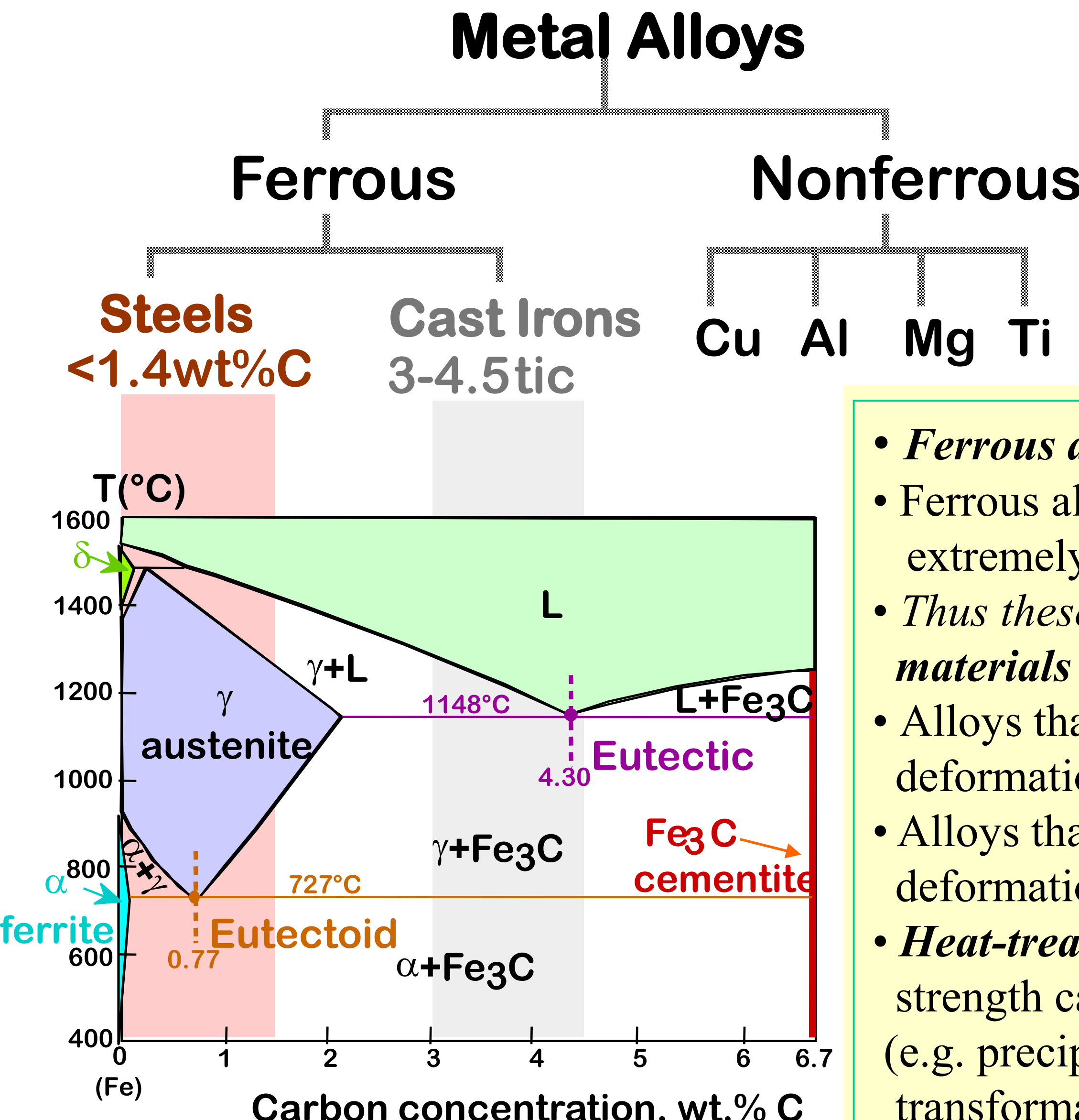
CHAPTER 11: METAL ALLOYS APPLICATIONS AND PROCESSING

ISSUES TO ADDRESS...

- How are metal alloys classified and how are they used?
- What are some of the common fabrication techniques?
- How do properties vary throughout a piece of material that has been quenched, for example?
- How can properties be modified by post heat treatment?

Classifications of Metal Alloys



<u>Some definitions:</u>

- ***Ferrous alloys***: iron is the prime constituent
- Ferrous alloys are relatively ***inexpensive*** and extremely ***versatile***
- *Thus these alloys* are ***wide spread engineering materials***
- Alloys that are so brittle that forming by deformation is not possible ordinary are ***cast***
- Alloys that are amenable to mechanical deformation are termed ***wrought***
- ***Heat-treatable -*** are alloys whose mechanical strength can be improved by heat-treatment (e.g. precipitation hardening or martensitic transformations).

Classification of Steels

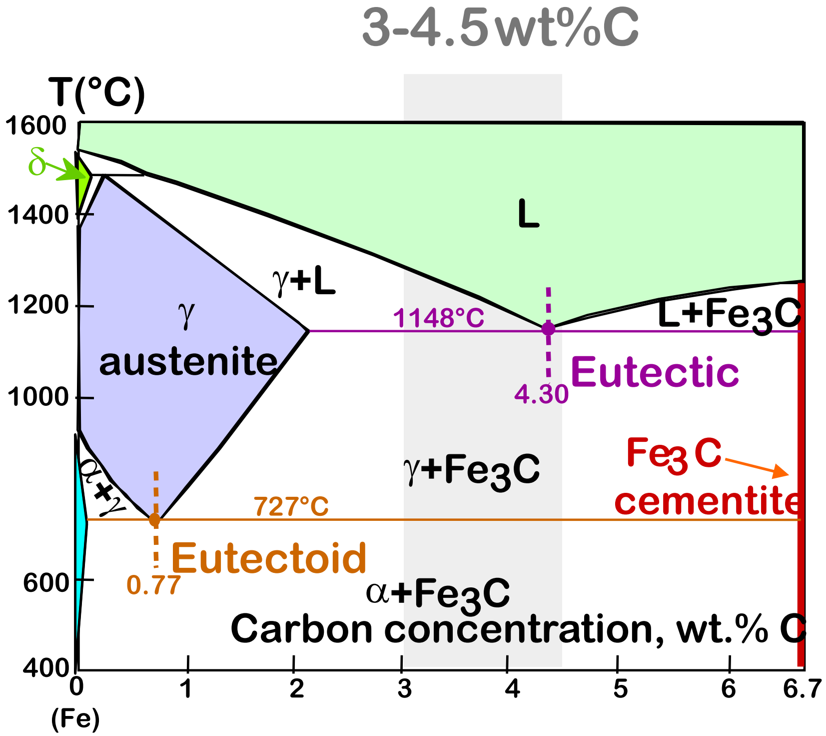
10-plane
0.1 or 0.4 C wt.%

	Low Alloy						High Alloy
	Low carbon <0.25wt%C		Medium-carbon 0.25-0.6wt%C		High carbon 0.6-1.4wt%C		
Name:	Plain	High strength	Plain	Heat treatable	Plain	Tool	Stainless
Additions:	none	Cu,V,Ni,Mo	none	Cr, Ni,Mo	none	Cr, V,Mo,W	Cr, Ni, Mo
Example *(ASTM#):*	1010	A633	1040	4340	1095	4190	304
Hardenability	0	+	+	++	++	+++	0
TS	-	0	+	++	+	++	0
EL	+	+	0	-	-	--	++
Applications:	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applications	wear applications	drills saws dies	high T applications turbines furnaces corrosion resistant

increasing strength, cost, decreasing ductility

CAST IRON

- The cast irons are the ferrous alloys with greater that 2.14 wt. % carbon, but typically contain 3-4.5 wt. % of C as well as other alloying elements, such as **silicon** (~3 wt..%) which controls kinetics of carbide formation



- These alloys have relatively low melting points (1150-1300°C), do not formed undesirable surface films when poured, and undergo moderate shrinkage during solidification. Thus can be easily melted and amenable to ***casting***

- There are ***<u>four general types</u>*** of cast irons:

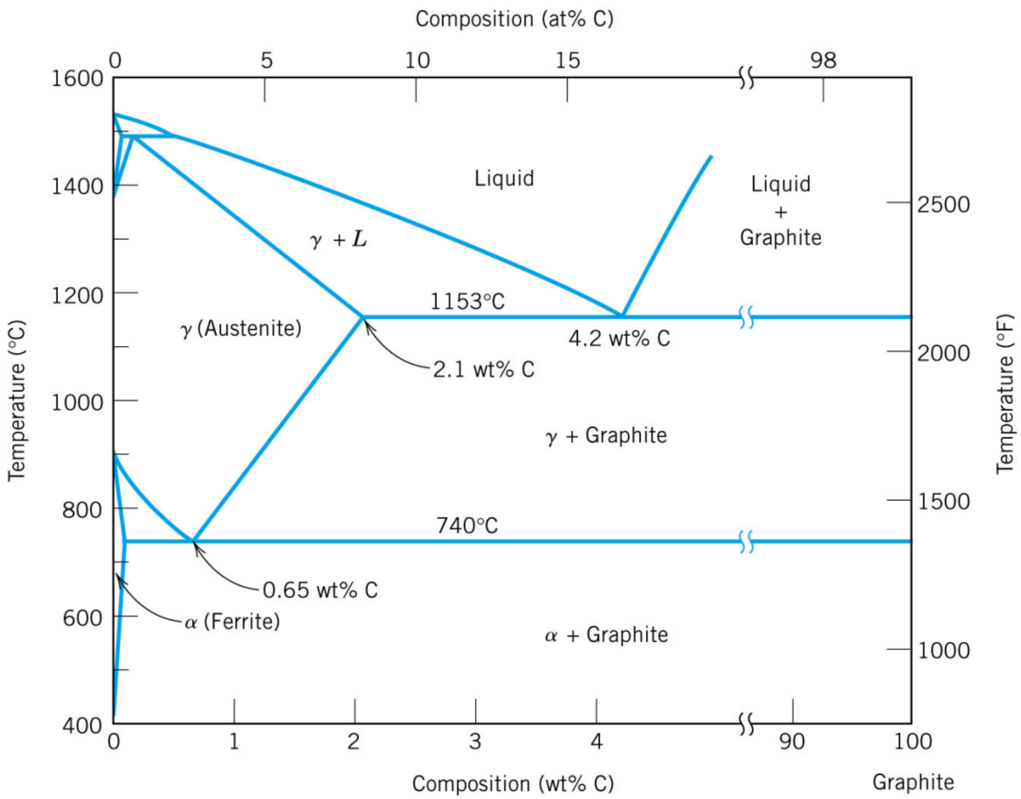
1. ***White iron*** has a characteristics white, crystalline fracture surface. Large amount of Fe_3C are formed during casting, giving hard brittle material
2. ***Gray iron*** has a gray fracture surface with finely faced structure. A large Si content (2-3 wt. %) promotes C ***flakes*** precipitation rather than carbide
3. ***Ductile iron:*** small addition (0.05 wt..%) of Mg to gray iron changes the flake C microstructure to spheroidal that increases (by factor ~20) steel ductility
4. ***Malleable iron***: traditional form of cast iron with reasonable ductility. First cast to white iron and then heat-treated to produce nodular graphite precipitates.

Equilibrium and Metastable Phases

- Cementite (Fe_3C) is a ***metastabl***e phase and after long term treatment decompose to form a-ferrite and carbon:

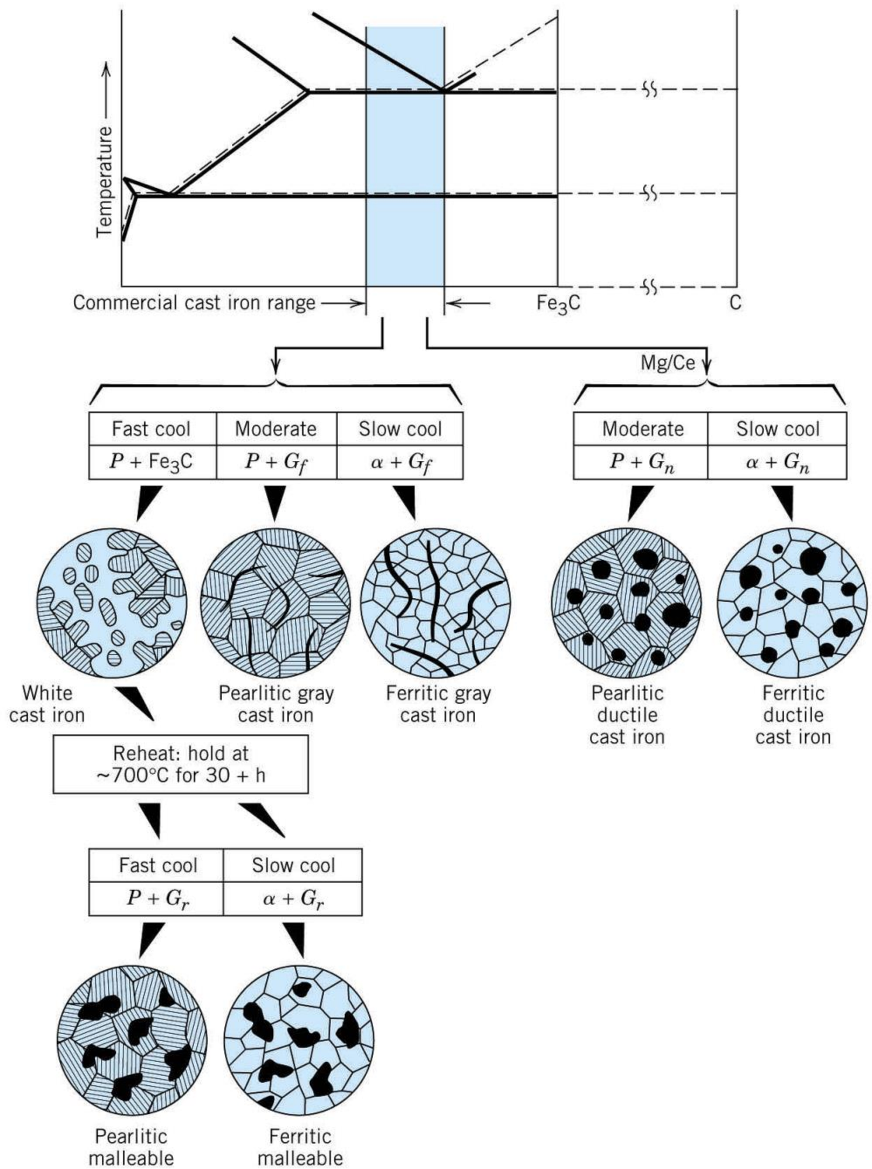
$$\mathbf{Fe3C \rightarrow 3Fe(S) + C(graphite)}$$

- Slow cooling and addition of some elements (e.g. Si) promote graphite formation
- Properties of cast irons are defined by the ***amount and microstructure*** of existing ***carbon phase***.



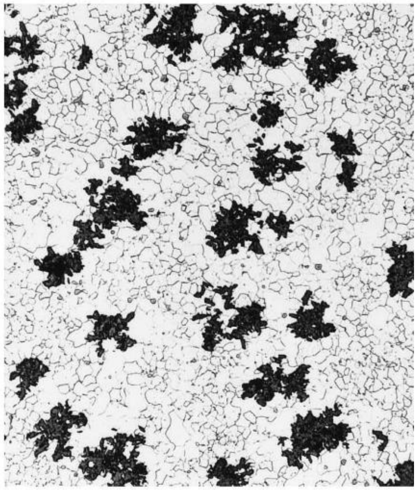
•Equilibrium iron-carbon phase diagram

White and Malleable Cast Irons



- The ***low-silicon cast*** irons (<1.0wt.%), produced under rapid cooling conditions
- Microstructure: most of ***cementite***
- Properties: extremely ***hard*** very but ***brittle***
- White iron is an intermediate for the production of malleable iron

White iron:
light Fe_3C regions surrounded by pearlite

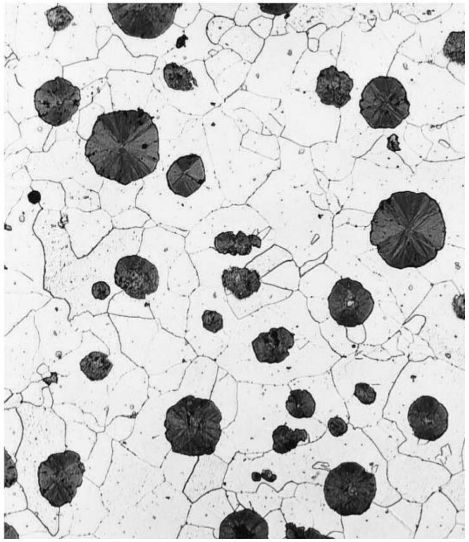


Malleable iron:
dark graphite rosettes in α-Fe matrix

Gray and Ductile Cast Irons

- ***The gray irons*** contain 1-31.0 wt..% of Si
- Microstructure: ***flake –shape*** graphite in ferrite matrix
- Properties: relatively weak and brittle in tension BUT very effective in ***damping vibrational*** energy an high resistive to wear!!

Gray iron:
Dark graphite flakes
In a-Fe matrix



Ductile iron:
dark graphite nodules
in α-Fe matrix

•***Ductile (or Nodular) iron*** :
small addition of Mg or/and Ce to the gray iron composition before casting

• Microstructure: Nodular or spherical-like graphite structure in pearlite or ferric matrix

• Properties: Significant increase in material ductility !!

• Applications: valves, pump bodies, gears and other auto and machine components.

RAPIDLY SOLIDIFIED FERROUS ALLOYS

- Eutectic compositions that permit cooling to a ***glass transition temperature*** at practically reachable quench rate (10^5 and 10^6 C°/s) –

  - rapidly solidified alloys
- ***Boron***, B, rather than carbon is a primary alloying element for ***amorphous*** ferrous alloys
- Properties:

  (a) absence of grain boundaries – easy magnetized materials

  (b) extremely fine structure – exceptional strength and toughness

Compositions (wt. %)					
B	Si	Cr	Ni	Mo	P
20					
10	10				
28		6		6	
6			40		14

•Some Amorphous Ferrous Alloys

NONFERROUS ALLOYS

Nonferrous Alloys

- **Cu Alloys**

Brass : Zn is prime impurity (costume jewelry, coins, corrosion resistant)

Bronze : Sn, Al, Si, Ni are prime impurities (bushings, landing gear)

Cu-Be precipitation-hardened for strength

- **Al Alloys**

-lower ρ: 2.7g/cm^3
-Cu, Mg, Si, Mn, Zn additions
-solid solutions or precipitation strengthened (structural aircraft parts & packaging)

- **Mg Alloys**

-very low ρ: 1.7g/cm^3
-ignites easily
-aircraft, missiles

- **Ti Alloys**

-lower ρ: 4.5g/cm^3 vs 7.9 for steel
-reactive at high T
-space applications

- **Noble metals**

-Ag, Au, Pt
- oxidation/corrosion resistant

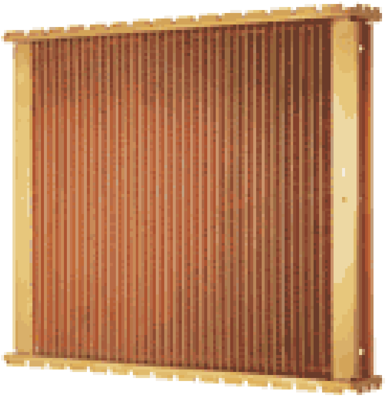
- **Refractory metals**

-high melting T
-Nb, Mo, W, Ta

Cooper and its Alloys

- Cooper: soft and ductile; unlimited cold-work capacity, but difficult to machine.
- Cold-working and solid solution alloying
- Main types of Copper Alloys:
  - ***Brasses***: <u>*zinc*</u> (Zn) is main substitutional impurity; applications: cartridges, auto-radiator. Musical instruments, coins
  - ***Bronzes***: tin (Sn), aluminum (Al), Silicon (Si) and nickel (Ni); stronger than brasses with high degree of corrosion resistance
  - ***Heat-treated*** (precipitation hardening) ***Cu-alloys***: <u>beryllium coopers</u>***;***

  relatively high strength, excellent electrical and corrosion properties BUT expensive; applications: jet aircraft landing gear bearing, surgical and dental instruments.



- Copper's advantages as primary metal and recycled metal, for brazed, long-life radiators and radiator parts for cars and trucks:

Aluminum and its Alloys

- Low density (~2.7 g/cm^3), high ductility (even at room temperature), high electrical and thermal conductivity and resistance to corrosion BUT law melting point (~660°C)
- Main types of Aluminum Alloys:
  - *Wrought* Alloys
  - *Cast* Alloys
  - Others: e.g. ***Aluminum-Lithium*** Alloys
- Applications: form food/chemical handling to aircraft structural parts

Typical alloying elements and alloy designation systems for Aluminum Alloys

Numerals	Major Alloying Element(s)
1XXX	None (>99.00 %Al)
2XXX	Cu
3XXX	Mn
4XXX	Si
5XXX	Mg
6XXX	Mg an Si
7XXX	Zn
8XXX	Other elements (e.g. Li)

Temper designation systems for Aluminum Alloys

Temper	Definition
F	As fabricated
O	Annealed
H1	Strain-hardened only
H2	Strain-hardened and partially annealed
H3	Strain-hardened and stabilized
T1	Cooled from elevated-T shaping and aged
T2	Cooled from elevated-T shaping, cold-work, aged
T3	Solution heat-treat., cold-work, naturally aged
T4	Solution heat-treat and naturally aged
T5	Cooled from elevated-T shaping, artificially aged
T6	Solution heat-treat. and artificially aged
T7	Solution heat-treat and stabilized
T8	Solution heat-treat, cold-work, artificially aged
T9	Solution heat-treat, artificially aged, cold-work

Magnesium and its Alloys

Formula 1
Gearbox Casting

- **Key Properties:**
- Light weight
  - Low density (1.74 g/cm^3 two thirds that of aluminium)
  - Good high temperature mechanical properties
  - Good to excellent corrosion resistance
- Very high strength-to density ratios (***specific strength***)
- In contrast with Al alloys that have fcc structure with (12) slip systems and thus high ductility, hcp structure of Mg with only three slip systems leads to its brittleness.

- Applications: from tennis rockets to aircraft and missiles

  Example: Aerospace

  RZ5 (Zn 3.5 - 5,0 SE 0.8 - 1,7 Zr 0.4 - 1,0 Mg remainder), MSR (AG 2.0 - 3,0 SE 1.8 - 2,5Zr 0.4 - 1,0 Mg remainder) alloys are widely used for aircraft engine and gearbox casings. Very large magnesium castings can be made, such as intermediate compressor casings for turbine engines. These include the Rolls Royce Tay casing in MSR, which weighs 130kg and the BMW Rolls Royce BR710 casing in RZ5. Other aerospace applications include auxiliary gearboxes (F16, Euro-fighter 2000, Tornado) in MSR or RZ5, generator housings (A320 Airbus, Tornado and Concorde in MSR) and canopies, generally in RZ5.

Titanium and its Alloys (1)

- ***Titanium and its alloys*** have proven to be technically superior and cost-effective materials of construction for a wide variety of aerospace, industrial, marine and commercial applications.
- The ***properties and characteristics*** of titanium which are important to design engineers in a broad spectrum of industries are:

  - **Excellent Corrosion Resistance:** Titanium is immune to corrosive attack by salt water or marine atmospheres. It also exhibits exceptional resistance to a broad range of acids, alkalis, natural waters and industrial chemicals.
  - **Superior Erosion Resistance:** Titanium offers superior resistance to erosion, cavitation or impingement attack. Titanium is at least twenty times more erosion resistant than the copper-nickel alloys.
  - **High Heat Transfer Efficiency:** Under "in service" conditions, the heat transfer properties of titanium approximate those of admiralty brass and copper-nickel.

Other Alloys

- ***<u>The Refractory Metals</u>***: **Nb** (m.p.=2468°C); **Mo** (°C); **W** (°C); **Ta**(3410°C)
  - Also: large elastic modulus, strength, hardness in wide range of temperatures
  - Applications:

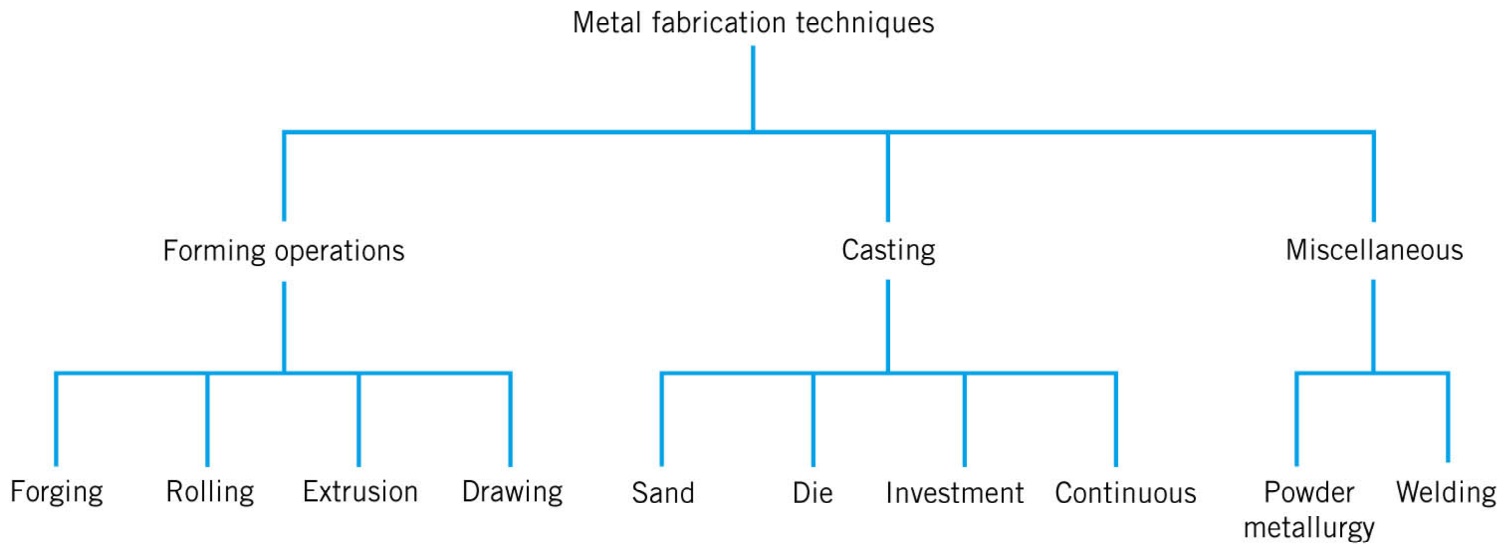
- ***<u>The Super alloys</u>*** – possess the superlative combination of properties
  - <u>Examples:</u>
  - Applications: aircraft turbines; nuclear reactors, petrochemical equipment

- ***<u>The Noble Metal Alloys</u>***: **Ru**(44), **Rh** (45), **Pd** (46), **Ag** (47), **Os** (75), **Ir** (77), **Pt** (78), **Au** (79)
  - expensive are notable in properties: soft, ductile, **oxidation resistant**
  - **Applications:** jewelry (Ag, Au, Pt), catalyst (Pt, Pd, Ru), thermocouples (Pt, Ru), dental materials etc.

- ***<u>Miscellaneous Nonferrous Alloys</u>***:
  - **Nickel** and **its alloy**: high corrosion resistant (<u>Example</u>: monel – 65Ni/28Cu/7wt%Fe – pumps valves in aggressive environment)
  - ***Lead, tin*** and ***their alloys***: soft, low recrystallization temperature, corrosion resistant (Applications: solders, x-ray shields, protecting coatings)

Fabrication of Metals

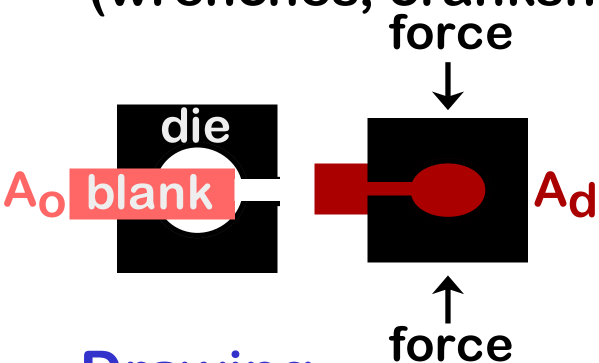
- Fabrication methods chosen depend on:
  - properties of metal
  - size and shape of final piece
  - cost



METAL FABRICATION METHODS-I

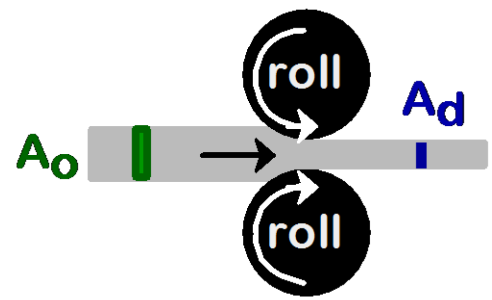
FORMING CASTING JOINING

- **Forging**
  (wrenches, crankshafts)

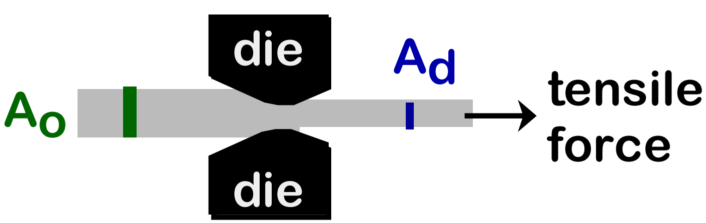


often at elev. T

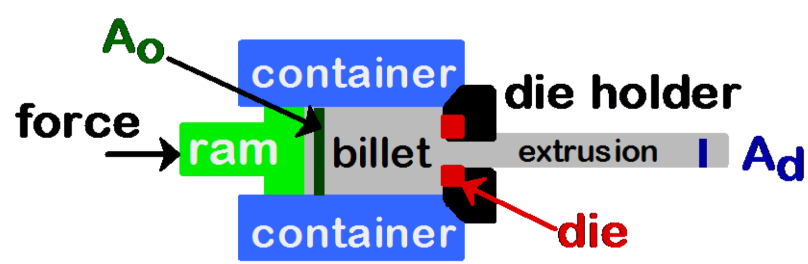
- **Rolling**
  (I-beams, rails)



- **Drawing**
  (rods, wire, tubing)



- **Extrusion**
  (rods, tubing)



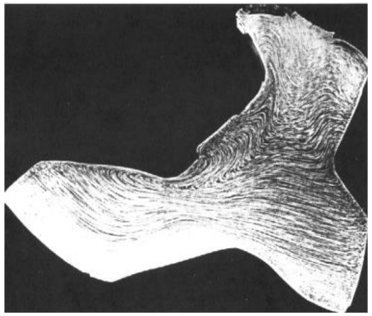
FORMING TEMPERATURE

- Hot working: deformation
  at T > T(recrystallization)
  + less energy to deform
  + large repeatable deform.
  - surface oxidation: poor finish

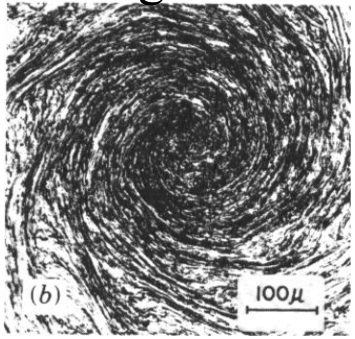
- Cold working: deformation
  at T < T (recrystallization)
  + higher quality surface
  + better mechanical properties
  + closer dimension control
  - expensive and inconvenient

- Cold worked microstructures
  --generally are very anisotropic!

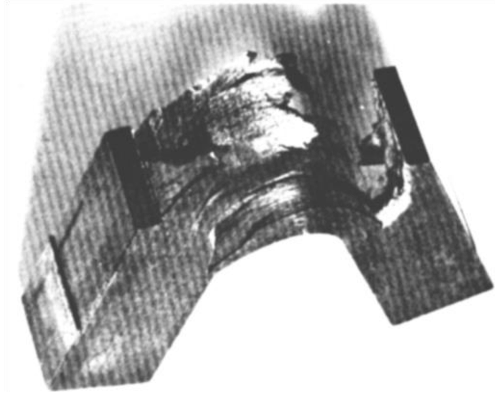
--Forged



--Swaged



--Fracture resistant!



Extrusion and Rolling

- The advantages of extrusion over rolling are as follows:

  - Pieces having more complicated cross-sectional geometries may be formed.

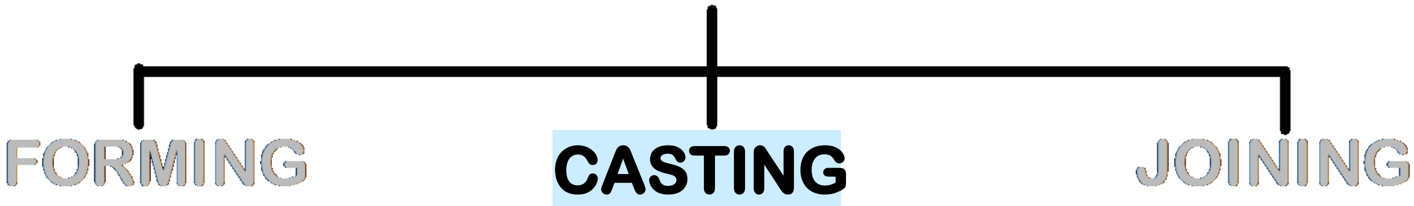
  - Seamless tubing may be produced.

- The disadvantages of extrusion over rolling are as follows:

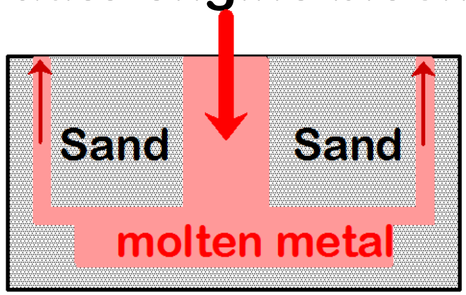
  - Nonuniform deformation over the cross-section.

  - A variation in properties may result over the cross-section of an extruded piece.

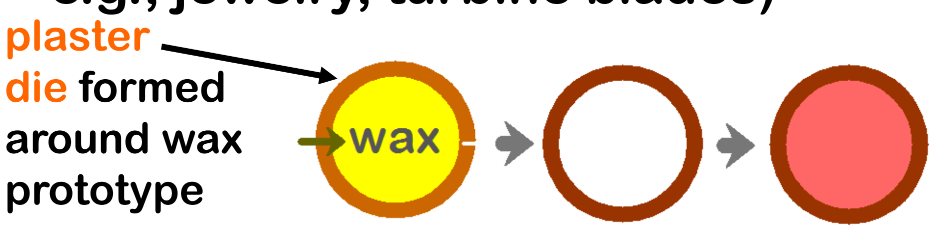
METAL FABRICATION METHODS-II



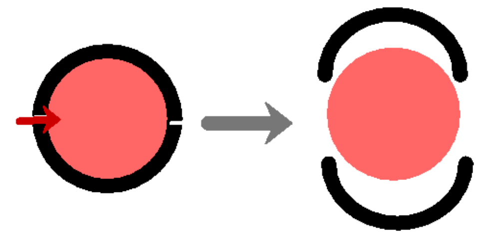
- **Sand Casting**
  (large parts, e.g., auto engine blocks)



- **Investment Casting**
  (low volume, complex shapes e.g., jewelry, turbine blades)



- **Die Casting**
  (high volume, low T alloys)



- **Continuous Casting**
  (simple slab shapes)

Casting

- The ***situations*** in which casting is the preferred fabrication technique are:
  - For large pieces and/or complicated shapes.
  - When mechanical strength is not an important consideration.
  - For alloys having low ductility.
  - When it is the most economical fabrication technique.

Different ***casting techniques***:

• **Sand casting**: a two-piece mold made of send is used, the surface finish is not an important consideration, casting rates are low, and large pieces are usually cast.

• **Die casting**: a permanent two-piece mold is used, casting rates are high, the molten metal is forced into the mold under pressure, and small pieces are normally cast.

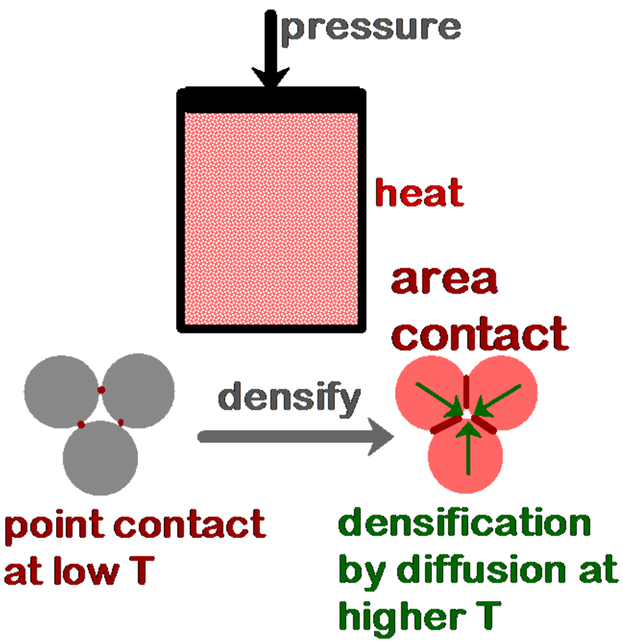
• **Investment casting**: a single-piece mold is used, which is not reusable; it results in high dimensional accuracy, good reproduction of detail, a fine surface finish; casting rates are low.

• **Continuous casting:** at the conclusion of the extraction process, the molten metal is cast into a continuous strand having either a rectangular or circular cross-section; these shapes are desirable for secondary metal-forming operations. The chemical composition and mechanical properties are uniform throughout the cross-section.

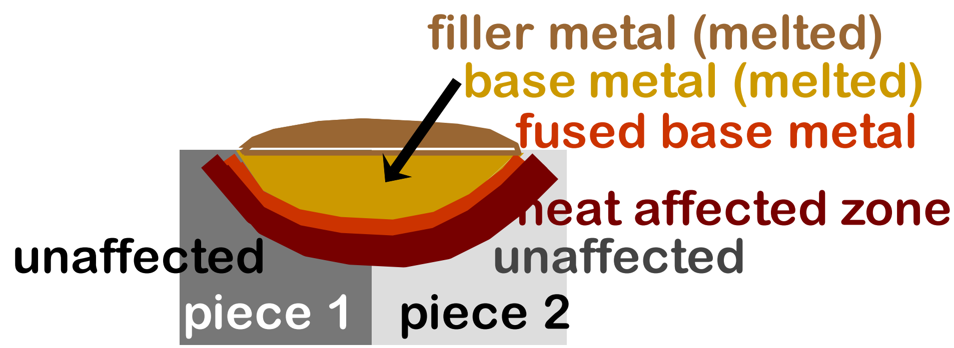
METAL FABRICATION METHODS-III

FORMING | CASTING | **Miscellaneous**

- Powder Processing



- Joining: Welding, brazing, soldering



- **Heat affected zone:**
  (region in which the microstructure has been changed).

Powder Processing

- Some of the advantages of powder metallurgy over casting are as follows:
  - It is used for materials having high melting temperatures.
  - Better dimensional tolerances result.
  - Porosity may be introduced, the degree of which may be controlled (which is desirable in some applications such as self-lubricating bearings).

- Some of the disadvantages of powder metallurgy over casting are as follows:
  - Production of the powder is expensive.
  - Heat treatment after compaction is necessary.

Annealing

Process: heat alloy to T_{Anneal}, for extended period of time then **cool slowly**.
Goals: (1) relieve stresses; (2) increase ductility and toughness; (3) produce specific microstructure

Types of Annealing

- **Stress Relief :**
  To reduce stress caused by:
  -plastic deformation
  -non-uniform cooling
  -phase transform.

- **Spheroidize** (steels):
  Make very soft steels for good machining.
  Heat just below T_E & hold for 15-25h.

- **Full Anneal** (steels):
  Make soft steels for good forming by heating to get γ, then cool in furnace to get coarse P.

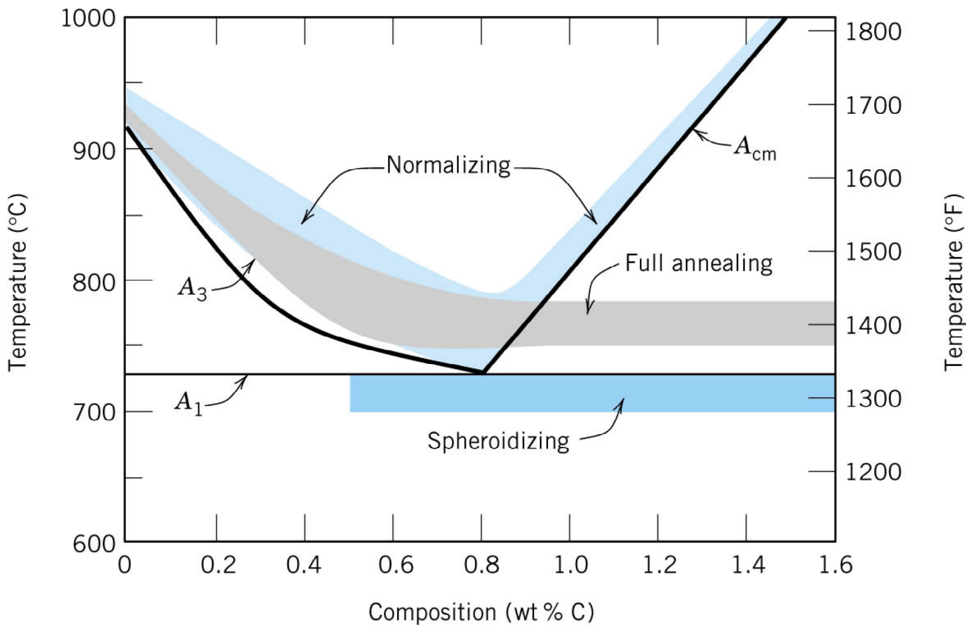
- **Process Anneal:**
  To eliminate negate effect of cold working by recovery/recrystallization

- **Normalize** (steels):
  Deformed steel with large grains heat-treated to make grains small.

Thermal Processing of Metals: Steels

- **Full annealing**:

Heat to between 15 and 40°C above the **A3** line (if the concentration of carbon is less than the eutectoid) or above the **A1** line (if the concentration of carbon is greater than the eutectoid) until the alloy comes to equilibrium; then furnace cool to room temperature.
The final microstructure is ***coarse pearlite***.



- **Normalizing:**

Heat to between 55 and 85°C above the upper critical temperature until the specimen has fully transformed to austenite, then cool in air. The final microstructure is ***fine pearlite***.

- **Quenching:**

Heat to a temperature within the austenite phase region and allow the specimen to fully austenite, then quench to room temperature in oil or water. The final microstructure is ***martensite.***

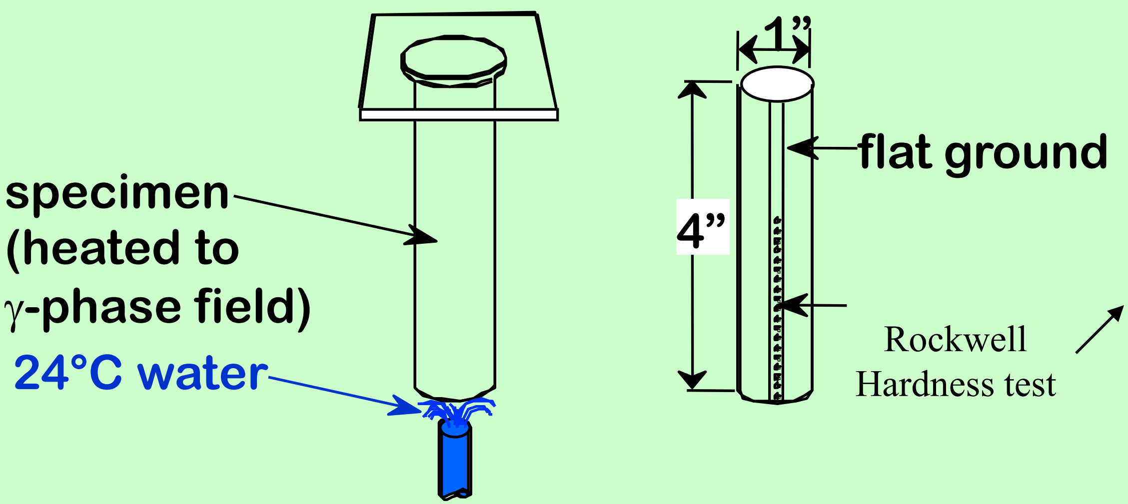
- **Tempering:**

Heat a quenched (martensitic) specimen, to a temperature between 450 and 650°C, for the time necessary to achieve the desired hardness. The final microstructure is ***tempered martensite***.

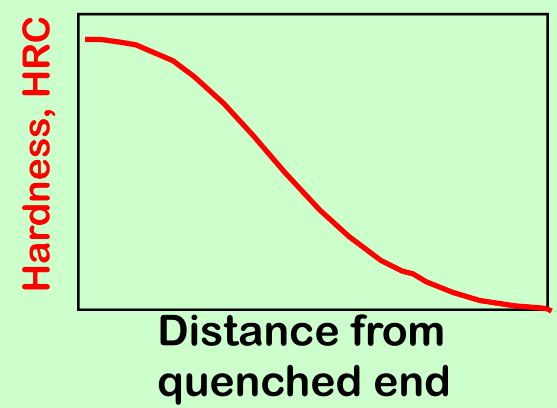
HARDENABILITY: STEELS

- Full annealing and Spheroidizing: to produce ***softer*** steel for good machining and forming
- Normalization: to produce more uniform fine structure that tougher than coarse-grained one
- Quenching: to produce ***harder*** alloy by forming martensitic structure

Jominy end-quenching test

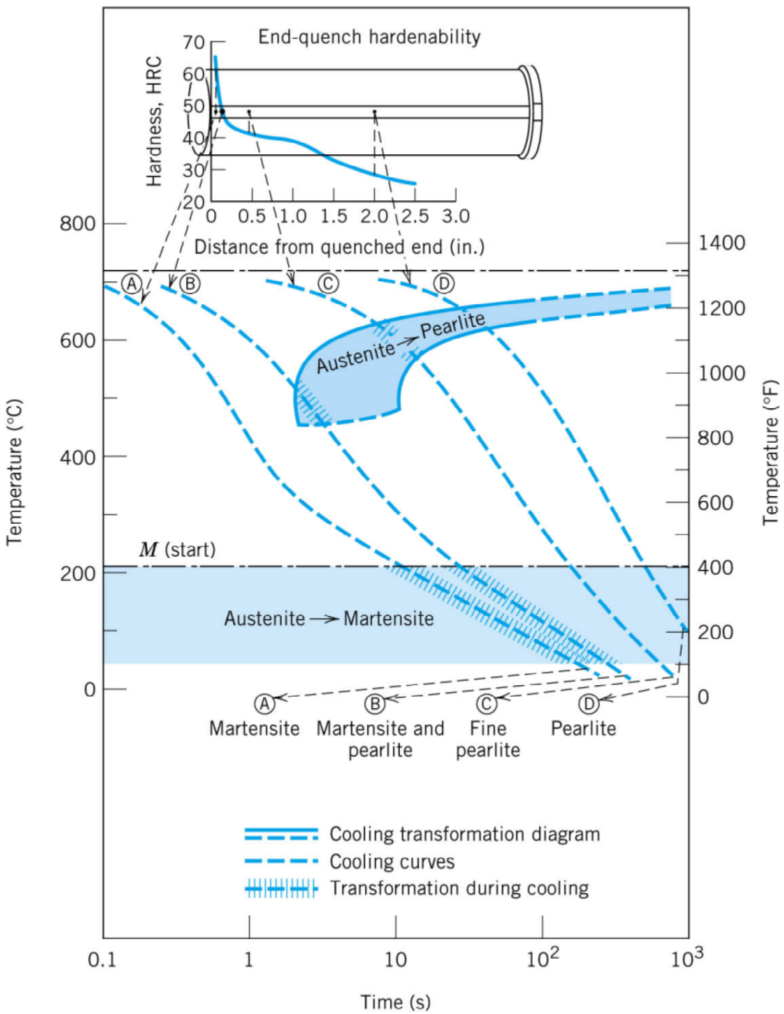


Hardness versus distance from the quenched end



WHY HARDNESS CHANGES W/POSITION?

Because the **cooling rate** varies with position !!



- Note: cooling rates before reaching Austenite – Martensite transformation are in the range 1 -50 C/s
- Measuring cooling rates at every point (e.g. by thermocouples) and finding rates correlations with the hardness one may develop quenching rate – hardness diagram

•But how one can change quenching rate?

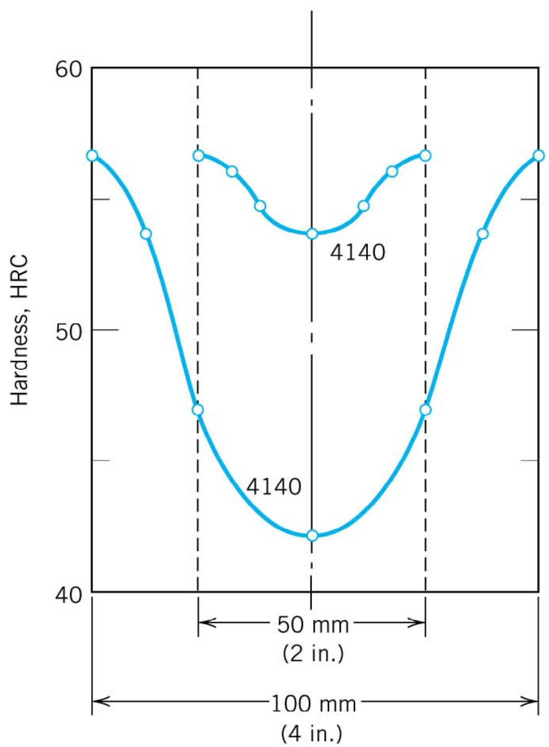
QUENCHING GEOMETRY

- Effect of geometry:

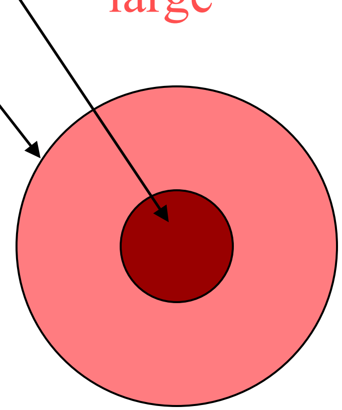
When surface-to-volume ratio increases:

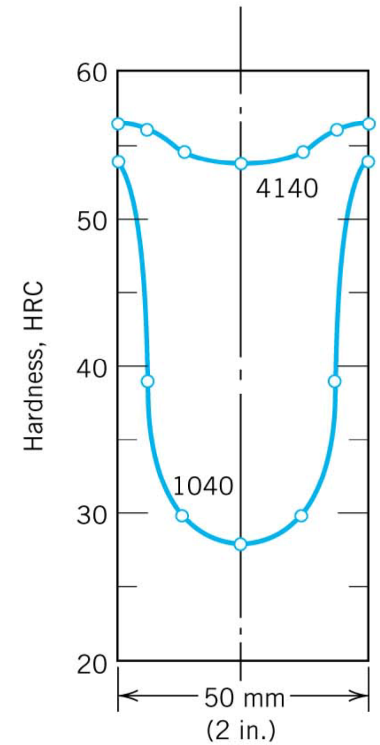
--cooling rate increases

--hardness increases



Position	Cooling rate	Hardness
center	small	small
surface	large	large

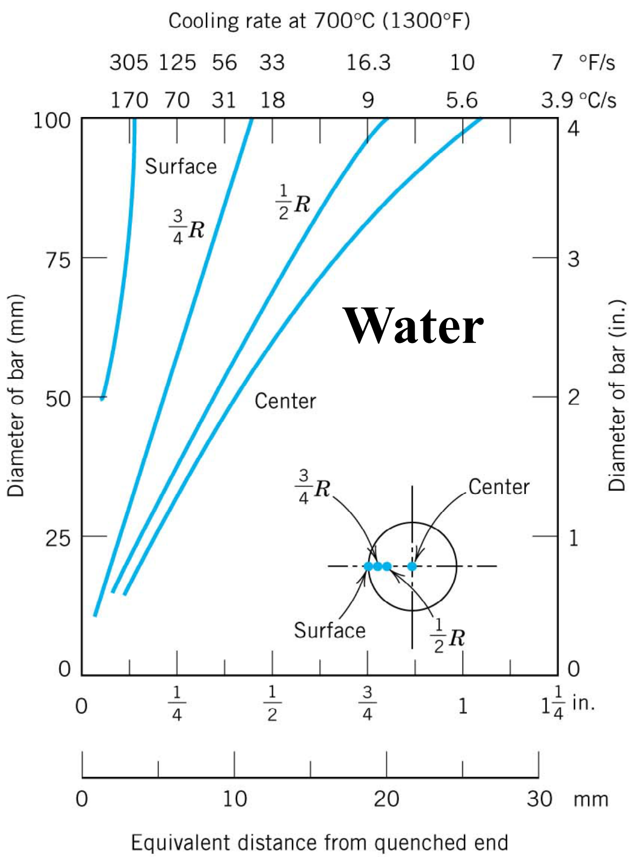


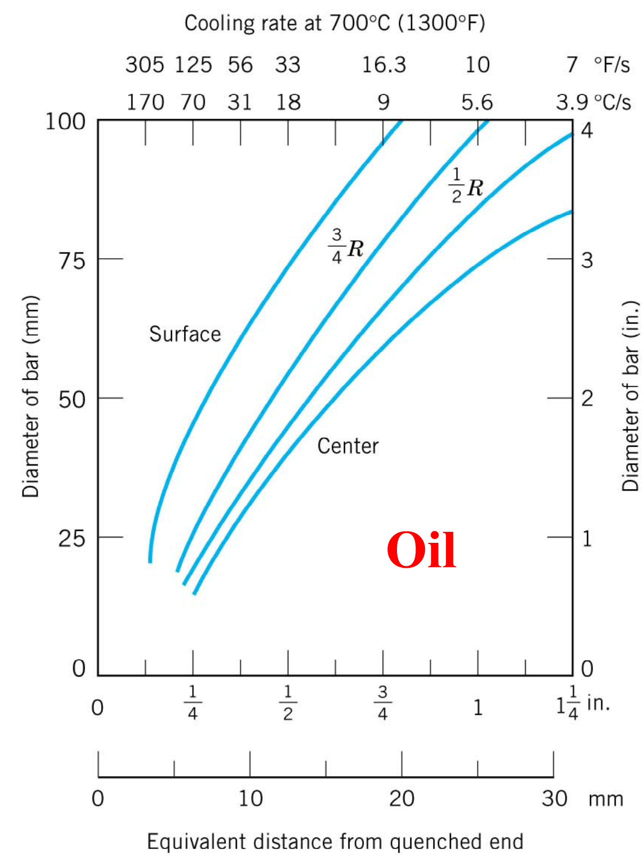


QUENCHING MEDIUM

- Effect of quenching medium:

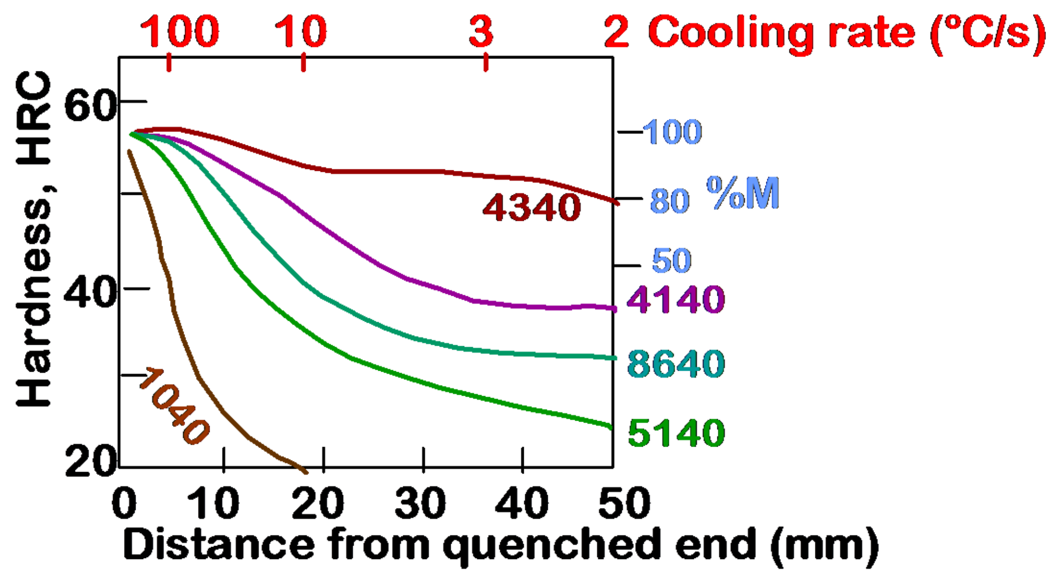
Medium	Severity of Quench	Hardness
air	small	small
oil	moderate	moderate
water	large	large



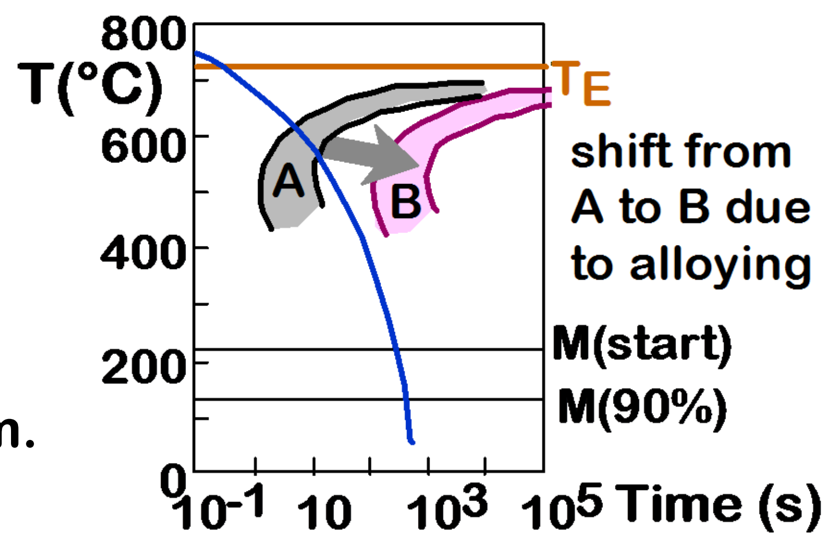


HARDENABILITY VS ALLOY CONTENT

- Jominy end quench results, C = 0.4wt%C

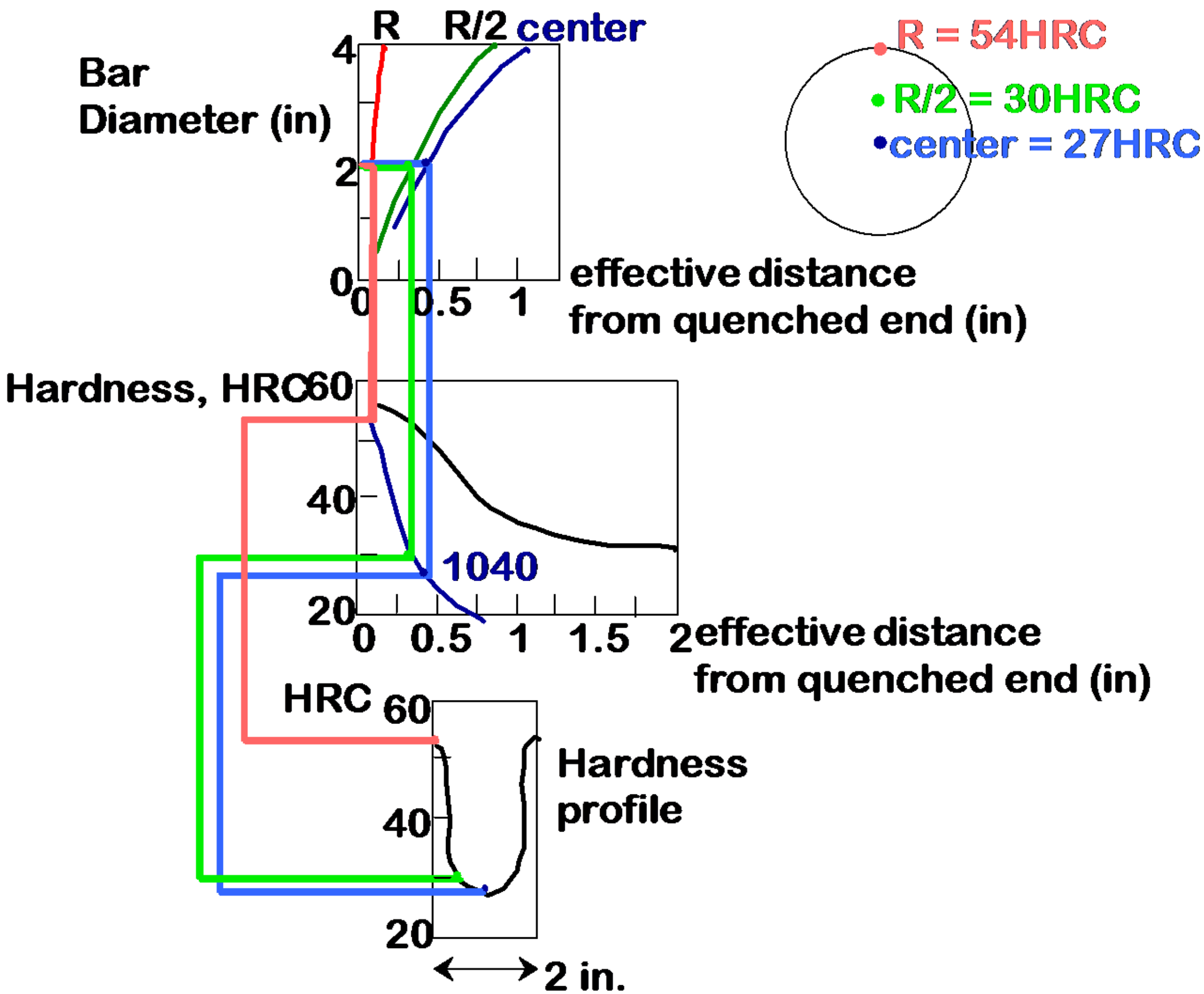


- "Alloy Steels" (4140, 4340, 5140, 8640)
  --contain Ni, Cr, Mo (0.2 to 2wt%)
  --**these elements shift the "nose".**
  --martensite is easier to form.



PREDICTING HARDNESS PROFILES

- Ex: Round bar, 1040 steel, water quenched, 2" diam.



SUMMARY

- Steels: increase TS, Hardness (and cost) by adding
  --C (low alloy steels)
  --Cr, V, Ni, Mo, W (high alloy steels)
  --ductility usually decreases w/additions.

- Non-ferrous:
  --Cu, Al, Ti, Mg, Refractory, and noble metals.

- Fabrication techniques:
  --forming, casting, joining.

- Hardenability
  --increases with alloy content.
- Precipitation hardening
  --effective means to increase strength in
  Al, Cu, and Mg alloys.