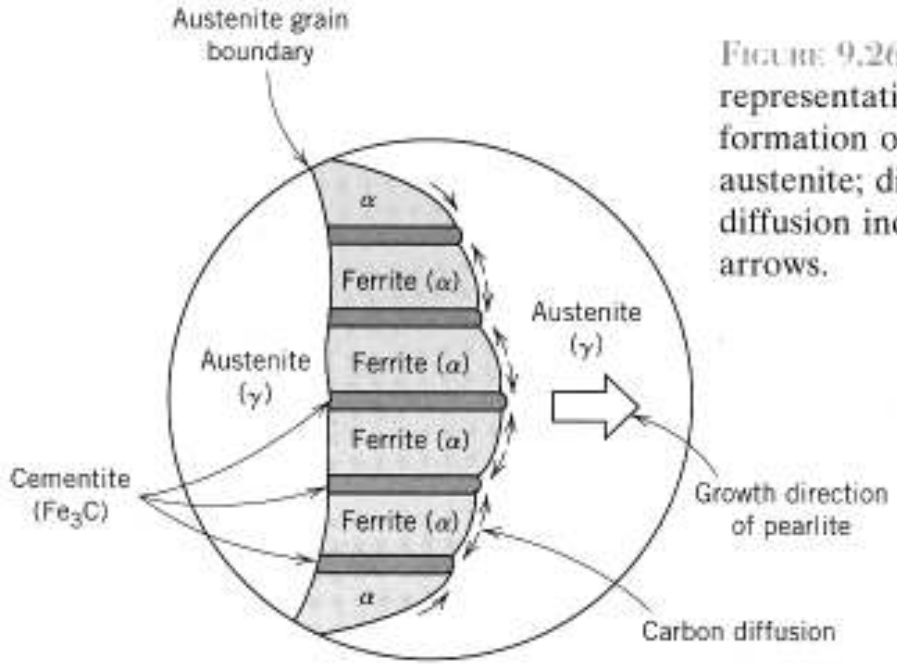


FIGURE 9.26 Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows.

Hypoeutectoid Steels

(< 0.77%C) eg 0.4%C steel

- Have to heat to higher T to get 100% γ (austenite) » 900°C
  Slow Cooled:
  $\gamma \rightarrow 800^{o}C \rightarrow \gamma + \alpha'$ (Proeutectoid/Primary Ferrite)

  $\gamma + \alpha' \rightarrow 712^{o}C \rightarrow \alpha' + \alpha + Fe_3C$ (Pearlite)
- Amounts of each:
- In this case because we want to distinguish between α and α' calculate just above transformation temp to get α'.
- Final grain consists proeutectoid α, formed before cooling down; and alternate layers of eutectoid α, and Fe_3C forming the pearlite structure

Hypoeutectoid Steels

- Increasing amounts of α while cooling - calculated using lever rule

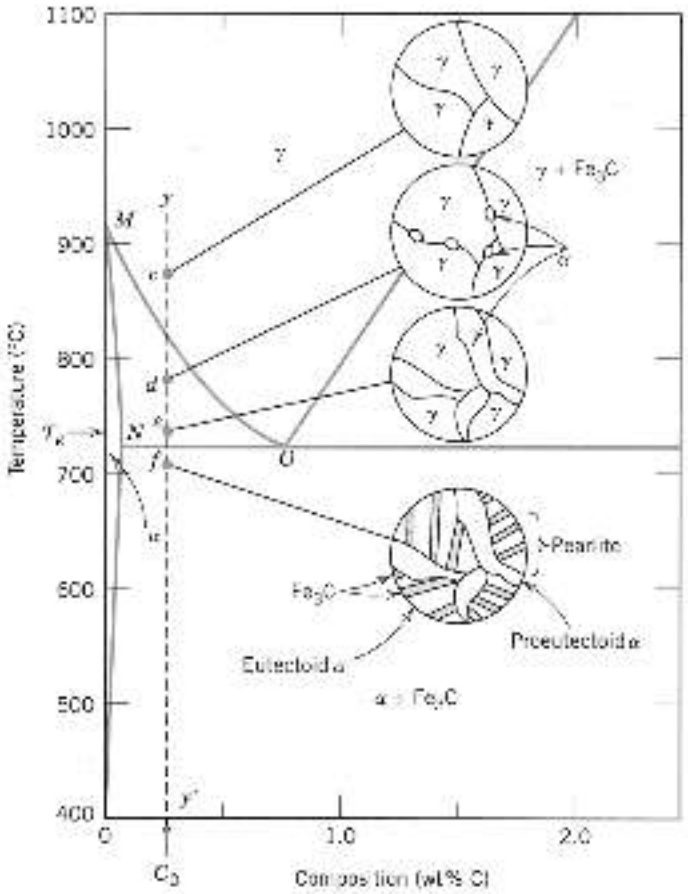
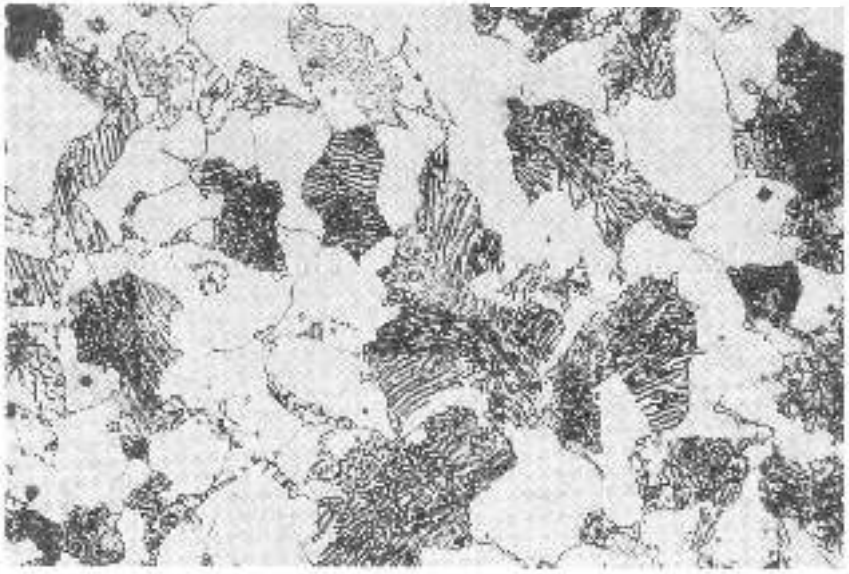


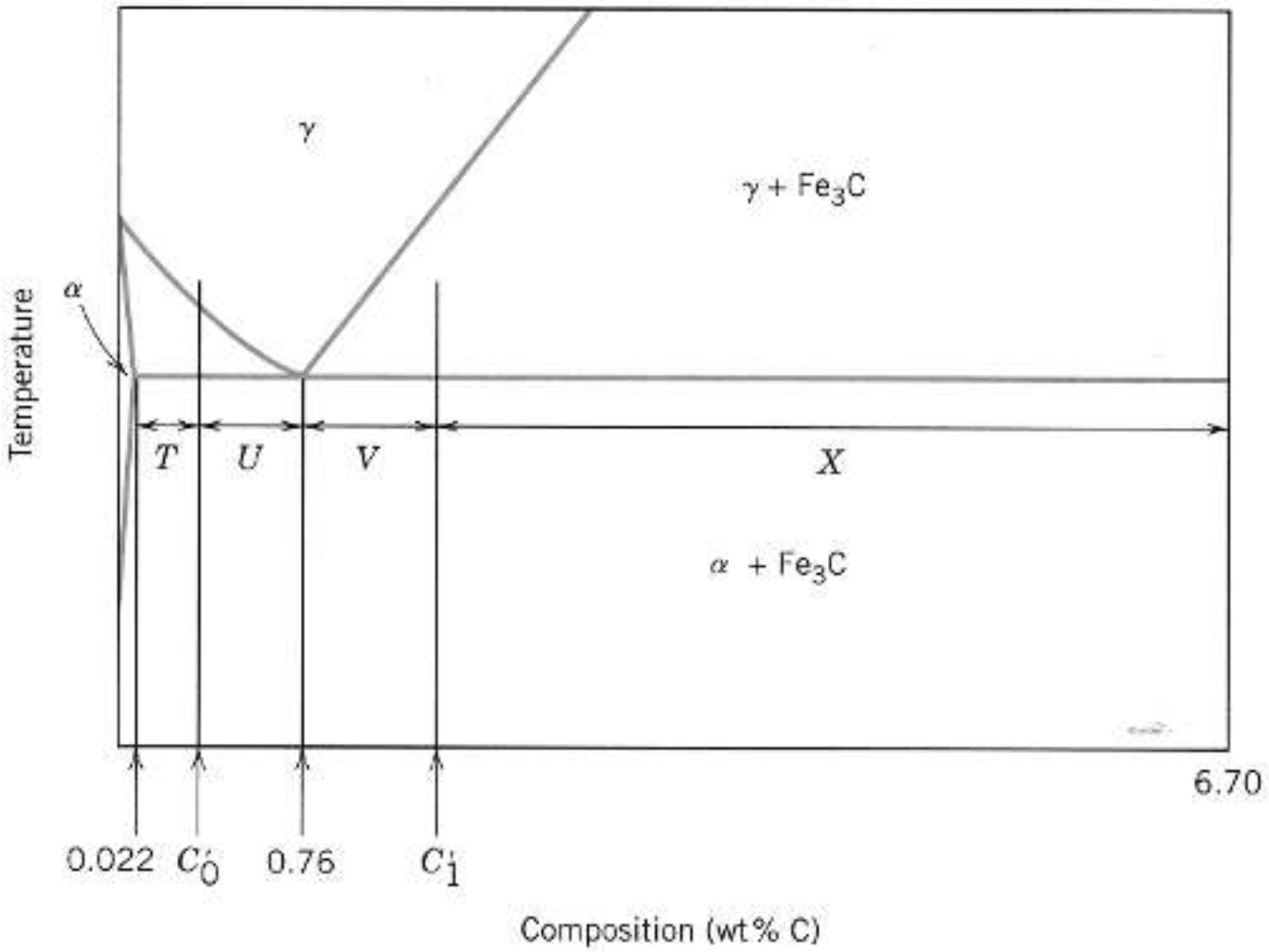
FIGURE 9.27 Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

FIGURE 9.28 Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635×.



Hypoeutectoid Steels

FIGURE 9.29
A portion of the $Fe–Fe_3C$ phase diagram used in computations for relative amounts of proeutectoid and pearlite microconstituents for hypoeutectoid (C_0') and hypereutectoid (C_1') compositions.



Hypereutectoid Steels

(> 0.77%C) eg 1.2%C steel

- Heat to ≈ 950°C to Austenitize (slow cool)

  $\gamma \rightarrow \gamma + (Fe_3C)'$ (Proeutectoid/ Primary Fe_3C)

  1.2%C 1.1% 6.67%

  Then at 727°C:

  $\gamma + Fe_3C \rightarrow \alpha + Fe_3C + Fe_3C'$ pearlite

- So below Eutectoid temp (723°C) there is Fe_3C and pearlite.
- Proeutectoid Cementite usually appears as white band along grain boundaries and Pearlite is lamallae.

Hypereutectoid Steels

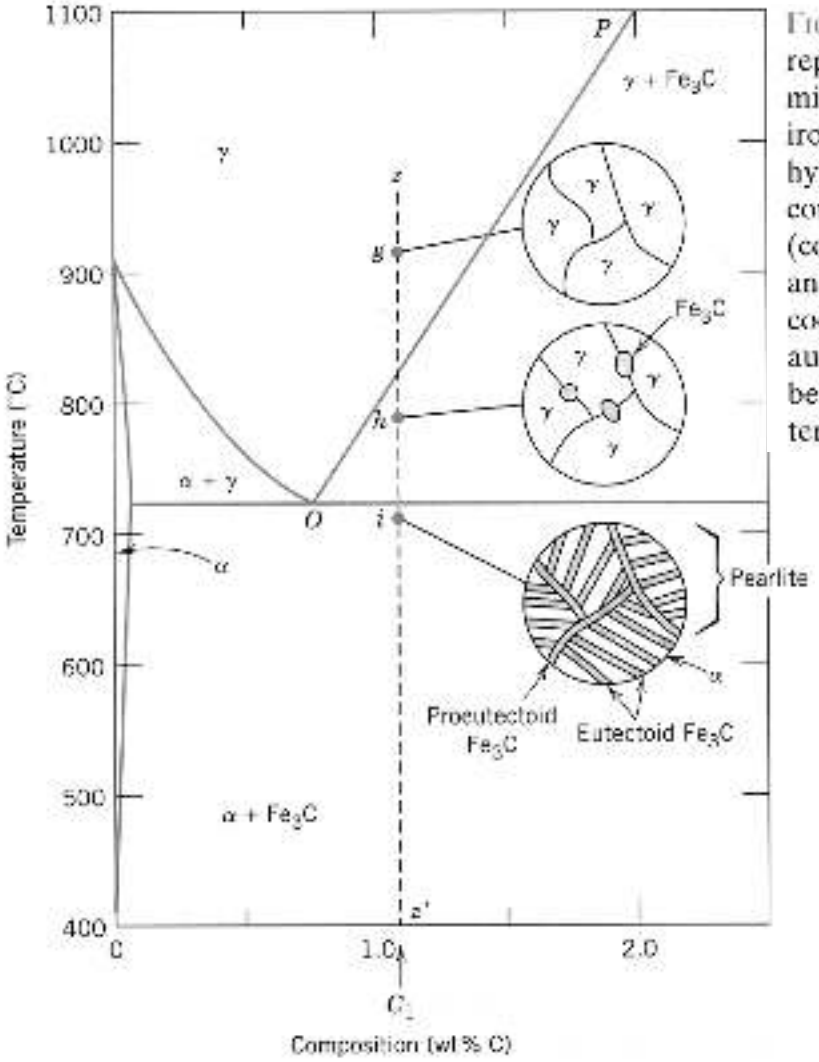
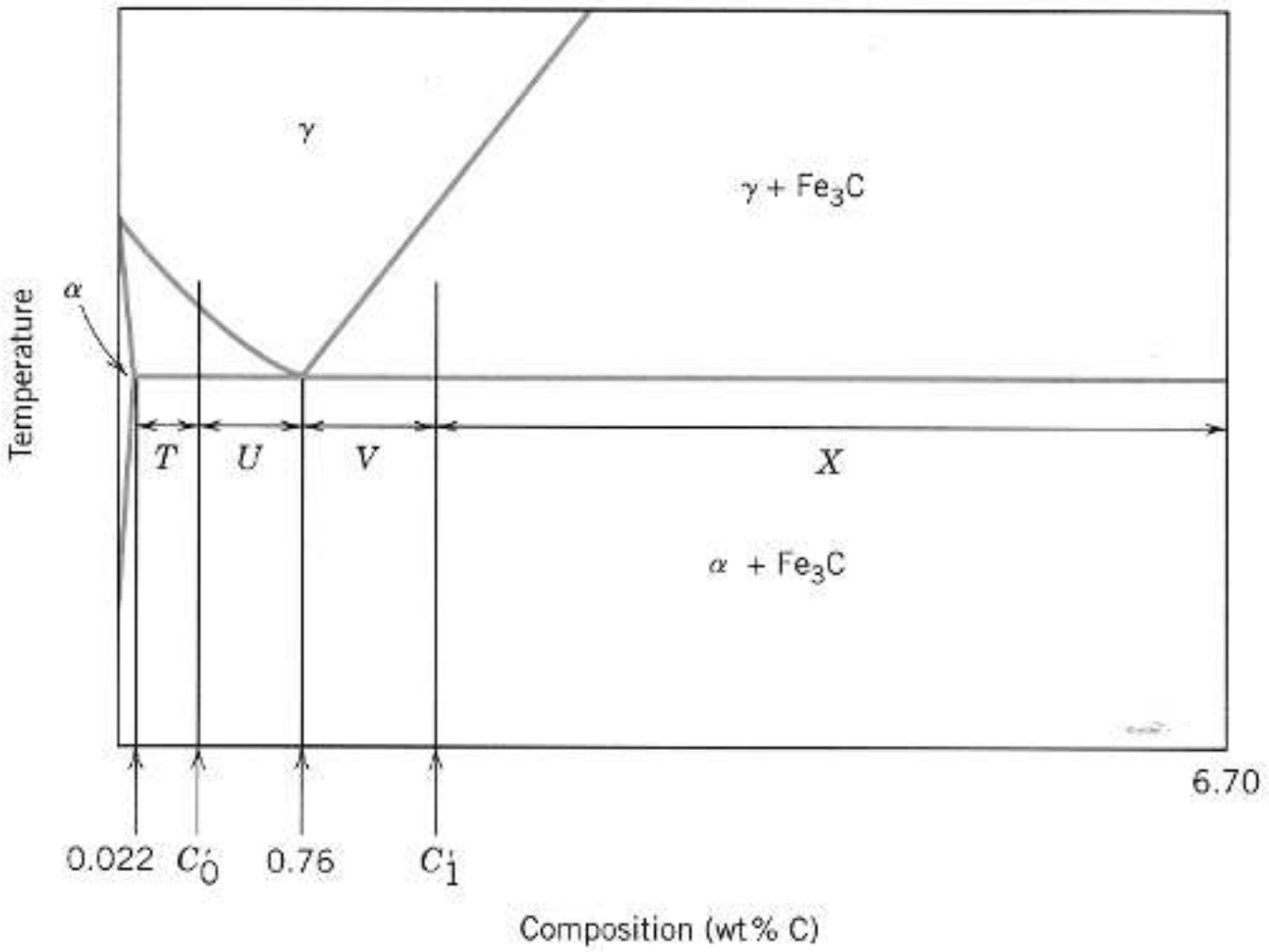


FIGURE 9.30 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

FIGURE 9.31 Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000×.

Hypoeutectoid Steels

FIGURE 9.29
A portion of the $Fe–Fe_3C$ phase diagram used in computations for relative amounts of proeutectoid and pearlite microconstituents for hypoeutectoid (C_0') and hypereutectoid (C_1') compositions.



Hypoeutectoid Steels

For a 99.65%Fe and 0.35C alloy at temp below eutectoid calculate the fractions of

total ferrite and cementite phases

$$\%W_{\alpha} = \frac{6.7 - 0.35}{6.67 - 0.02} x100 = 95\% \qquad \%W_{Fe3C} = \frac{0.35 - 0.02}{6.67 - 0.02} x100 = 5\%$$

Proeutectoid ferrite and pearlite phases

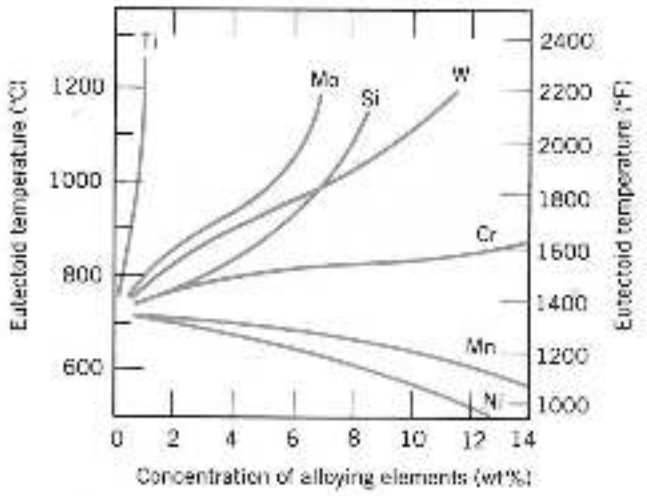
$$\%W_{p} = \frac{0.35 - .022}{0.76 - 0.022} x100 = 44\% \qquad \%W_{\alpha'} = \frac{0.76 - 0.35}{0.76 - 0.022} x100 = 56\%$$

eutectoid ferrite is total ferrite without proeutectoid ferrite

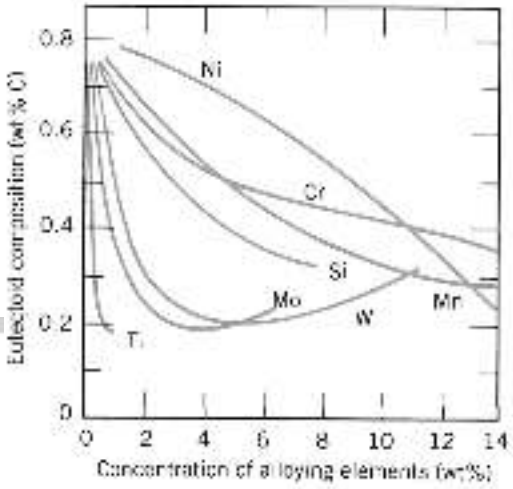
$$\%W_{\alpha e} = \%W_{\alpha} - \%W_{\alpha'} \qquad \%W_{\alpha e} = 95 - 56 = 39\%$$

Influence of Other Alloying Elements

- Elements like Titatnium, Chromium have significant effect on the eutectoid temperature and eutectoid composition (%C) of Iron
- In addition they also influence formation of pearlite with varying fractions of proeutectoid phase
- Generally steels are alloyed for different reasons like corrosion resistance etc.



The dependence of eutectoid temperature on alloy concentration for several alloying elements in steel.



The dependence of eutectoid composition (wt% C) on alloy concentration for several alloying elements in steel.

Controlling Eutectoid Reaction

- Amount: more eutectoid (hard) by increasing %C initially.
- Austenite grain size: reduce γ grain size means smaller pearlite colonies ® higher strength
- Cooling rate: Increased cooling rate means finer lamallae ® higher strength
- OTHER STRUCTURES
- These can be produced by different types of cooling and thermal treatments. Eg. Bainite, Martensite

Processing Heat Treatments

- For Steels:
- Annealing - generally describes a heat treatment which will soften metal, or remove certain affects.
- Three stages of annealing
  - Heating to the desired temperature
  - Holding or “soaking” at that temperature
  - Cooling, usually to room temperature

Purpose of Annealing

- Relieve Internal Stresses
  - Internal stresses can build up in metal as a result of processing.
    - Stresses may be caused by previous processing operations such as welding, cold working, casting, forging, or machining.
  - If internal stresses are allowed to remain in a metal, the part may eventually distort or crack.
  - Annealing helps relieve internal stresses and reduce the chances for distortion and cracking.

Purpose of Annealing

- Increasing Softness, Machinability, and Formability
  - A softer and more ductile material is easier to machine in the machine shop.
  - An annealed part will respond better to forming operations.
- Refinement of Grain Structures
  - After some types of metalworking (particularly cold working), the crystal structures are elongated.
  - Annealing can change the shape of the grains back to the desired form.

Annealing

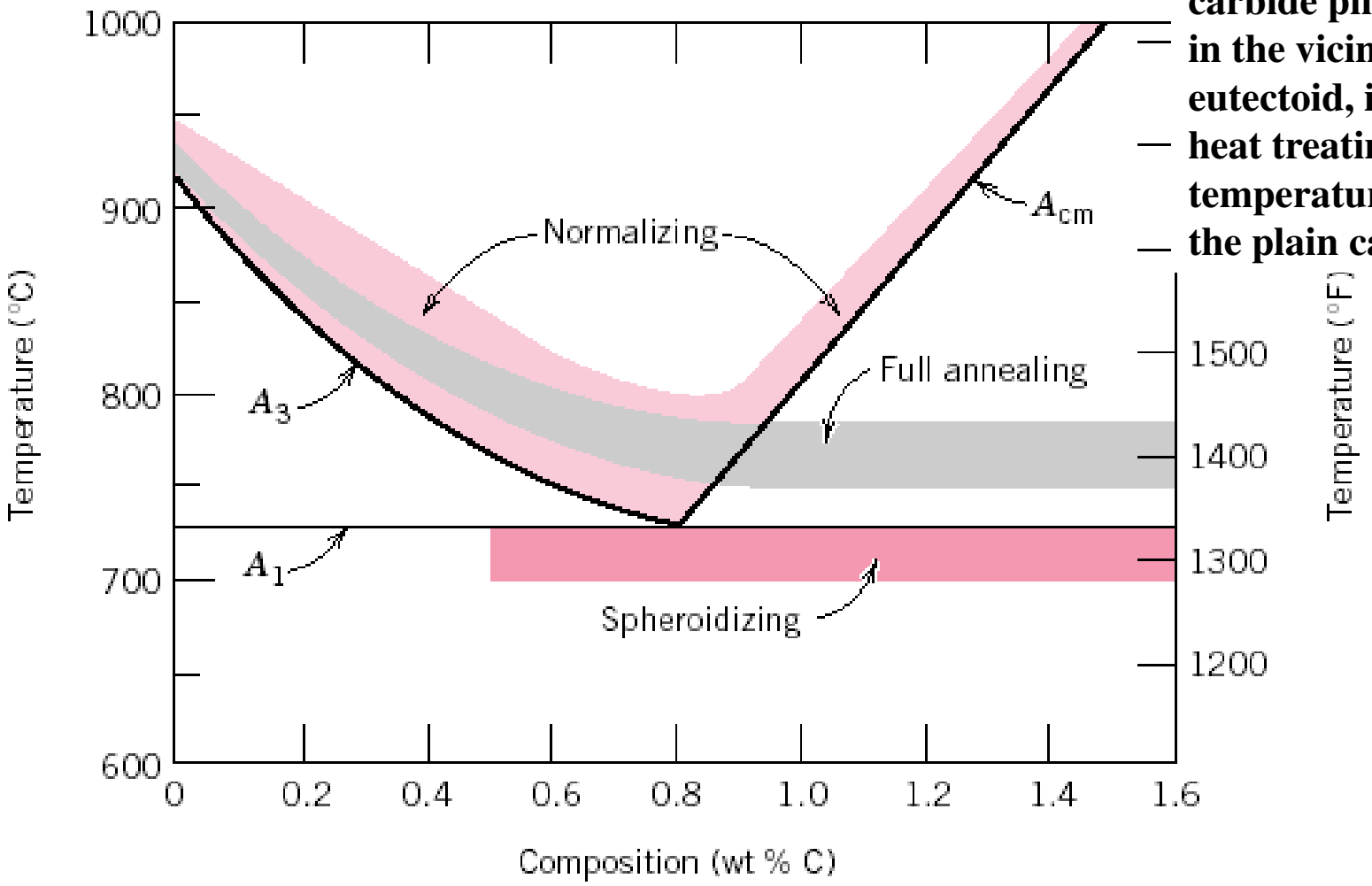


FIG. 11.9 The iron-iron carbide phase diagram in the vicinity of the eutectoid, indicating heat treating temperature ranges for the plain carbon steels.

Full annealing

- For hypoeutectoid steels - Heat into austenite region (A_3 + 50°C).

  Sufficient time for full austenitization, then cooled slowly in the furnace (≈ 20°C per hour) to less than ≈ 690°C then air-cooled.

  Gives a coarse pearlitic (and ferrite) structure - soft and ductile.

- For hypereutectoid steels - similar except heat into austenite + cementite region (A_1 + 50°C). Gives a coarse pearlitic (and spheroidal cementite) structure.

- Time and energy consuming (uniform properties throughout structure).

Process annealing

- A heat treatment used to negate the effects of cold work, i.e., to soften and increase the ductility of a previously strain-hardened metal
- In process annealing, parts are not as completely softened as they are in full annealing, but the time required is considerably lessened.
- Process annealing is frequently used as an intermediate heat-treating step during the manufacture of a part.

  A part that is stretched considerably during manufacture may be sent to the annealing oven three or four times before all of the stretching is completed.

Alteration of Grain Structure as a Result of Plastic Deformation

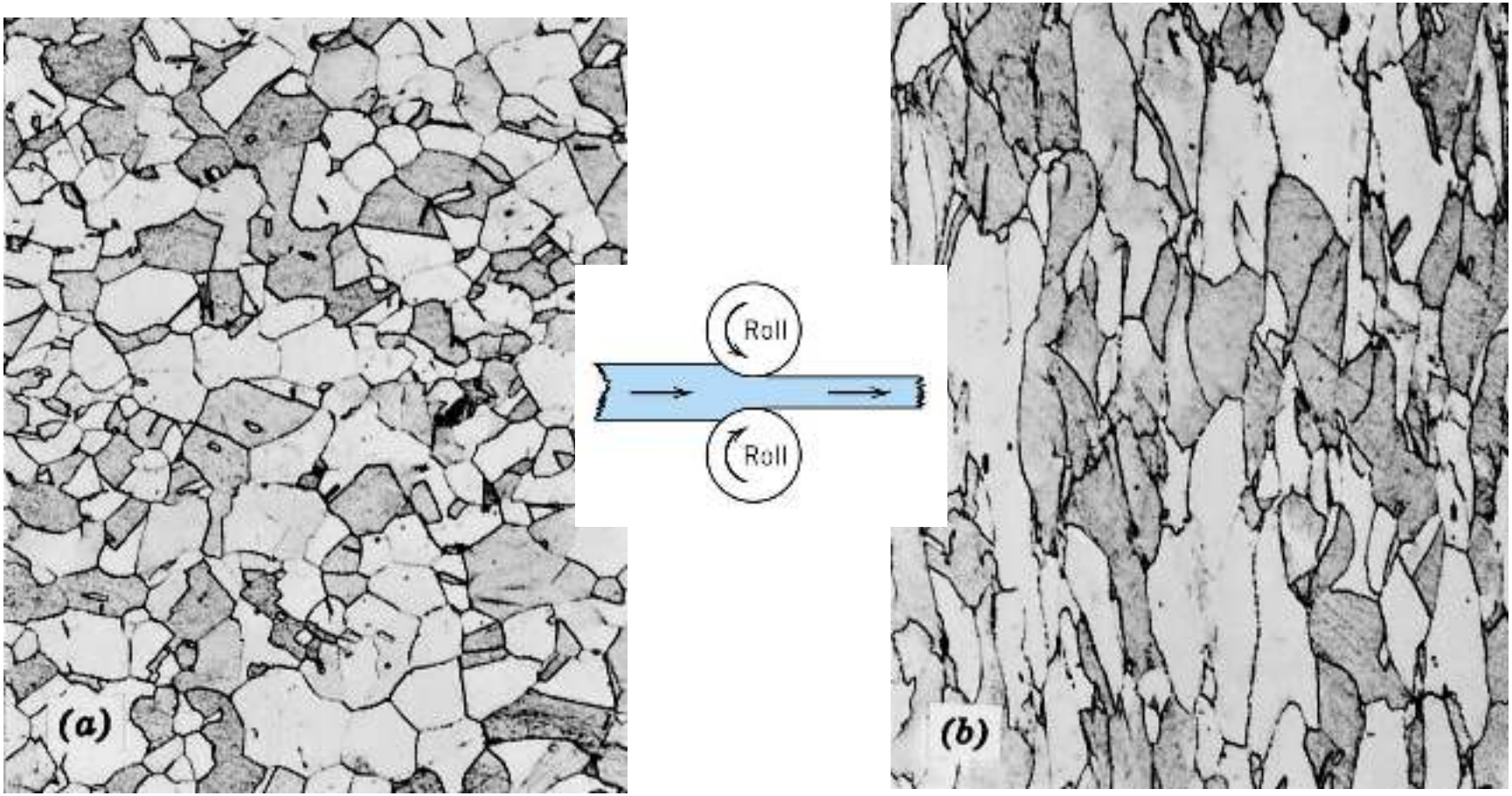


FIG. 7.11 Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (*a*) Before deformation the grains are equiaxed. (*b*) The deformation has produced elongated grains.

Process annealing

- Primarily used to restore ductility to low carbon (0.25%) steels (c.f. recrystallization) during cold-working operations.
- steels are heated to below A_1 (10-20°C below) typically 600-700°C and held long enough for ferrite recrystallisation and then cooled.
- Changes ferrite morphology and structure but does not significantly affect carbides or induce phase changes.
- Lower temperatures so cheaper and less scaling.

Process annealing

- Recovery and recrystallization processes are allowed to occur
- 1. Recovery
- Some of the stored internal strain energy is relieved by virtue of dislocation motion, as a result of enhanced atomic diffusion at the elevated temperature.
- 2. Recrystallization
- Recrystallization is the formation of a new set of strain free and equiaxed grains that have low dislocation densities and are characteristic of the precold-worked condition.
- Ordinarily a fine-grained microstructure is desired; the heat treatment is terminated before appreciable grain growth has occurred.

Stress Relief Annealing

- Can be used to relieve residual stresses in large steel castings, welded assemblies, cold-formed products.
- Heated to below A_1, typically 500-600°C)and then cooled.

Normalizing

- The name “normalizing” comes from the original intended purpose of the process — to return steel to the “normal” condition it was in before it was altered by cold working or other processing.

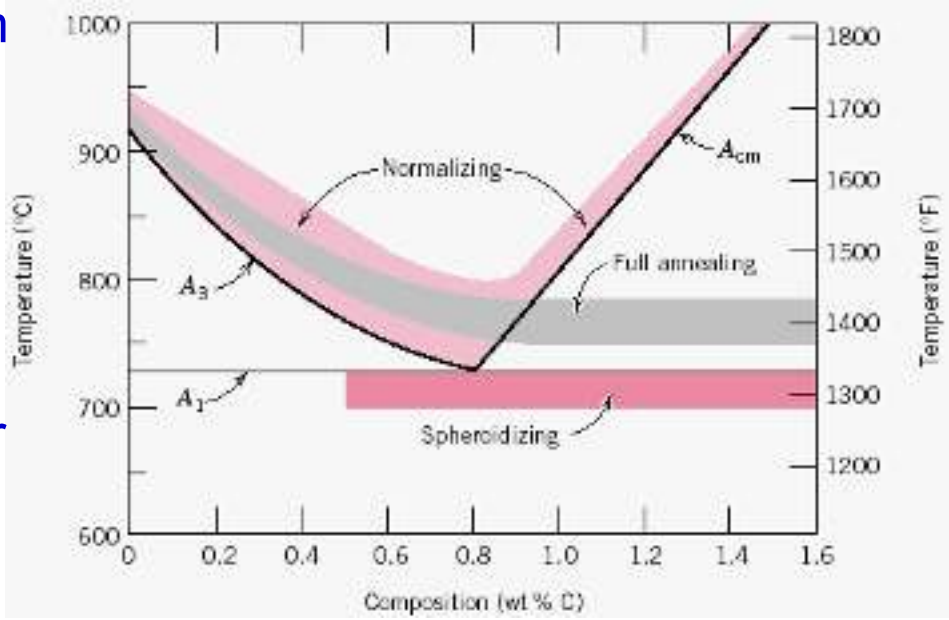
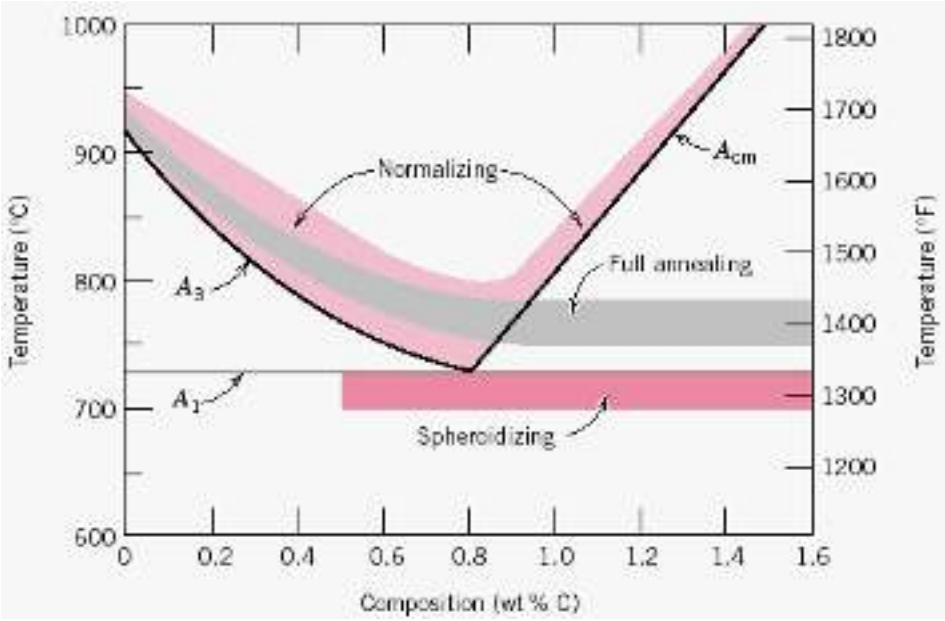


FIG. 11.9 The iron-iron carbide phase diagram in the vicinity of the eutectoid, indicating heat treating temperature ranges for the plain carbon steels.

- Heating the alloy to 55 to 85°C above the A_3 or A_{cm} and holding for sufficient time so that the alloy completely transforms to austenite, followed by air cooling

Normalizing

- To refine grains and produce a more uniform and desirable size distribution for steels that are plastically deformed
- Normalizing does not soften the material as much as full annealing
- The cooling process does not leave the material as ductile or as internally stress-free.



- A normalized part will usually be a little stronger, harder, and more brittle than a full-annealed part.

Spheroidizing

- Used to soften higher carbon (>0.6%) steels having high cementite contents; pearlite and primary Fe_3C.
- Want to make the Fe3C forms spheroids; this softens & toughens the higher C steels. (useful for machining and cold-forming operations).
  - Held just below Eutectoid temp (A1) for a long time; slow cooled.
  - Prolonged cycling above and below A1; slow cooled.
  - For tool steels; Heat to 750-800°C, hold for several hours and slow cool.
- NOTE: Increase hardness of these materials by subsequent normalizing, or Q&T.

Spheroidizing

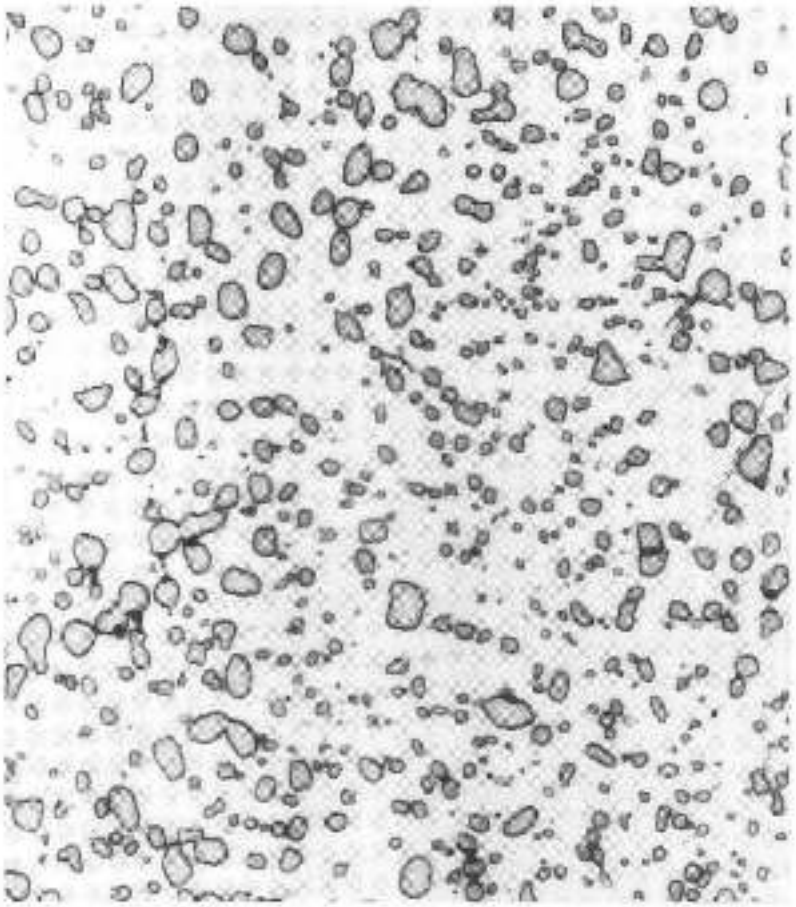
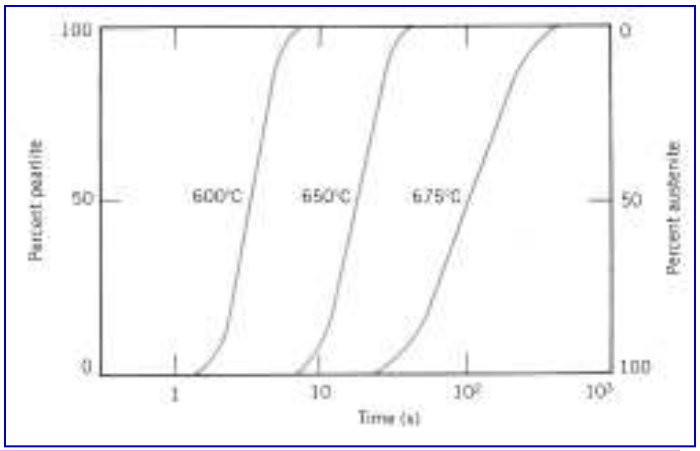
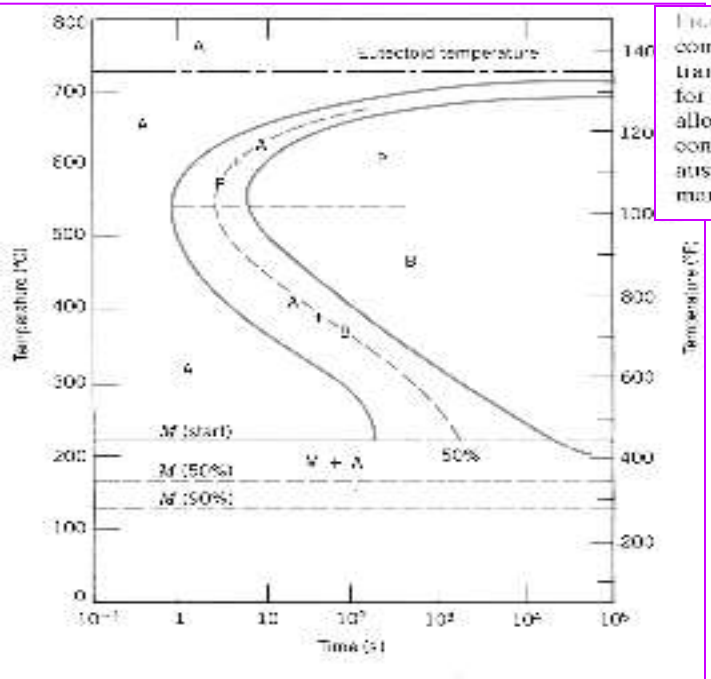


FIGURE 10.10 Photomicrograph of a steel having a spheroidite microstructure. The small particles are cementite; the continuous phase is α ferrite. 1000×.

Isothermal Transformation



For an iron–carbon alloy of eutectoid composition (0.76 wt% C), isothermal fraction reacted versus the logarithm of time for the austenite-to-pearlite transformation.



The complete isothermal transformation diagram for an iron–carbon alloy of eutectoid composition: A, austenite; B, bainite; M, martensite; P, pearlite.

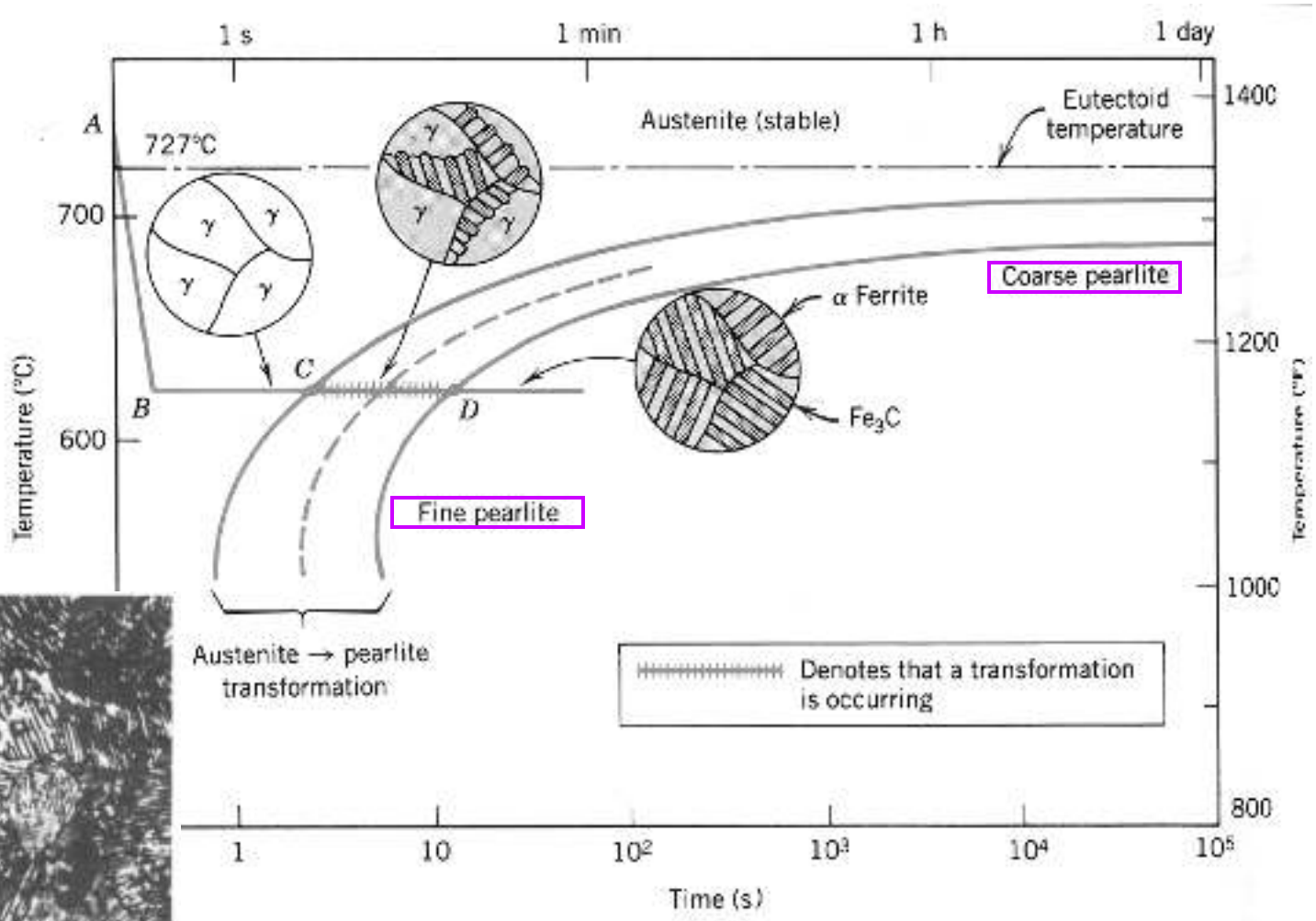
- Conventional heat treatment for producing martensitic steels
- continuous and rapid cooling of an austenitized specimen in some type of quenching medium, such as water, oil, or air

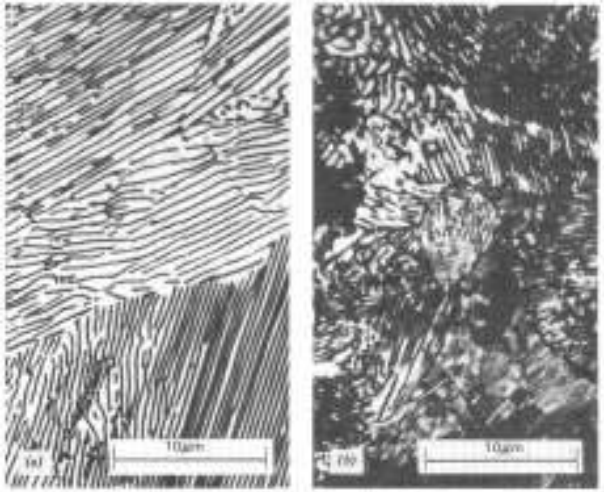
The optimum properties of a steel that has been quenched and then tempered can be realized only if,

- during the quenching heat treatment, the specimen has been converted to a high content of martensite

Isothermal Transformation

FIGURE 10.5 Isothermal transformation diagram for a eutectoid iron–carbon alloy, with superimposed isothermal heat treatment curve (*ABCD*). Microstructures before, during, and after the austenite-to-pearlite transformation are shown.





Photomicrographs of (a) coarse pearlite and (b) fine pearlite. 1000×.

Bainite and Matensite

FIGURE 10.11 The body-centered tetragonal unit cell for martensitic steel showing iron atoms (circles) and sites that may be occupied by carbon atoms (crosses). For this tetragonal unit cell, $c > a$.

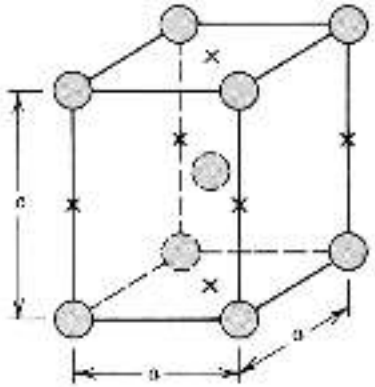


FIGURE 10.12 Photomicrograph showing the martensitic microstructure. The needle-shaped grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench. 1220×.

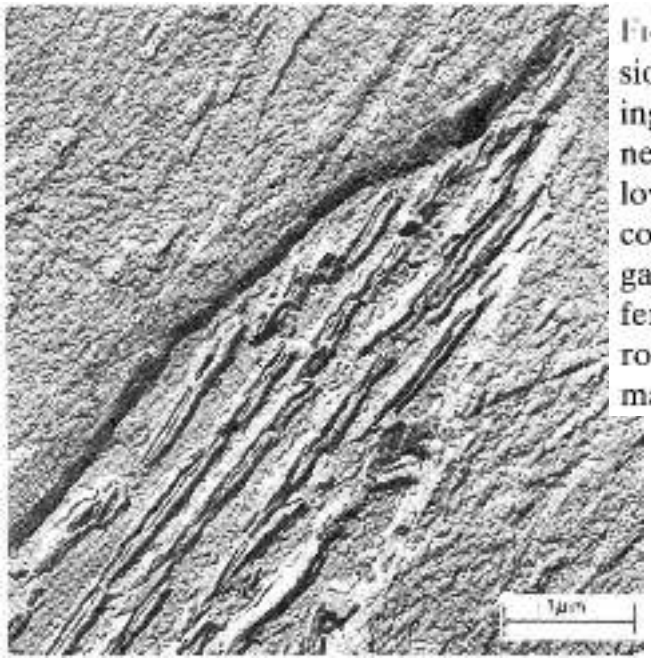


FIGURE 10.8 Replica transmission electron micrograph showing the structure of bainite. A needle of bainite passes from lower left to upper right-hand corners, which consists of elongated particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite needle is martensite.

Strengthening of Steel

- Problem with Martensite M_{50} and M_{90} is that the remaining is austentite
- Which causes instability and cracking
- M100 happens much below room temperature.
- To avoid cracking, alloys are added to steel to increase the M_{100} temperature

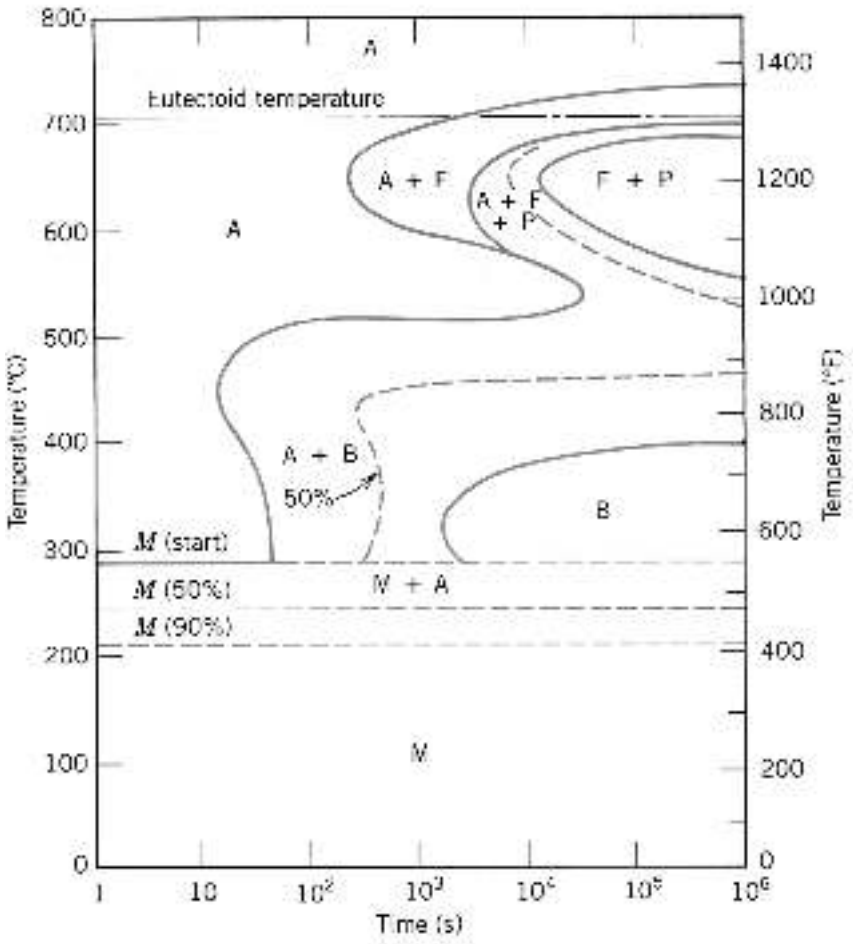


FIGURE 10.14 Isothermal transformation diagram for an alloy steel (type 4340). A, austenite; B, bainite; P, pearlite; M, martensite.

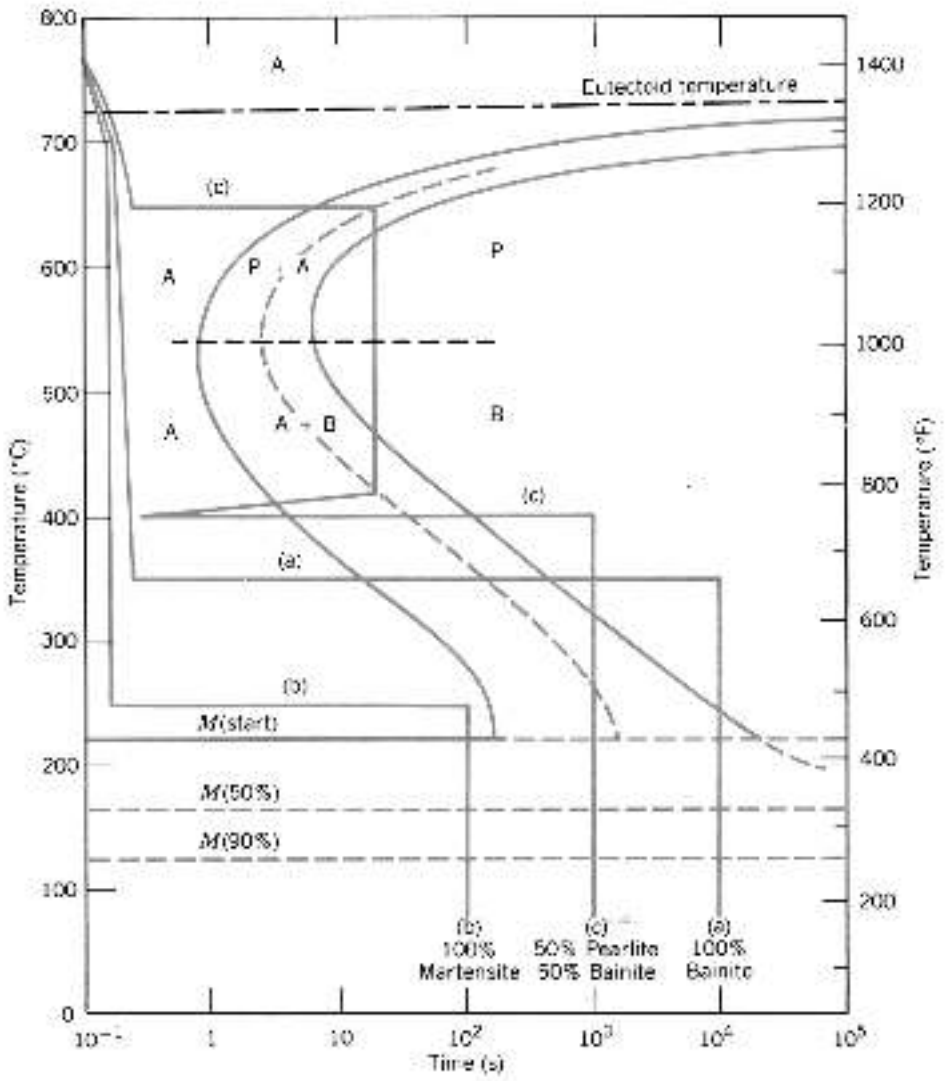
Strengthening of Steel

Table 4 Effects of alloy elements on the heat treatment of quenched and tempered alloy steels

Effect of alloy on hardenability during quenching	Effect of alloy on tempering
• Manganese contributes markedly to hardenability, especially in amounts greater than 0.8%. The effect of manganese up to 1.0% is stronger in low- and high-carbon steels than in medium-carbon steels.	• Manganese increases the hardness of tempered martensite by retarding the coalescence of carbides, which prevent grain growth in the ferrite matrix. These effects cause a substantial increase in the hardness of tempered martensite as the percentage of manganese in the steel increases.
• Nickel is similar to manganese at low alloy additions, but is less potent at the high alloy levels. Nickel is also affected by carbon content, the medium-carbon steels having the greatest effect. There is no alloy interaction between manganese and nickel that must be taken into account at lower austenitizing temperatures.	Nickel has a relatively small effect on the hardness of tempered martensite, which is essentially the same at all tempering temperatures. Because nickel is not a carbide former, its influence is considered to be due to a weak solid-solution strengthening.
Copper is usually added to alloy steels for its contribution to atmospheric-corrosion resistance and at higher levels for precipitation hardening. The effect of copper on hardenability is similar to that of nickel, and in hardenability calculations it has been suggested that the sum of copper plus nickel be used with the appropriate multiplying factor of nickel.	• Copper is precipitated out when steel is heated to about 425–650 °C (800–1200 °F) and thus can provide a degree of precipitation hardening.
• Silicon is more effective than manganese at low alloy levels and has a strengthening effect on low-alloy steels. However, at levels greater than 1% this element is much less effective than manganese. The effect of silicon also varies considerably with carbon content and other alloys present. Silicon is relatively ineffective in low-carbon steel but is very effective in high-carbon steels.	• Silicon increases the hardness of tempered martensite at all tempering temperatures. Silicon also has a substantial retarding effect on softening at 316 °C (600 °F), and has been attributed to the inhibiting effect of silicon on the conversion of ε-carbide to cementite[a].
• Molybdenum is most effective in improving hardenability. Molybdenum has a much greater effect in high-carbon steels than in medium-carbon steels. The presence of chromium decreases the multiplying factor, whereas the presence of nickel enhances the hardenability effect of molybdenum[a].	• Molybdenum retards the softening of martensite at all tempering temperatures. At over 540 °C (1000 °F), molybdenum partitions to the carbide phase and thus keeps the carbide particles small and numerous. In addition, molybdenum reduces susceptibility to temper embrittlement.
• Chromium behaves much like molybdenum and has its greatest effect in medium-carbon steels. In low-carbon steel and carburized steel, the effect is less than in medium-carbon steels, but is still significant. As a result of the stability of chromium carbide at lower austenitizing temperatures, chromium becomes less effective.	• Chromium, like molybdenum, is a strong carbide-forming element that can be expected to retard the softening of martensite at all temperatures. Also, by substituting chromium for some of the iron in cementite, the coalescence of carbides is retarded.
Vanadium is usually not added for hardenability in quenched and tempered structural steels (such as ASTM A 678, grade D) but is added to provide secondary hardening during tempering. Vanadium is a strong carbide former, and the steel must be austenitized at a sufficiently high temperature and for a sufficient length of time to ensure that the vanadium is in solution and thus able to contribute to hardenability. Moreover, solution is possible only if small amounts of vanadium are added (c).	• Vanadium is a stronger carbide former than molybdenum and chromium and can therefore be expected to have a much more potent effect at equivalent alloy levels. The strong effect of vanadium is probably due to the formation of an alloy carbide that replaces cementite-type carbides at high tempering temperatures and persists as a fine dispersion up to the A_1 temperature.
Tungsten has been found to be more effective in high-carbon steels than in steels of low carbon content (less than 0.35%). Alloy interaction is important in tungsten-containing steels, with manganese-molybdenum-chromium having a greater effect on the multiplying factors than silicon or nickel additions.	• Tungsten is also a carbide former and behaves like molybdenum in simple steels. Tungsten has been proposed as a substitute for molybdenum in reduced-activation ferritic steels for nuclear applications[d].
Titanium, niobium, and zirconium are all strong carbide formers and are usually not added to enhance hardenability for the same reasons given for vanadium. In addition, titanium and zirconium are strong nitride formers, a characteristic that affects their solubility in austenite and hence their contribution to hardenability.	• Titanium, niobium, and zirconium should behave like vanadium because they are strong carbide formers.
Boron can considerably improve hardenability, the effect varying notably with the carbon content of the steel. The full effect of boron on hardenability is obtained only in fully deoxidized (aluminum-killed) steels.	Boron has no effect on the tempering characteristics of martensite, but a detrimental effect on toughness can result from the transformation to nonmartensitic products.

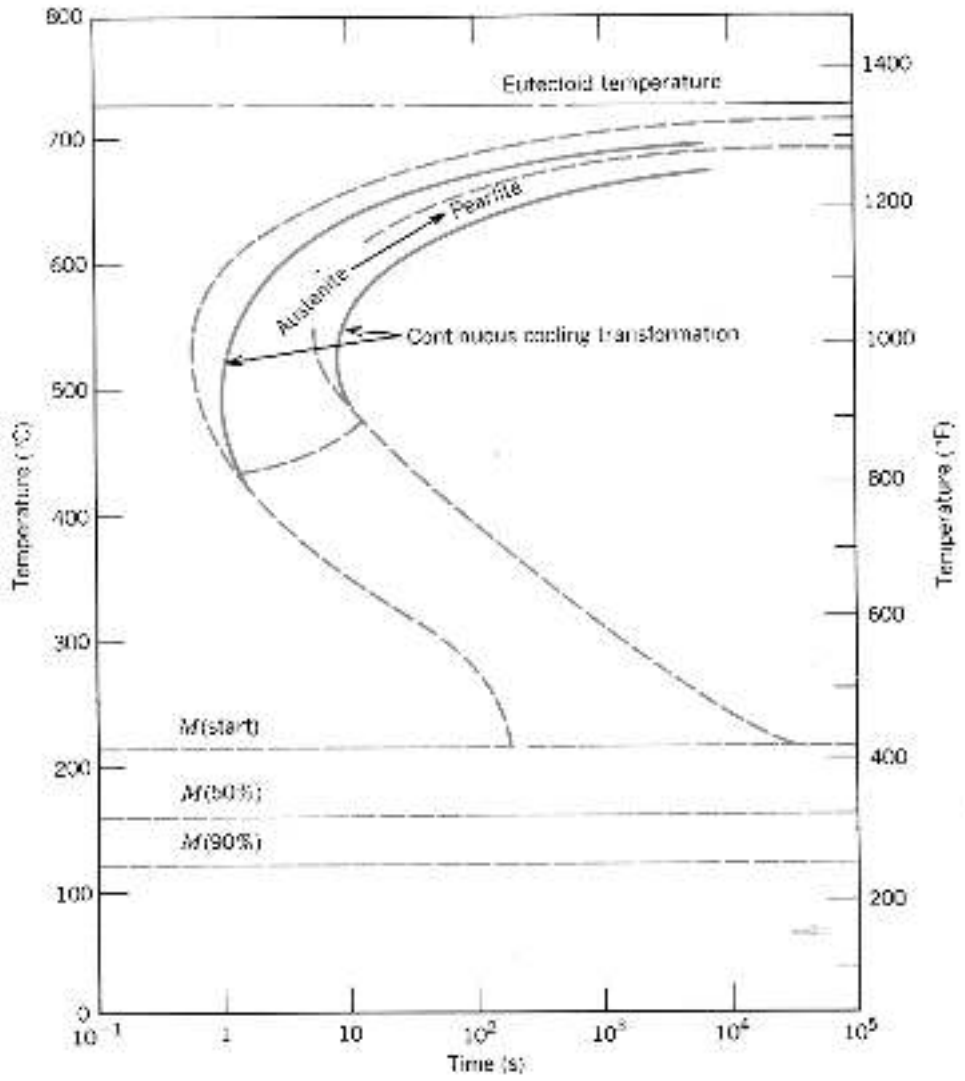
Strengthening of Steel

FIGURE 10.15
Isothermal transformation diagram for an iron–carbon alloy of eutectoid composition and the isothermal heat treatments (a), (b), and (c) in Example Problem 10.1.



Continuous Cooling Curve

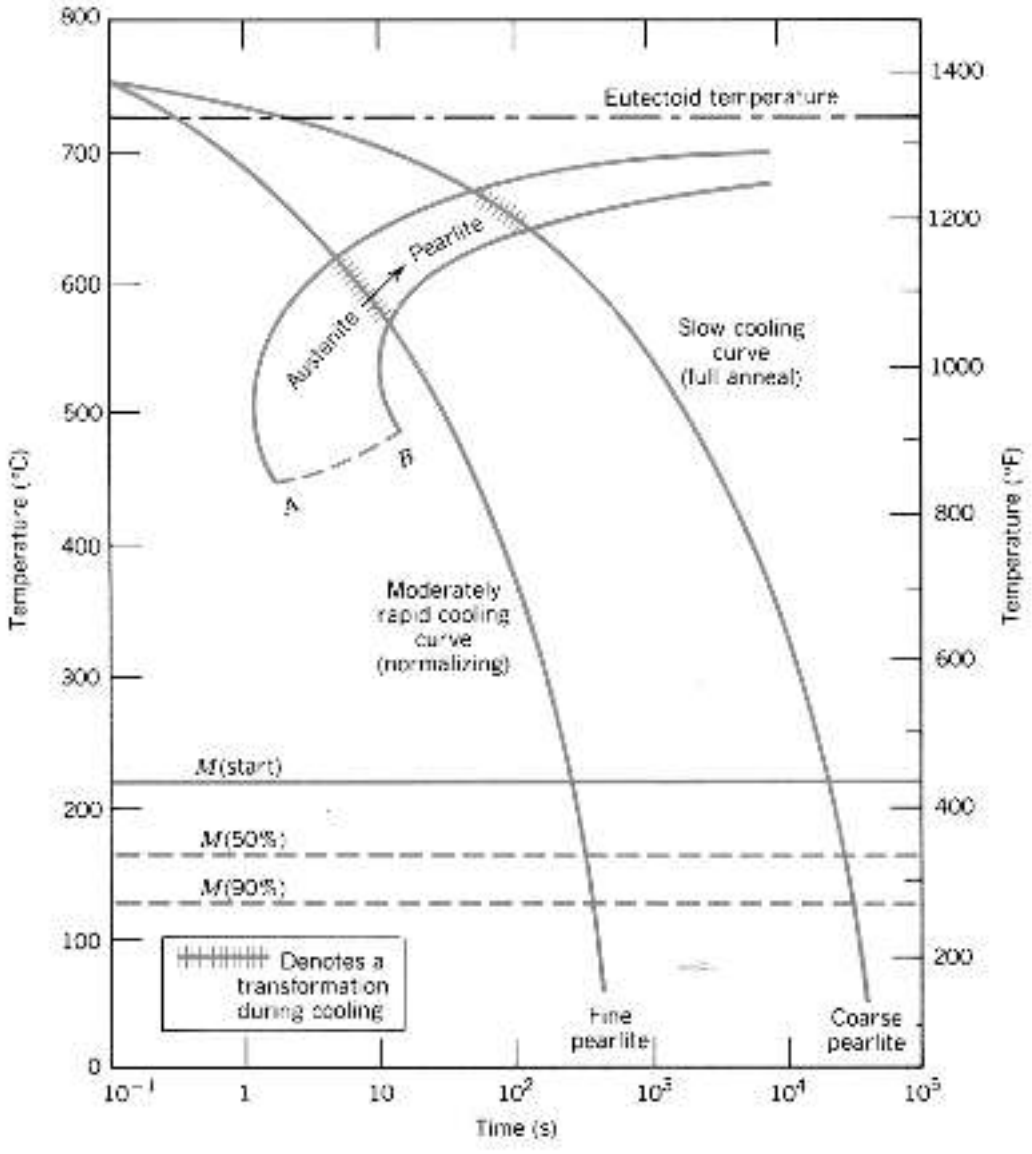
FIGURE 10.16
Superimposition of isothermal and continuous cooling transformation diagrams for a eutectoid iron–carbon alloy



- Isothermal transformation curves are valid only if maintained at same elevate temperature
- It is not practical for heat treatment
- Hence continuous cooling curves are drawn

Continuous Cooling Curve

FIGURE 10.17
Moderately rapid and slow cooling curves superimposed on a continuous cooling transformation diagram for a eutectoid iron–carbon alloy.



Continuous Cooling Curve

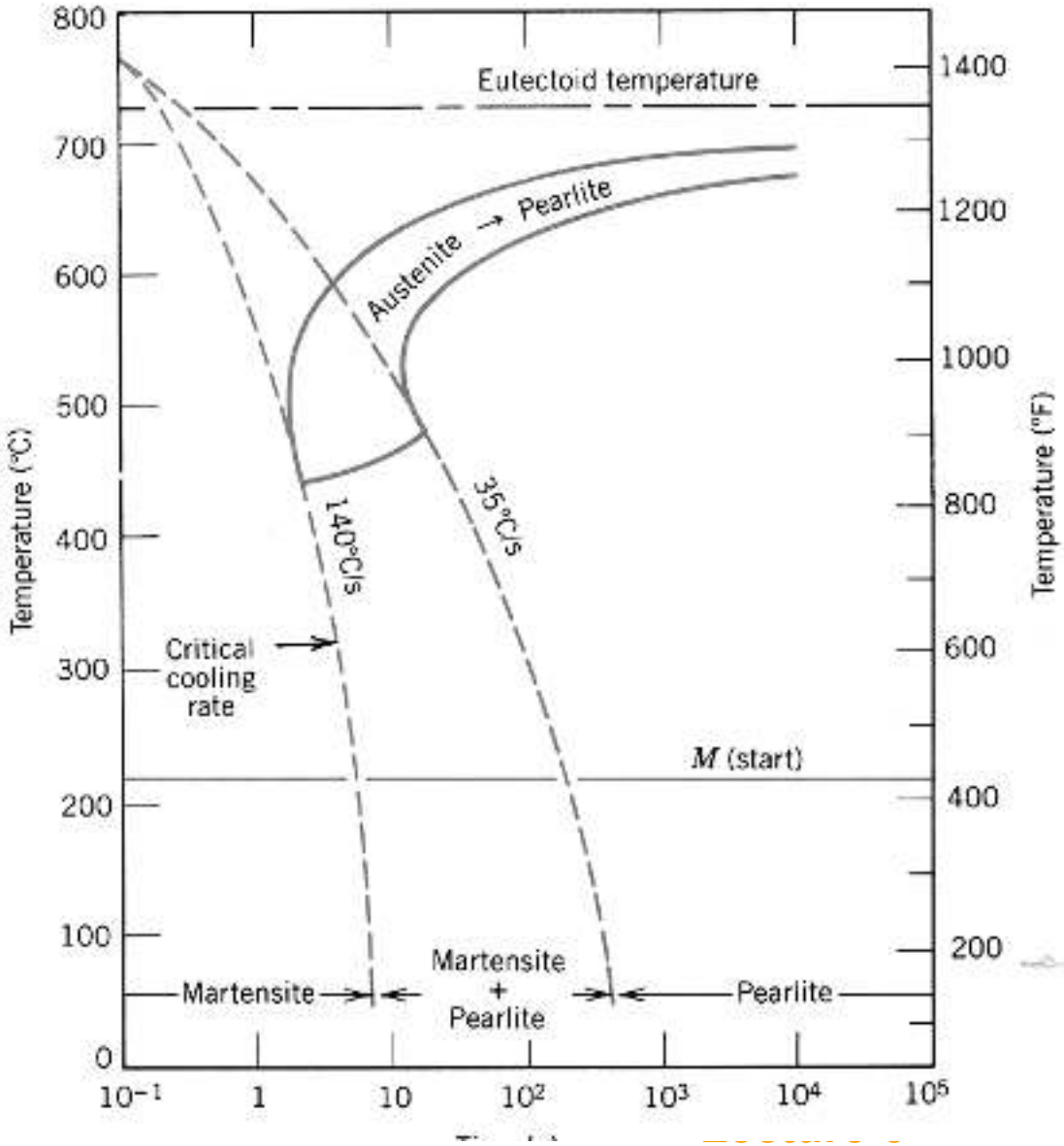


FIGURE 10.18
Continuous cooling transformation diagram for a eutectoid iron–carbon alloy and superimposed cooling curves demonstrating the dependence of the final microstructure on the transformations that occur during cooling.

Strength of Pearlite Steel

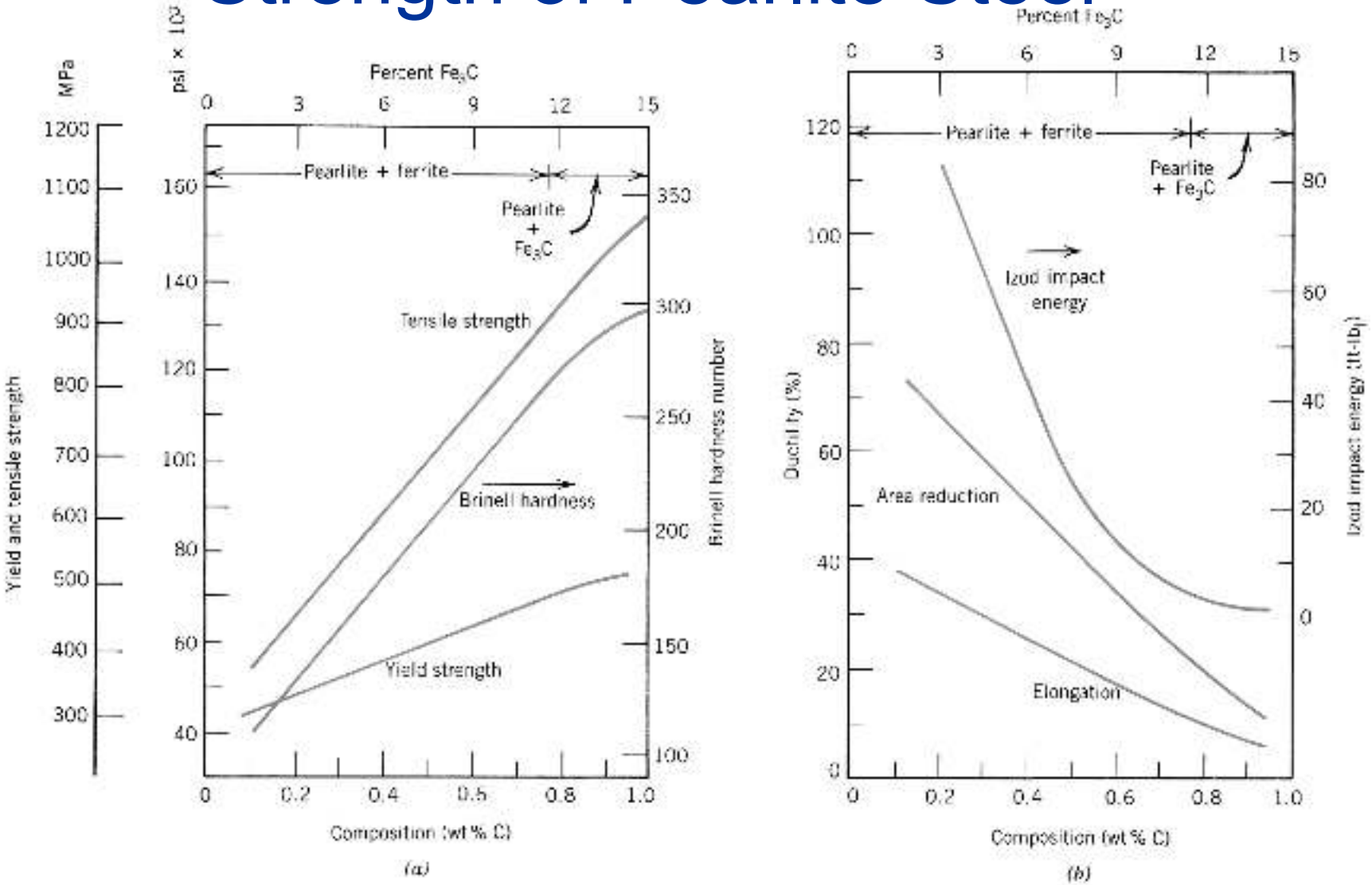


FIGURE 10.20 (*a*) Yield strength, tensile strength, and Brinell hardness versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite. (*b*) Ductility (%EL and %AR) and Izod impact energy versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite.

Strength of Spheroidite Steel

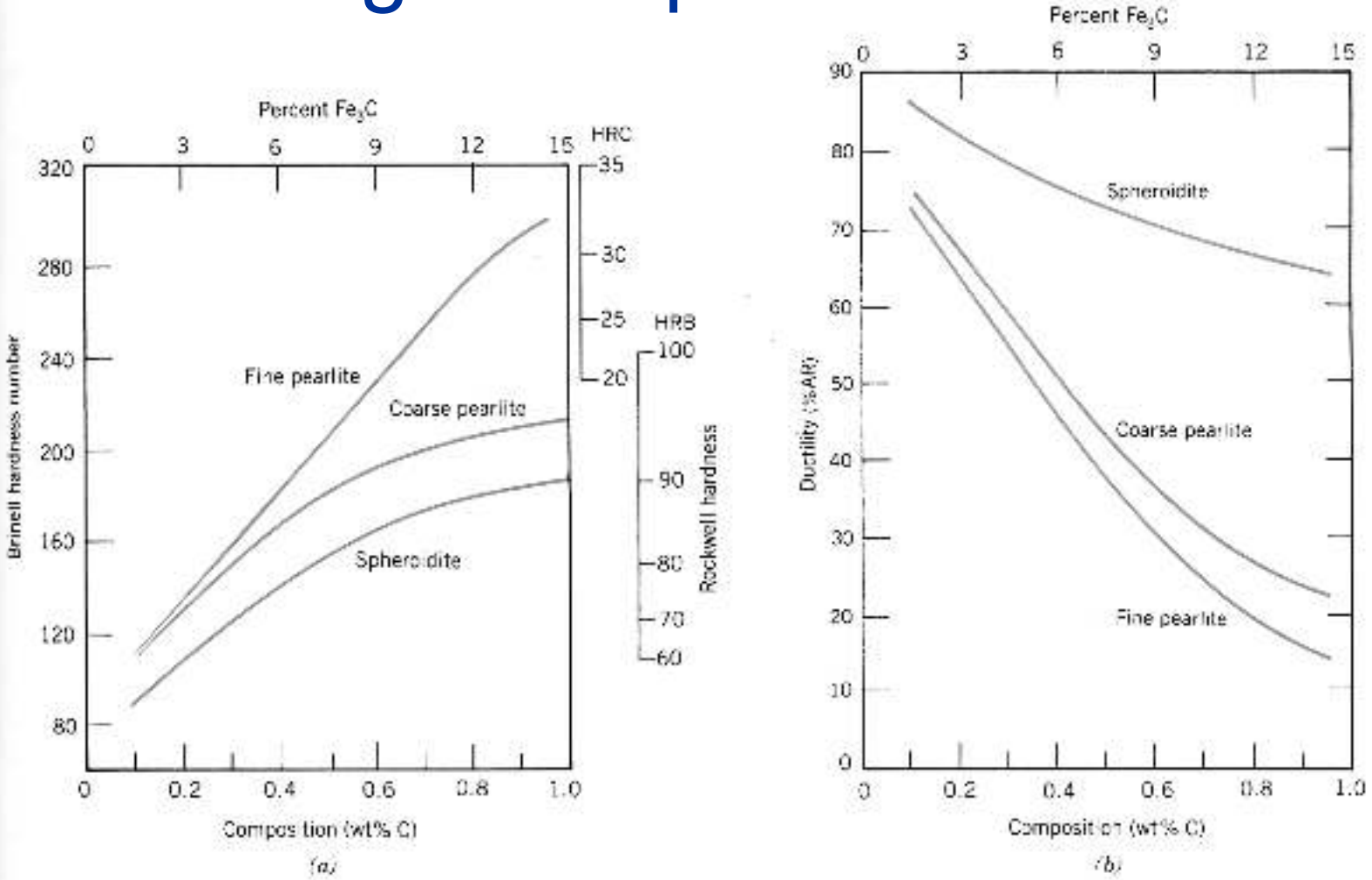


FIGURE 10.21 (*a*) Brinell and Rockwell hardness as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures. (*b*) Ductility (%AR) as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures.

Strength of Martenstic Steel

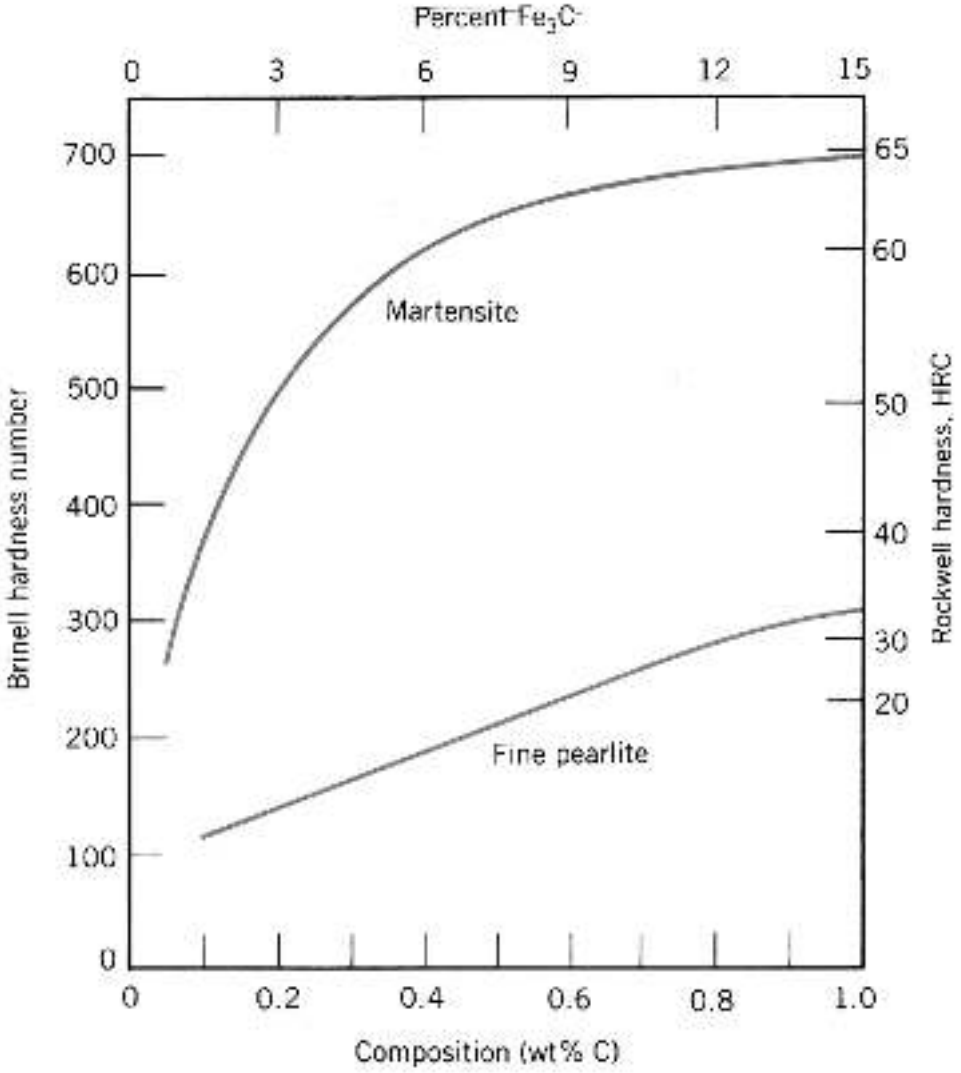


FIGURE 10.22
Hardness as a function of carbon concentration for plain carbon martensitic and fine pearlitic steels.

Quenching & Tempering

- In order to get martensitic steels need continuous, rapid cooling.
- Use quenching medium such as water, oil, air in order to get a high martensite content then temper.
- During cooling, impossible to get uniform cooling rate throughout specimen; surface always cools faster then interior thus variation in microstructure formed.
- Successful heat treating of steels to get predominantly martensite throughout cross section depends mainly on:
  - composition of steel alloy
  - type of quenching medium
  - size and shape of specimen

Tempering Steel

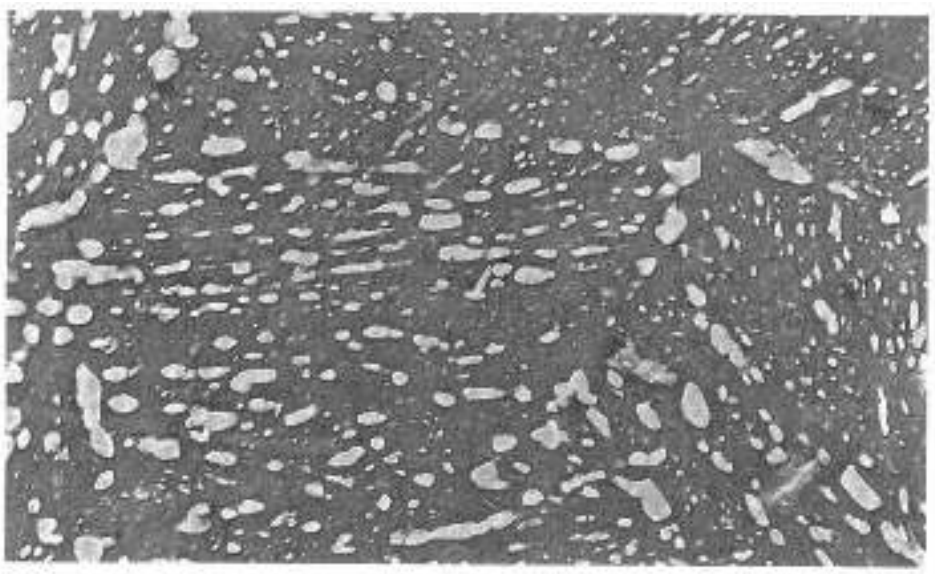
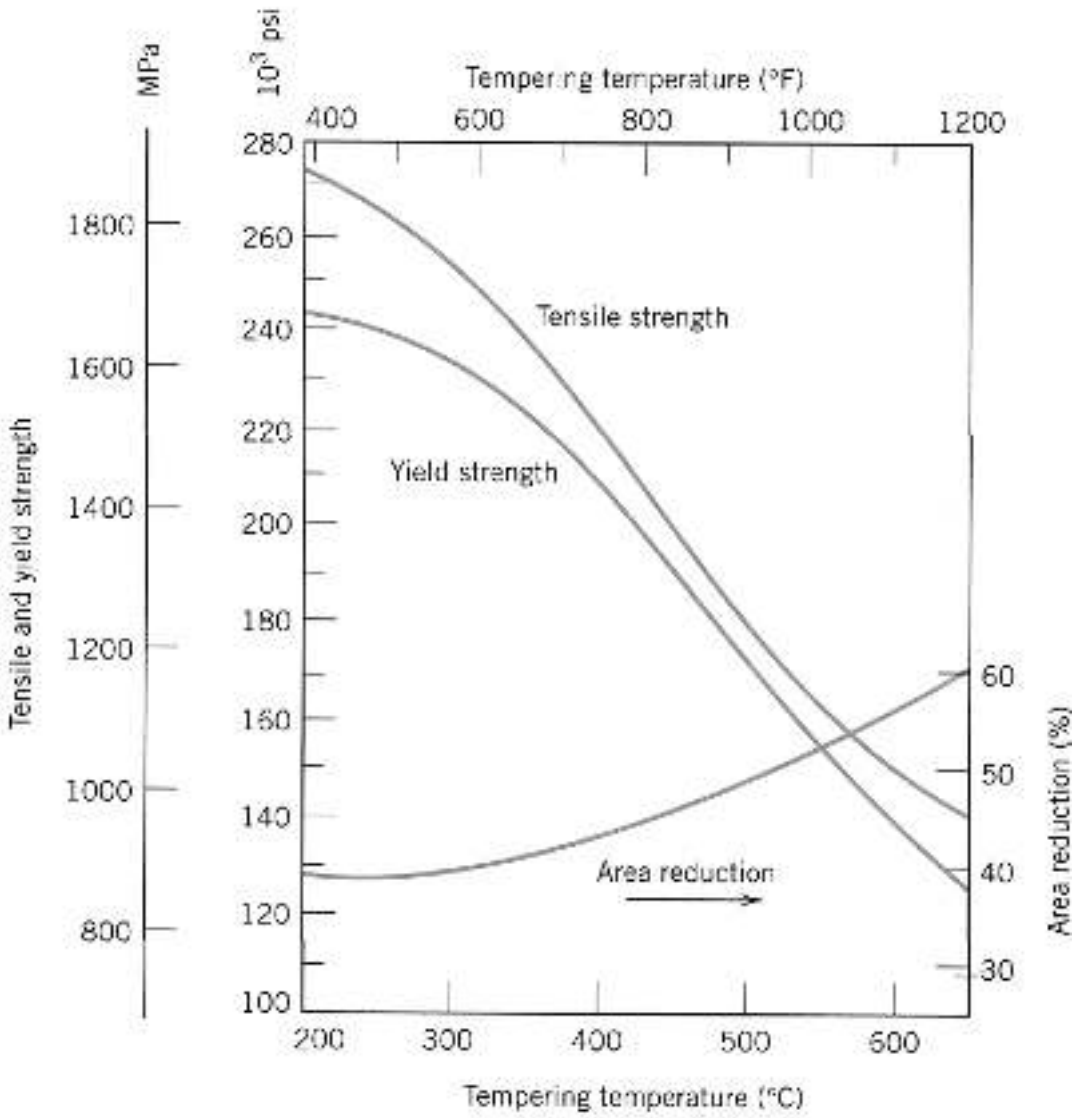


Figure 10.23 Electron micrograph of tempered martensite. Tempering was carried out at 594°C (1100°F). The small particles are the cementite phase; the matrix phase is α ferrite. 9300×.

- As quenched Martensite M_{50} has not enough ductility and toughness to be a good engineering structure
- To improve on these martensite is given subsequent heating below eutectoid temperature called tempering
- But strength and hardness decreases with increase in tempering temperature and time

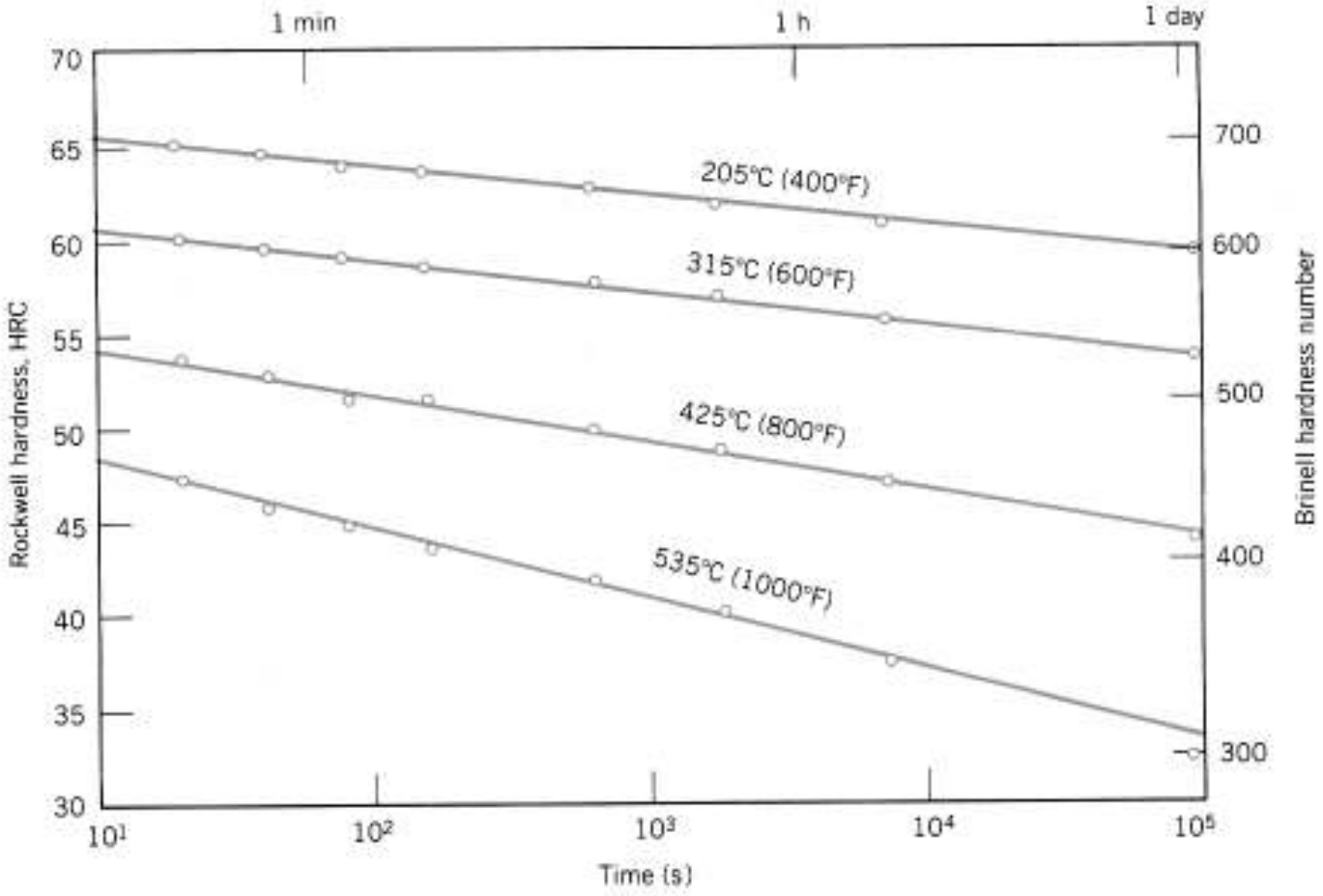
Tempering Steel

FIGURE 10.24 Tensile and yield strengths and ductility (%AR) versus tempering temperature for an oil-quenched alloy steel (type 4340).



Tempering Steel

FIGURE 10.25
Hardness versus tempering time for a water-quenched eutectoid plain carbon (1080) steel.



Tempering Alloy Steel

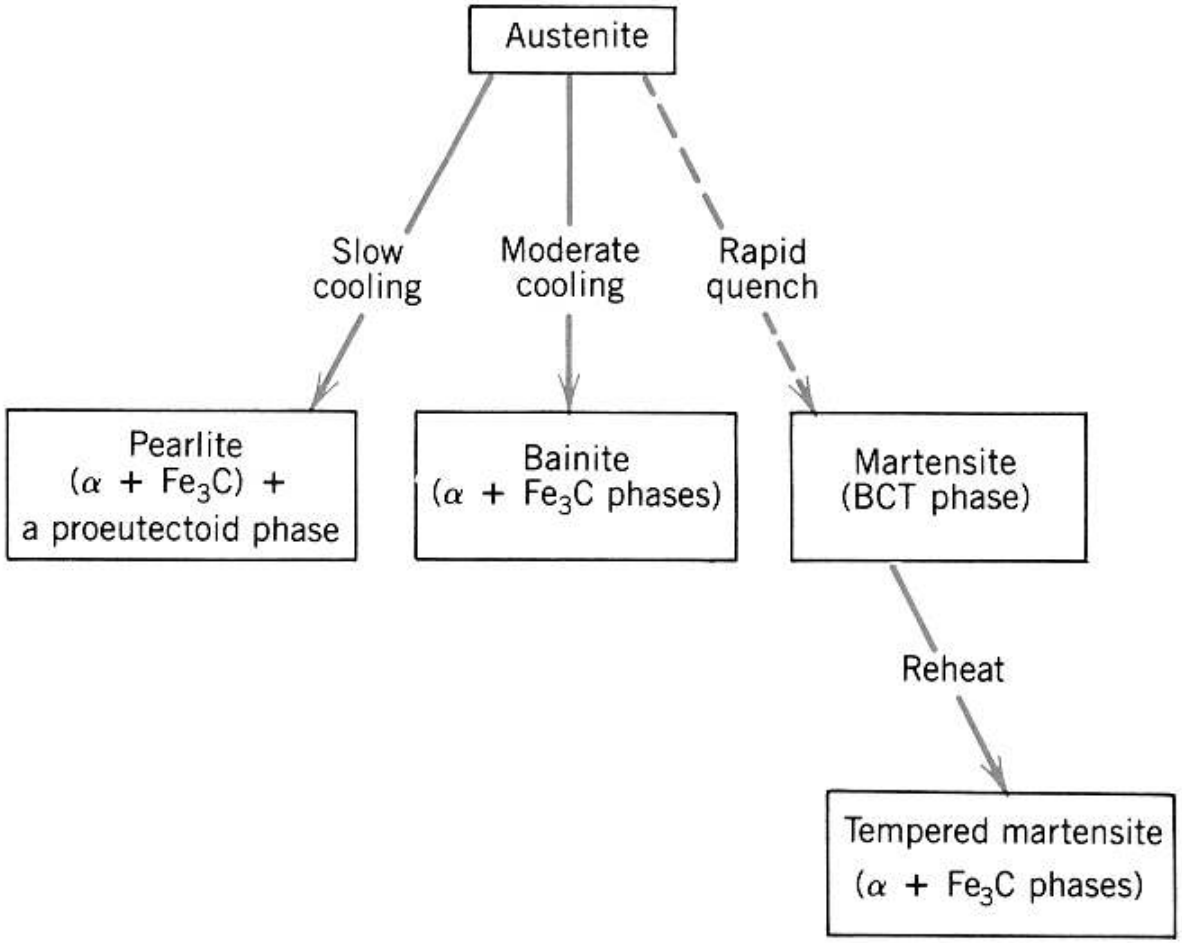


FIGURE 10.26 Possible transformations involving the decomposition of austenite. Solid arrows, transformations involving diffusion; dashed arrow, diffusionless transformation.

Quenching Media

- **Steel** - **Quenchant**
- plain carbon steels - water
- low/med alloyed steels - oil
- high alloy steels - air
- Martempering - Brine

Severity of quench

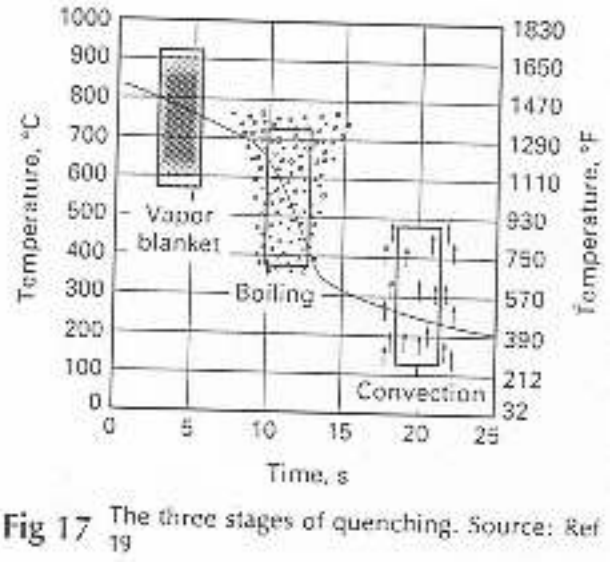


Fig 17 The three stages of quenching. Source: Ref 19

- 3 Stages of Quenching (liquid quenchants)
- Vapour Blanket: cooling medium is vapourized; forms thin "blanket" around sample. Low cooling rate.
- Boiling Stage: vapour no longer sustainable as T dropping; liquid boils on contact to form discrete vapour bubbles that leave surface. Effective heat transfer.
- Convection Stage: Temp is below boiling pt. of liquid, relies on convection of liquid to move heat away – slow Agitation - by pumps/impellors etc.

Defects & Distortions in Heat Treating

- Over-heating & "burning" (low alloy steels)
- Long time at high T causes MnS dissolution & reprecipitation along gbs - intergranular fracture. Occurs during forging/good temp control required.
- Residual Stresses - Heat treatment often causes these.
- - macro: long-range residual stresses, act over large regions compared to grain size, (design of parts).
- - micro: residual (short-range, tenelated stresses), lattice defects, precipitates, about grain size.

Defects & Distortions in Heat Treating

- **Effects of Residual Stresses**
  - dimensional changes, & crack initiation
- dimensional changes often occur when residual stress is eliminated eg. machining.
- Compressive Residual Stresses: Often useful as can reduce effect of imposed tensile stresses (reduce likelihood of fatigue, etc.) These type of residual stresses are often deliberately achieved during processing.
- Tensile Residual Stresses: Undesirable, especially at surface (some heat-treatments especially with phase transformations).
- Control Residual Stresses: By stress-relieving. Grinding of layers.

Residual Stresses Steels

Table 6 A c piled summary of the maximum residual stresses in surface heat-treated steels

Steel	Heat treatment	Residual stress (longitudinal)	
		MPa	ksi
832M13 (type)	Carburized at 970 °C (1780 °F) to 1 mm (0.04 in.) case with 0.8% surface carbon		
	Direct-quenched	280	40.5
	Direct-quenched, −80 °C (−110 °F) subzero treatment	340	49.0
	Direct-quenched, −90 °C (−130 °F) subzero treatment, tempered	200	29.0
805A20	Carburized and quenched	240–340(a)	35.0–49.0
805A20	Carburized to 1.1–1.5 mm (0.043–0.06 in.) case at 920 °C (1690 °F), direct oil quench, no temper	190–230	27.5–33.5
805A17		400	58
805A17	Carburized to 1.1–1.5 mm (0.043–0.06 in.) case at 920 °C (1690 °F), direct oil quench, tempered 150 °C (300 °F)	150–200	22–29
897M39	Nitrided to case depth of about 0.5 mm (0.02 in.)	400–600	58.0–87.0
905M39		800–1000	116.0–145.0
Cold-rolled steel	Induction hardened, untempered	1000	145.0
	Induction hardened, tempered 200 °C (390 °F)	650	94.0
	Induction hardened, tempered 300 °C (570 °F)	350	51
	Induction hardened, tempered 400 °C (750 °F)	170	24.5

(a) Immediately subsurface, that is, 0.05 mm (0.002 in.). Source: Ref 29

Defects & Distortions in Heat Treating

- **Quench Cracking**: - Caused by excessive quenching stresses.

  Due to:

- Part Design: sharp corners, keyways, splines etc. - stress concentrations. Use less severe quench (oil) etc.
- Steel Grade: some grades (higher % c etc) more susceptible
- Part Defects: stringers, inclusions etc.
- Heat-Treating: higher austenitizing temps more likely to cause cracking; coarse grain size; non-uniform cooling, soft spots from inadequate cooling (tongs etc.)

Defects & Distortions in Heat Treating

- **Quench Cracking**: - Caused by excessive quenching stresses.

  Due to:

- Decarburization - changes %C thus changes transformation

  (CCT) times.

- Warpage: rapid heating/non uniform/quenching residual stresses

  already present (rolling, grinding etc), uneven hardening & (scale).

  Long or thin parts.

- Use proper procedures, protect surfaces, fixtures.

Heat Treating Tool Steels

- Usually have high %carbon plus alloying elements for hardness. Cr, V, W, Mo (carbide formers etc.).
- Usually formed first (forged/machined) then heat-treated (not often normalized as air-cooling can cause hardening).
- Quenching medium depends on composition & thickness. Often "hot-quenched" in oil 540º/650ºC
- Tempered (+ often double-tempered to remove untempered martenite from transformation of retained austenite).
- $\rightarrow$ Quench $\rightarrow$ M + Retained γ $\rightarrow$ Temper $\rightarrow$ MT + M $\rightarrow$ Temper $\rightarrow$ MT

Heat Treating Tool Steels

Table 12.3 **Designations, Compositions, and Applications for Six Tool Steels**

AISI Number	*UNS Number*	*Composition (wt%)*[a]						*Typical Applications*
		C	*Cr*	*Ni*	*Mo*	*W*	*V*	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, wood-working tools

[a] The balance of the composition is iron. Manganese concentrations range between 0.10 and 1.4 wt%, depending on alloy; silicon concentrations between 0.20 and 1.2 wt% depending on alloy.

Table 3 Hardening and tempering of tool steels

Type	Basis of listing	Hardening: Preheat temperature °C	Hardening: Preheat temperature °F	Hardening: Hardening temperature °C	Hardening: Hardening temperature °F	Time at temperature, min	Quenching medium(a)	Tempering temperature °C	Tempering temperature °F
Molybdenum high-speed steels									
M1, M7, M10	Rapidly from preheat	730–845	1350–1550	1175–1220	2150–2225(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M2	Rapidly from preheat	730–845	1350–1550	1150–1230	2100–2250(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M2, M4, M30, M33, M34	Rapidly from preheat	730–845	1350–1550	1205–1275(b)	2200–2325(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M6	Rapidly from preheat	790	1450	1175–1205(b)	2150–2200(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M36	Rapidly from preheat	730–845	1350–1550	1205–1275(b)	2200–2325(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M41	Rapidly from preheat	730–845	1350–1550	1190–1220(b)	2175–2225(b)	2–5	O, A, or S	540–595(d)	1000–1100(d)
M42	Rapidly from preheat	730–845	1350–1550	1150–1210(b)	2100–2210(b)	2–5	O, A, or S	510–595(d)	950–1100(d)
M43	Rapidly from preheat	730–845	1350–1550	1190–1210(b)	2175–2210(b)	2–5	O, A, or S	510–595(d)	950–1100(d)
M46	Rapidly from preheat	730–845	1350–1550	1200–1225(b)	2190–2240(b)	2–5	O, A, or S	540–625(d)	1000–1150(d)
M47	Rapidly from preheat	730–845	1350–1550	1190–1220(b)	2175–2225(b)	2–5	O, A, or S	525–595(d)	975–1100(d)
Tungsten high-speed steels									
T1, T2, T4, T8	Rapidly from preheat	815–870	1500–1600	1260–1300(b)	2300–2375(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
T5, T6	Rapidly from preheat	815–870	1500–1600	1275–1290(b)	2325–2350(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
T15	Rapidly from preheat	815–870	1500–1600	1205–1260(b)	2200–2300(b)	2–5	O, A, or S	540–650(d)	1000–1200(d)
Chromium hot-work steels									
H10	Moderately from preheat	815	1500	1010–1040	1850–1900	15–40(e)	A	540–652	1000–1200
H11, H12	Moderately from preheat	815	1500	995–1025	1825–1875	15–40(e)	A	540–652	1000–1200
H13	Moderately from preheat	815	1500	995–1040	1825–1900	15–40(e)	A	540–652	1000–1200
H14	Moderately from preheat	815	1500	1010–1065	1850–1950	15–40(e)	A	540–652	1000–1200
H19	Moderately from preheat	815	1500	1065–1205	1950–2200	7–9	A or O	540–705	1000–1300
Molybdenum hot-work steels									
H41, H43	Rapidly from preheat	730–845	1350–1550	1065–1150	1950–2100	2–5	O, A, or S	565–650	1050–1200
H42	Rapidly from preheat	730–845	1350–1550	1175–1220	2150–2225	2–5	O, A, or S	565–650	1050–1200
Tungsten hot-work steels									
H21, H22	Rapidly from preheat	815	1500	1095–1205	2000–2200	2–5	A or O	595–652	1100–1250
H23	Rapidly from preheat	845	1550	1260–1290	2300–2350	2–5	O	650–815	1200–1500
H24	Rapidly from preheat	815	1500	1095–1230	2000–2250	2–5	O	565–650	1050–1200
H25	Rapidly from preheat	815	1500	1150–1260	2100–2300	2–5	A or O	565–675	1050–1250
H26	Rapidly from preheat	870	1600	1175–1260	2150–2300	2–5	O, A, or S	595–675	1100–1250
Medium-alloy air-hardening cold work steels									
A2	Slowly	790	1450	925–980	1700–1800	25–45	A	175–560	350–1050
A3	Slowly	790	1450	955–980	1750–1800	25–45	A	175–540	350–1000
A4	Slowly	635	1250	815–830	1500–1525	25–45	A	175–425	350–800
A6	Slowly	650	1200	830–870	1525–1600	25–45	A	195–425	380–800
A7	Very slowly	815	1500	830–885	1525–1625	25–60	A	150–540	300–1000
A8	Slowly	790	1450	980–1010	1800–1850	25–45	A	175–595	350–1100
A9	Slowly	790	1450	790–1025	1450–1875	25–45	A	510–620	950–1150
A10	Slowly	650	1200	790–815	1450–1500	25–45	A	175–425	350–800
Oil-hardening cold work steels									
D1	Slowly	650	1200	790–815	1450–1500	10–30	O	175–260	350–500
D2	Slowly	650	1200	760–800	1400–1475	5–30	O	175–260	350–500
D4	Slowly	...	...	790–815	1450–1500	10–30	O	175–315	350–600
D7	Slowly	650	1200	790–870 845–885	W:1450–1525 O:1550–1625	10–30	O or W	175–200	350–500
Shock-resisting steels									
S1	Slowly	...	...	900–955	1650–1750	15–45	O	205–650	400–1200
S2	Slowly	650(f)	1200(f)	845–900	1550–1650	5–20	B or W	175–425	350–800
S5	Slowly	790	1400	870–925	1600–1700	5–30	O	175–425	350–800
S7	Slowly	650–705	1200–1300	925–955	1700–1750	15–45	A or O	205–650	400–1150
Mold steels									
P2	...	980–1025(g)	1650–1700(g)	830–845(b)	1525–1550(b)	15	O	175–260	350–500
P3	...	980–1025(g)	1650–1700(g)	800–830(b)	1475–1525(b)	15	O	175–260	350–500
P4	...	980–1025(g)	1775–1825(g)	870–955(b)	1775–1825(b)	15	A	175–480	350–900
P5	...	980–1025(g)	1650–1700(g)	845–870(b)	1550–1600(b)	15	O or W	175–260	350–500
P6	...	980–1025(g)	1650–1700(g)	790–815(b)	1450–1500(b)	15	A or O	175–230	350–450
P20	...	870–900(h)	1600–1650(h)	815–870	1500–1600	15	O	480–595(i)	900–1100(i)
P21(j)	Slowly	Do not preheat		705–730	1300–1350	60–100	A or O	510–550	950–1025

(continued)

(a) O, oil quench; A, air cool; S, salt bath cool; W, water quench. (b) When the high-temperature heating is carried out in a salt bath, the range of temperatures should be about 15°C (25°F) lower than given in this line. (c) Double tempering recommended; do not draw less than 1 h at temperature on each draw. (d) Triple tempering recommended; do not draw less than 1 h at temperature on each draw. (e) Time range is approximate for each section. For parts of intricate shape, a minimum time is the least 1/2 minutes per 25 mm (1 in.) of cross section of the work. (f) Preferable for large tools to minimize cracking hazard with oil. Time range is approximate for each section. For parts of intricate shape, a minimum time is the least 1/2 minutes per 25 mm (1 in.) of cross section of the work. (g) Carburizing temperature. (h) After carburizing. (i) Carburized case hardness, Rc 58. (j) Is a precipitation hardening steel having a thermal treatment that involves solution treating and aging rather than hardening and tempering. (k) Recommended for large parts and tools with intricate sections

Heat Treating Tool Steels

Heat Treating Steels

Table 12.4 **Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels**

AISI Number	*UNS Number*	*Composition (wt%)*[a]	*Condition*[b]	*Mechanical Properties*			*Typical Applications*
				Tensile Strength [MPa (ksi)]	*Yield Strength [MPa (ksi)]*	*Ductility [%EL. in 50 mm (2 in.)]*	
			Ferritic				
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
			Austenitic				
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction

Table 9 Recommended annealing temperatures for selected duplex stainless steels

UNS No.	Designation	Annealing temperature(a) °C (°F)
S32900	329	925–955 (1700–1750)
S32950	7 Mo Plus	995–1025 (1825–1875)
S31500	3RE60	975–1025 (1785–1875)
S31803	SAF 2205	1020–1100 (1870–2010)
...		1020–1100 (1870–2010)
S31260	DP-3	1065–1175 (1950–2150)
S32550	Ferralium 255	1065–1175 (1950–2150)

(a) Cooling from the annealing temperature must be rapid, but it also must be consistent with solution of the precipitates.

to be so high, that maximum hardness is produced by air cooling in the center of sections up to approximately 305 mm (12 in.) thick.

Surface hardness ranges for the various heat-treated conditions from fully annealed to fully hardened are given in Fig 4.

The martensitic stainless steels are more sensitive to heat-treating variables than are carbon and low-alloy steels; rejection rates due to faults in heat treating are correspondingly high.

Prior Cleaning. To avoid contamination, all parts and heat-treating fixtures must be cleaned thoroughly before they are placed in the furnace. Proper cleaning is particularly important when the heat treatment is to be performed in a protective atmosphere. Grease, oil, and even location lines made by an ordinary lead pencil can cause carburization. Perspiration stains from fingerprints are a source of chloride contamination and

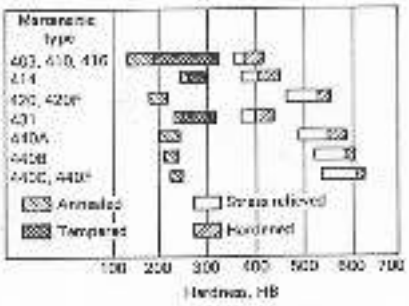


Fig 4 Effect of heat treatments on the hardness of wrought martensitic stainless steels

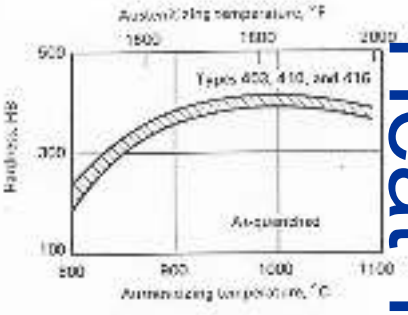


Fig 5 Effect of austenitizing temperature on air-quenched hardness. Specimens were wrought martensitic stainless steels containing 0.15% max C.

may cause severe scaling in oxidizing atmospheres. Furthermore, a protective atmosphere cannot be effective unless it is permitted to make unobstructed contact with metal surfaces.

Preheating. Martensitic stainless steels normally are hardened by being heated to the austenitizing range of 925 to 1065 °C (1700 to 1950 °F) and then cooled in air or oil.

The thermal conductivity of stainless steels is characteristically lower than that of carbon and alloy steels. Accordingly, high thermal gradients and high stresses during rapid heating may cause warpage and cracking in some parts. To avoid these problems, preheating is usually recommended in the treatment of martensitic stainless steels. In annealing or hardening, the following parts should be preheated:

- Heavy section parts
- Parts with both thin and thick sections
- Parts with sharp corners and reentrant angles
- Heavily ground parts
- Parts machined with heavy deep cuts
- Parts that have been cold formed or straightened
- Previously hardened parts that are being reheat treated

Preheating is normally accomplished at 760 to 790 °C (1400 to 1450 °F), and heating need be continued only long enough to ensure that all portions of each part have reached the preheating temperature. Large heavy parts are sometimes preheated at approximately 540 °C (1000 °F) prior to the 790 °C (1450 °F) preheat. Types 403, 410, and 416 require less preheating than the higher-carbon types 431, 420, and 440 grades.

Austenitizing temperatures, soaking times, and quenching media are summarized in Table 10. When maximum corrosion resistance and strength are desired, the steel should be austenitized at the high end of the temperature range. For alloys that are to be tempered above 565 °C (1050 °F), the

Table 10 Procedures for hardening and tempering wrought martensitic stainless steels to specific strength and hardness levels

Type	Austenitizing(a) Temperature(b) °C	Temperature(b) °F	Quenching medium	Tempering temperature(c) °C min	°C max	°F min	°F max	Tensile strength MPa	Tensile strength ksi	Hardness, HRC
403, 410	925–1010	1700–1850	Air or oil	565	605	1050	1125	760–965	110–140	25–31
				205	370	400	700	1105–1515	160–220	38–43
414	925–1051	1700–1925	Air or oil	595	650	1100	1200	760–965	110–140	25–31
				230	370	450	700	1105–1515	160–220	38–43
416, 416Se	925–1010	1700–1850	Oil	565	605	1050	1125	760–965	110–140	25–31
				230	370	450	700	1105–1515	160–220	38–45
420	980–1065	1800–1950	Air or oil(d)	315	370	600	700	1550–1930	225–280	48–56
431	980–1065	1800–1950	Air or oil(d)	565	605	1050	1125	860–1035	125–150	26–34
				230	370	450	700	1210–1515	175–220	40–47
440A	1010–1065	1850–1950	Air or oil(d)	150	370	300	700	...	...	48–57
440B	1010–1065	1850–1950	Air or oil(d)	150	370	300	700	...	...	53–59
440C, 440F	1010–1065	1850–1950	Air or oil(d)	...	160	...	325	...	...	60 min
				...	200	...	375	...	...	58 min
				...	230	...	450	...	...	57 min
				...	355	...	675	...	...	52–56

(a) Preheating to a temperature within the austenitizing range used (Table 12) is recommended for thin or complex, heavy sections, previously hardened parts, parts with extreme variations in section or with sharp reentrant angles, and parts that have been straightened or heavily ground. (b) Hardened to provide working and service clearance, particularly for types 420, 431, and 440A, B, C, and F. (c) Cool from austenitizing temperature range before tempering. Tempering in the range of 370 to 565 °C (700 to 1050 °F) is not recommended because it results in low and erratic impact properties and poor resistance to corrosion and stress corrosion. (d) For maximum toughness and maximum dimensional stability, a subzero treatment –73 ± 10 °C (–100 ± 20 °F) is recommended. This should incorporate continuous cooling from the austenitizing temperature to the cold transformation temperature.

Heat Treating Steels & Alloys

Temper Embrittlement

- The toughness of some steels can be reduced by tempering at certain temperatures (between 375 and 575°C and slow cooling). Usually due to presence of impurities (Mn, Ni, Cr, Sb, P, As, Sn).
- Avoid temper embrittlement by:
- 1) controlling composition
- 2) Temper above 575°C or below 375°C followed by fast cooling

Quenching Media

- **Steel** - **Quenchant**
- plain carbon steels - water
- low/med alloyed steels - oil
- high alloy steels - air
- Martempering - Brine

Severity of quench

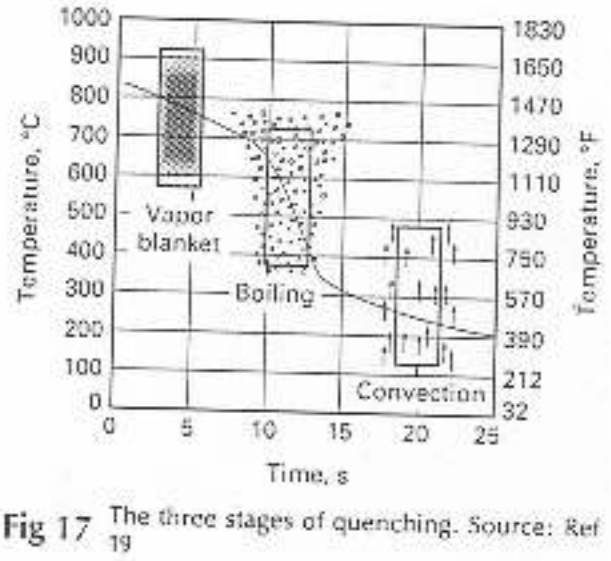


Fig 17 The three stages of quenching. Source: Ref 19

- 3 Stages of Quenching (liquid quenchants)
- Vapour Blanket: cooling medium is vapourized; forms thin "blanket" around sample. Low cooling rate.
- Boiling Stage: vapour no longer sustainable as T dropping; liquid boils on contact to form discrete vapour bubbles that leave surface. Effective heat transfer.
- Convection Stage: Temp is below boiling pt. of liquid, relies on convection of liquid to move heat away – slow Agitation - by pumps/impellors etc.

Defects & Distortions in Heat Treating

- Over-heating & "burning" (low alloy steels)
- Long time at high T causes MnS dissolution & reprecipitation along gbs - intergranular fracture. Occurs during forging/good temp control required.
- Residual Stresses - Heat treatment often causes these.
- - macro: long-range residual stresses, act over large regions compared to grain size, (design of parts).
- - micro: residual (short-range, tenelated stresses), lattice defects, precipitates, about grain size.

Defects & Distortions in Heat Treating

- **Effects of Residual Stresses**
  - dimensional changes, & crack initiation
- dimensional changes often occur when residual stress is eliminated eg. machining.
- Compressive Residual Stresses: Often useful as can reduce effect of imposed tensile stresses (reduce likelihood of fatigue, etc.) These type of residual stresses are often deliberately achieved during processing.
- Tensile Residual Stresses: Undesirable, especially at surface (some heat-treatments especially with phase transformations).
- Control Residual Stresses: By stress-relieving. Grinding of layers.

Residual Stresses Steels

Table 6 A c piled summary of the maximum residual stresses in surface heat-treated steels

Steel	Heat treatment	Residual stress (longitudinal)	
		MPa	ksi
832M13 (type)	Carburized at 970 °C (1780 °F) to 1 mm (0.04 in.) case with 0.8% surface carbon		
	Direct-quenched	280	40.5
	Direct-quenched, −80 °C (−110 °F) subzero treatment	340	49.0
	Direct-quenched, −90 °C (−130 °F) subzero treatment, tempered	200	29.0
805A20	Carburized and quenched	240–340(a)	35.0–49.0
805A20	Carburized to 1.1–1.5 mm (0.043–0.06 in.) case at 920 °C (1690 °F), direct oil quench, no temper	190–230	27.5–33.5
805A17		400	58
805A17	Carburized to 1.1–1.5 mm (0.043–0.06 in.) case at 920 °C (1690 °F), direct oil quench, tempered 150 °C (300 °F)	150–200	22–29
897M39	Nitrided to case depth of about 0.5 mm (0.02 in.)	400–600	58.0–87.0
905M39		800–1000	116.0–145.0
Cold-rolled steel	Induction hardened, untempered	1000	145.0
	Induction hardened, tempered 200 °C (390 °F)	650	94.0
	Induction hardened, tempered 300 °C (570 °F)	350	51
	Induction hardened, tempered 400 °C (750 °F)	170	24.5

(a) Immediately subsurface, that is, 0.05 mm (0.002 in.). Source: Ref 29

Defects & Distortions in Heat Treating

- **Quench Cracking**: - Caused by excessive quenching stresses.

  Due to:

- Part Design: sharp corners, keyways, splines etc. - stress concentrations. Use less severe quench (oil) etc.
- Steel Grade: some grades (higher % c etc) more susceptible
- Part Defects: stringers, inclusions etc.
- Heat-Treating: higher austenitizing temps more likely to cause cracking; coarse grain size; non-uniform cooling, soft spots from inadequate cooling (tongs etc.)

Defects & Distortions in Heat Treating

- **Quench Cracking**: - Caused by excessive quenching stresses.

  Due to:

- Decarburization - changes %C thus changes transformation

  (CCT) times.

- Warpage: rapid heating/non uniform/quenching residual stresses

  already present (rolling, grinding etc), uneven hardening & (scale).

  Long or thin parts.

- Use proper procedures, protect surfaces, fixtures.

Heat Treating Tool Steels

- Usually have high %carbon plus alloying elements for hardness. Cr, V, W, Mo (carbide formers etc.).
- Usually formed first (forged/machined) then heat-treated (not often normalized as air-cooling can cause hardening).
- Quenching medium depends on composition & thickness. Often "hot-quenched" in oil 540º/650ºC
- Tempered (+ often double-tempered to remove untempered martenite from transformation of retained austenite).
- $\rightarrow$ Quench $\rightarrow$ M + Retained γ $\rightarrow$ Temper $\rightarrow$ MT + M $\rightarrow$ Temper $\rightarrow$ MT

Heat Treating Tool Steels

Table 12.3 **Designations, Compositions, and Applications for Six Tool Steels**

AISI Number	*UNS Number*	*Composition (wt%)*[a]						*Typical Applications*
		C	*Cr*	*Ni*	*Mo*	*W*	*V*	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, wood-working tools

[a] The balance of the composition is iron. Manganese concentrations range between 0.10 and 1.4 wt%, depending on alloy; silicon concentrations between 0.20 and 1.2 wt% depending on alloy.

Table 3 Hardening and tempering of tool steels

Type	Form of heating	Hardening: Preheat temperature °C	Hardening: Preheat temperature °F	Hardening: Hardening temperature °C	Hardening: Hardening temperature °F	Time at temperature, min	Quenching medium(a)	Tempering temperature °C	Tempering temperature °F
Molybdenum high-speed steels									
M1, M7, M10	Rapidly from preheat	730–845	1350–1550	1175–1220	2150–2225(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M2	Rapidly from preheat	730–845	1350–1550	1150–1230	2100–2250(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M2, M4, M30, M33, M34	Rapidly from preheat	730–845	1350–1550	1205–1275(b)	2200–2325(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M6	Rapidly from preheat	790	1450	1175–1205(b)	2150–2200(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M36	Rapidly from preheat	730–845	1350–1550	1205–1275(b)	2200–2325(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
M41	Rapidly from preheat	730–845	1350–1550	1190–1220(b)	2175–2225(b)	2–5	O, A, or S	540–595(d)	1000–1100(d)
M42	Rapidly from preheat	730–845	1350–1550	1150–1210(b)	2100–2210(b)	2–5	O, A, or S	510–595(d)	950–1100(d)
M43	Rapidly from preheat	730–845	1350–1550	1190–1220(b)	2175–2225(b)	2–5	O, A, or S	510–595(d)	950–1100(d)
M46	Rapidly from preheat	730–845	1350–1550	1205–1275(b)	2200–2325(b)	2–5	O, A, or S	540–625(d)	1000–1150(d)
M47	Rapidly from preheat	730–845	1350–1550	1190–1220(b)	2175–2225(b)	2–5	O, A, or S	525–595(d)	975–1100(d)
		730–845	1350–1550	1180–1205(b)	2150–2200(b)	2–5	O, A, or S	525–595(d)	975–1100(d)
Tungsten high-speed steels									
T1, T2, T4, T8	Rapidly from preheat	815–870	1500–1600	1260–1300(b)	2300–2375(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
T5, T6	Rapidly from preheat	815–870	1500–1600	1275–1290(b)	2325–2350(b)	2–5	O, A, or S	540–595(c)	1000–1100(c)
T15	Rapidly from preheat	815–870	1500–1600	1205–1260(b)	2200–2300(b)	2–5	O, A, or S	540–650(d)	1000–1200(d)
Chromium hot-work steels									
H10	Moderately from preheat	815	1500	1010–1040	1850–1900	15–40(e)	A	540–652	1000–1200
H11, H12	Moderately from preheat	815	1500	995–1025	1825–1875	15–40(e)	A	540–652	1000–1200
H13	Moderately from preheat	815	1500	995–1040	1825–1900	15–40(e)	A	540–652	1000–1200
H14	Moderately from preheat	815	1500	1010–1065	1850–1950	15–40(e)	A	540–652	1000–1200
H19	Moderately from preheat	815	1500	1065–1205	1950–2200	2–5	A or O	540–705	1000–1300
Molybdenum hot-work steels									
H41, H43	Rapidly from preheat	730–845	1350–1550	1065–1150	1950–2100	2–5	O, A, or S	565–650	1050–1200
H42	Rapidly from preheat	730–845	1350–1550	1175–1220	2150–2225	2–5	O, A, or S	565–650	1050–1200
Tungsten hot-work steels									
H21, H22	Rapidly from preheat	815	1500	1095–1205	2000–2200	2–5	A or O	595–652	1100–1250
H23	Rapidly from preheat	845	1550	1205–1260	2200–2300	2–5	O	650–815	1200–1500
H24	Rapidly from preheat	815	1500	1095–1230	2000–2250	2–5	O	565–650	1050–1200
H25	Rapidly from preheat	815	1500	1150–1260	2100–2300	2–5	A or O	565–675	1050–1250
H26	Rapidly from preheat	870	1600	1175–1260	2150–2300	2–5	O, A, or S	595–675	1100–1250
Medium-alloy air-hardening cold work steels									
A2	Slowly	790	1450	925–980	1700–1800	25–45	A	175–540	350–1000
A3	Slowly	790	1450	955–980	1750–1800	25–45	A	175–540	350–1000
A4	Slowly	635	1250	815–830	1500–1525	25–45	A	175–425	350–800
A6	Slowly	650	1200	830–870	1525–1600	25–45	A	195–425	300–800
A7	Very slowly	815	1500	955–980	1750–1800	25–60	A	150–540	300–1000
A8	Slowly	790	1450	980–1010	1800–1850	25–45	A	175–595	350–1100
A9	Slowly	790	1450	790–1025	1800–1875	25–45	A	510–620	950–1150
A10	Slowly	650	1200	790–815	1450–1500	25–45	A	175–425	350–800
Oil-hardening cold work steels									
D1	Slowly	650	1200	790–815	1450–1500	10–30	O	175–260	350–500
D2	Slowly	650	1200	760–800	1400–1475	5–30	O	175–260	350–500
D4	Slowly	...	...	790–815	1450–1500	10–30	O	175–315	350–600
D7	Slowly	650	1200	790–870	W:1425–1525	10–30	O or W	175–200	350–500
				845–885	O 1550–1625				
Shock-resisting steels									
S1	Slowly	...	...	900–955	1650–1750	15–45	O	205–650	400–1200
S2	Slowly	650(f)	1200(f)	845–900	1550–1650	5–20	B or W	175–425	350–800
S5	Slowly	760	1400	870–925	1600–1700	5–30	O	175–425	350–800
S7	Slowly	650–705	1200–1300	925–955	1700–1750	15–45	A or O	205–650	400–1150
Mold steels									
P2	...	900–925(g)	1650–1700(g)	830–845(b)	1525–1550(b)	15	O	175–260	350–500
P3	...	900–925(g)	1650–1700(g)	830–843(b)	1525–1550(b)	15	O	175–260	350–500
P4	...	900–955(g)	1775–1825(g)	870–955(b)	1775–1825(b)	15	A	175–480	350–900
P5	...	900–925(g)	1650–1700(g)	845–870(b)	1550–1600(b)	15	O or W	175–260	350–500
P6	...	900–925(g)	1650–1700(g)	790–815(b)	1450–1500(b)	15	A or O	175–230	350–450
P20	...	870–900(h)	1600–1650(h)	815–870	1500–1600	15	O	480–595(i)	900–1100(i)
P21(j)	Slowly	Do not preheat		705–730	1300–1350	60–100	A or O	510–550	950–1025

(continued)

(a) O, oil quench; A, air cool; S, salt bath cool; W, water quench; B, brine quench. (b) When the high-temperature heating is carried out in a salt bath, the range of temperatures should be about 15°C (25°F) lower than given in this line. (c) Double tempering recommended; do not draw less than 1 h at temperature on each draw. (d) Triple tempering recommended; do not draw less than 1 h at temperature on each draw. Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (f) Preferable for large tools to minimize cracking. (g) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (h) Preferable for large tools to minimize cracking. (i) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (j) Preferable for large tools to minimize cracking. (k) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (l) Preferable for large tools to minimize cracking. (m) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (n) Preferable for large tools to minimize cracking. (o) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (p) Preferable for large tools to minimize cracking. (q) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (r) Preferable for large tools to minimize cracking. (s) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (t) Preferable for large tools to minimize cracking. (u) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (v) Preferable for large tools to minimize cracking. (w) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (x) Preferable for large tools to minimize cracking. (y) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (z) Preferable for large tools to minimize cracking. (aa) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (bb) Preferable for large tools to minimize cracking. (cc) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (dd) Preferable for large tools to minimize cracking. (ee) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (ff) Preferable for large tools to minimize cracking. (gg) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (hh) Preferable for large tools to minimize cracking. (ii) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (jj) Preferable for large tools to minimize cracking. (kk) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (ll) Preferable for large tools to minimize cracking. (mm) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (nn) Preferable for large tools to minimize cracking. (oo) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (pp) Preferable for large tools to minimize cracking. (qq) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (rr) Preferable for large tools to minimize cracking. (ss) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (tt) Preferable for large tools to minimize cracking. (uu) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (vv) Preferable for large tools to minimize cracking. (ww) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (xx) Preferable for large tools to minimize cracking. (yy) Time to apply at specified temperature for each steel. For parts containing a maximum section size of 12 mm (½ in.) of cross section of the steel. (zz) Preferable for large tools to minimize cracking.

Heat Treating Tool Steels

Heat Treating Steels

Table 12.4 **Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels**

AISI Number	*UNS Number*	*Composition (wt%)*[a]	*Condition*[b]	*Mechanical Properties*			*Typical Applications*
				Tensile Strength [MPa (ksi)]	*Yield Strength [MPa (ksi)]*	*Ductility [%EL. in 50 mm (2 in.)]*	
			Ferritic				
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
			Austenitic				
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction

Table 9 Recommended annealing temperatures for selected duplex stainless steels

UNS No.	Designation	Annealing temperature(a) °C (°F)
S32900	329	925–955 (1700–1750)
S32950	7 Mo Plus	995–1025 (1825–1875)
S31500	3RE60	975–1025 (1785–1875)
S31803	SAF 2205	1020–1100 (1870–2010)
...		1020–1100 (1870–2010)
S31260	DP-3	1065–1175 (1950–2150)
S32550	Ferralium 255	1065–1175 (1950–2150)

(a) Cooling from the annealing temperature must be rapid, but it also must be consistent with solution of the precipitates.

to be so high, that maximum hardness is produced by air cooling in the center of sections up to approximately 305 mm (12 in.) thick.

Surface hardness ranges for the various heat-treated conditions from fully annealed to fully hardened are given in Fig 4.

The martensitic stainless steels are more sensitive to heat-treating variables than are carbon and low-alloy steels; rejection rates due to faults in heat treating are correspondingly high.

Prior Cleaning. To avoid contamination, all parts and heat-treating fixtures must be cleaned thoroughly before they are placed in the furnace. Proper cleaning is particularly important when the heat treatment is to be performed in a protective atmosphere. Grease, oil, and even lecation lines made by an ordinary lead pencil can cause carburization. Perspiration stains from fingerprints are a source of chloride contamination and

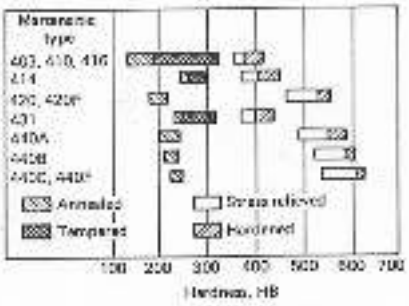


Fig 4 Effect of heat treatments on the hardness of wrought martensitic stainless steels

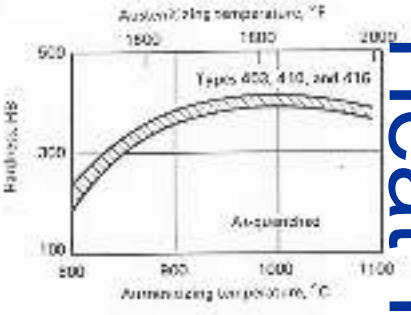


Fig 5 Effect of austenitizing temperature on air-quenched hardness. Specimens were wrought martensitic stainless steels containing 0.15% max C.

may cause severe scaling in oxidizing atmospheres. Furthermore, a protective atmosphere cannot be effective unless it is permitted to make unobstructed contact with metal surfaces.

Preheating. Martensitic stainless steels normally are hardened by being heated to the austenitizing range of 925 to 1065 °C (1700 to 1950 °F) and then cooled in air or oil.

The thermal conductivity of stainless steels is characteristically lower than that of carbon and alloy steels. Accordingly, high thermal gradients and high stresses during rapid heating may cause warpage and cracking in some parts. To avoid these problems, preheating is usually recommended in the treatment of martensitic stainless steels. In annealing or hardening, the following parts should be preheated:

- Heavy section parts
- Parts with both thin and thick sections
- Parts with sharp corners and reentrant angles
- Heavily ground parts
- Parts machined with heavy deep cuts
- Parts that have been cold formed or straightened
- Previously hardened parts that are being reheat treated

Preheating is normally accomplished at 760 to 790 °C (1400 to 1450 °F), and heating need be continued only long enough to ensure that all portions of each part have reached the preheating temperature. Large heavy parts are sometimes preheated at approximately 540 °C (1000 °F) prior to the 790 °C (1450 °F) preheat. Types 403, 410, and 416 require less preheating than the higher-carbon types 431, 420, and 440 grades.

Austenitizing temperatures, soaking times, and quenching media are summarized in Table 10. When maximum corrosion resistance and strength are desired, the steel should be austenitized at the high end of the temperature range. For alloys that are to be tempered above 565 °C (1050 °F), the

Table 10 Procedures for hardening and tempering wrought martensitic stainless steels to specific strength and hardness levels

Type	Austenitizing(a) Temperature(b) °C	Temperature(b) °F	Quenching medium(c)	Tempering temperature(d) °C min	°C max	°F min	°F max	Tensile strength MPa	Tensile strength ksi	Hardness, HRC
403, 410	955–1010	1700–1850	Air or oil	565	605	1050	1125	760–965	110–140	25–31
				205	370	400	700	1105–1515	160–220	38–43
414	925–1051	1700–1925	Air or oil	595	650	1100	1200	760–965	110–140	25–31
				230	370	450	700	1105–1515	160–220	38–43
416, 416Se	925–1010	1700–1850	Oil	565	605	1050	1125	760–965	110–140	25–31
				230	370	450	700	1105–1515	160–220	38–45
420	980–1065	1800–1950	Air or oil(e)	315	370	600	700	1550–1930	225–280	48–56
431	980–1065	1800–1950	Air or oil(e)	565	605	1050	1125	860–1035	125–150	26–34
				230	370	450	700	1210–1515	175–220	40–47
440A	1010–1065	1850–1950	Air or oil(e)	150	370	300	700	...	...	48–57
440B	1010–1065	1850–1950	Air or oil(e)	150	370	300	700	...	...	53–59
440C, 440F	1010–1065	1850–1950	Air or oil(e)	...	160	...	325	...	...	60 min
				...	230	...	375	...	...	58 min
				...	230	...	450	...	...	57 min
				...	355	...	675	...	...	52–56

(a) Preheating to a temperature within the previous annealing range (see Table 12) is recommended for thin parts, heavy sections, previously hardened parts, parts with extreme variations in section or with sharp reentrant angles, and parts that have been straightened or heavily ground. (b) Hardened to provide maximum corrosion resistance, particularly for types 420, 431, and 440A, B, C, and F. (c) Cool from austenitizing temperature range from 50 to 90 min. The low end of the austenitizing range is recommended for alloys previously tempered to 28 to 31 HRC; generally, however, corrosion resistance is enhanced by quenching from the upper limit of the austenitizing range. (d) Where air or oil is indicated, oil quenching should be used for parts more than 6.4 mm (¼ in.) thick; martempering baths at 150 to 400 °C (300 to 750 °F) may be substituted for an oil quench. (e) Generally, the low end of the tempering range of 150 to 370 °C (300 to 700 °F) is recommended for maximum hardness, the middle for maximum toughness, and the high end for maximum yield strength. Tempering in the range of 370 to 565 °C (700 to 1050 °F) is not recommended because it results in low and erratic impact properties and poor resistance to corrosion and stress corrosion. (f) For optimum combination of corrosion resistance and maximum dimensional stability, a cryogenic treatment –73 ± 10 °C (–100 ± 20 °F) is recommended. This should immediately follow oil quenching from the austenitizing temperature to the cold transformation temperature.

Heat Treating Steels & Alloys

Temper Embrittlement

- The toughness of some steels can be reduced by tempering at certain temperatures (between 375 and 575°C and slow cooling). Usually due to presence of impurities (Mn, Ni, Cr, Sb, P, As, Sn).
- Avoid temper embrittlement by:
- 1) controlling composition
- 2) Temper above 575°C or below 375°C followed by fast cooling

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Surface Treatment

Lecture 7

Quenching & Tempering

- In order to get martensitic steels need continuous, rapid cooling.
- Use quenching medium such as water, oil, air in order to get a high martensite content then temper.
- During cooling, impossible to get uniform cooling rate throughout specimen; surface always cools faster then interior thus variation in microstructure formed.
- Successful heat treating of steels to get predominantly martensite throughout cross section depends mainly on:
  - composition of steel alloy
  - type of quenching medium
  - size and shape of specimen

Hardenability

- Effects of alloy composition can change how far into specimen we get martensite - hardenability. (not the same as hardness).
- More like “the ability of a given steel to form martensite as a function of distance from the specimen surface”.
- **Measure Hardenability using the Jominy end-quench test.**

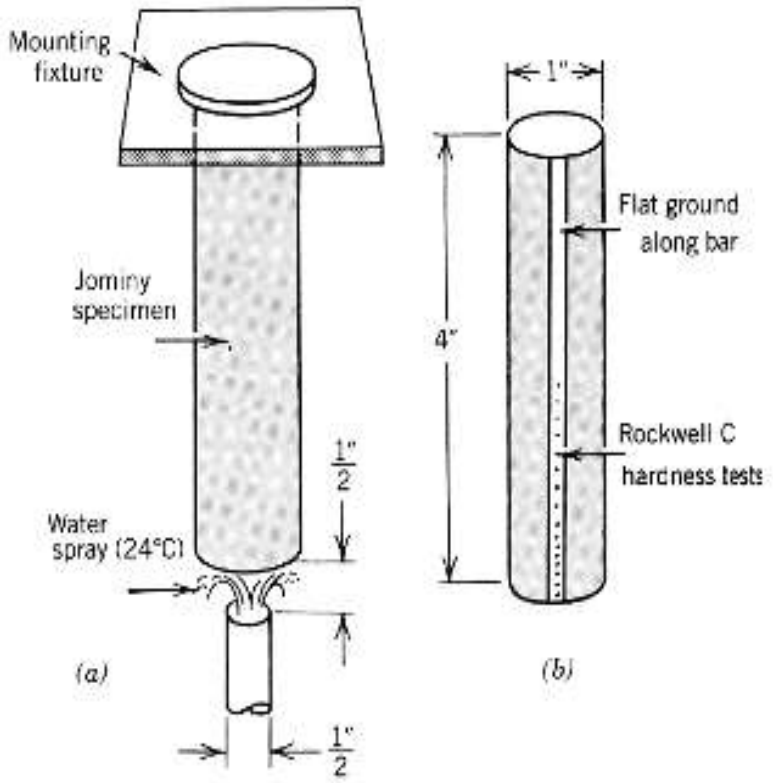


FIGURE 11.2
Schematic diagram of Jominy end-quench specimen (*a*) mounted during quenching and (*b*) after hardness testing from the quenched end along a ground flat.

Hardenability

- **Measure Hardenability using the Jominy end-quench test.**
- Standard sample size (cylinder)
- standard coolant (water spray @ 24°C)
- Austenitize sample in furnace then place on quenching rig and spray water on bottom end only.
- After cooling, grind 0.4mm flat on side and measure hardness as a function of distance from quenched end.

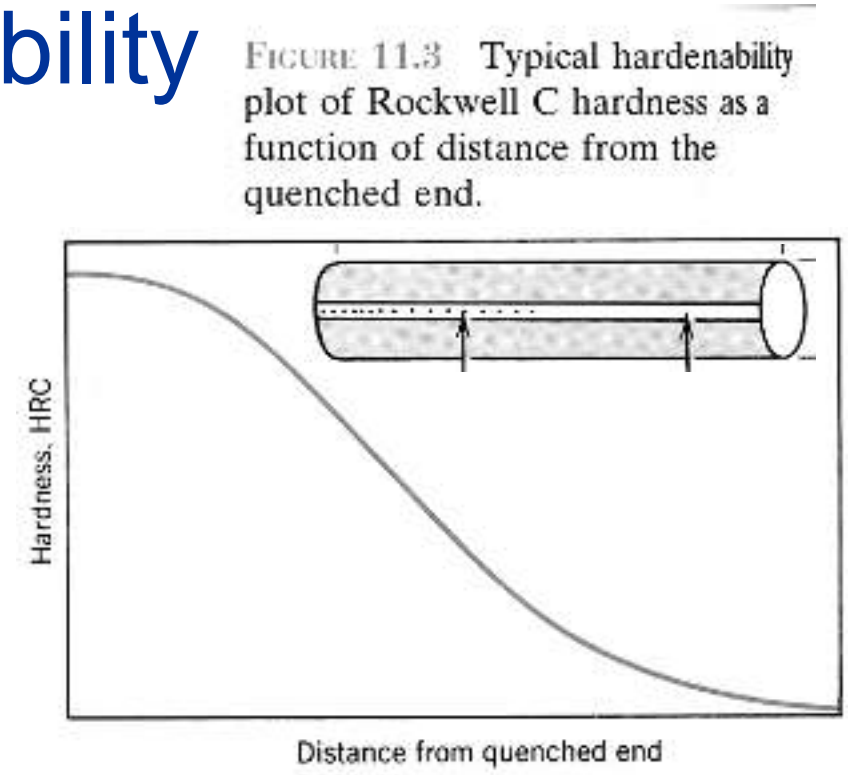


FIGURE 11.3 Typical hardenability plot of Rockwell C hardness as a function of distance from the quenched end.

Maximum hardness – 100% martensite @ quenched end

Steel with high hardenability has high hardenss for long distances

Hardenability Curves

- Correlation between continuous cooling curve of eutectoid steel and jominy hardnebility curve
- Different microstrucutre at 4 different points on the specimen

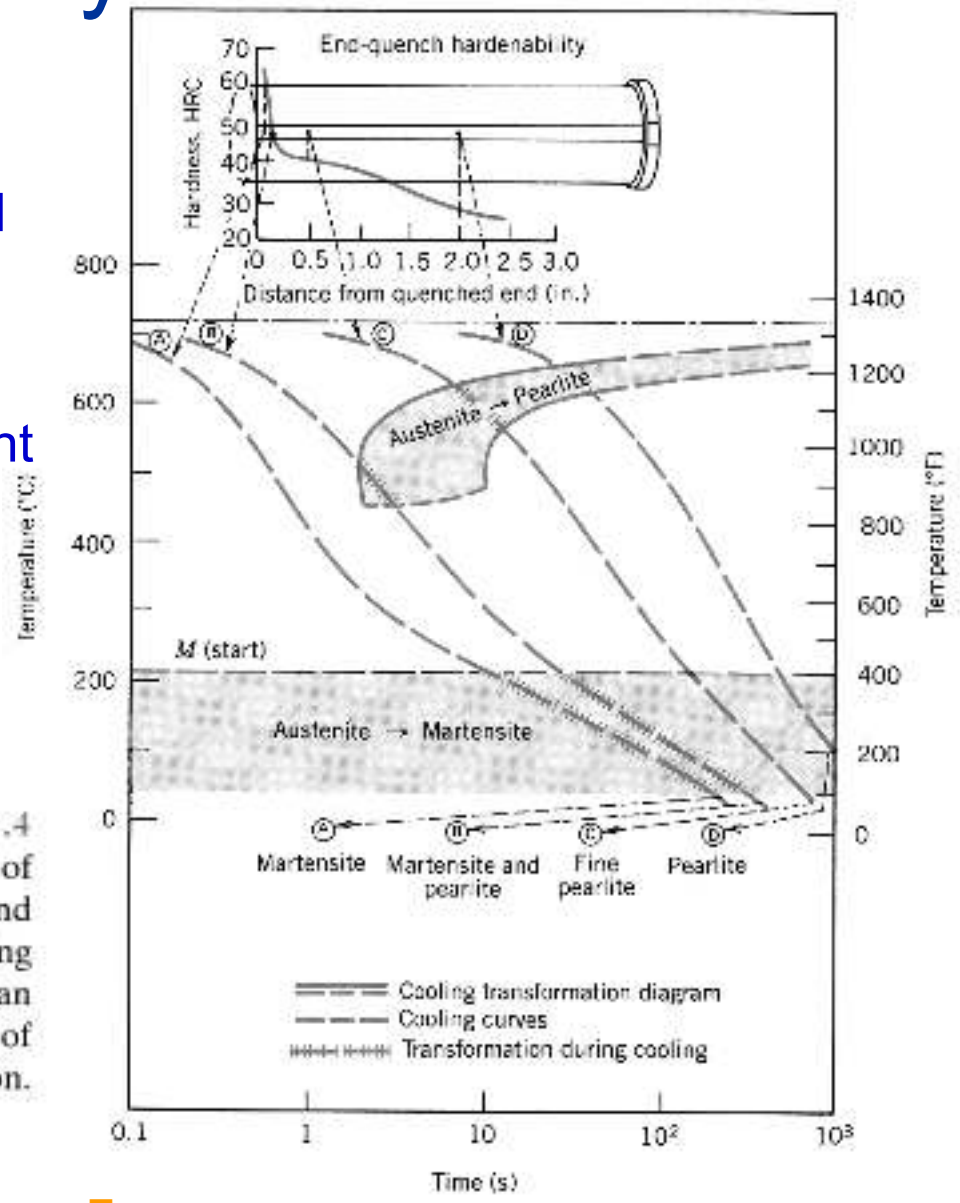


FIGURE 11.4
Correlation of hardenability and continuous cooling information for an iron–carbon alloy of eutectoid composition.

Hardenability Curves

- Initial hardness is same for 5 alloy steels
- This is a function of carbon content, which is .4% in all steels
- But plain carbon steel has the least hardenability
- It hardens only to a shallow depth while other alloys harden to a greater depth

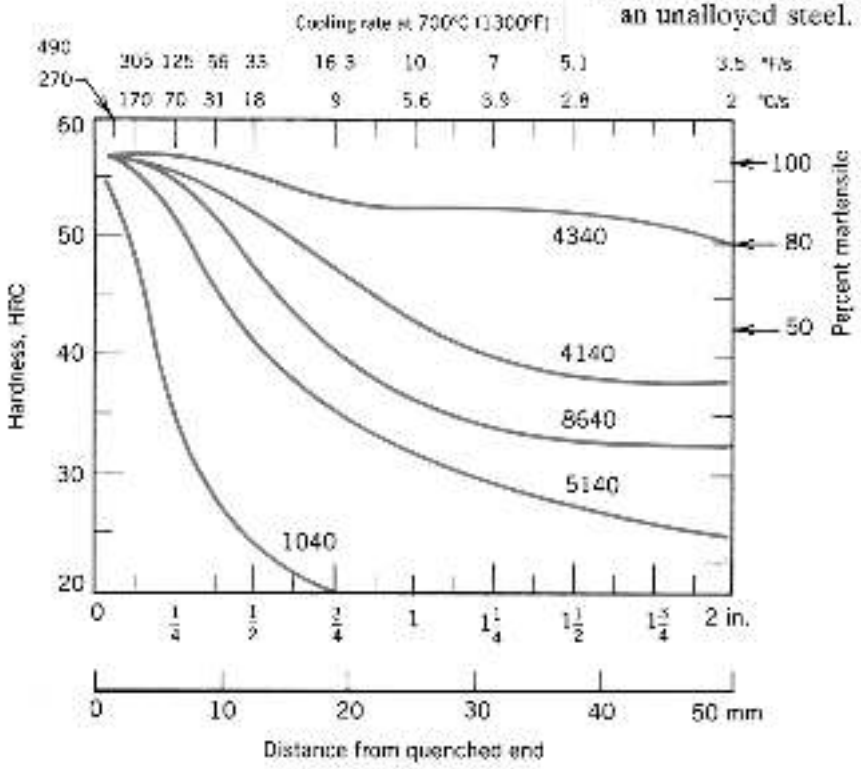
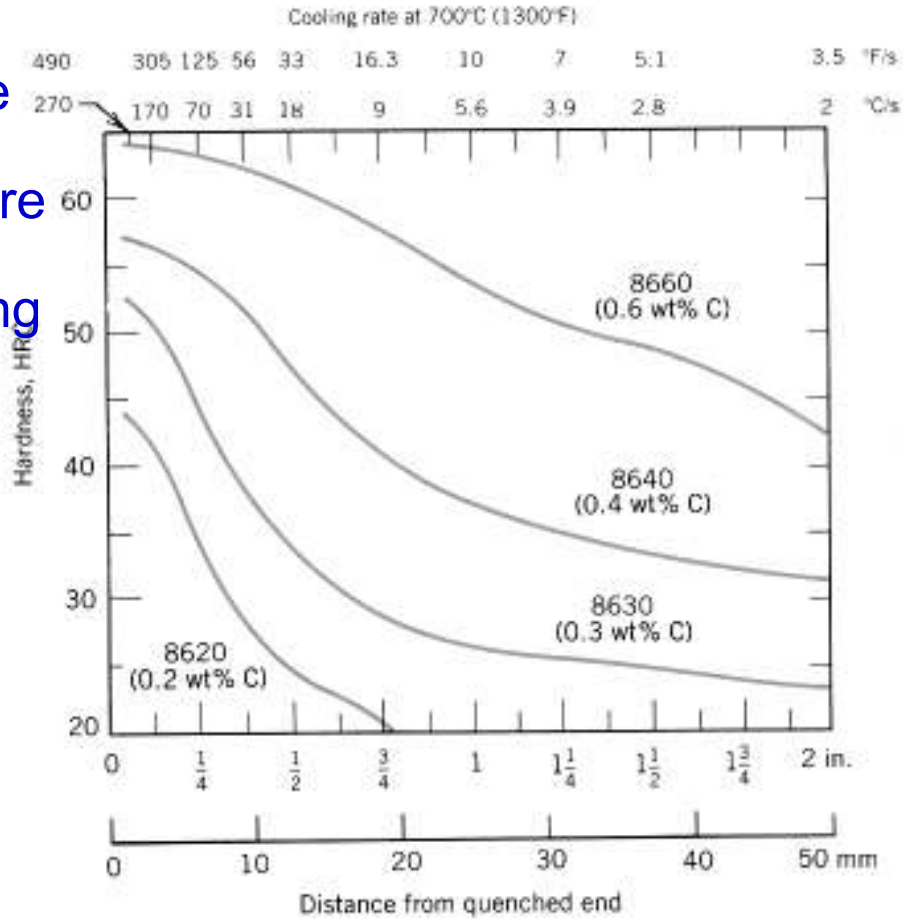


FIGURE 11.5
Hardenability curves for five different steel alloys, each containing 0.4 wt% C. Approximate alloy compositions (wt%) are as follows: 4340–1.85 Ni, 0.80 Cr, and 0.25 Mo; 4140–1.0 Cr and 0.20 Mo; 8640–0.55 Ni, 0.50 Cr, and 0.20 Mo; 5140–0.85 Cr; 1040 is an unalloyed steel.

Hardenability Curves

- At quenched end cooling rate is 600°c/s, so 100% martensite for all alloys
- After 6mm for 1040 steel it is pearlite and for other alloys here it is a mixture of martensite & bianite with increasing bianite as cooling rate reduces
- Alloying elements delay pearlite formation
- Hardenability also depends on the carbon content

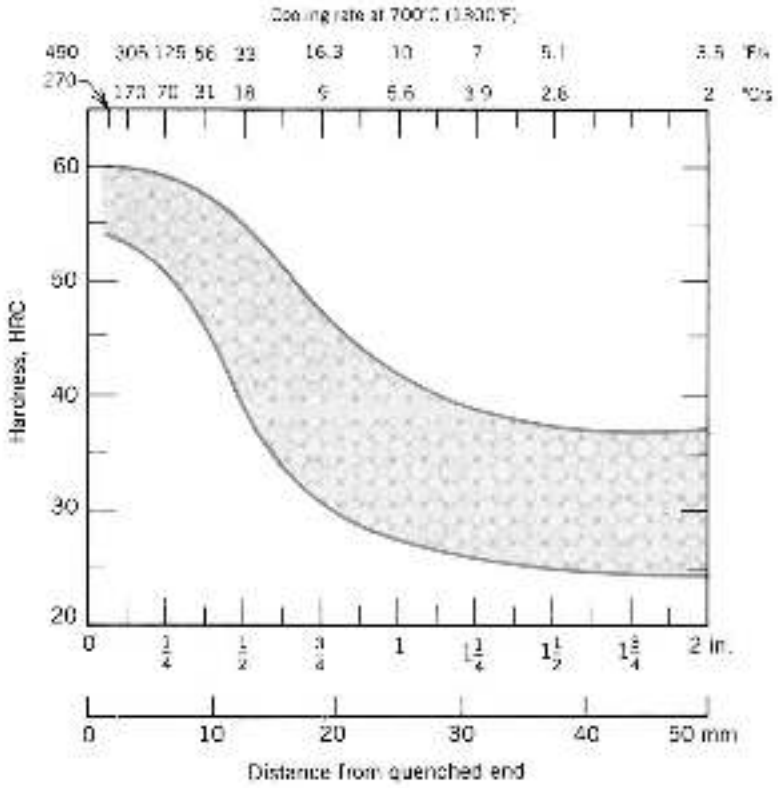
FIGURE 11.6
Hardenability curves for four 8600 series alloys of indicated carbon content.



Hardenability Curves

- In industrial production, there may be slight variations in the composition and grain size between batches
- So hardenability is given as a band instead

FIGURE 11.7 The hardenability band for an 8640 steel indicating maximum and minimum limits.



Quenchant, Specimen size/shape

- "Severity" of quench - indicates rate of cooling.
- Increasing severity of quench:
  - air (mild)
  - oil (often used for alloys steels)
  - water (severe - can cause cracking in higher carbon steels)
- Degree of agitation
  - more agitated bath will increase heat removal.
- Geometry of specimen
  - bigger specimens - more variation in cooling rate through thickness.
  - As cooling is through specimen surface, ratio of *surface area to mass* affects cooling rate. Thus irregular/acircular shapes harden better than cubes/spheres.

Effect of Quenchant

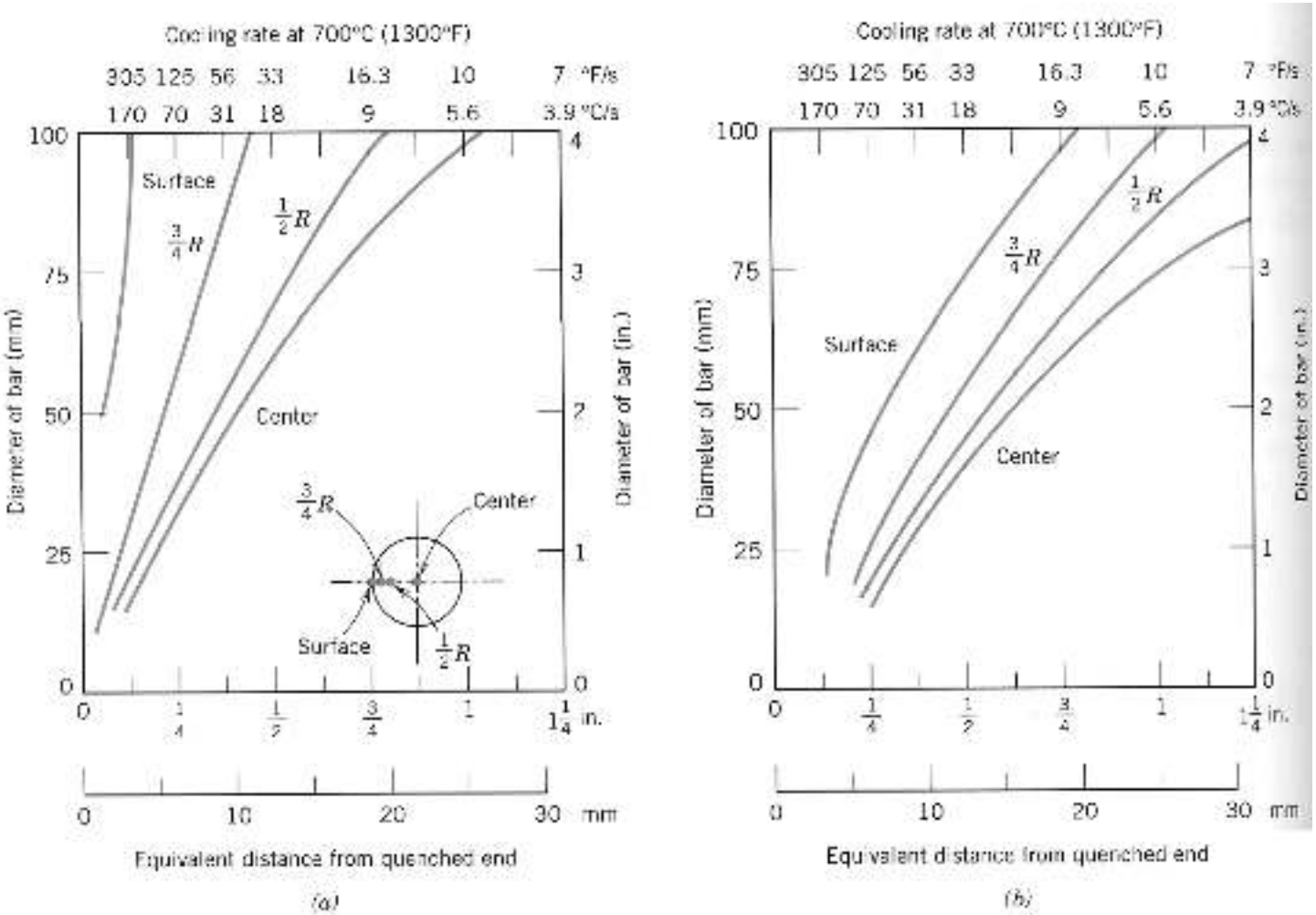
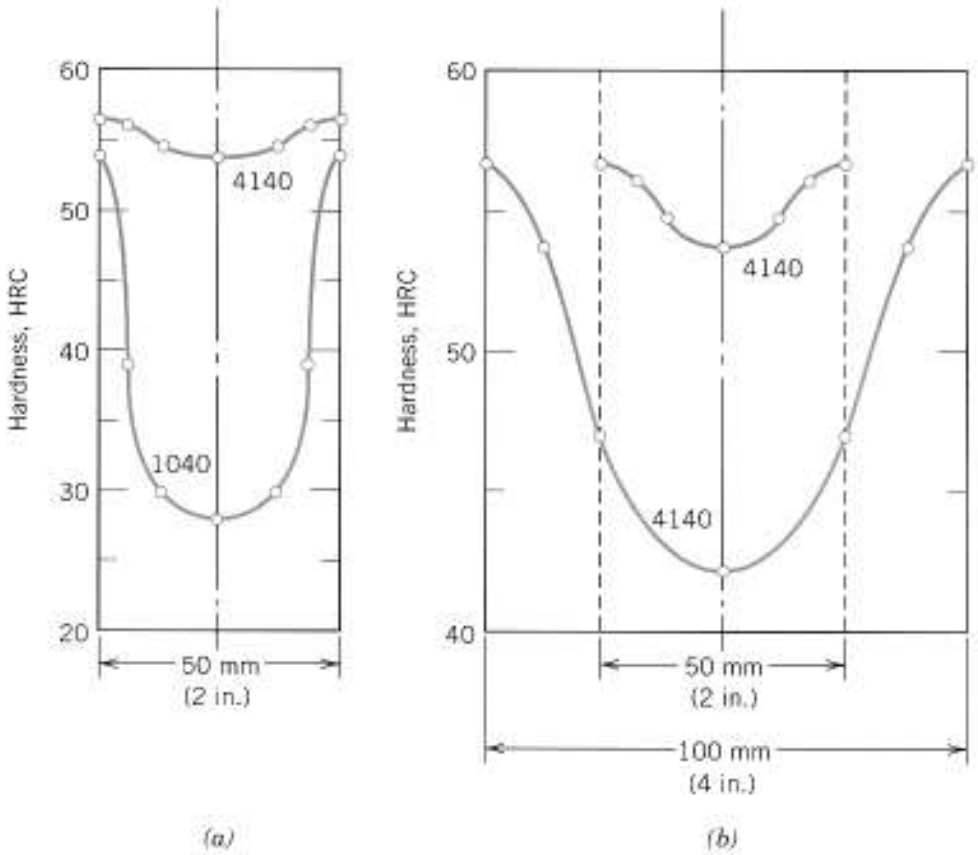


FIGURE 11.8 Cooling rate as a function of diameter at surface, three-quarters radius ($\frac{3}{4}R$), midradius ($\frac{1}{2}R$), and center positions for cylindrical bars quenched in mildly agitated (*a*) water and (*b*) oil. Equivalent Jominy positions are included along the bottom axis.

Effect of Quenchant

- Useful in determining the cooling rates inside in the surface
- Are done for shapes other than cylinders as well

FIGURE 11.9 Radial hardness profiles for (*a*) 50 mm (2 in.) diameter cylindrical 1040 and 4140 steel specimens quenched in mildly agitated water, and (*b*) 50 and 100 mm (2 and 4 in.) diameter cylindrical specimens of 4140 steel quenched in mildly agitated water.



Example Problem

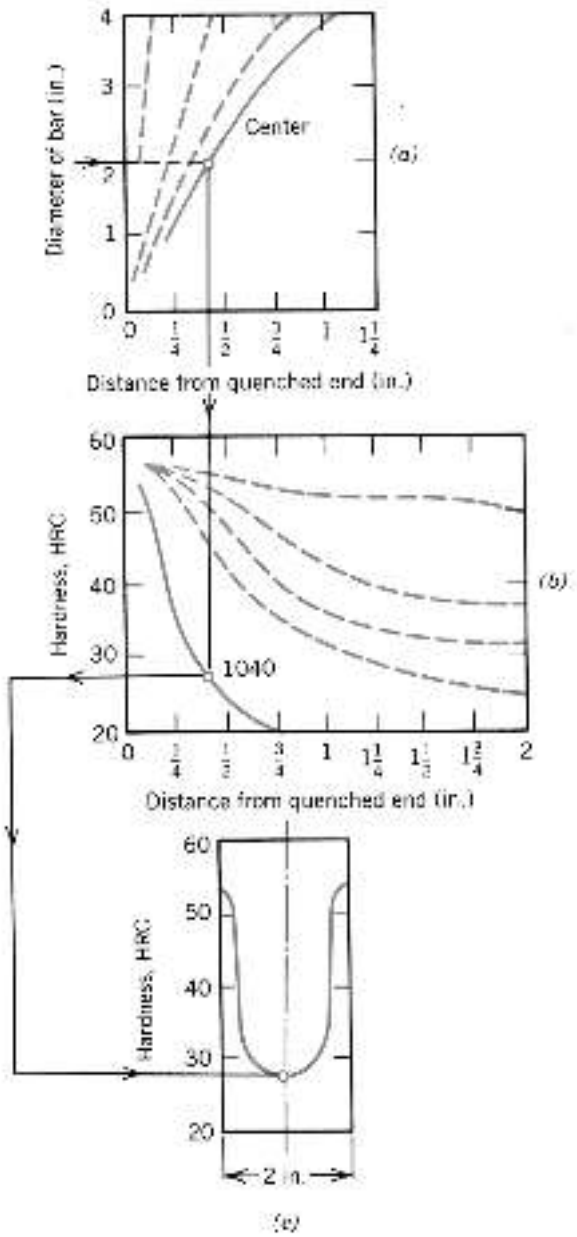


Figure 11.10 Use of hardenability data in the generation of hardness profiles. (*a*) The cooling rate at the center of a water-quenched 50 mm (2 in.) diameter specimen is determined. (*b*) The cooling rate is converted into an HRC hardness for 1040 steel. (*c*) The Rockwell hardness is plotted on the radial hardness profile.

- Determine radial hardness of 50mm dia cylinder of 1040 steel quenched in mildly agitated water

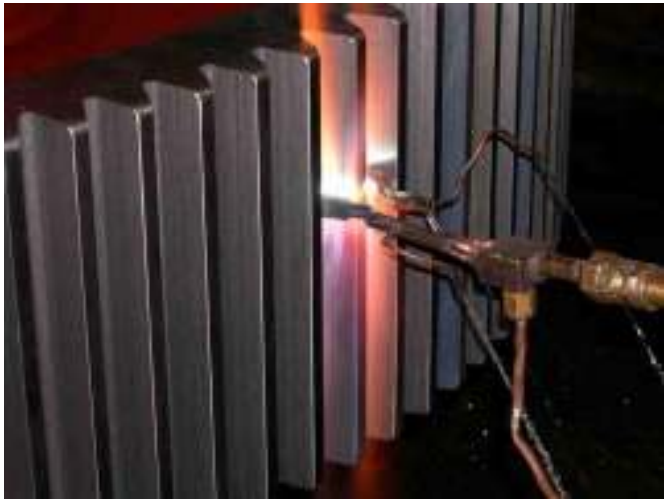
1. Determine the cooling rate of 50mm dia 1040 steel in mildly agitated water
2. Convert cooling rates at different radial positions into hardness values
3. Plot graph

Surface Hardening of Steel

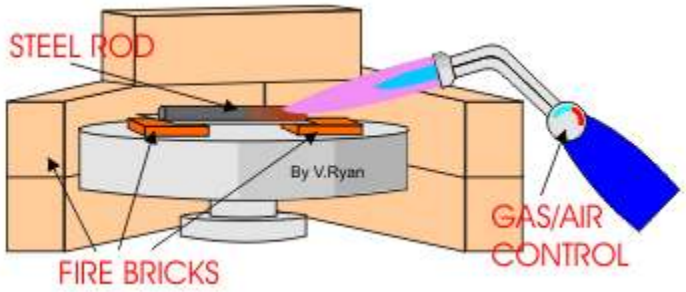
- Products require different properties at different locations. Hard, wear-resistant surface coupled with a tough, fracture-resistant core. This can be achieved by surface hardening methods classified into 3 groups
  - selective heating of the surface,
  - altered surface chemistry,
  - deposition of an additional surface layer.
- **Selective Heating Techniques** - if a steel has sufficient carbon, generally greater than 0.3%, different properties obtained by varying thermal histories of the various regions. Maximum hardness depends on the carbon content of the material, while the depth of that hardness depends on the depth of heating and the material's hardenability.

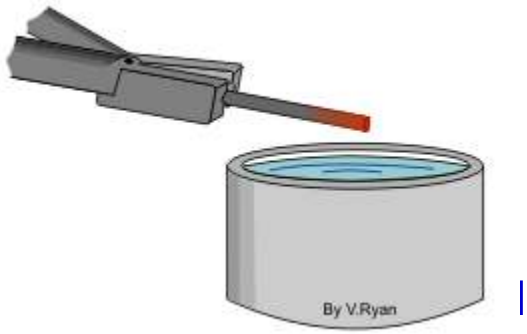
Selective Heating Techniques

- **Flame hardening :-** high-intensity oxyacetylene flame raises surface temperature - reforms austenite - then water quenched and tempered.
- Heat input is rapid and concentrated on surface.



- Slow heat transfer and short heating times leave the interior at low temperature (free from any significant change).
- Considerable flexibilitv - rate and depth of he
- om thin skins on
- ds limited by
- and-held torc
- computerized units.





Selective Heating Techniques

- **Induction hardening :-** steel part is placed inside a conductor coil
  - alternating current forms changing magnetic field which induces surface currents in the steel, which heat by electrical resistance . Extremely rapid and efficiency is high.
- Well suited to surface hardening - rate and depth of heating controlled directly by amperage and frequency.
- Ideal for round bars and cylindrical parts but also adapted to complex shapes. High quality, good reproducibility, possibility of automation.

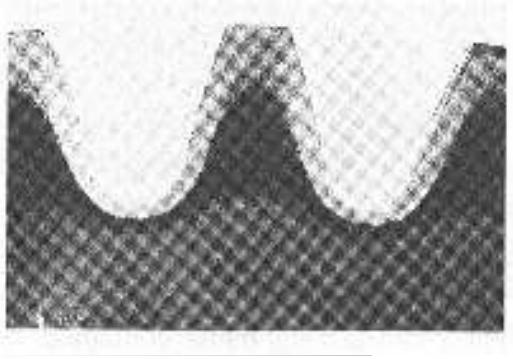


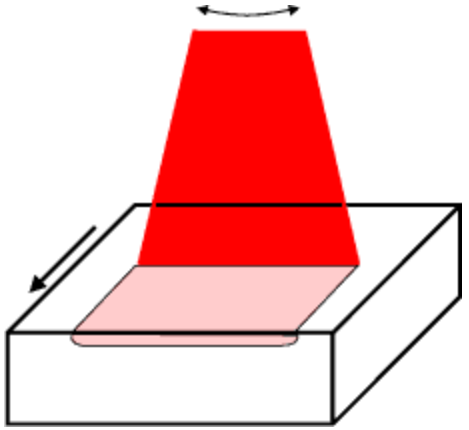
FIGURE 5.21 Section of gear teeth showing induction-hardened surfaces. *(Courtesy of TOCCO Division, Park-Ohio Industries, Inc.)*

Selective Heating Techniques

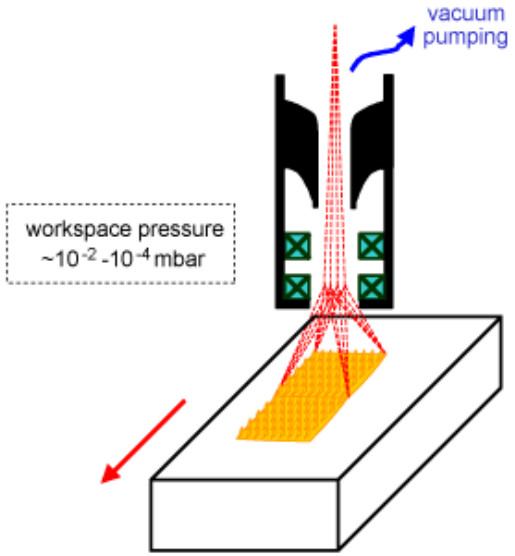
- **Laser-beam hardening :-** used to produce hardened surfaces on variety of geometries
- An absorptive coating - Z or Manganese phosphate is often applied to the steel to improve the efficiency of converting light energy into heat
- Surface is scanned with the laser, where beam size, beam intensity, and scanning speed (often as high as 100 in./min) are selected to obtain the desired amount of heat input and depth of heating
- Heat can be effectively removed through transfer into the cool, underlying metal, but a water or oil quench is often used.
- 0.4% C steel can attain surface hardnesses as high as Rockwell C 65.
- High speeds, produces little distortion, induces residual compressive stresses on the surface. Automation possible and mirrors and optics can shape and manipulate the beam.

Selective Heating Techniques

- **Electron-beam hardening:-** Heat source is a beam of high-energy electrons focused and directed by electromagnetic controls. Automated possible.
- Electrons cannot travel in air, however, so the entire operation must be performed in a hard vacuum, and this provides the major limitation.



- Still other selective heating techniques employ immersion in a lead pot or salt bath as the means heating the surface.

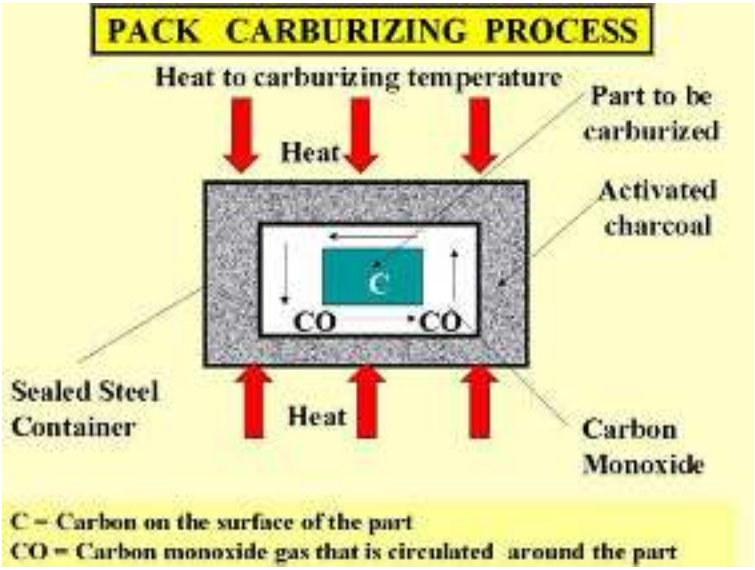


Altering Surface Chemistry

- For steels with insufficient carbon for selective heating, can alter surface chemistry.
- **Carburizing:-** most common technique - addition of carbon by diffusion from a high-carbon source. Then Heat Treated
- Pack carburizing process: components are packed in a high-carbon solid medium (carbon powder or cast iron turnings) and heated for 6 to 72 hours at roughly 900°C. Hot carburizing compound produces CO gas, - reacts with the metal, releasing carbon, which is readily absorbed by the hot austenite.
- When sufficient carbon has diffused to the desired depth, parts are thermally processed.

Altering Surface Chemistry

- When sufficient carbon has diffused to the desired depth, parts are thermally processed.
- Direct quenching can produce different surface and core properties due to different carbon contents at these locations and the different cooling rates. A slow cool from carburizing, reaustenitizing, and quench are also common.



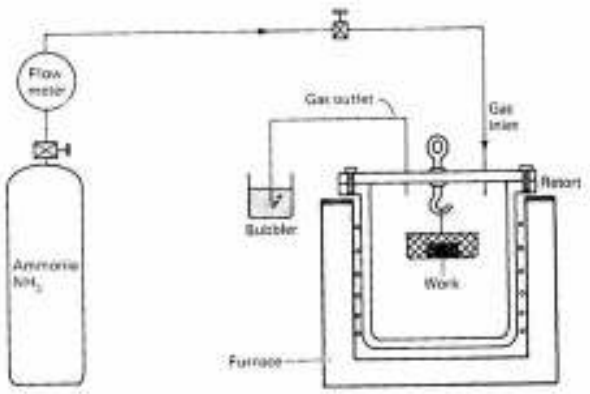
- The carbon content of the surface usually varies from 0.7 to 1.2% . Case depth may range from a few microns, to a max of approx. 5 mm.
- Problems: heating is inefficient, temperature uniformity is questionable, handling is often difficult, and not readily adaptable to continuous operation.

Altering Surface Chemistry

- Gas carburizing: overcomes many of these. Replace solid carburizing compound with a carbon-containing gas. Mechanisms and processing are the same, - operation is faster and more easily controlled. Accuracy and uniformity are increased, and continuous operation is possible.
- Special types of furnaces are required to safely contain the CO-containing gas.
- Liquid carburizing: steel parts immersed in a molten carbon-containing bath. Originally - cyanide, (supplies carbon & nitrogen) Safety/environmental concerns limited use, but noncyanide liquid compounds have been developed. Most applications involve the production of thin cases on small parts.

Altering Surface Chemistry

- **Nitriding:** hardens surface by producing alloy nitrides in special steels (contain nitride-forming elements such as aluminum, chromium, molybdenum, or vanadium).



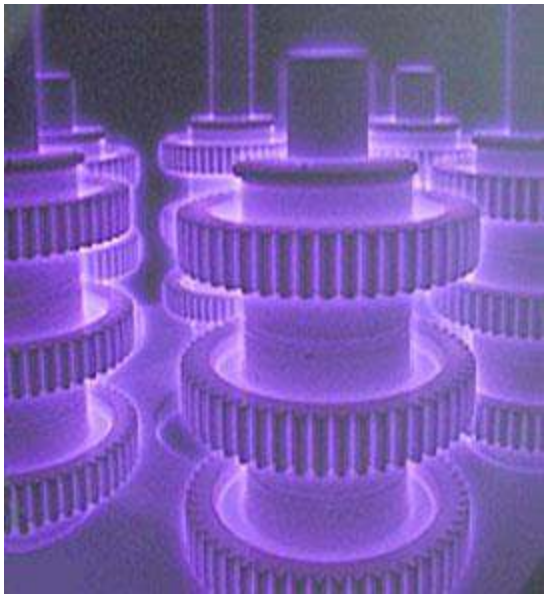
- Parts heat-treated and tempered at 525 to 675°C prior to nitriding. Heated in dissociated ammonia (nitrogen and hydrogen) for 10 to 40 hours at 500 to 625°C.
- Nitrogen diffusing into the steel then forms alloy nitrides, hardening the metal to a depth of about 0.025 in. - 0.65 mm.
- Very hard cases are formed and distortion is low. No subsequent thermal processing is required (subsequent heating should be avoided because the differential thermal expansions/contractions will crack the hard, nitrided case).

Altering Surface Chemistry

- Finish grinding should also be avoided, if possible, because of the exceptionally thin nitrided layer. Thus, while the surface hardness is higher than for most other hardening methods, the long times at elevated temperatures, coupled with the exceptionally thin case, restrict the application to the production of high-quality surfaces.
- Ion nitriding: plasma process - attractive alternative to conventional methods. Parts are placed in an evacuated chamber and 500 to 1000V DC potential is applied between the parts and the chamber walls.
- Low-pressure nitrogen gas is ionized.

Altering Surface Chemistry

- The ions are accelerated towards product surface, where they impact and generate sufficient heat to promote inward diffusion. This is the only heat associated with the process.
- Advantages: shorter cycle times, reduced consumption of gases, significantly reduced energy costs, reduced space requirements and the possibility of total automation.
- Product quality is improved over that of conventional nitriding and is applicable to a wider materials range.
- Ion carburizing: a low-pressure methane plasma is created, producing atomic carbon which is transferred to the surface.



Precipitation Hardening

- Strength and hardness of some metals increase by forming small, well dispersed particles of other phases. The process is done by phase transformations induced through heat treatments
- In some alloys can get small, uniform particles to precipitate out of (solid) solution. Hence name “precipitation hardening”, also known as "AGE" - hardening. Examples include:
- Al-Cu, Cu-Be, Cu-S, Mg-Al, Some alloy and stainless steels
- The principle of this hardening is different from heat-treatment.

Precipitation Hardening

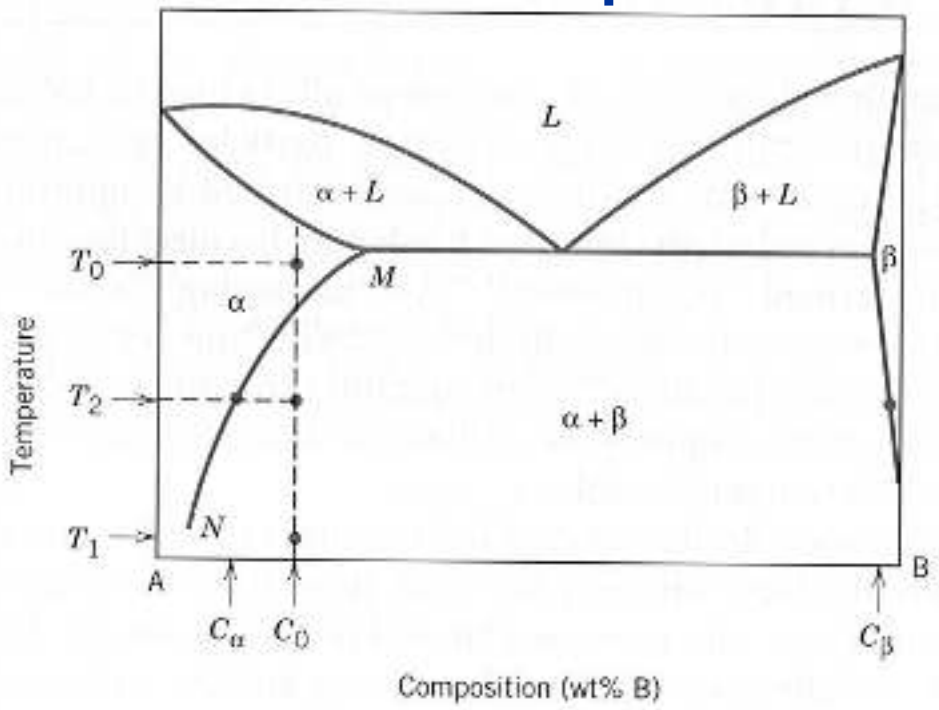


FIGURE 11.11 Hypothetical phase diagram for a precipitation hardenable alloy of composition C_0.

Prerequisite for ppt. hardening

M = Max. solubility of metal B in metal A.

Solid solubility decreases to **N** as T↓

Solution heat treating & Precipitation Heat Treat'

Procedure: Overall composition C_0 .

- Heat to T_0 ; Hold until only α - phase present.
- Quench (rapid cooling) to T_1 ; because rapid, no diffusion occurs - SSSS - Super-saturated solid solution of α formed. β atoms "trapped" in α. Not thermodynamically stable.
- Heat back up to T_2 ; diffusion can occur, small precipitates of β-phase form.

Precipitation Hardening

If heated only upto T_2, Second β-phase precipitates out as very small particles - provide strengthening effect.

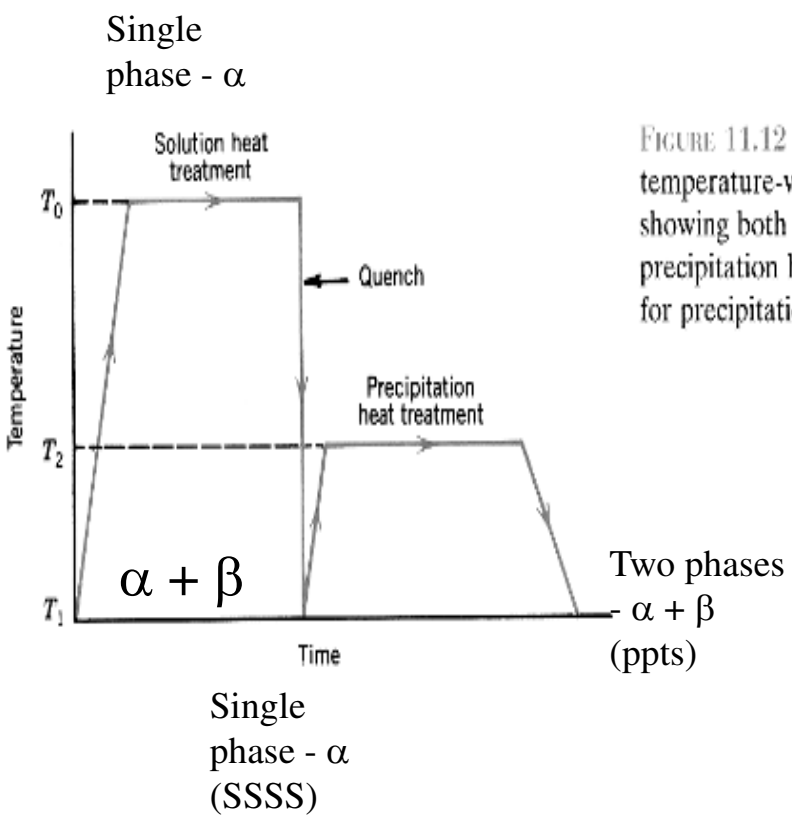
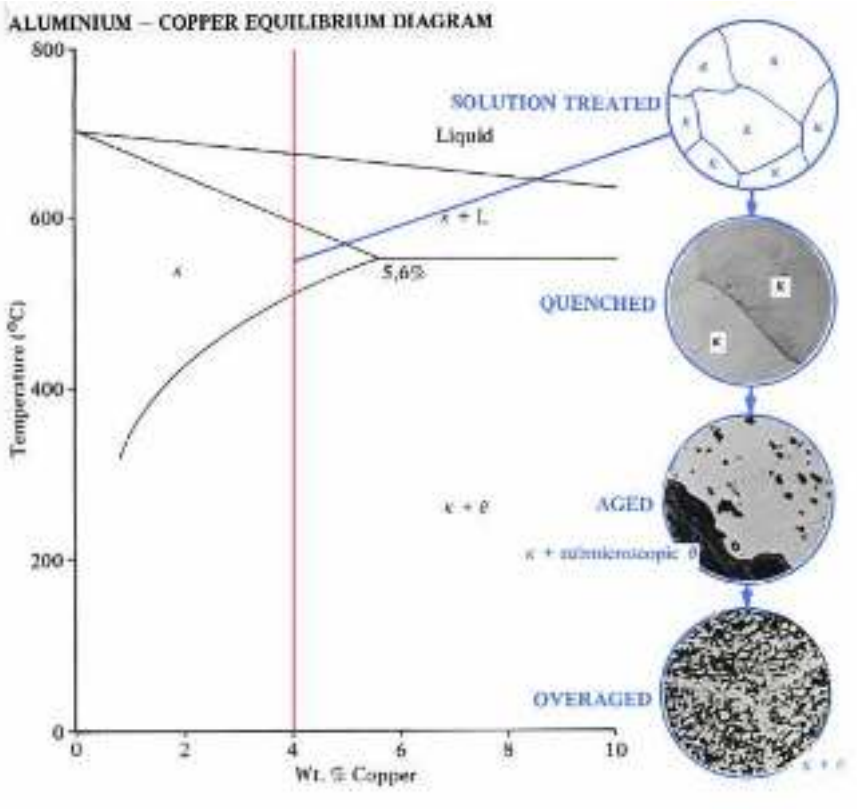


FIGURE 11.12 Schematic temperature-versus-time plot showing both solution and precipitation heat treatments for precipitation hardening.



Precipitation Hardening

Max. strength/hardness

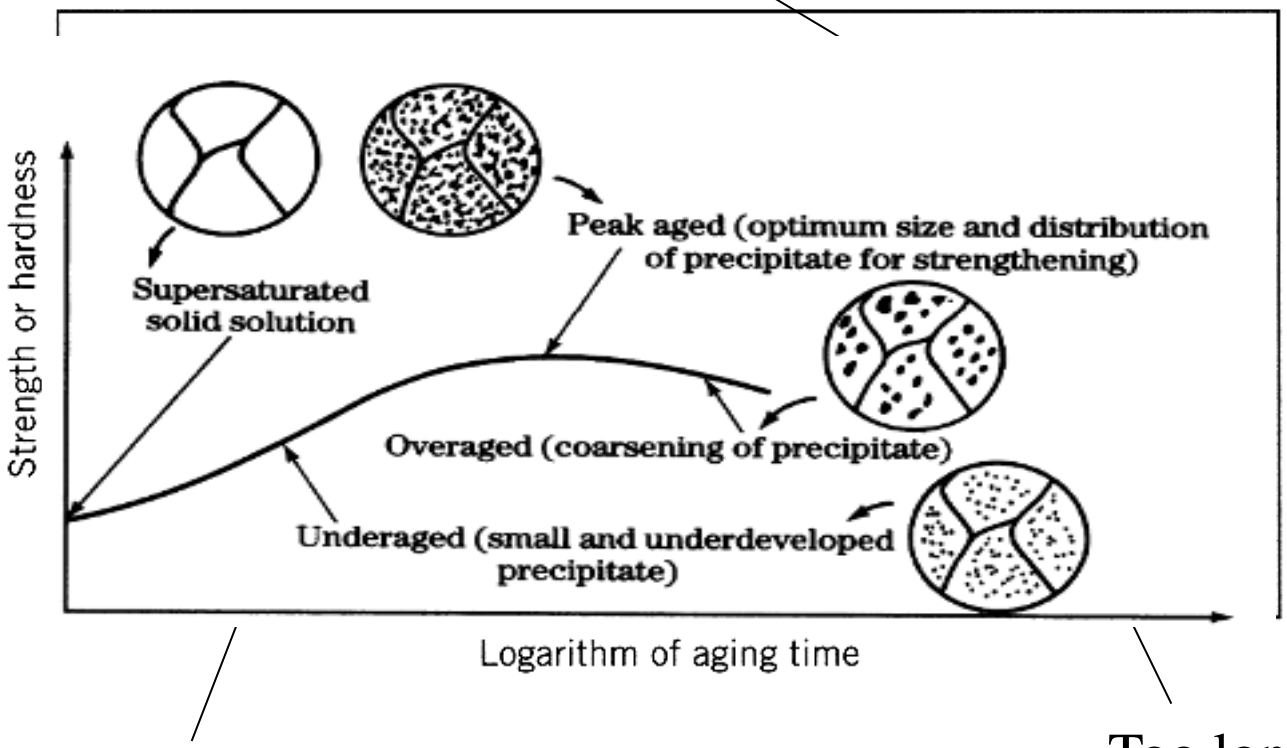


FIGURE 11.13 Schematic diagram showing strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.

Formation & growth of ppts.

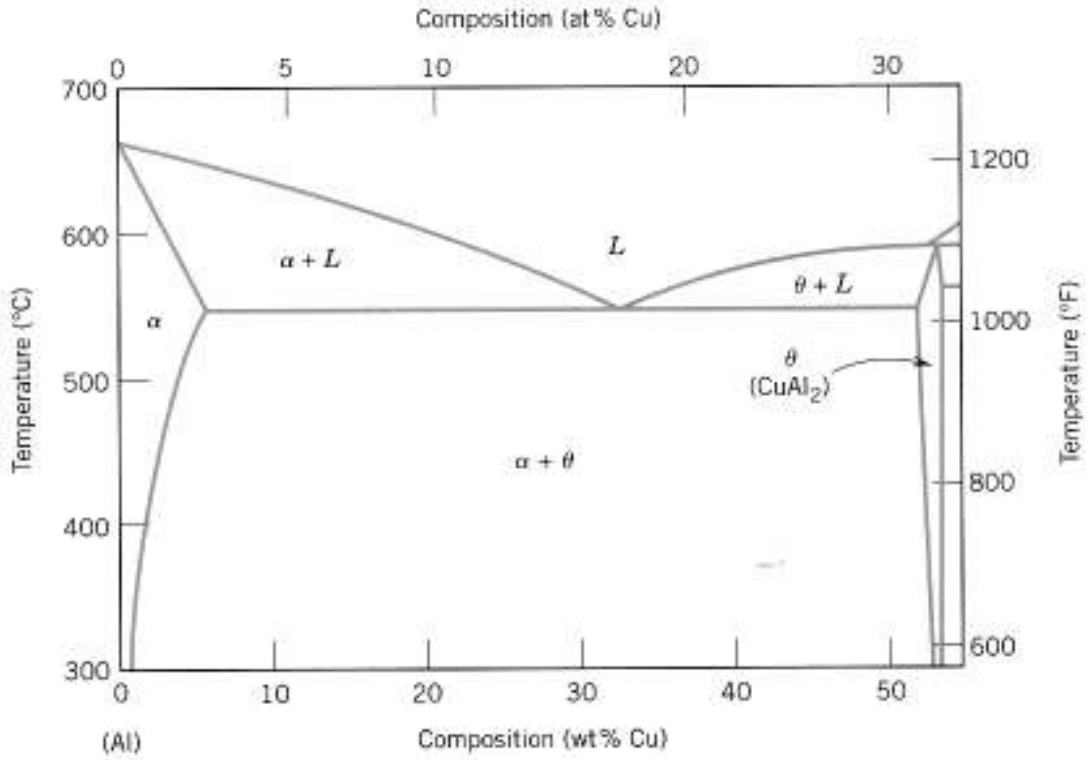
These are very small (5×10^{-9}m) initially but grow with time.

Too long at temperature and ppts get too large and softening occurs.

Precipitation Hardening

Precipitation hardening is commonly used in Aluminium alloys such as the Al-Cu system:

Al + 4%Cu



$\alpha + \theta \rightarrow$ Heat (~550°C) $\rightarrow$ Quench (0°C) $\rightarrow \alpha$ (ssss) $\rightarrow$ Heat/age (~150°C) $\alpha + \theta_{ppt}$

Precipitation Hardening

Single phase - α (SSSS)

$\alpha + \theta''_{ppt}$

$\alpha + \theta_{ppt}$

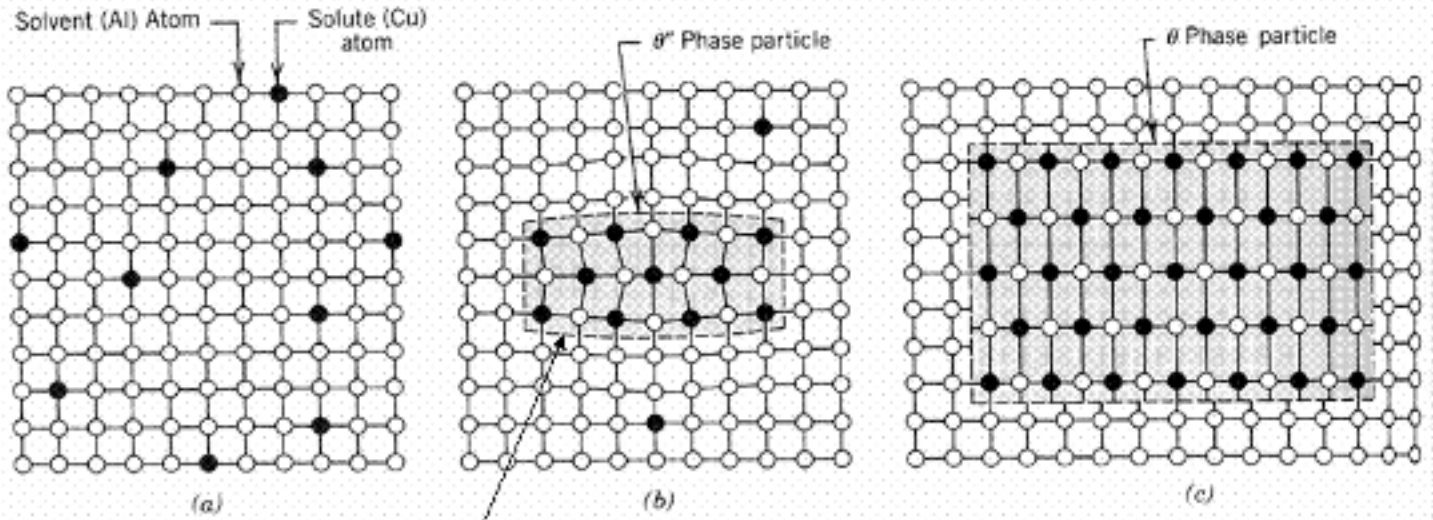


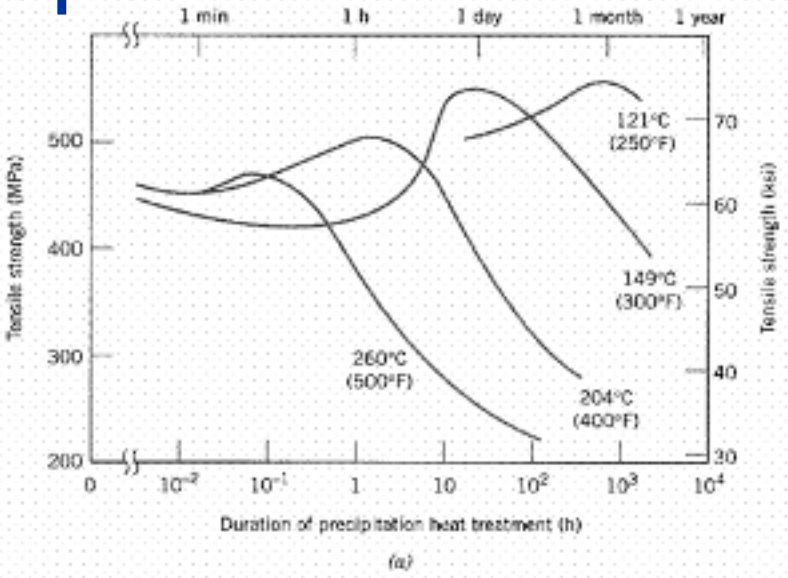
FIGURE 11.15 Schematic depiction of several stages in the formation of the equilibrium precipitate (θ) phase. (*a*) A supersaturated α solid solution. (*b*) A transition, θ'', precipitate phase. (*c*) The equilibrium θ phase, within the α matrix phase. Actual phase particle sizes are much larger than shown here.

Lattices are trying to match up with each other (stay coherent) - large lattice strain - high resistance to dislⁿ movement

Can no longer match up with each other (incoherent) - less resistance to dislⁿ movement

Precipitation Hardening

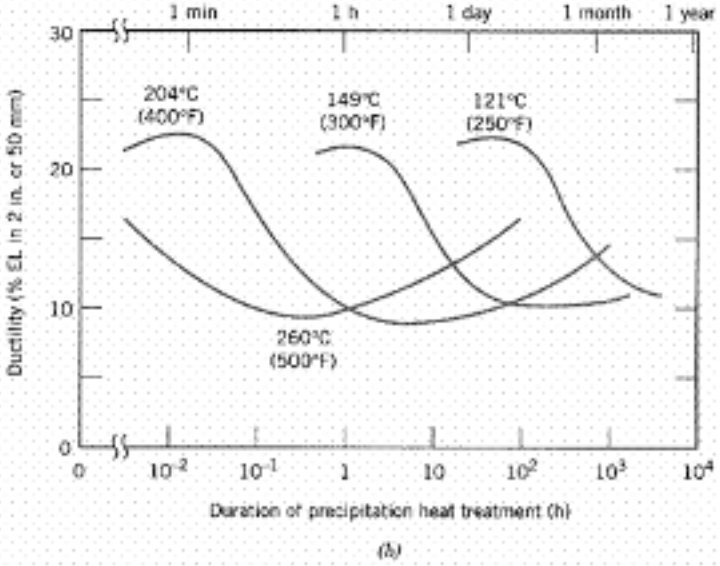
FIGURE 11.16 The precipitation hardening characteristics of a 2014 aluminum alloy (0.9 wt% Si, 4.4 wt% Cu, 0.8 wt% Mn, 0.5 wt% Mg) at four different aging temperatures: (*a*) tensile strength, and (*b*) ductility (%EL).



"Artificial ageing" - heat supplied by furnace.

Higher strength achieved at lower ageing temperatures but for longer times

"Natural ageing" - aged at ambient temperature. (so will start ageing at RT unless stored at low temperature - freezer! E.g. some Al-alloy rivets



If cold-working is to be done - carried out after quenching and before ageing

Precipitation Hardening

- How an age hardening rivet could be inserted into the wing of an aeroplane during assembly?
- The rivet would be made from an appropriate aluminium-copper alloy. The rivet would be kept refrigerated, to slow down the age hardening effect.
- Once a correct size hole has been drilled through the skin and the frame of the wing, the rivet would be set in place using a suitable riveting gun.
-
- It would easily go in “soft” and once left there, over time, it would harden and therefore increase in strength, thus holding the two parts firmly together.

Why Join Materials?

- Transfer load/stress.
- Assembly of small pieces to make larger, more complex component
- Different materials/different properties.
  - electrical
  - thermal
  - mechanical (e.g. wear)
  - optical
  - chemical (e.g. corrosion resistance)
- Economics:
  - low cost material for bulk of component with high cost insert etc.

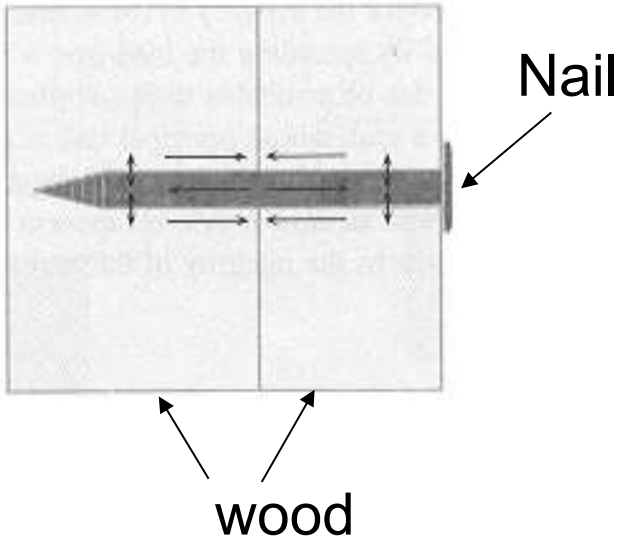
Types of Joining Processes?

- Three basic options for assembly/joining mechanical, chemical or physical.:
- Mechanical - (rely on residual stresses produced in joint):
  - nails
  - rivets
  - bolts
  - seams
- Chemical - reactions
  - adhesions
  - glues
- Physical - phase change/diffusion (liquid - solid)
  - welding, soldering, brazing

Types of Joining Processes?

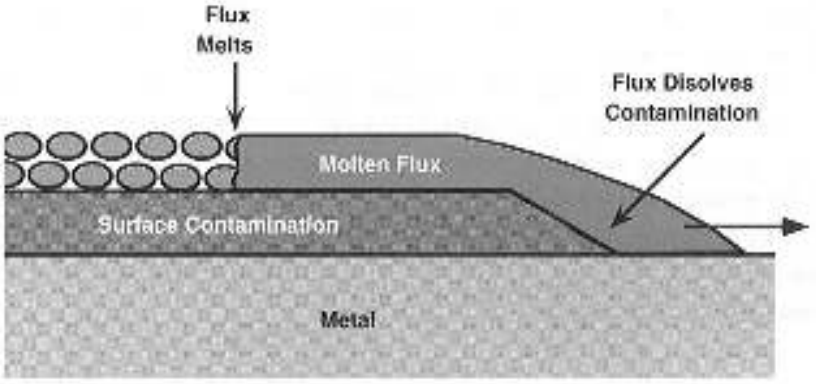
1. Nailing two pieces of wood together relies on the mechanical frictional forces between the wood and the nail to keep the two pieces of wood in contact at the point of attachment. The pieces are held in place by a balance of mechanical forces, tensile in nail and compressive in wood.

2. A flour and water paste will stick sheets of paper together because the wet flour (starch) swells and penetrates the cellulose fibres of the paper, to form a stiff joint when the excess water evaporates. Hydration of the starch (a chemical reaction) combines with mechanical interlocking of the hardened starch with the cellulose fibres to ensure the mechanical integrity of the bond.

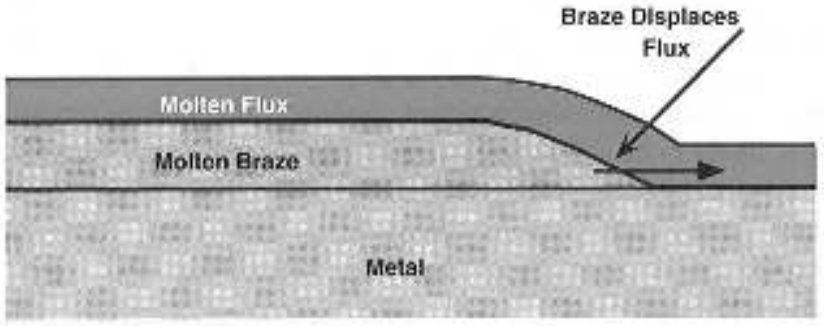


Types of Joining Processes?

3. An electrical copper contact can be soldered because the flux in the flux-cored solder dissolves the protective oxide film on the copper, allowing molten solder to wet the copper. The solder provides a strong joint because of the strength of the metallic bond which is formed between the (clean) copper substrate and the solder alloy. The wetting of the copper and the spreading of the solder are physical processes.



(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.

Joining Processes

- **Requirements Of Joint**
- Mechanical Requirements: strength, toughness, stiffness, creep, fatigue.
- Chemical Requirements: effects of environment (corrosion), UV Radiation, oxidation (crevice corrosion)
- Physical Requirements: sealing (gas/liquid), thermal/electrical/optical
- **Joining Problems**
- Controlling process (window)
- Poor bonding/holes/defects
- Change in properties (HAZ) microstructure
- Stress concentrations; Residual stresses
- For dissimilar materials: Elastic modulus mismatch, Coefficient of thermal expansion mismatch, Chemical reactivity/corrosion

Mechanical Requirements

- Strength, toughness and stiffness (usually specified in terms of the mechanical properties: the uniaxial yield strength, fracture toughness and the elastic moduli (tensile modulus, shear modulus and Poisson's ratio).
- However, any joint is a region of heterogeneity over which the material properties generally change dramatically, and sometimes discontinuously. Properties of the assembly cannot be described in terms of any average of the bulk.
- Variables such as:
  - Joint geometry (relation to testing axis)
  - Welding cycle (heat affected zone size)
  - Filler metal composition

Chemical Requirements

- Effects of chemical attack by the environment, and degradation associated with irradiation.
- UV radiation is a common cause of embrittlement and cracking in commercial plastics.
- High energy neutrons give rise to displacement damage in nuclear reactor pressure-vessel steels which raises their yield stress and reduces ductility.
- Corrosion and oxidation are increased by the chemical heterogeneities associated with the joining process.
- Variations of chemical potential across the joint acts as driving force for corrosion. (Insufficiently stabilized stainless steel susceptible to 'weld decay').
- Riveted steel plates are frequently subject to crevice corrosion associated with the accumulation of H^+ ions in a reentrant crevice at the joint.

Physical Requirements

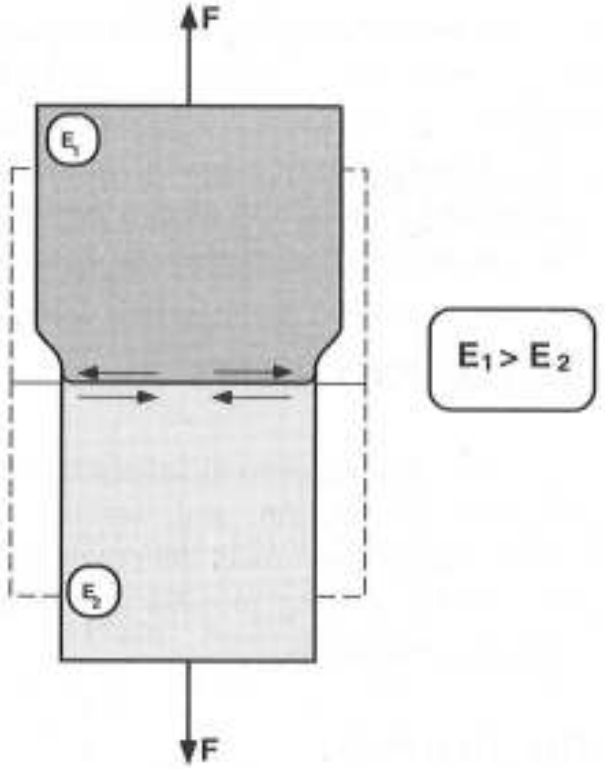
- Form a seal from the surroundings, and thus prevent access or egress of gas or fluid.
- Provide thermal or electrical conduction/insulation across joint.
- Optical requirements.

Joining Dissimilar Materials

- Important to distinguish joints made between similar materials (metals, ceramics, composites or plastics) and joints between dissimilar materials (steel bonded to copper, metal bonded to rubber or ceramic, or a metallic contact to a semiconductor).
- In the case of dissimilar (unlike) materials, the engineering compatibility of the two components must be considered.
- Mismatch of the elastic modulus is a common form of mechanical incompatibility which leads to stress concentrations and stress discontinuities at the bonded interface between the two materials.

Joining Dissimilar Materials

- E.g. When a normal load is transferred across the interface between two materials with different elastic moduli, the stiffer (higher modulus) component restricts the lateral contraction of the more compliant (lower modulus) component, generating shear stresses at the interface which may lead to debonding.



- Thermal expansion mismatch is a common problem in metal/ceramic joints. Leads to the development of thermal stresses which tend to be localized at the joint and reduce its load-carrying capacity, ultimately leading to failure of the component. (On cooling from elevated temperature, metal shrinks more than ceramic causing stresses).

Joining Dissimilar Materials

- Poor chemical compatibility is commonly associated with undesirable chemical reactions in the neighborhood of the joint.
- These reactions may occur between the components, for example the formation of brittle, intermetallic compounds during the joining process, or they may involve a reaction with the environment, as in the formation of an electro-chemical corrosion couple due to a change in the electrochemical potential across the joint interface.

Joint Defects and Tolerances

- Problems of materials compatibility, (unlike materials)
- Chemical effects leading to microstructural changes, such as the precipitation of new phases during brazing or welding.
- The mechanical strength of the joint usually differs from that of the parent components, as does the joint's resistance to environmental attack.
- Most joining processes give rise to residual stresses in the assembled components, (may improve or degrade performance assembly).
- All processes should meet recognized standards for dimensional requirements (permitted tolerances), as well as for any deleterious processing defects (regions of incomplete bonding, porosity, inclusions or microcracking).

Common Joining Problems

- **Joining Similar Materials**
- Successful engineering processes have a working window for the process parameters, within which acceptable performance can be assured for the system. E.g. heating, cooling, pressure cycles, controlled atmosphere, dimensional accuracy.
- Outside this working window, undesirable consequences may include dimensional distortions, imperfectly bonded components, excessive residual stresses and severe contamination of the bonded region.
- Many problems associated with the joint in service can be traced to the various sources of heterogeneity. Changes in microstructure which occur in the heat affected zone (HAZ) that borders a weld, give rise to differences in chemical potential and corrosion susceptibility.

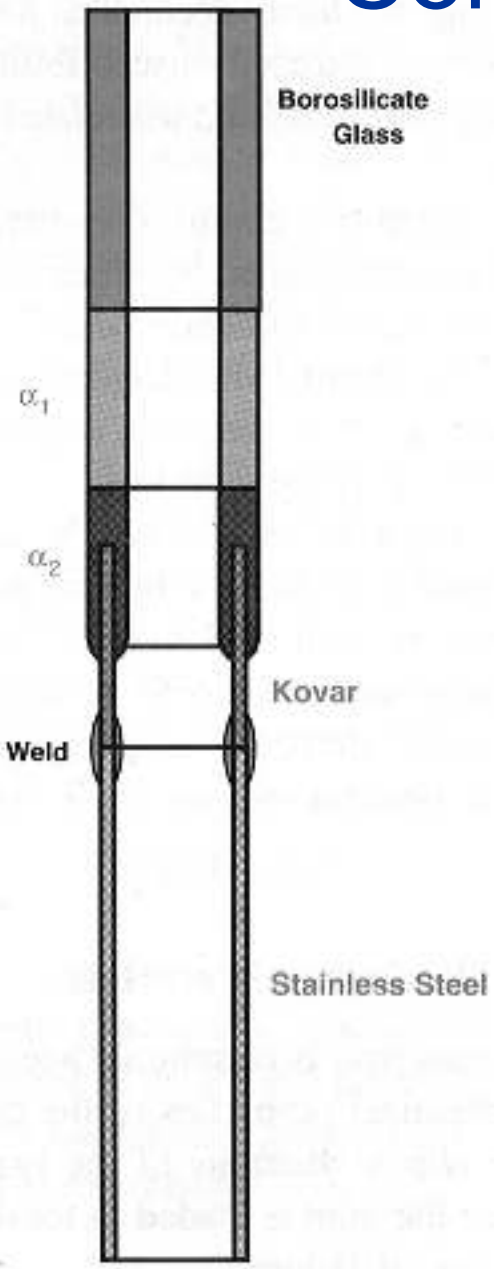
Common Joining Problems

- They also change the local mechanical properties: either a reduction in the yield strength, and hence increased susceptibility to dynamic (mechanical) fatigue, or an increase in the hardness, and associated susceptibility to brittle failure.
- Residual stresses (for example, thermal shrinkage stresses or the stresses associated with solvent evaporation from an adhesive joint) may overload the joint to the point of failure, even in the absence of an applied load.
- Dimensional mismatch may be accommodated by a filler whose performance in service depends on the constraints exerted by the assembled components.
- Most joints will be less than perfect, and will contain some defects in the form of inclusions, microcracks, pores and imperfectly bonded regions. The size, position and elastic compliance of these defects frequently affect the final performance of the assembled components.

Common Joining Problems

- **Joining Dissimilar Materials**
- A joint between dissimilar materials is commonly accompanied by mismatch in the mechanical, physical and chemical properties of the components which have been joined.
- A mismatch in the elastic modulus of the two materials will give rise to localized shear stresses when the joint is loaded in tension and may lead to mechanical failure.
- Chemical reactivity between the components may lead to undesirable interface reactions and the products of these reactions are often brittle. Reactions accompanied by a volume change generate local stresses. If chemical potentials are different electrochemical corrosion may occur.

Common Joining Problems

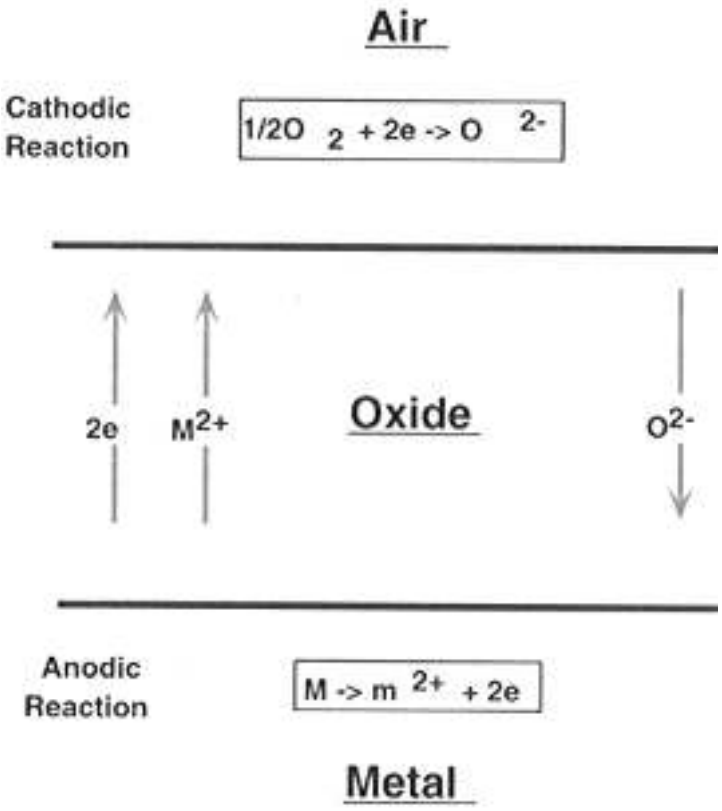


- Thermal expansion mismatch is a major concern in the bonding of brittle materials, especially those which are required to withstand thermal shock or thermal fatigue.
- Bonding which provides a transition region over which the expansion coefficient is monotonically changed in controlled steps and expansion coefficients are matched to minimize the elastic modulus mismatch at the interface give a complex, but successful, graded joint.

A graded glass seal between stainless steel and borosilicate glass makes use of a low thermal expansion coefficient alloy (Kovar) and intermediate glass compositions in order to 'grade' the residual thermal stresses.

Surfaces and contamination

- Free surface of a material is usually contaminated by environment (gaseous , liquid – water, air, lubricant, grease etc.)
- Atoms adsorbed onto the surface – even in high vacuum (10^{-6}) adsorption of one layer of atoms sticking per second is possible.



- Also chemical reactions can occur. Oxidation of metals. (Gold is only metal that does not oxidize.
- Some oxides adhere strongly and are protective (Al_2O_3) but others tend to crack and spall off (steel).

Surfaces and contamination

- For some joining processes (especially soldering and adhesive bonding) surface contamination can be a serious problem and surface preparation is then very important.
- Surface films can easily form on surfaces (grease - fingerprints!) and can prevent good joining.
- In some cases heating to the joining temperature can remove some surface contaminants, but can also cause more oxidation. Hence need for protective gases/atmospheres.
- **Surface Roughness**
- This can also cause problems as surfaces are never completely smooth. Also more contamination is trapped on a rough surface and the surfaces to be joined are not in good contact.

What is Welding?

- A process in which materials of the same fundamental type or class are brought together and caused to join (and become one) through the formation of primary (and, occasionally, secondary) chemical bonds under the combined action of heat and pressure.
- The American Heritage Dictionary: "To join (metals) by applying heat, sometimes with pressure and sometimes with an intermediate or filler metal having a high melting point."
- ISO standard R 857 (1958) "Welding is an operation in which continuity is obtained between parts for assembly, by various means,"
- Coat of arms of The Welding Institute (commonly known as TWI): "e duobus unum," which means "from two they become one."

Welding

1. Central point is that multiple entities are made one by establishing continuity. (continuity implies the absence of any physical disruption on an atomic scale, unlike the situation with mechanical fastening where a physical gap, no matter how tight the joint, always remains.

- Continuity does not imply homogeneity of chemical composition across the joint, but does imply continuation of like atomic structure.
- Homogenous weld:

1. Two parts of the same austenitic SS joined with same alloy as filler
2. Two pieces of Thermoplastic PVC are thermally bonded or welded

- Heterogeneous weld:

1. Two parts of gray CI joined with a bronze filler metal (brazing).
2. 2 unlike but compatible thermoplastics are joined by thermal bonding.

Welding

- When material across the joint is not identical in composition (i.e., Homogeneous), it must be essentially the same in atomic structure, (allowing the formation of chemical bonds):

1. Primary metallic bonds between similar or dissimilar metals,
2. Primary ionic or covalent or mixed ionic-covalent bonds between similar or dissimilar ceramics
3. Secondary hydrogen, van der waals, or other dipolar bonds between similar or dissimilar polymers.

- If materials are from different systems, welding (by the strictest definition) cannot occur. E.G. Joining of metals to ceramics or even thermoplastic to thermosetting polymers.
- There is a disruption of bonding type across the interface of these fundamentally different materials and a dissimilar adhesive alloy is required to bridge this fundamental incompatibility.

Welding

2. The second common and essential point among definitions is that welding applies not just to metals.

- It can apply equally well to certain polymers (e.g., thermoplastics), crystalline ceramics, inter-metallic compounds, and glasses.
- May not always be called welding –
- thermal bonding for thermoplastics
- fusion bonding or fusing for glasses
- but it is welding!

Welding

3. The third essential point is that welding is the result of the combined action of heat and pressure.

- Welds (as defined above) can be produced over a wide spectrum of combinations of heat and pressure:
- From: no pressure when heat is sufficient to cause melting,
- To: pressure is great enough to cause gross plastic deformation when no heat is added and welds are made cold.

4. The fourth essential point is that an intermediate or filler material of the same type, even if not same composition, as the base material(s) may or may not be required.

Welding

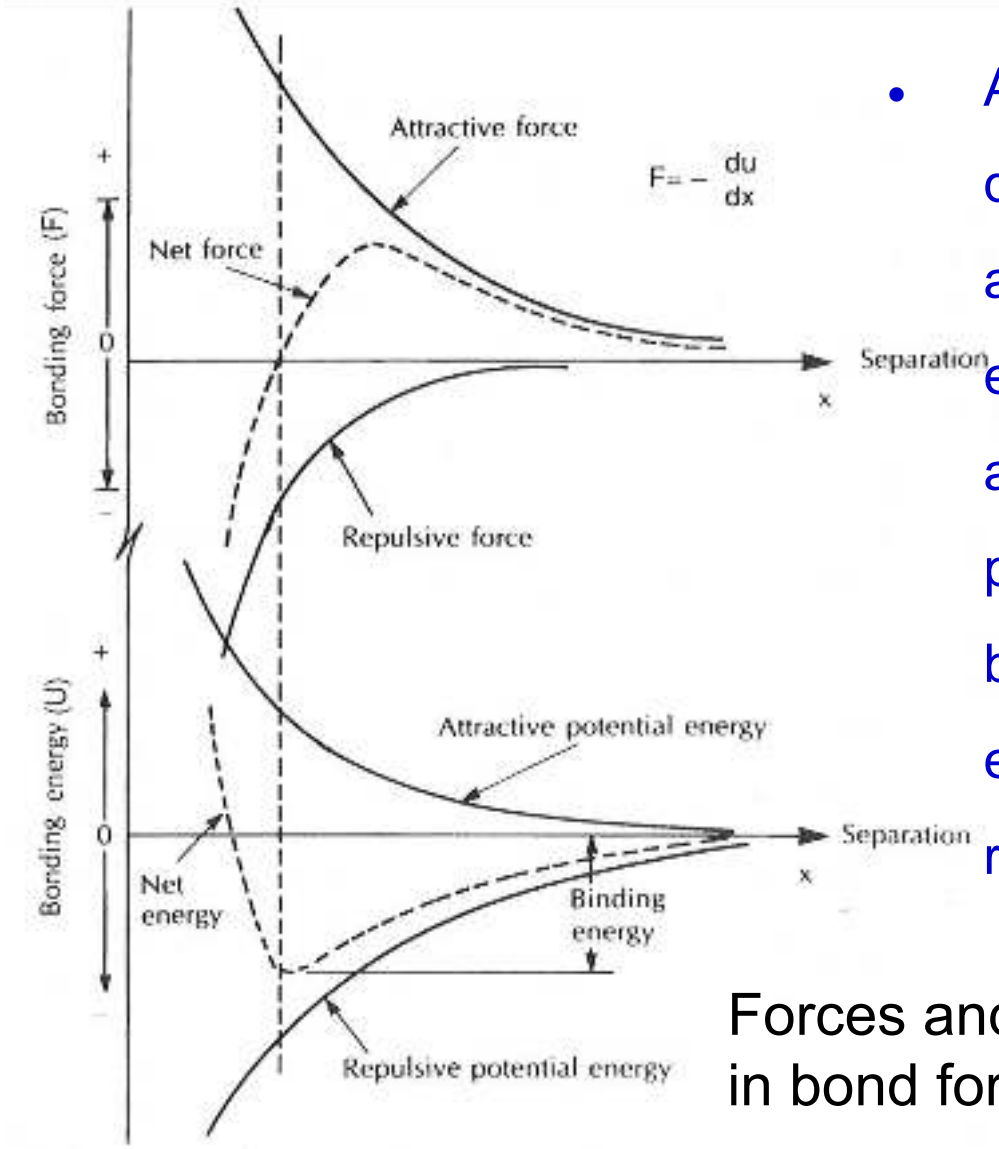
5. The fifth and final essential point is that welding is used to join parts, although it does so by joining materials.

- Creating a weld between two materials requires producing chemical bonds by using some combination of heat and pressure.
- How much heat and how much pressure affect joint quality but also depends on the nature of the actual parts or physical entities being joined: part shape, dimensions, joint properties. One must prevent intolerable levels of distortion, residual stresses, or disruption of chemical composition and microstructure.
- Welding is a secondary manufacturing process used to produce an assembly or structure from parts or structural elements.

Nature of Ideal Weld

- **Achieving Continuity**
- Understanding exactly what happens when two pieces of metal are brought into contact is crucial to understanding how welds are formed.
- When two or more atoms are separated by an infinite distance there is no force of attraction or repulsion between them.
- As they are brought together from this infinite separation a force of electrostatic or Coulombic attraction arises between the positively charged nuclei and negatively charged electron shells or clouds.
- This force of attraction increases with decreasing separation. The potential energy of the separated atoms also decreases as the atoms come together.

Nature of Ideal Weld



- As the distance of separation decreases to the order of a few atom diameters, the outermost electron shells of the approaching atoms begin to feel one another's presence, and a repulsion force between the negatively charged electron shells increases more rapidly than the attractive force.

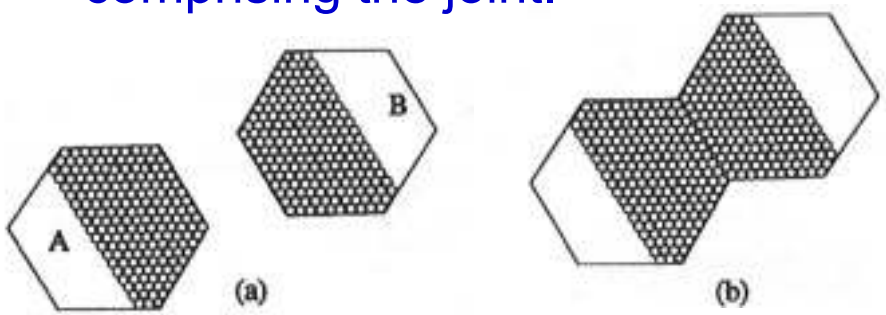
Forces and potential energies involved in bond formation between atoms.

Nature of Ideal Weld

- Attractive and repulsive forces combine and at some separation distance net force becomes zero.
- This separation is known as the equilibrium interatomic distance or equilibrium interatomic spacing.
- At this spacing, net energy is a minimum and the atoms are bonded.
- When all of the atoms in an aggregate are at their equilibrium spacing, each and everyone achieves a stable outer electron configuration by sharing or transferring electrons.
- The tendency for atoms to bond is the fundamental basis for welding.
- To produce a weld - bring atoms together to their equilibrium spacing in large numbers to produce aggregates. The result is creation of continuity between aggregates or crystals, - formation of ideal weld.
- In ideal weld there is no gap and the strength of the joint would be the same as the strength of the weakest material comprising the joint.

Impediments To Make Ideal Weld

- If two perfectly flat surfaces of aggregates of atoms are brought together to the equilibrium spacing for the atomic species involved, bond pairs form and the two pieces are welded together perfectly.
- In this case, there is no remnant of a physical interface and there is no disruption of the structure of either material involved in the joint. The resulting weld has the strength expected from the atom-to-atom binding energy so the joint efficiency is 100%. “Joint efficiency" is the ratio of the joint strength to the strength of the base materials comprising the joint.



Nature of continuity in a metal in part A and B.

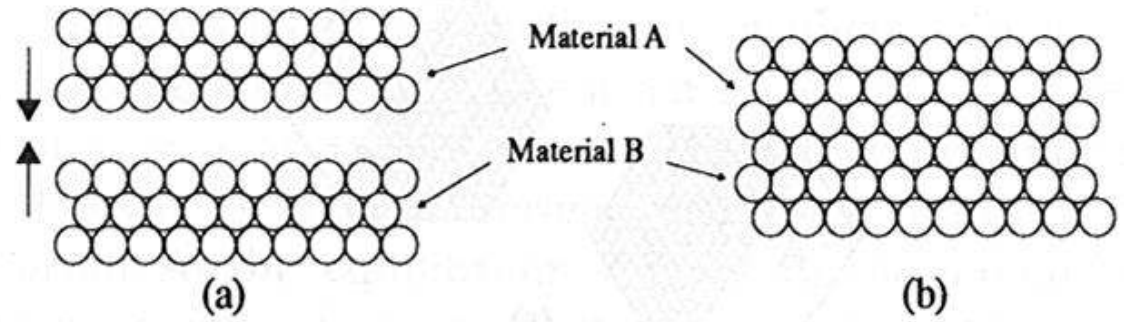
a) two separate aggregates (crystals, grains, parts)

b) forming a single part after welding.

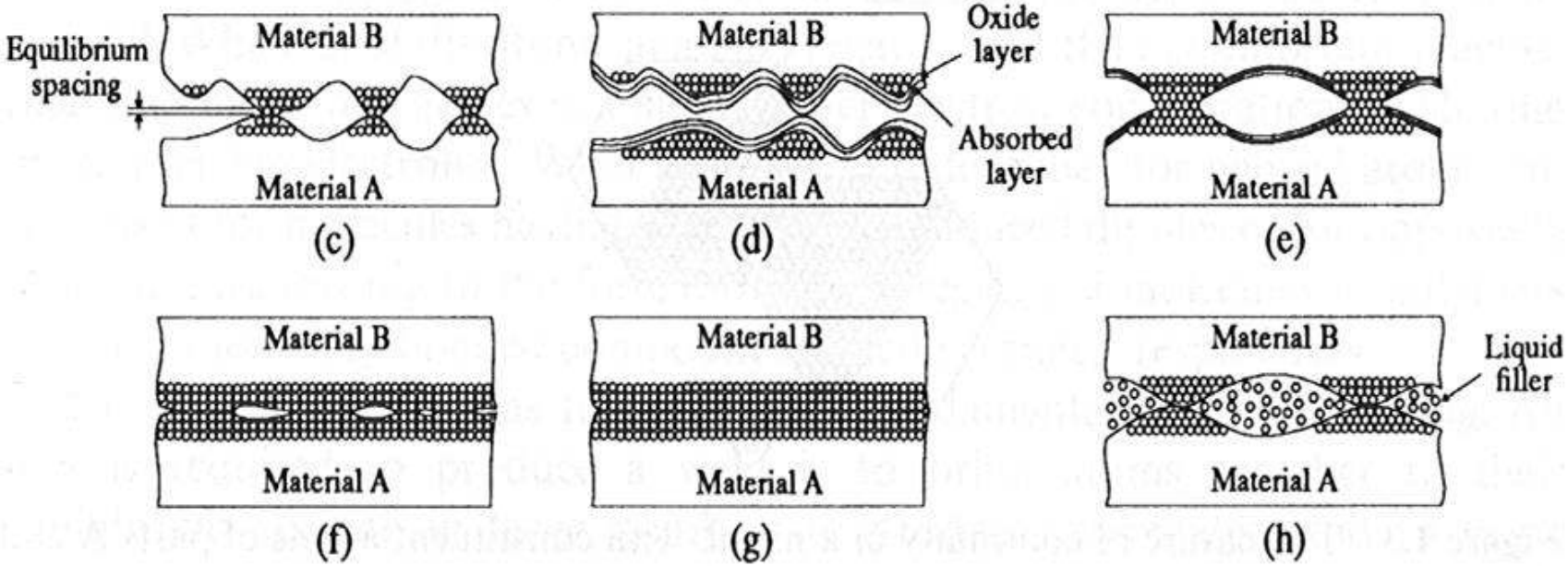
Impediments To Make Ideal Weld

- In reality, two materials never perfectly smooth, so perfect matching up of all atoms across an interface at equilibrium spacing never occurs.
- Thus, a perfect joint or ideal weld can never be formed simply by bringing the two material aggregates together.
- Real materials have highly irregular surfaces on a microscopic scale.
- Peaks and valleys of 10 -1000's of atoms high or deep lead to few points of intimate contact at which the equilibrium spacing can be achieved.
- Typically, only one out of approximately every billion (10^9) atoms on a well-machined (e.g., 4 rms finish) surface come into contact to be able to create a bond, so the strength of the joint is only about one-billionth (10^{-9}) of the theoretical cohesive strength that can be achieved.
- This situation is made even worse by the presence of oxide, tarnish and adsorbed moisture layers usually found on real materials.
- Bonding (welding) can be achieved only by removing or disrupting these layers and bringing the clean base material atoms to the equilibrium spacing for the materials involved. Any other form of surface contamination, such as paint or grease or oil, also causes problems.

Impediments To Make Ideal Weld



Two perfectly smooth and clean surfaces brought together to form a weld.



Two real materials (c) and (d) progressively forced together by pressure (e and f) to form a near-perfect weld (g). Melting to provide a supply of atoms (h) to form a near-perfect weld.

What It Takes To Make A Real Weld

- To make a real weld (obtain continuity) requires overcoming the impediments of surface roughness and few points of intimate contact and intervening contaminant layers.
- There are two ways of improving the situation:

1. cleaning the surface of real materials,
2. bringing most, if not all, of the atoms of those material surfaces into intimate contact over large areas.

- There are two ways of cleaning the surface:

1. chemically, using solvents to dissolve away contaminants or reducing agents to convert oxide or tarnish compounds to the base metals,
2. mechanically, using abrasion or other means to physically disrupt the integrity of oxides or tarnish layers.

- Once the surfaces are cleaned, they must be kept clean until the weld is produced. (requires shielding). Every viable welding process must somehow provide and/or maintain cleanliness in the joint area.

What It Takes To Make A Real Weld

- Two ways of bringing atoms together in large numbers to overcome asperities. Apply heat and/or pressure.

1. Apply heat. In the solid state, heating helps by
   a. Driving off volatile adsorbed layers of gases or moisture (usually hydrogen-bonded waters of hydration) or organic contaminants;
   b. Either breaking down the brittle oxide or tarnish layers through differential thermal expansion or, occasionally, by thermal decomposition (e.g. Copper oxide and titanium oxide);
   c. Lowering the yield strength of the base materials and allowing plastic deformation under pressure to bring more atoms into intimate contact across the interface.
   d. Melting of the substrate materials, allowing atoms to rearrange by fluid flow and come together to equilibrium spacing, or by melting a filler material to provide an extra supply of atoms of the same or different but compatible types as the base material.

What It Takes To Make A Real Weld

2. Apply pressure.
   a. disrupting the adsorbed layers of gases or moisture by macro- or microscopic deformation,
   b. fracturing brittle oxide or tarnish layers to expose clean base material atoms,
   c. plastically deforming asperities to increase the number of atoms, and thus the area, in intimate contact.

- Very high heat and little or no pressure can produce welds by relying on the high rate of diffusion in the solid state at elevated temperatures or in the liquid state produced by melting or fusion.
- Little or no heat with very high pressures can produce welds by forcing atoms together by plastic deformation on a macroscopic scale (as in forge welding) or on a microscopic scale (as in friction welding), and/or by relying on atom transport by solid-phase diffusion to cause intermixing and bonding.

What It Takes To Make A Real Weld

TABLE I.1 Advantages and Disadvantages of Welding as a Joining Process

Advantages	Disdvantages
1. Joints of exceptional structural integrity and efficiency, will not accidently loosen or disassemble	1. Impossible to disassemble joints without destroying detail parts
2. Wide variety of process embodiments	2. Heat of welding degrades base properties
3. Applicable to many materials within a class	3. Unbalanced heat input leads to distortion or residual stresses
4. Manual or automated operation	4. Requires considerable operator skill
5. Can be portable for indoor or outdoor use	5. Can be expensive (e.g., thick sections)
6. Leak-tight joints with continuous welds	6. Capital equipment can be expensive (e.g., electron-beam guns and vacuum chambers)
7. Cost is usually reasonable	

Joining Dissimilar Materials

- Important to distinguish joints made between similar materials (metals, ceramics, composites or plastics) and joints between dissimilar materials (steel bonded to copper, metal bonded to rubber or ceramic, or a metallic contact to a semiconductor).
- In the case of dissimilar (unlike) materials, the engineering compatibility of the two components must be considered.
- Mismatch of the elastic modulus is a common form of mechanical incompatibility which leads to stress concentrations and stress discontinuities at the bonded interface between the two materials.

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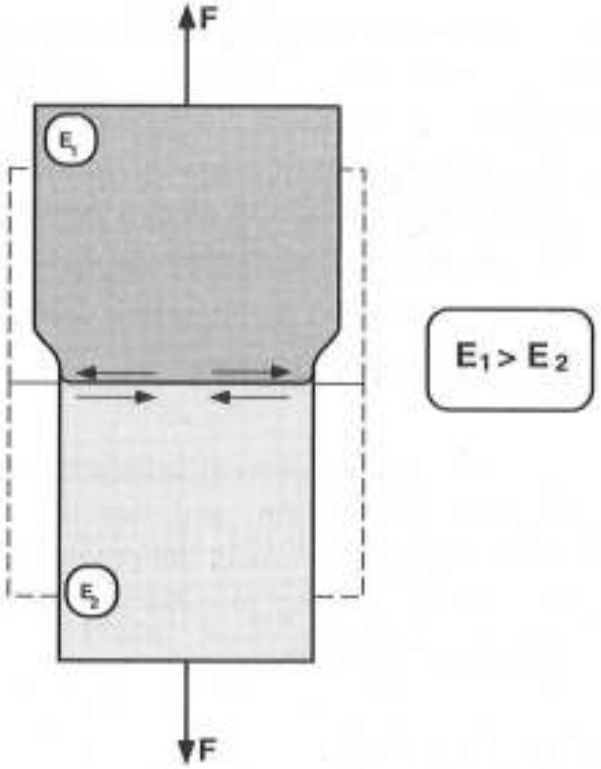

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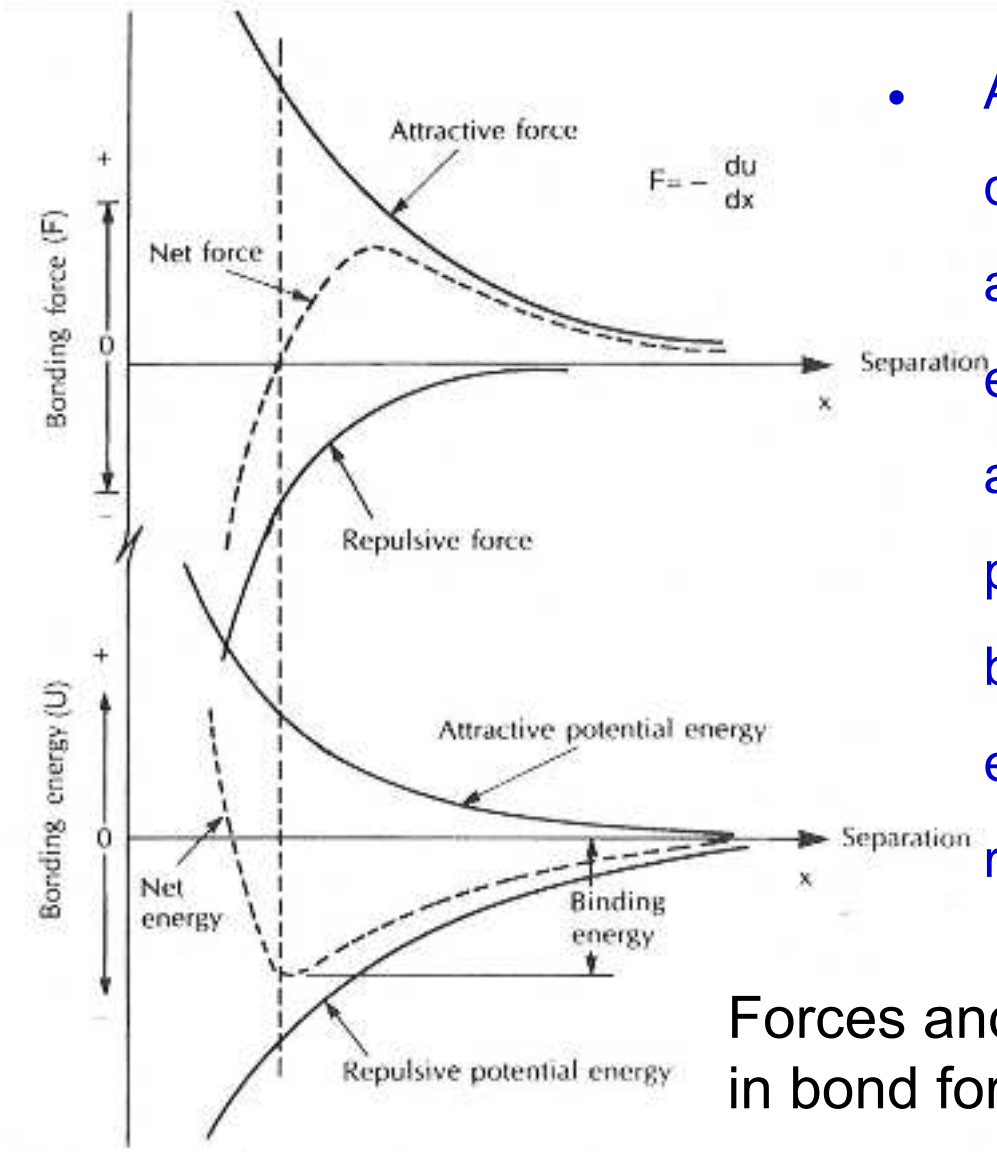

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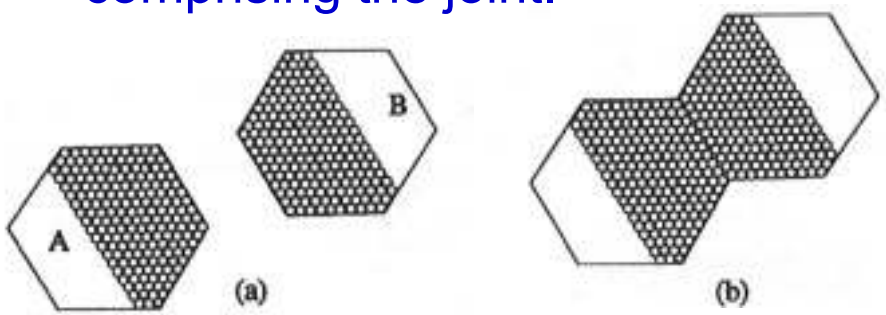
Impediments To Make Ideal Weld

- If two perfectly flat surfaces of aggregates of atoms are brought together to the equilibrium spacing for the atomic species involved, bond pairs form and the two pieces are welded together perfectly.
- In this case, there is no remnant of a physical interface and there is no disruption of the structure of either material involved in the joint. The resulting weld has the strength expected from the atom-to-atom binding energy so the joint efficiency is 100%. “Joint efficiency" is the ratio of the joint strength to the strength of the base materials comprising the joint.



Nature of continuity in a metal in part A and B.

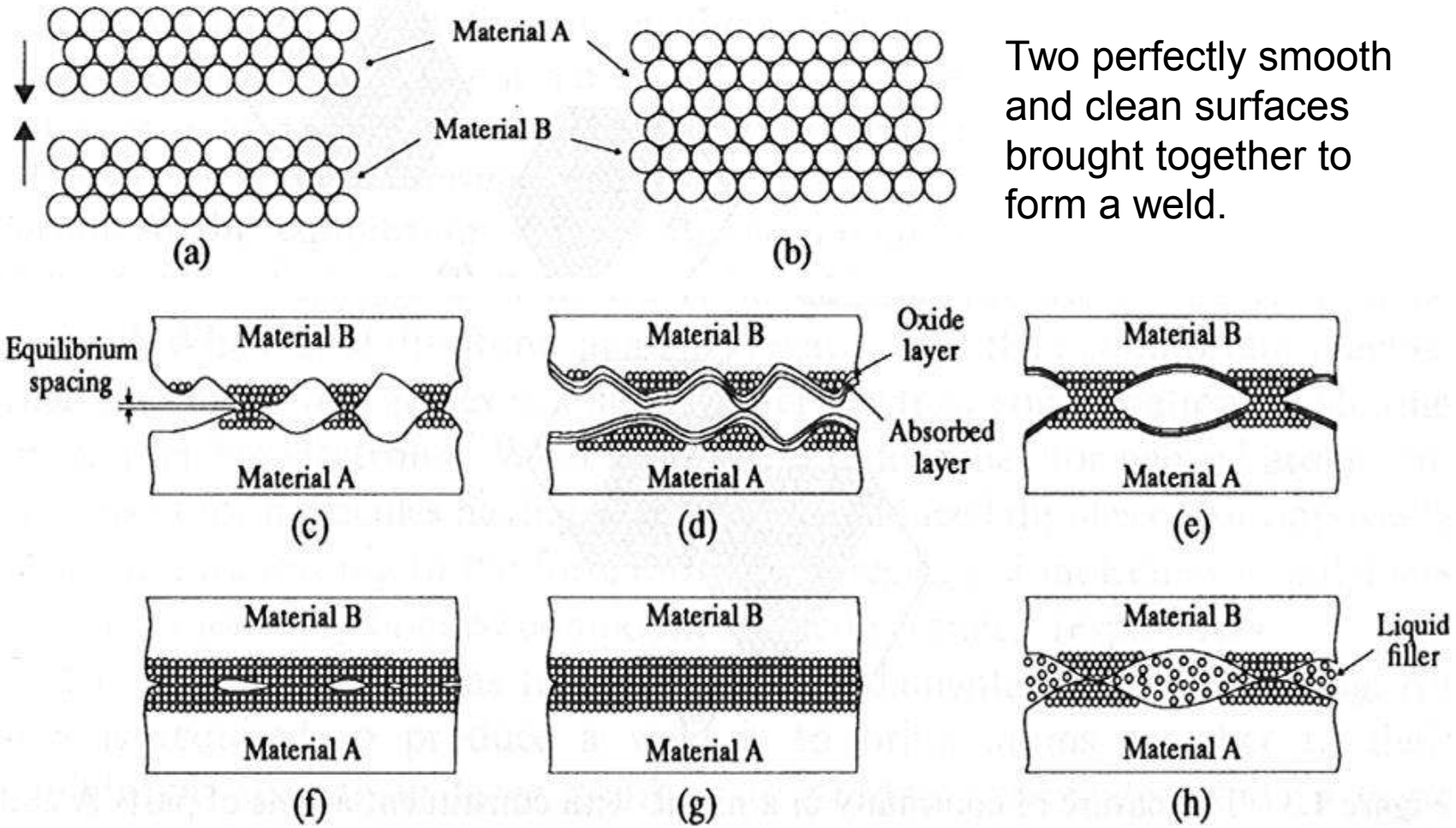
a) two separate aggregates (crystals, grains, parts)

b) forming a single part after welding.

Impediments To Make Ideal Weld

- In reality, two materials never perfectly smooth, so perfect matching up of all atoms across an interface at equilibrium spacing never occurs.
- Thus, a perfect joint or ideal weld can never be formed simply by bringing the two material aggregates together.
- Real materials have highly irregular surfaces on a microscopic scale.
- Peaks and valleys of 10 -1000's of atoms high or deep lead to few points of intimate contact at which the equilibrium spacing can be achieved.
- Typically, only one out of approximately every billion (10^9) atoms on a well-machined (e.g., 4 rms finish) surface come into contact to be able to create a bond, so the strength of the joint is only about one-billionth (10^{-9}) of the theoretical cohesive strength that can be achieved.
- This situation is made even worse by the presence of oxide, tarnish and adsorbed moisture layers usually found on real materials.
- Bonding (welding) can be achieved only by removing or disrupting these layers and bringing the clean base material atoms to the equilibrium spacing for the materials involved. Any other form of surface contamination, such as paint or grease or oil, also causes problems.

Impediments To Make Ideal Weld



Two perfectly smooth and clean surfaces brought together to form a weld.

Two real materials (c) and (d) progressively forced together by pressure (e and f) to form a near-perfect weld (g). Melting to provide a supply of atoms (h) to form a near-perfect weld.

What It Takes To Make A Real Weld

- To make a real weld (obtain continuity) requires overcoming the impediments of surface roughness and few points of intimate contact and intervening contaminant layers.
- There are two ways of improving the situation:

1. cleaning the surface of real materials,
2. bringing most, if not all, of the atoms of those material surfaces into intimate contact over large areas.

- There are two ways of cleaning the surface:

1. chemically, using solvents to dissolve away contaminants or reducing agents to convert oxide or tarnish compounds to the base metals,
2. mechanically, using abrasion or other means to physically disrupt the integrity of oxides or tarnish layers.

- Once the surfaces are cleaned, they must be kept clean until the weld is produced. (requires shielding). Every viable welding process must somehow provide and/or maintain cleanliness in the joint area.

What It Takes To Make A Real Weld

- Two ways of bringing atoms together in large numbers to overcome asperities. Apply heat and/or pressure.

1. Apply heat. In the solid state, heating helps by
   a. Driving off volatile adsorbed layers of gases or moisture (usually hydrogen-bonded waters of hydration) or organic contaminants;
   b. Either breaking down the brittle oxide or tarnish layers through differential thermal expansion or, occasionally, by thermal decomposition (e.g. Copper oxide and titanium oxide);
   c. Lowering the yield strength of the base materials and allowing plastic deformation under pressure to bring more atoms into intimate contact across the interface.
   d. Melting of the substrate materials, allowing atoms to rearrange by fluid flow and come together to equilibrium spacing, or by melting a filler material to provide an extra supply of atoms of the same or different but compatible types as the base material.

What It Takes To Make A Real Weld

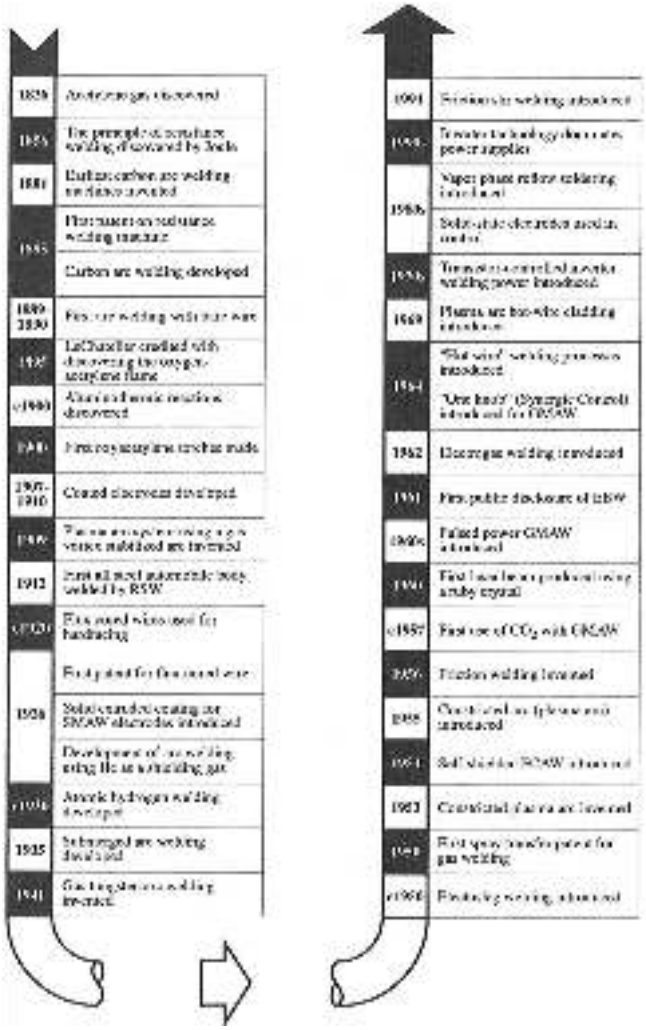
2. Apply pressure.
   a. disrupting the adsorbed layers of gases or moisture by macro- or microscopic deformation,
   b. fracturing brittle oxide or tarnish layers to expose clean base material atoms,
   c. plastically deforming asperities to increase the number of atoms, and thus the area, in intimate contact.

- Very high heat and little or no pressure can produce welds by relying on the high rate of diffusion in the solid state at elevated temperatures or in the liquid state produced by melting or fusion.
- Little or no heat with very high pressures can produce welds by forcing atoms together by plastic deformation on a macroscopic scale (as in forge welding) or on a microscopic scale (as in friction welding), and/or by relying on atom transport by solid-phase diffusion to cause intermixing and bonding.

What It Takes To Make A Real Weld

TABLE I.1 Advantages and Disadvantages of Welding as a Joining Process

Advantages	Disdvantages
1. Joints of exceptional structural integrity and efficiency, will not accidently loosen or disassemble	1. Impossible to disassemble joints without destroying detail parts
2. Wide variety of process embodiments	2. Heat of welding degrades base properties
3. Applicable to many materials within a class	3. Unbalanced heat input leads to distortion or residual stresses
4. Manual or automated operation	4. Requires considerable operator skill
5. Can be portable for indoor or outdoor use	5. Can be expensive (e.g., thick sections)
6. Leak-tight joints with continuous welds	6. Capital equipment can be expensive (e.g., electron-beam guns and vacuum chambers)
7. Cost is usually reasonable	



MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Welding - Fundamentals

Lecture 8

Welding - Introduction

- Permanent joining of 2 materials by coalescence through
  - Temperature - Pressure - Metallurgical/material conditions
- 3 distinctive mechanisms for obtaining continuity (joining by welding):
- Solid phase plastic deformation (with/without recrystallization). E.g. cold welding processes, hot deformation welding processes.
- Diffusion E.g. diffusion welding processes, brazing etc.
- Melting and solidification. E.g. welding processes where melting occurs.
- Require:
- 1) source of heat and/or pressure
- 2) means of cleaning/protecting
- 3) caution regarding microstructure.

Oxyfuel Gas Welding - OFW

- Processes that use flame (from combustion of gas & oxygen) to heat parts. Now used for portability & versatility.
- Acetylene (C_2H_2) principle fuel. Heat is generated in 2 stages of combustion while acetelyne combusts with Oxygen
- $C_2H_2 + 0_2 \rightarrow 2CO + H_2 + \text{Heat}$ Primary combustion
- $2C0 + 0_2 \rightarrow 2C0_2 + \text{Heat}$ Secondary "
- $H_2 + ½0_2 \rightarrow H_20 + \text{Heat}$ Secondary "
- First stage near the tip of the torch, second stage beyond the first combustion zone
- Can generate heat of ~ 3250°C
- (Other fuels possible: natural gas/methane, propane, butane, hydrogen)

Oxyfuel Gas Welding - OFW

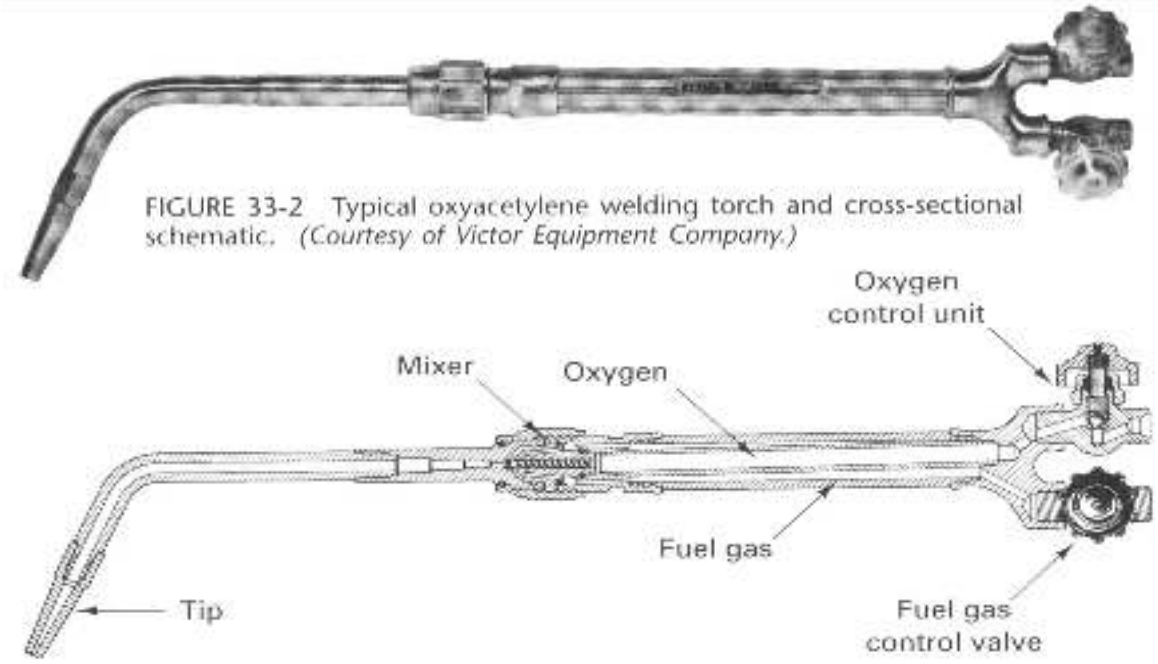
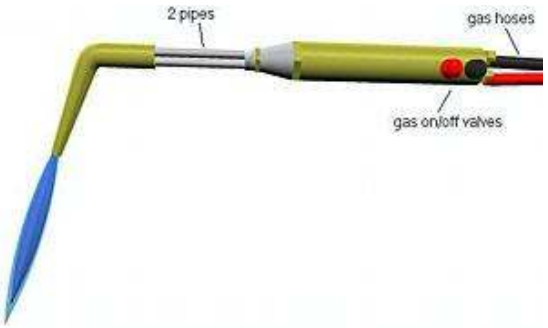


FIGURE 33-2 Typical oxyacetylene welding torch and cross-sectional schematic. *(Courtesy of Victor Equipment Company.)*



- Start: Open acetylene (fuel) valve, light with spark; open oxygen to desired flame.
- Stop: Shut acetylene (fuel) valve, flame goes out; shut oxygen valve.

Oxyfuel Gas Welding - OFW

- Two regions of flame:
- Inner core (hottest - near weld)
- Outer envelope - preheat, shield from oxidation
- Oxygen/fuel gas ratio:
- 1:1 to 1.15:1 neutral flame (welding)
- > 1.15:1 oxidising flame, hotter, used in copper and copper alloys (but not steel – oxygen reduces carbon content)
- < 1:1 reducing/carburizing flame, cooler - no carburization but good protection from oxidation or for removing surface oxides prior to welding.

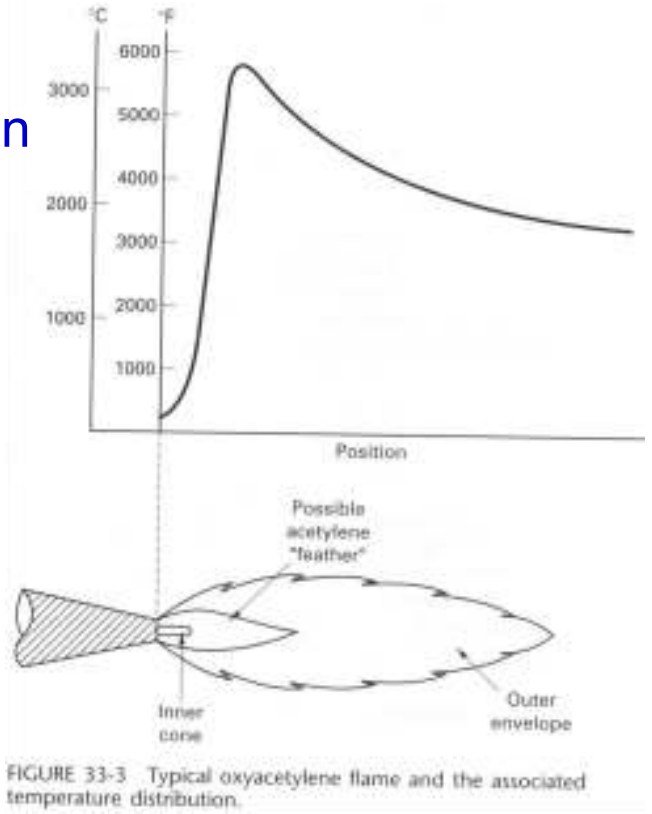


FIGURE 33-3 Typical oxyacetylene flame and the associated temperature distribution.

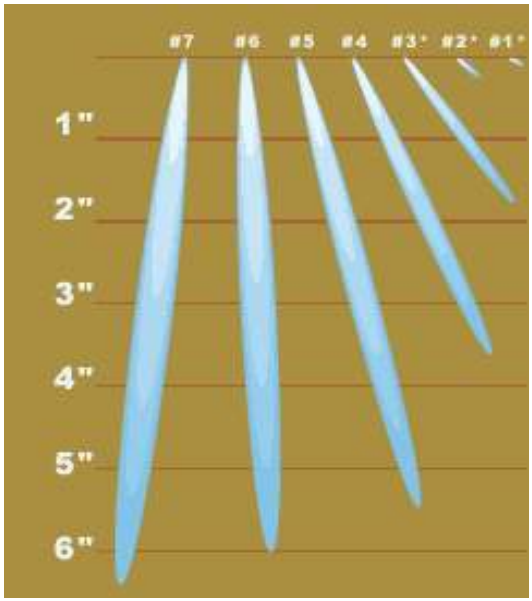
Oxyfuel Gas Welding - OFW

Cylinders:

0_2 is stored in pure form at 1.7 MPa.

C_2H_2/acetone/filler (Acetelyne is not safe at higher pressure, so dissolved in Acetone and the cylinders are filled with porous filler which absorbs acetone and helps in dissolving acetelyne)

Also MAPP gas (methyl acetylene propadiene)



Regulators:

1-15 psi (7-105 kPa) is the pressure used in this welding - controlled by regulators. Precautions to prevent mixing by accident. (RH & LH)

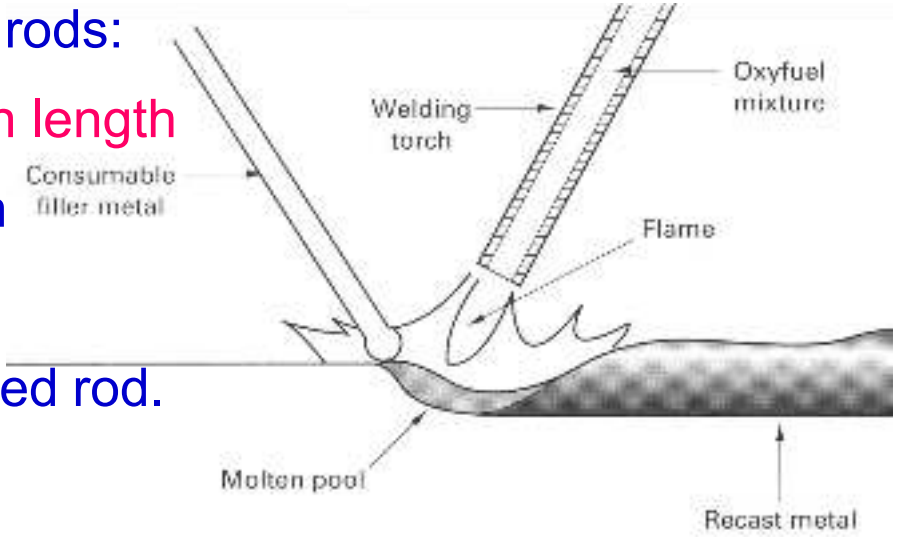
Torch:

Orifice size varied to change shape of flame & flow rate

Large tips: high flow & high heat without high velocity or blowing metal.

OFW – Advantages and Disadvantages

- Generally Fusion Welding – no pressure
- Due to gaps in surfaces filler-metal rods:
  - 1.5 - 9.5 mm dia & 0.6 - 0.9 m in length
- For better bonding, fluxes - to clean surfaces; prevent oxidation
- Can be powders, pastes,or precoated rod.



- Advantages - Disadvantages
- Easy heat control, but slow (low energy density).
- But gases etc can cause contamination.
- Large area of metal heated (distortion).
- Not used a lot in mass production, mainly in field, repair, mixed workshops.
- Portable equipment

OFW – Advantages and Disadvantages

TABLE 33-1. Engineering Materials and Their Compatibility with Oxyfuel Welding

Material	Oxyfuel Welding Recommendation
Cast iron	Recommended with cast iron filler rods; braze welding recommended if there are no corrosion objections
Carbon and low-alloy steels	Recommended for low-carbon and low-alloy steels, using rods of the same material; more difficult for higher carbon
Stainless steel	Common for thinner material; more difficult for thicker
Aluminum and magnesium	Common for aluminum thinner than 1 in.; difficult for magnesium alloys
Copper and copper alloys	Common for most alloys; more difficult for some types of bronzes
Nickel and nickel alloys	Common for nickel, Monels, and Inconels
Titanium	Not recommended
Lead and zinc	Recommended
Thermoplastics, thermosets, and elastomers	Hot-gas welding used for thermoplastics, not used with thermosets and elastomers
Ceramics and glass	Seldom used with ceramics, but common with glass
Dissimilar metals	Difficult; best if melting points are within 50°F; concern for galvanic corrosion
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Difficult

Oxyacetelyn Flame Cutting

- Melts metal and gas blows the metal away from the gap creating the kerf
- In ferrous metals iron actually burns (oxidizes at high temperatures)

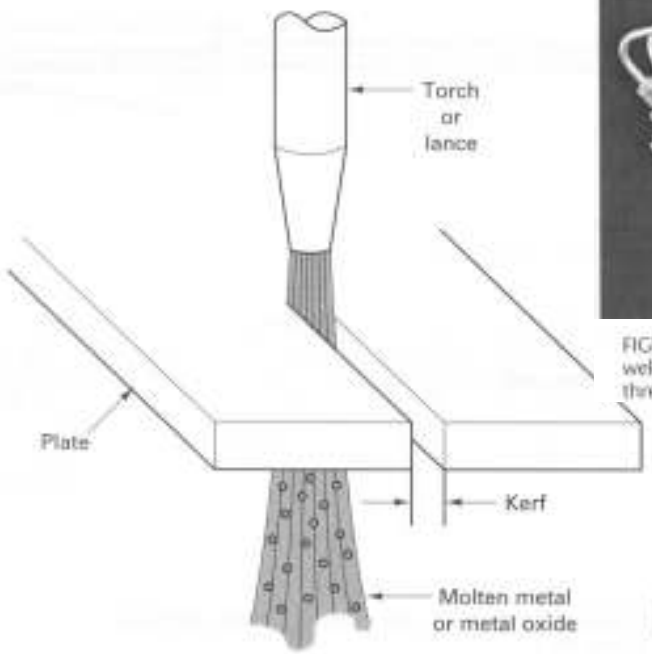


FIGURE 33-6 Flame cutting of a metal plate.

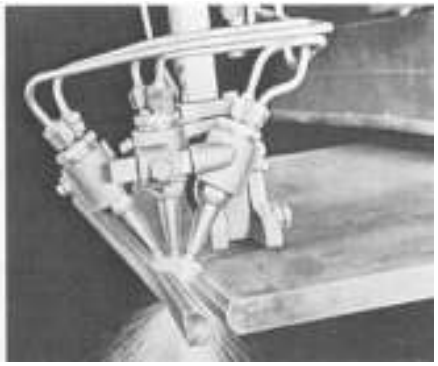


FIGURE 33-9 Plate edge being prepared for welding. The beveled shape is produced by three simultaneous oxyacetylene cuts.

- Advantages - Disadvantages
- Low rate of heat input, large heat affected zone, slow process
- Not suited for operations where finish and tolerance are critical
- Large area of metal heated (distortion).
- Used only metals that oxidize readily. SS, aluminum alloys are difficult
- Low cost of equipment

Arc welding

- 1880s - Arc used as heat source. Carbon, electrode, filler rod.
- Now shielded metal arc welding is most common form of welding.

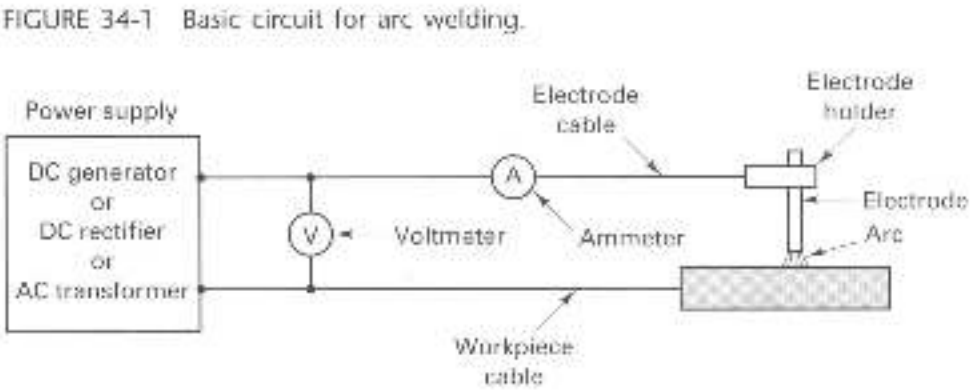
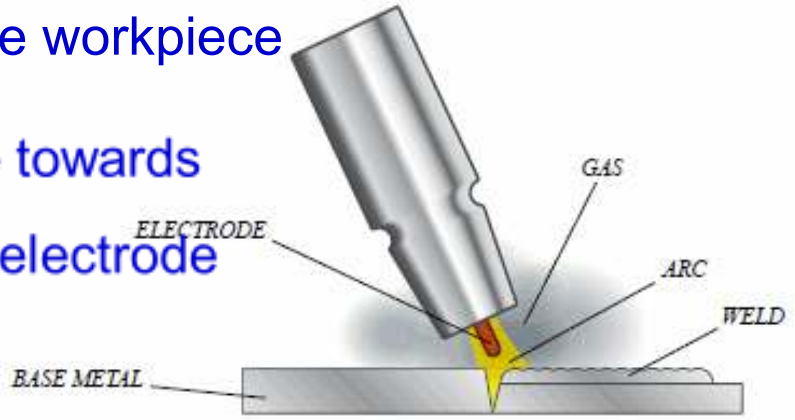


FIGURE 34-1 Basic circuit for arc welding.

- Circuit – Basic (1- 4000 Amps of current and 20 to 50 V)
- Arc is formed between an electrode and a workpiece, different polarities.
- Arc consists of thermally emitted e^- and positive ions from the electrode and workpiece. e^-s and ions are accelerated by the potential field (voltage) between the source and the work. Heat is produced when e^-s and ions collide with opposite charged element.
- e^-s are much smaller than +ve ions but have higher kinetic energy (higher velocities).

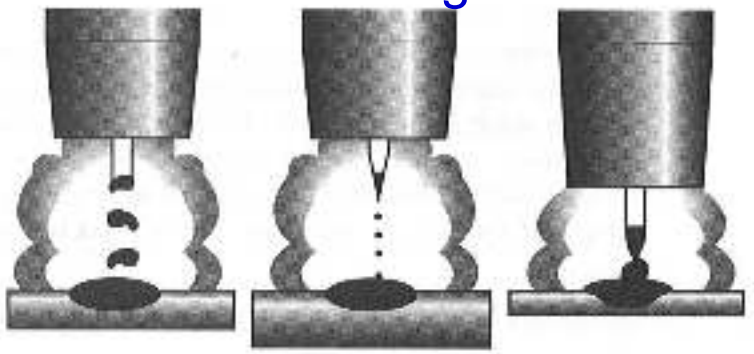
Arc welding

- **Consumable Electrode:** Electrode is consumed, providing filler metal to fill voids. $T_{Melting} < T_{arc}$.
- Droplets from arc are transferred to the workpiece



- Maintain stable arc by moving electrode towards workpiece at the same time as moving electrode along workpiece (gap or joint).

- Schematic of modes of molten metal transfer in arc welding:
- (a) drop globular
- (b) spray
- (c) short-circuiting.



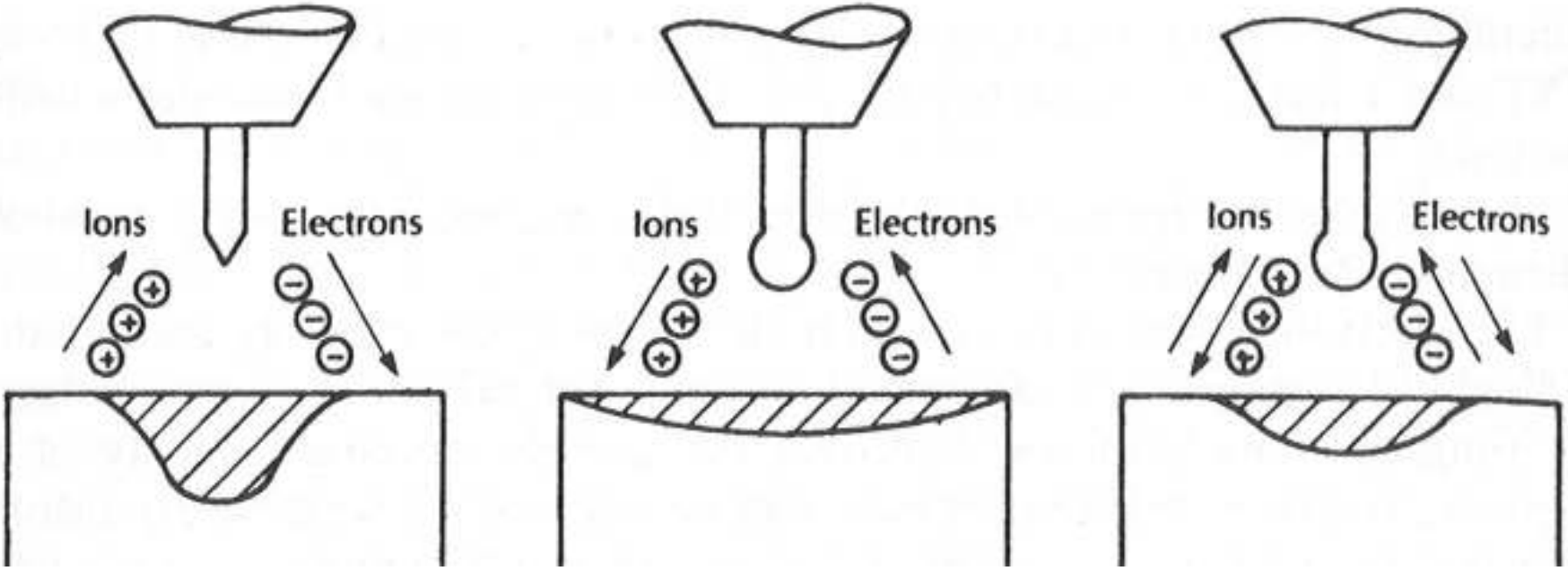
Arc Welding

- Manual arc welding - usually uses shielded (covered/coated) electrodes.
- Automatic - may use continuous bare metal wire, fed automatically but continuously controlled to control arc and shielding.
- **Non-Consumable Electrode:** Separate wire used as filler
- Arc electrode is Tungsten.
- Still require shielding.
- **Selection:** variety of processes available, requires based on application, voltage, current, polarity (straight, reversed or alternating)
- Arc length, speed, arc atmosphere, filler metal, flux
- Quality also depends on the skilled operator – reduce dependence by robotic welding or automation of process

Current Modes

- Different current modes can be used:
- DC – direct current
- EN – electrode negative
- EP – electrode positive
- AC – alternating current
- When using DC supply:
- When work is +ve (ANODE)
- Direct current straight polarity – DCSP/SPDC
- or Direct current electrode negative – DCEN
- When work is -ve (CATHODE)
- Direct current reversed polarity – DCRP/RPDC
- or Direct current electrode positive – DCEP

Current Modes



DCSP (EN)	DCRP (EP)	AC
No cleaning action	Strong cleaning action	Cleaning every half cycle
70% heat at work	30% heat at work	50% heat at work
30% heat at W	70% heat at W	50% heat al W
Excellent electrode current capacity	Poor electrode current capacity	Good electrode current capacity

Summary of characteristics of various modes for arc welding process.

Current Modes

- In DCSP (DCEN), e^-s are emitted from the electrode and accelerated to very high speeds and kinetic energies while traveling through the arc.
- These high-energy e^-s collide with the workpiece, give up their kinetic energy, and generate considerable heat in the workpiece.
- Consequently, DCSP results in deep penetrating, narrow welds, but with higher workpiece heat input. About two-thirds of the net heat available from the arc (after losses from various sources) enters the workpiece.
- High heat input may or may not be desirable, depending on factors such as required weld penetration, weld width, workpiece mass, susceptibility to heat-induced defects or degradation, and concern for distortion or residual stress.

Current Modes

- In DCRP (DCEP), the heating effect of the electrons is on the (tungsten) electrode rather than on the workpiece. Consequently, larger water-cooled electrode holders are required, shallow welds are produced, and workpiece heat input can be kept low.
- This operating mode is good for welding thin sections or heat-sensitive metals and alloys. This mode also results in a scrubbing action on the workpiece by the large positive ions that strike its surface, removing oxide and cleaning the surface.
- This mode is thus preferred for welding metals and alloys that oxidize easily, such as aluminum or magnesium.

Current Modes

- The DCSP mode is much more common with nonconsumable electrode arc processes than the DCRP mode.
- Many of these effects are far less pronounced with other electric arc welding processes employing consumable electrodes than with GTAW. Most particularly, there is little difference in penetration between DCSP and DCRP.
- This is so since the concentration of heat at the electrode with RP aids in melting the consumable electrode, as is desired, but this heat is returned to the weld when the molten metal droplets transfer to the pool. On the other hand, the cleaning action of the RP mode at the workpiece still takes place.

Current Modes

- Third mode, employing alternating current or AC.
- The AC mode tends to result in some of the characteristics of both of the DC modes, during the corresponding half cycles, but with some bias toward the straight polarity half-cycle due to the greater inertia (i.e., lower mobility) and, thus, greater resistance of large positive ions.
- During this half-cycle, the current tends to be higher due to the extra emission of electrons from the smaller, hotter electrode versus larger, cooler workpiece. In the AC mode, reasonably good penetration is obtained, along with some oxide cleaning action.

Arc Welding Variables

- Welding voltage and current
- Welding arc polarity and arc length
- Welding speed
- Arc atmosphere
- Electrode material
- Filler material
- Flux

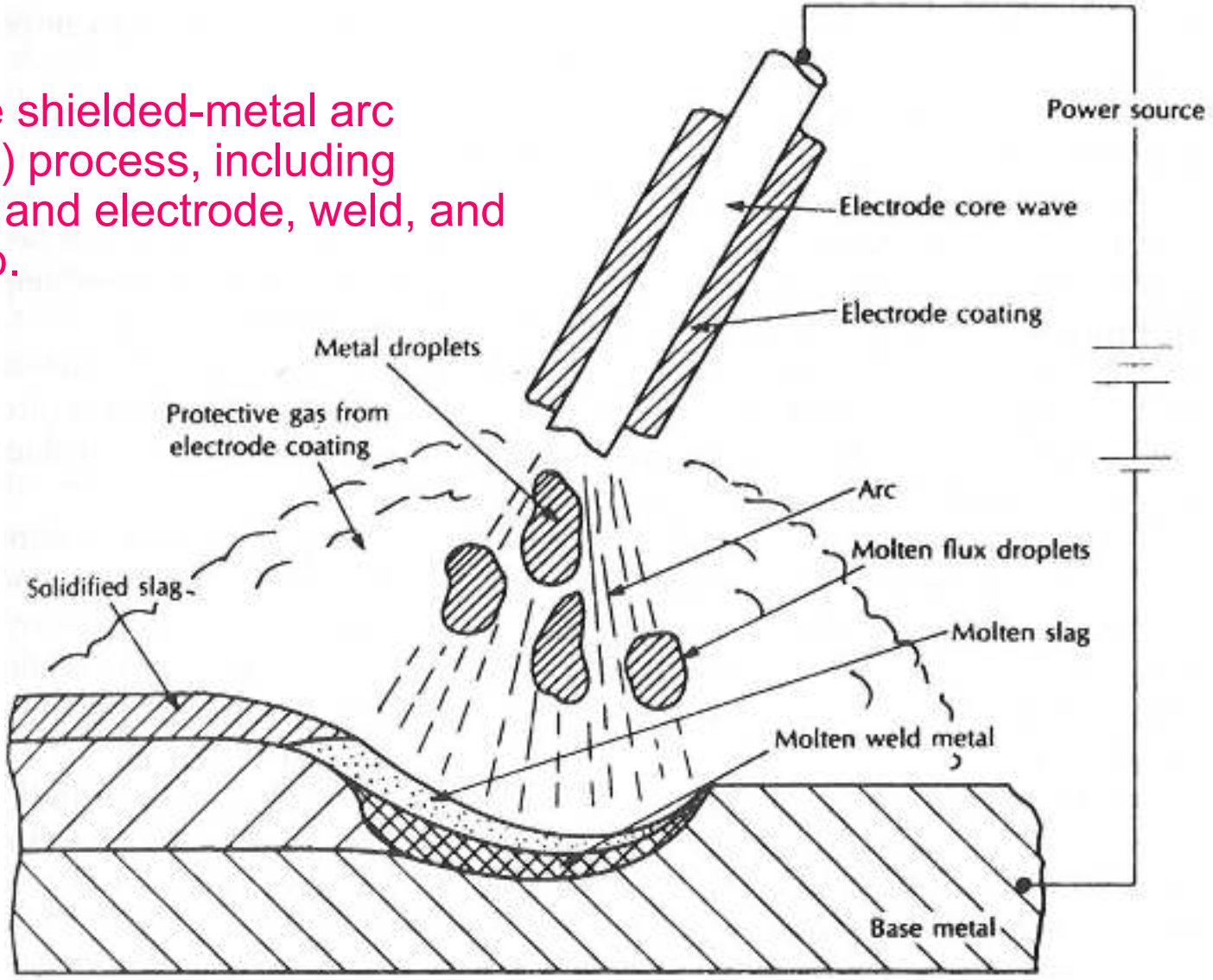
- So quite a few things to get right (or conversely, it doesn't take much to produce a bad weld!)

Shielded Metal Arc Welding - SMAW

- (aka Stick Welding).
- Very common, very versatile - low cost.
- Heat from arc between tip of flux-coated, discontinuous, consumable ("stick") electrode and the surface of the work.
- Core wire conducts current from constant current power supply and provides filler metal to joint.
- Some arc heat is lost by conduction and as resistance heating.
- SMAW can operate in DCEP or DCEN and also in AC mode depending on coating.
- Typical currents: 50-300 A, 10-30V
- Deposition rates of 1 – 10 kg/hr.

Shielded Metal Arc Welding - SMAW

Schematic of the shielded-metal arc welding (SMA W) process, including electrode holder and electrode, weld, and electrical hookup.



Shielded Metal Arc Welding - SMAW

- Electrode covering is very important. Surrounding the wire electrode is bonded coating having chemical components that adds characteristics.
  - Provides a protective atmosphere (gas shield)
  - Stabilizes the arc (readily ionized compounds)
  - Acts as flux to deoxidize and/or remove contaminants
  - Provides slag coating - impurities, oxidation protection, slows cooling rate.
  - Reduces spatter
  - Adds alloying elements and/or grain refiners
  - Affects arc penetration
  - Affects shape of weld bead
  - Adds additional filler metal

Shielded Metal Arc Welding - SMAW

- Classified by: - tensile strength of deposited metals
- - position can be used in
- - type of polarity
- E7016 means tensile strength of 70000psi, used in all positions, AC DC or RP, with low hydrogen + potassium coating

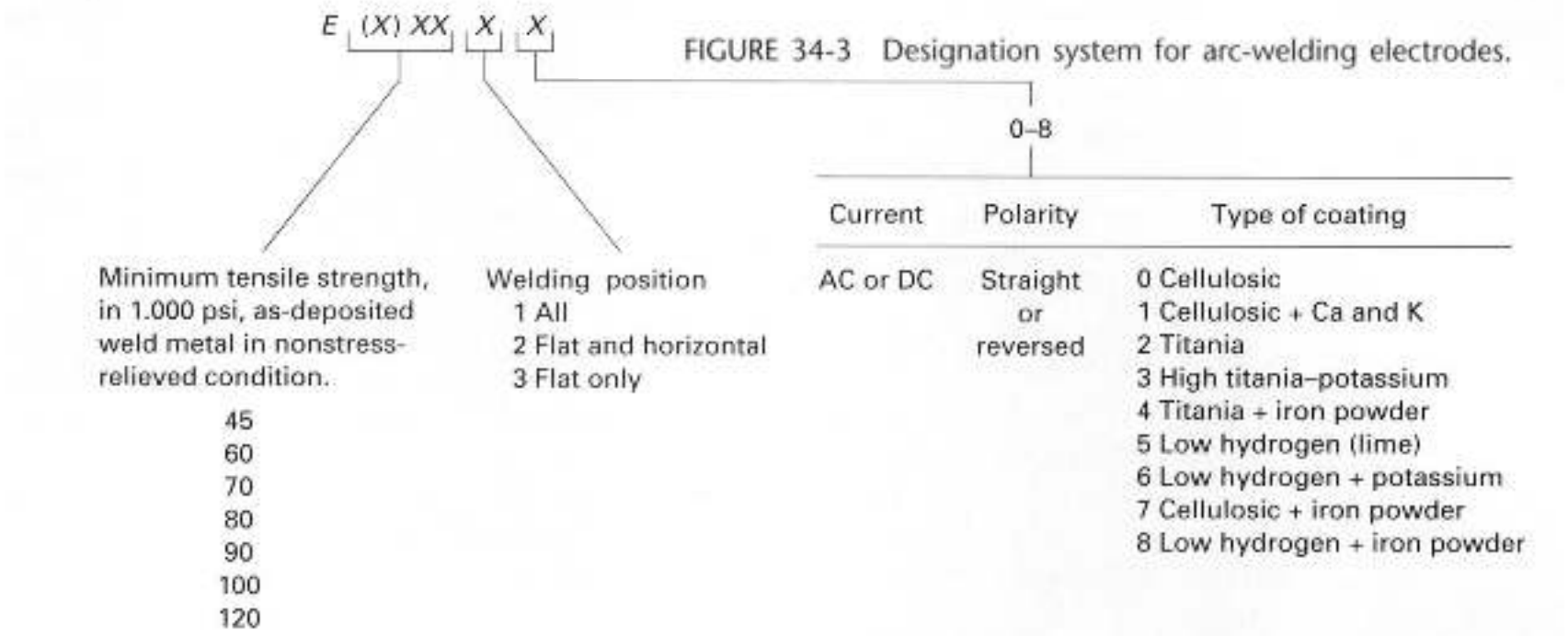


FIGURE 34-3 Designation system for arc-welding electrodes.

Shielded Metal Arc Welding - SMAW

Usability of the Electrode Based on Last Digit

Classification		Welding—				
AWS	ASME	Current	Type of Covering	Position	Arc Type	Approximate Iron Powder[a] (%)
6010	F-3	DCEP	Cellulose–sodium	All	Digging	0–10
6011	F-3	Ac and DCEP	Cellulose–potassium	All	Digging	0
6012	F-2	Ac and DCEN	Rutile—sodium	All	Medium	0–10
6013	F-2	Ac and dc	Rutile–potassium	All	Light	0–10
6019	F-2	Ac and dc	Iron oxide rutile–potassium	All	Medium	0–10
6020	F-1	Ac and dc	High iron oxide	F, Hf	Medium	0
6022	F-1	Ac and dc	High iron oxide	F, H	Hi speed	0–10
6027	F-1	Ac and dc	Iron oxide-iron powder	F, Hf	Medium	50
7014	F-2	Ac and dc	Rutile-iron powder	All	Light	25–40
7015	F-4	DCEP	Low hydrogen-sodium	All	Medium	0
7016	F-4	Ac and DCEP	Low hydrogen-potassium	All	Medium	0
7018	F-4	Ac and DCEP	Low hydrogen-potassium-iron powder	All	Medium	25–40
7018M	F-4	DCEP	Low hydrogen-iron powder	All	Medium	10–25
7024	F-1	Ac and dc	Rutile-iron powder	F,Hf	Light	50
7027	F-1	Ac and dc	Iron oxide-iron powder	F,Hf	Medium	50
7028	F-1	Ac and DCEP	Low hydrogen-potassium-iron powder	F,Hf	Medium	50
7048	F-4	Ac and DCEP	Low hydrogen-potassium-iron powder	All	Medium	25–40

[a]Iron powder percentage based on weight of the covering.

Shielded Metal Arc Welding - SMAW

AWS Classification	Minimum Tensile Strength ksi	Minimum Tensile Strength MPa	Minimum Yield Strength at 0.2% Offset ksi	Minimum Yield Strength at 0.2% Offset MPa	Elongation (%)	Radiographic Standard AWS Grade	Minimum V-Notch Impact[a] (ft-lb)
E6010	62	430	50	340	22	2	20 at −20° F
E6011	62	430	50	340	22	2	20 at −20° F
E6012	67	460	55	380	17	Not required	Not required
E6013	67	460	55	380	17	2	Not required
E6020	62	430	50	340	2	1	Not required
E6022	67	460	Not required		Not required	Not required	Not required
E6027	62	430	50	340	2	2	20 at −20° F
E7014	72	500	60	420	17	2	Not required
E7015	72	500	60	420	22	1	20 at −20° F
E7016	72	500	60	420	22	1	20 at −20° F
E7018	72	500	60	420	22	1	20 at −20° F
E7024	72	500	60	420	17	2	Not required
E7027	72	500	60	420	22	2	20 at −20° F
E7028	72	500	60	420	22	2	20 at −20° F
E7048	72	500	60	420	22	1	20 at −20° F

[a]20 ft-lb at −20° F = 27 joules at −29° C and 20 ft-lb at 0° F = 27 joules at −18°C.

Abridged specifications for mild steel covered electrodes.

Shielded Metal Arc Welding - SMAW

- **Electrode coatings:** the cellulose and titania (rutile) coatings contain SiO_2 & TiO_2 (small amounts of FeO, MgO, Na_2O) + volatiles
  - On decomposition, volatile matter release hydrogen that dissolve the weld metal leading to cracking
  - Cellulosic generates H_2, CO, H_2O, CO_2
  - Rutile (TiO_2) generates up to 40% H_2,
  - Limestone ($CaCO_3$) generates CO_2 and CaO slag with little or no H_2
- Low hydrogen electrodes are available that provide shielding without hydrogen release
- Electrodes can absorb water and become another source of hydrogen, so baking electrodes to remove water is done

Shielded Metal Arc Welding - SMAW

- To start weld: touch electrode tip to metal quickly & raise short distance (striking an arc) - “frizzing” begins.
- Tip should not touch workpiece again.
- Arc heat melts tip of wire, & coating & metal.
- Glassy slag formed can be chipped off once the weld is cooled.
- For heavier depositions, coating can contain iron (or alloy) powder.
- Other alloying elements can be used to alter the chemistry of the weld
- Commonly used to weld Carbon steels, Alloy steels, SS, Cast irons
- Temperature of Arc: ~ 5000°C, 15 - 45 V, 10 - 500 A.

Shielded Metal Arc Welding - SMAW

- Simple, inexpensive, Quick, portable, versatile
- limited to short electrodes (heating) - not always suited to mass prod'n.
- Discontinuous processes
- Welder has to stop, chip slag and change electrodes when down to last 2 inches of electrode.
- Limits production rate. (duty cycle).

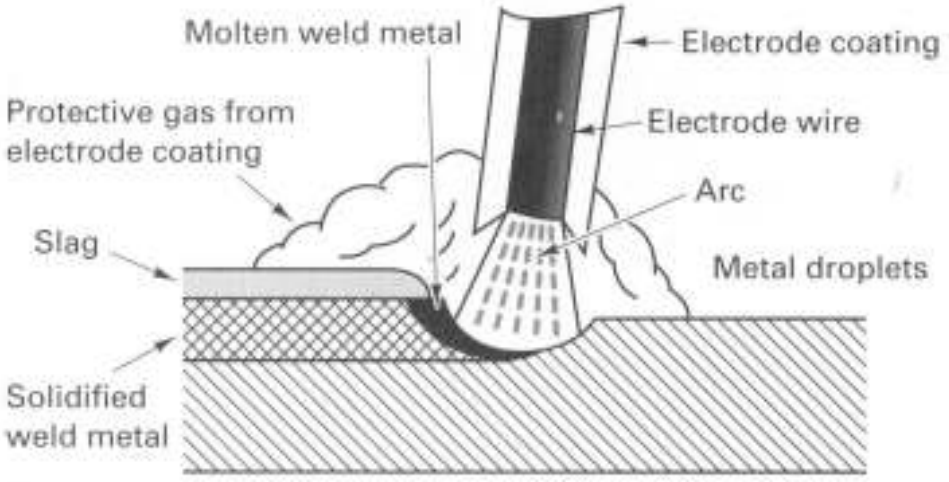


FIGURE 34-4 Schematic diagram of shielded metal arc welding (SMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

Flux-Cored Arc Welding - FCAW

- (a.k.a Open-arc welding) Opposite of shielded electrode - Tube of metal with flux powder inside. "Inside-out" electrode.
- Same principle as SMAW electrode (filler provides shielding, slag, arc stabilizers etc). Slag formed (chipped off).
- Better shielding than SMAW. Continuous electrode – no binder required. Good for welding in the field.
- Can use gas shielding as well (often CO_2 with DCEP for ferrous metals).
- DCEN or DCEP. No problems of electrode overheating (up to 500A)

Flux-Cored Arc Welding - FCAW

- Larger, better contoured welds than SMAW. Better penetration as well
- Easier for automation - continuous feed
- High deposition rates (2-15 kg/hr)
- Portable

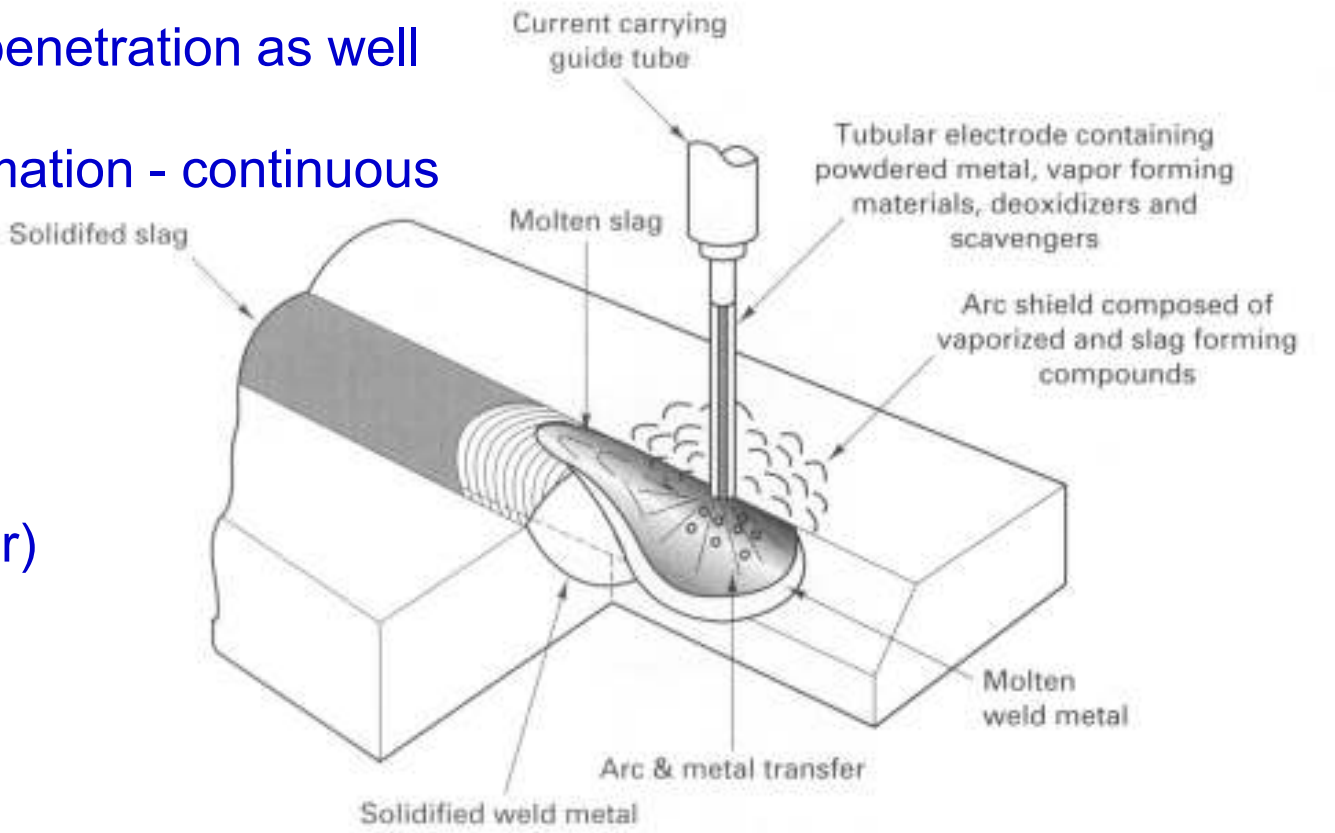


FIGURE 34-11 Schematic representation of the flux-cored arc welding process (FCAW). *(Courtesy of The American Welding Society, New York.)*

Gas Metal Arc Welding - GMAW

- If gas flowing through can protect, there is no need for flux coating
- Formerly known as (MIG - Metal Inert Gas) - Arc between workpiece + automatically fed, continuous, consumable, bare-wire electrode/filler (no separate filler rod required).
- Inert gas shielding. Argon, helium or mixture of both for reactive metals (Ti, Al, Mg).
- Ferrous metals - up to 20% CO_2 or 2% O_2 to stabilize arc & contour
- Wire is automatically fed by wire feeder & trigger
- Variety of control methods & other variations.

Gas Metal Arc Welding - GMAW

- Generally, FAST, economical, no flux or slag, so multiple pass immediately after first, automated, lightweight.
- DCRP (Reverse Polarity) is most popular mode. Electrons from workpiece (-ve) strike wire (+ve) causing heating and melting of wire.
- Heat is recovered as molten drops fall onto workpiece. (good penetration).
- Other modes can be used – DCSP, AC.
- Smooth welds produced.

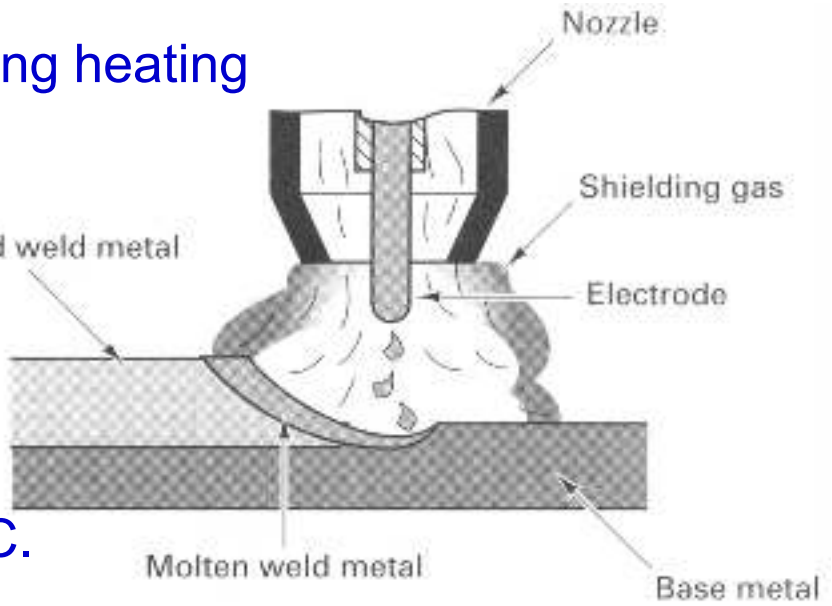
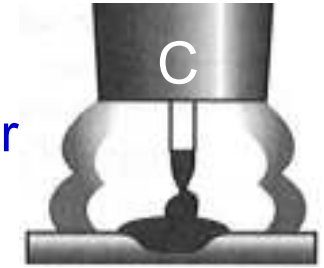


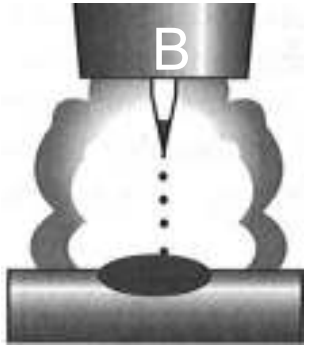
FIGURE 34-10 Schematic diagram of gas metal arc welding (GMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

Gas Metal Arc Welding - GMAW

- Short-circuiting mode GMAW-S – globules periodically touch workpiece to form short-circuit (50 times per second). Good for welding thin sheets and out of position (Used for steels only). DCEN. (Causes splatter)



- Spray transfer GMAW-ST – very stable metal transfer, directional and free from spatter. Use DCEP (DCRP) at high voltages. Can also be used for out-of-position welding (not flat).



- Limited use for thin sheet metal as high energy & heat.
- Globular transfer – large globules form on electrode tip and fall by gravity to workpiece. Slower, more spatter. DCEN

Gas Metal Arc Welding - GMAW

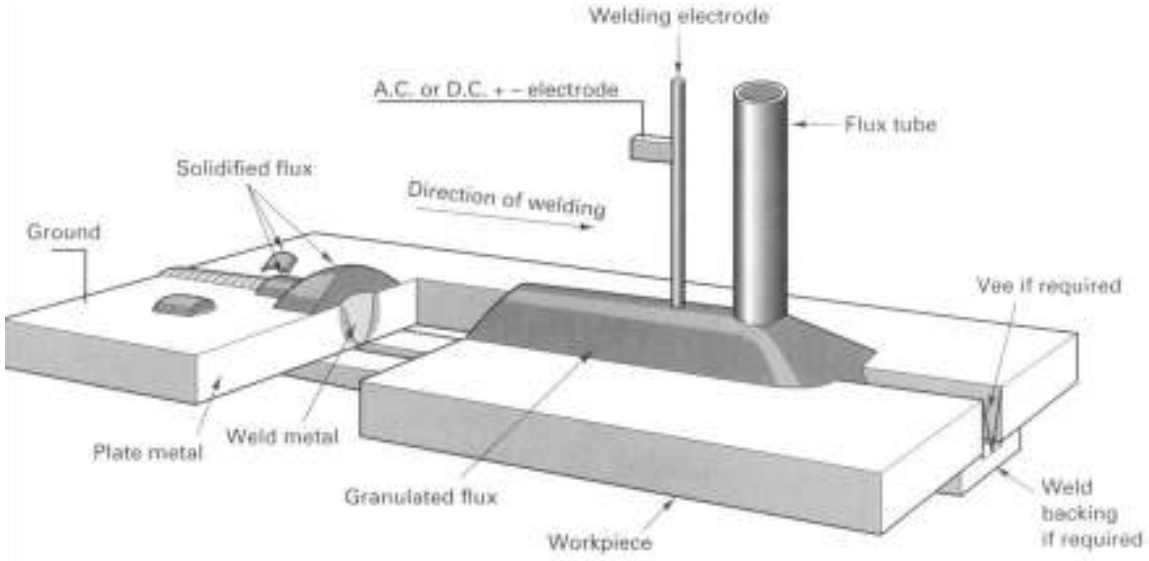
- Pulsed Spray Transfer GMAW-P – invented in 1960 to overcome limitations of conventional ST.
- Low currents are passed to create metallic globules. Then high current busts "explode" globules of molten metal onto workpiece –
- Lower workpiece temperatures, thinner metals, less distortion, less discolouration, less spatter, fine microstructure. Allows use of spray transfer on thinner metals at lower currents.
- All positions, safer, high speed, lower energy (reduced cost)
- DCEN mode usually used.

Gas Metal Arc Welding - GMAW

- GMAW is fast, economical, flexible. No changing of electrode, no flux formed, multi-pass welding without intermediate cleaning.
- Readily automated.
- Requires less manipulative skill than GTAW and SMAW
- High deposition rates (5 – 20 kg/hr)
- High efficiencies (80 - 90%)
- Power supplies relatively expensive.
- Advanced – GMAW -Wire is pre-heated as enters nozzle; less arc energy required, less base metal melted, less penetration.

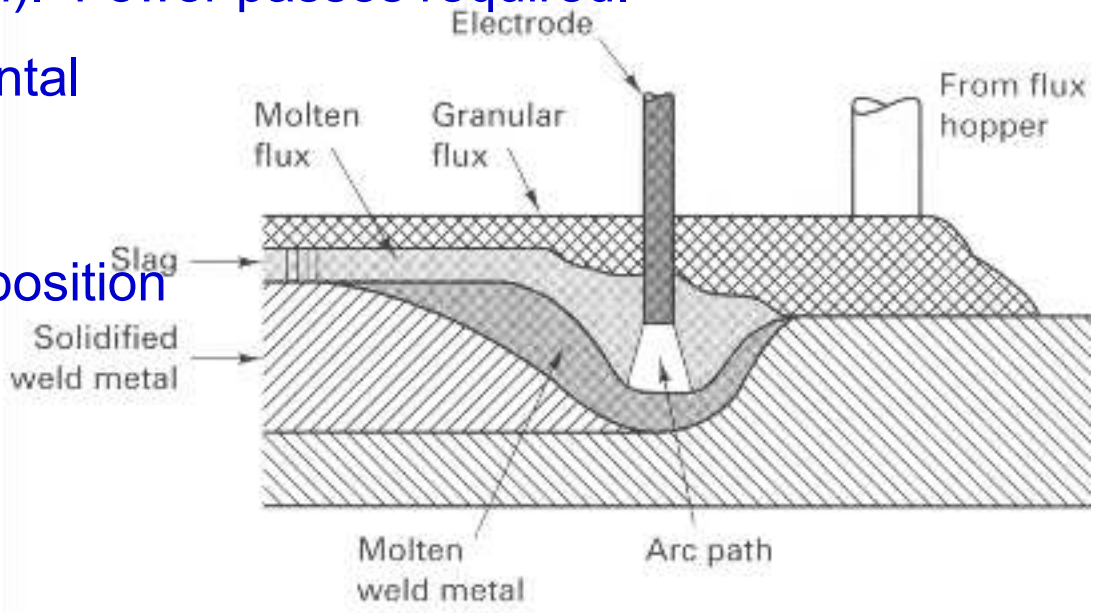
Submerged Arc Welding - SAW

- No shielding gas is used. Deposit thick layer of granular flux where joint is to be made just ahead of bare-wire consumable electrode. Arc maintained under surface of flux.
- Some flux melts, removes impurities from weld pool; unmelted gives thermal shielding; melted slag/flux forms glass on cooling.
- Flux provides thermal insulation - slow cooling, soft, ductile welds. Cold flux cracks off easily, unmelted flux recycled.



Submerged Arc Welding - SAW

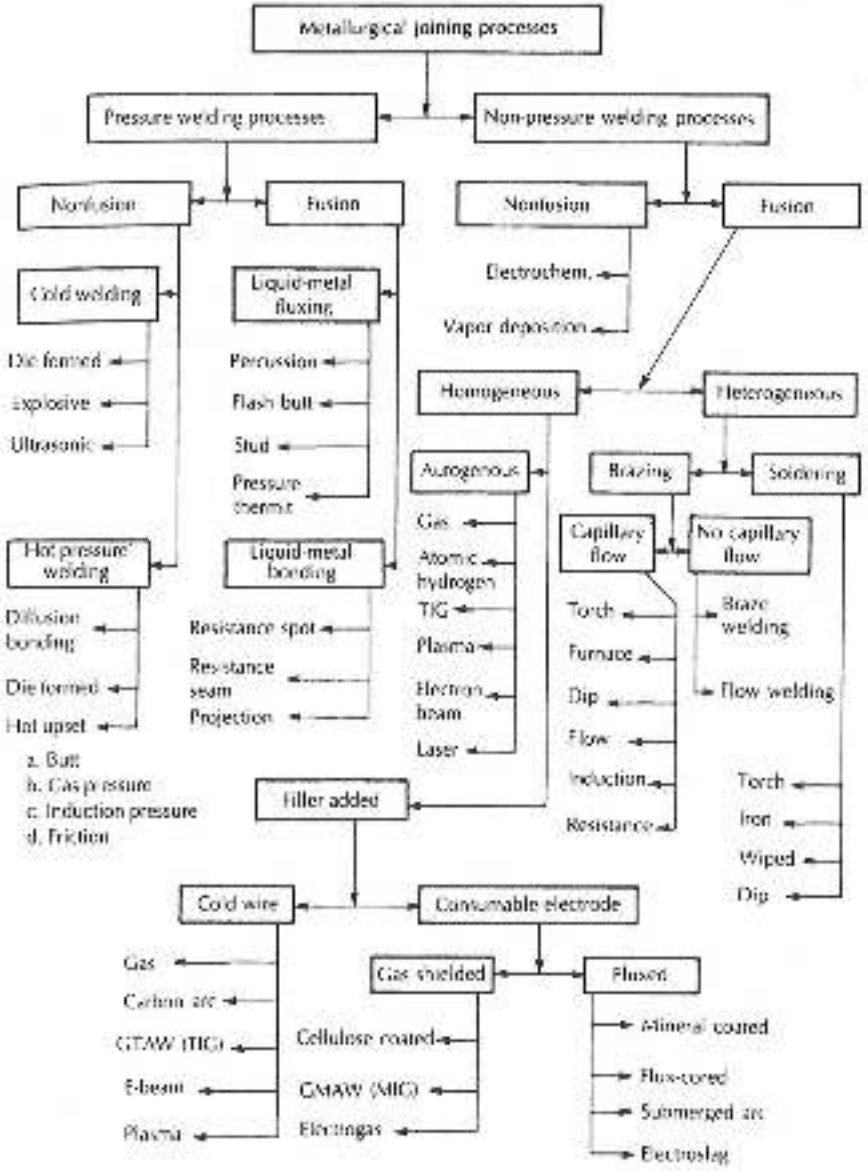
- Best for flat, butt or fillet welds in < 0.3%C steels (with pre & post-heating - Med. C steels / alloy steels / CI / SS, copper, nickel alloys).
- Not for high-C steels, tool steels, Al, Mg, Ti, Pb, Zn.
- High currents - so speed, high deposition rates (27 – 45 kg/hr), clean.
- 1½" deep single pass (38 mm). Fewer passes required.
- Good for automation. Horizontal position only.
- Electrodes classified by composition
- Solid wire (wire is alloyed)
- Plain carbon steel wire (alloy additions in flux)



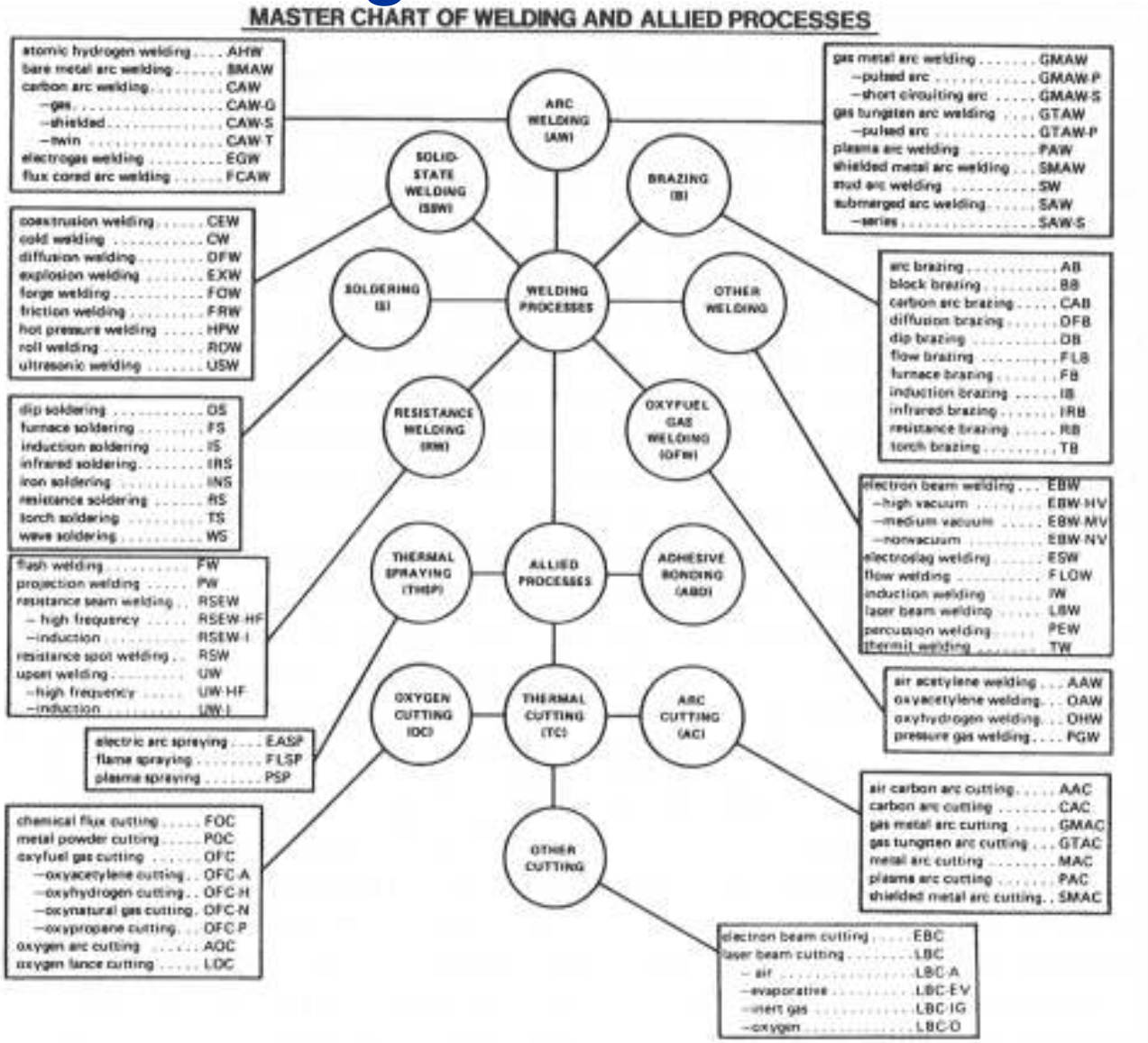
Submerged Arc Welding - SAW

- Tubular steel wire (alloy additions in centre)
- Larger electrodes carry more current – rapid deposition but shallow welds
- Flux need to have low MP and brittleness but high fluidity
- Limitation of submerged arc welding:
- Flux handling and maintaining flux quality (moisture etc).
- Large volumes of slag to be removed.
- High heat inputs – large grain size structure.
- Slow cooling rate (segregation, hot-cracking).
- Horizontal position only; Mechanized only.

Welding - Classification



Welding - Classification



MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

ARC Welding

Lecture 9

Submerged Arc Welding - SAW

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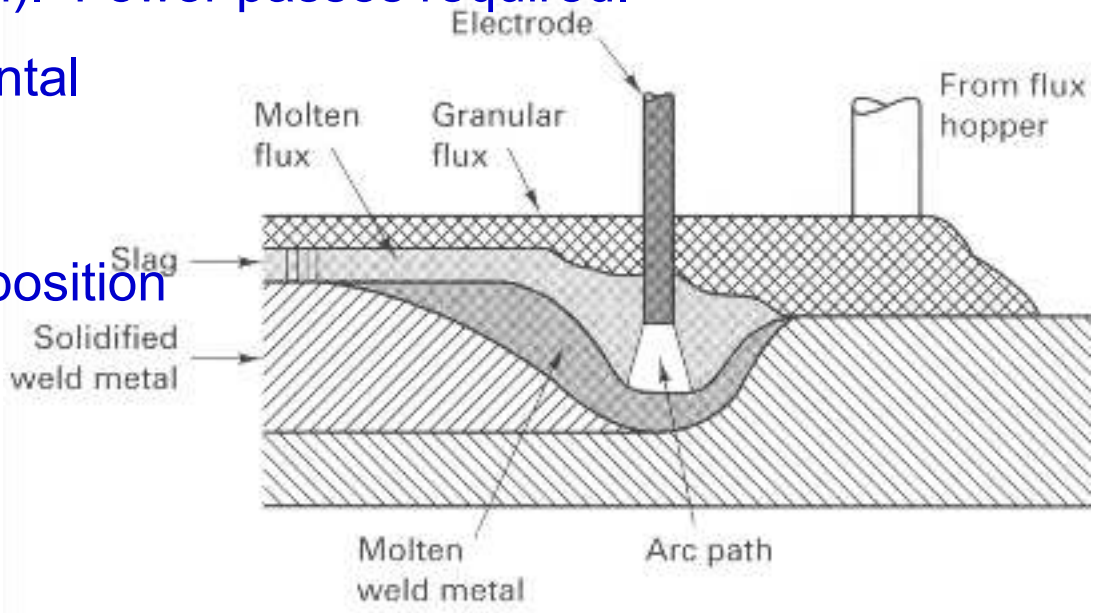

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- Limitation of submerged arc welding:
- Flux handling and maintaining flux quality (moisture etc).
- Large volumes of slag to be removed.
- High heat inputs – large grain size structure.
- Slow cooling rate (segregation, hot-cracking).
- Horizontal position only; Mechanized only.

Stud Welding - SW

- Arc welding process used to attach studs/fasteners to metal (plates etc).
- Special gun - stud acts as electrode.
- Small amount of melting at stud/workpiece then automatically presses stud to plate.

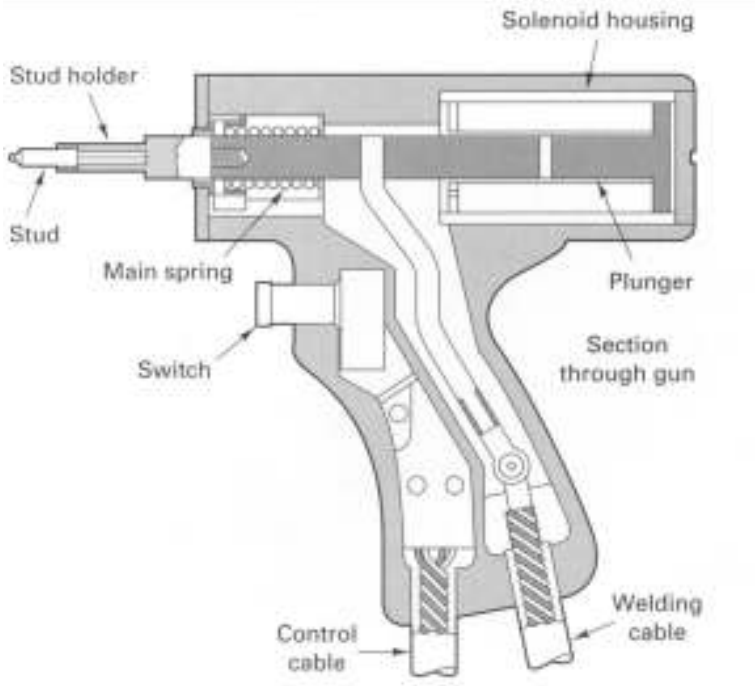
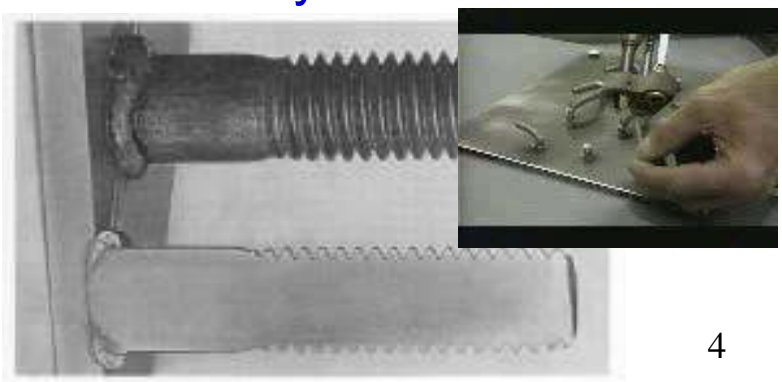


FIGURE 34-14 Schematic diagram of a stud welding gun. *(Courtesy of American Machinist.)*

- Completely automated - >1000 welds per hr - factory use.
- Power -Large currents required.

  150 - 1000 A 30 - 40 V DC/AC



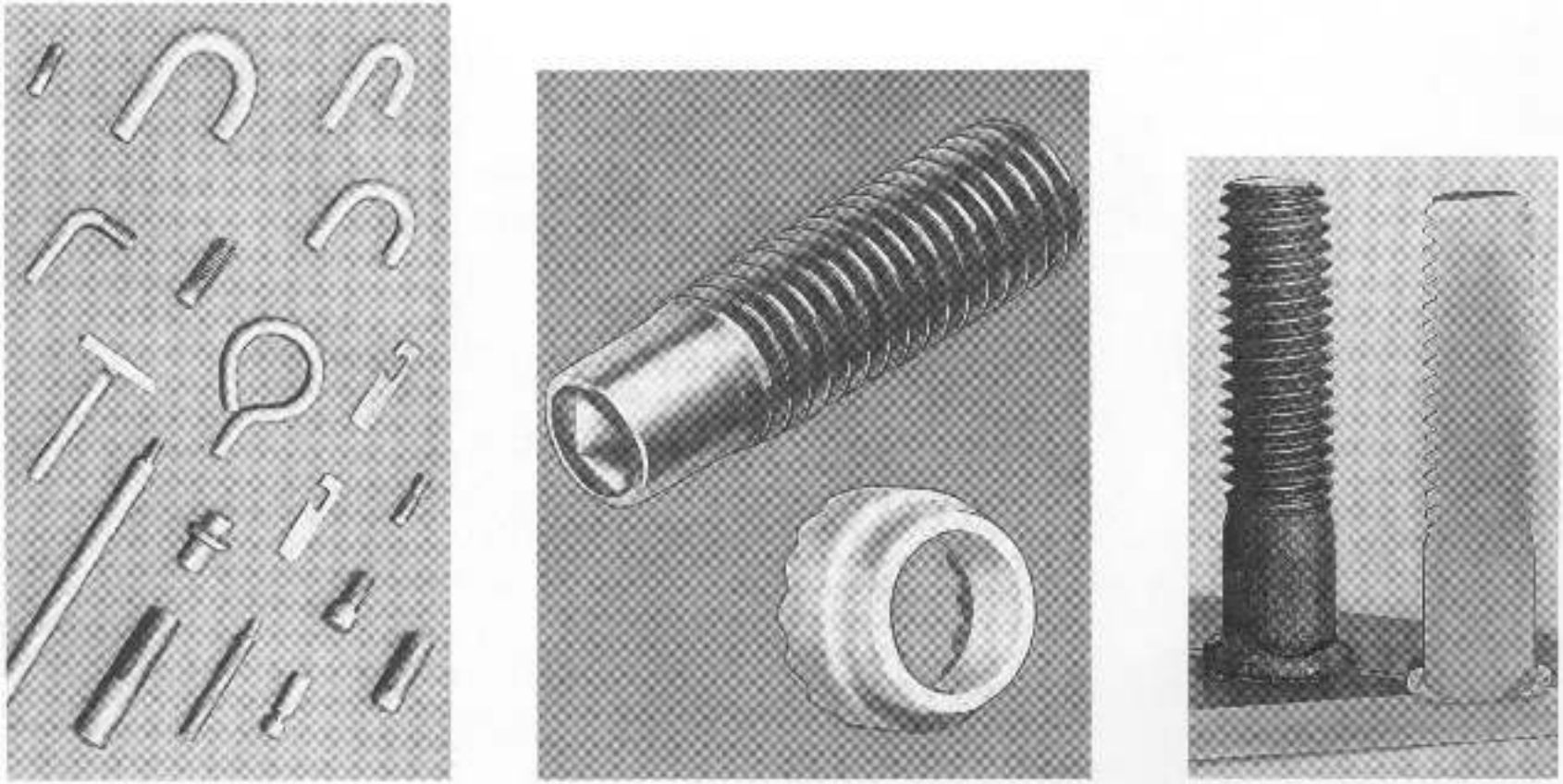


FIGURE 34-15 (*Left*) Types of studs used for stud welding. (*Center*) Stud and ceramic ferrule. (*Right*) Stud after welding and a section through a welded stud. *(Courtesy of Nelson Stud Welding Co.)*

Gas Tungsten Arc Welding - GTAW

- (Tungsten Inert Gas - TIG) Permanent (non-consumable) tungsten electrode is used to form arc with workpiece. Filler metal required
- Inert gas (he and/or ar) flows around electrode.
- Protects electrode & shields weld pool (stable arc-long electrode life).
- If metal pieces fit well, filler may not be needed. If it is needed use separate wire

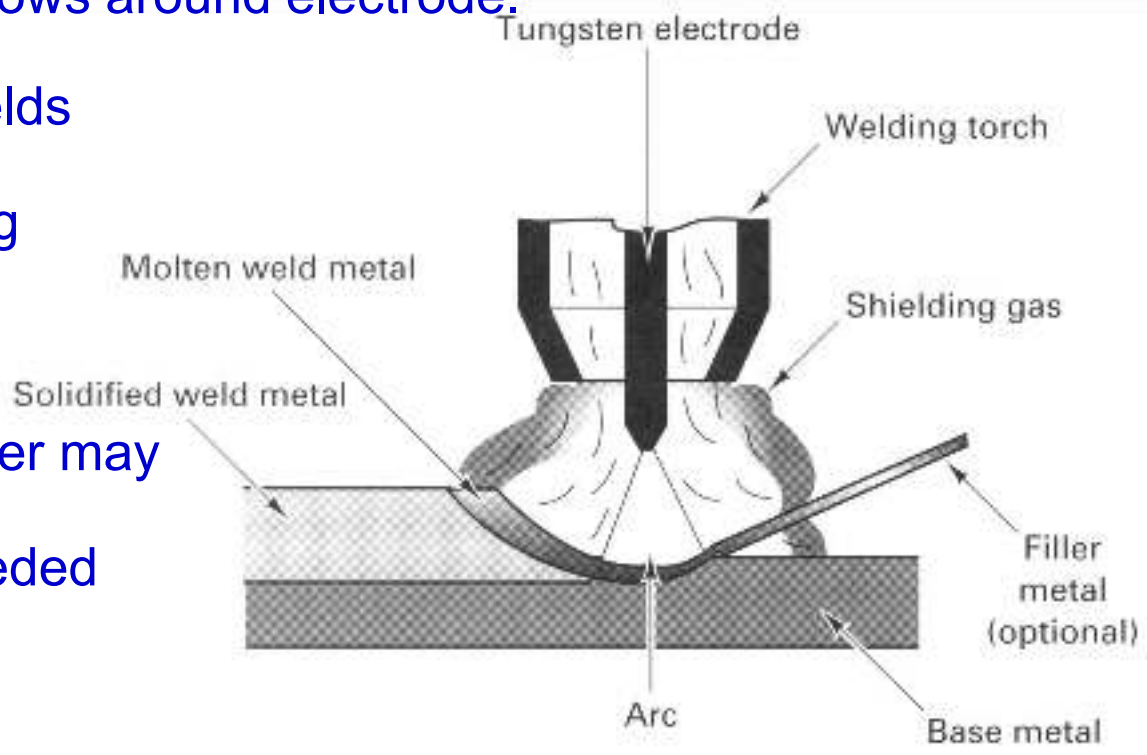


FIGURE 34-6 Schematic diagram of gas tungsten arc welding

Gas Tungsten Arc Welding - GTAW

- Tungsten electrode usually alloyed with 1-2% thorium/cerium oxides to give better current carrying capacity.
- Argon gives best shielding (heavier) and easier start.
- Helium gives hotter arc. Often use mixture.
- With skilled workers high quality weld, (clean and nearly invisible) can be produced

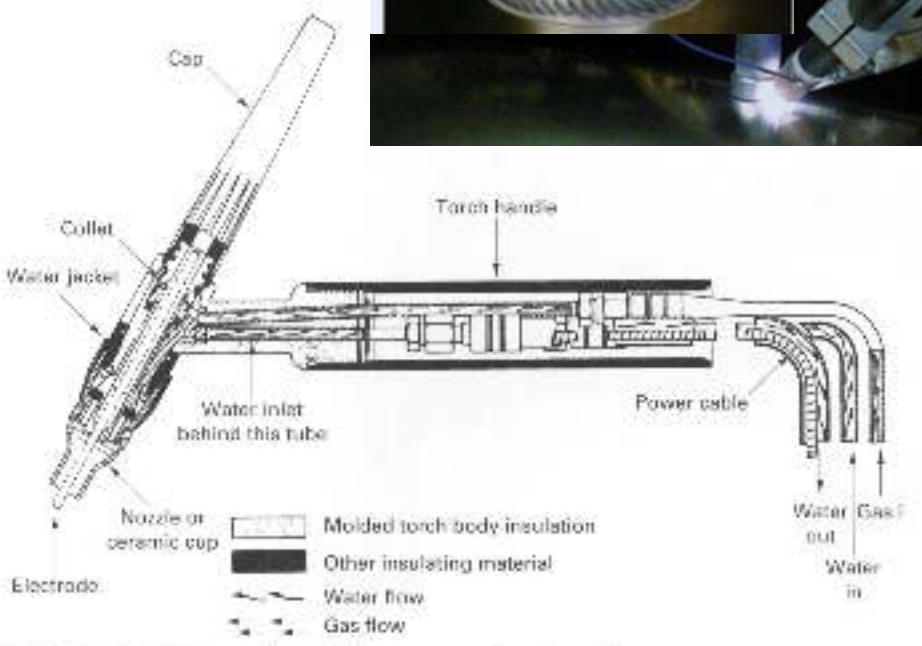


FIGURE 34-5 Welding torch used in nonconsumable-electrode, gas tungsten arc welding (GTAW), showing feed lines for power, cooling water, and inert gas flow. (Courtesy of Linde Division, Union Carbide Corporation.)

Gas Tungsten Arc Welding - GTAW

- Produces very clean welds, no flux, no slag etc.
- Surfaces must be clean (oil, rust, grease, paint)
- Slow deposition rate – 0.5 to 1 kg/hour.
- It can be increased by preheating the wire and oscillating the wire as well

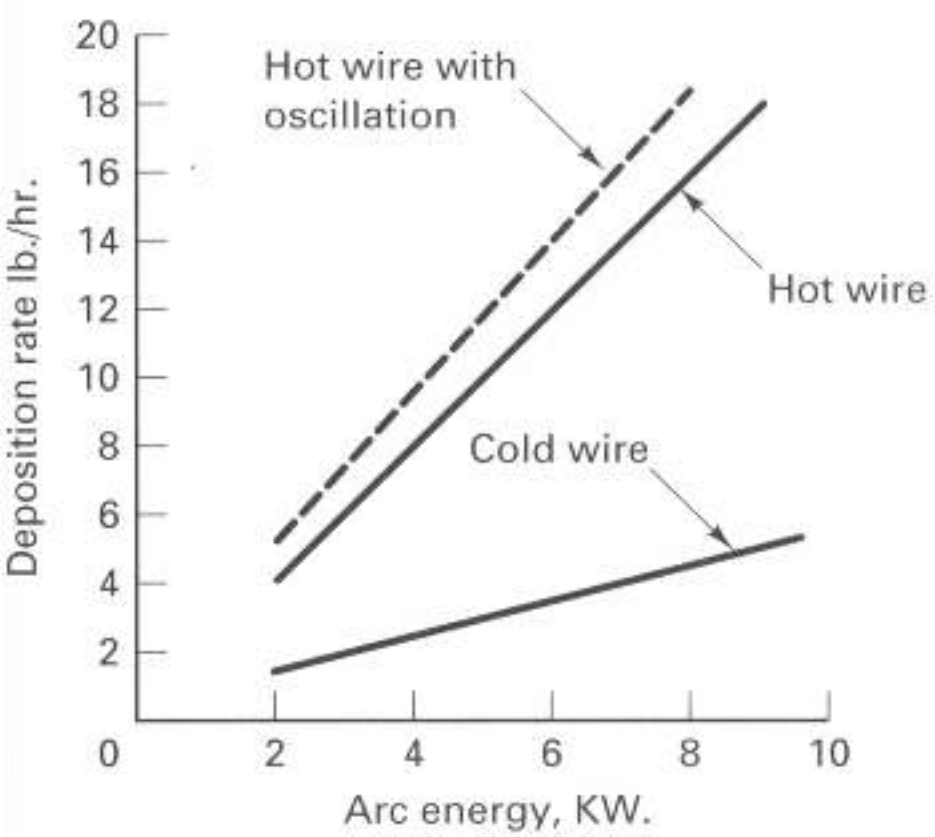


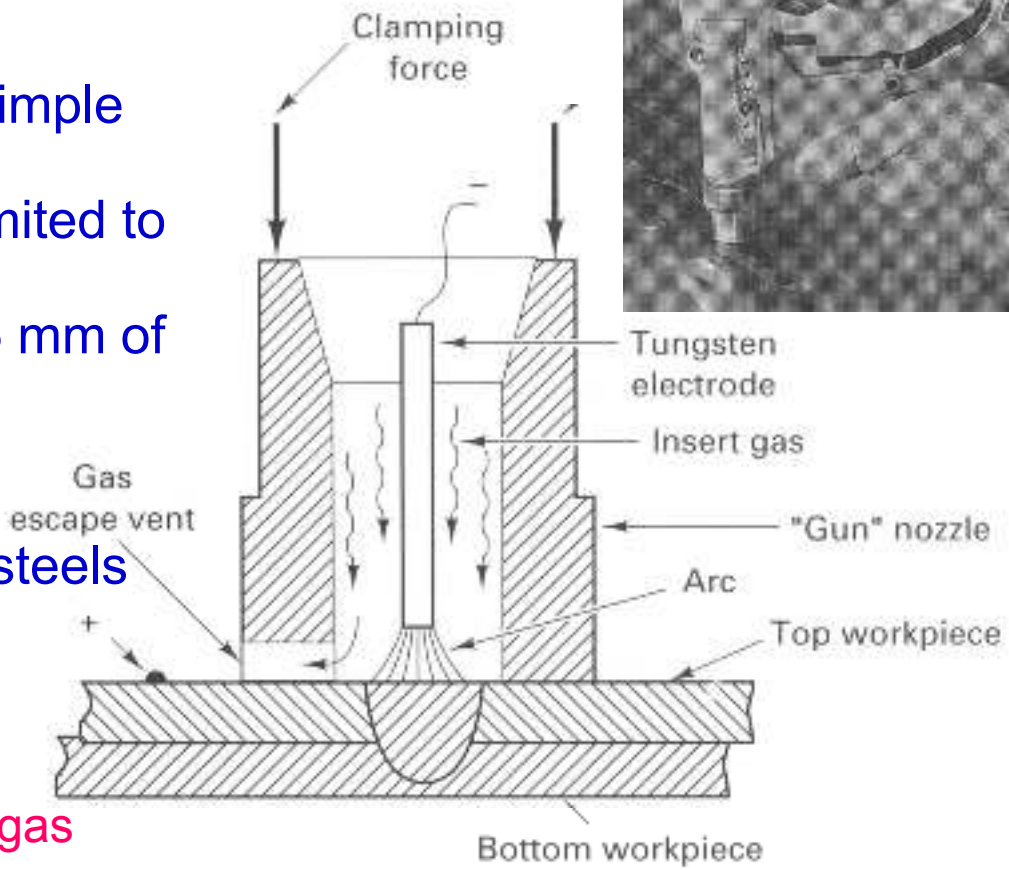
FIGURE 34-7 Comparison of the metal deposition rates in GTAW welding with cold, hot, and oscillating hot filler wire. *(Courtesy of Welding Journal.)*

Gas Tungsten Arc Welding - GTAW

- Can be used in: DCSP (EN) – No cleaning action, deeper penetration (more common)
- DCRP (EP) – Strong cleaning action, shallow (water cooled)
- AC – cleaning on half cycle, intermediate.
- Can weld All Metals & Alloys! Especially reactive ones (Al, Ti, Mg) and refractory ones because of Inert Gas used,
- 20-40 V 125 - 1000 A
- Good for welding thin sections (low heat input – especially in DCRP).
- Very clean process due to excellent shielding.

Gas Tungsten Arc Spot Welding

- Variation of GTAW to produce spot welds. Nozzle clamps metals together; arc heats through to interface and forms a weld.
- An extremely efficient and simple way to make weld joints. Limited to a maximum thickness of 1.6 mm of the sheet closest to the arc.
- Used for MS, SS, low alloy steels and aluminum alloys.



Schematic and photo of gas tungsten arc spot-welding

Gas Tungsten Arc Spot Welding

- Special welding gun; nozzle is used to apply pressure to hold the parts in close contact. Nozzle is made of copper or stainless steel and is normally water cooled since the arc is contained entirely within the nozzle.
- The nozzle design controls the distance between the tungsten electrode and the work surface; it should have ports for shielding gases to escape.
- The nozzles can also be designed to help locate the arc spot weld, especially with respect to corners or edges of the top sheet.
- Used to make tack welds at inside or outside corner joints, etc. Includes a trigger switch which will actuate the arc spot operation.

Gas Tungsten Arc Spot Welding

- Normal sequence: - Nozzle is placed on the joint and sufficient pressure is applied to bring the parts in intimate contact.
- Trigger is depressed, which starts the welding cycle. Gas flow is initiated to purge the area within the gun nozzle. (water starts to flow).
- Arc will be initiated and will continue for the set time. The shielding gas will continue to flow for a predetermined post-flow time.
- Normally, the thinnest metals joined are 24 gauge. (0.56 mm).
- The shielding gas will be either argon or helium; helium provides a smaller weld nugget with a greater depth of penetration. Argon produces a larger weld nugget with shallower penetration.

Gas Tungsten Arc Spot Welding

- Direct current should be used for all materials, except aluminum, with the electrode negative (straight polarity).
- Alternating current with continuous high frequency should be employed on aluminum. If aluminum is well cleaned, the electrode negative (straight polarity) can be used.
- Parts to be welded should be clean of oil, dirt, grease, scale, etc
- The weld diameter is the basis for the shear strength of arc spot welds. The shear strength will be similar to resistance spot welds made in the same material.

Gas Tungsten Arc Spot Welding

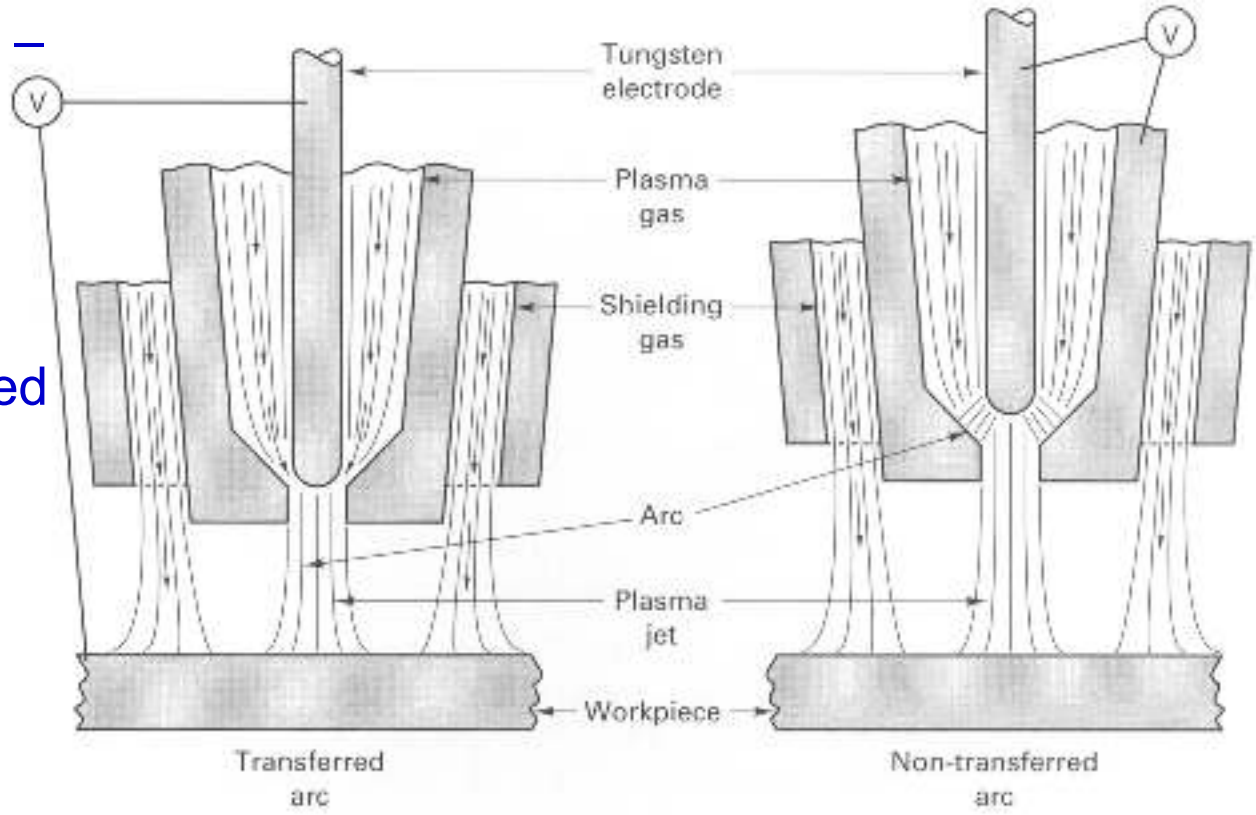
- Gas tungsten arc spot welding is widely used in the manufacture of automotive parts, appliances, precision metal parts, and parts for electronic components.
- It is normally applied as a semiautomatic process; however, it can be mechanized and used for high-volume production work.

Plasma Arc Welding - PAW

- (similar to GTAW) – non consumable electrode
- Make & maintain arc between Tungsten electrode & gun (non-transferred arc) or between electrode and workpiece (transferred arc).
- Inert gas (argon) passed through inner orifice to form "plasma" (primary arc), hot plasma gas heats workpiece (+ filler if required).
- Inert gas from outer nozzle provides shielding (Ar, He, Ar-He mix)
- Very hot (16,500°C +) focussed.
- Fast welding, narrow heat-affected zone, less distortion, deeper penetration, cleaner (less likelihood of tungsten contamination)

Plasma Arc Welding - PAW

- Depending on gas pressure can melt, melt through, or melt + blow away (plasma cutting).
- Left Transferred arc – used for welding/cutting,
- Right Non-transferred arc – used for thermal spraying.



Plasma Arc Welding - PAW

- Two modes of Plasma welding:
- Melt-in (conduction) mode: lower pressure/current plasma workpiece melts by conduction of heat from plasma contact on surface.
- Good for thin sections (0.025 – 1.5mm), fine welds at low currents and thicker welds >3mm at higher currents.
- Keyhole mode: very high current plasma has very high energy density and vapourizes a cavity through the workpiece and makes a weld by moving the “keyhole” along the weld line. Molten metal flows in behind keyhole to fill in joint. Up to 20mm thick.
- **Main disadvantage;** more expensive and complicated than GTAW

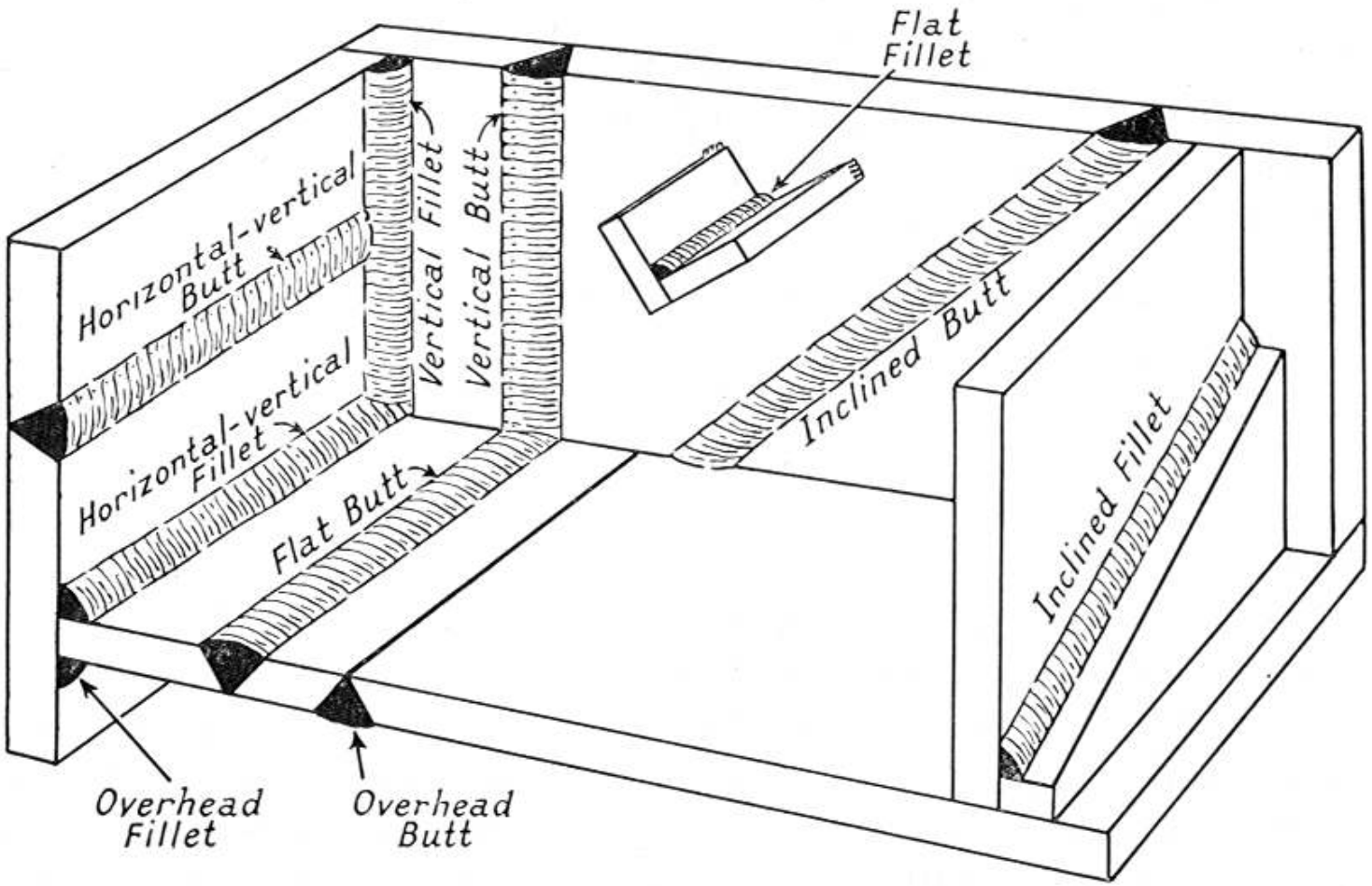


Fig. 2—Diagrammatic representation of the principal welding positions

Resistance Welding - Theory

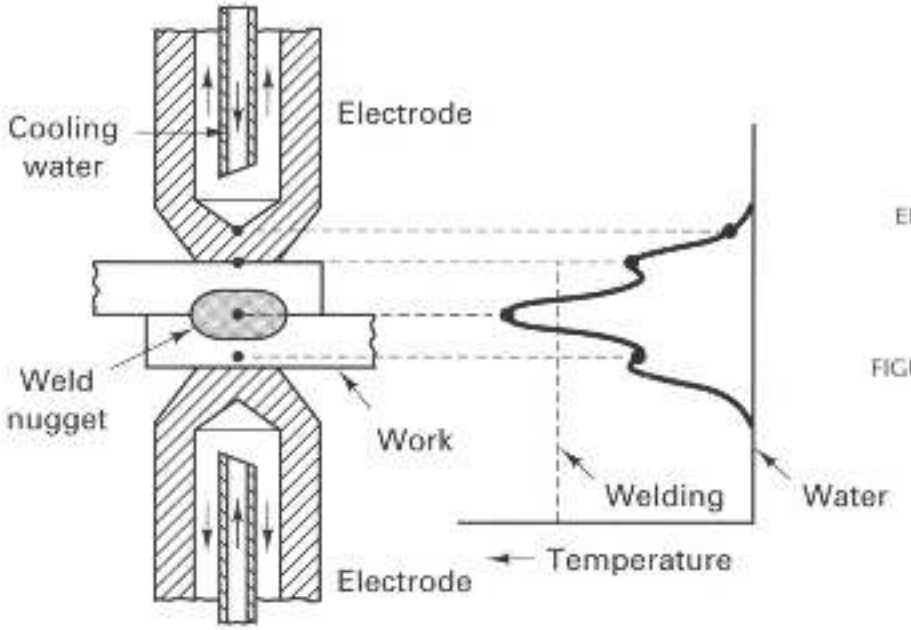
- Arc and oxy-fuel welding used heat (mainly)
- Resistance welding uses less heat + pressure to get coalescence.
- Same electrodes supply heat and apply pressure Heat supplied by electrical resistance of workpiece.
- Pressure (varied through weld cycle) is applied externally (some sort of press/clamping device)
- When hot enough apply pressure, get bonding (not necessary to get melting in all cases). - "Forging" weld.
- Resistance welding is not classified as Solid-State welding (where there is no melting involved) by the AWS

Resistance Welding - Theory

- No filler metal, no shielding gases required. Good for automation.
- Pass Current, $H = I^2Rt$ (get heating).
- Workpiece is part of circuit. Total resistance between electrodes:
  1. Resistance of the workpiece
  2. Contact resistance between workpiece and electrodes
  3. Resistance between workpiece surfaces (Faying surfaces, affected by surface cleanliness etc.)
- To get weld where wanted (i.e. at 3) need to make R(1) and R(2) << R(3).
- R(1) - usually low as joining metals (bulk electrical conductivity is high)
- R(2) - Use high conductivity electrodes (copper - water cooled) + proper shape + pressure.

Resistance Welding - Theory

- Additional heat and pressure can be supplied in some cases, to get grain refinement and tempering.
- V. high current up to 100,000 A (0.5 - 10V) DC
- Welding time is ≈ 0.25 seconds
- Usually used for overlap welding of sheets and plates.



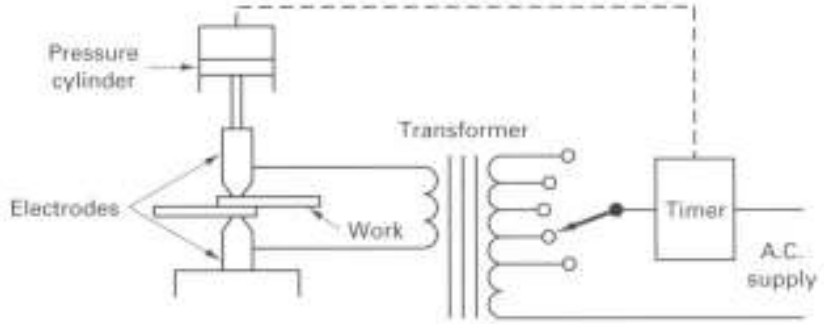


FIGURE 35-1 The fundamental resistance-welding circuit.

FIGURE 35-2 The desired temperature distribution across the electrodes and the workpieces in lap resistance welding.

Resistance Welding - Theory

- Forging pressure:

1. holds workpieces together and contains molten nugget as it expands (solid to liquid). (Expelled liquid reduces weld quality).
2. Pressure helps control contact resistance and rate of melting at surfaces. (Higher pressure lowers resistance).
3. For some techniques pressure is needed to forge weld together but will leave indentations.

- Ideal nugget should be 0.6 – 0.7 of combined thickness of two-ply (equal) joint.
- Magnitude + Timing of pressure is important.
  - Too much - spreading of material and/or “denting”
  - Too little - high heating/burning electrodes

Resistance Welding - Theory

- Current and current control:
- Control required - electronic current + pressure best
- Temperature achieved is primarily due to magnitude and duration of current supplied
- High currents at short intervals during welding to maintain heat and reduce dissipation
- The cycle of current and pressure can be programmed
- Quality depends on this schedule than on the worker skill
- High currents are required
- So transformers required to convert line current (high V)

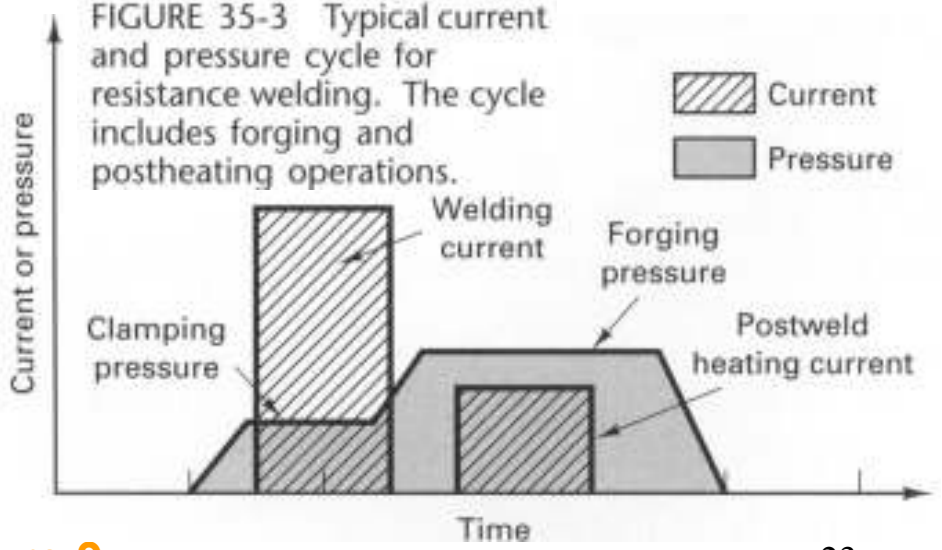


FIGURE 35-3 Typical current and pressure cycle for resistance welding. The cycle includes forging and postheating operations.

Resistance Spot Welding - RSW

- Simple, Common, fast, economical and Versatile
- Usually used for joining 2 overlapped materials, that does not require disassembly
- Dominant method of spot welding in automobile that has 2000 to 5000 spot welds
  - Overlapped sheets placed between water cooled electrodes
  - Contact electrodes top + bottom
  - Squeeze, and Pass Current
  - Open clamp & Joint finished.
  - Usually semi-automated

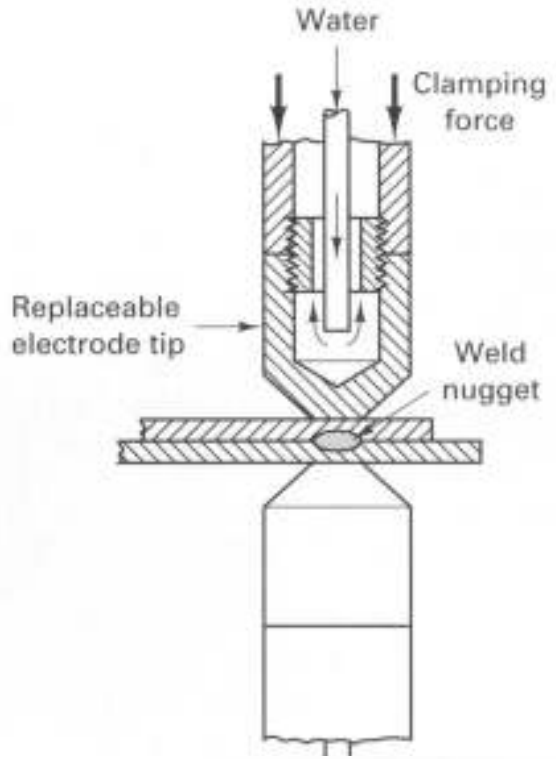


FIGURE 35-4 The arrangement of the electrodes and the work in spot welding, showing design for replaceable electrode tips.

Resistance Spot Welding - RSW

- Get "nugget" of coalesced metal. 1.5 –13mm diameter.
- Usually need access from both sides.
- Good spot weld (as in figures) usually formed between electrodes.
- Want weld to be stronger than HAZ
- Can be tested by doing a Tear Test
- Max 3 mm sheets usually (for similar metals)

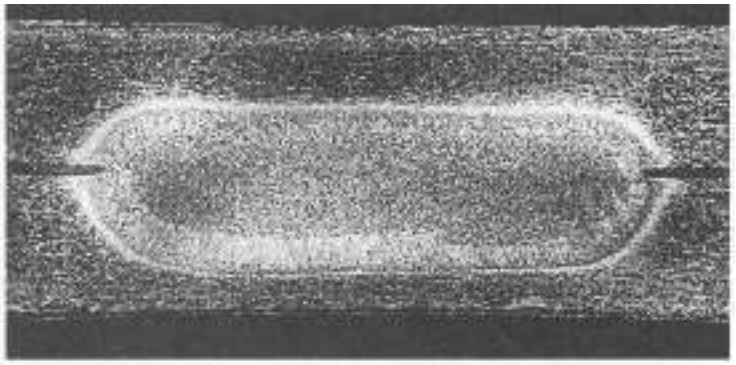


FIGURE 35-5 A spot-weld nugget between two sheets of 0.05-in. (1.3-mm) aluminum alloy. The nugget is not symmetrical because the radius of the upper electrode was greater than that of the lower electrode. *(Courtesy Locheed Aircraft Corporation.)*

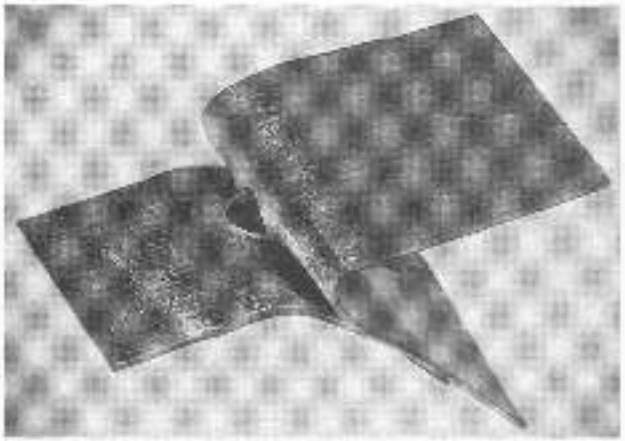


FIGURE 35-6 Tear test of a satisfactory spot weld, showing how failure occurs outside of the weld.

Resistance Spot Welding - RSW

- Portable spot welding guns are now available. Can be mounted on robotic arms – automotive industry.
- Steel is most commonly spot-welded material, but most commercial metals can be spot welded even to each other.
- Very high conductivity metals can be difficult to spot weld (Ag-Cu-Al).

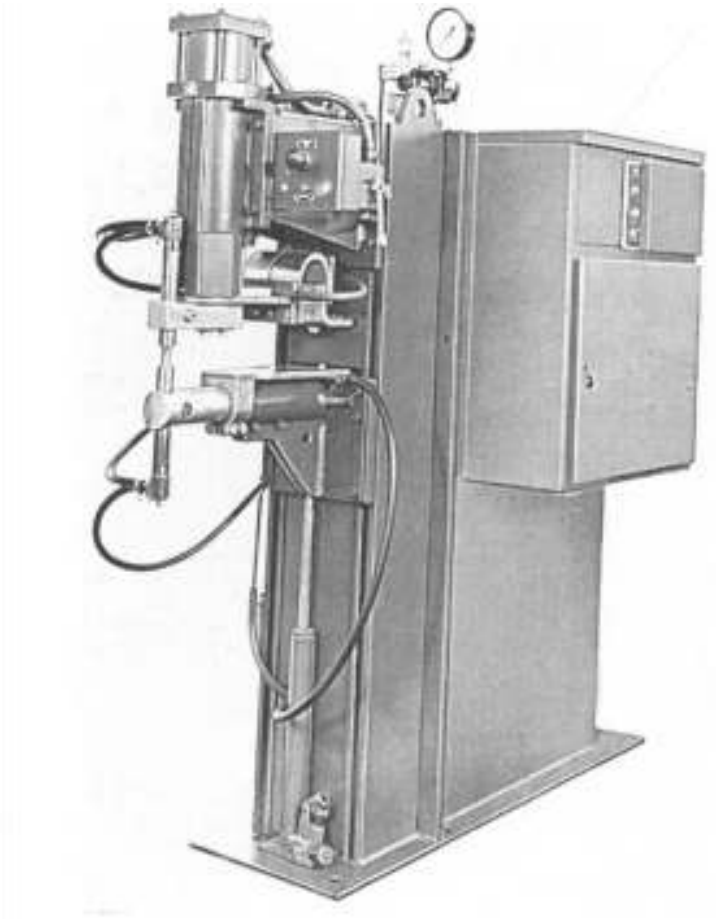


FIGURE 35-8 Single-phase, air-operated, press-type resistance welder with microprocessor control. *(Courtesy Sciaky Bros., Inc.)*

Resistance Spot Welding - RSW

- Electrodes must conduct welding current to work, set current density at location, apply fore, dissipate heat during the cycle
- Electrical and thermal properties are important. It should resist deformation and should not melt under welding conditions

TABLE 35-1. Metal Combinations That Can Be Spot Welded

Metal	Aluminum	Brass	Copper	Galvanized Iron	Iron (Wrought)	Monel	Nichrome	Nickel	Nickel Silver	Steel	Tin Plate	Zinc
Aluminum	×										×	×
Brass		×	×	×	×	×	×	×	×	×	×	×
Copper		×	×	×	×	×	×	×	×	×	×	×
Galvanized iron		×	×	×	×	×	×	×	×	×	×	
Iron (wrought)		×	×	×	×	×	×	×	×	×	×	
Monel		×	×	×	×	×	×	×	×	×	×	
Nichrome		×	×	×	×	×	×	×	×	×	×	
Nickel		×	×	×	×	×	×	×	×	×	×	
Nickel silver		×	×	×	×	×	×	×	×	×	×	
Steel		×	×	×	×	×	×	×	×	×	×	
Tin plate	×	×	×	×	×	×	×	×	×	×	×	
Zinc	×	×	×									×

Resistance Seam Welding - RSEW

- 2 distinct methods of RSEW, in the first method, sheet metals are joined to produce liquid or gas tight seams (Gas tanks, mufflers etc)
- Overlapping spot welds, usually produced by rotating disc electrodes
- Timed pulses of current produce overlapping welds. Timing of current and movement of work can be controlled to get proper overlap
- Workpiece is cooled by air or water

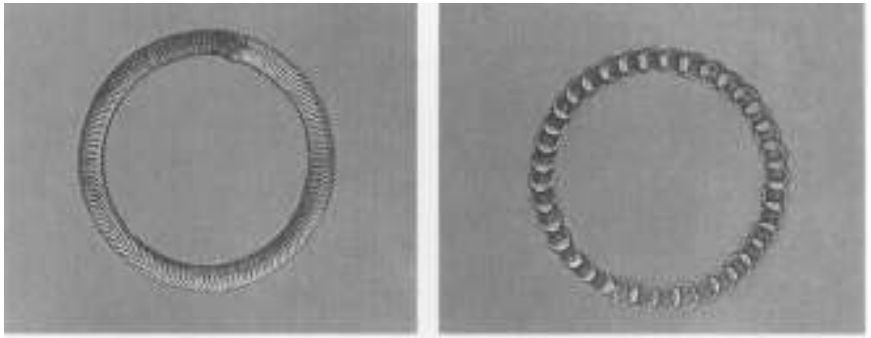


FIGURE 35-9 Seam welds made with overlapping spots of varied spacing. (Courtesy Taylor-Winfield Corporation.)

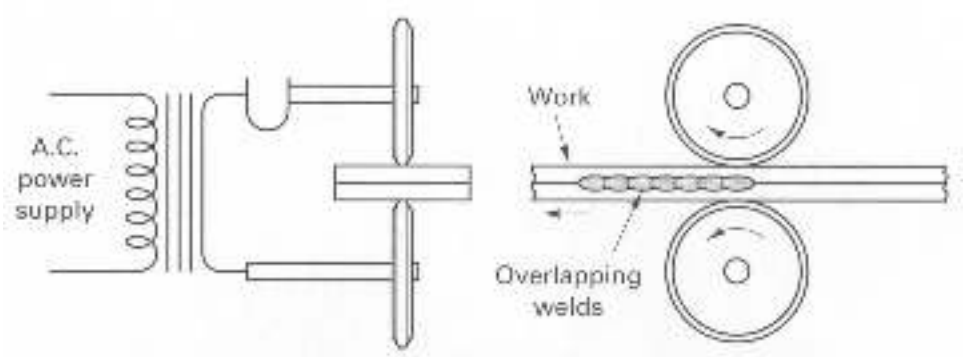


FIGURE 35-10 Schematic representation of seam welding.

Resistance Seam Welding - RSEW

- In the second method, butt welding between metal plates eg. making seam welded tubing, plate is deformed into tube and butt welded.
- High frequency current (450 kHz) is used to localize current + heating. (sometimes known as mash welding).
- Once the temperature is reached, pressure applied to form the weld
- 0.13 mm - 19 mm thick, 80m /min.
- Most metals or combinations including dissimilar ones

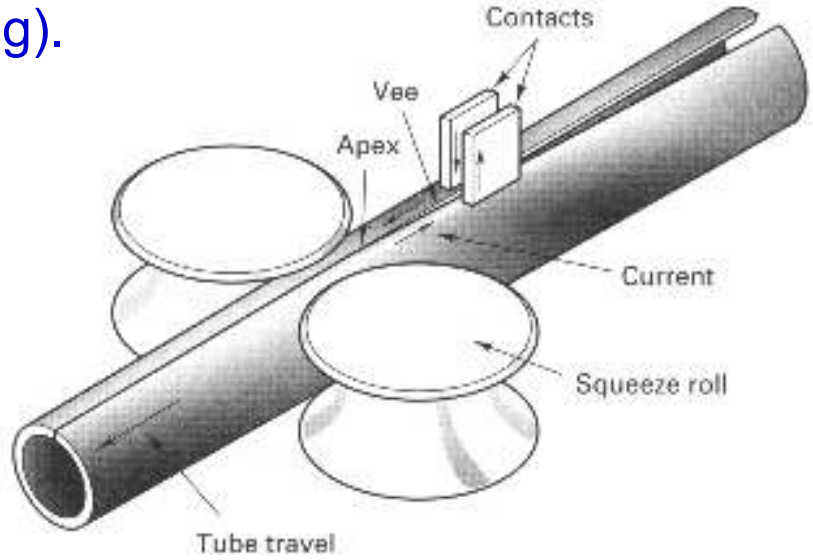


FIGURE 35-12 Using high-frequency ac current to produce a resistance seam weld in butt-welded tubing. Arrows from the contacts indicate the path of the high-frequency current.

Projection Welding - RPW

- Conventional spot welding, in mass production, the problem is maintenance of electrode. As the small electrodes carry high current, and apply pressure as well
- In projection welding, Rather than use one pair of contact electrodes on machine and keep doing enough spots to give strength: emboss (press) projections onto one workpiece where welds are required.

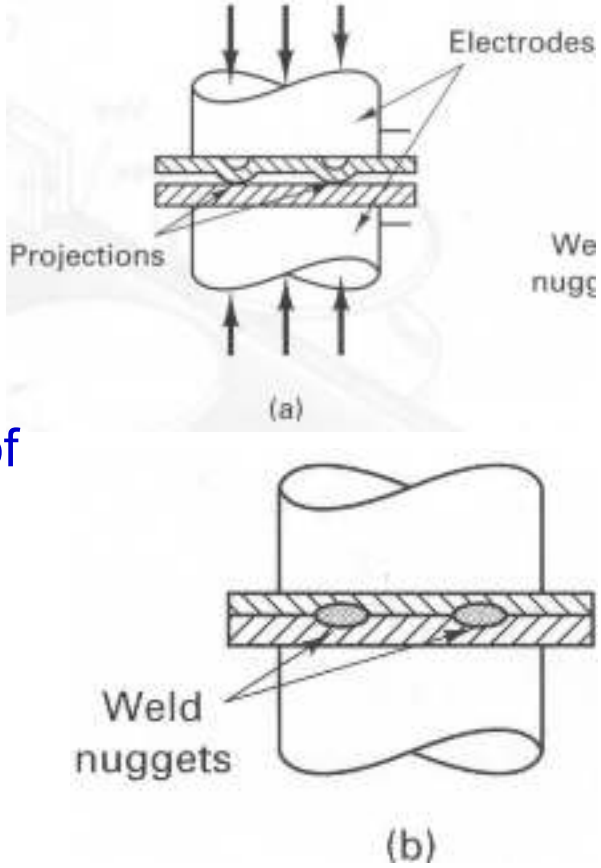
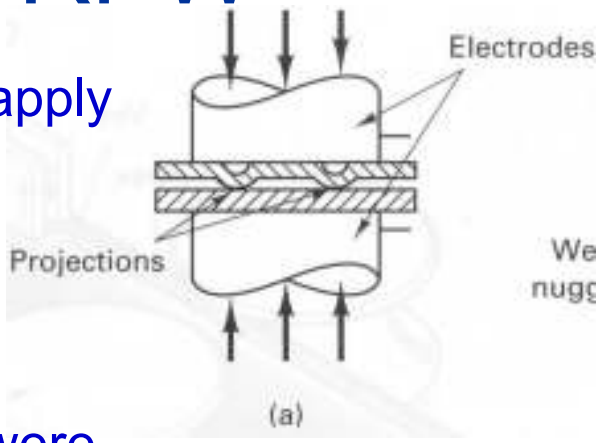
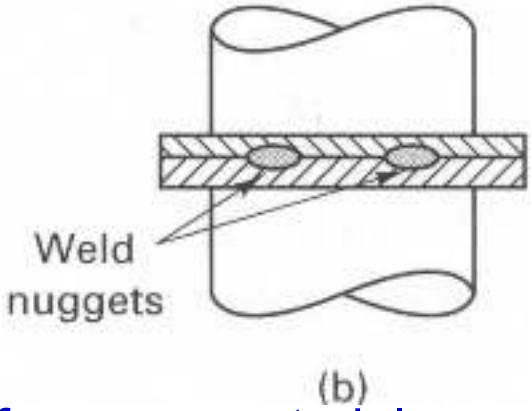


FIGURE 35-13 Principle of projection welding: prior to application of current and pressure (a) and after formation of the welds (b).

Projection Welding - RPW

- Pass current through large area electrodes and apply pressure on the Workpiece
  - dimples (contact points) heat up
  - apply pressure - welds form where dimples were.
- Easy to press/manufacture dimples or projections (vary shape) while doing other operations, without additional cost
- Better to have projections on thicker material (heat forms on material with projection
- RSW machines can be changed to RPW by varying electrode size





Resistance Welding - Summary

Advantages	Limitations
• Rapid & Easily automated	• High capital cost; Access to 2 sides
• Unskilled operators	• Limited joint configuration (mostly lap)
• Dissimilar metals joined	• Equipment needs good maintenance
• Less Distortion of parts	• Some materials (Al, Mg) need cleaning
• High reliability/ reproducibility	• Some steels (>0.15%C) can form martensite unless post-heat heated locally.
• Conserve material: no flux/filler/gas	

Solid State Welding

- **Non-fusion** – welds that can be produced without the need for melting or fusion.
- Some rely on substantial pressure to cause gross plastic deformation to produce a weld (Forge -, cold -, roll -, explosive welding) while others rely on friction to generate heat (friction and ultrasonic welding) and others on diffusion etc.
- Generally non-fusion processes offer some advantages – see table.
- Usually lower heating, no fusion zone, minimal heat affected zone, minimal intermixing so often good for dissimilar materials.

Solid State Welding

TABLE 4.2 Relative Advantages and Shortcomings of Nonfusion Welding Processes

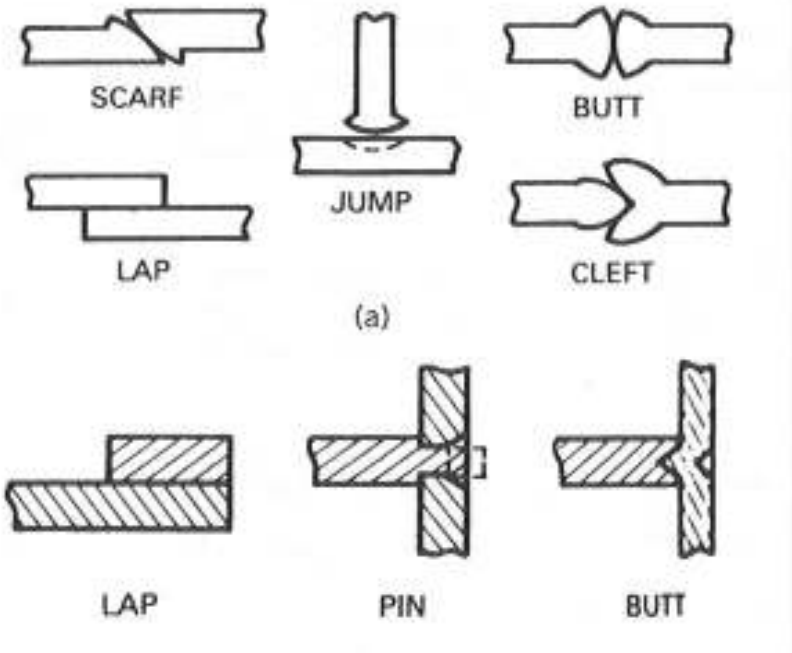
Advantages	Shortcomings
1. General absence of melting and, thus, solidification (so, structure is retained)	1. Stringent requirements for cleaning joint faying surfaces for some processes (e.g., CW, ROW, HPW, DFW, and solid-state deposition welding)
2. Low heat input (minimally disrupts microstructure)	2. Elaborate tooling is required for some processes (e.g., DFW)
3. Wide variety of process embodiments	3. Challenging inspection of joint quality
4. Applicable to many materials within a class as well as between classes (since there is little or no intermixing)	4. Repairing process-induced defects is difficult to impossible
5. High joint efficiency is possible for many situations where the same cannot be said for fusion welding processes	5. Processes require specialized equipment are rarely portable, and almost always must be automated

Forge Welding FOW

- Most ancient of welding processes. Forge welding of gold and silver nuggets in prehistoric times.
- Blacksmith
  - heat, shape, flux, heat, join/shape etc.
- high degree of skill/experience required.
- temperature, surface cleanliness, shape, deformation.
- Not that common now on large scale.
- Low carbon steels, high carbon steels and extruded aluminum alloys.
- Forge seam welding used to make butt-weld rolled pipe.

Forge Welding FOW

- Forge seam welding used to make butt-weld rolled pipe.
- Heated steel strip is formed into a cylinder and edges pressed together (lap/butt)
- Pressure as the metal passed through rolls create welds



Manual (a) and automated (b) forge welding joint designs.

Cold Welding CW

- "solid state process in which pressure is applied at room temperature to produce coalescence of metals by plastic deformation".
- No HEATING required!
- Metallurgical bond formed by plastic deformation
- Metals (at least one) must be ductile with little work-hardening. Prime examples are FCC metals such as Al, Cu, Pb, Au,Ag, Pt.
- Good for joining dissimilar metals. E.g. Al to Cu electrical connections.
- Clean surfaces are essential; mechanical brushing or abrasion or chemical etching (acids/alkalis)

Cold Welding CW

- Overlay, deform (30-50% Cold Work), solid state bond, some localized heating.
- Use mechanical or hydraulic presses or rolls.
- Common in electrical joints

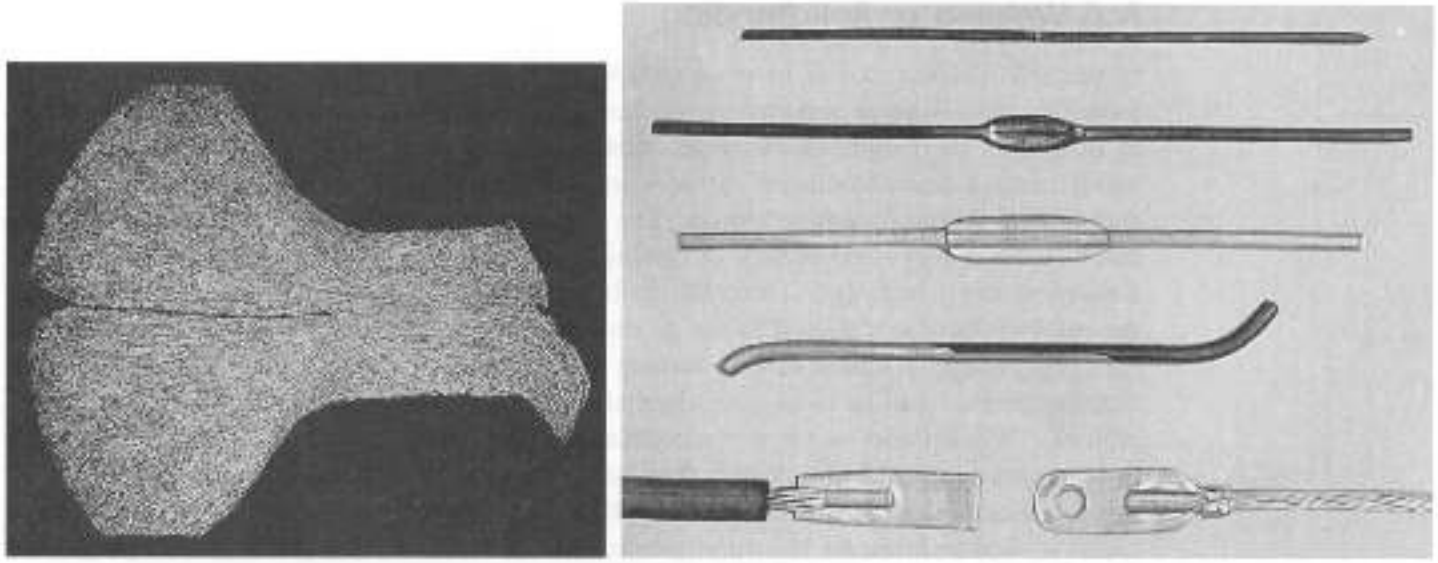
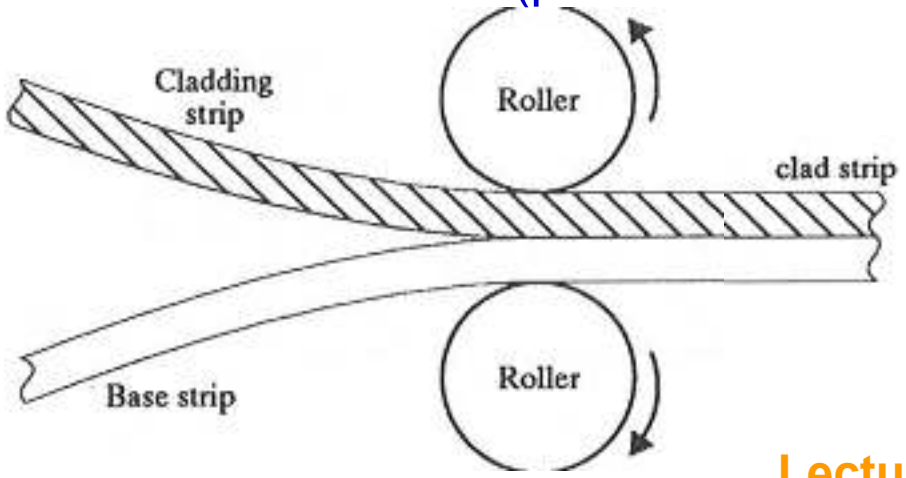


FIGURE 36-1 (*Left*) Section through a cold weld. (*Right*) Small parts joined by cold welding. *(Courtesy of Koldweld Corporation.)*

Roll Welding / Roll Bonding ROW

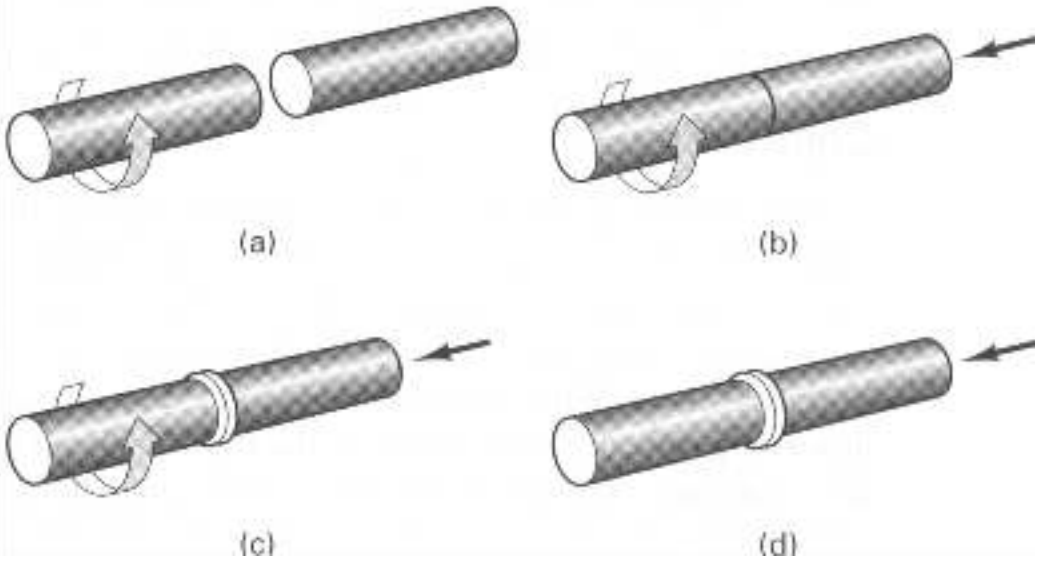
- Roll 2 or more sheets together (Hot or Cold), pressure - produces weld.
- Rolling reduces thickness, which increases length or width. The new area of interface, on pressure, welds together
- Often used for "CLADDING" eg. Alclad aluminum alloys. 2024 Al with pure Al surfaces or steel with s/s/ cladding (U.S. dimes/quarters)
- Use masking material to prevent bonding in certain locations.
- Then can deform (pressure/heat etc) to form channels - fridge panels.



Friction Welding FRW

- **Rotation**
- Heat required generated by friction at interface
- Smooth faces, one stationary, one rotating
- Pressure increased
- Heat generated
- When hot enough, stop rotation/press
- Softened metal squeezed out

FIGURE 36-2 Sequence for making a friction weld. (a) Components with square surfaces are inserted into a machine where one part is rotated and the other is held stationary. (b) The components are pushed together with a low axial pressure to clean and prepare the surfaces. (c) The pressure is increased, causing an increase in temperature, softening, and possibly some melting. (d) Rotation is stopped and the pressure is increased rapidly, creating a forged joint with external flash.



Friction Welding FRW

- FLASH (can be machined off); 100 mm ø bar, 250 mm ø tubes
- Quick and Efficient process; No melting - solid state; Narrow weld – small Heat affected zone HAZ
- Surface contamination squeezed out
- Many metals. (dissimilar as well) Clean, no fillers, etc.
- But Geometrical Restrictions + hot ductility in one component

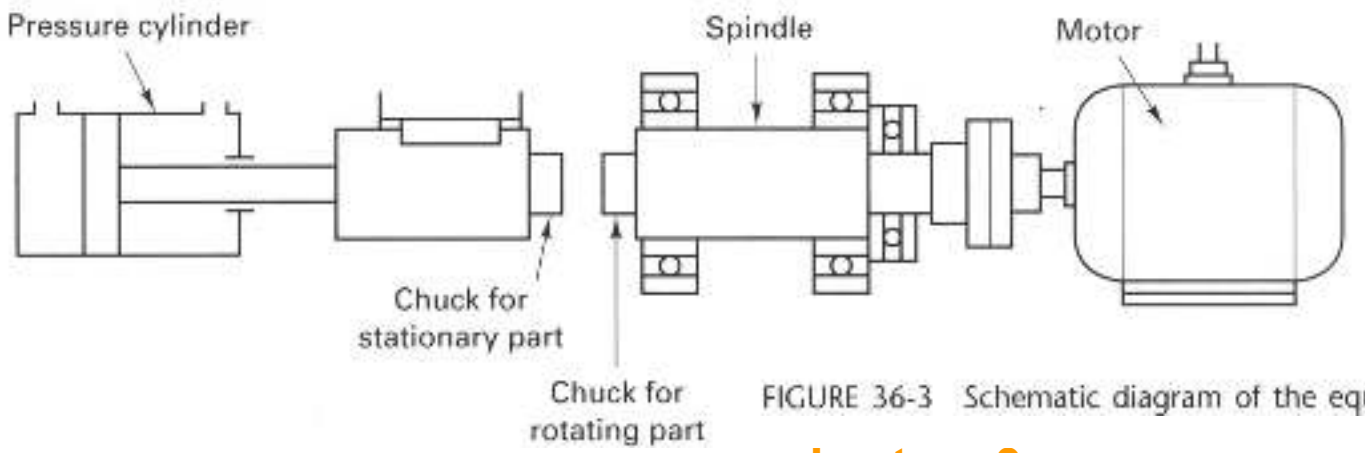


FIGURE 36-3 Schematic diagram of the equipment used for friction welding.

Friction Welding FRW

- In inertia welding, moving piece is attached to a flywheel which is brought to certain speed and isolated from the motor
- Energy is stored in a flywheel and it is pressed with stationary piece
- The kinetic energy of the flywheel is converted to frictional heat at interface
- Weld is complete when the wheel stops spinning and pieces remain pressed.

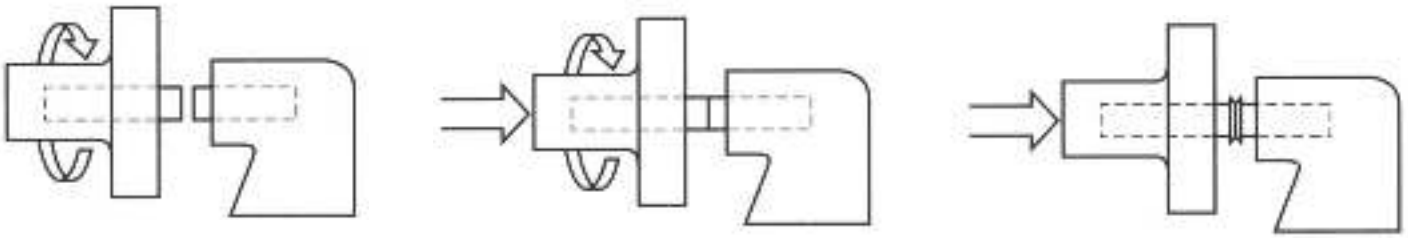


FIGURE 36-4 Schematic representation of the three steps in inertia welding.

Friction Welding FRW

- Welding is in short duration. High heat input and limited time for dissipation, less HAZ
- Oxides and impurities are displaced rapidly outward to flash which can be removed after welding
- All energy is converted (high efficiency)
- No melting, can be any metals/combinations
- Some bearing materials cannot be done
- Grain size refined so strength is same as base metal
- Environmentally attractive, no smoke, no flux, or fumes or gases released

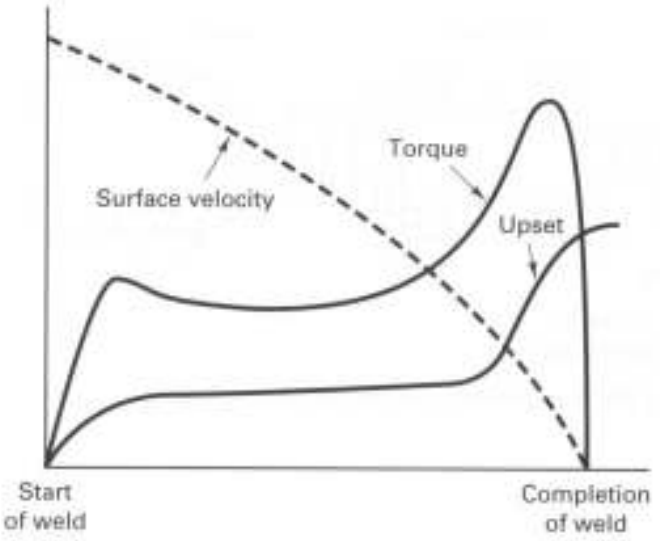


FIGURE 36-5 Relationship between surface velocity (speed), torque, and upset throughout the inertia welding process.

Friction Welding FRW

- At least one of the components to be welded should be rotationally symmetric
- Primarily used to join tubes or round bars of same size
- Linear, orbital and angular reciprocating motion can extend the friction welding to non circular shapes
  - Like square or rectangular bars
- One or preferably both of the components need to be ductile when hot
- This will permit deformation during the forging

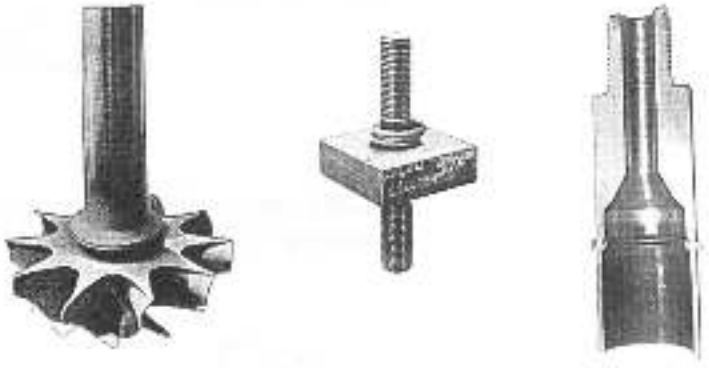
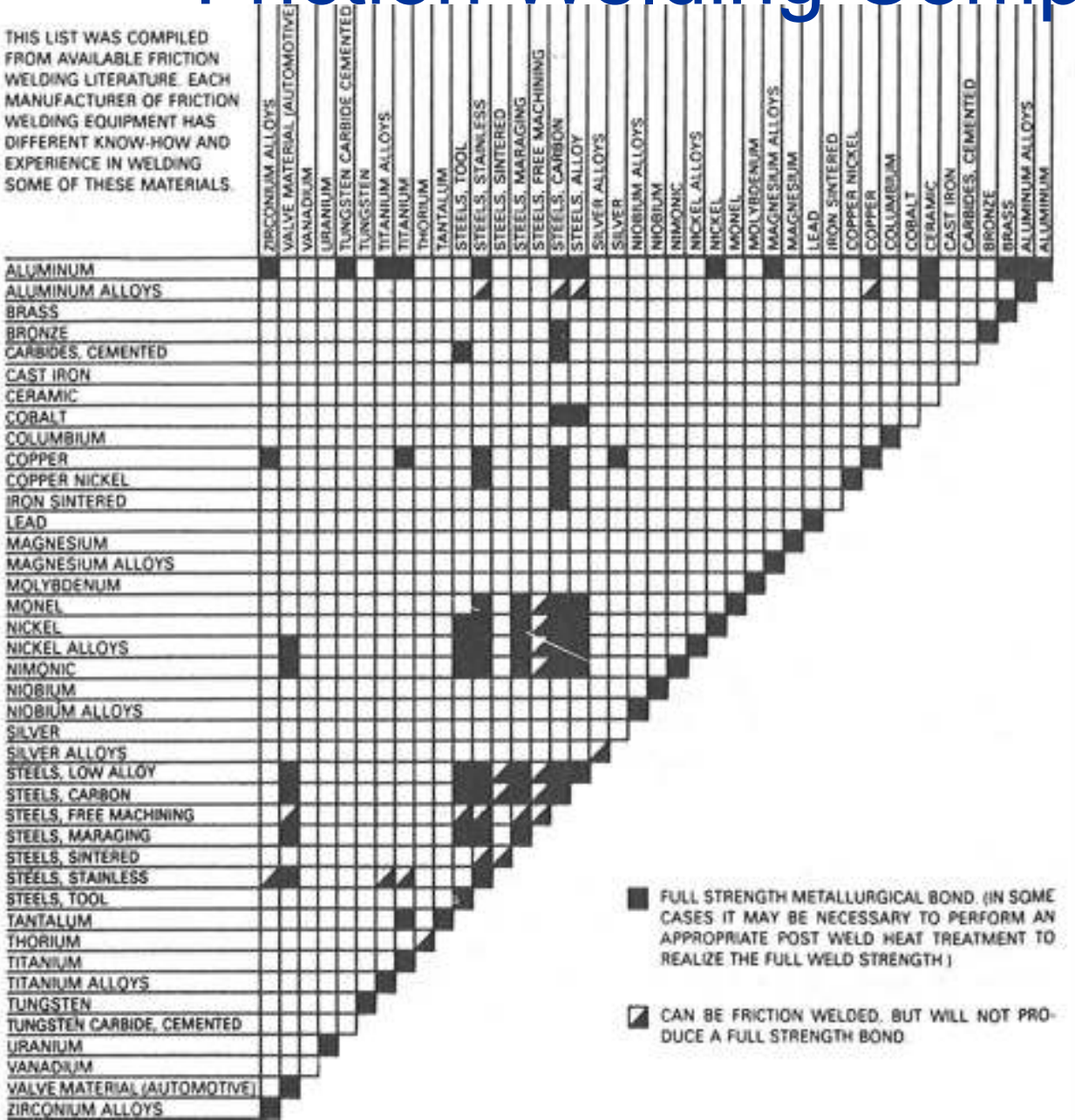


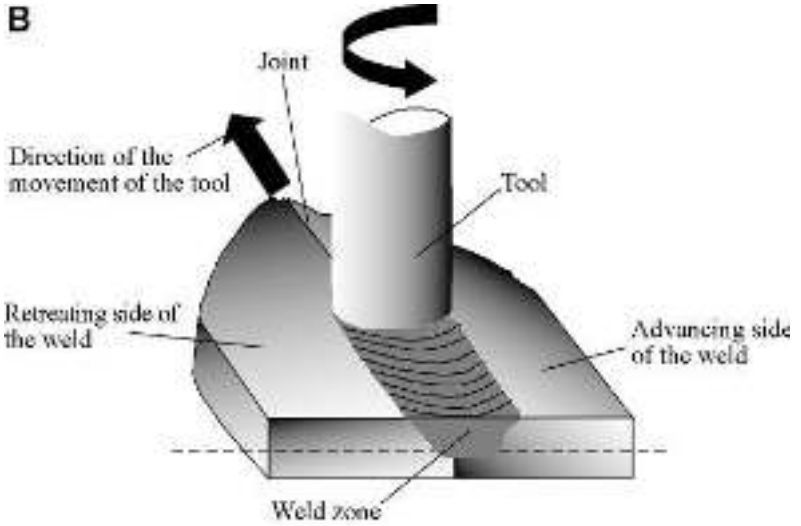
FIGURE 36-6 Some typical friction-welded parts. (*Left*) Impeller made by joining a chrome–moly steel shaft to a nickel–steel casting. (*Center*) Stud plate with two mild steel studs joined to a square plate. (*Right*) Tube component where a turned segment is joined to medium-carbon steel tubing. *(Courtesy of Newcor Bay City, Div. of Newcor, Inc.)*

Friction Welding Compatibility



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

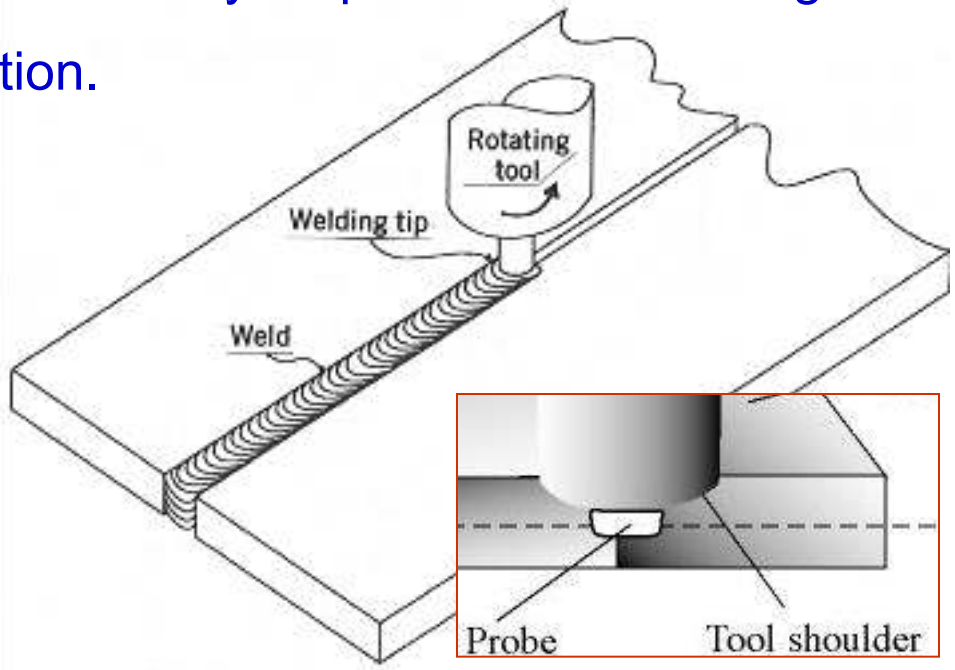
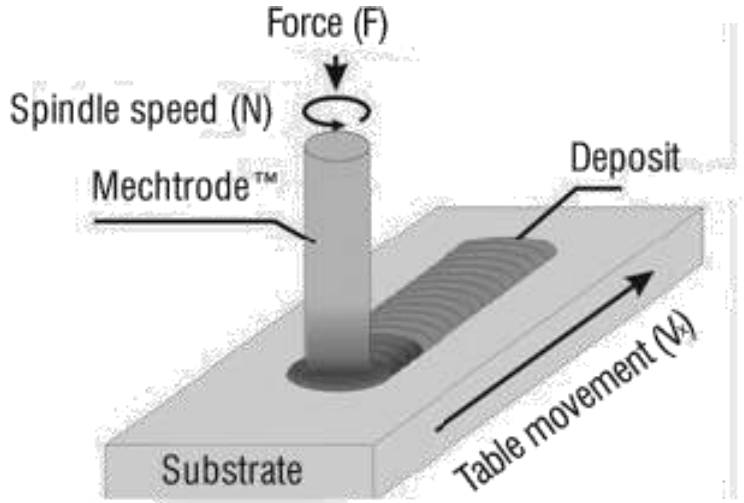
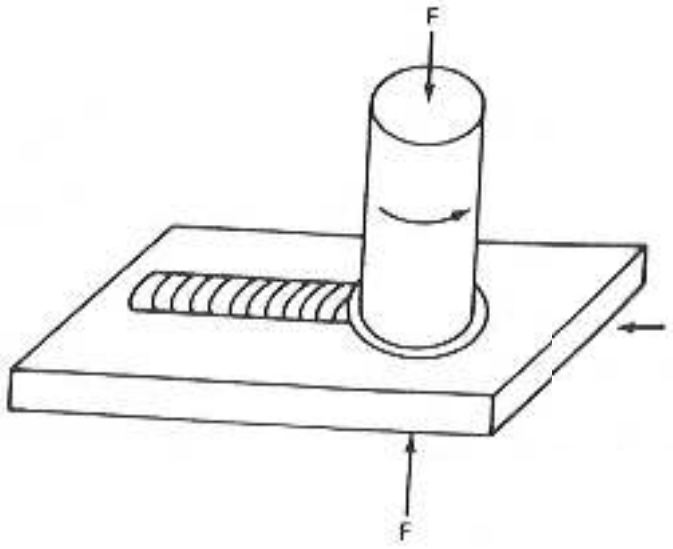


Figure 4.15 Schematic of friction stir welding.

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.





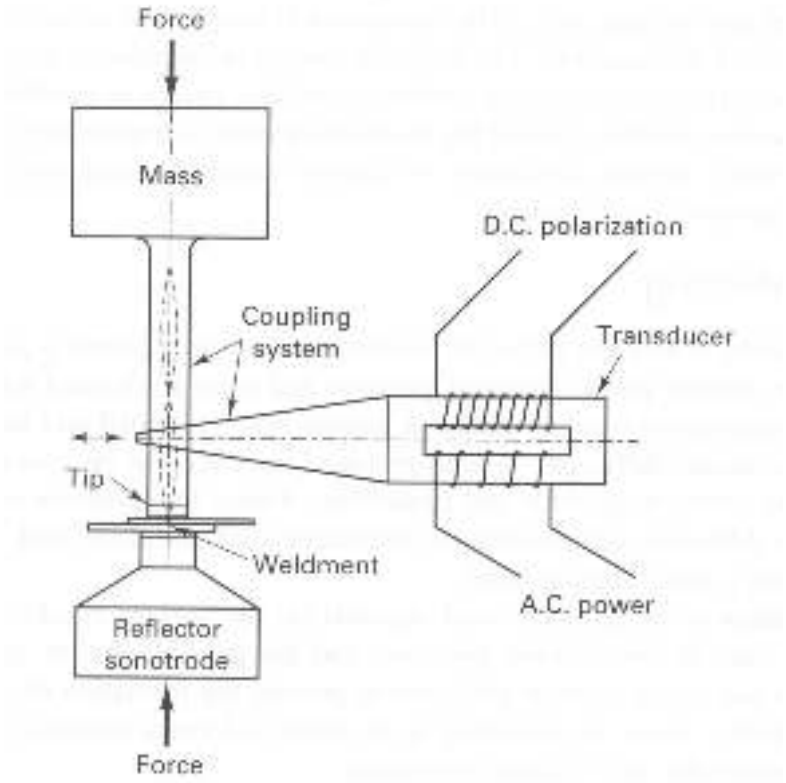
Other Welding Processes

Ultrasonic Welding USW

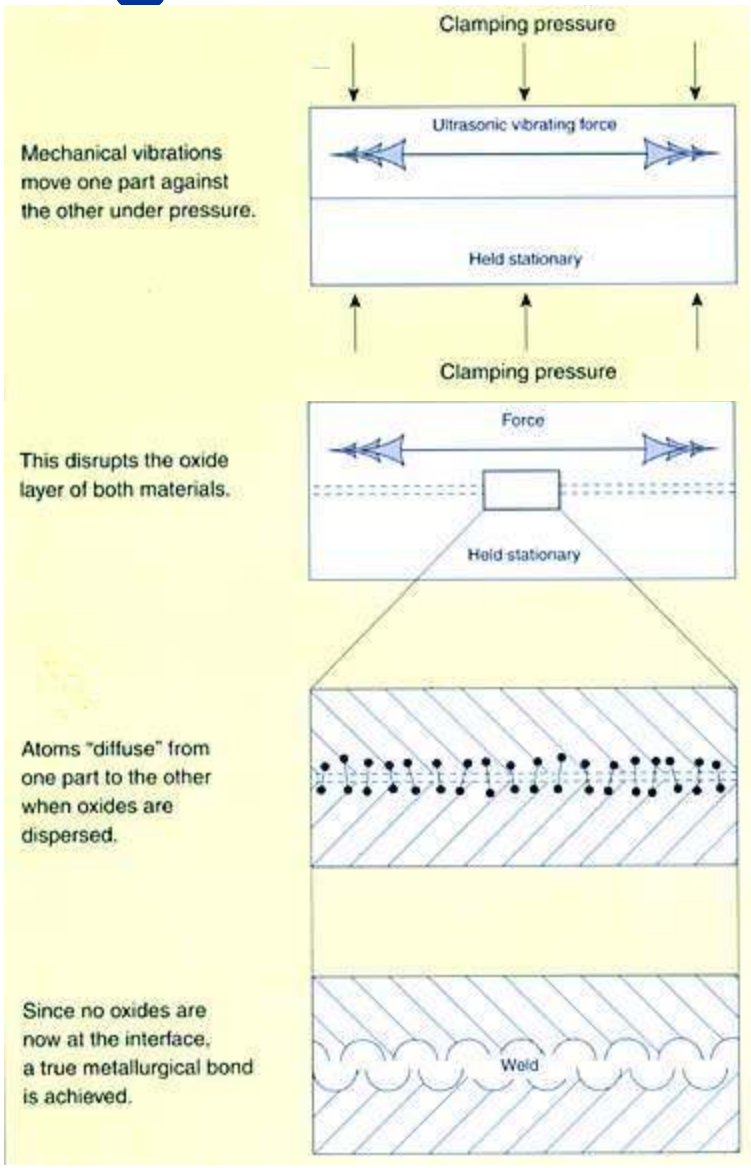
Vibrational motion causing friction.

- 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

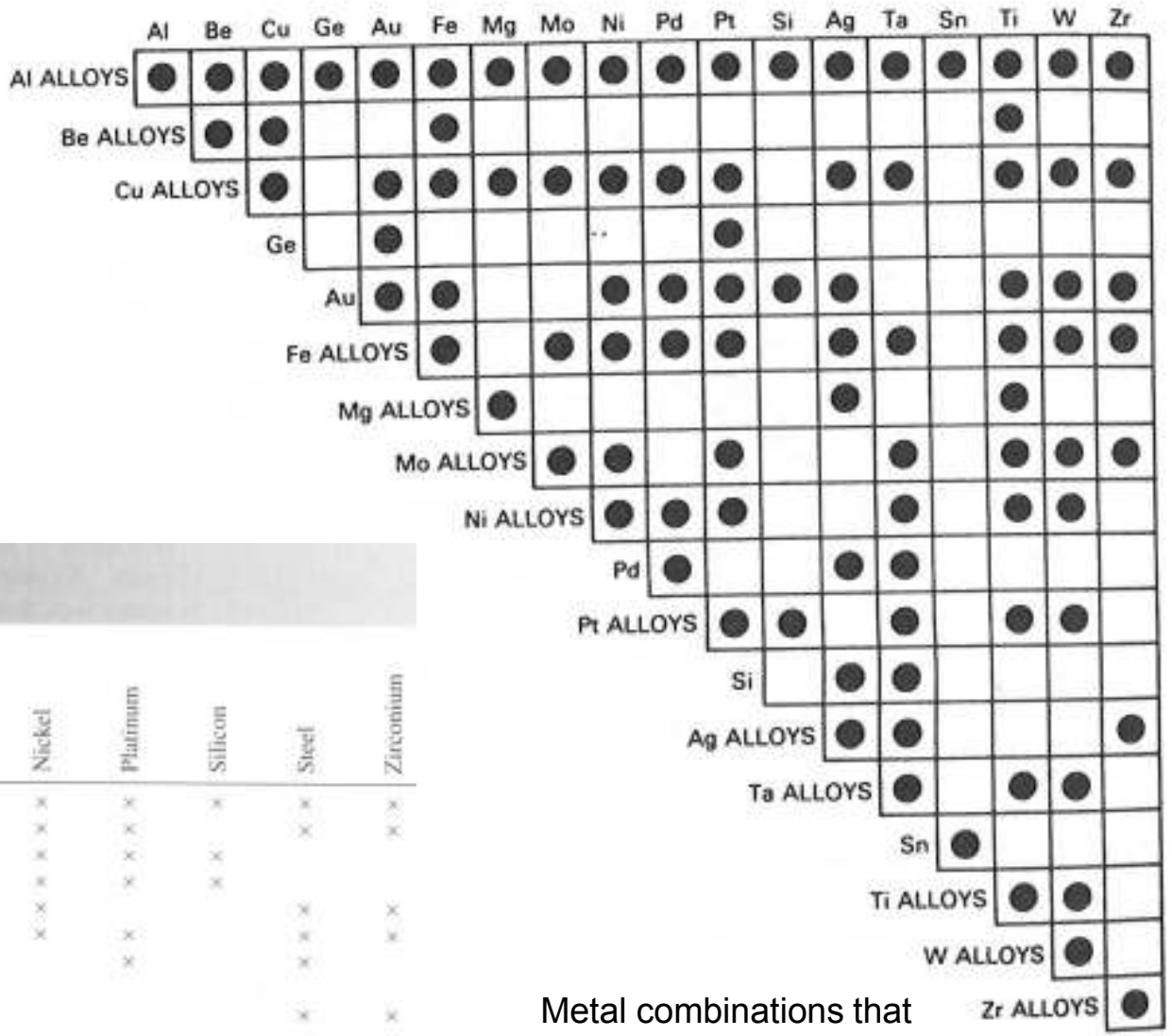


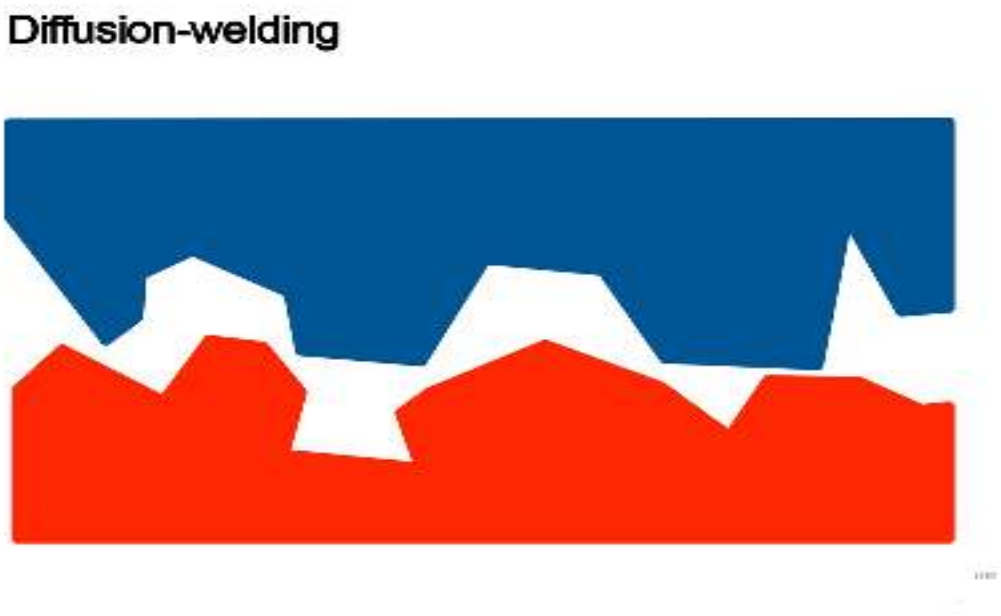
TABLE 36-1. Metal Combinations Weldable by Ultrasonic Welding

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

Metal combinations that can be ultrasonically welded

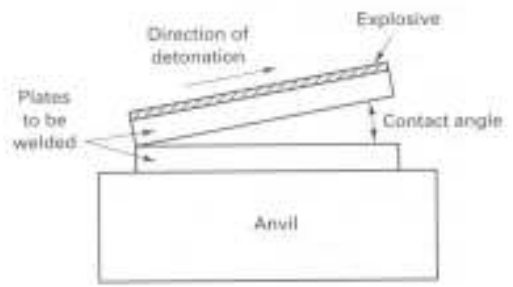
Diffusion Welding DFW

- 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



- 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).

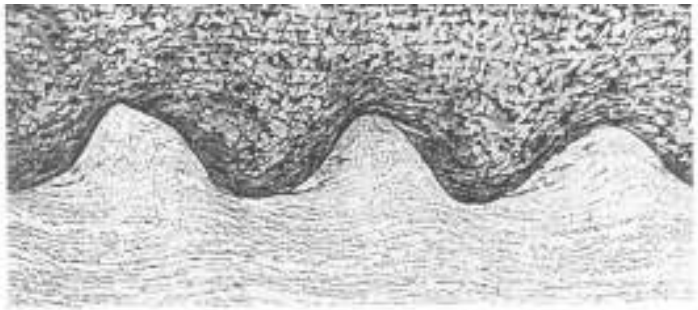
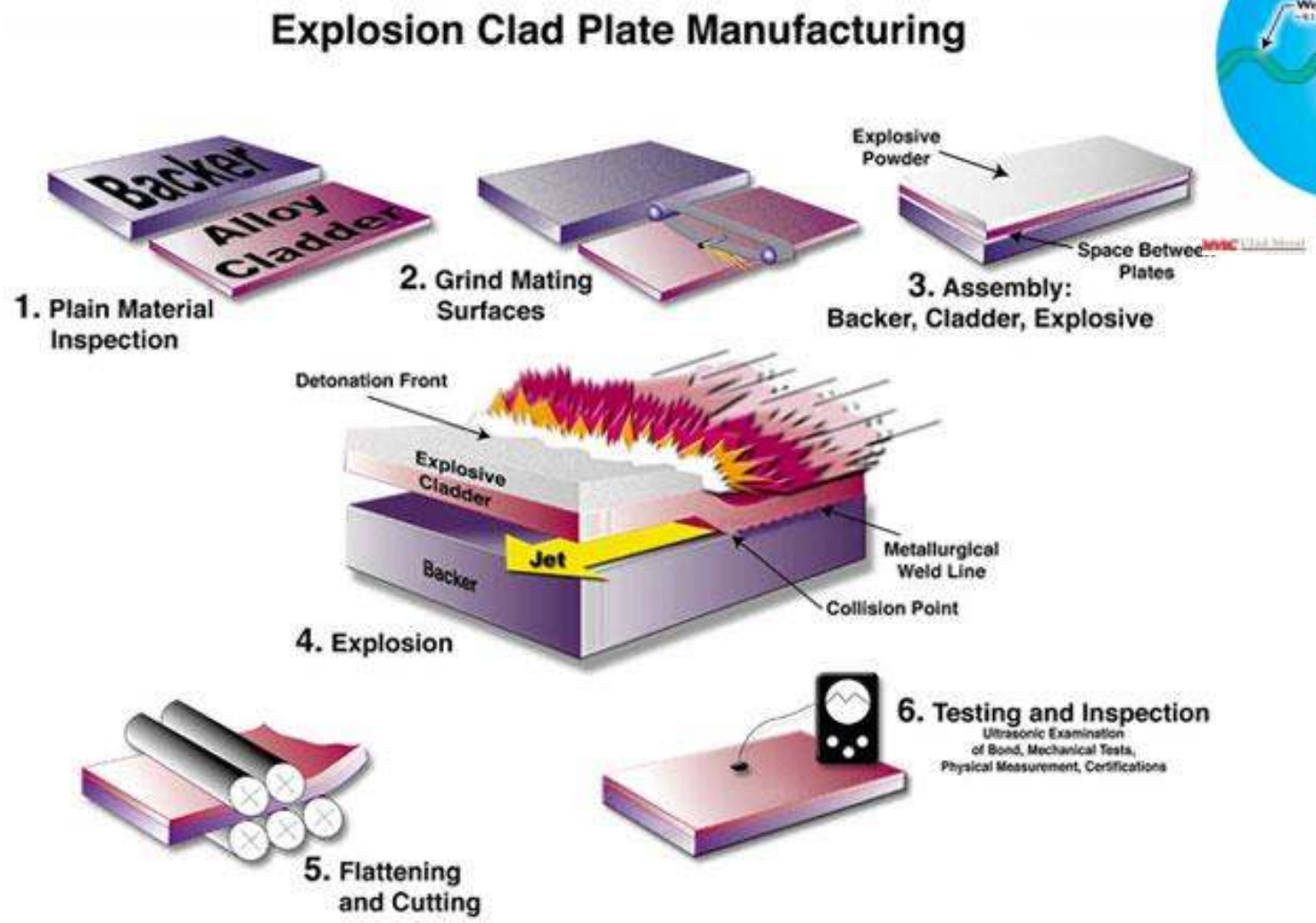
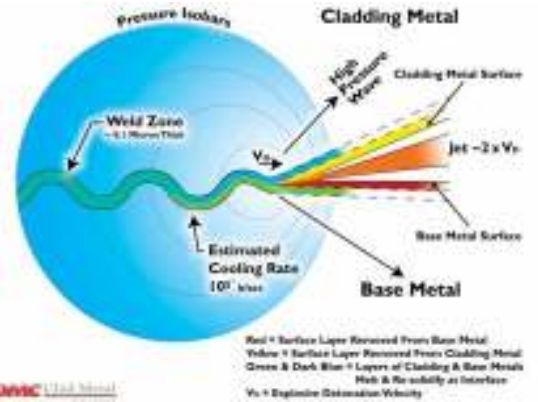


FIGURE 36-8 (*Top*) Schematic of the explosive welding process. (*Bottom*) Explosive weld between mild steel (top) and stainless steel (bottom), showing the characteristic wavy interface.

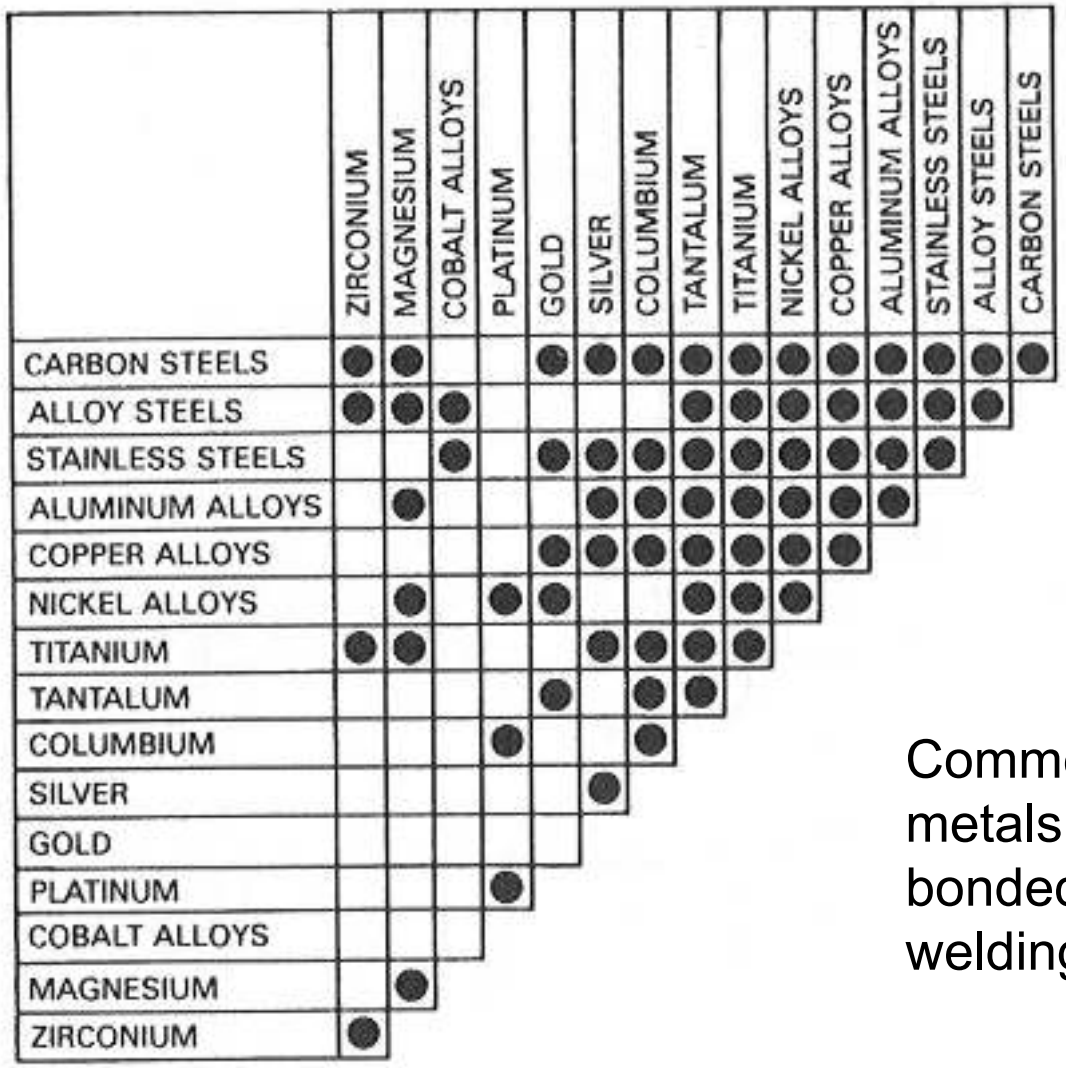
  - produces compressive shock wave forcing metals together.
  - air squeezed out at supersonic velocities cleaning off surface film causing localized heating.
  - deformation also causes heating, good atom contact. weld formed.
- low temperature weld (usually a distorted interface – wavy).

Explosive Welding EXW





Explosive Welding EXW



- 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.

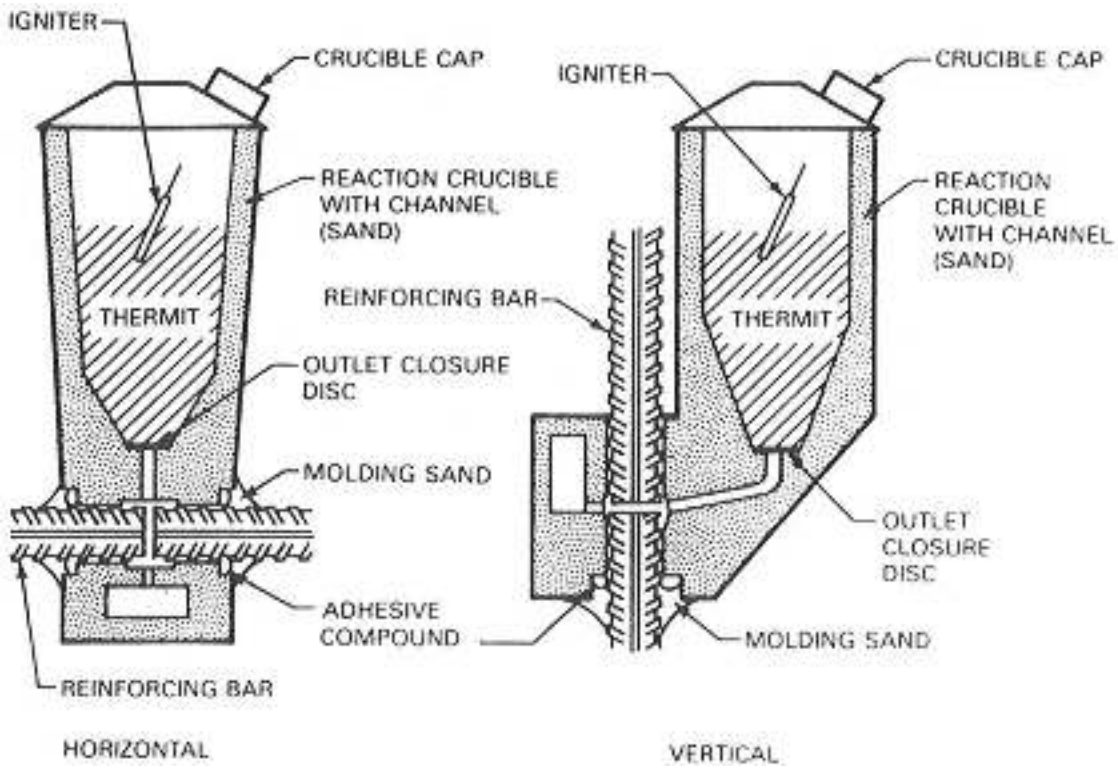
Commercially important metals that can be bonded by explosive welding

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. $8Al + 3Fe_3O_4 \rightarrow 9Fe + 4Al_2O_3 + heat$
- 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.

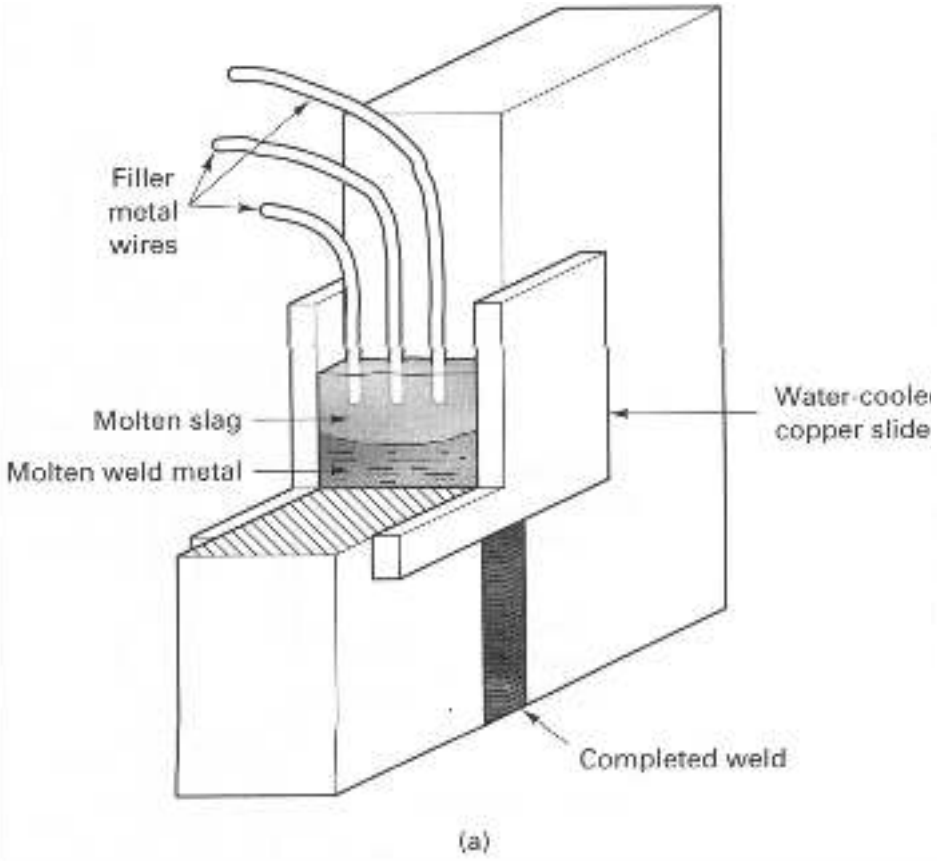


Typical arrangement of the Thermit process for welding concrete reinforcing steel bars, horizontally or vertically.

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



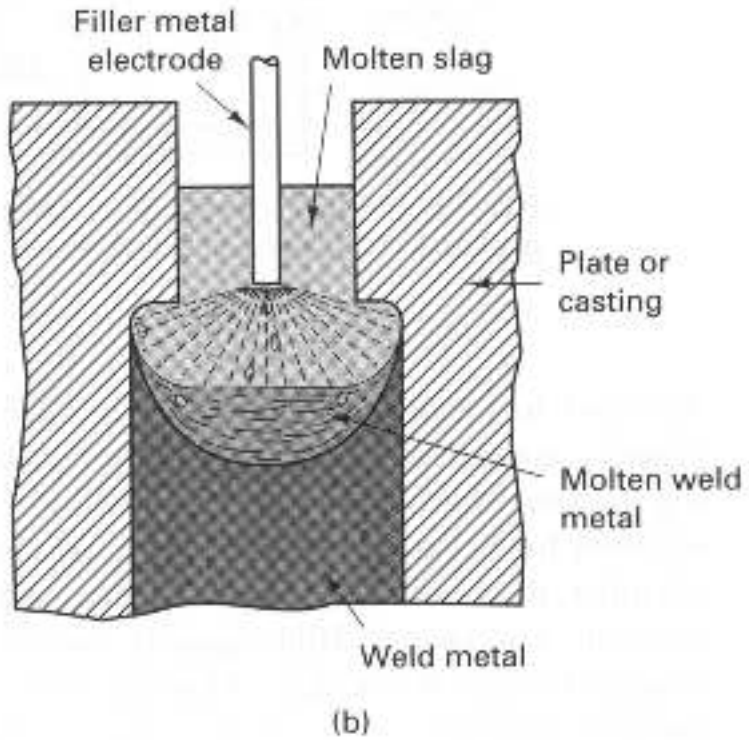
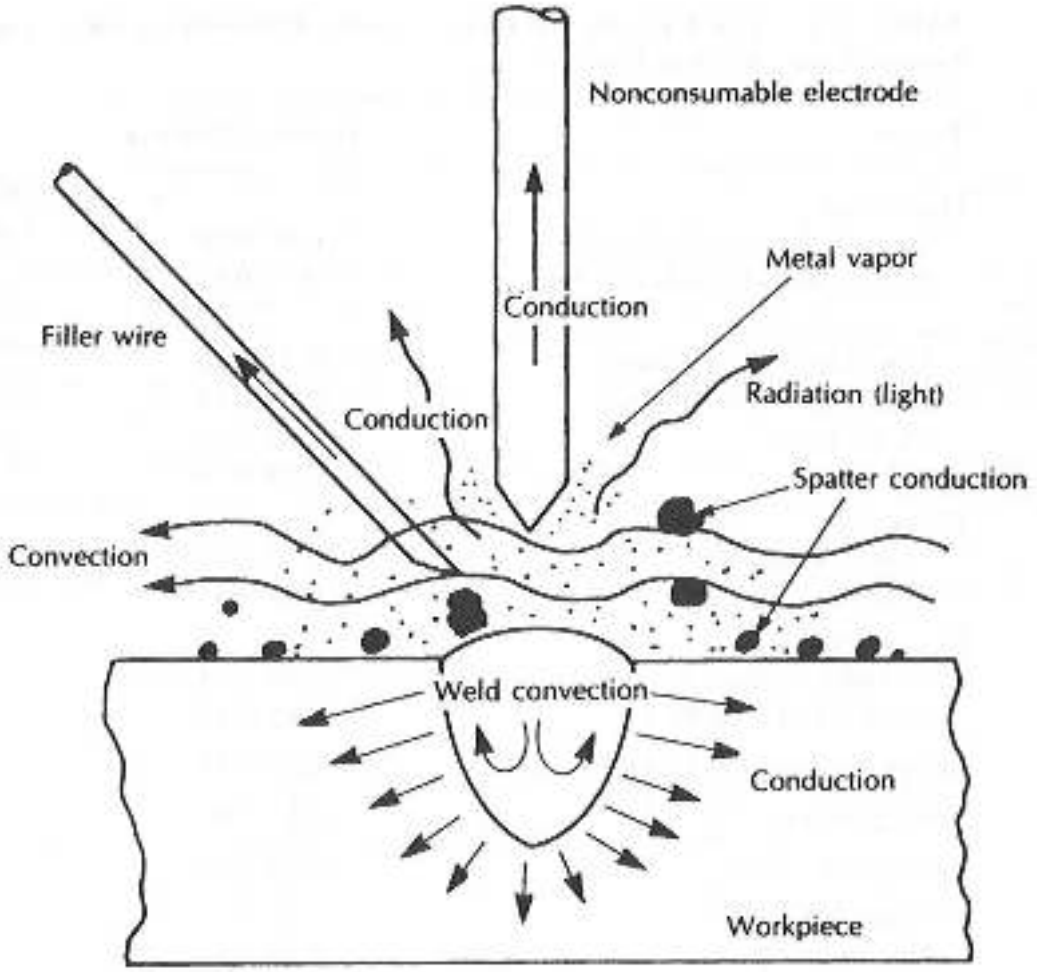


FIGURE 36-9 (*Top*) Arrangement of equipment and workpieces for making a vertical weld by the electroslag process. (*Bottom*) Cross section of an electroslag weld, looking through the water-cooled copper slide.

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



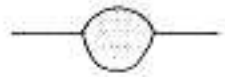
Causes of loss of energy during transfer from a welding source to the workpiece.

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 ($W m^{-2}$)	Condition	Fused Zone Profile
Flux-shielded arc welding	5×10^9 to 5×10^8		
Gas-shielded arc welding	5×10^9 to 5×10^8	Normal current	
		High current	
Plasma	5×10^9 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

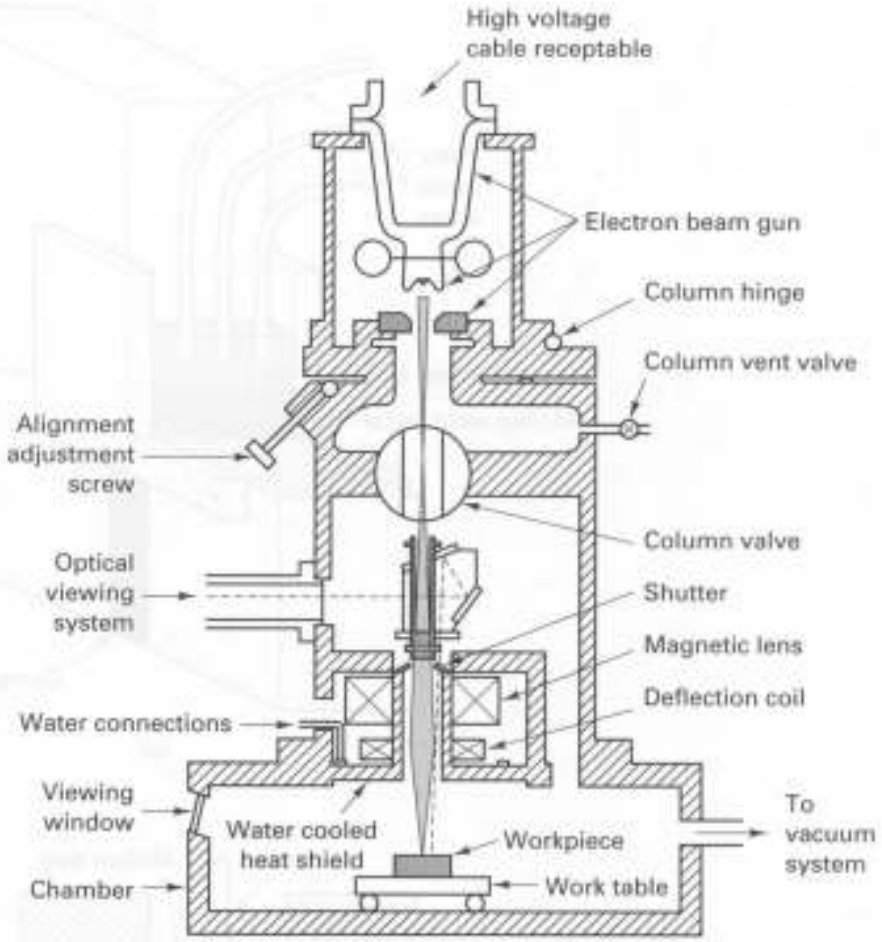


FIGURE 36-10 Schematic diagram of the electron beam welding process. *(Courtesy of American Machinist.)*

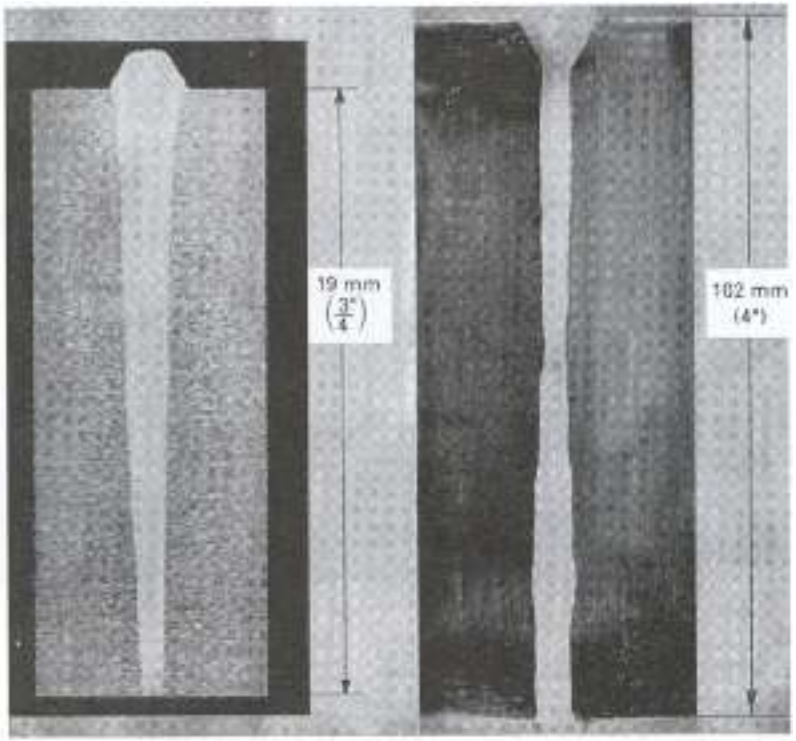
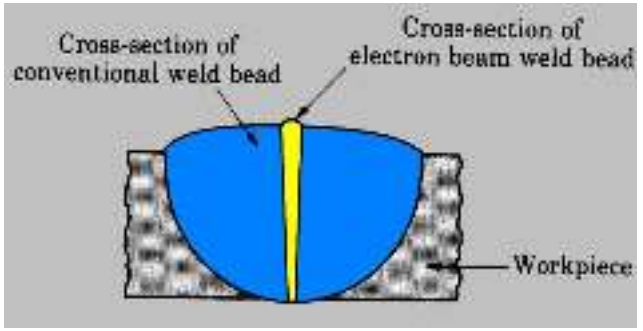


FIGURE 36-11 *(Left to right)* Electron beam welds in $\frac{3}{4}$-in.-thick 7079 aluminum, and 4-in.-thick stainless steel. *(Courtesy of Hamilton Standard*

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

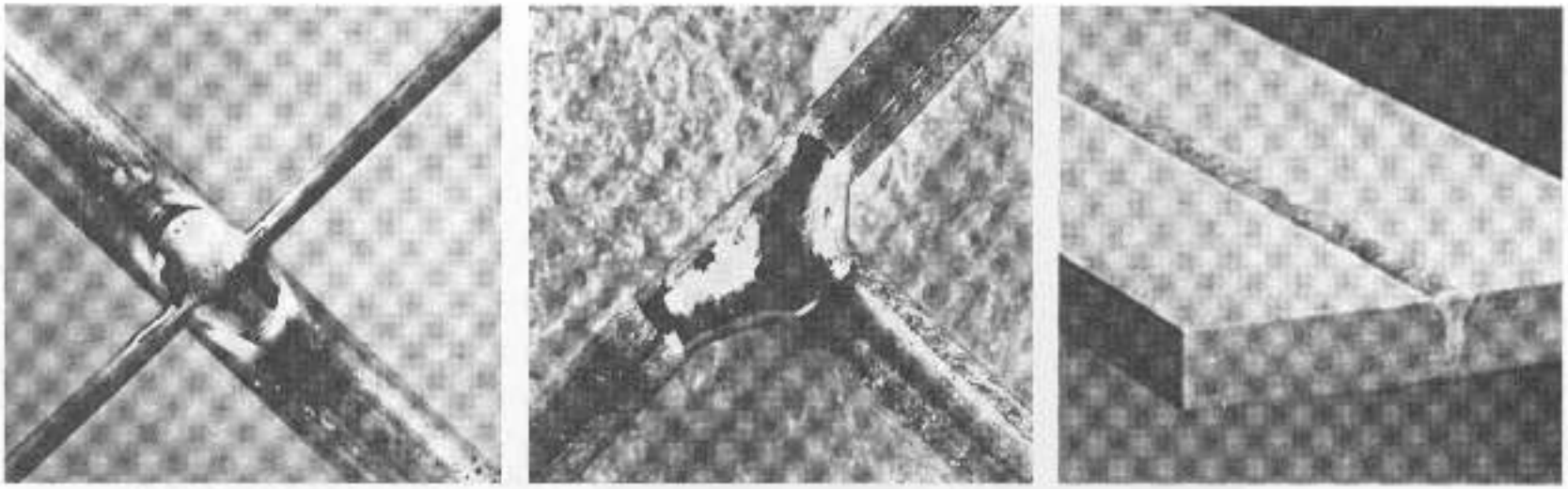
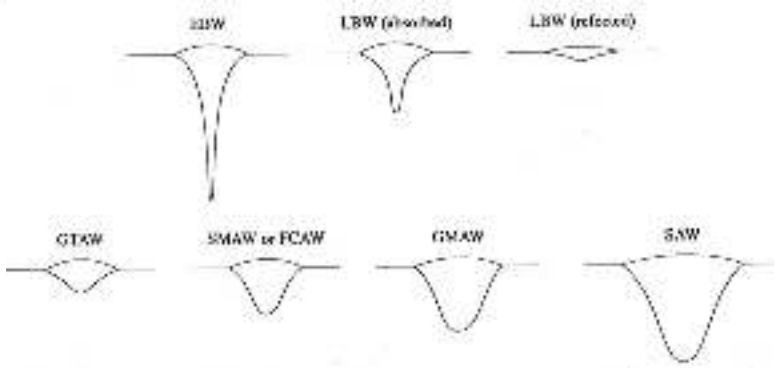


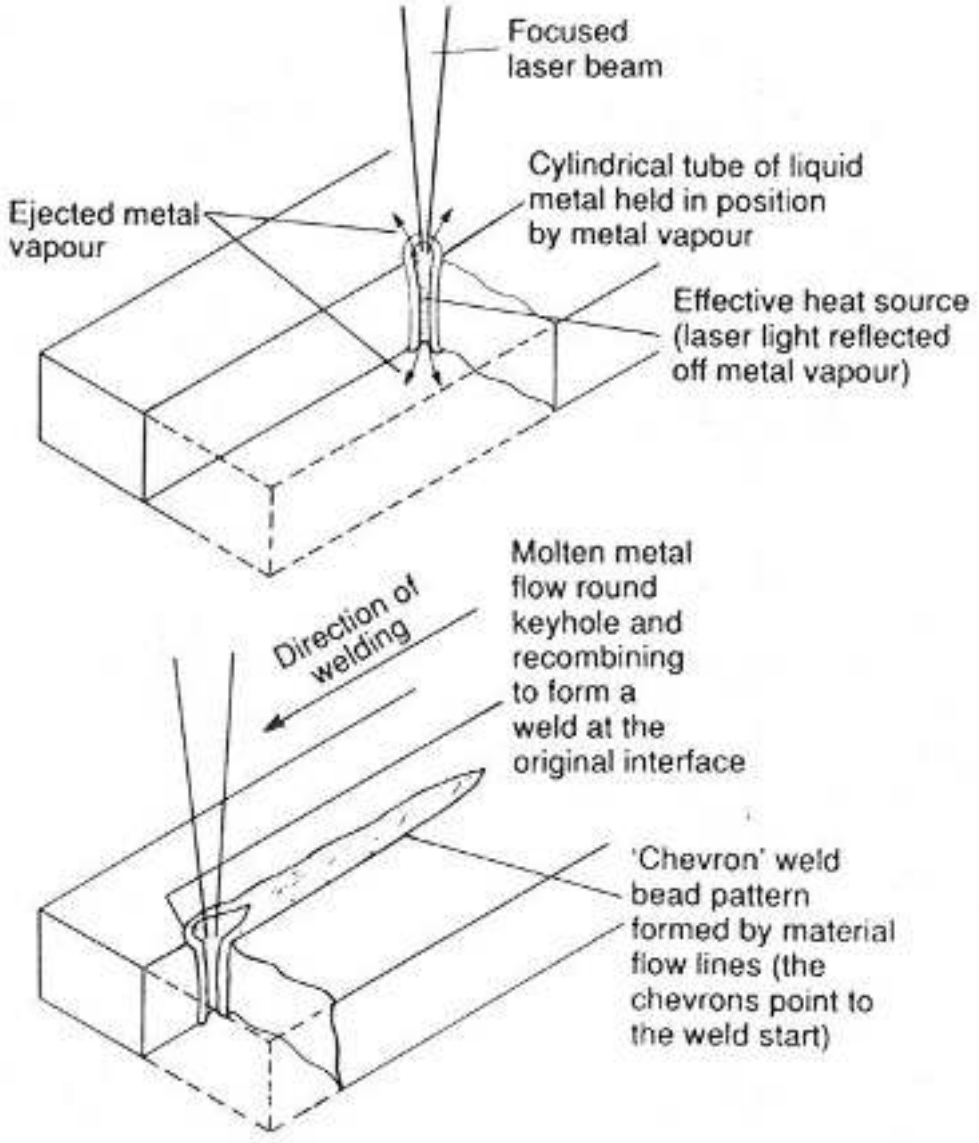
FIGURE 36-12 (*Left*) Small electronic welds made by laser welding. *(Courtesy of Linde Division, Union Carbide Corporation.)*, (*Right*) Laser butt weld of 0.125-in. (3-mm) stainless steel, made at 60 in./min (1.5 m/min) with a 1250-W laser. *(Courtesy of Coherent, Inc.)*



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

Arc Welding

- A welding arc is a gaseous electrical conductor that changes electrical energy into heat.
- Electrical discharges are formed and sustained by the development of conductive charge carriers in a gaseous medium.
- The current carriers in the gaseous medium are produced by thermionic emission; in which outer electrons from atoms in the gaseous medium and an electrode or workpiece are stripped away to be free to contribute to current flow.
- Positive ions are formed in the gaseous medium as a consequence.

Arc Welding

- Resulting arcs can be steady (from a DC power supply), intermittent (due to occasional, irregular short circuiting), continuously unsteady (as the result of an AC power supply), or pulsing (as the result of a pulsing direct current power supply).
- This variety makes an electric arc such a useful heat source for welding with many processes and process variations.
- The Arc Plasma. Current is carried in an arc by a plasma.
- A plasma is the ionized state of a gas, comprised of a balance of negative electrons and positive ions

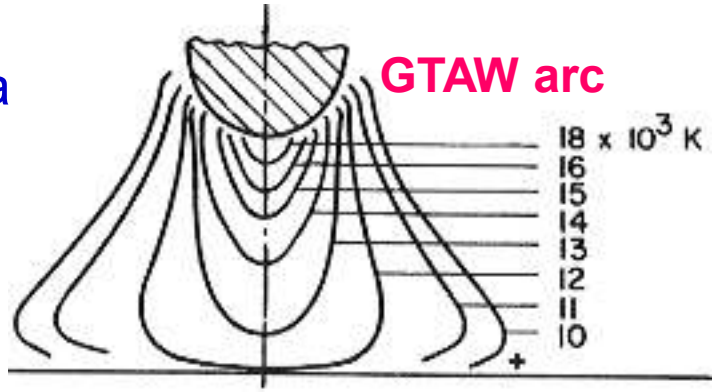
Arc Welding

- Both +ve and –ve ions are created by thermionic emission from an electrode and secondary collisions between these electrons and atoms in the gaseous medium (self-generated or externally supplied inert shielding gas) to maintain charge neutrality.
- The electrons, which support most of the current conduction due to their smaller mass and greater mobility, flow from a negative (polarity) terminal called a cathode and move toward a positive (polarity) terminal called an anode.

Arc Welding

- The establishment of a neutral plasma state by thermal means (i.e., collision processes) requires the attainment of equilibrium temperatures, the magnitude of which depend on the ionization potential (the ease or difficulty of forming positive ions by stripping away electrons) from which the plasma is produced (e.g., air, argon, helium).
- Arc Temperature. The temperature of welding arcs has been measured by spectral emission of excited and ionized atoms and normally is in the range of 5000 to 30,000 K, depending on the precise nature of the plasma and current conducted by it.

Arc Welding



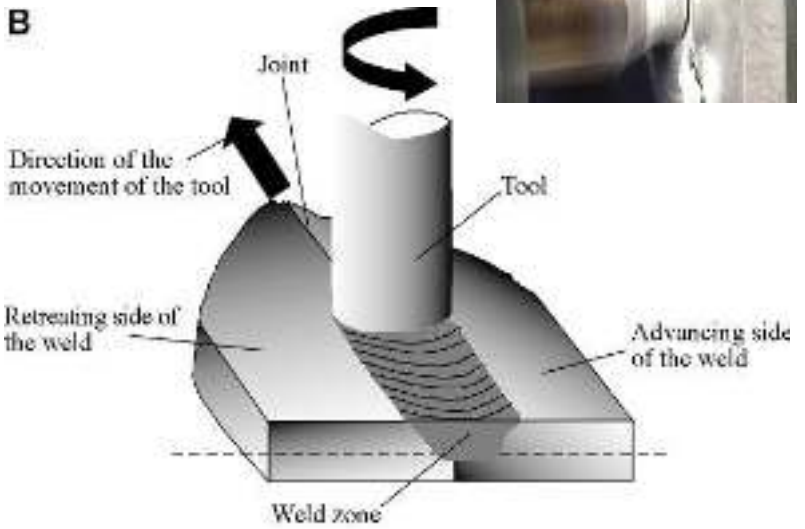
- Two important factors that affect the plasma temperature are what precisely constitutes the particular plasma, and its density.
- For shielded-metal and flux-cored arcs, a high concentration of easily ionized materials such as alkali metals, like sodium and potassium, from flux coatings or cores of the consumable electrodes used with these processes, result in a maximum temperature of about 6000K. (Lowered by the presence of fine particles of molten flux or slag as well as molten metal and metal vapor).

Arc Welding

- For pure inert gas-shielded arcs, such as those found in GTAW, the central core temperature of the plasma can approach 30,000 K, except as lowered by metal vapor from the nonconsumable electrode and any molten metal particles from any filler used. For a process where the plasma is pure and concentrated and there is no metal transfer, as in PAW, plasma core temperatures of 50,000 K could be attained.
- The actual temperature in an arc is limited by heat loss, rather than by any theoretical limit. These losses are due to radiation, convection, conduction, and diffusion.

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

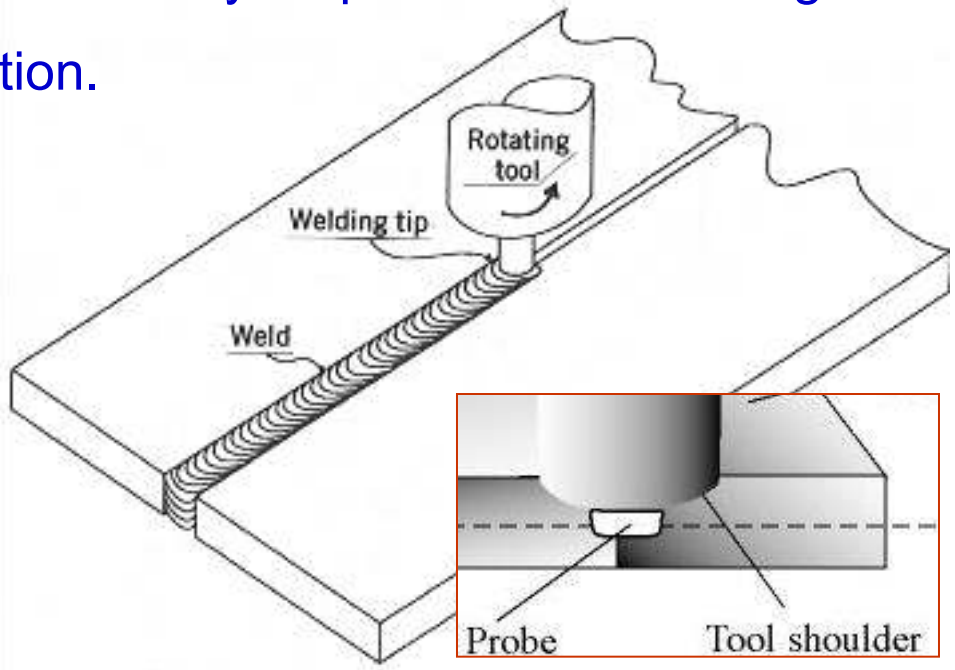
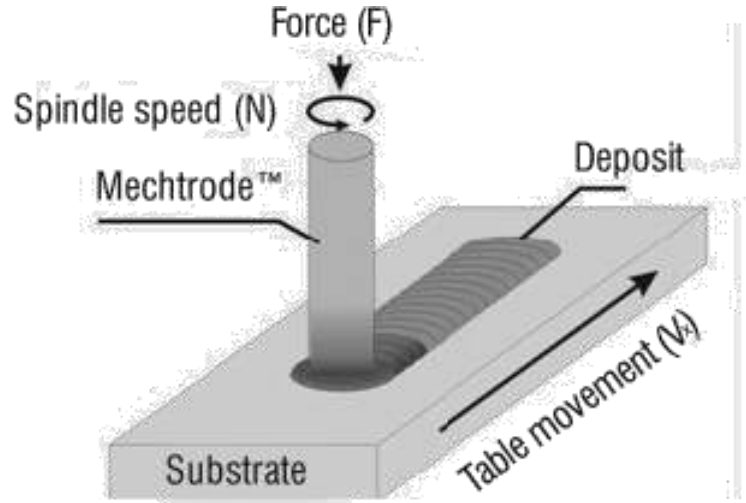
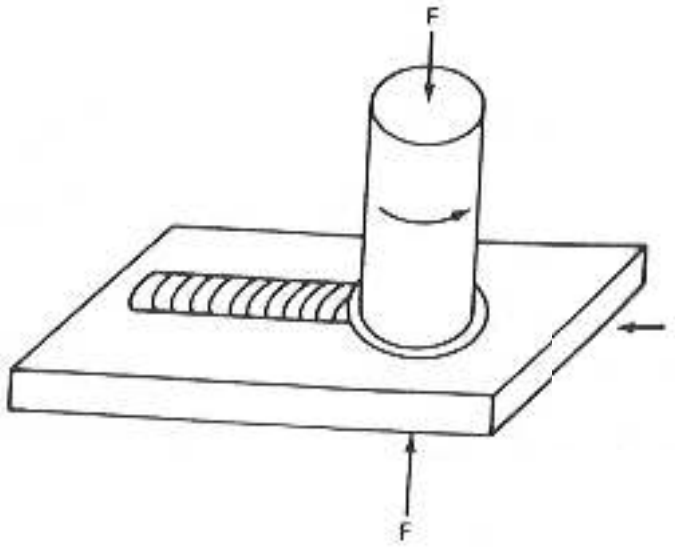


Figure 4.15 Schematic of friction stir welding.

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

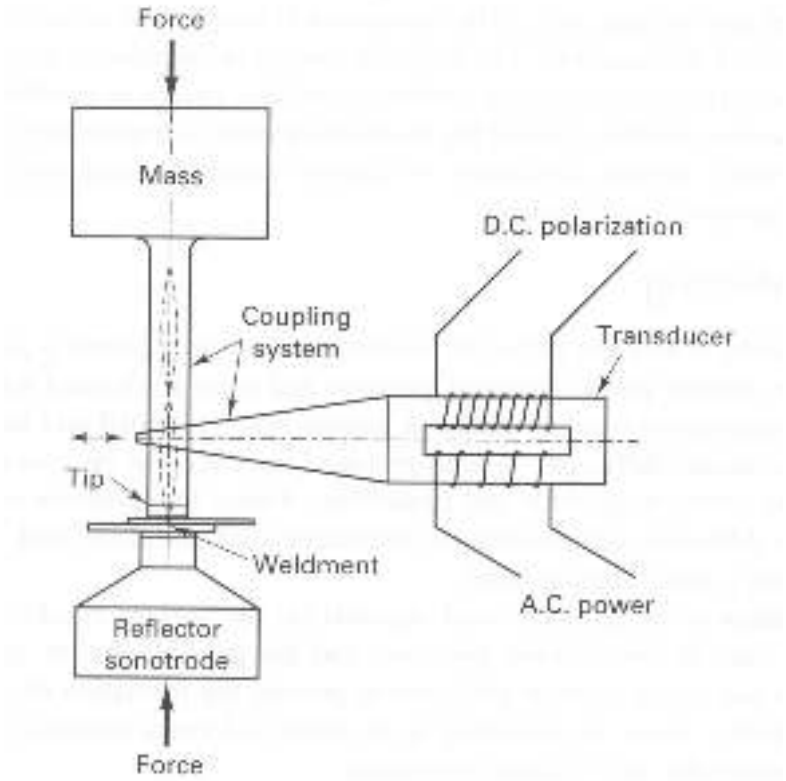
Lecture 10

Ultrasonic Welding USW

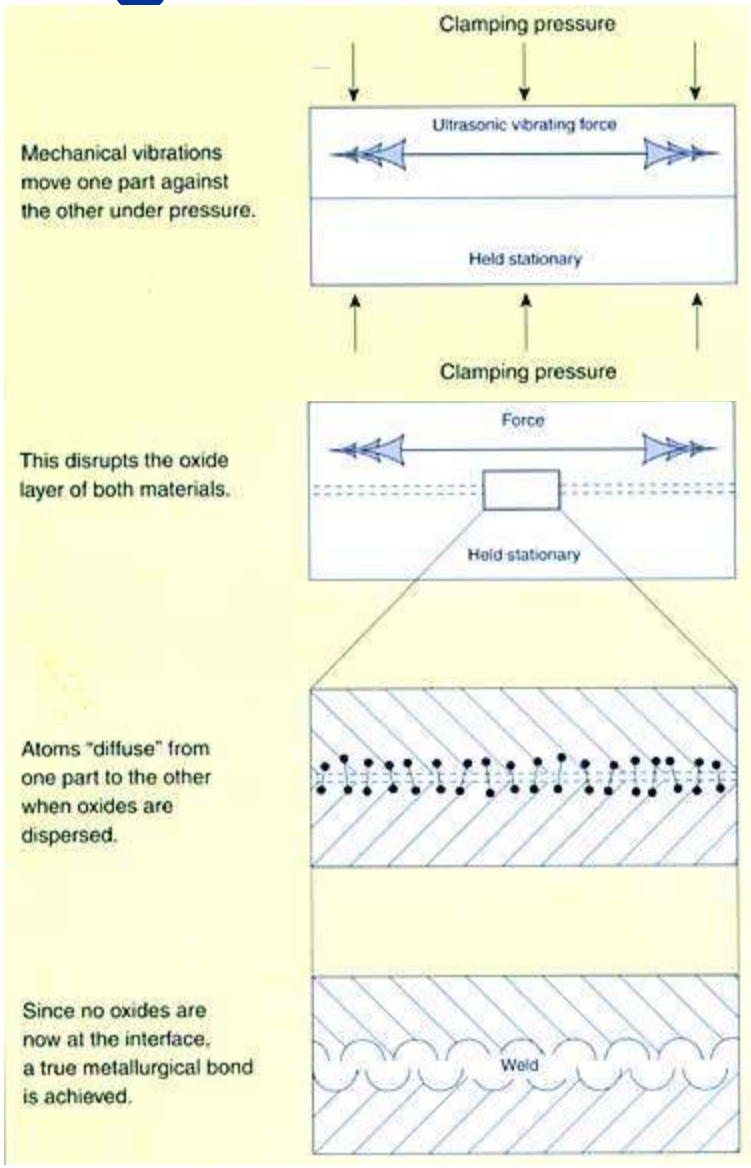
Vibrational motion causing friction.

- 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

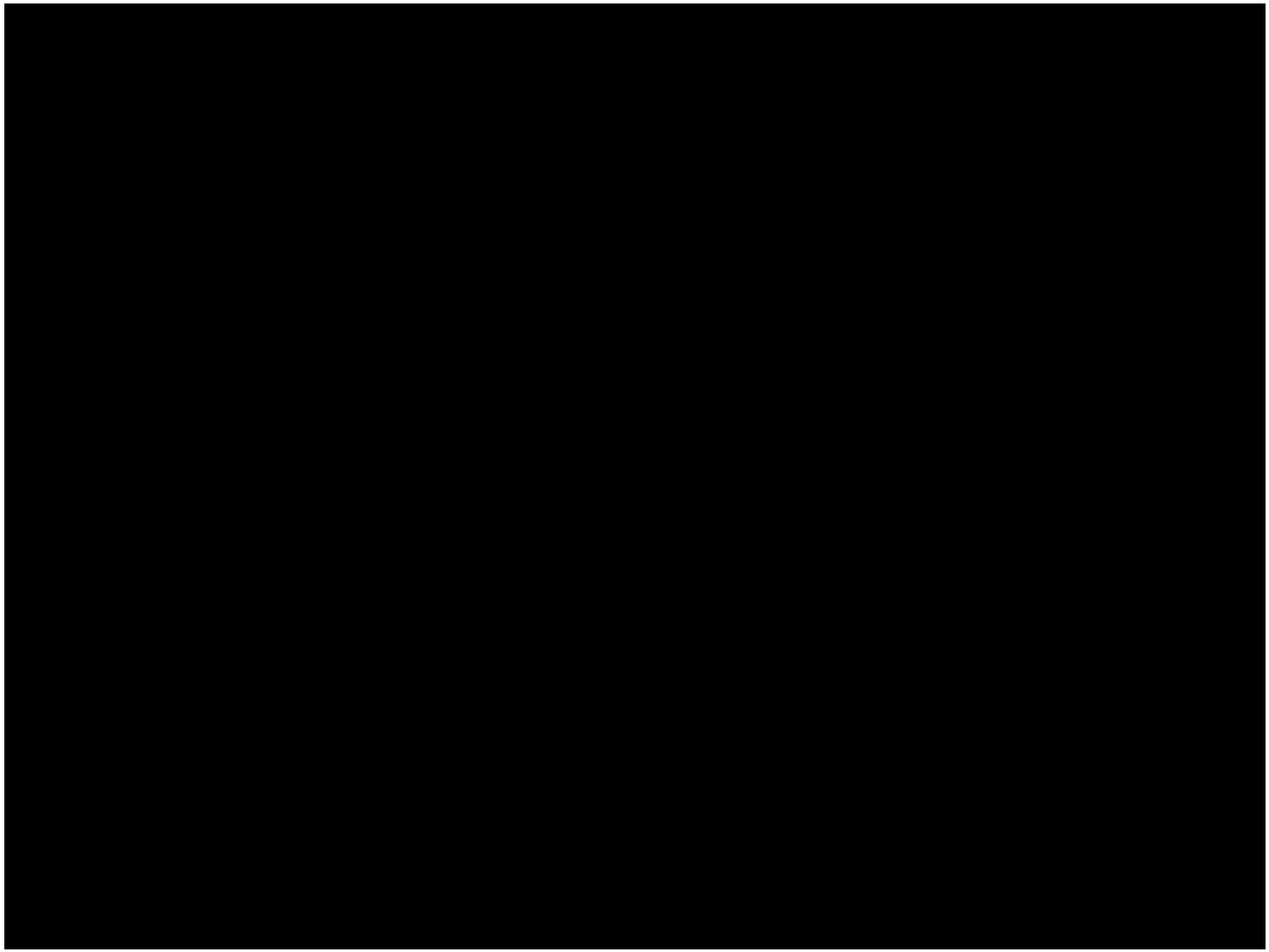
Ultrasonic Welding USW



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

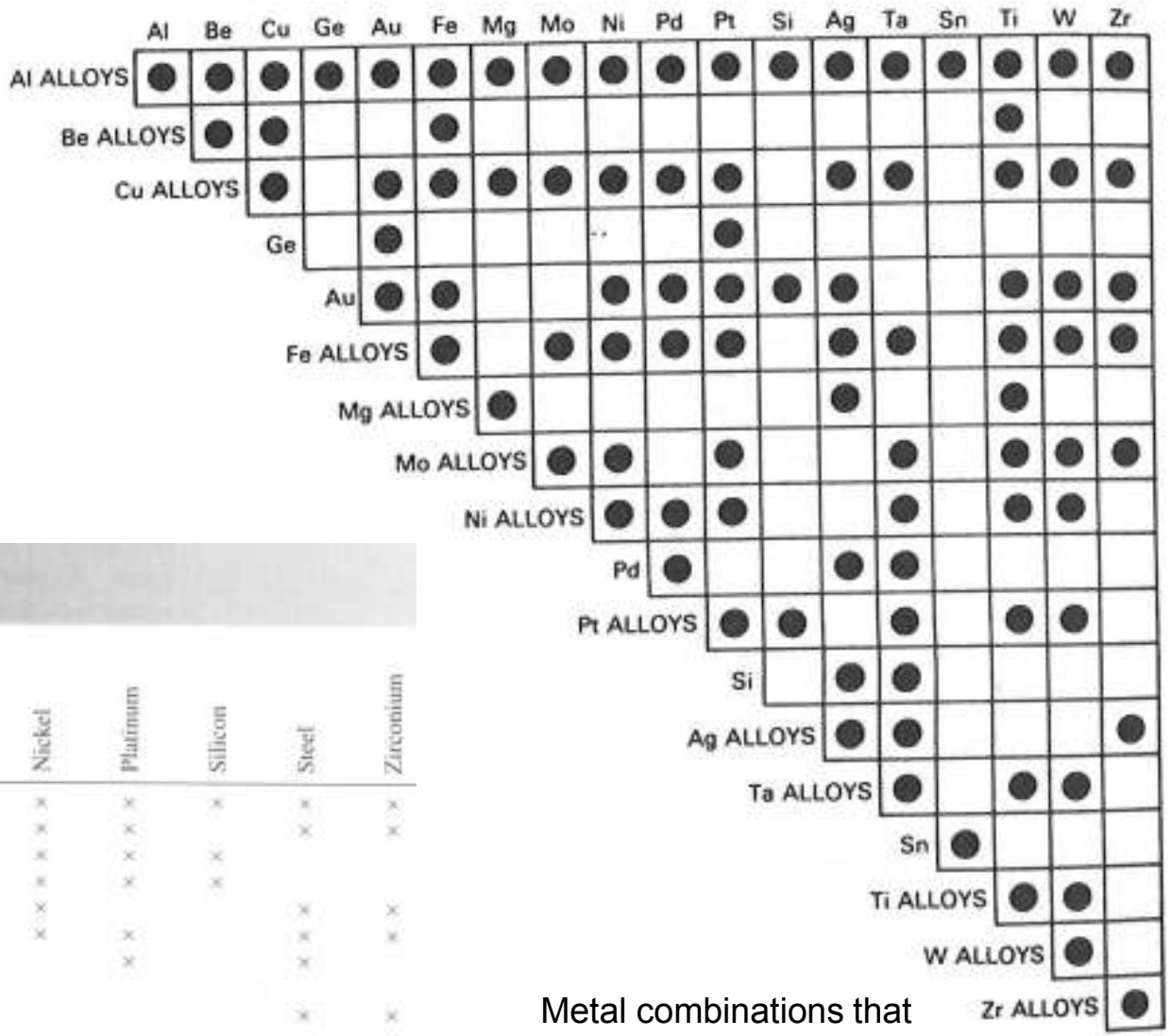


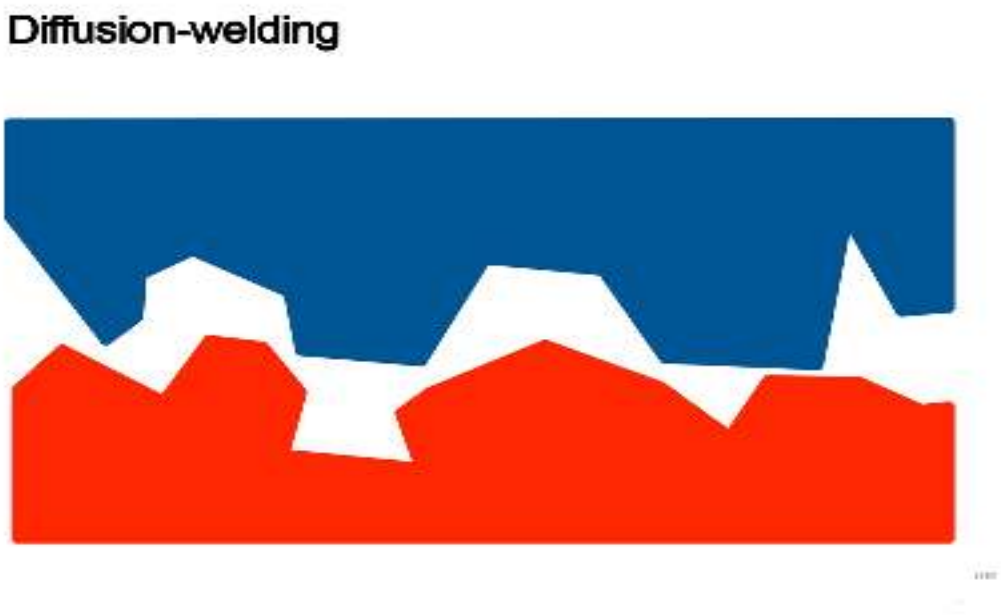
TABLE 36-1. Metal Combinations Weldable by Ultrasonic Welding

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

Metal combinations that can be ultrasonically welded

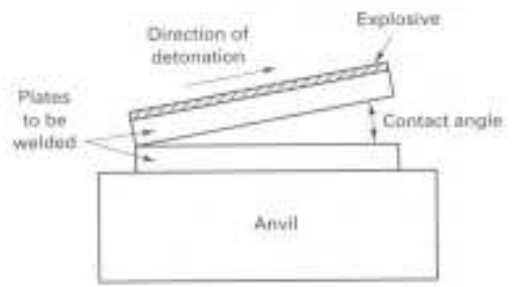
Diffusion Welding DFW

- 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



- 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).

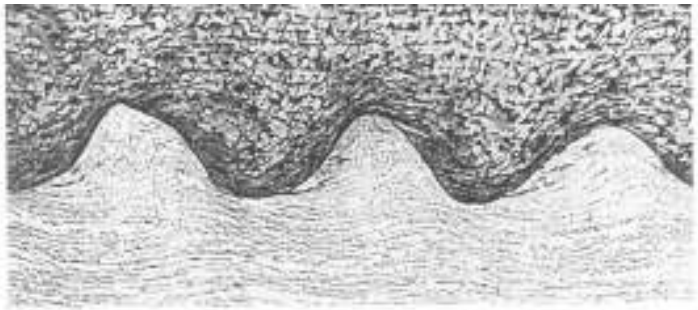
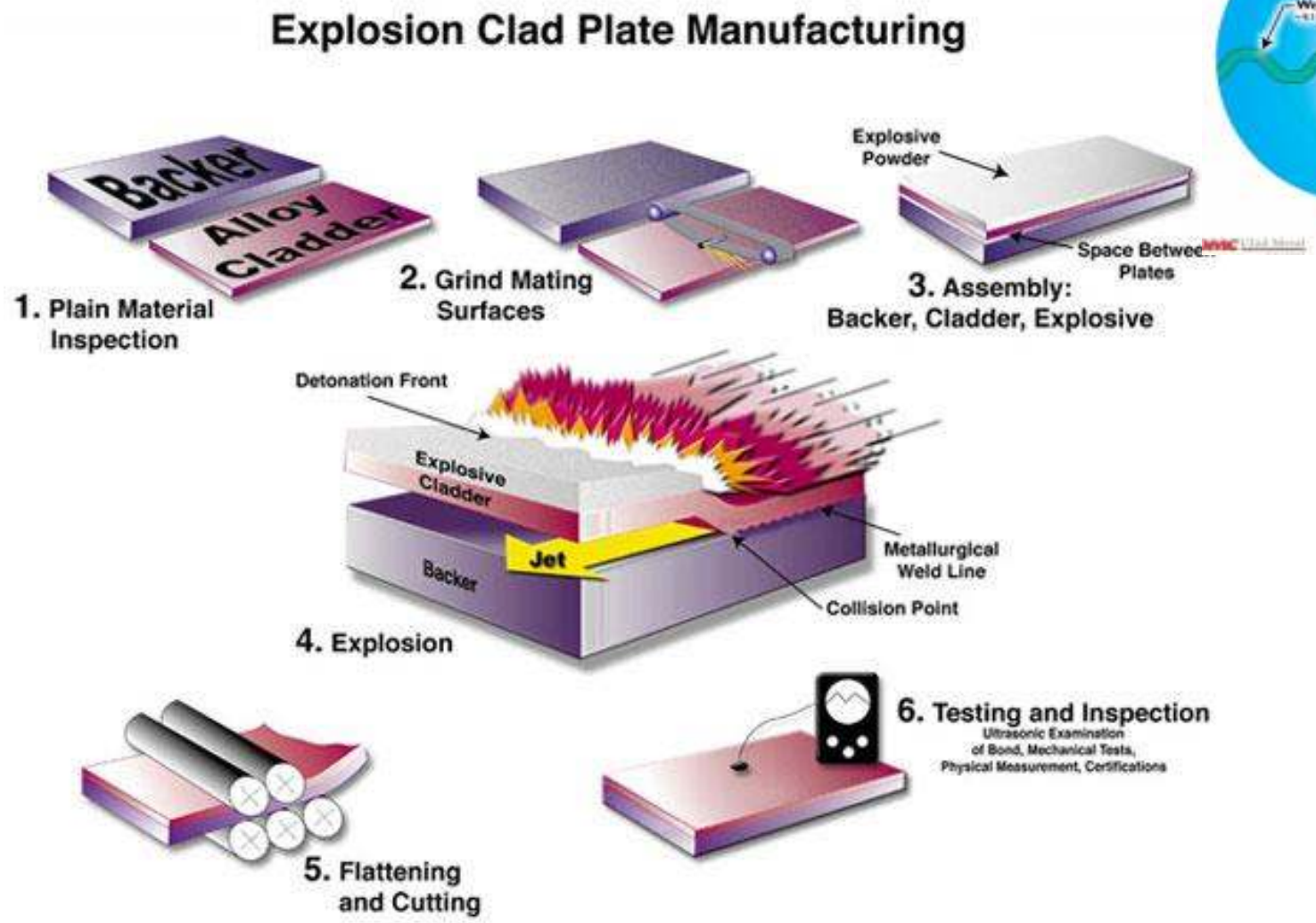
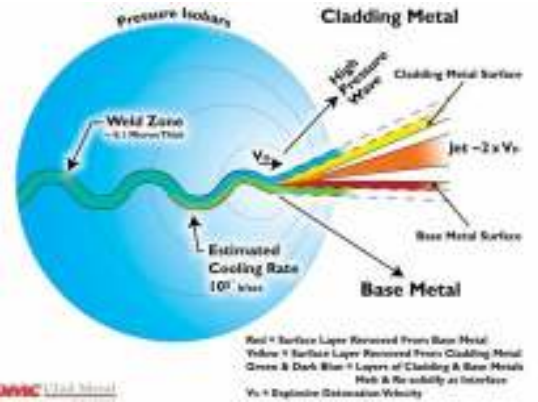


FIGURE 36-8 (*Top*) Schematic of the explosive welding process. (*Bottom*) Explosive weld between mild steel (top) and stainless steel (bottom), showing the characteristic wavy interface.

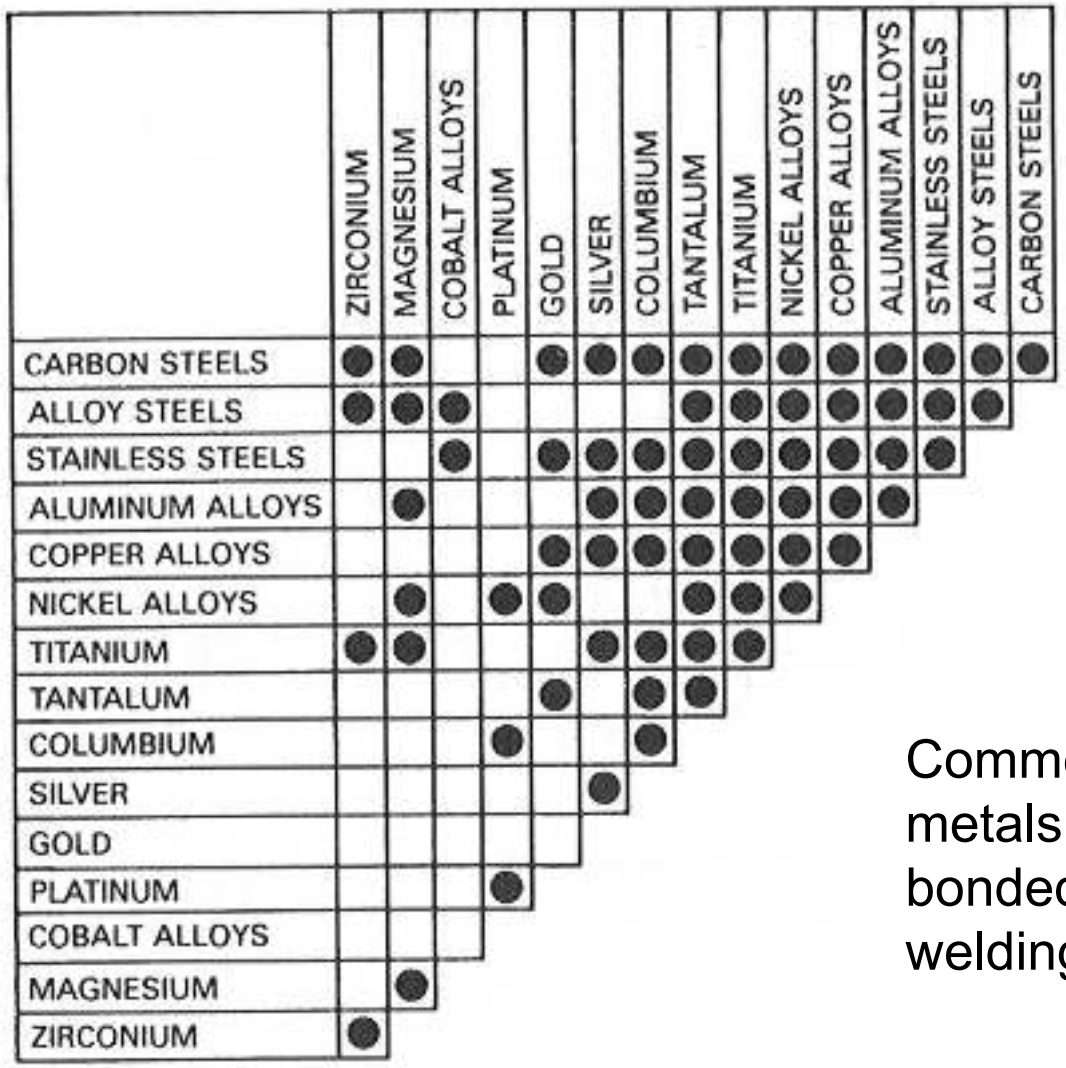
  - produces compressive shock wave forcing metals together.
  - air squeezed out at supersonic velocities cleaning off surface film causing localized heating.
  - deformation also causes heating, good atom contact. weld formed.
- low temperature weld (usually a distorted interface – wavy).

Explosive Welding EXW





Explosive Welding EXW



- 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

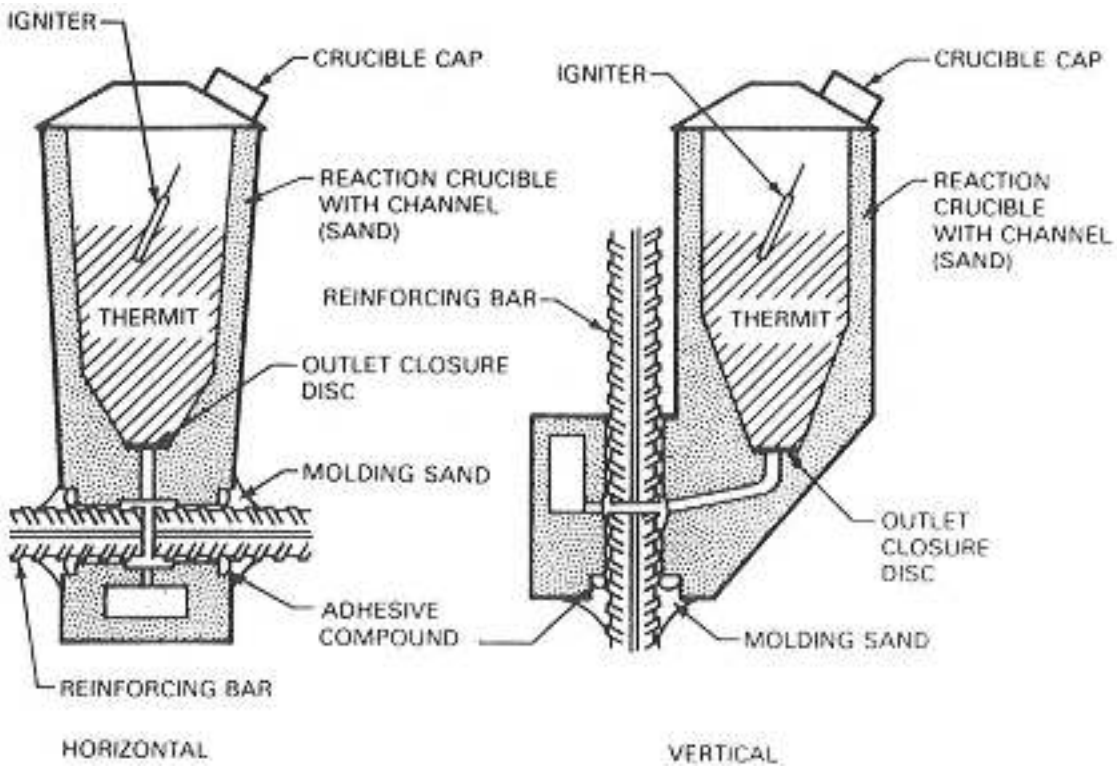
Other Welding Processes

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. $8Al + 3Fe_3O_4 \rightarrow 9Fe + 4Al_2O_3 + heat$
- 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.

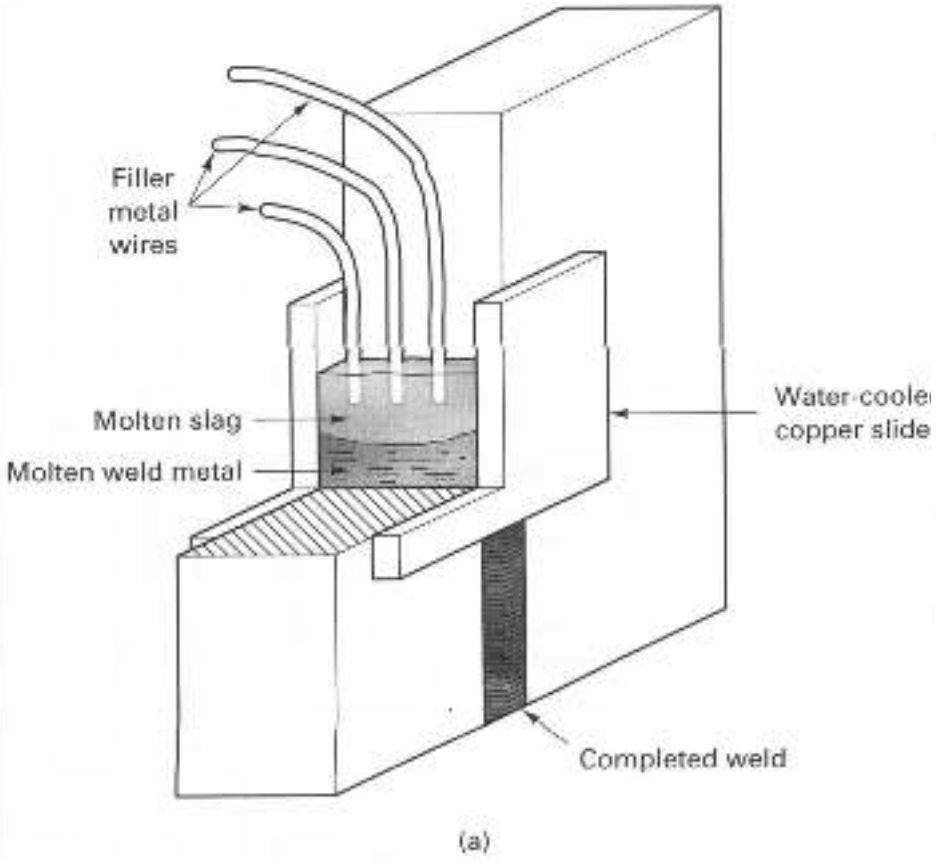


Typical arrangement of the Thermit process for welding concrete reinforcing steel bars, horizontally or vertically.

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



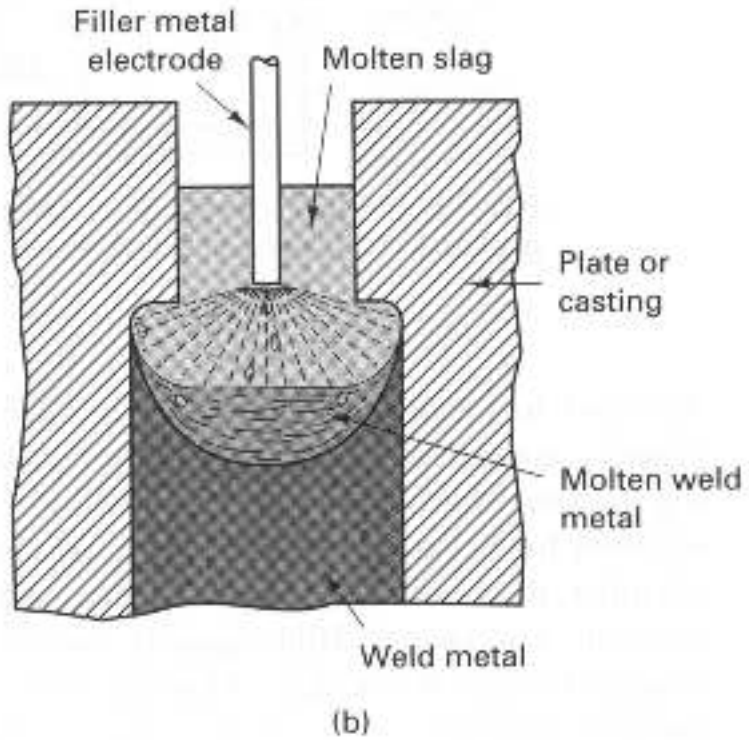
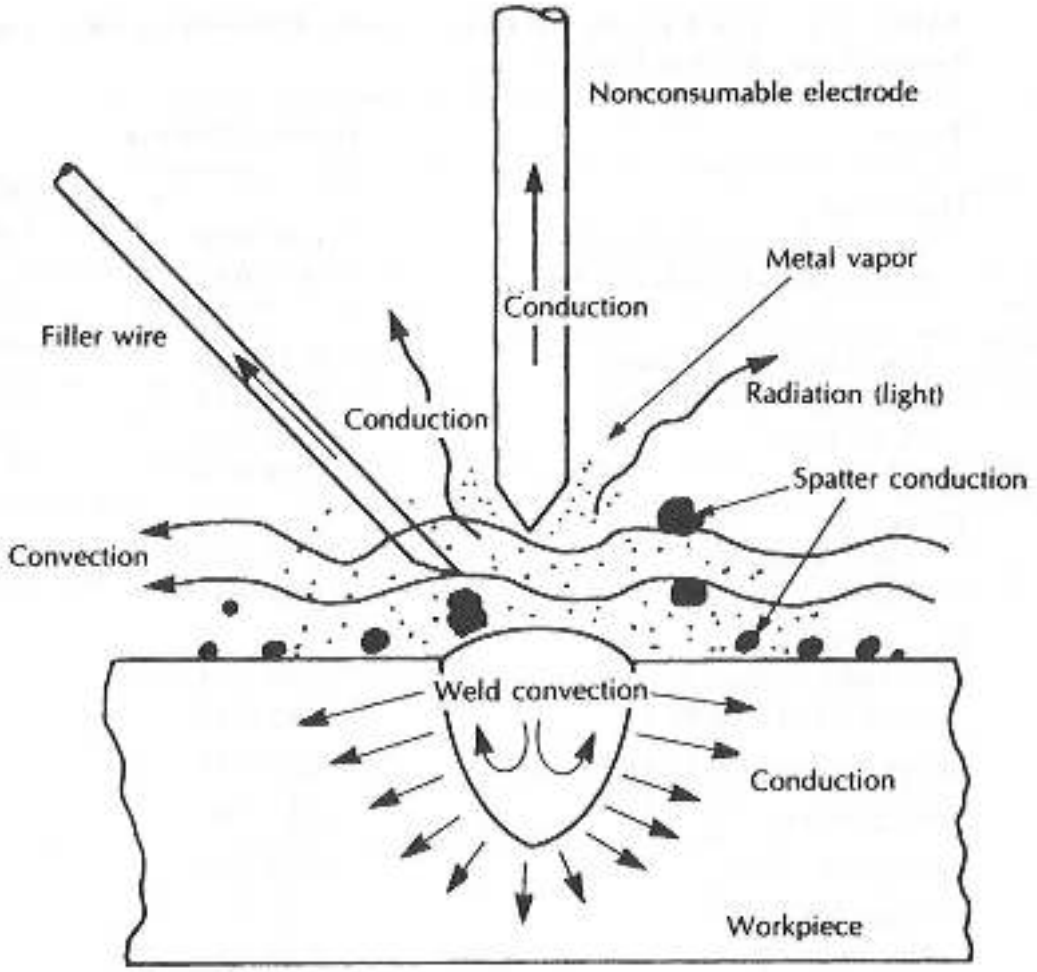


FIGURE 36-9 (*Top*) Arrangement of equipment and workpieces for making a vertical weld by the electroslag process. (*Bottom*) Cross section of an electroslag weld, looking through the water-cooled copper slide.

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



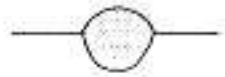
Causes of loss of energy during transfer from a welding source to the workpiece.

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 ($W m^{-2}$)	Condition	Fused Zone Profile
Flux-shielded arc welding	5×10^9 to 5×10^8		
Gas-shielded arc welding	5×10^9 to 5×10^8	Normal current	
		High current	
Plasma	5×10^9 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

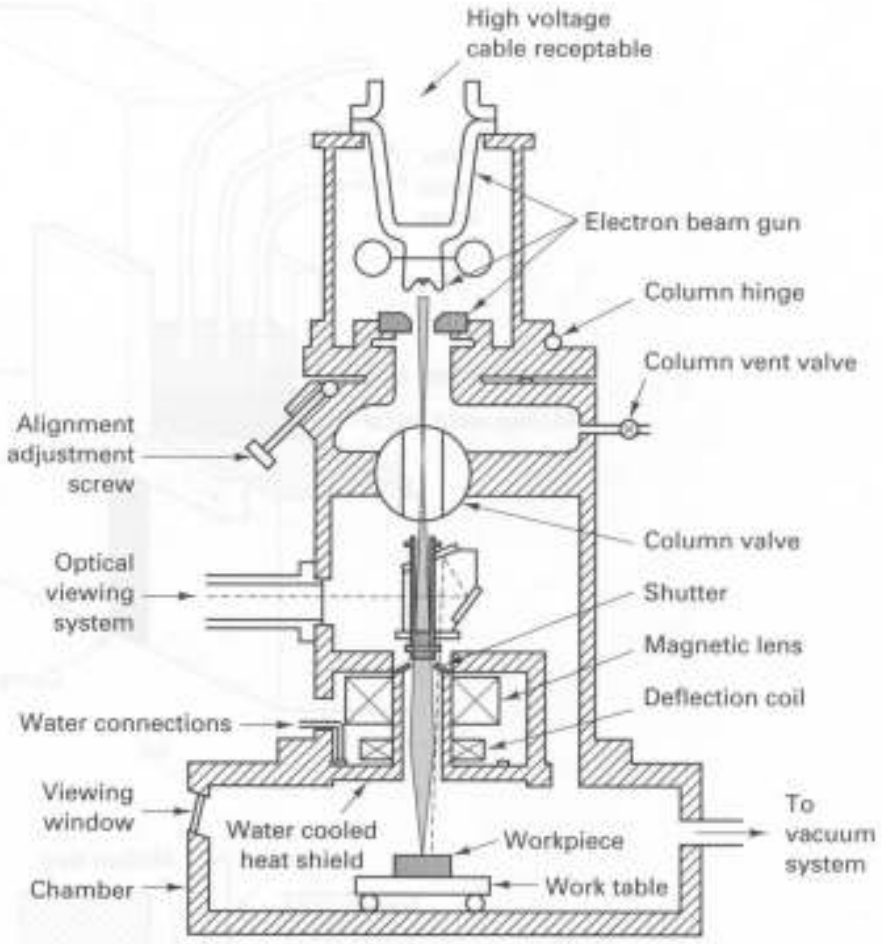


FIGURE 36-10 Schematic diagram of the electron beam welding process. *(Courtesy of American Machinist.)*

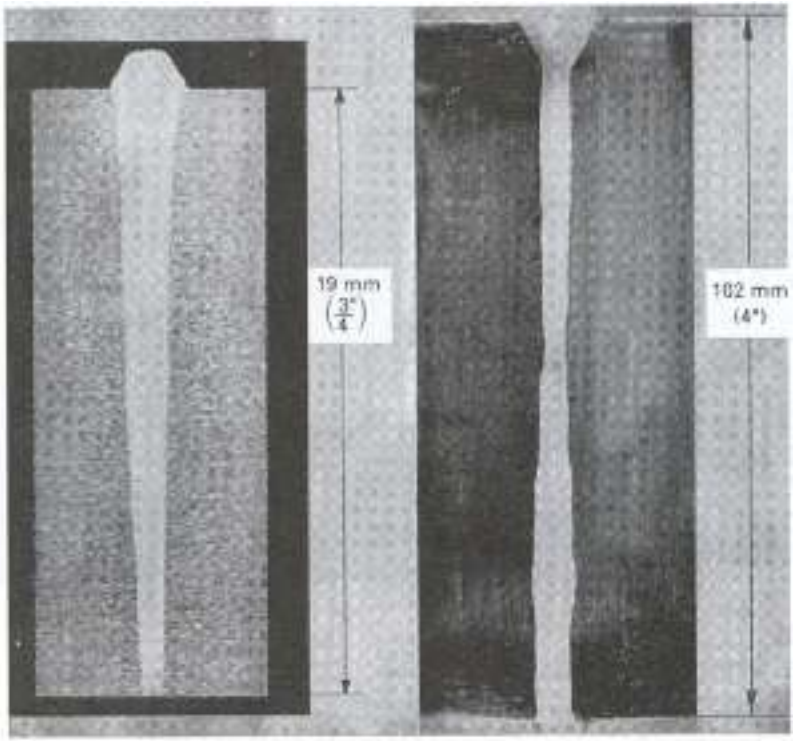
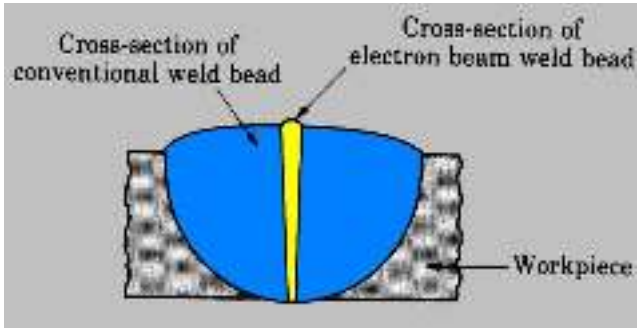


FIGURE 36-11 (*Left to right*) Electron beam welds in $\frac{3}{4}$-in.-thick 7079 aluminum, and 4-in.-thick stainless steel. *(Courtesy of Hamilton Standard*

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

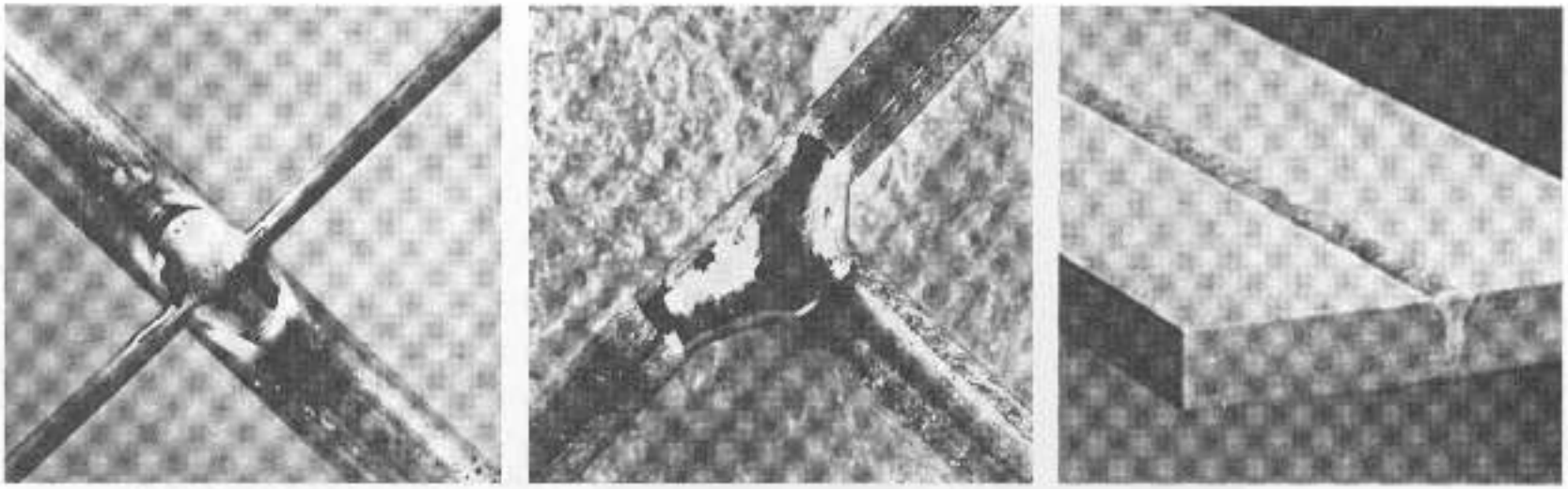
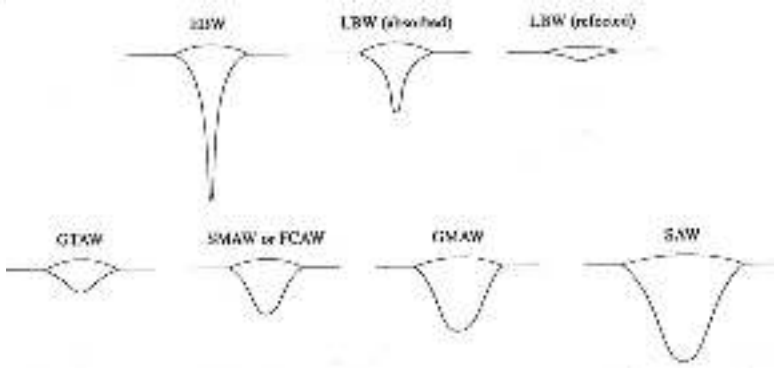


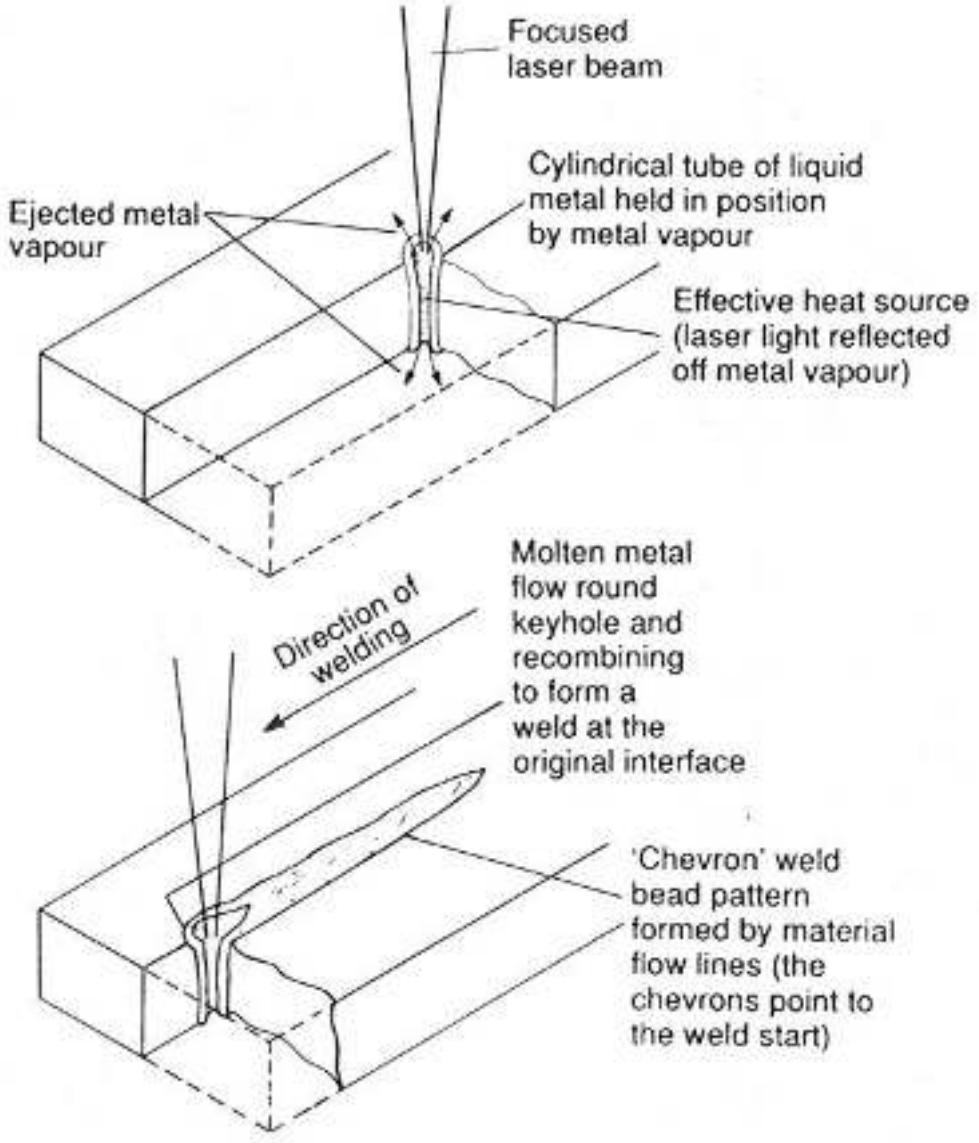
FIGURE 36-12 (*Left*) Small electronic welds made by laser welding. *(Courtesy of Linde Division, Union Carbide Corporation.)*, (*Right*) Laser butt weld of 0.125-in. (3-mm) stainless steel, made at 60 in./min (1.5 m/min) with a 1250-W laser. *(Courtesy of Coherent, Inc.)*



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.

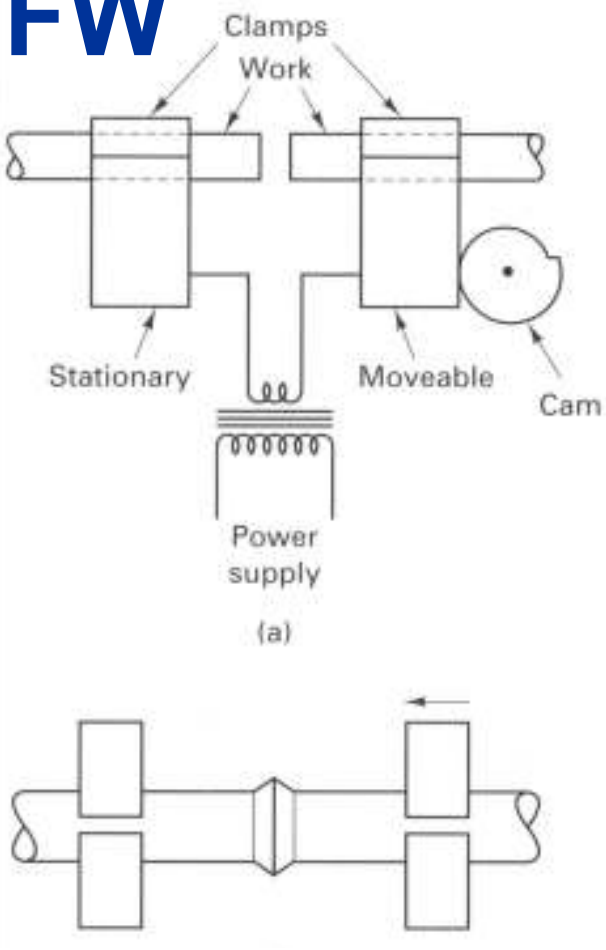


FIGURE 36-14 Schematic diagram of the flash welding process: (a) equipment and setup; (b) completed weld.

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).

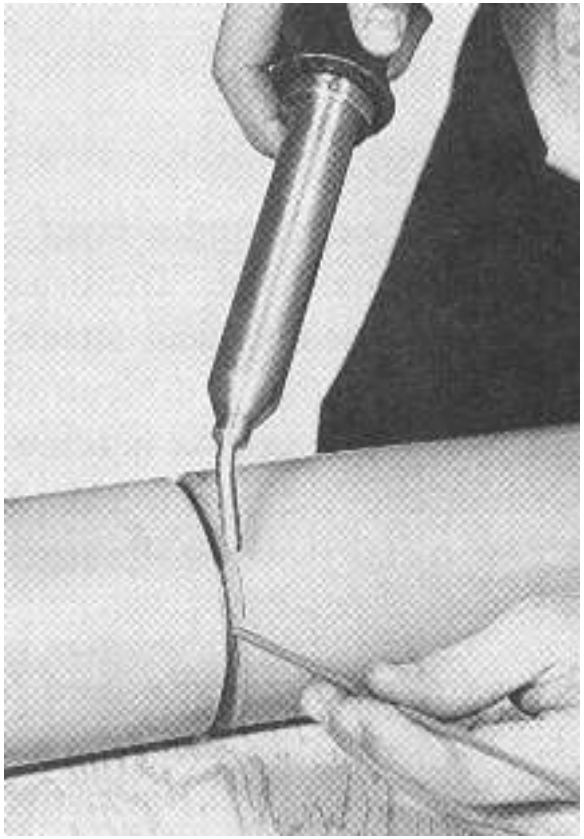


FIGURE 36-16 Using a hot-gas torch to make a weld in plastic pipe.

Welding of Plastics

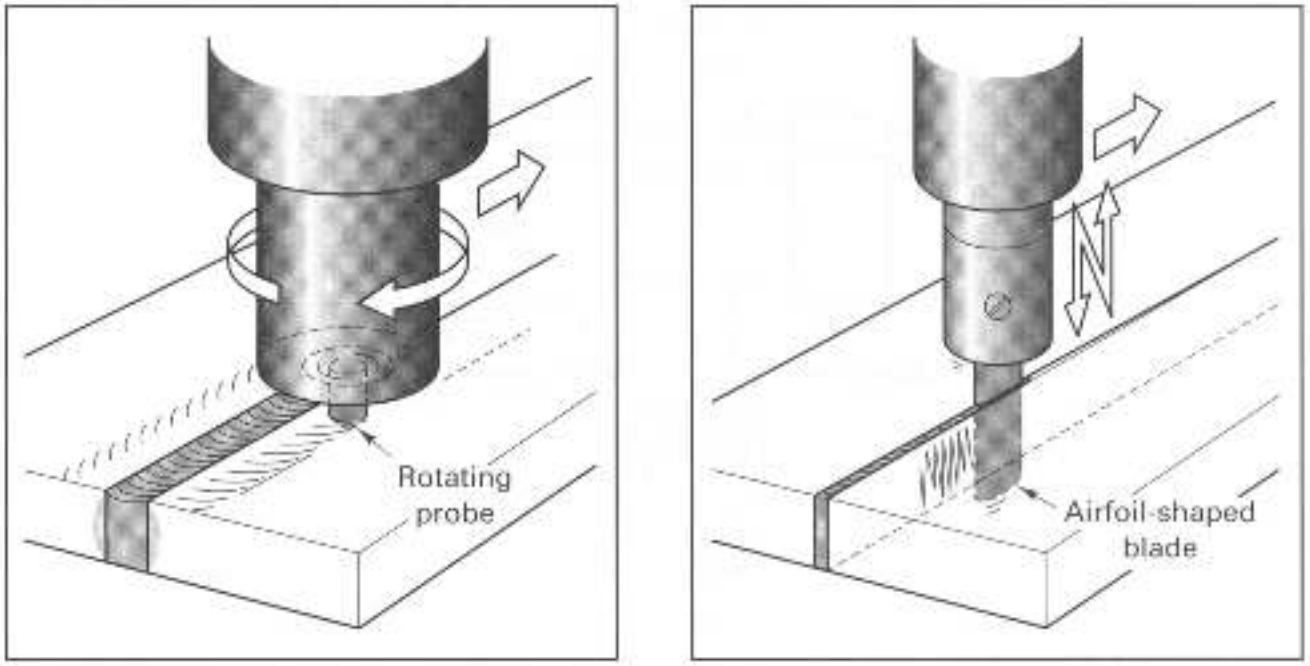


FIGURE 36-15 Friction stir welding using rotary and reciprocal motions to produce welds in plastics. The shoulder on the rotating probe provides additional friction heating to the top surface and prevents expulsion of the softened material from the joint. *(Courtesy of ASM International.)*

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.

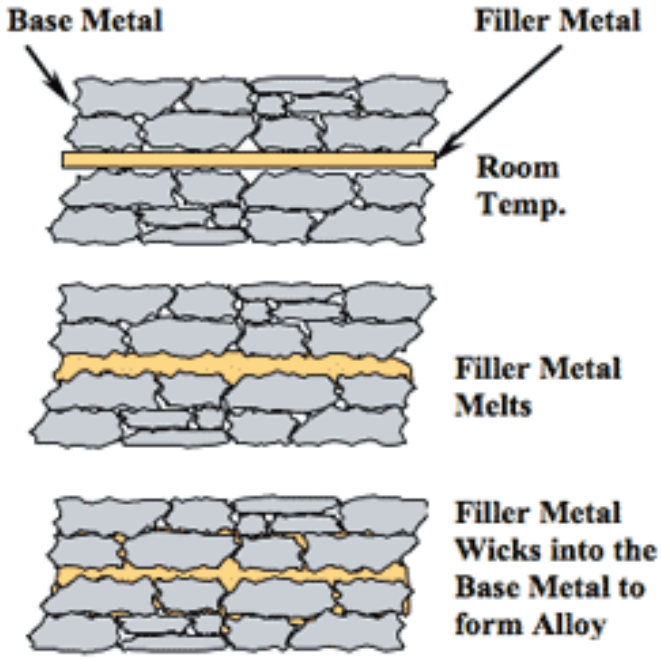
Brazing & Soldering - Introduction

- 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

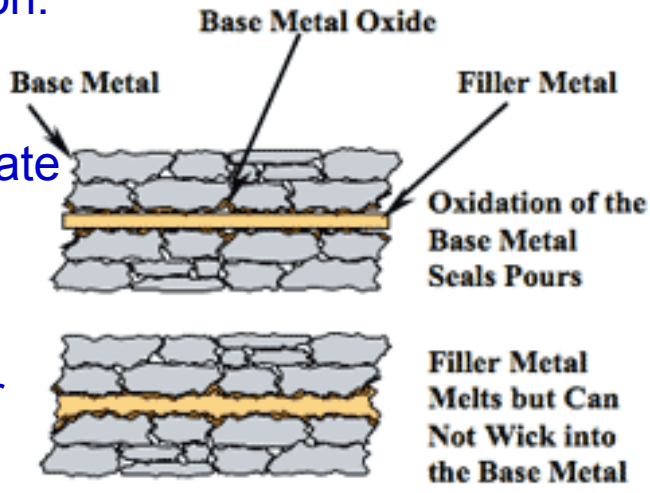
Main differences between welding & brazing:

- 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).

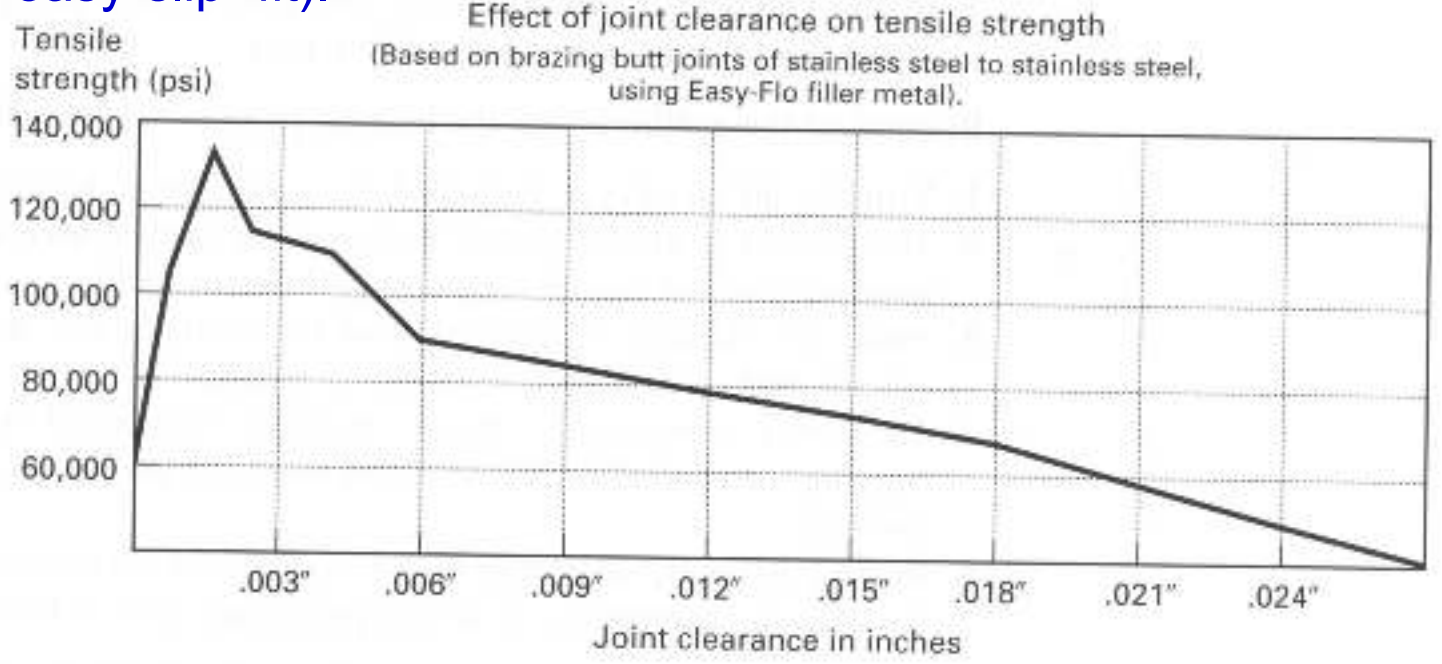


FIGURE 37-1 Typical variation of tensile strength with different joint clearances in a butt joint design. *(Courtesy of Handy & Harman).*

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°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)

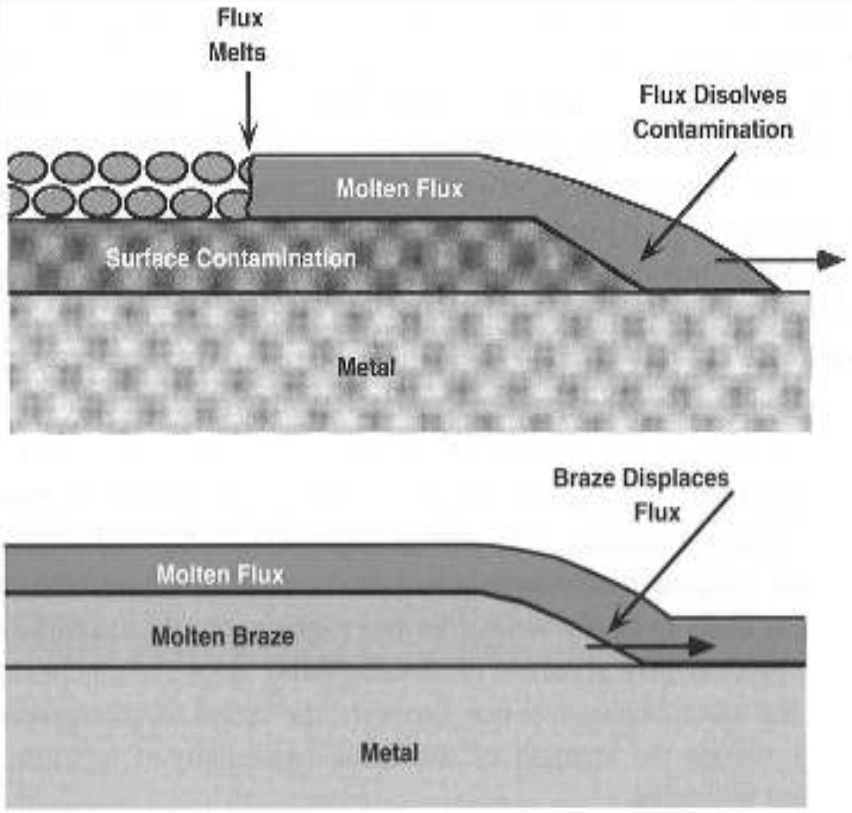


Fig. 7.2. All soldering and brazing procedures depend on a *flux* to wet the surfaces of the components and dissolve surface films and contamination, before being displaced by the molten braze or solder alloy (which must therefore also wet the components). (a) The flux *melts* and dissolves the film 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

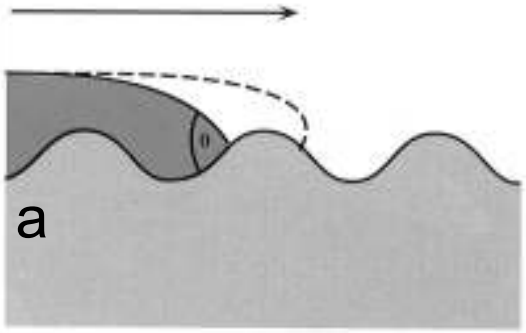
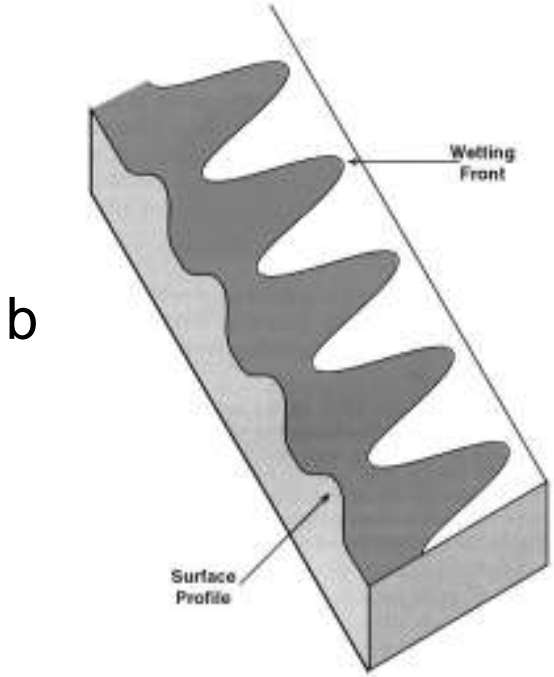
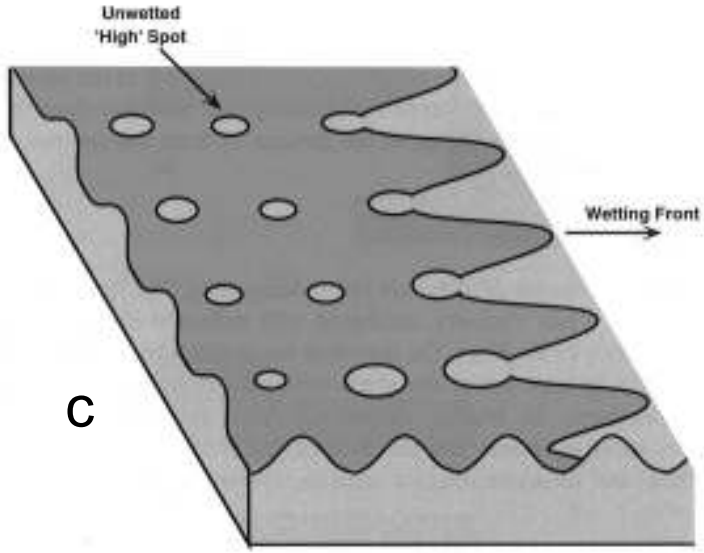


Fig. 7.3. The *surface* roughness has a large effect on the extent and rate of wetting. (a) Machining or grinding grooves *parallel* to the advancing front of the melt *inhibit* wetting by introducing a periodic variation in the *wetting angle* and hence in the spreading force. (b) Grooves *perpendicular* 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.





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

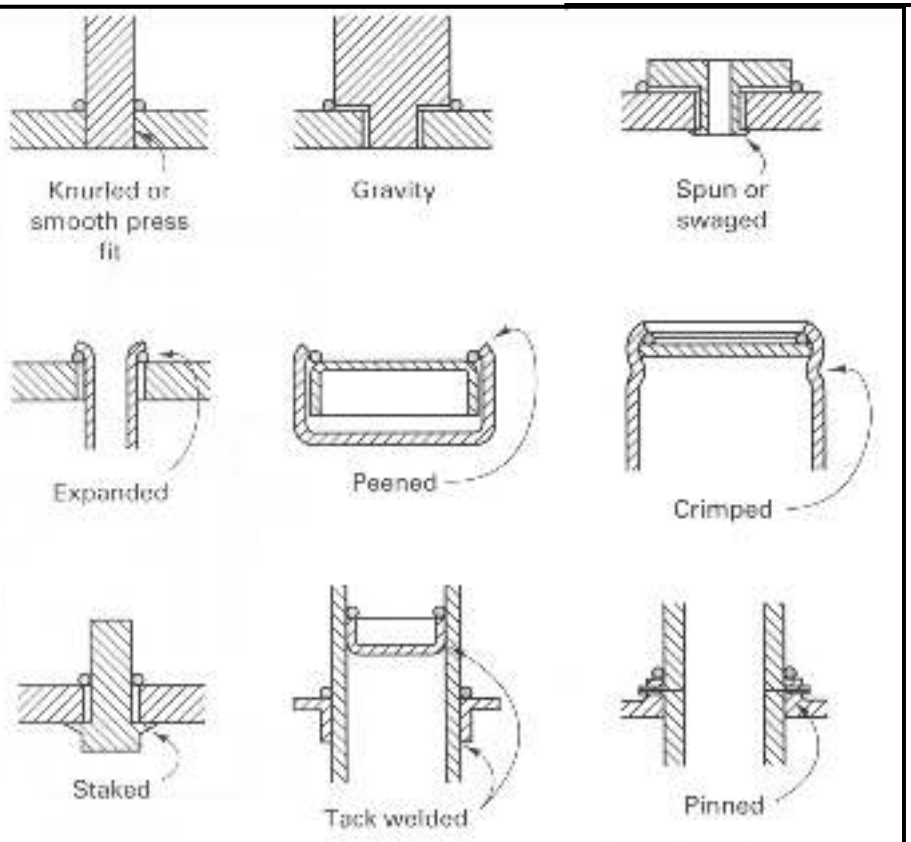


FIGURE 37-2 Methods of applying braze metal and positioning or fixturing various joints.

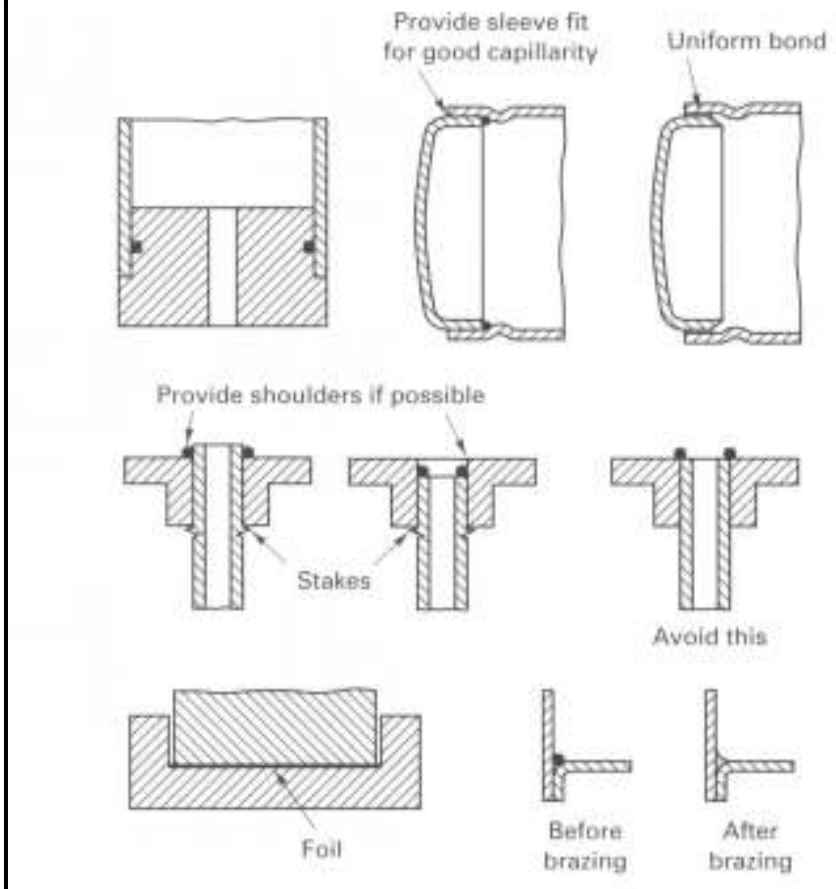


FIGURE 37-3 Techniques to apply brazing wire, foil, or sheet to assure proper flow into the joint.

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

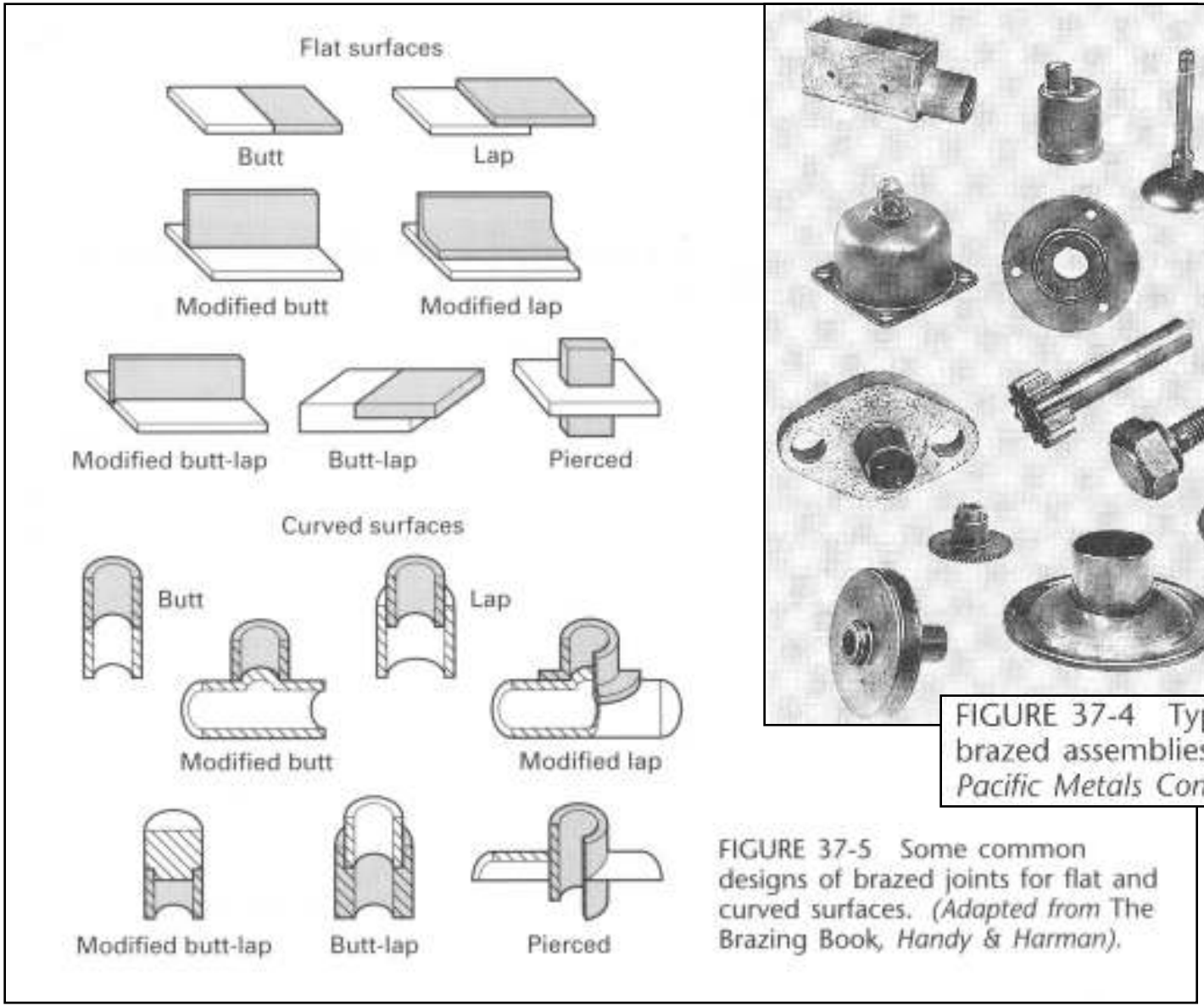


FIGURE 37-5 Some common designs of brazed joints for flat and curved surfaces. *(Adapted from* The Brazing Book, *Handy & Harman).*

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

Brazed Joint DESIGN

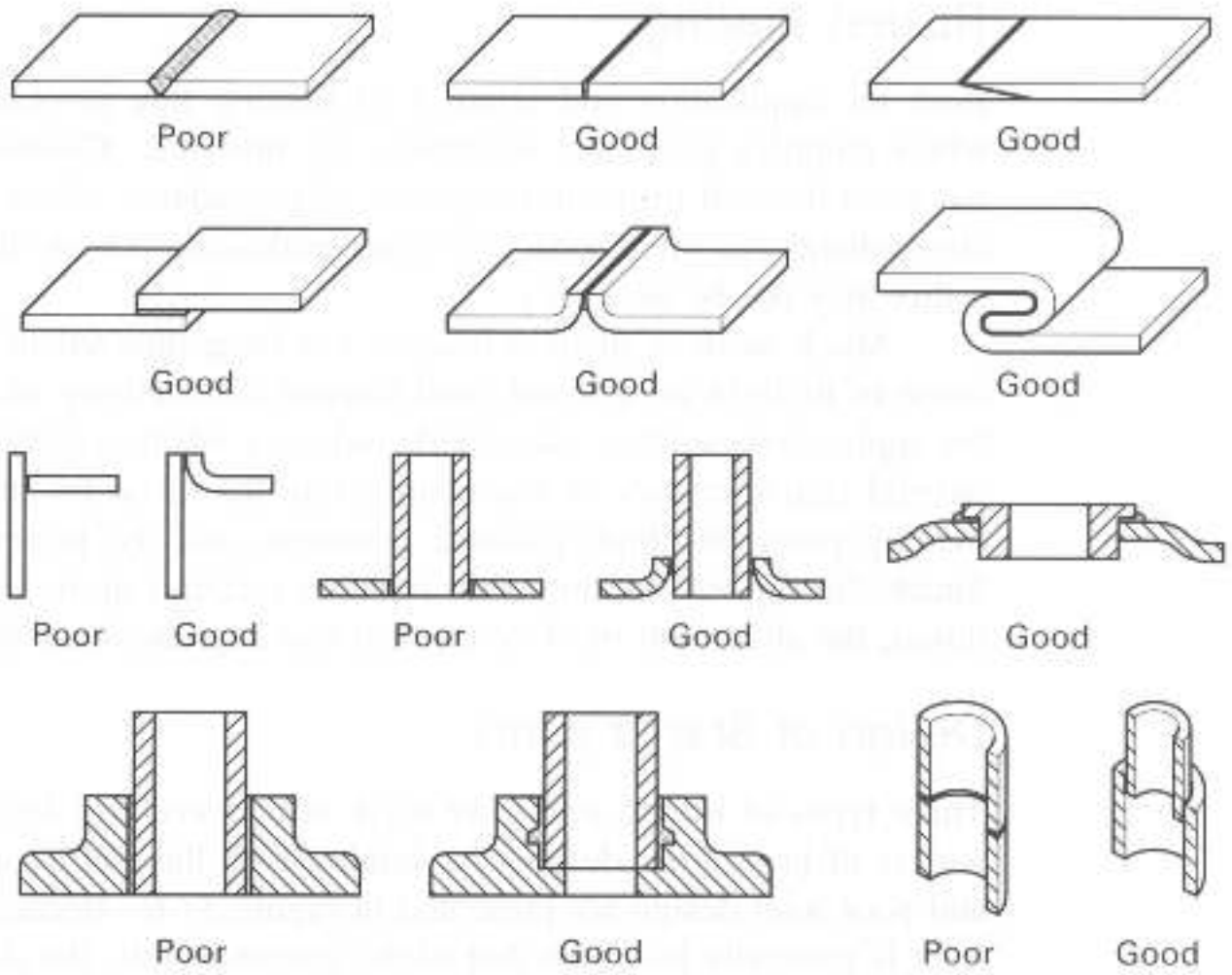


FIGURE 37-6 Examples of good and bad joint design for brazing.

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.

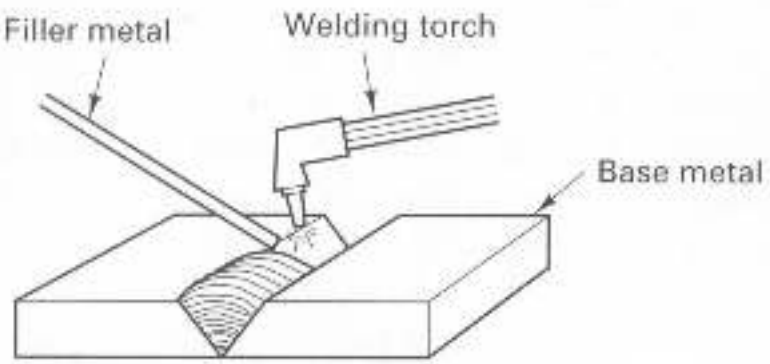


FIGURE 37-7 Schematic of the braze welding process.

Soldering

- Brazing-type operation where filler metal melting point is below 450°C (840°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.).

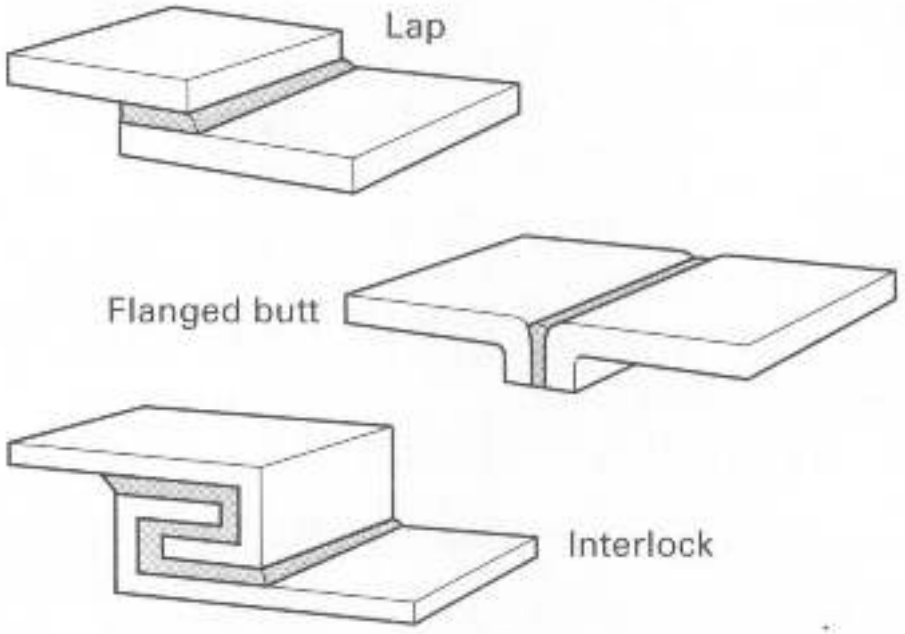


FIGURE 37-8 Some common designs for soldered joints. (C

Metals to be Joined

TABLE 37-4 Engineering Materials and Their Compatibility with Soldering

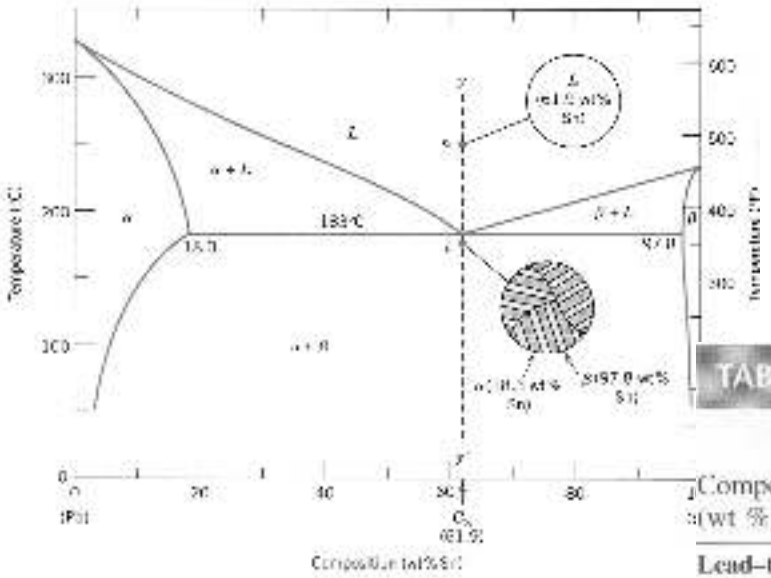
Material	Soldering Recommendation
Cast iron	Seldom used since graphite and silicon inhibit bonding
Carbon and low-alloy steels	Difficult for low-carbon materials; seldom used for high-carbon materials
Stainless steel	Common for 300 series; difficult for 400 series
Aluminum and magnesium	Seldom used; 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).

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

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

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

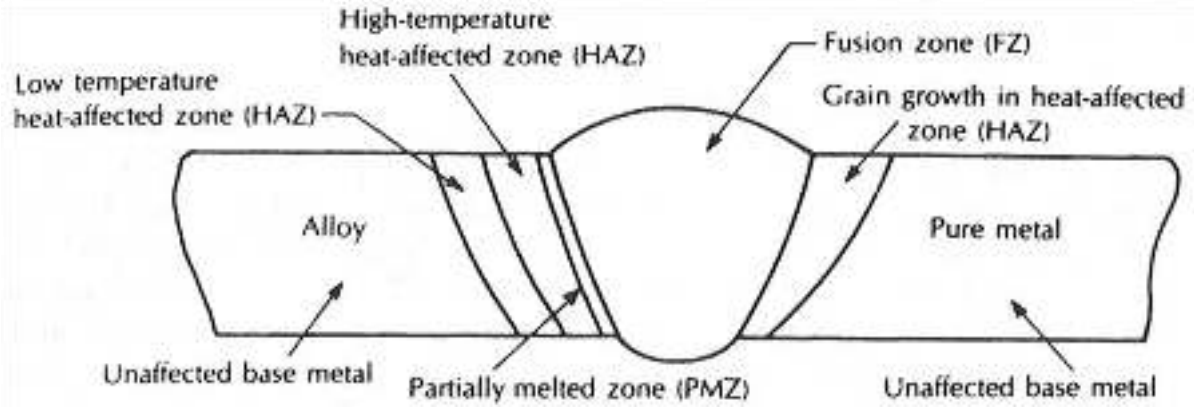
Flow of Heat in Welds

- 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).

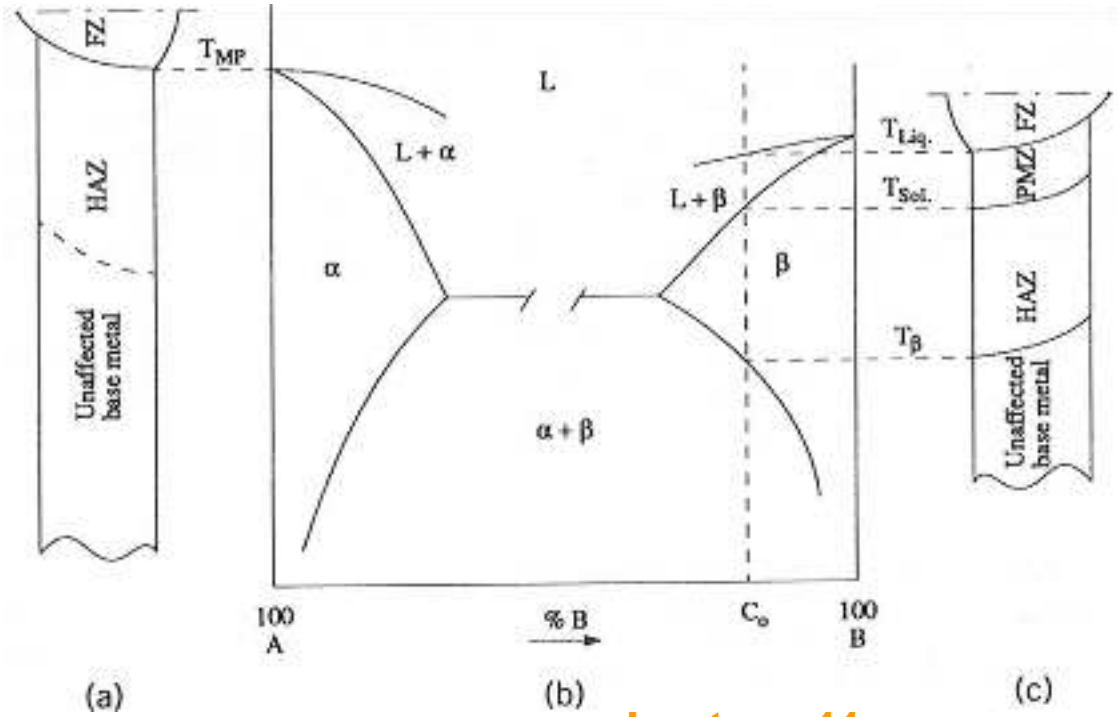
Weld Zones Prediction

- 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:

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

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 ($J.g^{-1}.K^{-1}$)

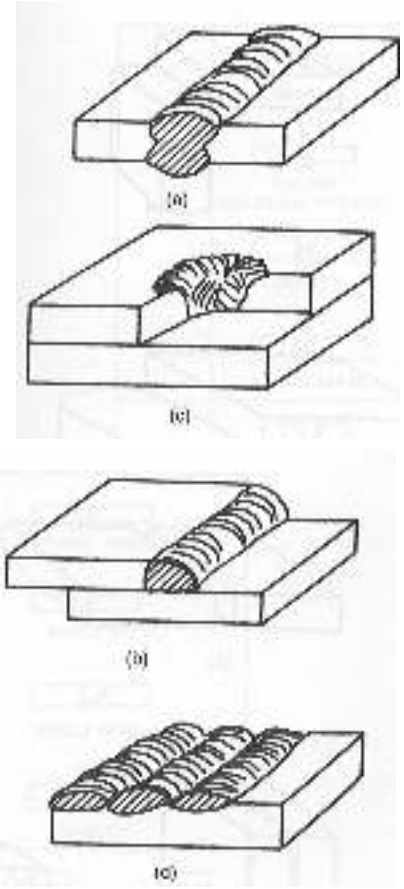
ρC = volumetric specific heat ($J.m^{-1}.K^{-1}$)

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

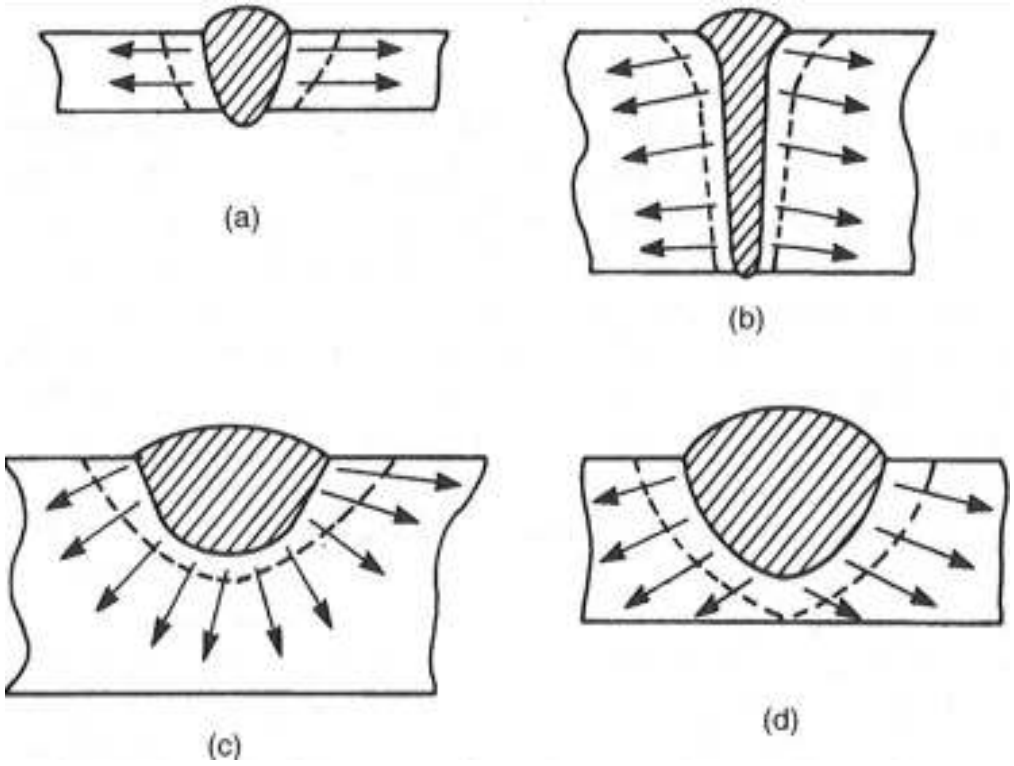
Note: increasing the initial temperature, T_0, (by preheating) decreases the cooling rate,R.

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



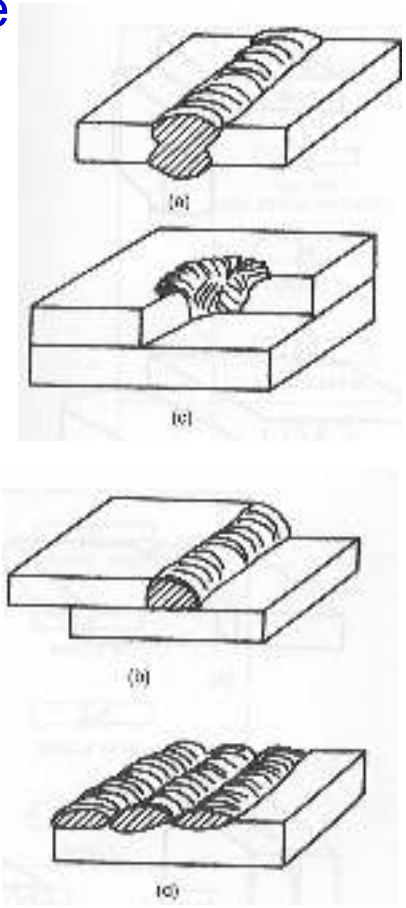
Fundamental types of welds, including (a) groove, (b) fillet, (c) plug, and (d) surfacing.



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

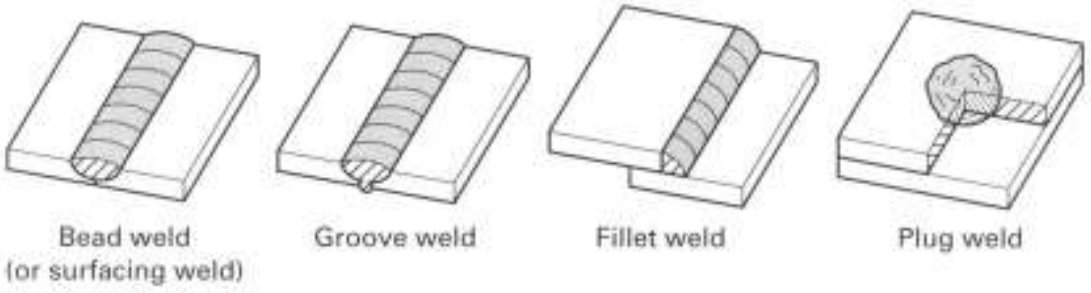


FIGURE 39-1 Four basic types of fusion welds.

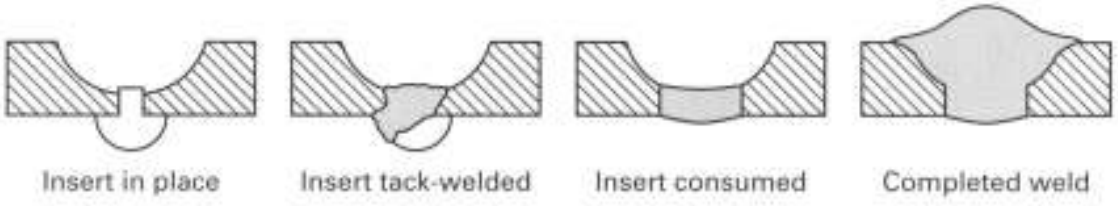


FIGURE 39-2 Use of a consumable backup insert in making fusion welds. *(Courtesy of Arcos Corporation.)*

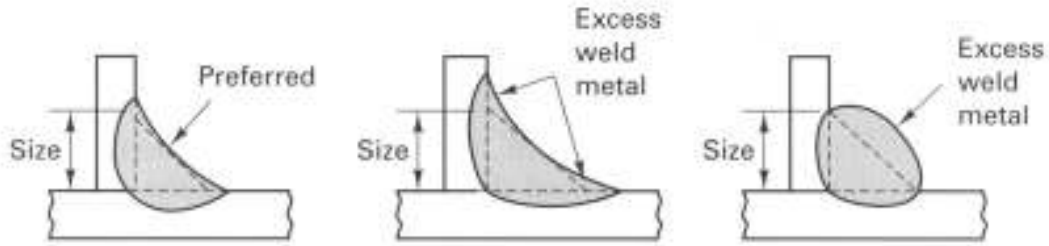


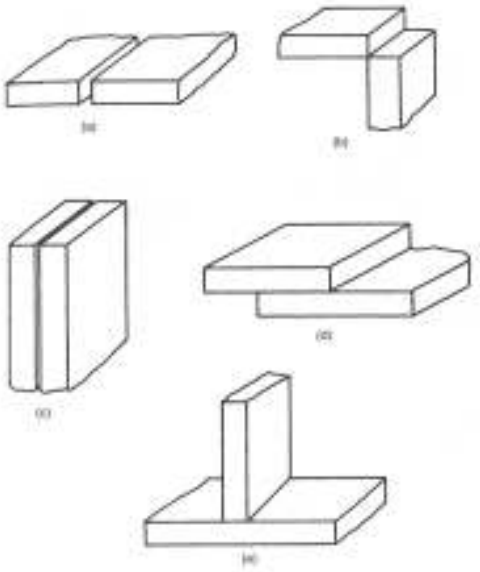
FIGURE 39-3 Preferred shape and the method of measuring the size of fillet welds.

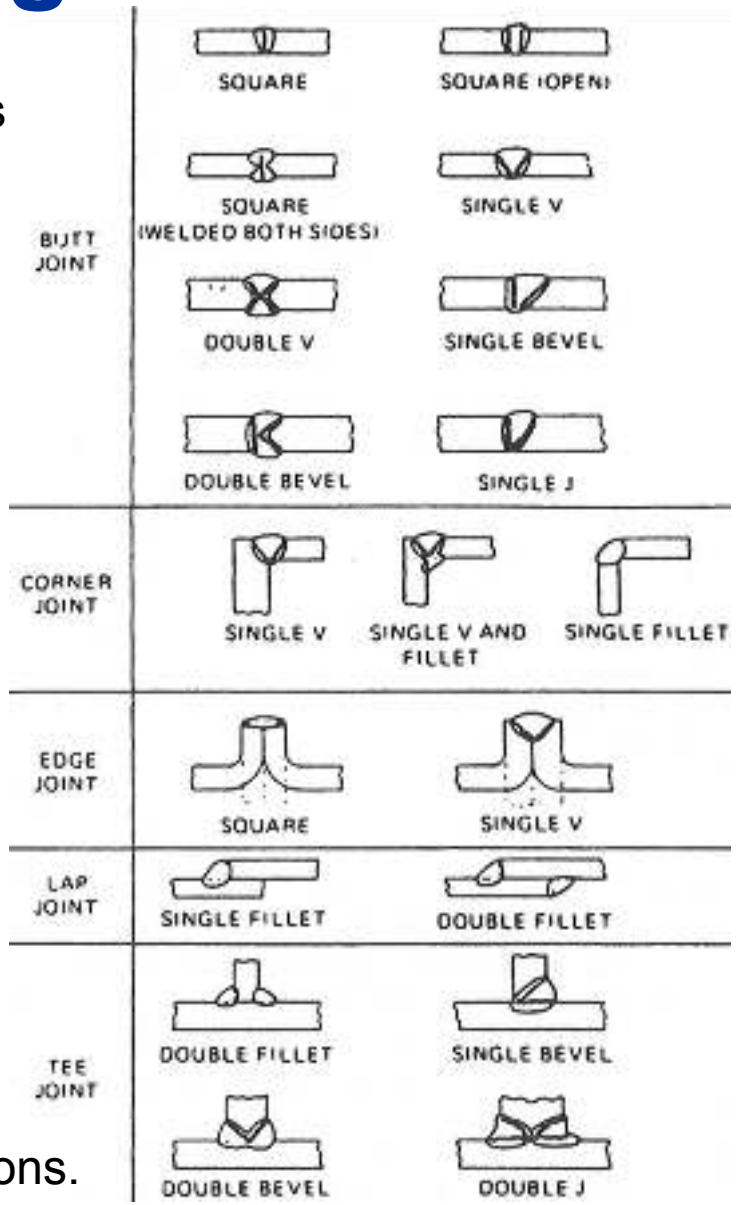
- Inserts are used in pipelines or other places where welding is restricted to one side only

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

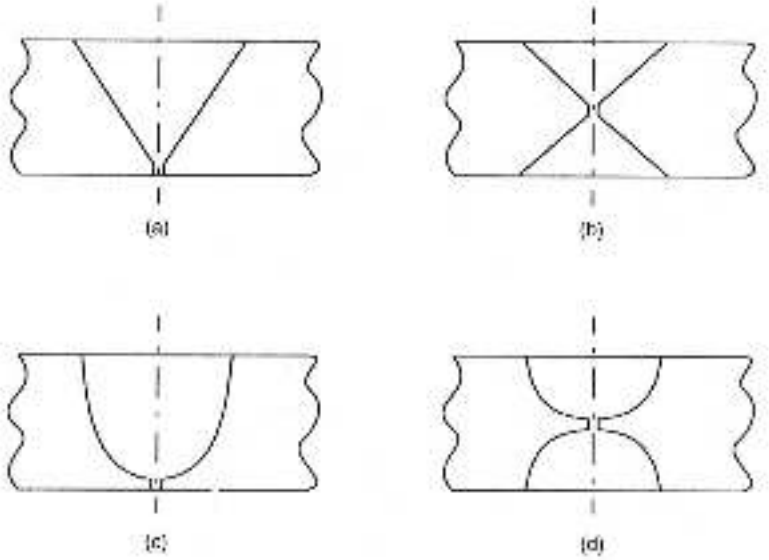
Five basic weld designs (a) butt, (b) corner, (c) edge, (d) lap, (e) tee.





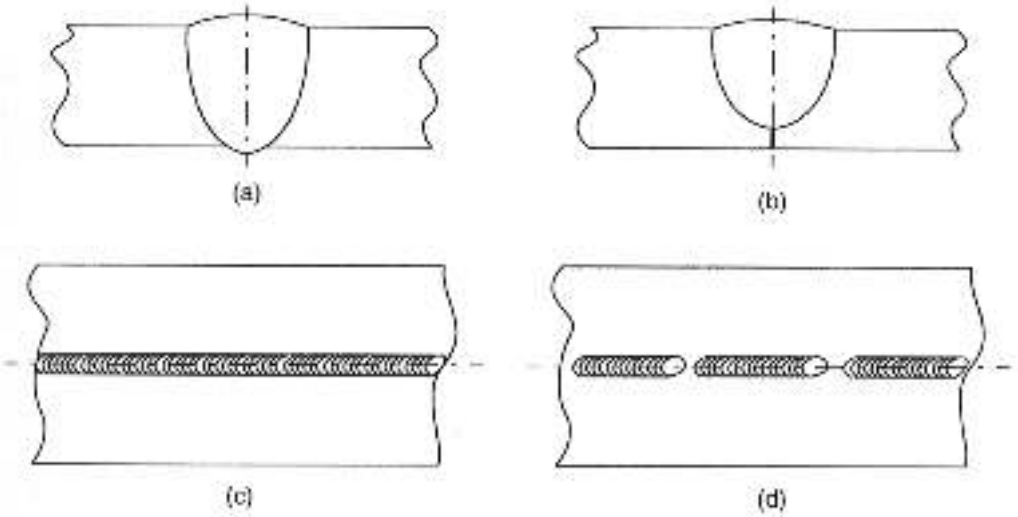
Some typical weld joint variations.

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

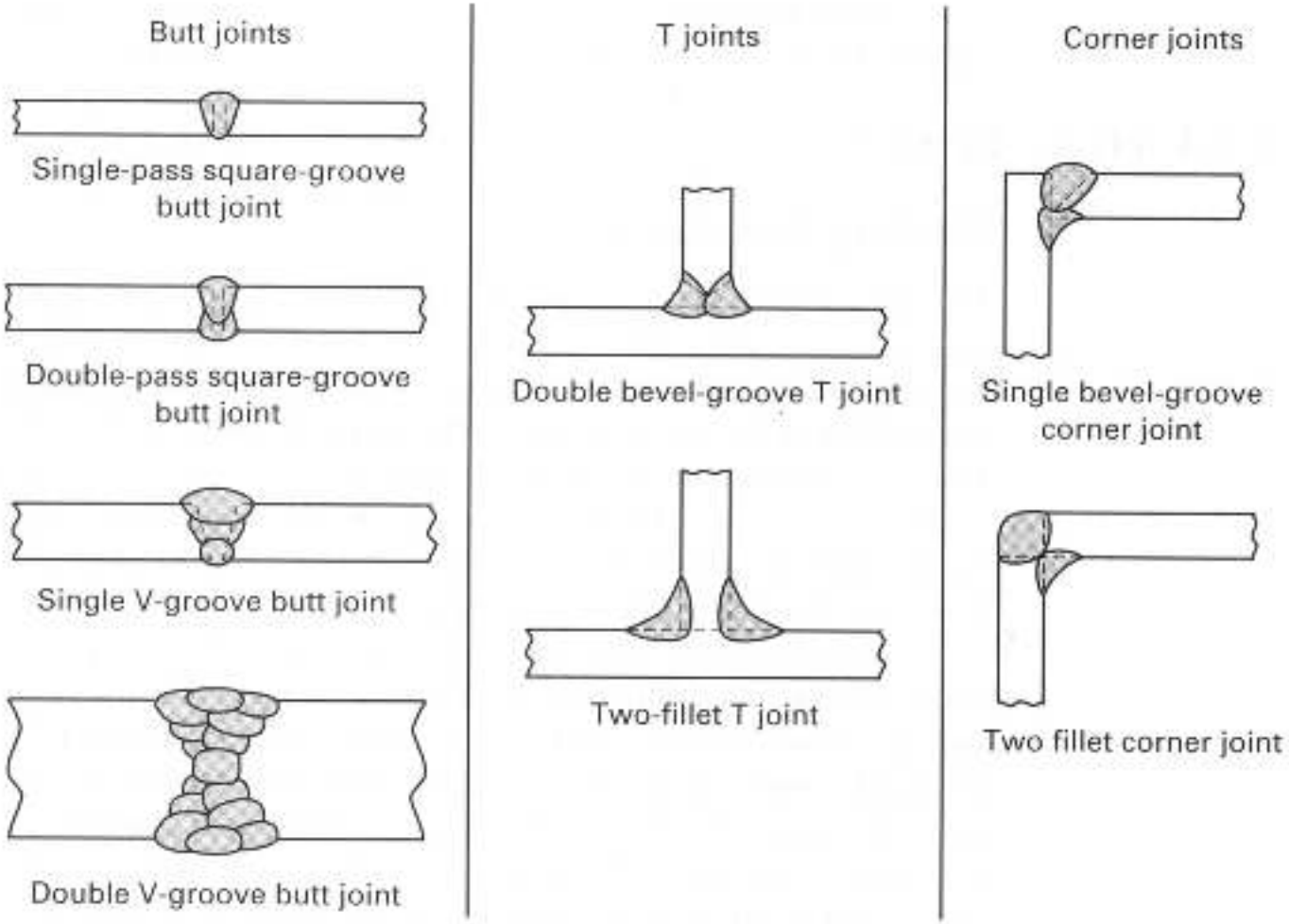


FIGURE 39-5 Various weld procedures used to form several common joints. *(Courtesy of Republic Steel Corporation.)*

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.

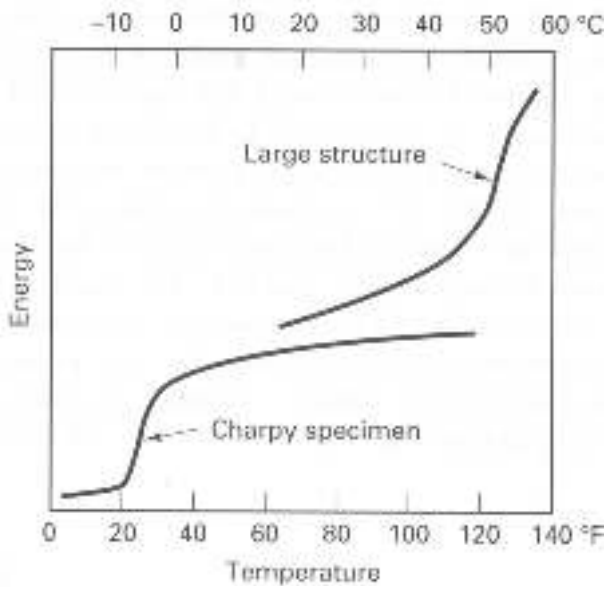


FIGURE 39-6 Effect of size on the transition temperature and energy-absorbing ability of a certain steel.

- 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)

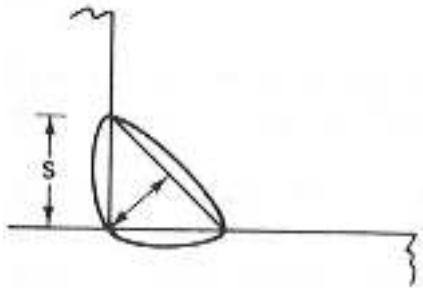
Weld Design Considerations

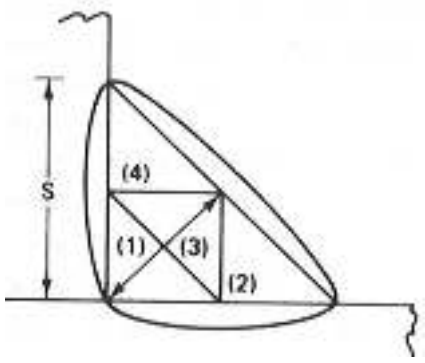
- Joint designed primarily for load-carrying ability.
- Variable in design and layout can affect costs, distortion, reliability, inspection, corrosion, type of defects.
- Select design that requires least amount of weld metal. (minimizes distortion, residual stresses).

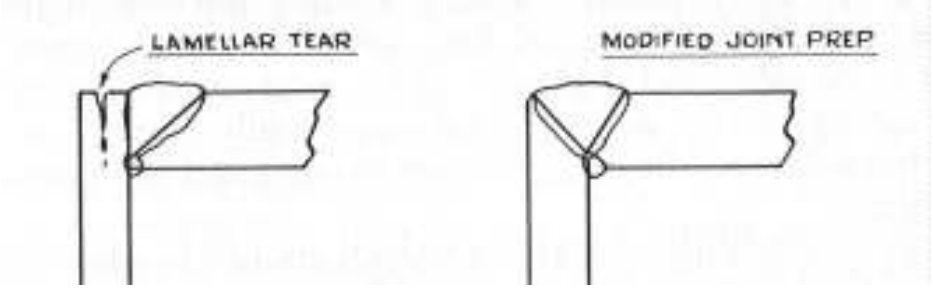
1. Where possible use square grooves (cheaper) and partial penetration (helps maintain dimensions – unmelted metal in contact) except where stress raisers cannot be tolerated (fatigue).
2. Use lap and fillet (instead of groove) welds where fatigue is not a problem (cheaper).

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

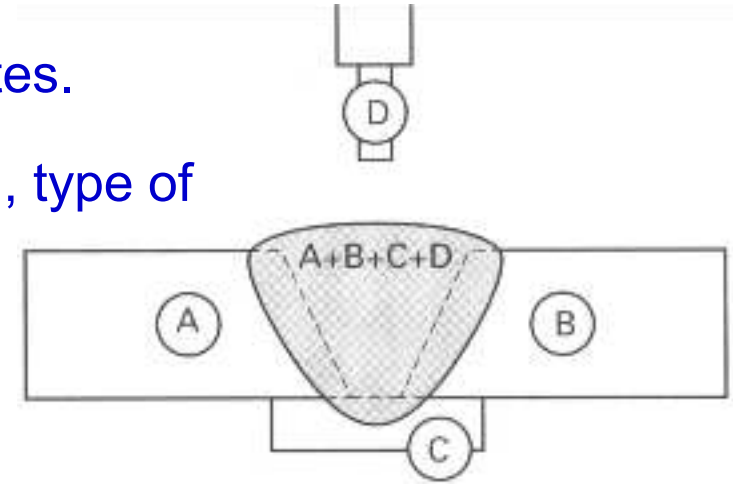


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

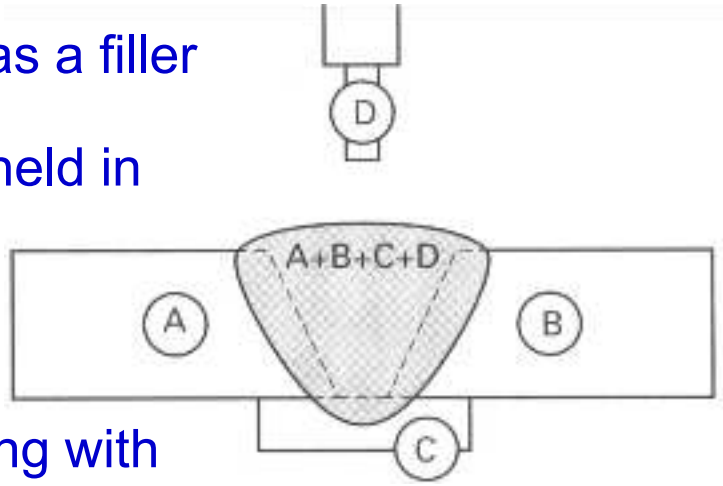


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

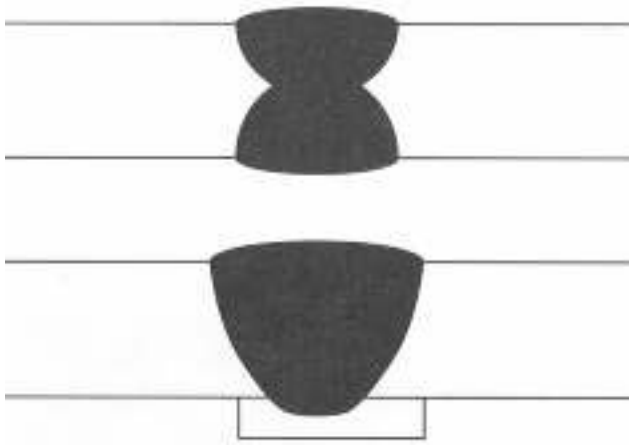
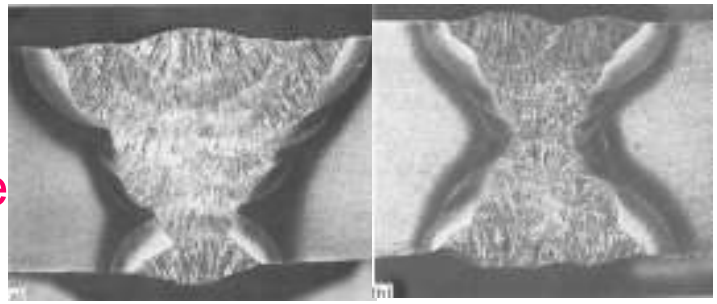


FIGURE 39-9 Comparison of two butt-weld designs. In the top weld, a large percentage of the weld pool is base metal. In the bottom weld, most of the weld pool is filler metal.

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

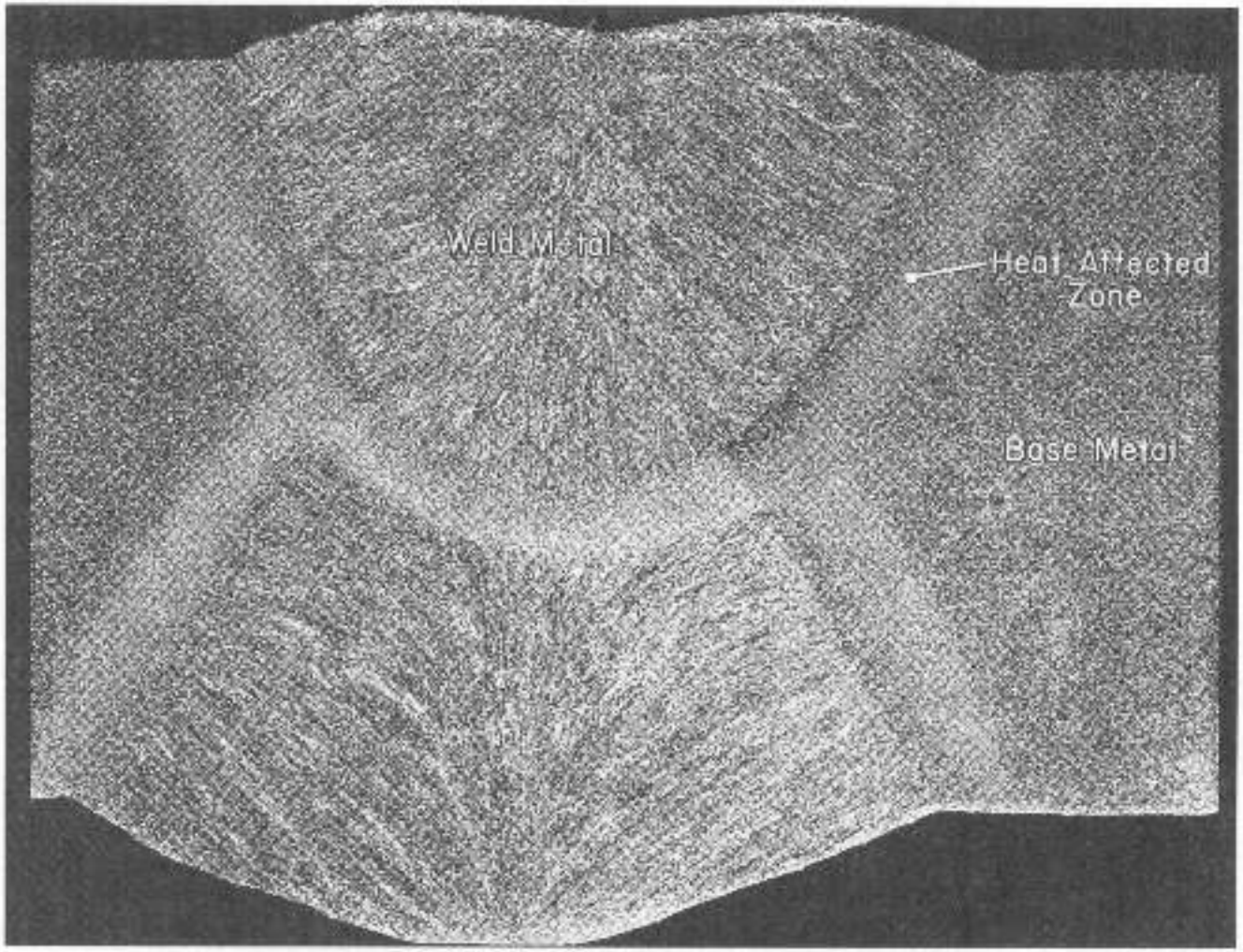


FIGURE 39-8 Grain structure and various zones in a fusion weld.

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

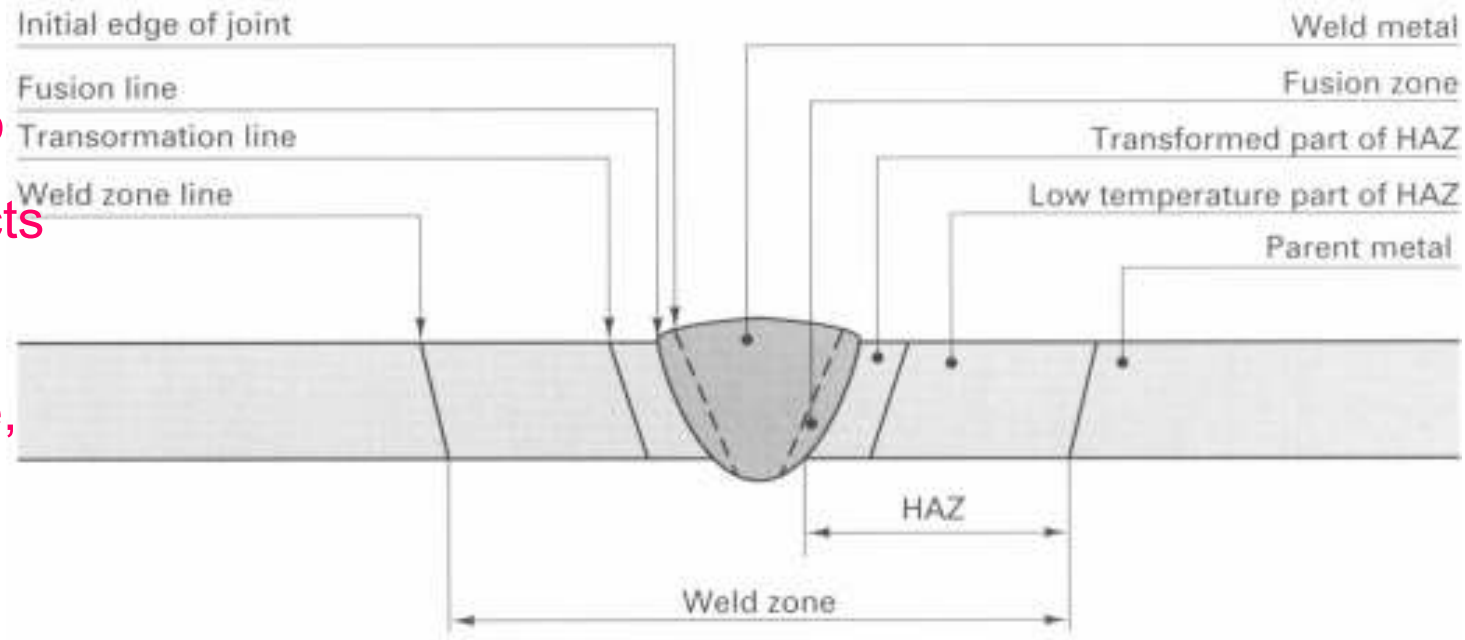


FIGURE 39-10 Schematic of a fusion weld in steel, presenting proper terminology for the various regions and interfaces. Part of the heat-affected zone has been heated above the transformation temperature. *(Courtesy of Sandvik AB.)*

Soldering

- Brazing-type operation where filler metal melting point is below 450°C (840°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.).

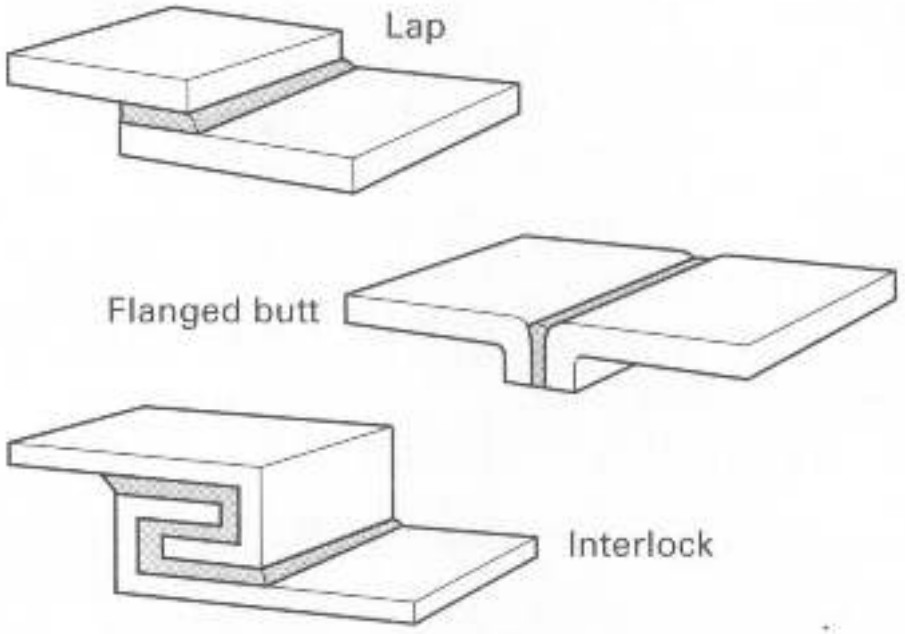


FIGURE 37-8 Some common designs for soldered joints. (C

Metals to be Joined

TABLE 37-4 Engineering Materials and Their Compatibility with Soldering

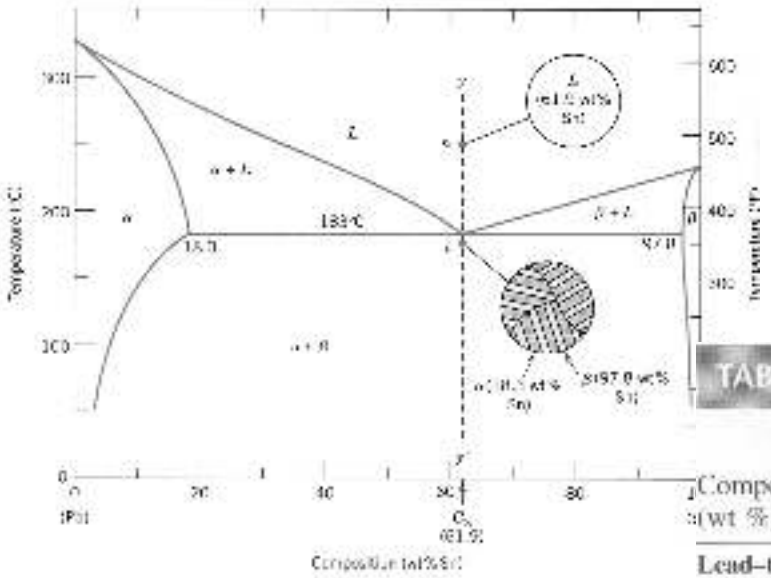
Material	Soldering Recommendation
Cast iron	Seldom used since graphite and silicon inhibit bonding
Carbon and low-alloy steels	Difficult for low-carbon materials; seldom used for high-carbon materials
Stainless steel	Common for 300 series; difficult for 400 series
Aluminum and magnesium	Seldom used; 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).

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

TABLE 37-3 Some Common Solders and Their Properties

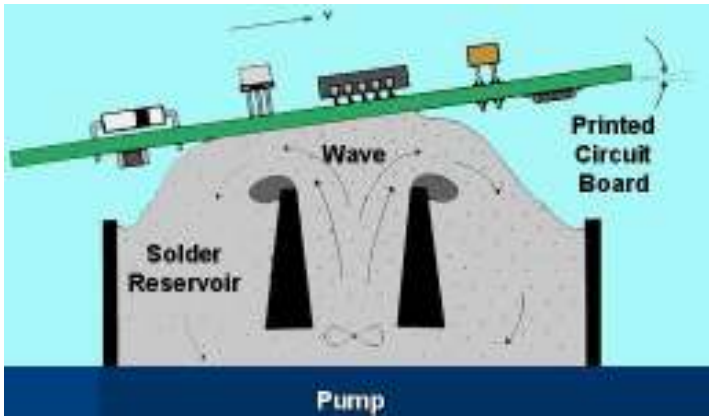
Composition (wt %)	Freezing Temperature (°F) Liquidus	Solidus	Range	Applications
Lead–tin solders				
98 Pb–2 Sn	611	601	10	Side seams in three-piece can
90 Pb–10 Sn	576	514	62	Coating and joining metals
80 Pb–20 Sn	531	361	170	Filling and seaming auto bodies
70 Pb–30 Sn	491	361	130	Torch soldering
60 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

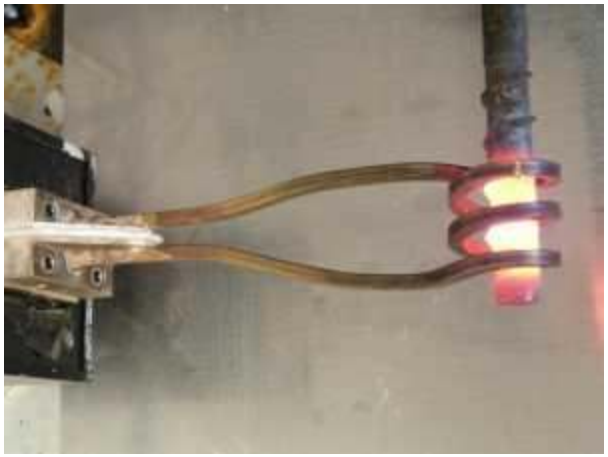
Soldering Fluxes

- 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

Soldering Heat





MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Adhesive & Mechanical Fastening

Lecture 11

Adhesive Bonding

Adhesive Bonding

- Inexpensive and weigh less than fasteners for similar strength joints
- provide thermal and electrical insulation; act as a damper to noise, shock, and vibration; stop a propagating crack; and provide protection against galvanic corrosion when dissimilar metals are joined
- Seal against moisture, gases, and fluids; Offer corrosion resistance
- Most adhesives can be applied quickly, and useful strengths are achieved in a short period of time. (2 seconds!)
- Surface preparation may be reduced - bonding can occur over an oxide film, and rough surfaces are good - increased contact area.
- Tolerances are less critical since the adhesives are more forgiving than alternative methods of bonding
- Smooth contours are obtainable, (no holes required cf. bolts).

Adhesive Materials and Properties

- Biggest advantage is in load distribution, unlike mechanical fasteners
- Non metallic (adhesive) material is used to join surfaces
- Can be thermoplastic or thermosetting resins, elastomers, ceramics…
- Applied as drops, beads, pellets, tapes, coatings (liquids, pastes…)
- Curing can be influenced by heating, radiation or light, catalyst or chemical reactions
- Different applications of adhesive fastening
  - Heavy duty or Load bearing (structural adhesive)
  - Light duty or fixturing (mainly to hold pieces together)
  - Sealing (forming liquid or gas-tight joints)
- Due to load bearing nature of structural adhesive, strength and rigidity of the adhesive material over a period of time is important

Adhesive Materials and Properties

1. **EPOXY –** oldest and more common (single or two component) single component needs heat to cure, two component cures at RT
2. **CYANOACRYLATES -** single component cures at RT, moisture promotes curing < 2s
3. **ANAEROBICS -** single component, remains liquid in air, shut of O in joints, cures by polymerizing in the presence of Fe or Cu. 6 to 24 hrs to attain useful strength
4. **ACRYLICS -** two component can be applied and stored separately. Once joined, they cures at RT. thermoplastic
5. **URETHANE –** used in low temp service <65°C
6. **SILICONE –** resistant yet flexible joint. Cures from moisture on surface
7. **HIGH-TEMPERATURE ADHESIVES –** expensive as silicone, good for use clost to 300°C. slow curing. Aerospace applications

Adhesive Materials and Properties

8. **HOT MELTS -** not considered to be true structural adhesives, but are being used to transmit loads, mostly in composite mat'l assemblies

- They are thermoplastic resins - solid at room temperature but melt abruptly when heated into the range of 200 to 300°F (l00 to 150°C)
- Applied as heated liquids to form bond as the molten adhesive cools
- Or position the adhesive in the joint prior to operations (paint bake process) in automobile manufacture. while baking, the adhesive melts, flows into seams, and seals against corrosive moisture entry
- The hot melts provide reasonable strength within minutes, but do soften and creep when exposed to elevated temperatures and become brittle when cold.

Adhesive Materials and Properties

TABLE 38-1. Some Common Structural Adhesives, Their Cure Temperatures, Maximum Service Temperatures, and Strengths Under Various Types of Loadings

Adhesive Type	Cure Temperature (°F)	Service Temperature (°F)	Lap Shear Strength (psi at °F)[a]	Peel Strength at Room Temperature (lb/in.)
Butyral–phenolic	275 to 350	−60 to 175	1000 at 175 2500 at RT	10
Epoxy				
Room-temperature cure	60 to 90	−60 to 180	1500 at 180 2500 at RT	4
Elevated-temperature cure	200 to 350	−60 to 350	1500 at 350 2500 at RT	5
Epoxy–nylon	250 to 350	−420 to 180	2000 at 180 6000 at RT	70
Epoxy–phenolic	250 to 350	−420 to 500	1000 at 175 2500 at RT	10
Neoprene–phenolic	275 to 350	−60 to 180	1000 at 180 2000 at RT	15
Nitrile–phenolic	275 to 350	−60 to 250	2000 at 250 4000 at RT	60
Polyimide	550 to 650	−420 to 1000	1000 at 1000 2500 at RT	3
Urethane	75 to 250	−420 to 175	1000 at 175 2500 at RT	50

[a]RT, room temperature.

Design Considerations

1. What materials are being joined? What are their porosity, hardness, & surface conditions? Difference in thermal expansions (contractions)
2. How will the joined assembly be used? What type of joint is proposed, what will be the bond area, and what will be the applied stresses? How much strength is required? Will there be mechanical vibration, acoustical vibration, or impacts?
3. What temperatures might be required to effect the cure, and what temperatures might be encountered during service? (highest temperature, lowest temperature, rates of temperature change, frequency, duration of exposure to extremes, properties required, and differential expansions or contractions.)

Design Considerations

4. Will there be subsequent exposure to solvents, water or humidity, fuels or oils, light, ultraviolet radiation, acid solutions, or general weathering?
5. What is the desired level of flexibility or stiffness? How much toughness is required?
6. Over what length of time is stability desired? What portion of this time will be under load?
7. Is appearance important?
8. How will the adhesive be applied? What equipment, labor, and skill are required?
9. What will it cost?

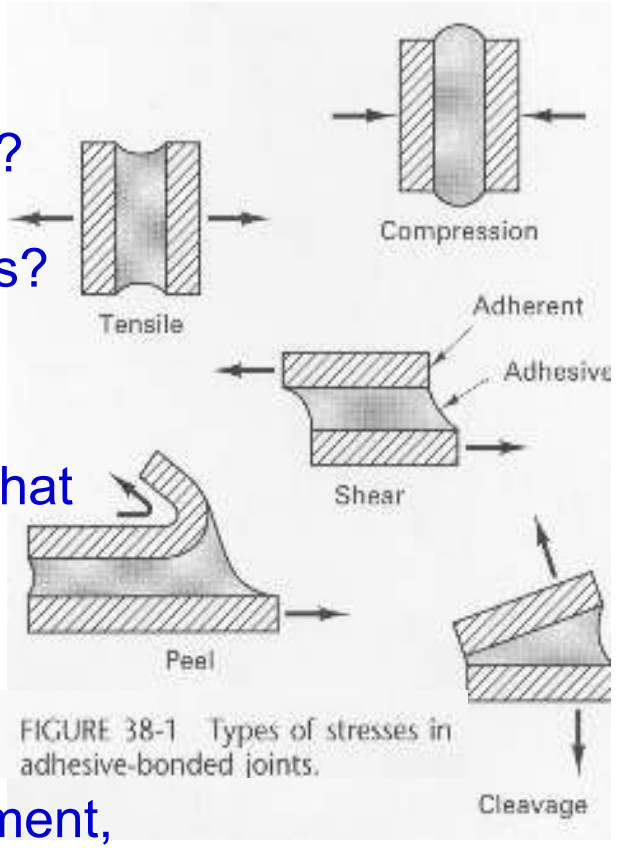


FIGURE 38-1 Types of stresses in adhesive-bonded joints.

Design Considerations

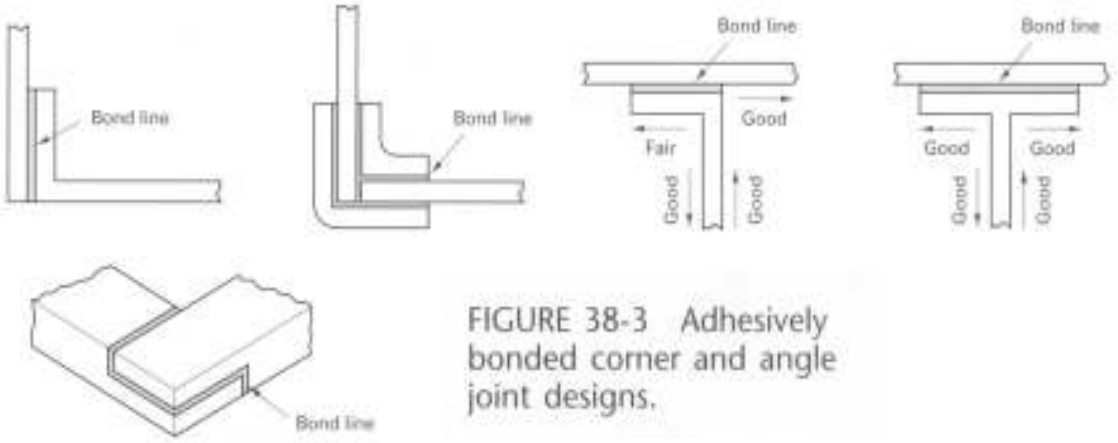


FIGURE 38-3 Adhesively bonded corner and angle joint designs.

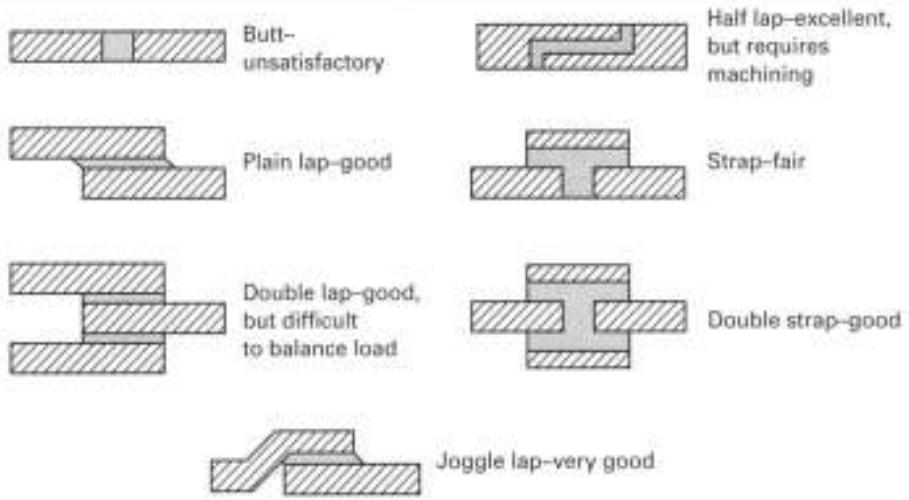
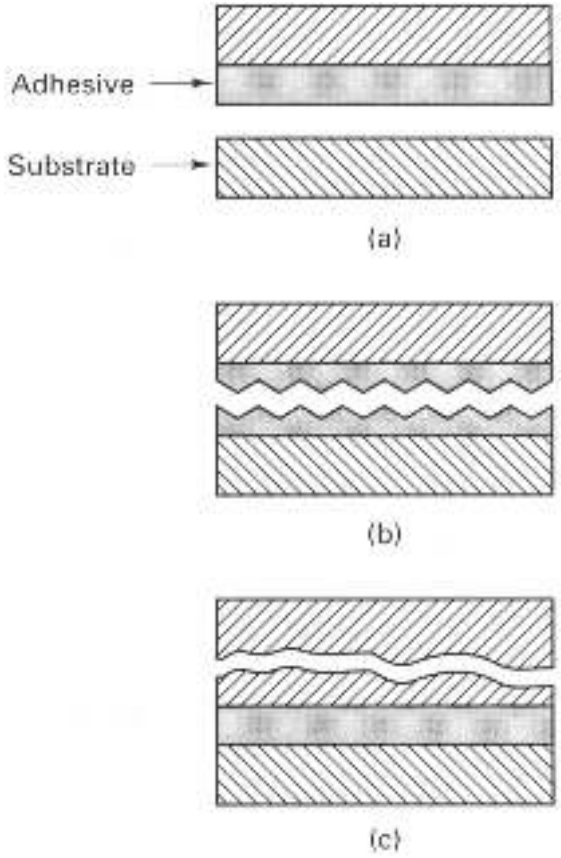


FIGURE 38-2 Possible designs of adhesive-bonded joints and a rating of their performance in service.

FIGURE 38-4 Failure modes of adhesive joints: (a) adhesive failure; (b) cohesive failure within the adhesive; (c) cohesive failure within the substrate.



Adhesive Bonding Advantages

1. Most material/combination can be joined (size, shape, and thickness).
2. For most adhesives, low curing temperatures, (usually <180°C). Heat-sensitive materials can be joined without damage and HAZ.
3. Foils can be joined to each other or to heavier sections. When joining dissimilar materials, the adhesive provides a bond that can tolerate the stresses of differential expansion and contraction.
4. Adhesives bond the entire joint area → good load distribution and fatigue resistance; stress concentrations are avoided (unlike screws). Total joint strength comparable with alternative methods. (Shear strengths of industrial adhesives > 20MPa or 300 PSI)
5. Additives can enhance strength, increase flexibility, provide resistance to various environments.

Adhesive Bonding Disadvantages

1. No universal adhesive. Selection is complicated by available options.
2. Most adhesives are not stable above 350°F (180°C). (Max 260°C).
3. High-strength adhesives are often brittle (poor impact properties). Resilient ones often creep. Some become brittle at low temperatures
4. Long-term durability and life expectancy are difficult to predict.
5. Surface preparation and cleanliness, adhesive preparation, and curing can be critical for consistent results. Adhesives are sensitive to grease, oil, moisture. Surface roughness and wetting must be controlled.
6. Difficult to determine the quality by traditional NDT techniques.
7. Adhesives contain toxic chemicals/solvents, or produce upon curing.
8. Many structural adhesives deteriorate under certain operating conditions, UV light, ozone, acid rain, moisture, and salt.
9. Adhesively bonded joints cannot be readily disassembled.

Mechanical Fastening

Mechanical Joining Methods

- Often based on localized, point-attachment processes, in which the join is provided by a nail, a rivet, a screw or a bolt.
- These joints depend on residual tensile stresses in the attachment to hold the components in compression.
- The joint is usually formed by an ordered array of point-attachments, rivets at the edge of a ship's plate, or the uniformly spaced bolts around a pressure vessel flange.
- Mechanical joints are also made along a line of attachment, such as that formed when a piece of sheet is bent to form a cylinder (a paint can, for example) and the two edges are joined with an interlock seam.

Mechanical Fasteners

- Here too the residual stresses (tensile around the circumference of the can, compressive along the joint) ensure integrity of joint.
- Many mechanical joints are designed for ease of assembly and disassembly (for example, bolted joints).
- The effectiveness of mechanical fasteners depends upon
  - The material of the fastener,
  - Fastener design (including the load-bearing area of the head)
  - Hole preparation, The installation procedure.
- The desire is to achieve uniform load transfer, minimum stress concentration, and uniformity of installation torque or interference fit.

Mechanical Fasteners

- **Integral fasteners:** formed areas of a component that interfere or interlock with other components - most commonly found in sheet metal products: lanced/shear-formed tabs, extruded hole flanges, embossed protrusions, edge seams, and crimps.
- e.g. beverage can lids, tabs etc.

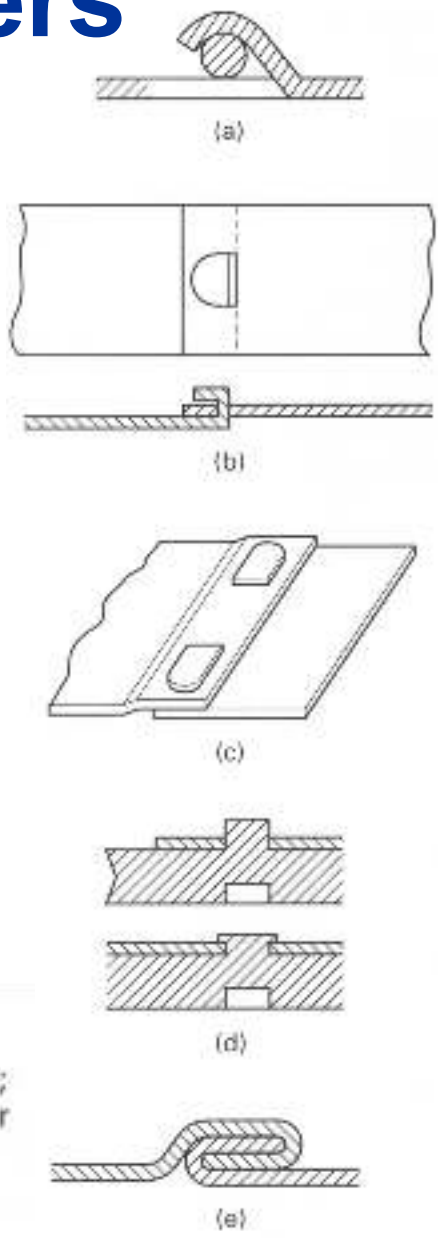


FIGURE 38-5 Several types of integral fasteners: (a) lanced tab to fasten wires or cables to sheet or plate; (b) and (c) assembly through folded tabs and slots for different types of loading; (d) use of a flattened embossed protrusion; (e) single-lock seam.

Mechanical Fasteners

- **Discrete fasteners:** separate pieces used to join primary components: bolts, nuts, screws, nails, rivets, quick-release fasteners, staples, and wire stitches.
- Over 150 billion discrete fasteners - annual consumption in the US, 27 billion by auto industry. (ANSI BI8.12.) The fasteners are easy to install, remove, and replace.
- Various finishes and coatings can be applied to withstand a multitude of service conditions.

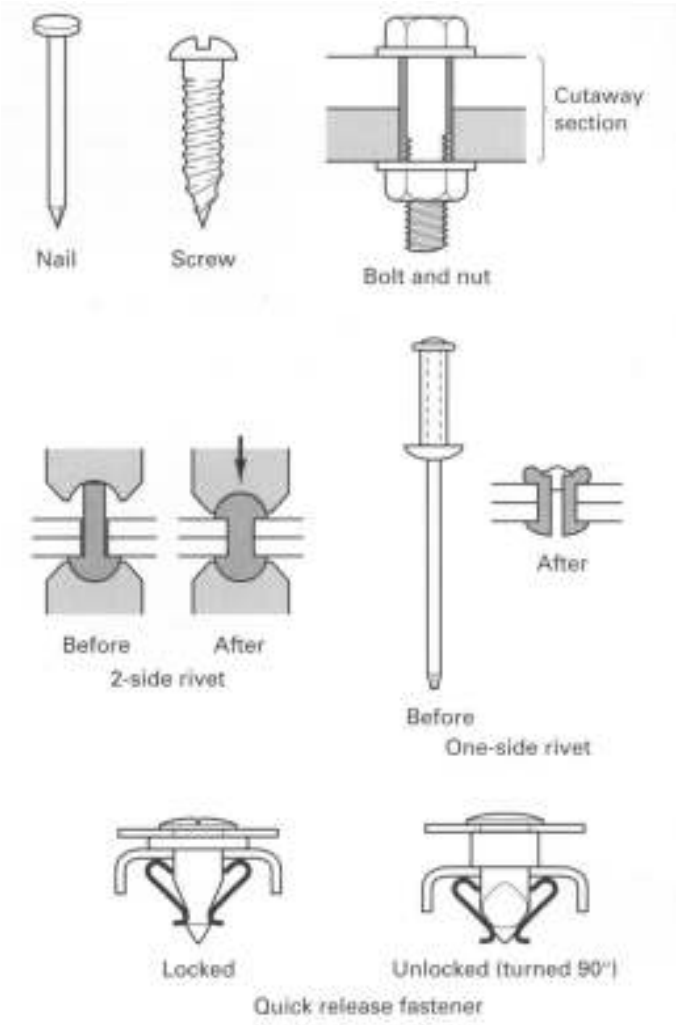


FIGURE 38-6 Various types of discrete fasteners, including a nail, screw, nut and bolt, two-side access supported rivet, one-side access blind rivet, and quick-release fastener.

Mechanical Fasteners

- **Shrink and expansion fits:** dimensional change introduced to one or both of the components by heating or cooling (heating one part, heating one and cooling other, or cooling one).
- Assembled and a strong interference fit is established when temperature uniformity is restored.
- Joint strength is exceptionally high. Can be used to produce a pre-stressed condition in a weak material; to replace costly stronger one.
- Similarly, a corrosion-resistant cladding or lining can be easily provided to a less-costly bulk material.
- **Press fits:** similar to above but using mechanical force.

Mechanical Fasteners - Advantages

1. Ease of disassembly and reassembly. (threaded fasteners) and semipermanent fasteners (such as rivets) can be drilled out.
2. The ability to join similar or different materials in different sizes, shapes, and joint designs. Some joint designs, such as hinges and slides, permit limited motion between the components.
3. Low manufacturing cost compared to the components being joined. They are readily available in a variety of mass-produced sizes.
4. Installation does not adversely affect the base materials as with techniques involving the application of heat and/or pressure.
5. Little or no surface preparation or cleaning is required.

Role of Residual Stress

- Mechanical joints use compressive residual stresses across the join in order to maintain the components in contact.
- They therefore require a balancing tensile stress elsewhere in the system.
- These tensile stresses may either be in the fastening (nails, bolts or rivets), or in the components themselves (the interlock seam).

Manufacturing Concerns

- Often require aligned holes for mechanical fasteners. Many ways to make holes; drilling, punching, chemical machining, lasers etc.
- Each produces holes with characteristic features; surface finish, tolerance, properties etc.
- If bolts need nuts then two-sided access is required (if threaded hole – one side only).
- Self-tapping screws (harder screws or softer materials).
- Stapling is quick, cheap method that does not require prior hole.
- Rivets give good strength but are semi-permanent.
- Snap fits require material is sufficiently elastic.

Design and Selection

- Must consider many factors including possible joint failure as fasteners are vulnerable sites. Joints usually fail due to oversight in:
  - Design of fastener and its method of manufacture.
  - Material used for fastener. Joint design.
  - Means and details of installation.
- E.g. Insufficient strength or corrosion resistance, (galvanic corrosion is common with dissimilar metal fasteners). Non-metallic fasteners (nylon, fiberglass) can sometimes be used at low stresses.
- 90% of cracks in airframes originate at fastener holes (stress raisers) and fasteners fail by fatigue.

Design and Selection

- Problems worsen if too loose or too tight.
- Rolled threads and formed heads are better than machined and fillets are important between head and shank of bolts.

Table 18.2 The Galvanic Series

Increasingly inert (cathodic) ↑

- Platinum
- Gold
- Graphite
- Titanium
- Silver
- 316 Stainless steel (passive)
- 304 Stainless steel (passive)
- Inconel (80Ni–13Cr–7Fe) (passive)
- Nickel (passive)
- Monel (70Ni–30Cu)
- Copper–nickel alloys
- Bronzes (Cu–Sn alloys)
- Copper
- Brasses (Cu–Zn alloys)
- Inconel (active)
- Nickel (active)
- Tin
- Lead
- 316 Stainless steel (active)
- 304 Stainless steel (active)
- Cast iron
- Iron and steel
- Aluminum alloys
- Cadmium
- Commercially pure aluminum
- Zinc
- Magnesium and magnesium alloys

Increasingly active (anodic) ↓

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Welding Joints & Metallurgy

Lecture 11

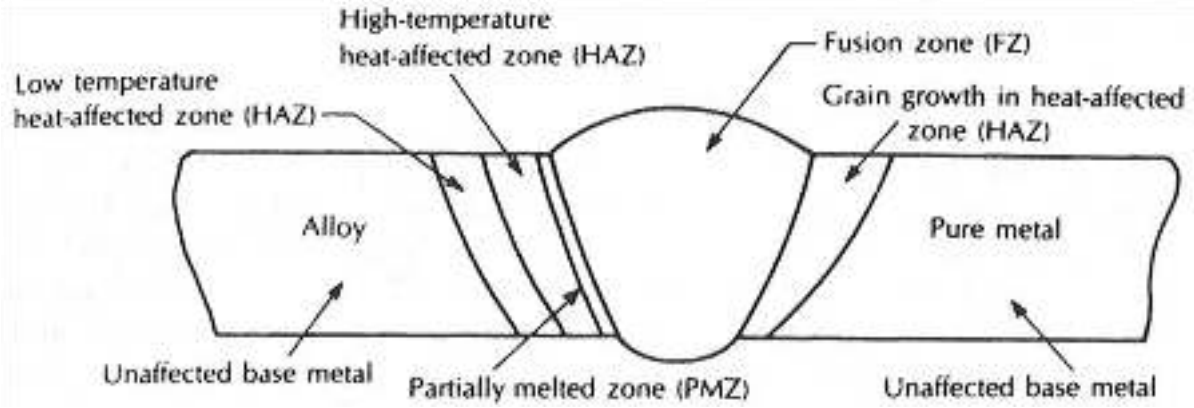
Flow of Heat in Welds

- 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).

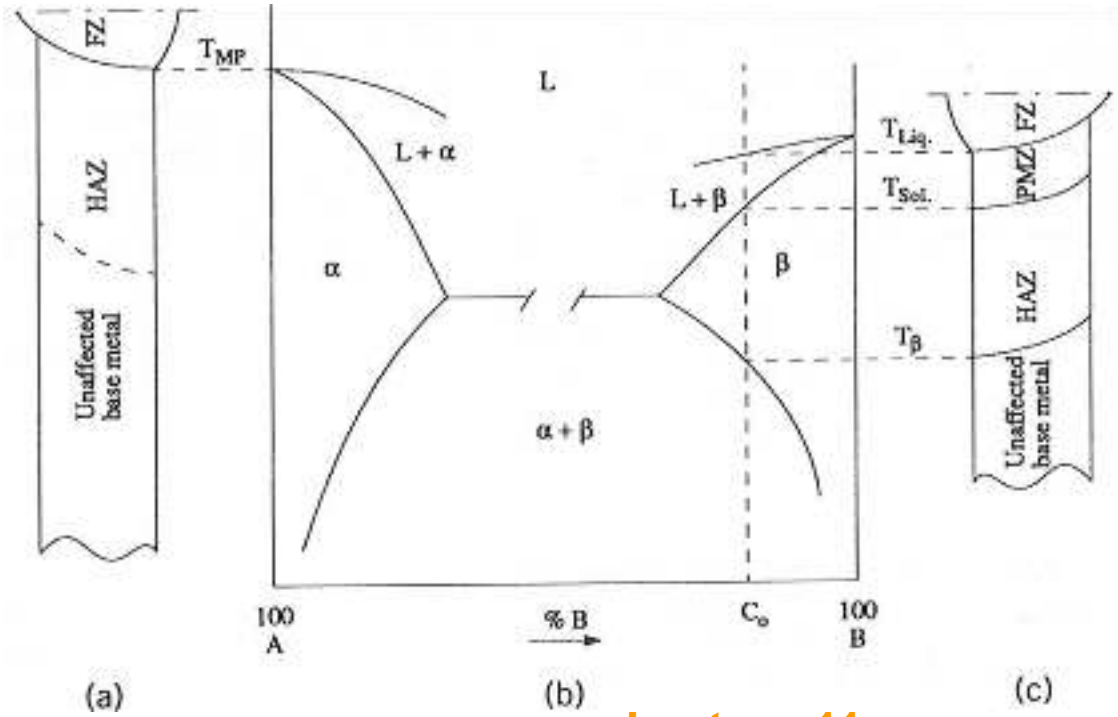
Weld Zones Prediction

- 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:

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

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 ($J.m^{-1}.s^{-1}.K^{-1}$)

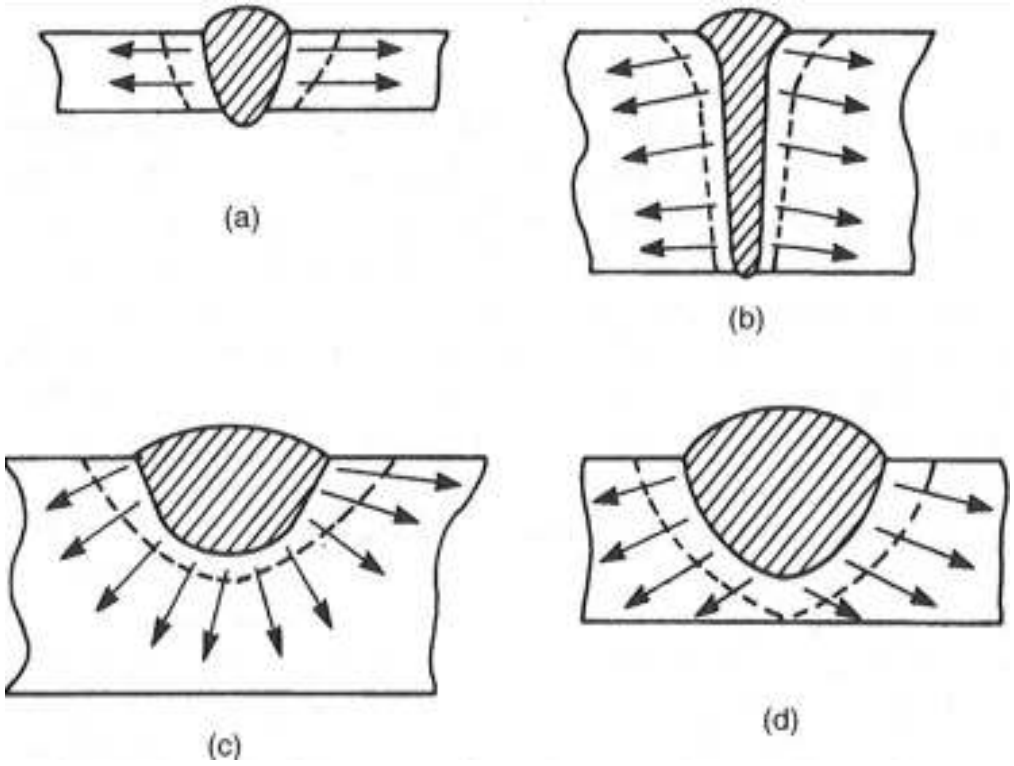
ρ = density of metal ($g.m^{-3}$)

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 = $\eta EI/v$ for arc welding processes

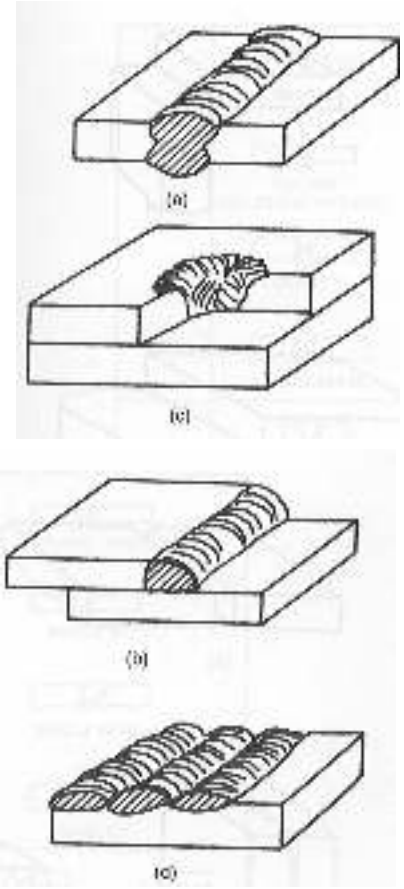
Note: increasing the initial temperature, T_0, (by preheating) decreases the cooling rate,R.



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

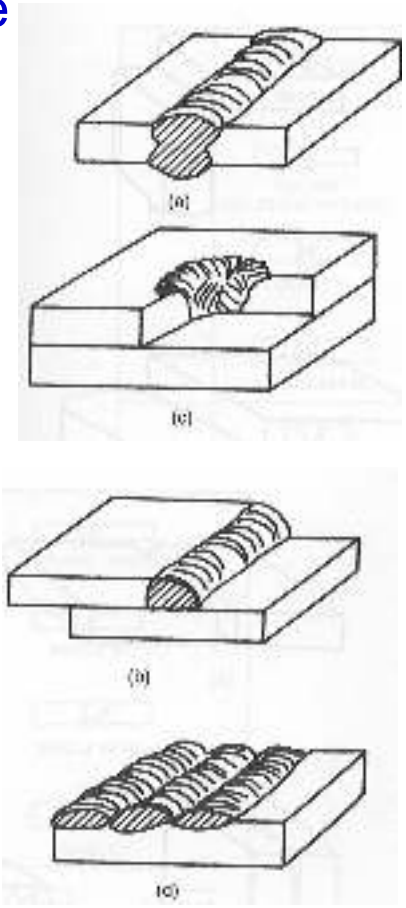
- Heat flow in weld is affected by size and shape of weld.
- Surfacing or Bead welds, made directly, no surface preparation. Used for joining thin sheets, adding coatings over surfaces (wear resistance)
- Groove Welds – full thickness strength, done as V, Double V u, and J (one side prepared). The type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

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

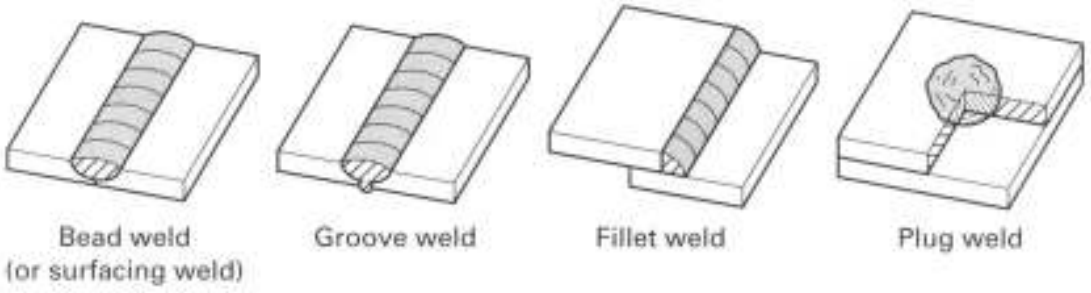


FIGURE 39-1 Four basic types of fusion welds.

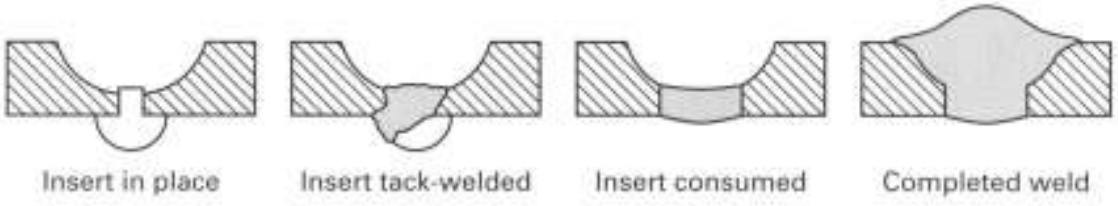


FIGURE 39-2 Use of a consumable backup insert in making fusion welds. *(Courtesy of Arcos Corporation.)*

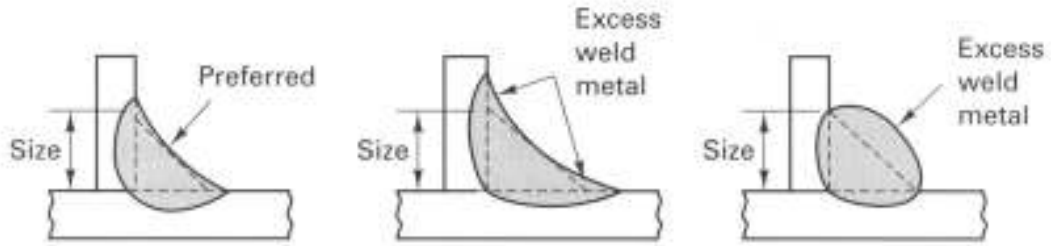


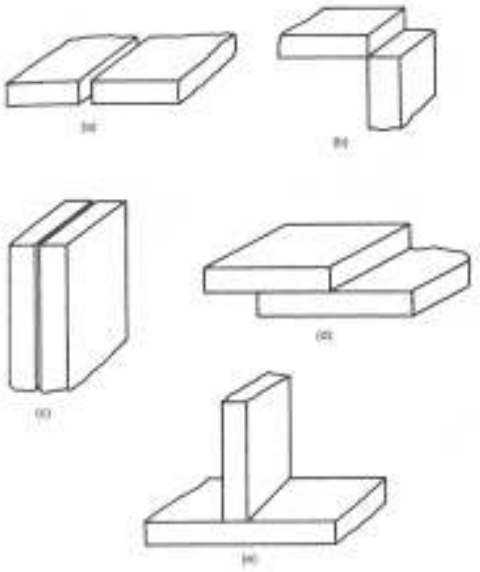
FIGURE 39-3 Preferred shape and the method of measuring the size of fillet welds.

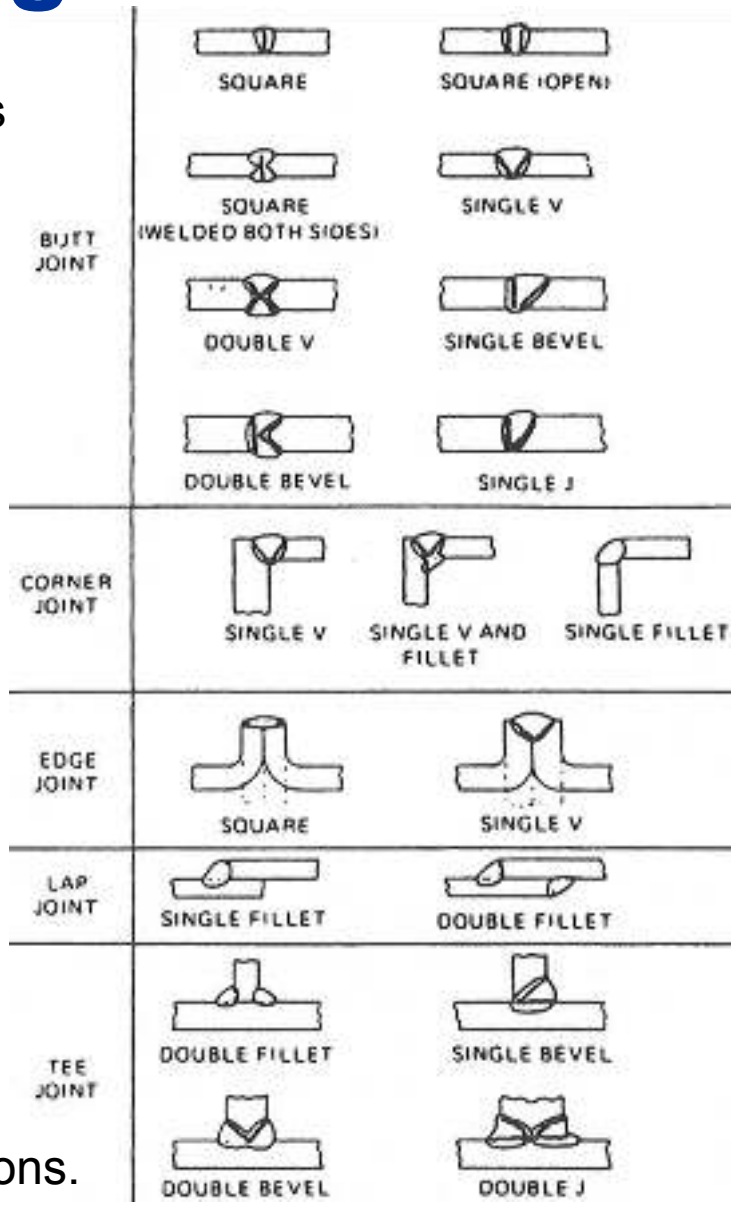
- Inserts are used in pipelines or other places where welding is restricted to one side only

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

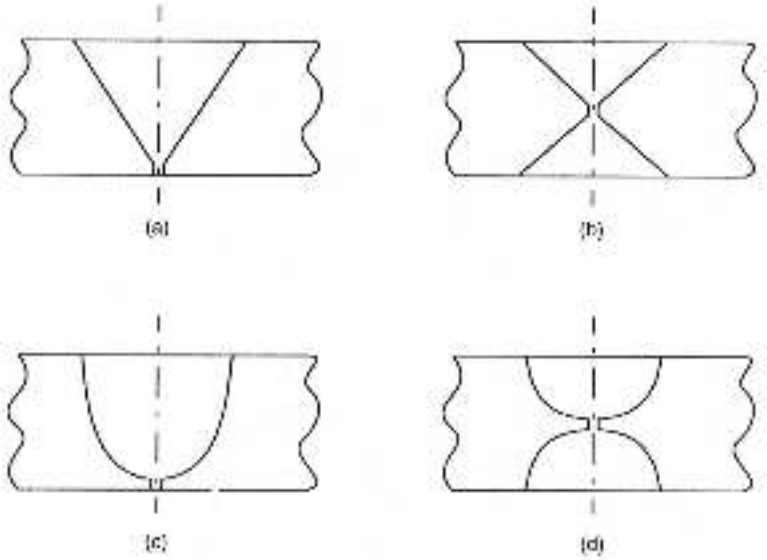
Five basic weld designs (a) butt, (b) corner, (c) edge, (d) lap, (e) tee.





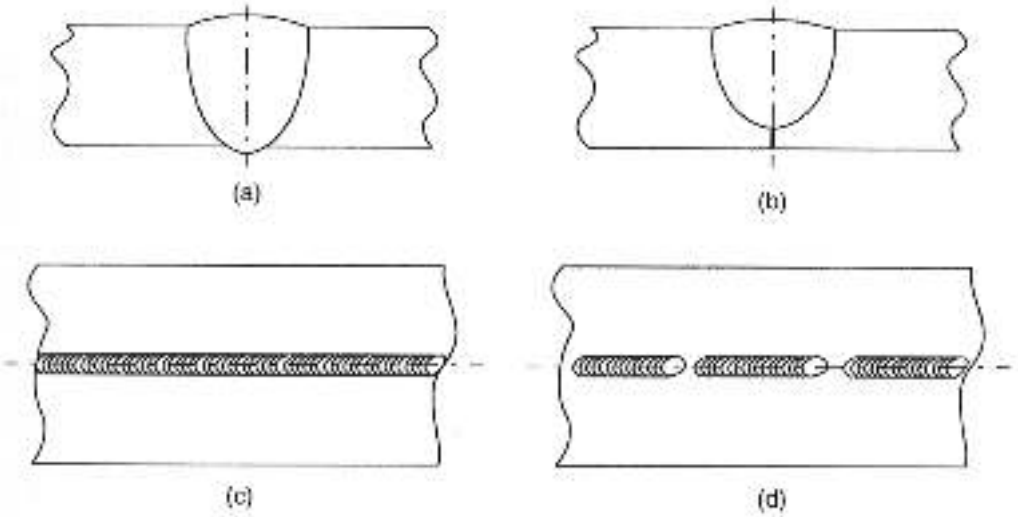
Some typical weld joint variations.

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

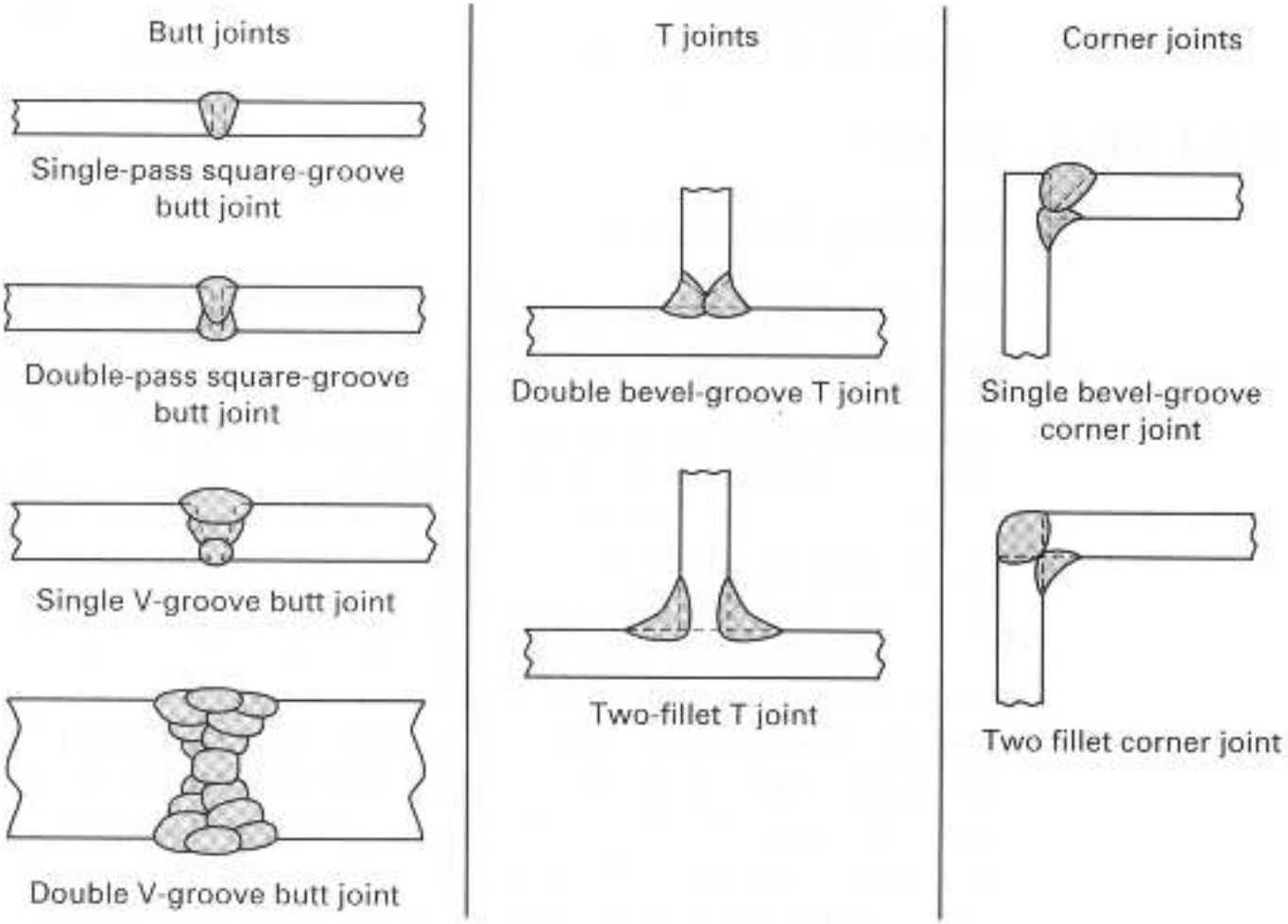


FIGURE 39-5 Various weld procedures used to form several common joints. *(Courtesy of Republic Steel Corporation.)*

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.

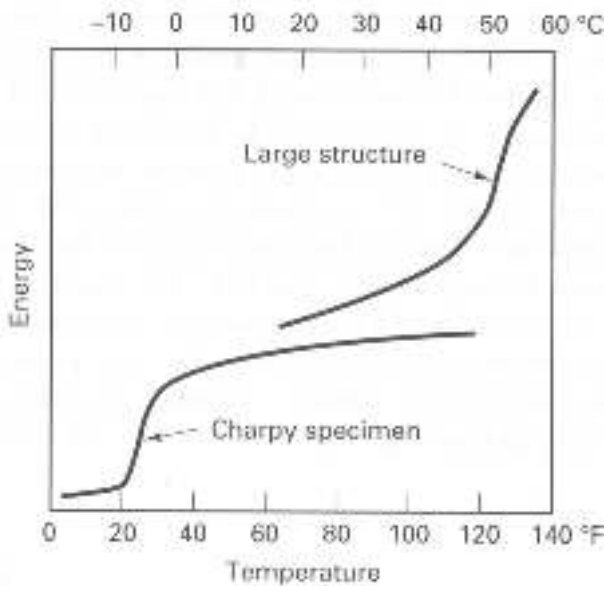


FIGURE 39-6 Effect of size on the transition temperature and energy-absorbing ability of a certain steel.

- 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)

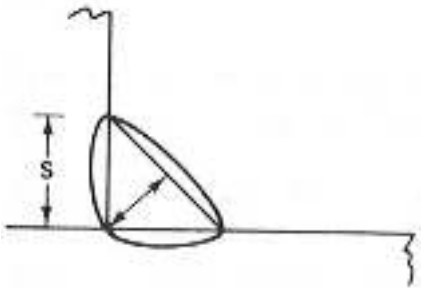
Weld Design Considerations

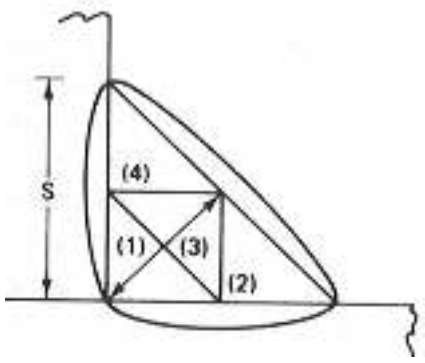
- Joint designed primarily for load-carrying ability.
- Variable in design and layout can affect costs, distortion, reliability, inspection, corrosion, type of defects.
- Select design that requires least amount of weld metal. (minimizes distortion, residual stresses).

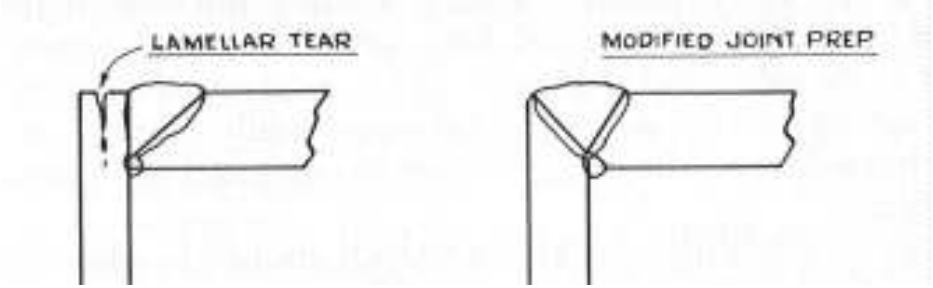
1. Where possible use square grooves (cheaper) and partial penetration (helps maintain dimensions – unmelted metal in contact) except where stress raisers cannot be tolerated (fatigue).
2. Use lap and fillet (instead of groove) welds where fatigue is not a problem (cheaper).

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

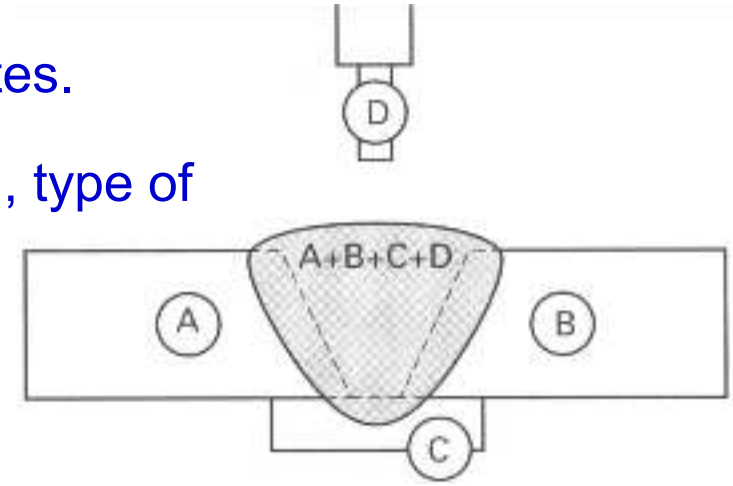


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

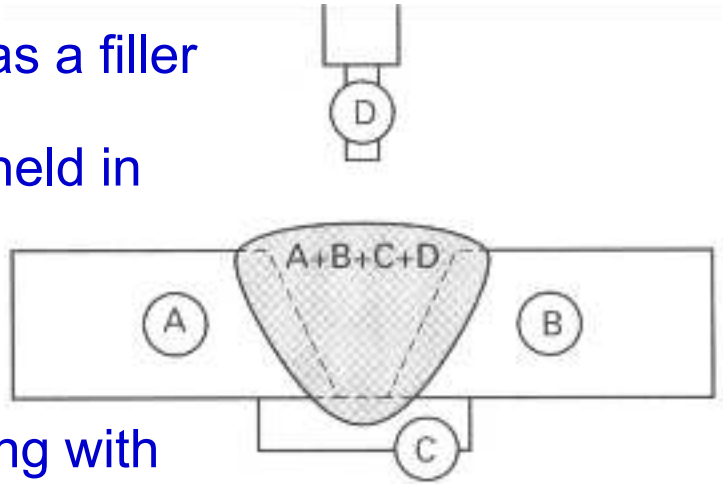


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

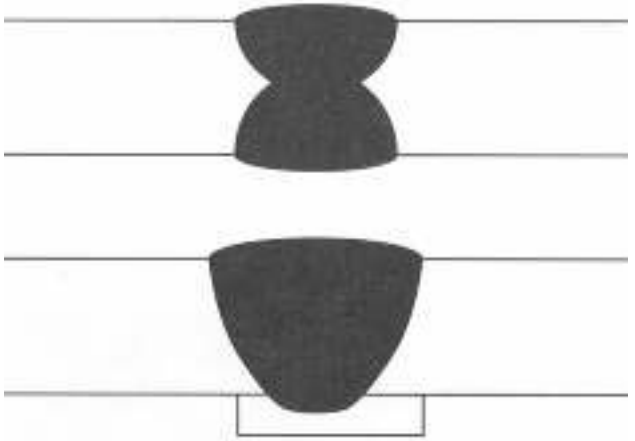
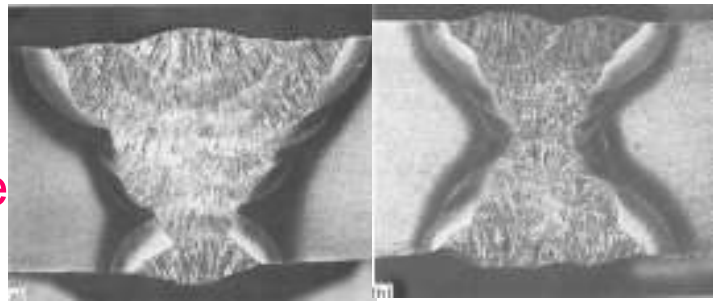


FIGURE 39-9 Comparison of two butt-weld designs. In the top weld, a large percentage of the weld pool is base metal. In the bottom weld, most of the weld pool is filler metal.

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

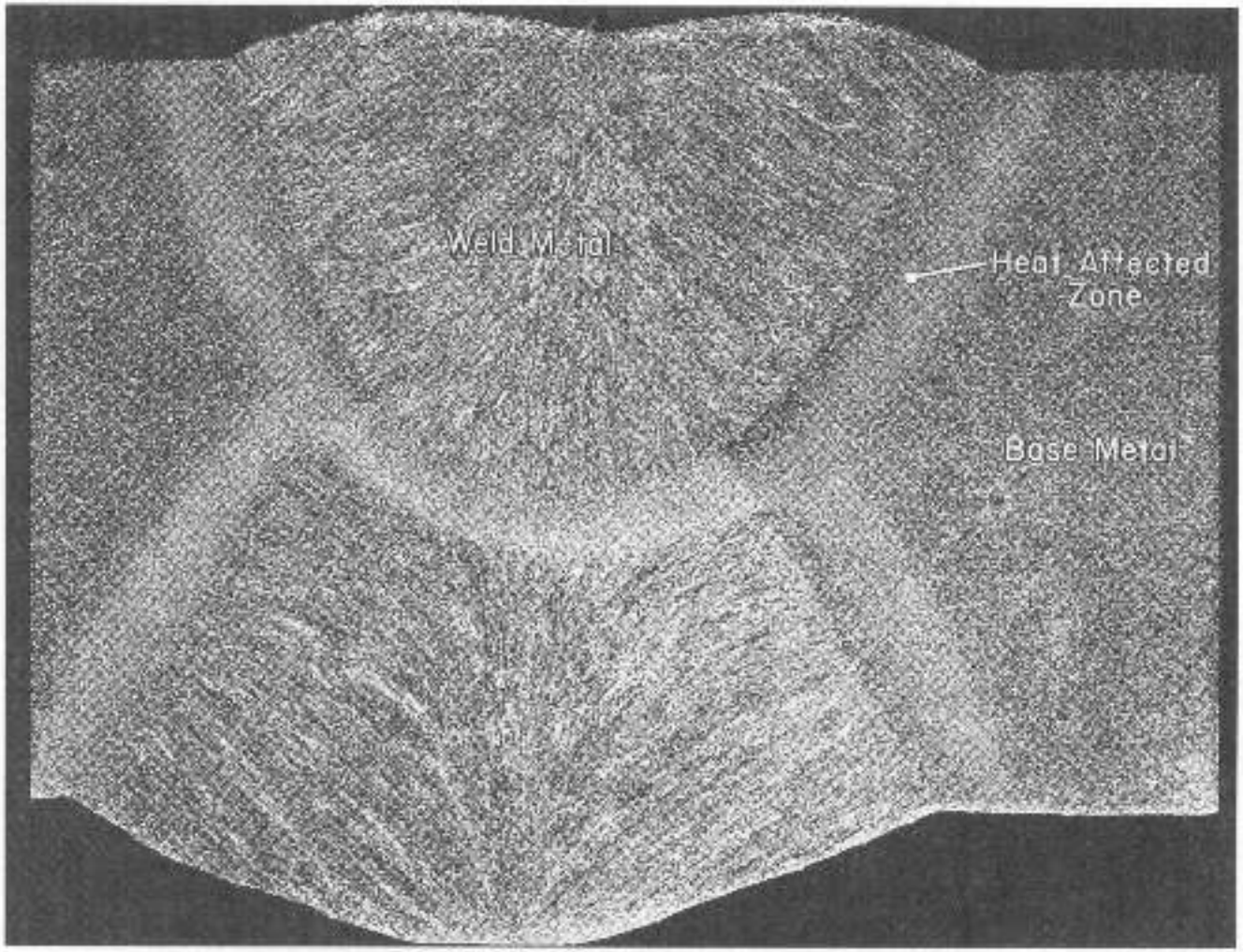


FIGURE 39-8 Grain structure and various zones in a fusion weld.

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

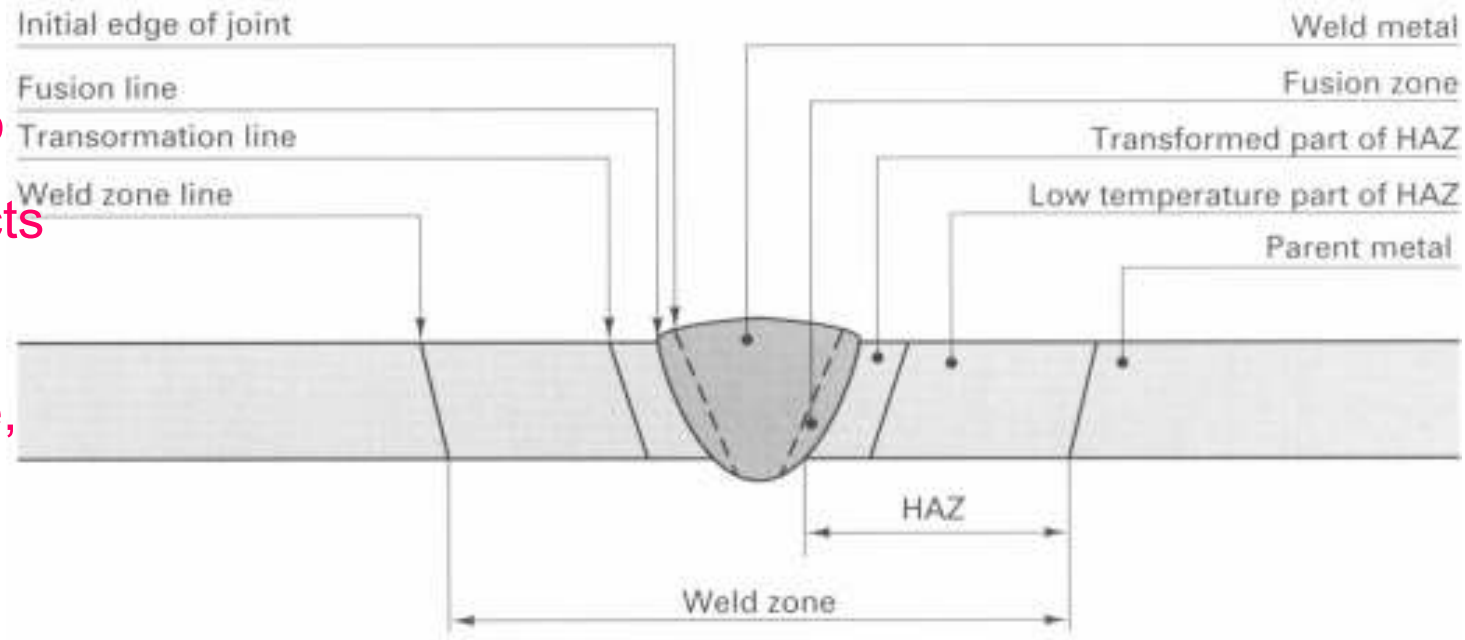


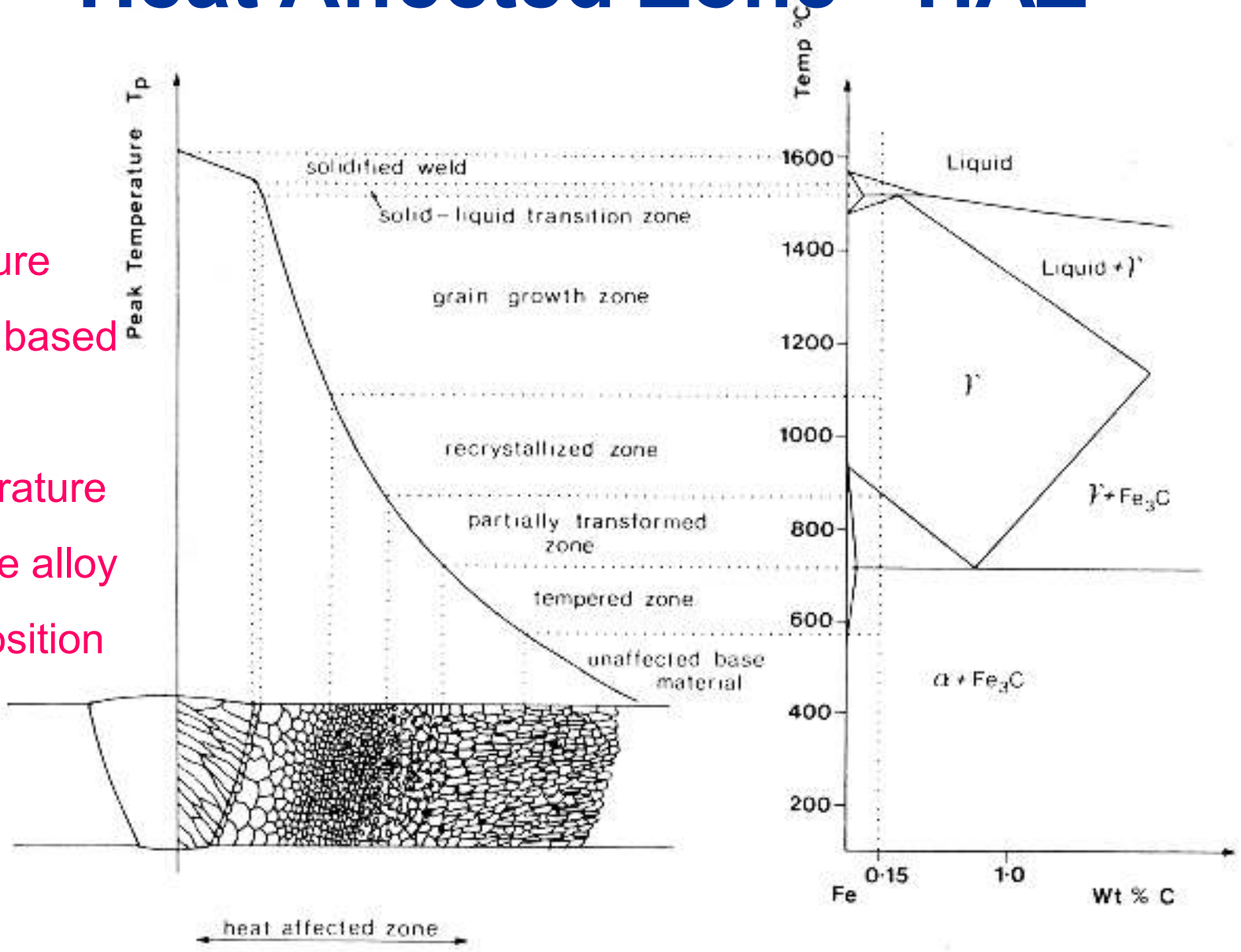
FIGURE 39-10 Schematic of a fusion weld in steel, presenting proper terminology for the various regions and interfaces. Part of the heat-affected zone has been heated above the transformation temperature. *(Courtesy of Sandvik AB.)*

Heat Affected Zone - HAZ

- Grain structure
  - grain structure in weld depends on cooling rate, type of metal, shape of weld etc. Can be
    - coarse, fine, equiaxed, dendritic.
    - Electrodes “designed” to give fine equiaxed grains but depends on volume of weld and cooling rate.
- Other casting defects may be present:
  - entrapped gases
  - segregation
  - grain-size variation
  - orientation variation

Heat Affected Zone - HAZ

Structure varies based on the temperature and the alloy composition



Heat Affected Zone - HAZ

- Thermal characteristics of process have different HAZ
- Low heat input – high heat in metal, slower cooling and more HAZ resultant structures are ductile (low strength and hardness)
- High heat input – low heat in metal, faster cooling and less HAZ

Base metal thickness and thermal conductivity also have effect on HAZ

TABLE 39-1 Classification of Common Welding Processes by Rate of Heat Input

Low rate of heat input	*High rate of heat input*
Oxyfuel welding (OFW)	Plasma arc welding (PAW)
Electroslag welding (ESW)	Electron beam welding (EBW)
Flash welding (FW)	Laser welding (LBW)
	Spot and seam resistance welding (RW)
Moderate rate of heat input	Percussion welding
Shielded metal arc welding (SMAW)	
Flux cored arc welding (FCAW)	
Gas metal arc welding (GMAW)	
Submerged arc welding (SAW)	
Gas tungsten arc welding (GTAW)	

Heat Affected Zone - HAZ

- Control thermal characteristics of weld:
  - Low rates of heat input (slow heating) large HAZ
  - high input rate (fast heating) - small HAZ (fast cooling)
- HAZ increases as
  - initial temperature increases
  - welding speed decreases
  - thermal conductivity of base metal increases
  - base metal thickness decreases
- Geometry affects HAZ
  - Fillet weld has smaller HAZ than Butt weld

Heat Affected Zone - HAZ

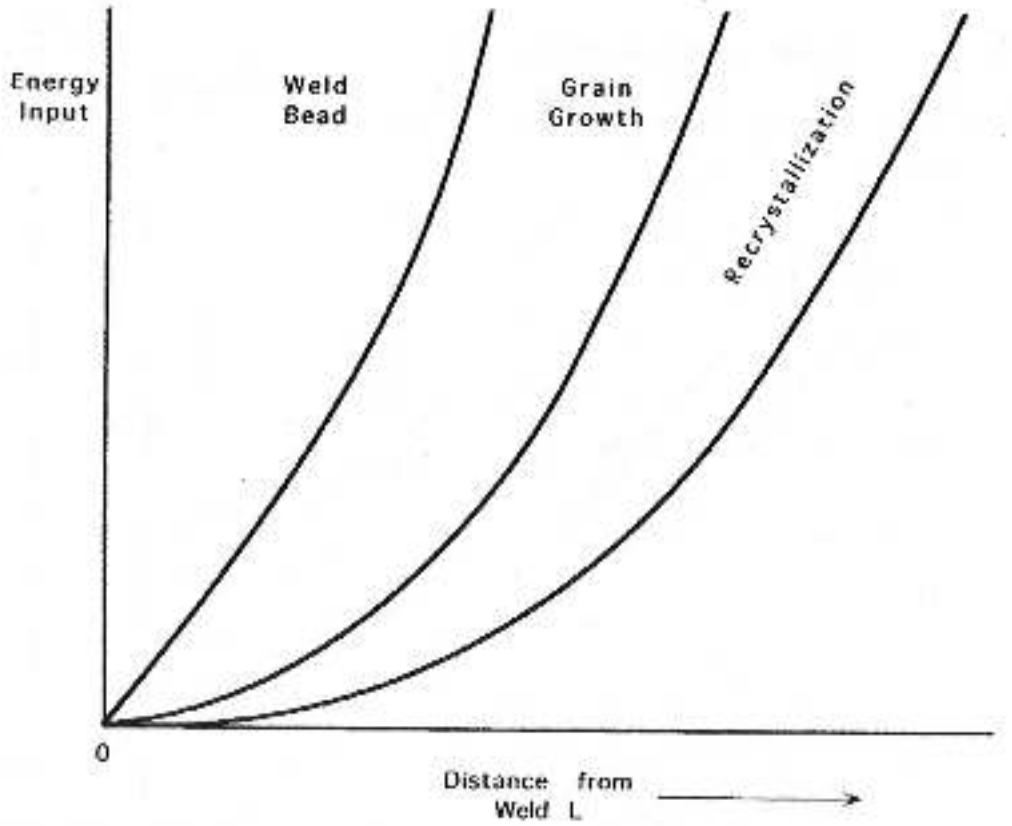


Fig. 6.29. The energy input to the weld determines the *size* of the weld bead and the *extent* of the HAZ region. Within the HAZ, the input energy determines the extent of *grain growth* and the extent of the *recrystallization* zone. Reproduced from *Introduction to the Physical Metallurgy of Welding*, Easterling (1983) Butterworths.

Heat Affected Zone - HAZ

- If as weld quality is not acceptable, heat treatment after welding is done
- Micro structure variations can be reduced or eliminated but the results will be restricted to those that can be achieved by heat treatment
  - Cold working conditions cannot be achieved
  - Another major problem is the controlled heating and cooling of large structures.
  - Complex structures are produced by welding and there are not many quench tanks or furnaces that could accommodate these

Heat Affected Zone - HAZ

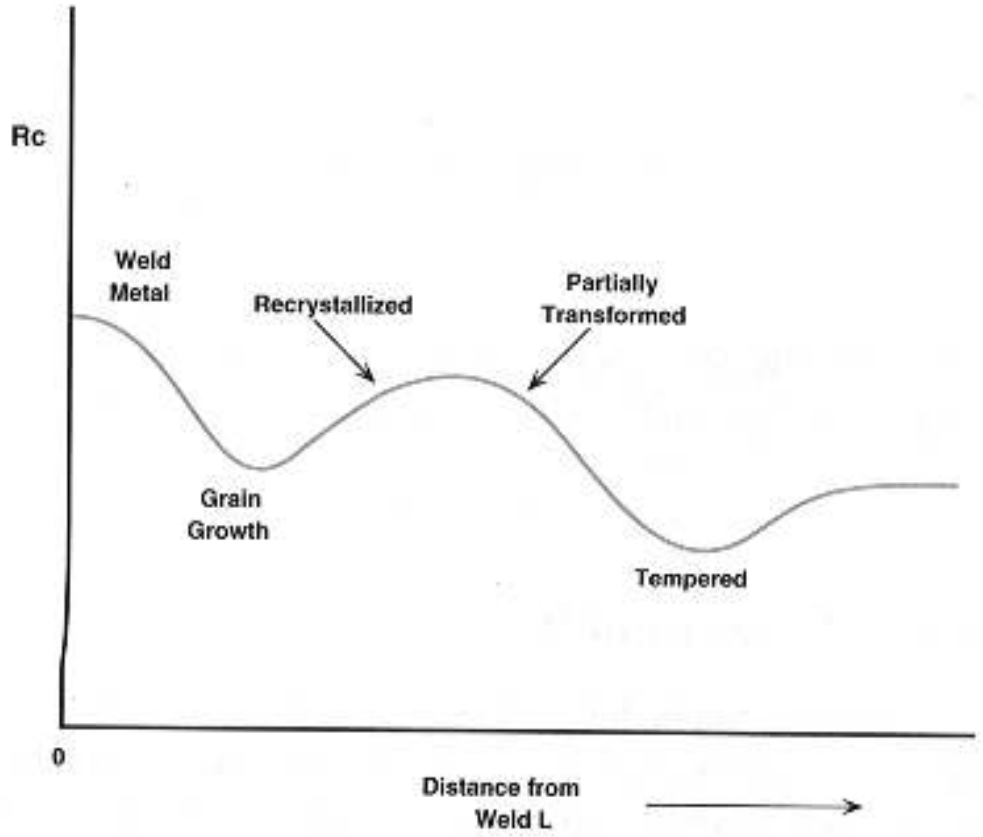
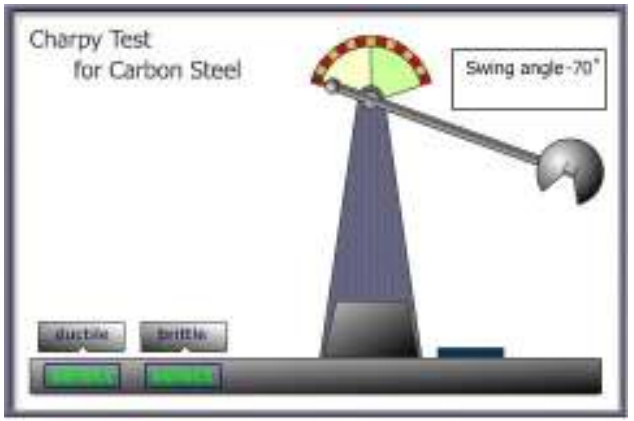


Fig. 6.30. The *hardness* is expected to vary across the weld and HAZ, and the microstructural changes may lead to more than one hardness minimum (or maximum).

Heat Affected Zone - HAZ



- http://www.binaryblue.com.au/05_charpy_test.html

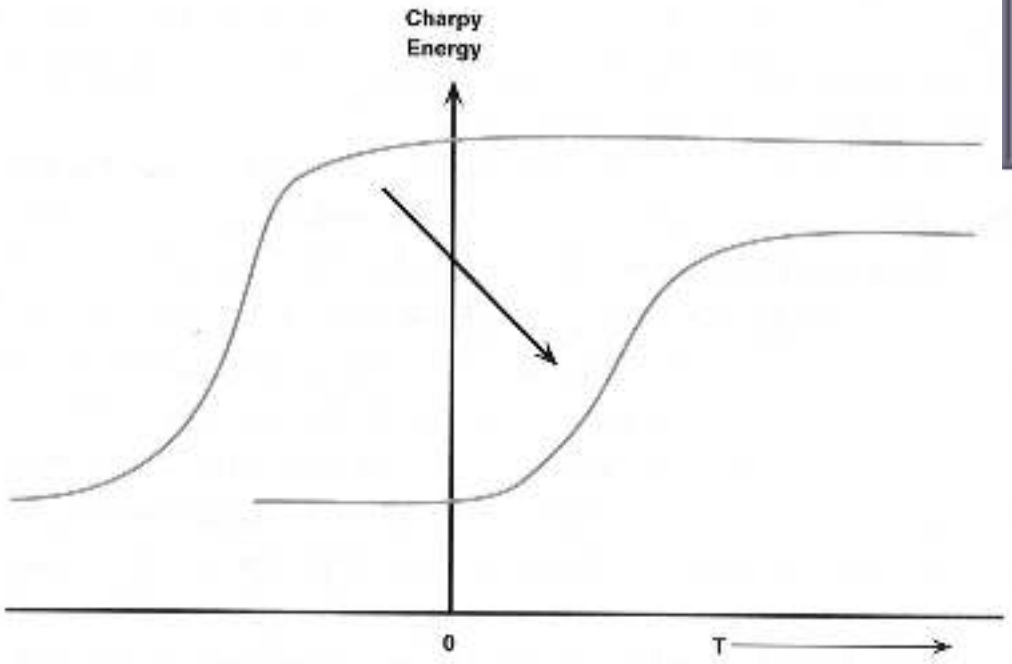


Fig. 6.31. *Charpy tests* performed on specimens taken from the HAZ generally show degradation of the *notch impact energy* and an increase in the *ductile–brittle transition temperature* with respect to the bulk steel.

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- Reduce gradient in microstructural change by pre-heating
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- For steels with >0.3%C normal welding may cause untempered martensite (also in alloy steels with increased hardenability)
  - pre- and post-weld heat treatments
- Low carbon, low alloy steels great for welding!!!!!
- **Brazing and soldering** don't cause melting of base metal but can get HAZ depending on metal/system.
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- Residual welding stresses due to:
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FIGURE 39-11 Schematic of the residual stresses in a fusion weld.

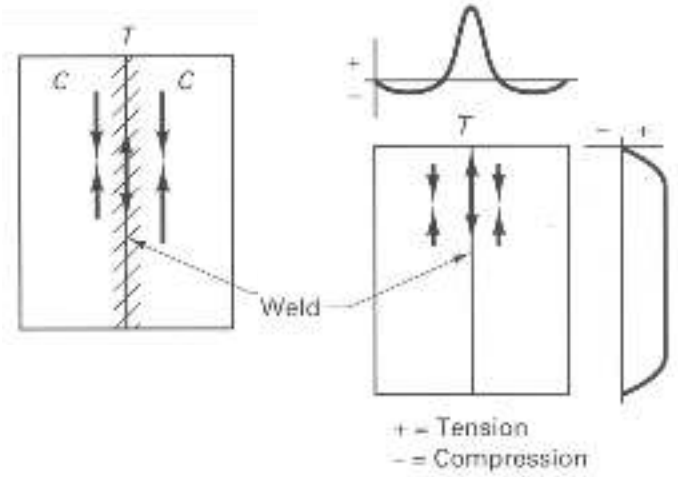

FIGURE 39-12 Longitudinal residual stresses in a butt-welded joint.

- So metal becomes thicker instead of longer causing a week zone
- Similarly, FZ & HAZ contracts while it is restricted by cooler UBM
- So it remains in a stretched condition, called "residual tension"
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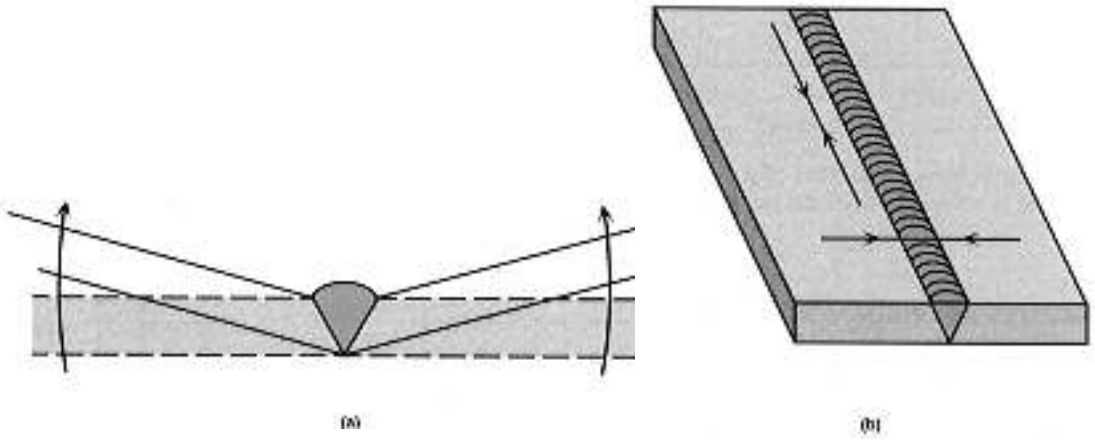
Residual Stresses

Fig. 6.4. (a) *Asymmetry* perpendicular to the weld line leads to a residual bending moment about the weld axis. (b) The principal *residual stresses* in the plane of the surface are *shrinkage* stresses parallel and perpendicular to the weld line.



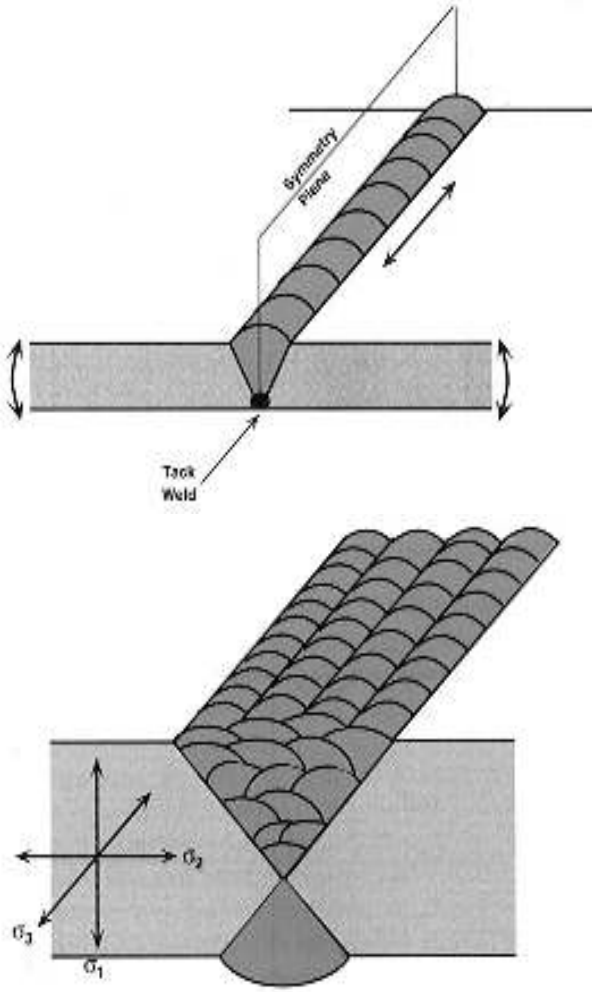


Fig. 6.1. In a single pass weld the *longitudinal shrinkage stresses* and the *transverse bending moment* dominate the residual stress pattern. In a multipass weld the *triaxial stress* pattern is complex and varies throughout the welded zone.

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- Presence of stress concentrators is very harmful:
  - notches
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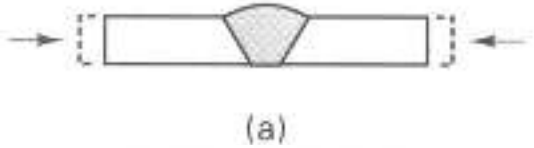
- Hence adherence to welding codes/practice is important and also good weld design.

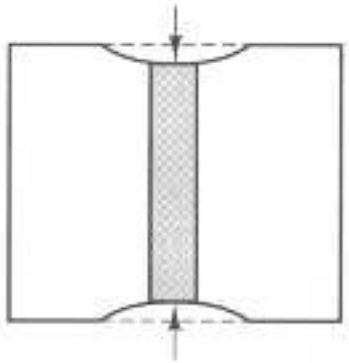
Distortion

- Common result of thermal stresses induced by welding is distortion or warping of the assembly
- Various distortions occur in welding depending on various weld configurations
- There are no fixed rules to avoid these distortions
- However, there are some general guidelines to reduce these distortions



(a)

FIGURE 39-13 Shrinkage of a typical butt weld in the transverse (*left*) and longitudinal (*right*) directions.



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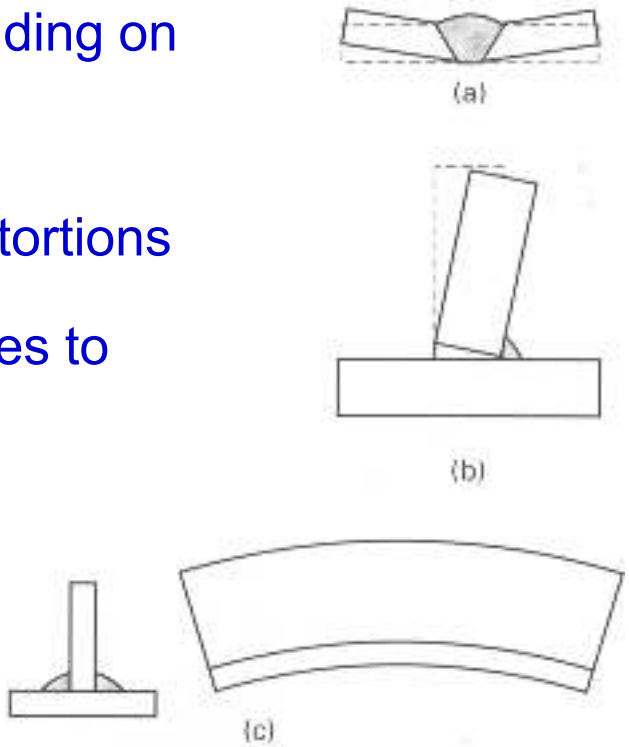


(a)

(b)

(c)

FIGURE 39-14 Distortions observed in several welding operations: (a) V-groove butt weld; (b) one-side fillet weld in a T-joint; (c) two-fillet weld T-joint with a high vertical web.

Reducing Distortion

- Reduce heat input in to the weld
- Minimise volume of weld metal needed to form a joint
- Faster welding usually better (reduces welding time, as well as volume of metal that is heated)
- Design weld sequences to have as few weld passes as possible
- Allow base material as much freedom of movement
- Multiweld assemblies should be welded towards point of greatest freedom from center to the edge

Reducing Distortion

- Initial position can be disoriented to compensate for distortion and get to desired final shape
- Restrain components completely so that plastic deformation occurs in weld/material - (good for small weldments in relatively ductile materials that do not crack)
- Stagger welds (eg. alternate sides of plate)
- Peen the weld and introduce compressive stresses
- Stress relief heat treatment prior to machining which may unbalance residual stresses.

Reducing Cracking

- Joint design is complex (to keep restraints to minimum so as to prevent distortion/warping and cracking
- Selection of metal alloys (structure) with welding in mind and special consideration given to welding thicker materials
  - groove required to get access to root of joint
  - minimum weld metal - maximum properties (J- and U- joints best - minimum weld metal - more expensive to prepare)
- Minimum HAZ
- Proper size and shape of the weld bead reduces cracking

Reducing Cracking

- Weld beads with high penetration (depth/width) are more prone to cracking
- Reduce stresses by making cooling uniform or relaxing them by promoting plasticity in weld metals
- Preheat and additional heating between weld passes to retard cooling
- Some weld codes require thermal stress relief after weld before use
- Dissolved H_2 in metal, electrode causes cracking, baking electrodes or using low H_2 electrodes are good as well to prevent cracking

Weldability and Joinability

TABLE 39-2. Weldability and Joinability of Various Materials[a]

Material	Arc Welding	Oxyacetylene Welding	Electron Beam Welding	Resistance Welding	Brazing	Soldering	Adhesive Bonding
Cast iron	C	R	N	S	D	N	C
Carbon and low-alloy steel	R	R	C	R	R	D	C
Stainless steel	R	C	C	R	R	C	C
Aluminum and magnesium	C	C	C	C	C	S	R
Copper and copper alloys	C	C	C	C	R	R	C
Nickel and nickel alloys	R	C	C	R	R	C	C
Titanium	C	N	C	C	D	S	C
Lead and zinc	C	C	N	D	N	R	R
Thermoplastics	Heated tool R	Hot gas R	N	Induction C	N	N	C
Thermosets	N	N	N	N	N	N	C
Elastomers	N	N	N	N	N	N	R
Ceramics	N	S	C	N	N	N	R
Dissimilar metals	D	D	C	D	D/C	R	R

[a]C, commonly performed; R, recommended (easily performed with excellent results); D, difficult; N, not used; S, seldom used.

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Welding Metallurgy

Lecture 12

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

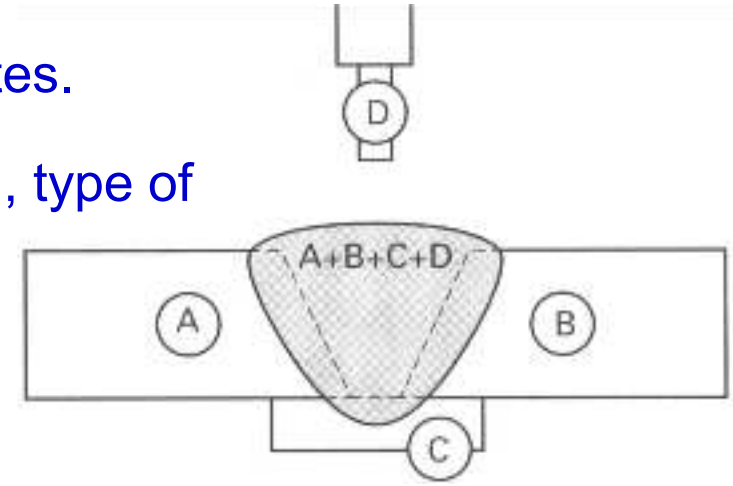


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

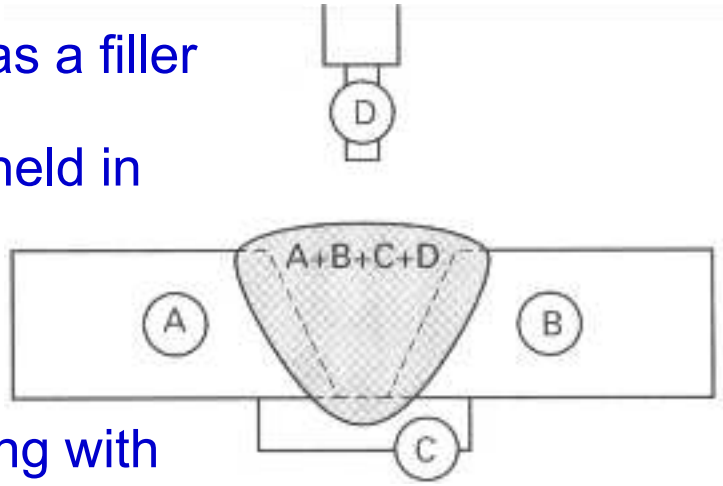


FIGURE 39-7 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget is a complex alloy of the four metals.

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

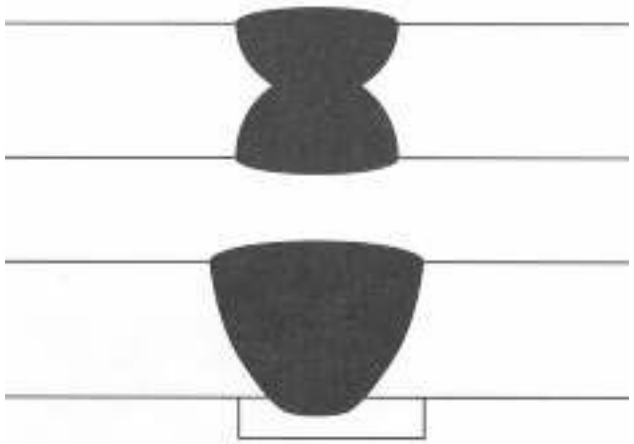
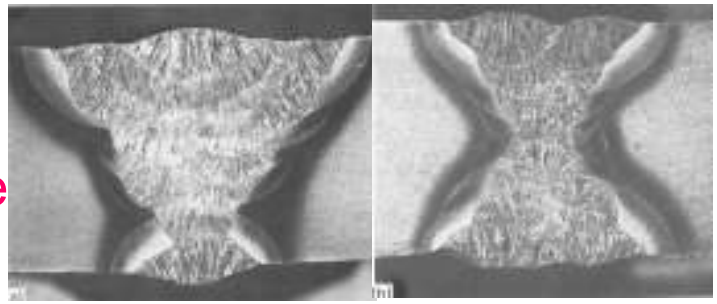


FIGURE 39-9 Comparison of two butt-weld designs. In the top weld, a large percentage of the weld pool is base metal. In the bottom weld, most of the weld pool is filler metal.

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

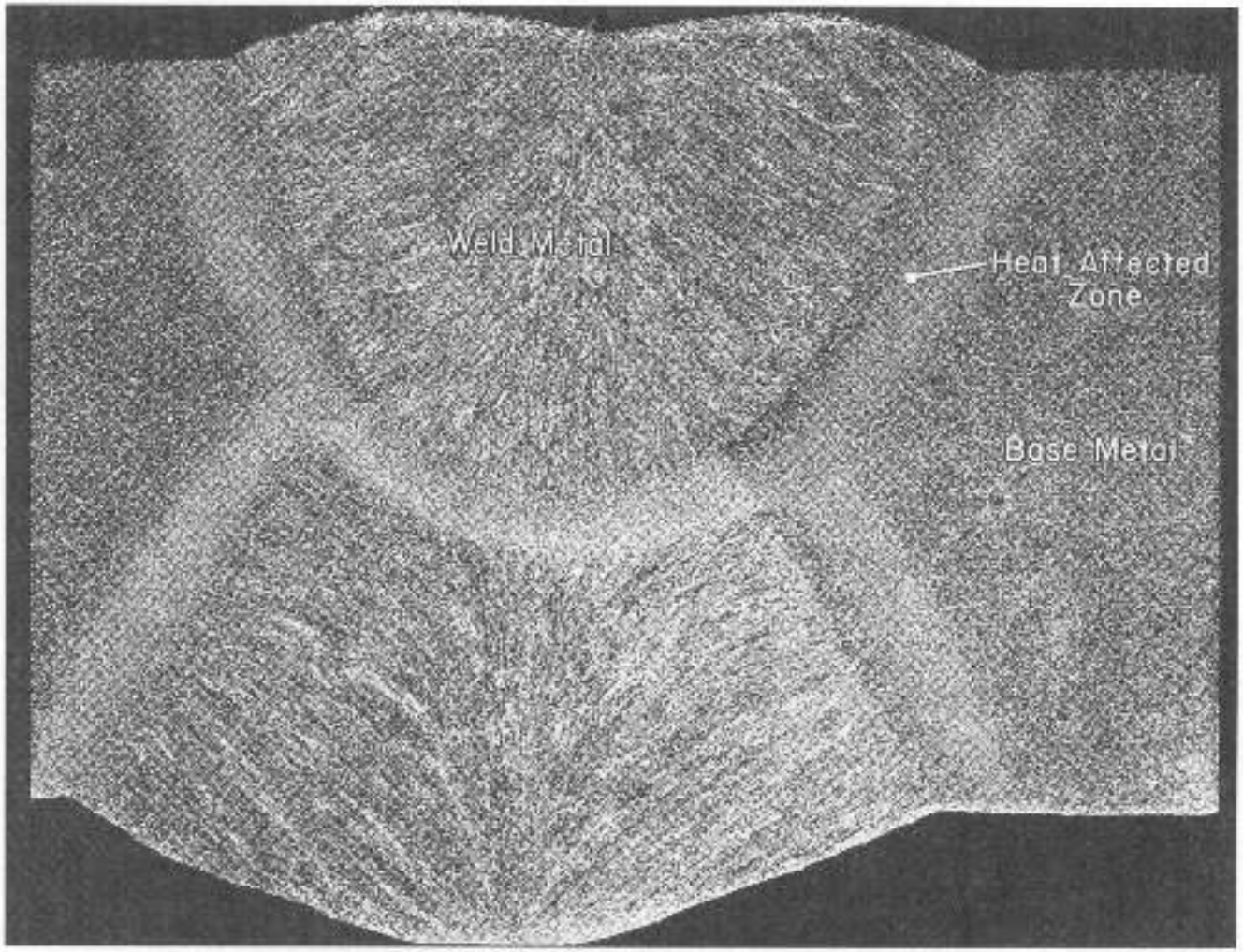


FIGURE 39-8 Grain structure and various zones in a fusion weld.

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

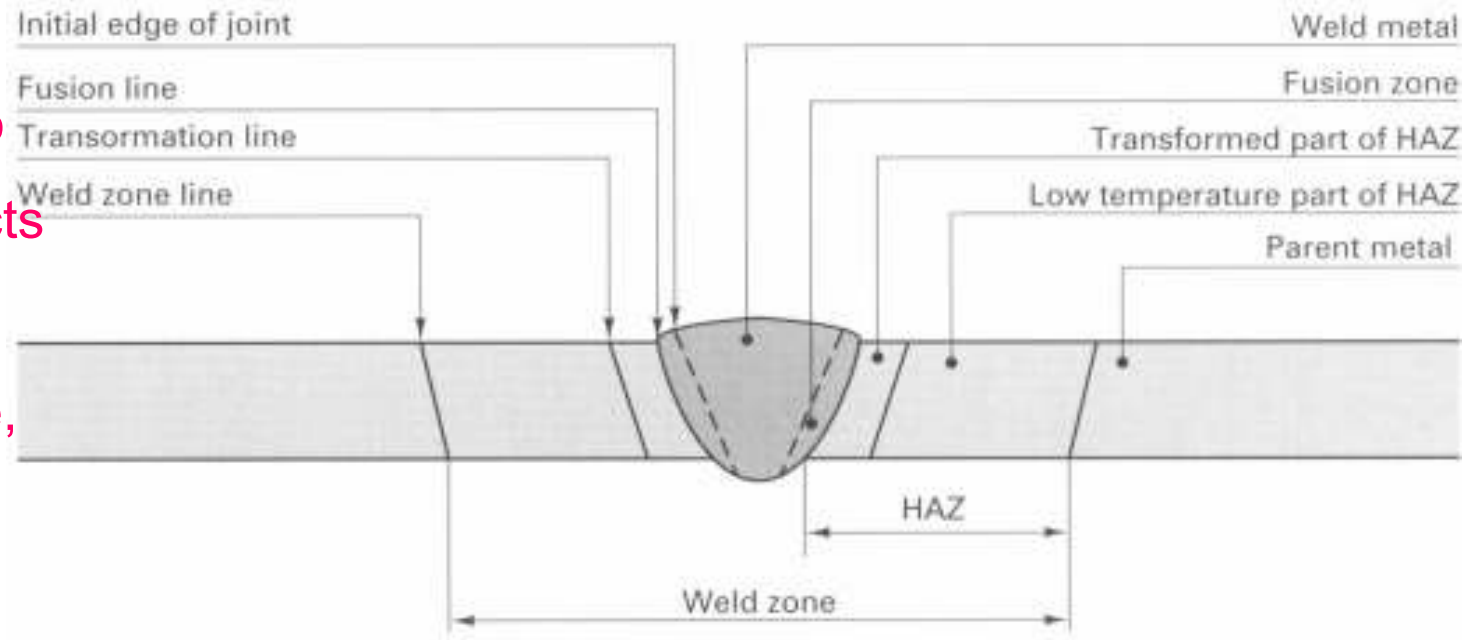


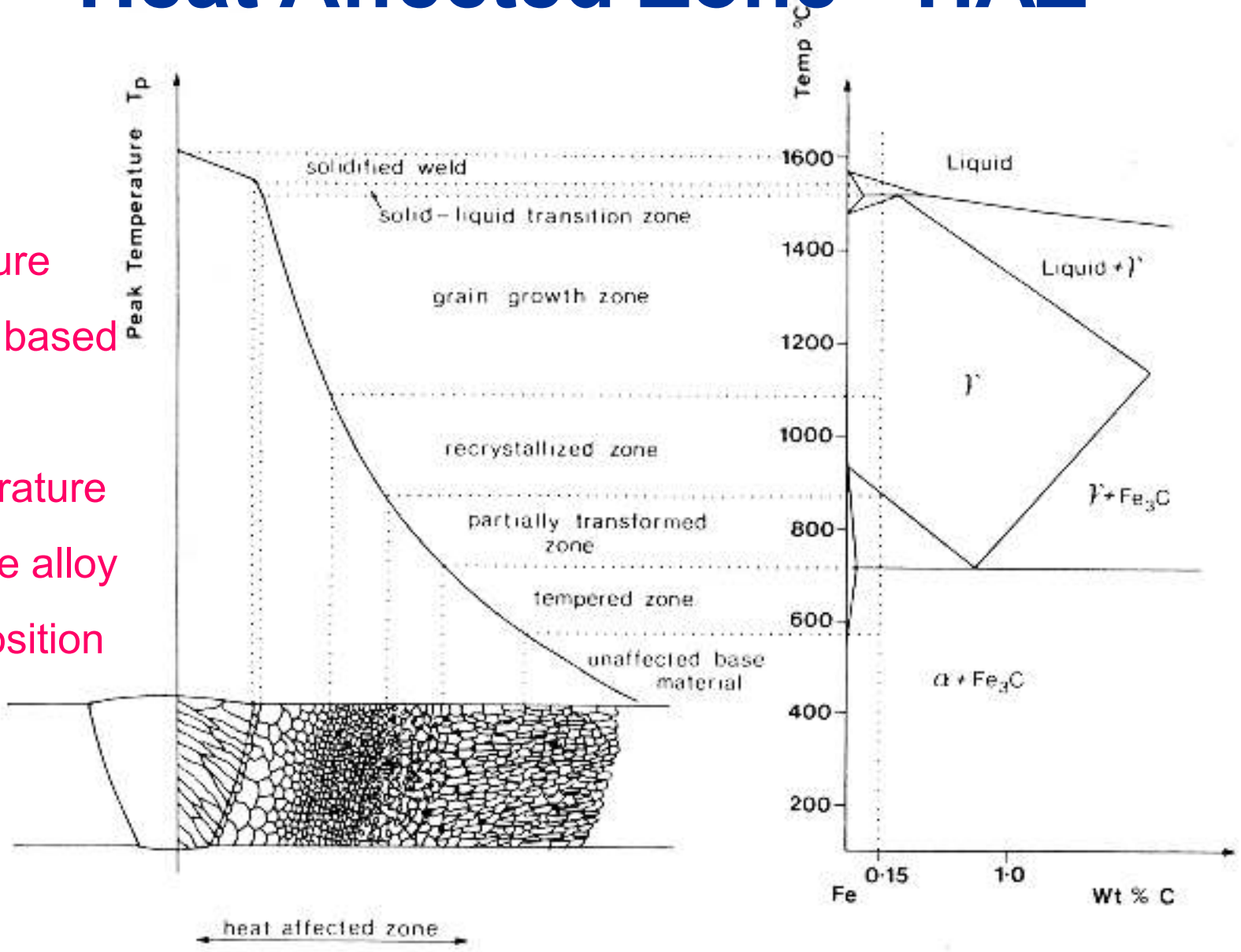
FIGURE 39-10 Schematic of a fusion weld in steel, presenting proper terminology for the various regions and interfaces. Part of the heat-affected zone has been heated above the transformation temperature. *(Courtesy of Sandvik AB.)*

Heat Affected Zone - HAZ

- Grain structure
  - grain structure in weld depends on cooling rate, type of metal, shape of weld etc. Can be
    - coarse, fine, equiaxed, dendritic.
    - Electrodes “designed” to give fine equiaxed grains but depends on volume of weld and cooling rate.
- Other casting defects may be present:
  - entrapped gases
  - segregation
  - grain-size variation
  - orientation variation

Heat Affected Zone - HAZ

Structure varies based on the temperature and the alloy composition



Heat Affected Zone - HAZ

- Thermal characteristics of process have different HAZ
- Low heat input – high heat in metal, slower cooling and more HAZ resultant structures are ductile (low strength and hardness)
- High heat input – low heat in metal, faster cooling and less HAZ

Base metal thickness and thermal conductivity also have effect on HAZ

TABLE 39-1. Classification of Common Welding Processes by Rate of Heat Input

Low rate of heat input	*High rate of heat input*
Oxyfuel welding (OFW)	Plasma arc welding (PAW)
Electroslag welding (ESW)	Electron beam welding (EBW)
Flash welding (FW)	Laser welding (LBW)
	Spot and seam resistance welding (RW)
Moderate rate of heat input	Percussion welding
Shielded metal arc welding (SMAW)	
Flux cored arc welding (FCAW)	
Gas metal arc welding (GMAW)	
Submerged arc welding (SAW)	
Gas tungsten arc welding (GTAW)	

Heat Affected Zone - HAZ

- Control thermal characteristics of weld:
  - Low rates of heat input (slow heating) large HAZ
  - high input rate (fast heating) - small HAZ (fast cooling)
- HAZ increases as
  - initial temperature increases
  - welding speed decreases
  - thermal conductivity of base metal increases
  - base metal thickness decreases
- Geometry affects HAZ
  - Fillet weld has smaller HAZ than Butt weld

Heat Affected Zone - HAZ

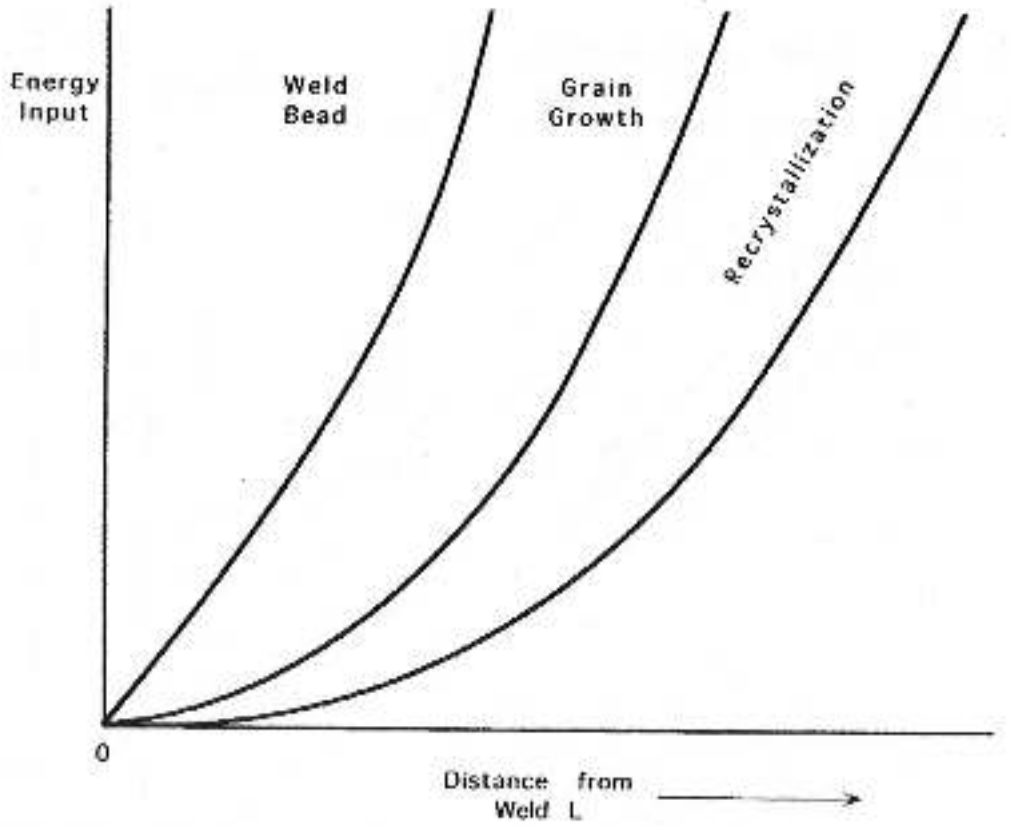


Fig. 6.29. The energy input to the weld determines the *size* of the weld bead and the *extent* of the HAZ region. Within the HAZ, the input energy determines the extent of *grain growth* and the extent of the *recrystallization* zone. Reproduced from *Introduction to the Physical Metallurgy of Welding*, Easterling (1983) Butterworths.

Heat Affected Zone - HAZ

- If as weld quality is not acceptable, heat treatment after welding is done
- Micro structure variations can be reduced or eliminated but the results will be restricted to those that can be achieved by heat treatment
  - Cold working conditions cannot be achieved
  - Another major problem is the controlled heating and cooling of large structures.
  - Complex structures are produced by welding and there are not many quench tanks or furnaces that could accommodate these

Heat Affected Zone - HAZ

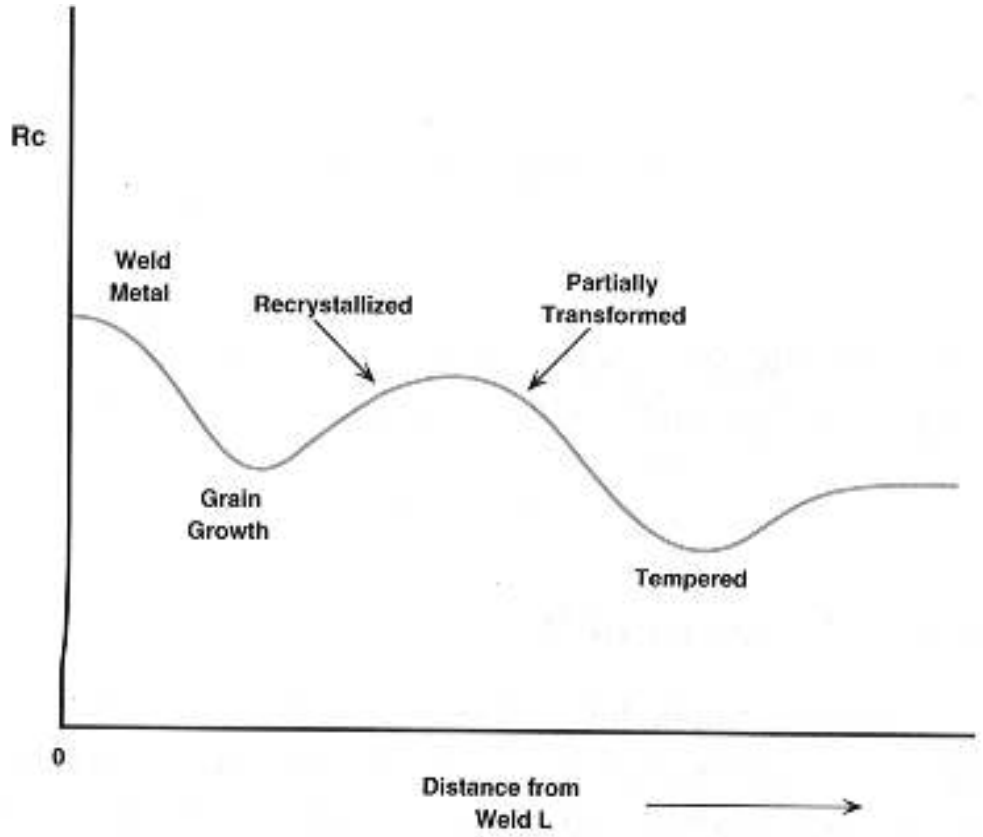
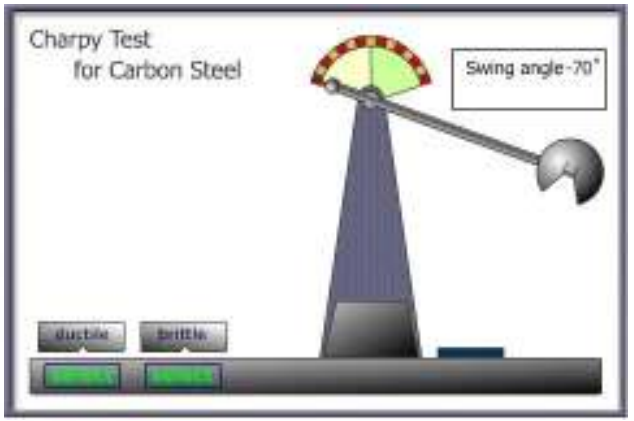


Fig. 6.30. The *hardness* is expected to vary across the weld and HAZ, and the microstructural changes may lead to more than one hardness minimum (or maximum).

Heat Affected Zone - HAZ



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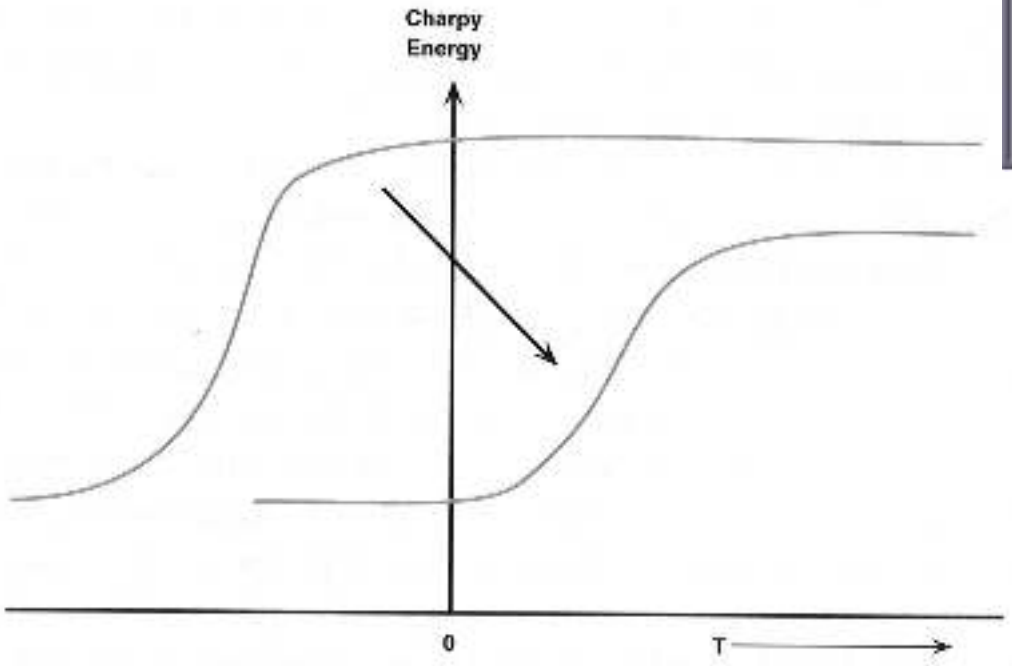

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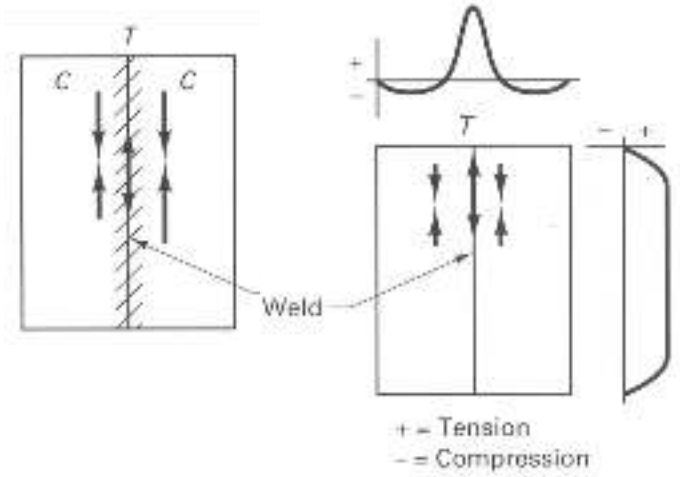

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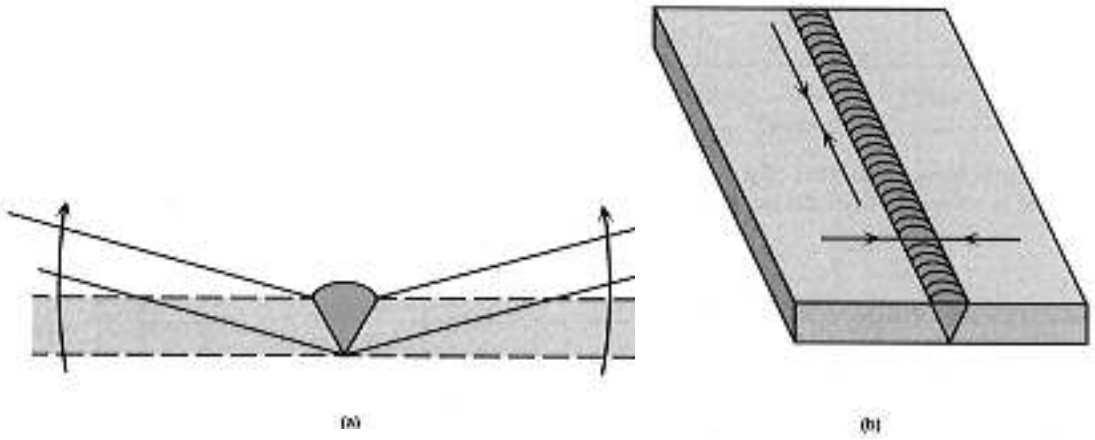
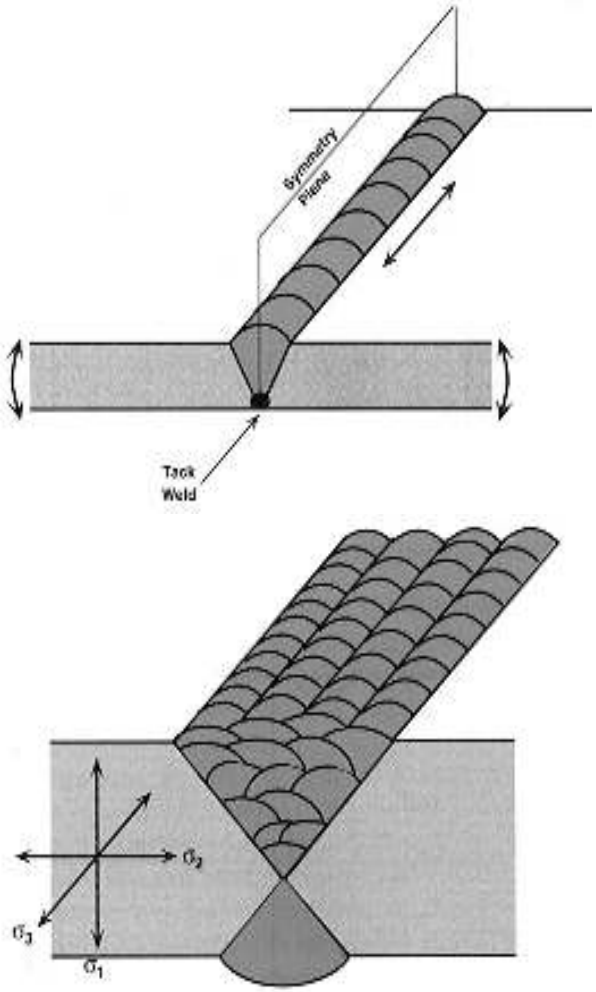


(a) (b)



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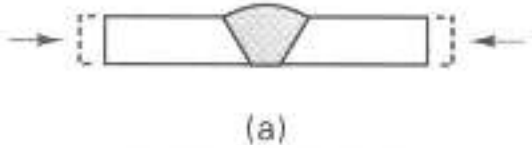

(a)

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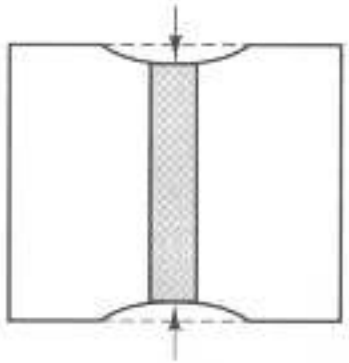

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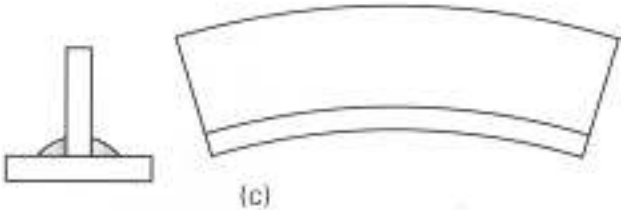

(c)

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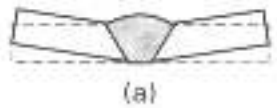
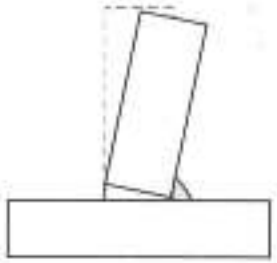


(a)



(b)

Reducing Distortion

- Reduce heat input in to the weld
- Minimise volume of weld metal needed to form a joint
- Faster welding usually better (reduces welding time, as well as volume of metal that is heated)
- Design weld sequences to have as few weld passes as possible
- Allow base material as much freedom of movement
- Multiweld assemblies should be welded towards point of greatest freedom from center to the edge

Reducing Distortion

- Initial position can be disoriented to compensate for distortion and get to desired final shape
- Restrain components completely so that plastic deformation occurs in weld/material - (good for small weldments in relatively ductile materials that do not crack)
- Stagger welds (eg. alternate sides of plate)
- Peen the weld and introduce compressive stresses
- Stress relief heat treatment prior to machining which may unbalance residual stresses.

Reducing Cracking

- Joint design is complex (to keep restraints to minimum so as to prevent distortion/warping and cracking
- Selection of metal alloys (structure) with welding in mind and special consideration given to welding thicker materials
  - groove required to get access to root of joint
  - minimum weld metal - maximum properties (J- and U- joints best - minimum weld metal - more expensive to prepare)
- Minimum HAZ
- Proper size and shape of the weld bead reduces cracking

Reducing Cracking

- Weld beads with high penetration (depth/width) are more prone to cracking
- Reduce stresses by making cooling uniform or relaxing them by promoting plasticity in weld metals
- Preheat and additional heating between weld passes to retard cooling
- Some weld codes require thermal stress relief after weld before use
- Dissolved H_2 in metal, electrode causes cracking, baking electrodes or using low H_2 electrodes are good as well to prevent cracking

Weldability and Joinability

TABLE 39-2. Weldability and Joinability of Various Materials[a]

Material	Arc Welding	Oxyacetylene Welding	Electron Beam Welding	Resistance Welding	Brazing	Soldering	Adhesive Bonding
Cast iron	C	R	N	S	D	N	C
Carbon and low-alloy steel	R	R	C	R	R	D	C
Stainless steel	R	C	C	R	R	C	C
Aluminum and magnesium	C	C	C	C	C	S	R
Copper and copper alloys	C	C	C	C	R	R	C
Nickel and nickel alloys	R	C	C	R	R	C	C
Titanium	C	N	C	C	D	S	C
Lead and zinc	C	C	N	D	N	R	R
Thermoplastics	Heated tool R	Hot gas R	N	Induction C	N	N	C
Thermosets	N	N	N	N	N	N	C
Elastomers	N	N	N	N	N	N	R
Ceramics	N	S	C	N	N	N	R
Dissimilar metals	D	D	C	D	D/C	R	R

[a]C, commonly performed; R, recommended (easily performed with excellent results); D, difficult; N, not used; S, seldom used.

MECH 423 Casting, Welding, Heat Treating and NDT

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

Credits: 3.5 Session: Fall

Non Destructive Testing

Lecture 12

Destructive Testing Vs NDT

- Goals of Manufacturing:
  - - cost effective/competitive
  - - fitness for purpose
  - - high quality/reliability (absence of defects/flaws)
  - - not over/under-designed
- In order to confirm that our efforts have been successful, and that the product is free from any flaws or defects, it is important to do testing
- There are variety of testing methods which includes destructive and non-destructive testing

Destructive Testing Vs NDT

- To ensure quality/reliability:
- Destructive Testing – components subjected to conditions that induce failure.
- Determine condition where failure occurs and this will give insight into the determination of performance characteristics
  - Tensile, (hardness) shear/torsion tests etc….
- What are problems with Destructive Testing?
- lose piece (economics), does tested piece represent batch?
- Information becomes statistical

Destructive Testing Vs NDT

- Proof Testing - often used for critical (dynamic) parts such as rotors, turbines, pressure vessels etc.
- Apply more than “service stress”: - if passes then okay for designed stress.It should not be subjected to abuse or above rated level
- Hardness – With controlled processing hardness should be within a range and this gives an idea about the quality of the product tested
- Abnormal range indicates error in processing. Leaves indent but can be done on 'real' components
- Easy remove indent, but more surface properties and no information about cracks or voids

Destructive Testing Vs NDT

- What does NDT do? – part is examined in a manner that retains usefulness for future service
- internal, external flaws (surface)
- dimensions (critical etc.)
- material structure/chemistry
- physical + mechanical properties

Destructive Testing Vs NDT

TABLE 11-1. Advantages and Limitations of Destructive and Nondestructive Testing

Destructive Testing
ADVANTAGES
1. Provides a direct and reliable measurement of how a material or component will respond to service conditions.
2. Provides quantitative results, useful for design.
3. Does not require interpretation of results by skilled operators.
4. Usually find agreement as to meaning and significance of test results.
DISADVANTAGES
1. Applied only to a sample; must show that the sample is representative of the group.
2. Tested parts are destroyed during testing.
3. Usually cannot repeat a test on the same item or use the same specimen for multiple tests.
4. May be restricted for costly or few-in-number parts.
5. Hard to predict cumulative effect of service usage.
6. Difficult to apply to parts in use; if done, testing terminates their useful life.
7. Extensive machining or preparation of test specimens is often required.
8. Capital equipment and labor costs are often high.

Destructive Testing Vs NDT

TABLE 11-1. Advantages and Limitations of Destructive and Nondestructive Testing

Nondestructive Testing
ADVANTAGES
1. Can be performed directly on production items without regard to cost or quantity available.
2. Can be performed on 100% of production lot (when high variability is observed) or a representative sample (if sufficient similarity is noted).
3. Different tests can be applied to the same item, and a test can be repeated on the same specimen.
4. Can be performed on parts that are in service; the cumulative effects of service life can be monitored on a single part.
5. Little or no specimen preparation is required.
6. The test equipment is often portable.
7. Labor costs are usually low.
DISADVANTAGES
1. Results often require interpretation by skilled operators.
2. Different observers may interpret the test results differently.
3. Properties are measured indirectly and results are often qualitative or comparative.
4. Some test equipment requires a large capital investment.

Non-Destructive Testing (NDT)

- Usually based on :
  1. a probing medium
  2. means by which 'probe' interacts with flaw/defect/material
  3. sensor to detect response
  4. indicator/recorder
  5. interpretation/evaluation
- Some processes very limited: ie,
- to magnetic materials; to electrically conducting materials
- to small conducting materials; to simple geometries
- to thin geometries

Visual Inspection

- Simplest, widely used NDT.
- Eye is very discerning. Can be trained to make good judgements based on visual signals.
- Use mirrors, lights, magnifying glass to enhance capability.

TABLE 11-2. Visual Inspection

Principle: Illuminate the test specimen and observe the surface. Use of optical aids or assists is permitted. While most inspection is by human eye, video cameras and computer-vision systems can be employed.
Advantages: Simple, easy to use, relatively inexpensive.
Limitations: Depend on skill and knowledge of inspector. Limited to detection of surface flaws.
Material limitations: None.
Geometrical limitations: Any size or shape providing viewing accessibility of surfaces to be inspected.
Permanent record: Photographs or videotapes are possible. Inspectors' reports also provide valuable records.

Liquid Penetrant Inspection

TABLE 11-3. Liquid Penetrant Inspection

Principle: A liquid penetrant is drawn into surface flaws by capillary action and subsequently revealed by developer material in conjunction with visual inspection.

Advantages: Simple, inexpensive, versatile, portable, easily interpreted, and applicable to complex shapes.

Limitations: Can only detect flaws that are open to the surface; surfaces must be cleaned before and after inspection; deformed surfaces and surface coatings may prevent detection; and the penetrant may be wiped or washed out of large defects.

Material limitations: Must have nonporous surface.

Geometrical limitations: Any size or shape permitting accessibility of surfaces to be inspected.

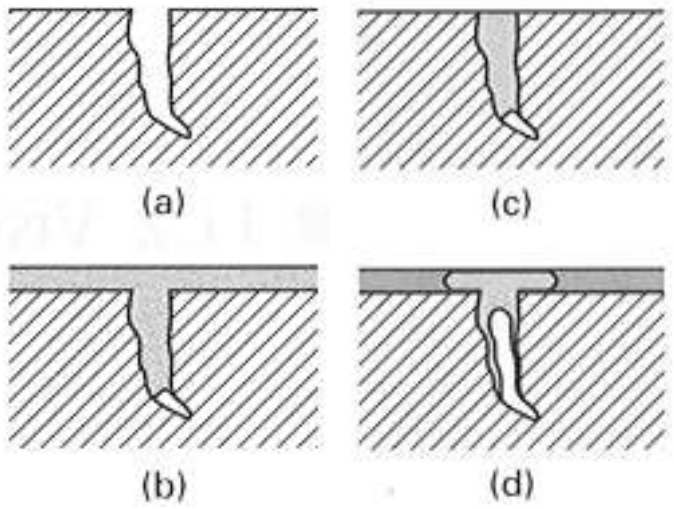
Permanent record: Photographs, videotapes, and inspectors' reports provide the most common records.

a) initial surface with open crack;

b) penetrant is applied and is pulled into the crack by capillary action;

c) excess penetrant is removed;

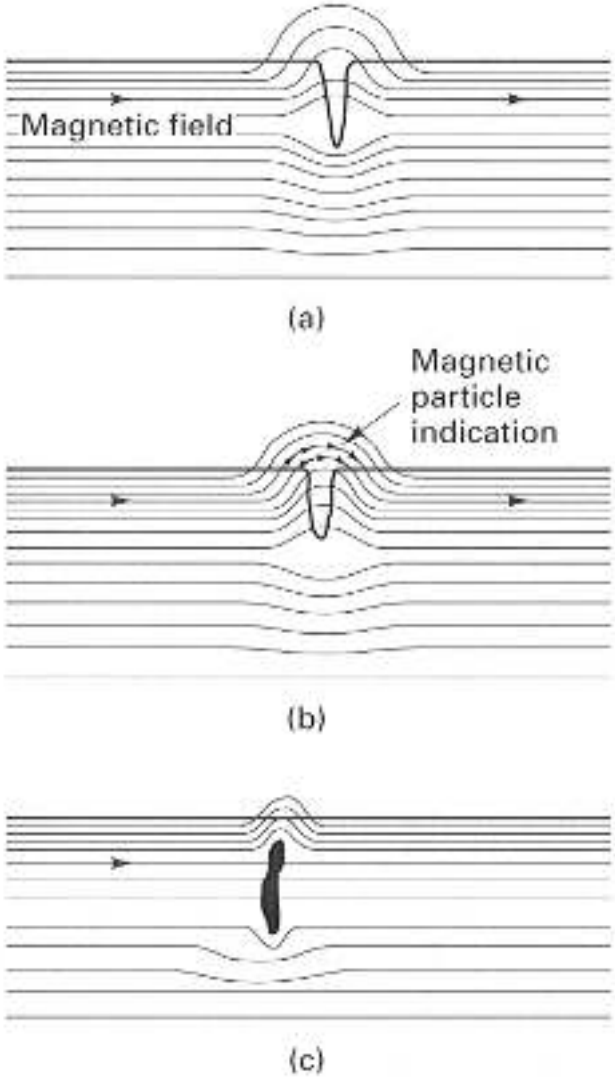
d) developer is applied, some penetrant is extracted, and the product inspected.



Magnetic Particle Inspection

- Produce magnetic fields in ferromagnetic materials - Iron, steel, nickel, cobalt
- Cracks and/or defects will distort field lines
- Use small magnetic particles to show disruptions/anomalies
- Defects perpendicular to field show up
- Defects parallel to field do not disrupt fields sufficiently to show up. Coil for axial field.
- (Demagnetize after)
- Can use fluorescent dye on particles to show up better in UV

Magnetic Particle Inspection

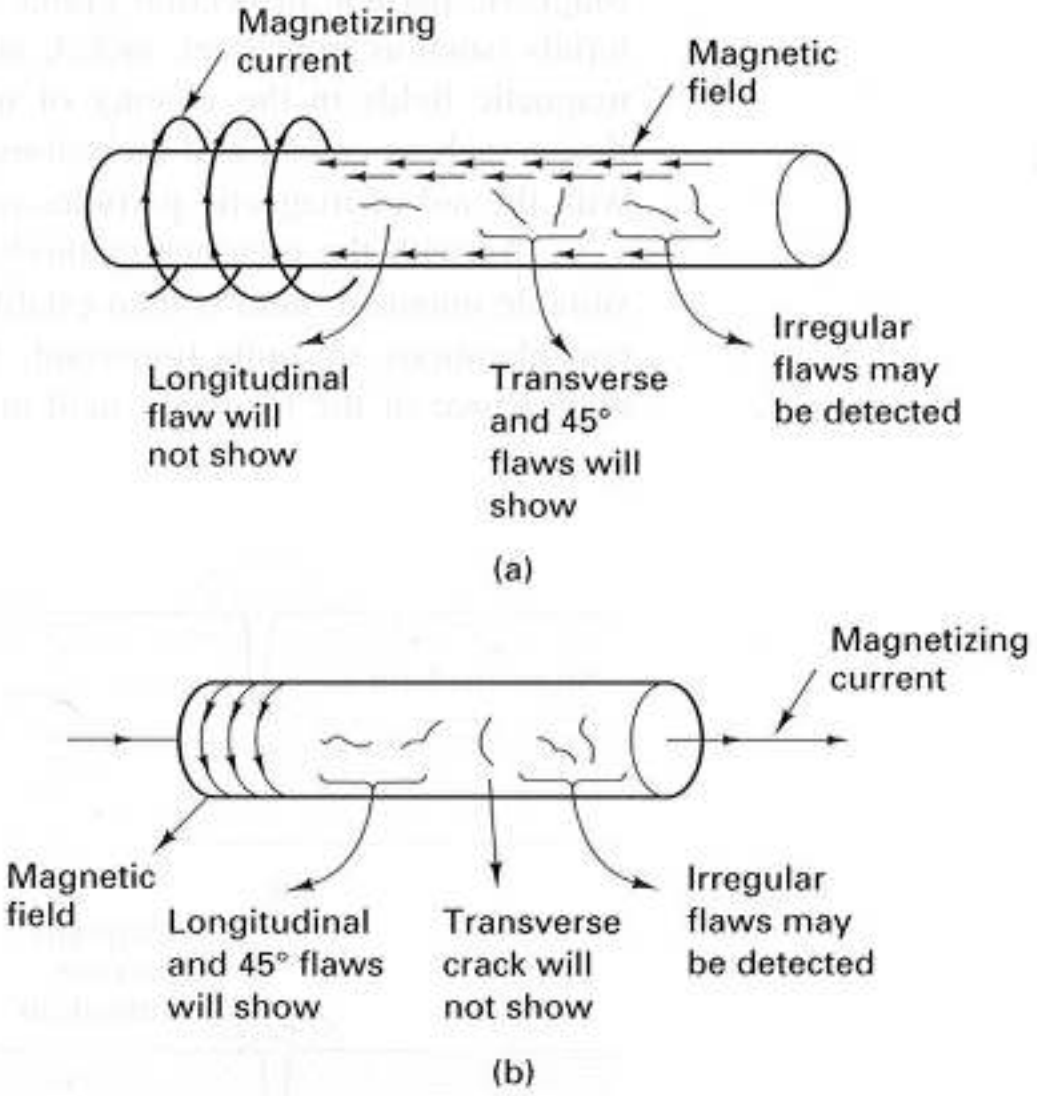


(a) Magnetic field showing disruption by a surface crack;

(b) magnetic particles are applied and are preferentially attracted to field leakage;

(c) subsurface defects can also produce surface-detectable disruptions if they are sufficiently close to the surface.

Magnetic Particle Inspection



(a) A bar placed within a magnetizing coil will have an axial magnetic field. Defects parallel to this field may go unnoticed while those that disrupt the field and are sufficiently close to a surface are likely to be detected.

(b) When magnetized by a current passing through it, the bar has a circumferential magnetic field and the geometries of detectable flaws are reversed.

Magnetic Particle Inspection

TABLE 11-4. Magnetic Particle Inspection

Principle: When magnetized, ferromagnetic materials will have a distorted magnetic field in the vicinity of flaws and defects. Magnetic particles will be strongly attracted to surface regions where the flux is concentrated.

Advantages: Relatively simple, fast, easy-to-interpret portable units exist; can reveal both surface and subsurface flaws and inclusions (as much as $\frac{1}{4}$ in. deep) and small, tight cracks.

Limitations: Parts must be relatively clean; alignment of the flaw and the field affects the sensitivity so that multiple inspections with different magnetizations may be required; can only detect defects at or near surfaces; must demagnetize part after test; high current source is required; some surface processes can mask defects; postcleaning may be required.

Material limitations: Must be ferromagnetic; nonferrous metals such as aluminum, magnesium, copper, lead, tin, and titanium, and the ferrous (but not ferromagnetic) austenitic stainless steels cannot be inspected.

Geometrical limitations: Size and shape are almost unlimited, most restrictions relate to the ability to induce uniform magnetic fields within the piece.

Permanent record: Photographs, videotapes, and inspectors' reports are most common. In addition, the defect pattern can be preserved on the specimen by an application of transparent lacquer, or transferred to a piece of transparent tape that has been applied to the specimen and peeled off.

Magnetic Particle Inspection

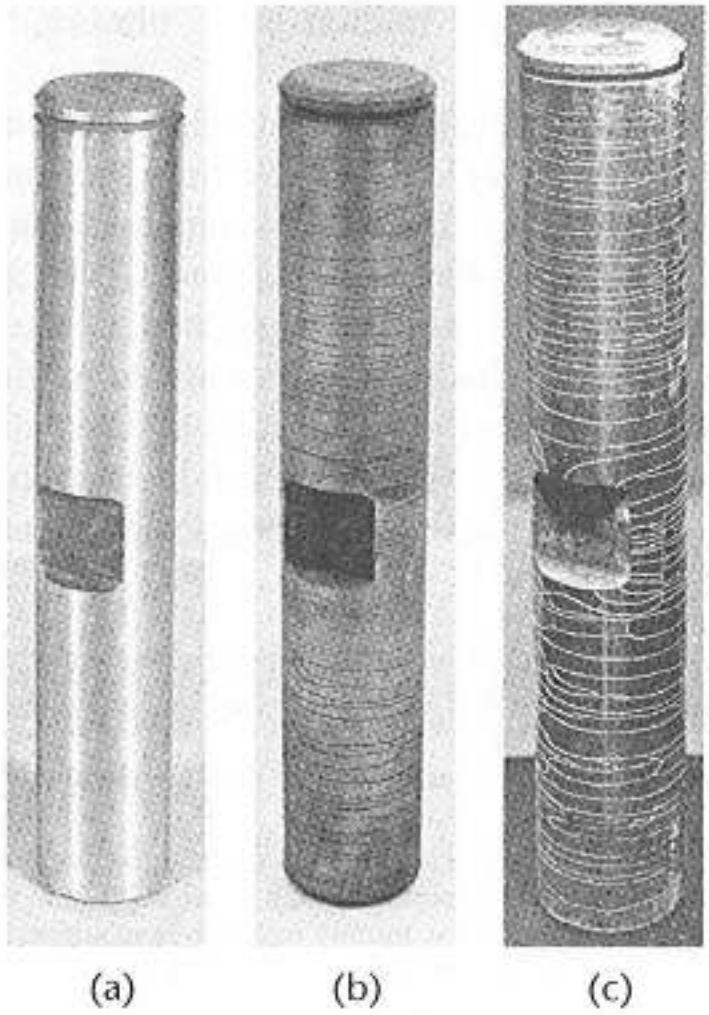


FIGURE 11-4 Front-axle king pin for a truck. (a) as manufactured and apparently sound; (b) inspected under conventional magnetic particle inspection to reveal numerous grinding-induced cracks.; (c) fluorescent particles and ultraviolet light make the cracks even more visible.

Ultrasonic Inspection

- Developed from 'sound' testing - Cracked bells - do not ring true, Strike & listen - special hammers; “Wheel tappers” - Railway wheels
- Limited to audible sounds so only 'spots' large defects; Composite panels – delamination
- Reducing wavelength of signal for smaller defects. 100 kHz - 25MHz
- Use transducer (piezoelectric) to send mechanical vibrations into sample (use coupling medium - oil/water)
- Sound waves propagate through material with velocity (depends on density + E)
- Receiver (transducer) turns vibrations back into electrical signal - evaluate signal

Ultrasonic Inspection

1. Pulse - Echo - pulse sent into material – receiver picks up echoes from flaws and opposing surfaces. Time display shows echoes form 'within' sample (1 or 2 transducers).
2. Through-Transmission - going through material

- Access to both sides is required. Sending & receiving transducers on each side.
- Flaws present will decrease amplitude of signal

3. Resonance Testing - Used to determine the thickness of a plate/sheet. Measure frequency at which resonance occurs and knowing speed of sound in material can calculate thickness from time of signal transverse - Good for composites

Ultrasonic Inspection

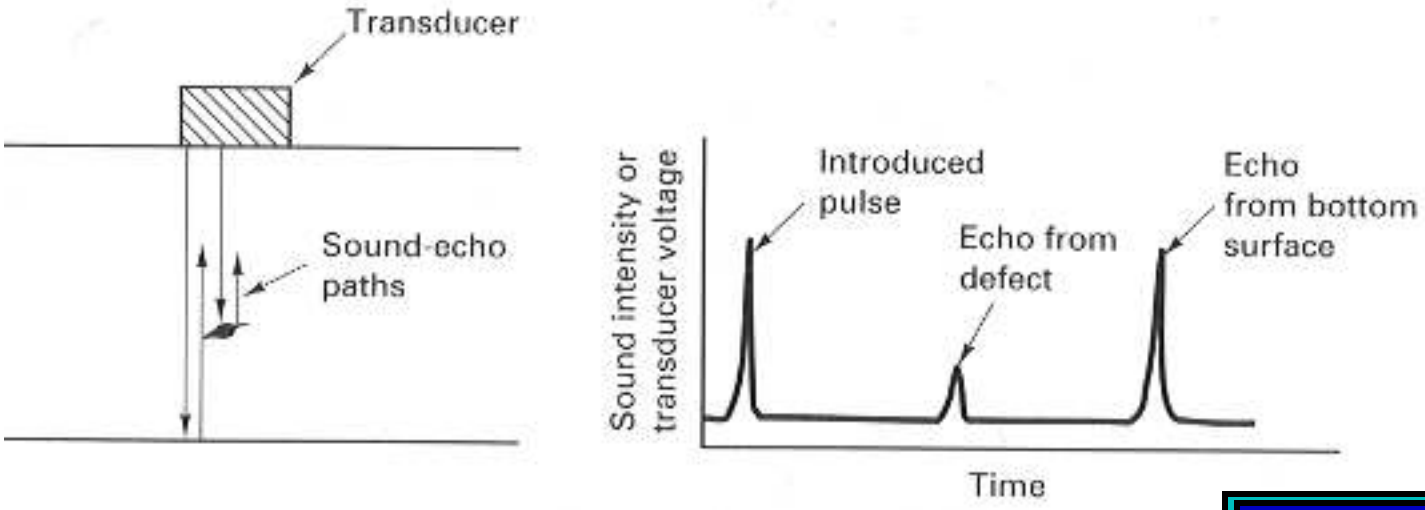


FIGURE 11-5 (a) Ultrasonic inspection of a flat plate with a single transducer; (b) plot of sound intensity or transducer voltage versus time showing the initial pulse and echoes from the bottom surface and intervening defect.

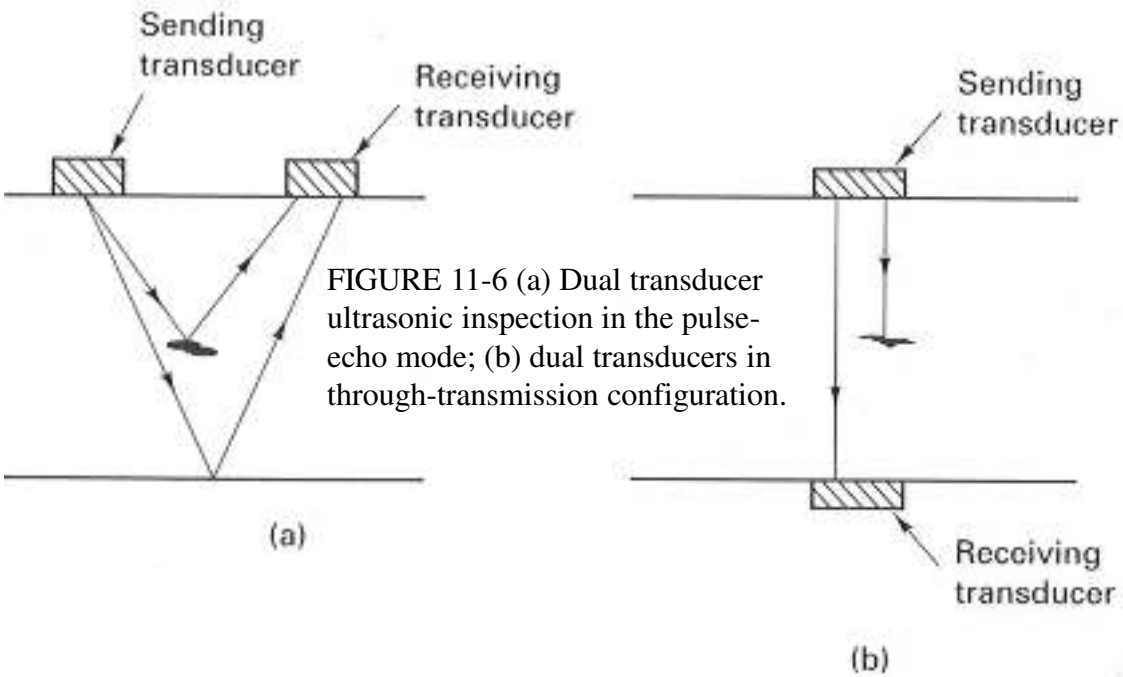
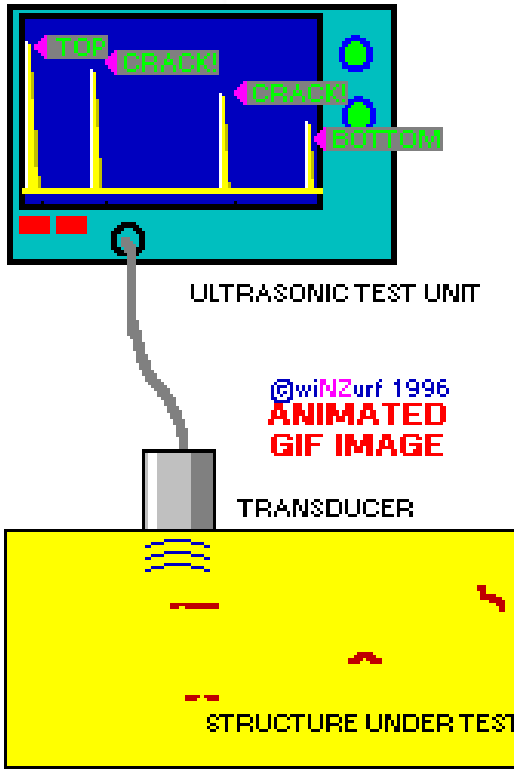


FIGURE 11-6 (a) Dual transducer ultrasonic inspection in the pulse-echo mode; (b) dual transducers in through-transmission configuration.



Ultrasonic Inspection

TABLE 11-5. Ultrasonic Inspection

Principle: Sound waves are propagated through a test specimen and the transmitted or reflected signal is monitored and interpreted.

Advantage: Can reveal internal defects; high sensitivity to most cracks and flaws; high-speed test with immediate results; can be automated and recorded; portable; high penetration in most important materials (up to 60 ft in steel); indicates flaw size and location; access to only one side is required; can also be used to measure thickness, Poisson's ratio, or elastic modulus; presents no radiation or safety hazard.

Limitations: Difficult to use with complex shapes; external surfaces and defect orientation can affect the test (may need dual transducer or multiple inspections); a couplant is required; the area of coverage is small (inspection of large areas requires scanning); trained, experienced, and motivated technicians may be required.

Material limitations: Few—can be used on metals, plastics, ceramics, glass, rubber, graphite, and concrete, as well as joints and interfaces between materials.

Geometric limitations: Small, thin, or complex-shape parts or parts with rough surfaces and nonhomogeneous structure pose the greatest difficulty.

Permanent record: Ultrasonic signals can be recorded for subsequent playback and analysis. Strip charts can also be used.

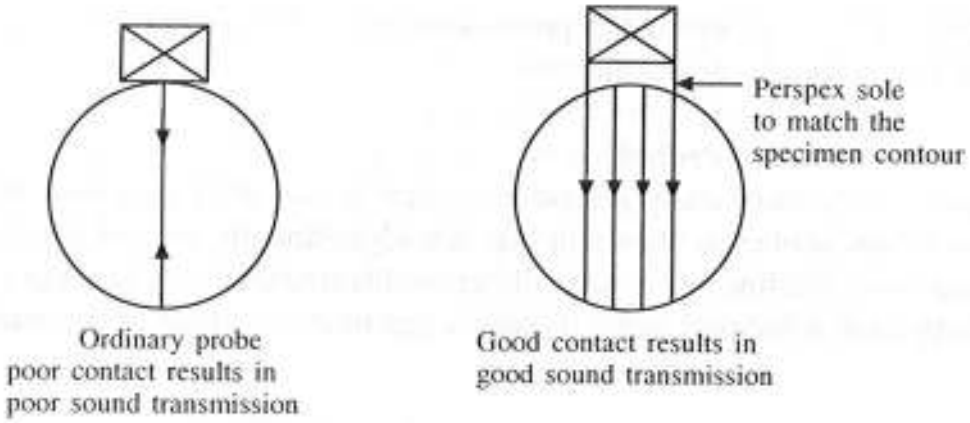


Fig. 6.9 Probes with contour corrected soles

Radiographic Inspection

- When radiation goes through object it is differentially absorbed by variations in density, thickness, chemistry defects etc.
- Recorded on film like x-ray or displayed on screen
- x-rays - very short wavelength EM, good penetration (high voltage source)
- Gamma rays - EM radiation from radioactive nuclei
- Neutron beams - from nuclei reactors (better resolution/penetration)

Radiographic Inspection

- x-rays & gamma - absorption depends on thickness, density and atomic structure, higher Z then higher absorption (ie thick lead stops!)
- Neutrons - absorbed differently. Unusual contrasts (eg heavy water is good absorber) Used for checking gas turbine blades.
- Radiation is scattered on passing through, produces 'fogging', reduces resolution, thicker sample - more fogging
- use standard test piece; “penetrator” to correlate with sample.

Radiographic Inspection

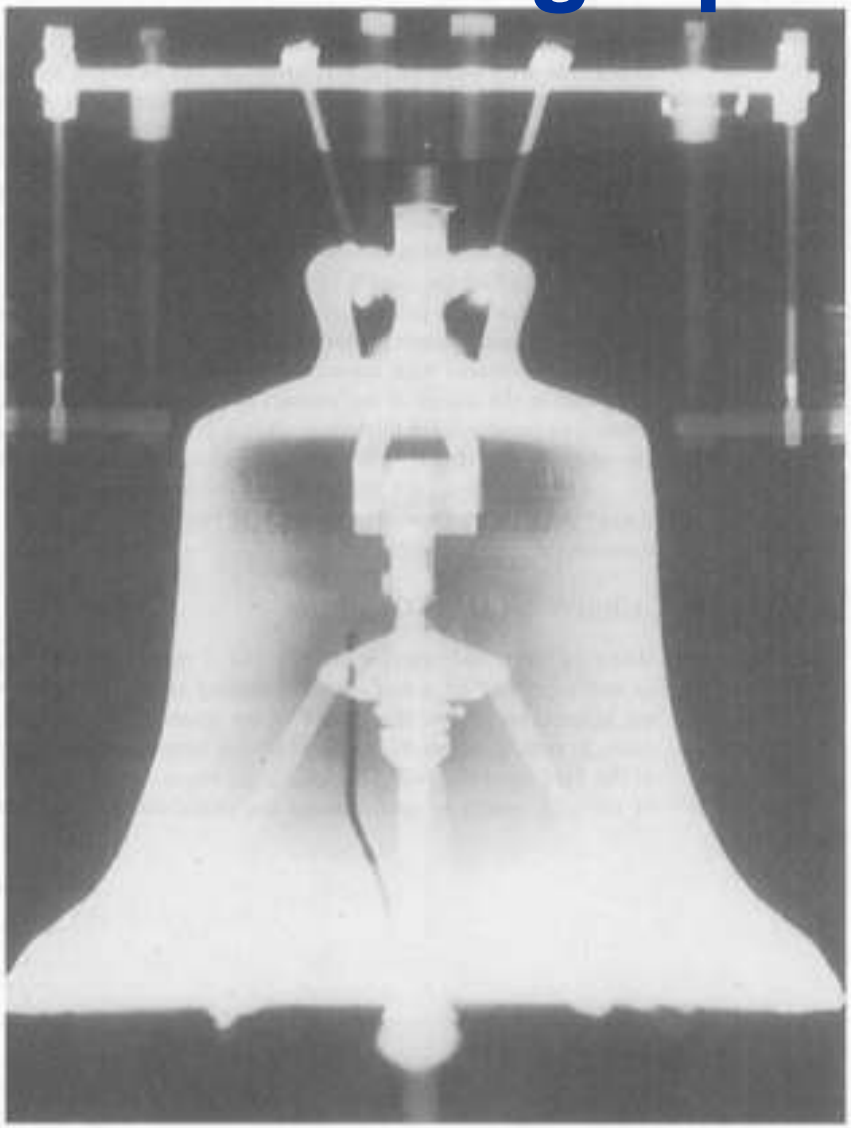


FIGURE 11-7 Full-size radiograph of the Liberty Bell. The photo reveals the famous crack, as well as the iron spider installed in 1915 to support the clapper and the steel beam and supports which were set into the yoke in 1929. *(Courtesy of Eastman Kodak company.)*

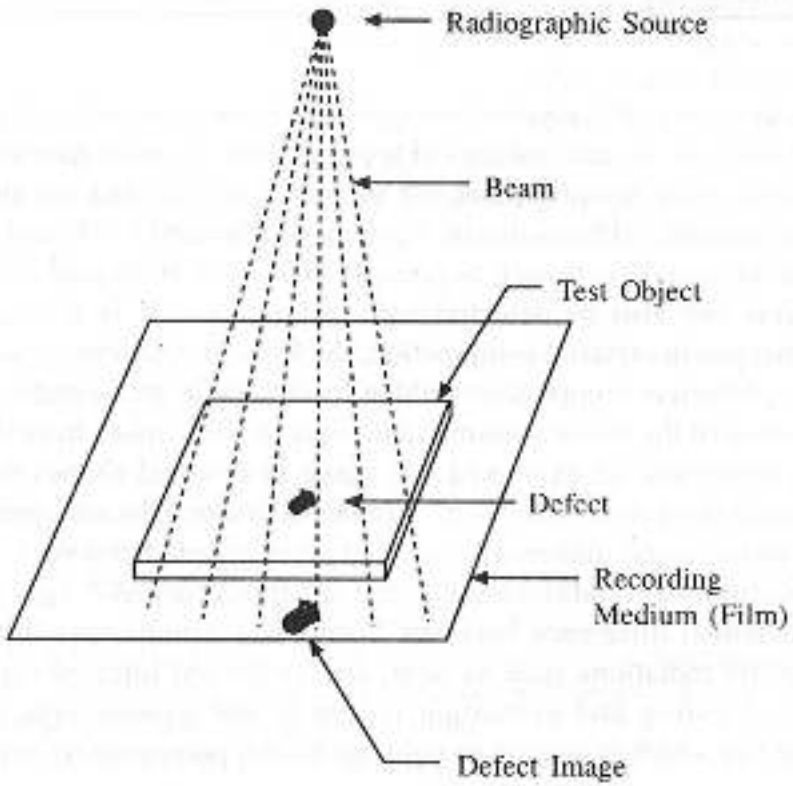
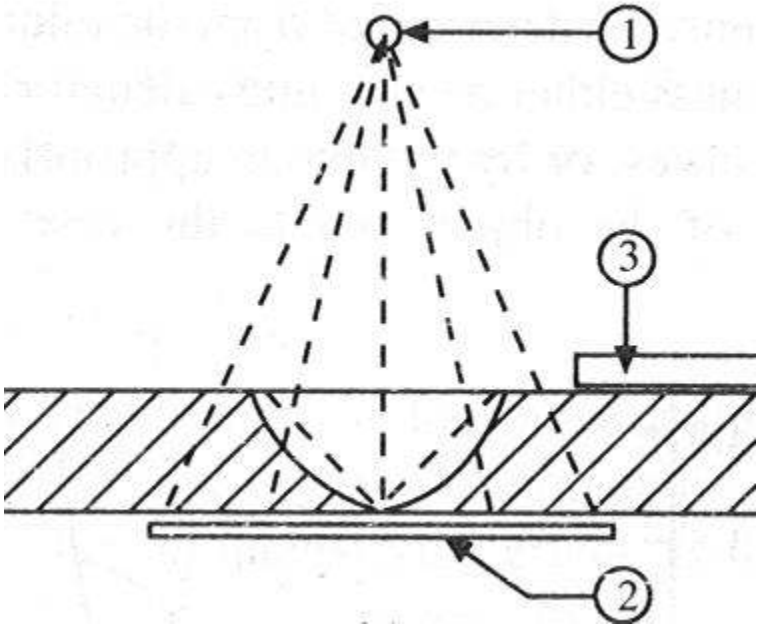


Fig. 7.1 Principle of radiographic inspection

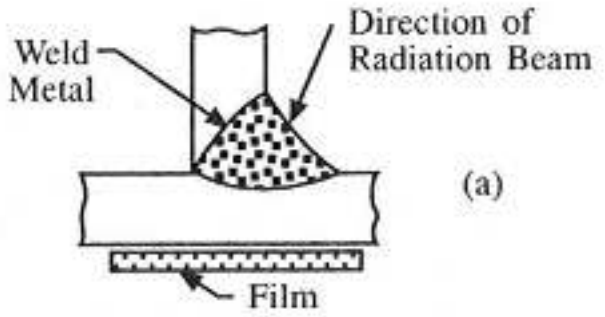
Radiographic Inspection

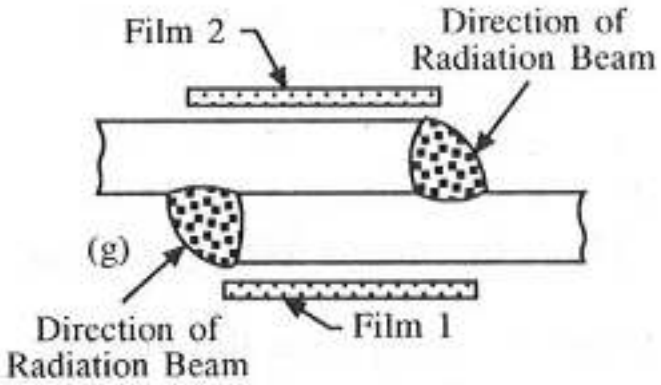


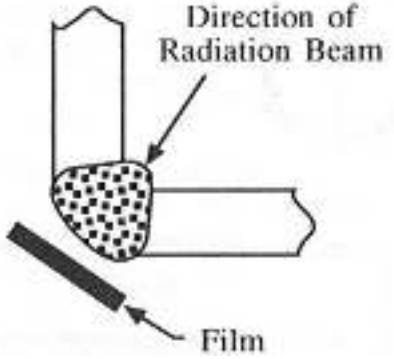
(1) Source

(2) Film

(3) Penetrameter







Radiographic Inspection

TABLE 11-6. Radiography

Principle: Some form of radiation is passed through the sample and is differentially absorbed depending on the thickness, type of material, and the presence of flaws or defects.

Advantages: Probes the internal regions of a material; provides a permanent record of the inspection; can be used to determine the thickness of a material; very sensitive to density changes.

Limitations: Most costly of the NDT methods (involves expensive equipment, film, and processing); radiation precautions are necessary (potentially dangerous to human health); the defect must be at least 2% of the total section thickness to be detected (thin cracks can be missed if oriented perpendicular to the beam); film processing requires time, facilities, and care; the image is a two-dimensional projection of a three-dimensional object, so the location of an internal defect requires a second inspection at a different angle; complex shapes can present problems; a high degree of operator training is required.

Material limitations: Applicable to most engineering materials.

Geometric limitations: Complex shapes can present problems in setting exposure conditions and obtaining proper orientation of source, specimen, and film. Two-side accessibility is required.

Permanent record: A photographic image is part of the standard test procedure.

EDDY Current Testing

- Expose material (electrical conductor) to magnetic field (alternating).
- Induces small electrical currents on/near to sample surface. These eddy currents produce their own magnetic fields which reduces the coil field strength. Monitor charges (as impedance is changed & thus current).
- Cracks, defects affect eddy current paths/conductivity and can thus be monitored. Used for surface/near surface flaws
- Eddy-current test equipment can range from simple, portable units with hand-held probes to fully automated systems with computer control and analysis.

EDDY Current Testing

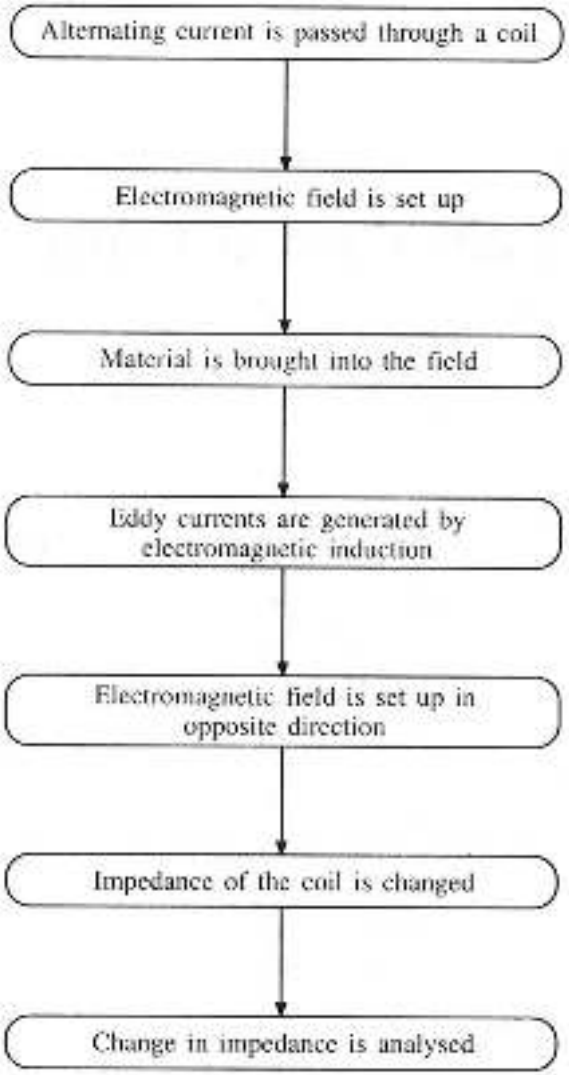


Fig. 5.1 Sequence of Testing

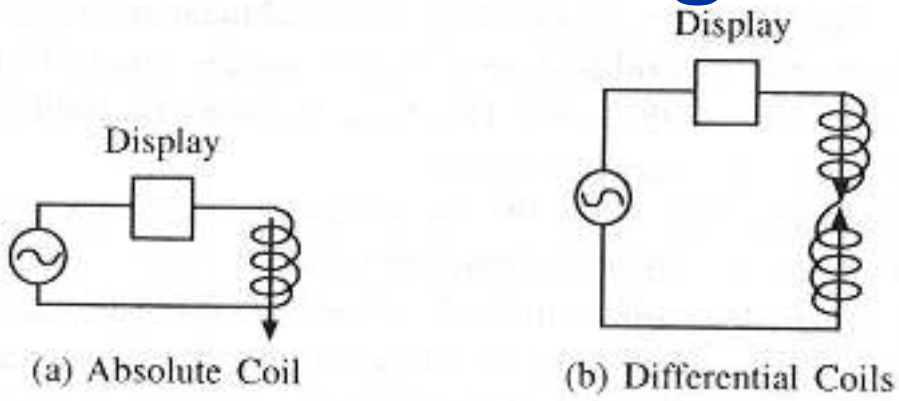
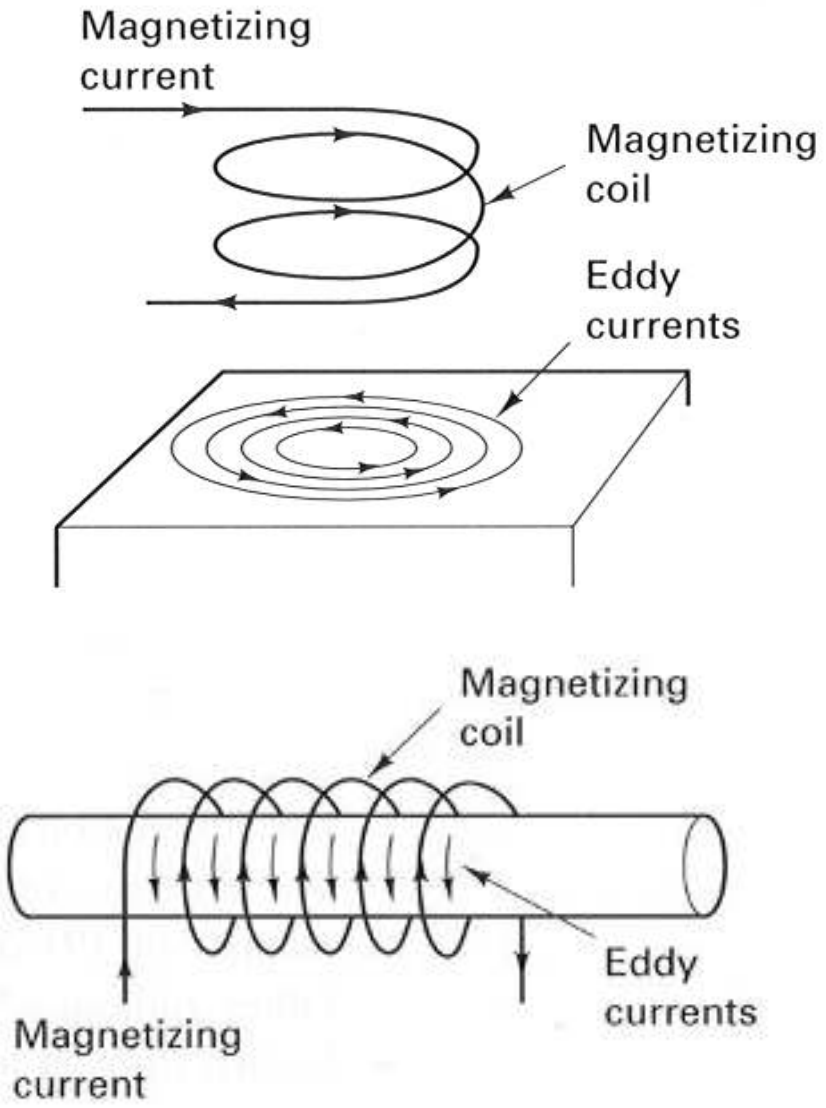


Fig. 5.5 Types of coils

- Also for
- stress concentrations
- metal chemistry
- heat treatment
- hardness
- plating/coating thickness
- By monitoring changes in conductivity or magnetic fields.

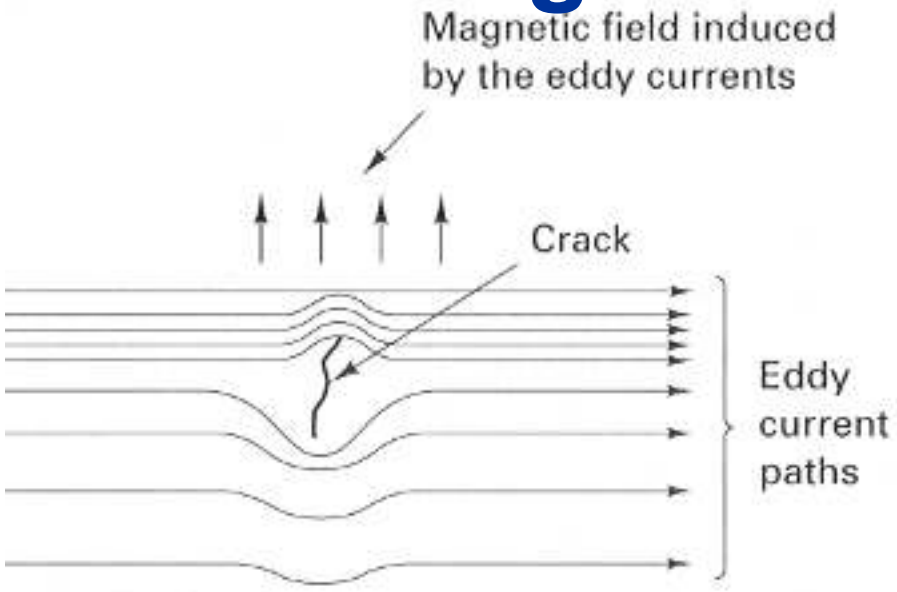
EDDY Current Testing

FIGURE 11-8 Relation of the magnetizing coil, magnetizing current, and induced eddy currents. The magnetizing current is actually an alternating current, producing a magnetic field that forms, collapses, and reforms in the opposite direction. This dynamic magnetic field induces the eddy currents and the changes in the eddy currents produce a secondary magnetic field which interacts with the sensor coil or probe.



EDDY Current Testing

FIGURE 11-9 Eddy currents are constrained to travel within the conductive material, but the magnitude and path of the currents will be affected by defects and changes in material properties. By focusing on the magnitude of the eddy currents, features such as differences in heat treatment can be detected.



- Each system, however, includes:

1. A source of magnetic field capable of inducing eddy currents in the part being tested. This source generally takes the form of a coil (or coil-containing probe) carrying alternating current. Various coil geometries are used for different-shaped specimens.

EDDY Current Testing

2. A means of sensing the field changes caused by the interaction of the eddy currents with the original magnetic field. Either the exciting coil itself or a secondary sensing coil can be used to detect the impedance changes.

- Differential testing can be performed using two oppositely wound coils wired in series.
- In this method, only differences in the signals between the two coils are detected as one or both coils are scanned over the specimen.

EDDY Current Testing

3. A means of measuring and interpreting the resulting impedance changes.

- The simplest method is to measure the induced voltage of the sensing coil, a reading that evaluates the cumulative effect of all variables affecting the eddy-current field.
- Phase analysis can be used to determine the magnitude and direction of the induced eddy-current field.
- Familiarity with characteristic impedance responses can then be used to identify selected features in the specimen.

EDDY Current Testing

TABLE 11-7. Eddy-Current Testing

Principle: When an electrically conductive material is brought near an alternating-current coil that produces an alternating magnetic field, surface currents (eddy currents) are generated in the material. These surface currents generate their own magnetic field, which interacts with the original, modifying the impedance of the originating coil. Various material properties and/or defects can affect the magnitude and direction of the induced eddy currents and can be detected by the electronics.

Advantages: Can detect both surface and near-surface irregularities; applicable to both ferrous and nonferrous metals; versatile—can detect flaws, variations in alloy or heat treatment, variations in plating or coating thickness, wall thickness, and crack depth; intimate contact with the specimen is not required; can be automated; electrical circuitry can be adjusted to select sensitivity and function; pass/fail inspection is easily conducted; high speed; low cost; no final cleanup is required.

Limitations: Response is sensitive to a number of variables, so interpretation may be difficult; sensitivity varies with depth, and depth of inspection depends on the test frequency; reference standards are needed for comparison; trained operators are generally required.

Material limitations: Only applicable to conductive materials, such as metals; some difficulties may be encountered with ferromagnetic materials.

Geometric limitations: Depth of penetration is limited; must have accessibility of coil or probe; constant separation distance between coils and specimen is required for good results.

Permanent record: Electronic signals can be recorded using devices such as strip-chart recorders.

Acoustic Emission

- Materials emit high frequency sound when stressed. 1MHz (i.e. cracking, etc.)
- Not good for static defect inspection but good for continual in-service monitoring. (composites).

Other Methods

- Leak Testing
- Thermal Methods
- Optical Holography methods
- Strain Sensing
- Computer Tomography
- Topography (SEM, STM etc)

Speckle Shearography

- Shearography identifies the strain-concentrated areas as anomaly areas in the fringe pattern.
- It detects both surface and sub-surface defects.
- comparison of two states of deformation under loading.

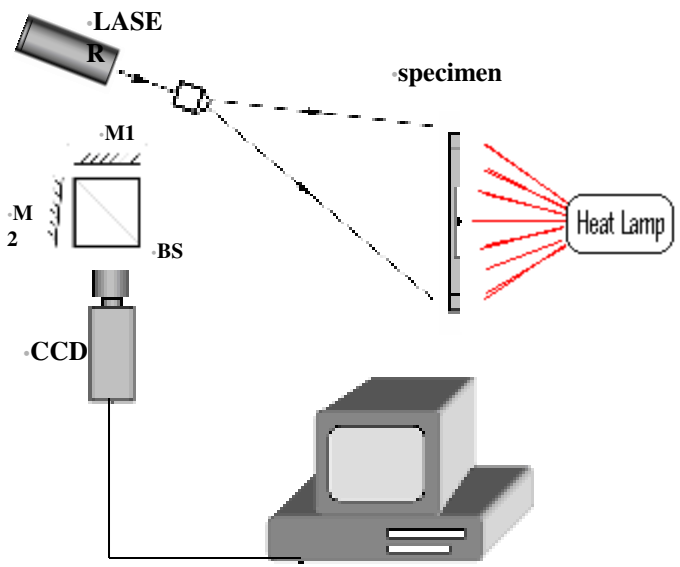
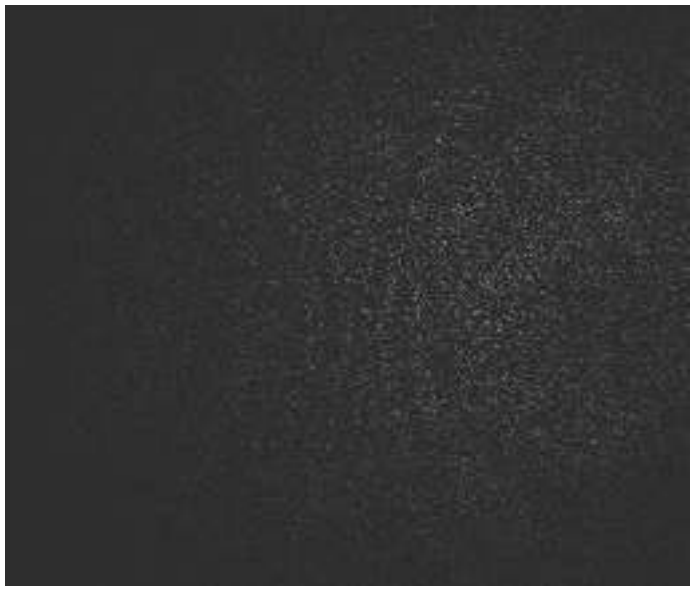
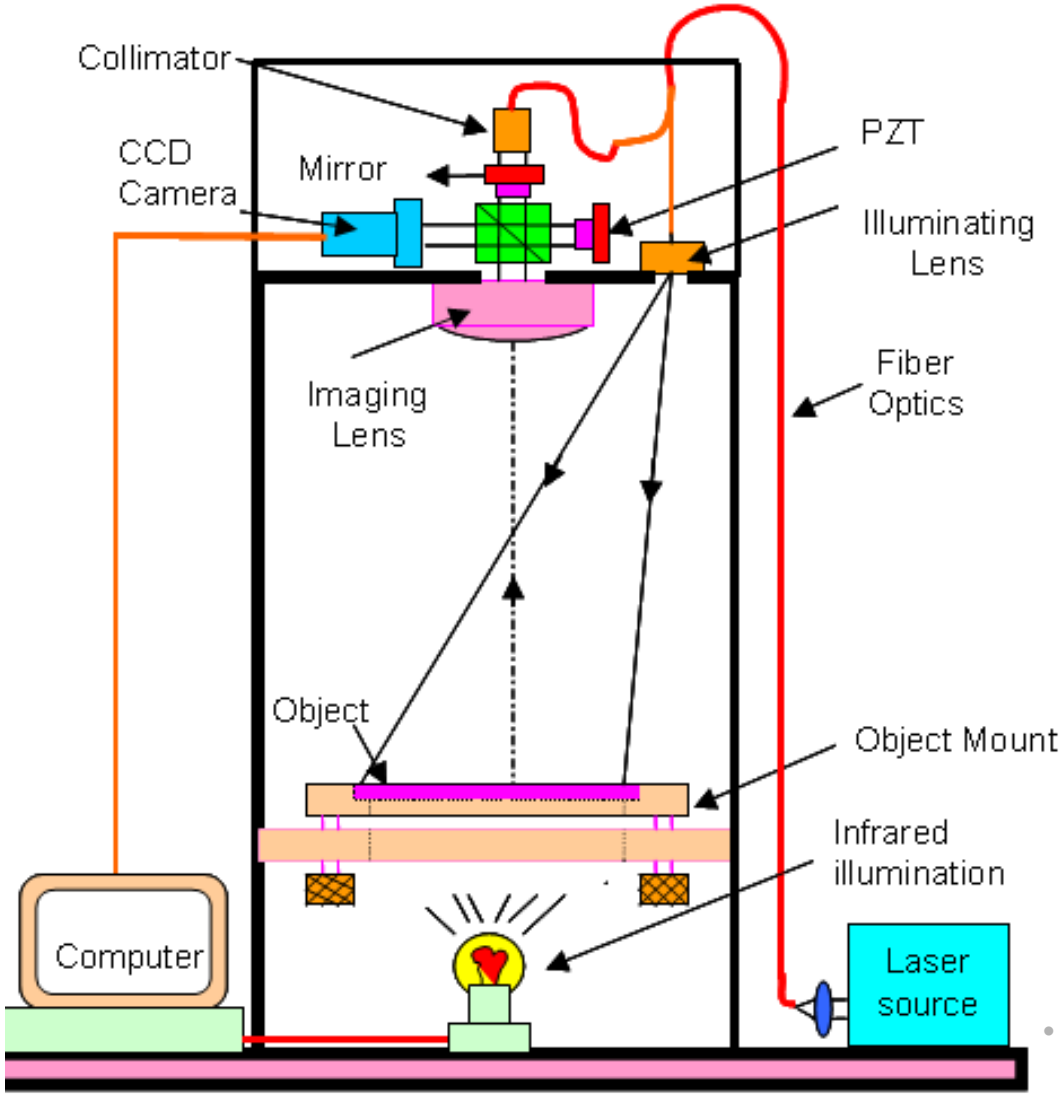


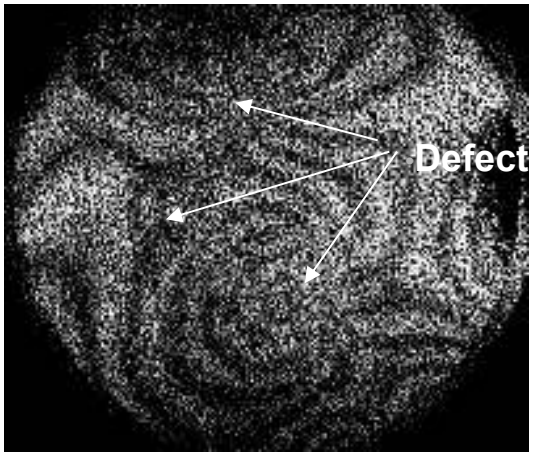
Image processing

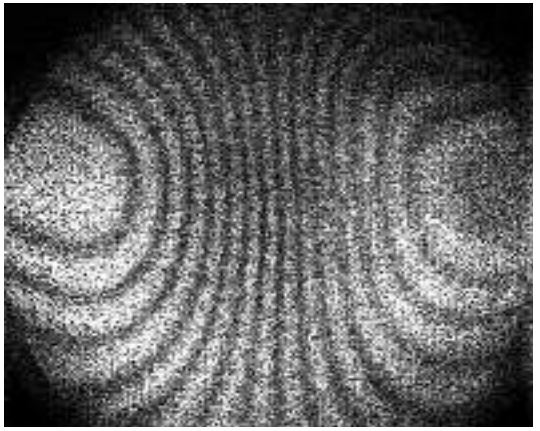
Fringes



Applications



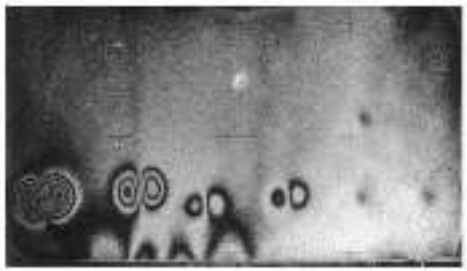




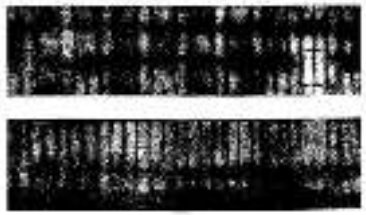
system based on laser speckle interferometry

Speckle Shearography

Applications



Delaminations in a honeycomb panel, the means of stressing is partial vacuum.



Weakness in three adhesive-bond lines of a composite assemblies, the means of stressing is vibrational excitation.

A delamination in a filament-wound composite pressure vessel, the means of stressing is pressurization.

Separations in a cord-reinforced rubber panel, the means of stressing is partial vacuum.

A crack in a composite turbine blade, the means of stressing is radiating the object surface with heat (thermal stressing)

MECH 423 Casting, Welding, Heat Treating and NDT

Time: _ T _ J _13:15 - 14:45

Credits: 3.5

Review

Lecture 13

Grading

Assessment Criteria	Share towards final	
Presentation	10 %	10 %
Lab (preliminary and final)	10 %	10 %
Assignments (3)	15 %	15 %
Exams:	(with Midterm)	(without Midterm)
Midterm (optional)	15 %	0%
Final	50 %	65%
Total	100%	100%

- Final Lab report as per manual
- Project report due next week

Final

- Closed book exam for 3 hours
- 80 marks
  - 15 True or False questions (1 mark each)
  - 15 multiple choice questions (1 mark each)
  - 10 small questions (2 marks each)
- 3 questions, that require design, calculations or explanation, of which you attend 2 questions (15 marks each)
- Relevant formulae and pictures will be given along with the question paper

Writing Strategy

- Questions will be similar to the ones in the assignments
- Answers, it will be better to be crisp looking at all the possibilities of the questions in full
- No bonus for lengthy answers
- I will be marking based on keywords for example
- Normalizing process - Keywords will be, how much and how long you will heat the sample, and how fast and by what method you will cool it. Include crystal size, shape, advantages and disadvantages as well.

Preparing Strategy

- Casting
  - Types, classifications, relative advantages and limitations, considerations, techniques etc.
- Heat Treatment
  - Types, classifications, relative advantages and limitations, considerations, techniques etc.
- Welding
  - Types, classifications, relative advantages and limitations, considerations, techniques etc.
- NDT
  - Types, classifications, relative advantages and limitations, considerations, techniques etc.

MECH 423 Casting, Welding, Heat Treating and NDT

Time: _ T _ J _13:15 - 14:45

Credits: 3.5

Review

Lecture 13

Grading

Assessment Criteria	Share towards final	
Presentation	10 %	10 %
Lab (preliminary and final)	10 %	10 %
Assignments (4)	15 %	15 %
Exams:	(with Midterm)	(without Midterm)
Midterm (optional)	15 %	0%
Final	50 %	65%
Total	100%	100%

- Final Lab report due on 9th December
- Assignment 4 and project report due today

Final

- Closed book exam for 3 hours
- 80 marks
  - 15 True or False questions (1 mark each)
  - 15 multiple choice questions (1 mark each)
  - 10 small questions (2 marks each)
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- Casting
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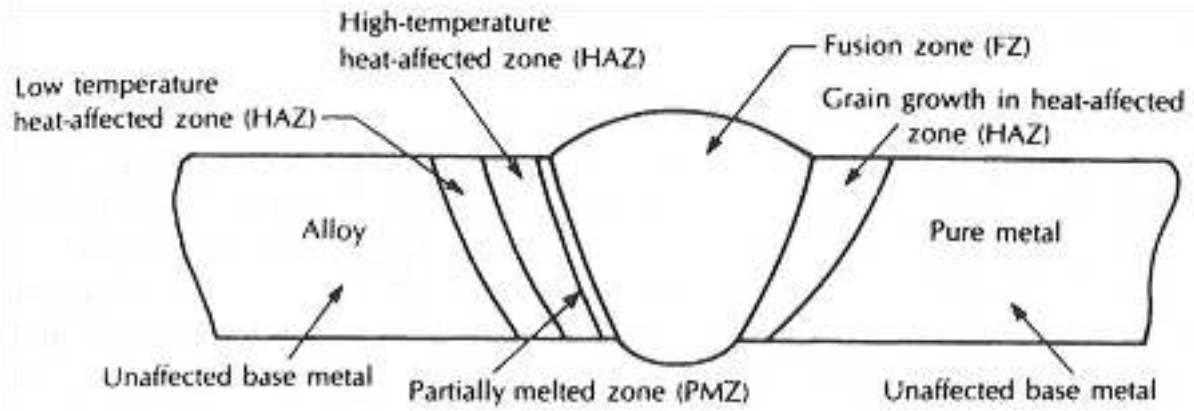
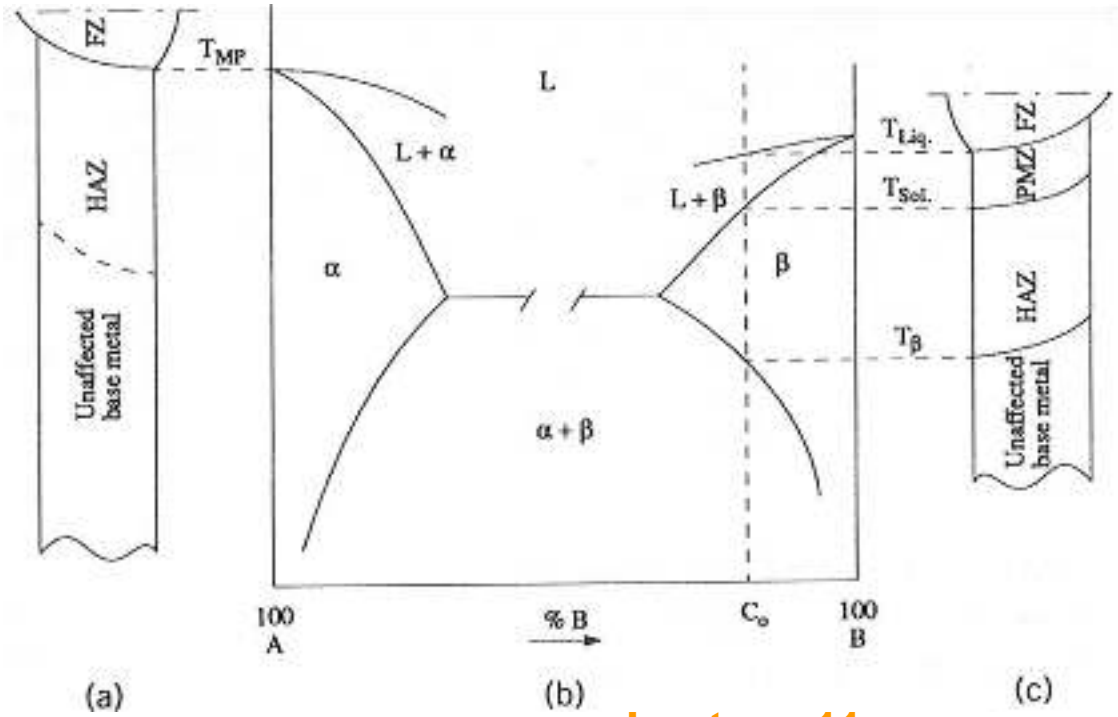
- NDT
  - Types, classifications, relative advantages and limitations, considerations, techniques etc.

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)

Welding process	*SAW, steel*	*SMAW, steel*	*GMAW, CO_2-steel*	*GMAW, Ar-steel*	*GTAW, Ar-steel*	*GTAW, He-Al*	*GTAW, Ar-Al*
η	0,91÷0,99	0,66÷0,85	0,75÷0,93	0,66÷0,70	0,25÷0,75	0,55÷0,80	0,22÷0,46

Simplified Welding Equations

Solidification rate

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

Solidification time, S_t , in seconds:

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

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

Simplified Welding Equations

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:

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

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

Simplified Welding Equations

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

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

MECH 423/2 - 2013

CASTING, WELDING, HEAT-TREATING & NON-DESTRUCTIVE TESTING

Assignment #1. Due Date: September 27th 2.45 pm

1. Using Chvorinov's rule with n = 2, calculate the dimensions of an effective riser ($t_r = 1.25t_c$) for a casting that is a 50mm by 100mm by 150mm rectangular plate. Assume that the riser and casting do not share a common cooling surface (they are just connected by a gate and runner). The riser has to be a cylinder of height/diameter ratio of 1.5.

   What fraction of the total weight of casting plus riser is the actual casting? (Ignore the runner).

   If the riser had feeding aids comprised of an insulating sleeve (x = 0.65) and a hot topping (y = 0.7) what would the new riser dimensions have to be to give the same riser solidification time and what would be the new percentage yield? (see note below for information)

   Note:
   The thermal properties of feeding aids can be readily incorporated into the modulus method of riser calculation. Cylindrical risers are the most common because this shape has a high modulus for a given volume of metal and because this shape is easy to mold. The modulus of a cylindrical riser, ignoring any contiguous (adjoining) areas, M_r, is given by:

$$M_r = \frac{V_r}{A_r} = \frac{DH}{4H + 2D}$$

   Riser insulation in the form of a sleeve and hot topping may be regarded as effectively decreasing the surface area of the riser. The effect of the sidewall (sleeve) insulation may be represented by a factor *x* and that of a hot topping by a factor *y,* both relative to sand (where *x* = 1, y = 1, for sand). The factors *x* and *y* have been termed apparent surface alteration factors (ASAF). The effective modulus M_r of a cylindrical riser incorporating feeding aids on both the side-wall and top is given by:

$$M_r = \frac{DH}{4Hx + 2Dy}$$

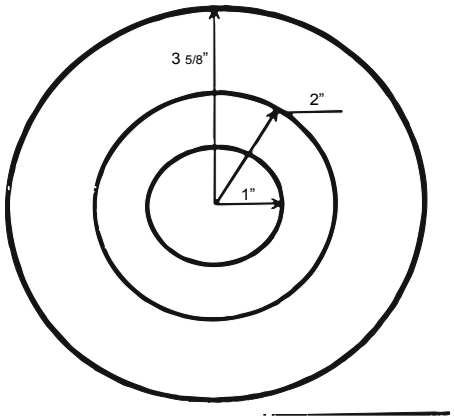
   The ASAF values of insulating and exothermic feeding aid materials vary and generally range from 0.50 to 0.90. The smaller the ASAF value, the more efficient the insulation. The ASAF values for feeding aids are generally available from manufacturers of these products.

2. In casting experiments performed using a certain alloy and type of sand mold, it took 155 sec for a cube-shaped casting to solidify. The cube side was 50 mm. Using Chvorinov's rule with n = 2, (a) Determine the value of the mold constant. (b) If the same alloy and mold type were used, find the total solidification time for a cylindrical casting in which the diameter = 30 mm and length = 50 mm

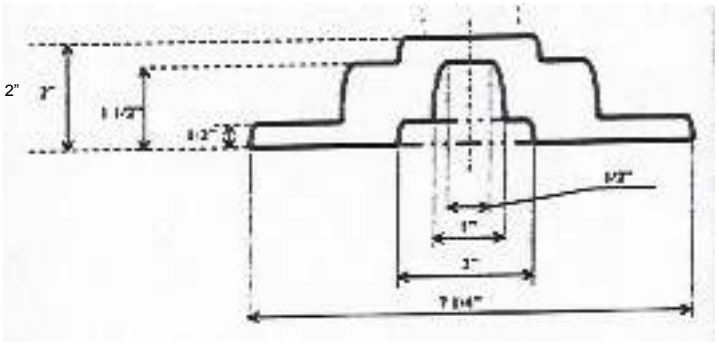
3. The attached figure shows a casting that is made to be made from an aluminum alloy (A356) by sand casting. Provide sketches showing how you would design the casting

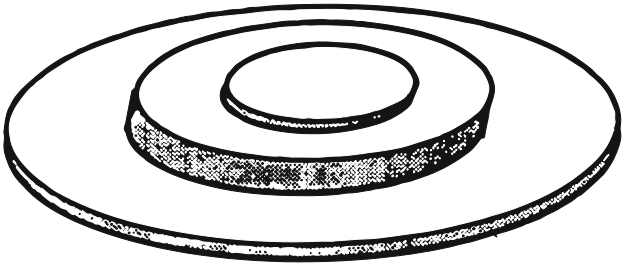
system (sprue, runners, gates, parting line, cores) for this casting if it is to be cast in a two-part sand mould (cope & drag). Point out the features you are using, explaining their importance. You do not have to provide engineering drawings or worry about exact dimensions - see illustrations in text for relative scales. The layout of the "plumbing" system is what I am looking for.

Superior view



Cross-section





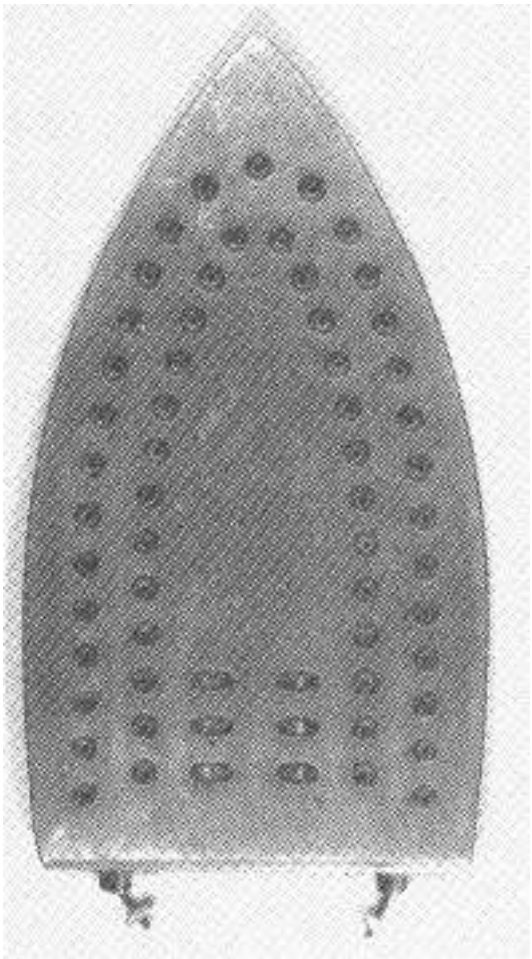
MECH 423/2 - 2013

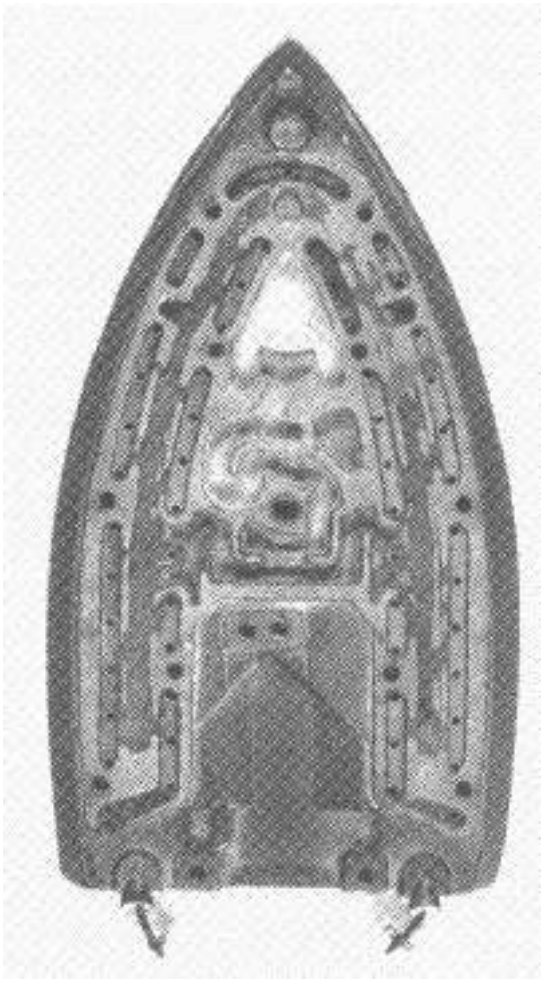
CASTING, WELDING, HEAT-TREATING & NON-DESTRUCTIVE TESTING

Assignment #2. Due Date: October 25th 2.45 pm

Question 1 The item depicted below is the baseplate of a high-quality household steam iron. It is rated for operation at up to 1200 watts, and is designed to provide both steady steam and burst-of-steam features. Incorporated into the design is an integral electrical resistance heating "horseshoe" that must be thermally coupled to the baseplate, but remain electrically insulated. (This component often takes the form of a resistance heating wire, surrounded by ceramic insulation, all encased in a metal tube). There is a complex series of channels designed to receive the steam and distribute it out evenly through a number of small vent holes in the base, each about 1.6mm (1/16-inch) in diameter. There are about a dozen larger threaded recesses, about 3.2 mm (1/8-inch) in diameter, that are used in assembling the various components.

- Discuss the various features/properties that this component must possess in order to function in an adequate fashion.
- What material or materials would appear to be strong candidates?





Question 2 Using the isothermal transformation diagram for an iron-carbon alloy of eutectoid composition (Figure 10.14 attached), specify the nature of the final microstructure (in terms of microconstituents present and approximate percentages of each) of a small specimen that has been subjected to the following time-temperature treatments. In each case assume that the specimen begins at 760°C (1400°F) and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.

(a) Begins at 760°C: cool rapidly to 700°C (1290°F), hold for 10^4 s, then quench to room temperature.

(b) Reheat the specimen in part (a) to 700°C (1290°F) for 20 h.

(c) Begins at 760°C: rapidly cool to 600°C (1110°F), hold for 4 s, rapidly cool to 450°C (840°F), hold for 10 s, then quench to room temperature.

(d) Begins at 760°C: cool rapidly to 400°C (750°F), hold for 2 s, then quench to room temperature.

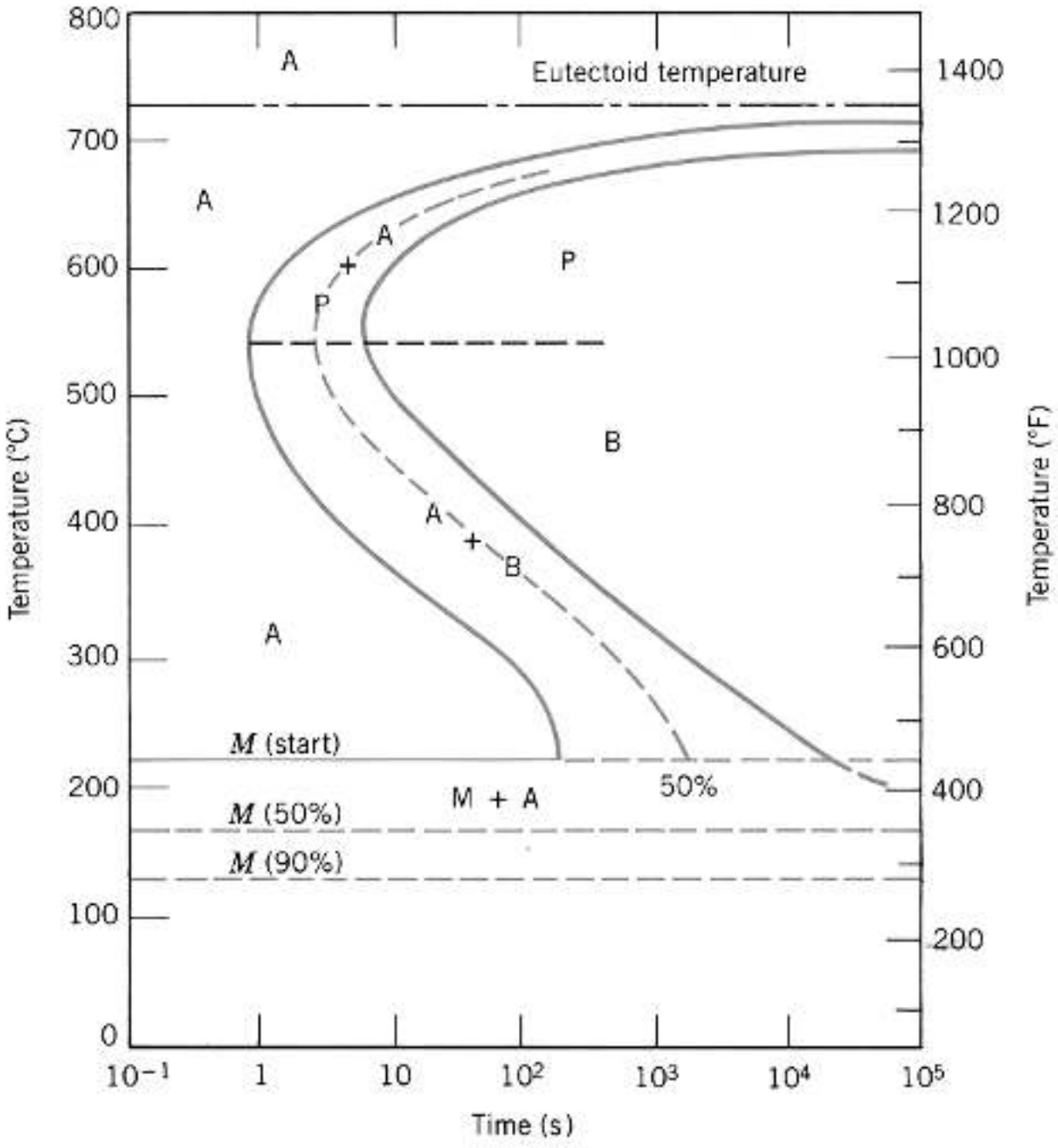
(e) Begins at 760°C: cool rapidly to 400°C (750°F), hold for 20 s, then quench to room temperature.

(f) Begins at 760°C: cool rapidly to 400°C (750°F), hold for 200 s, then quench to room temperature.

(g) Begins at 760°C: rapidly cool to 575°C (1065°F), hold for 20 s, rapidly cool to 350°C (660°F), hold for 100 s, then quench to room temperature.

(h) Begins at 760°C: rapidly cool to 250°C (480°F), hold for 100 s, then quench to room temperature in water. Reheat to 315°C (600°F) for 1 h and slowly cool to room temperature.

ITT Diagram for Eutectoid Steel



MECH 423/2 - 2013

CASTING, WELDING, HEAT-TREATING & NON-DESTRUCTIVE TESTING

Assignment #3. Due Date: November 22nd 2.45 pm

1. What is meant by the terms “natural aging” and “artificial aging”?

2. Can all alloys be strengthened by precipitation hardening?

3. Explain what is meant by “solid state” welding, and name 8 of them?

4. Why is quality of weld produced by Submerged Arc Welding very good?

5. What features are necessary if the strength of the brazed joint is to be equal or excel the strength of the metal being brazed