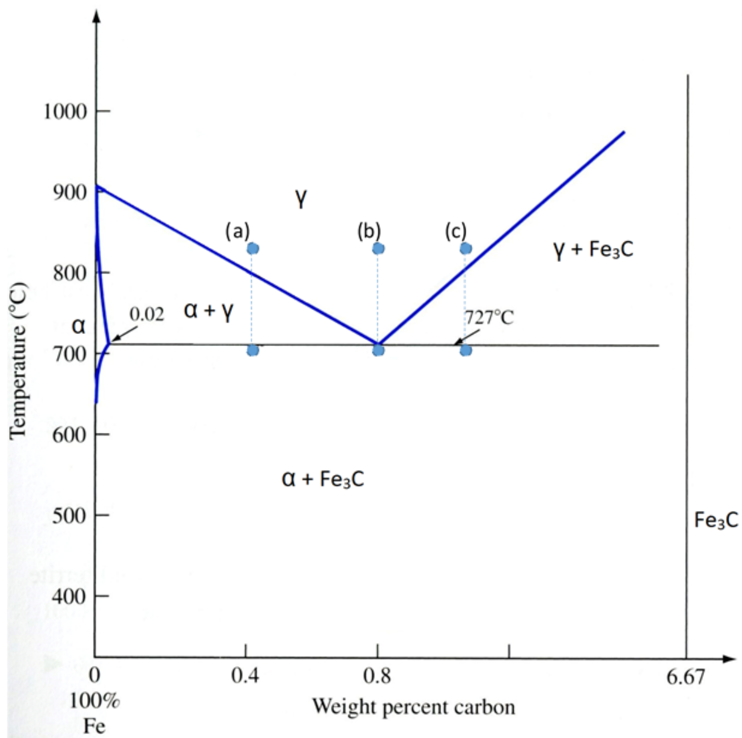
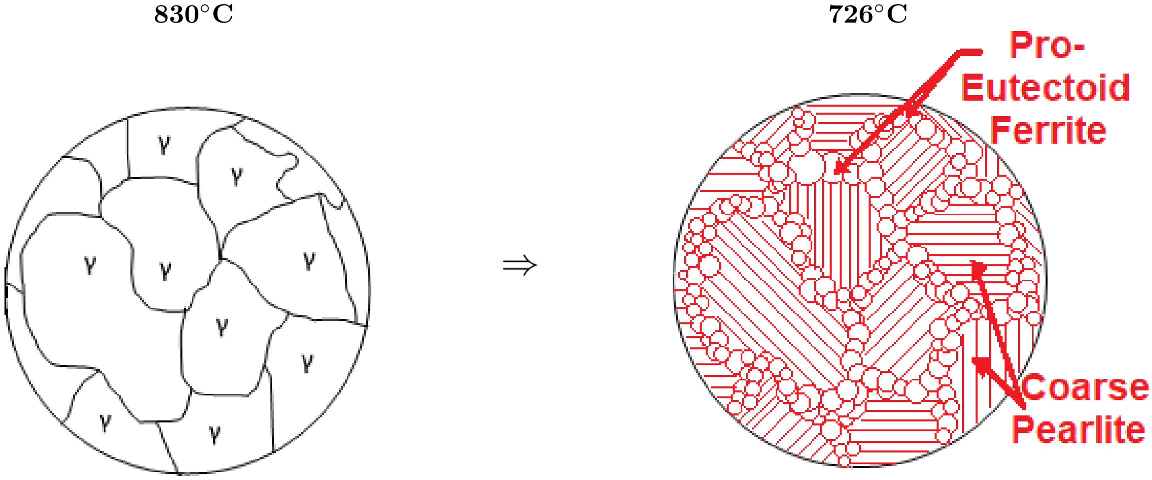
Carbon Steel.

1. [19 *pts*] Three compositions of plain carbon steel are cooled *very slowly in a turned-off furnace* from $\approx 830°C$ (see phase diagram below). For each composition, the FCC grains of $\gamma-$austenite (prior to transformation) are shown in an optical micrograph of the material surface. Sketch and label the phases making up the microstructures present in the right hand micrograph *just after* the austenite has completed transformation (note: the gray outlines of the prior γ grains may prove helpful).



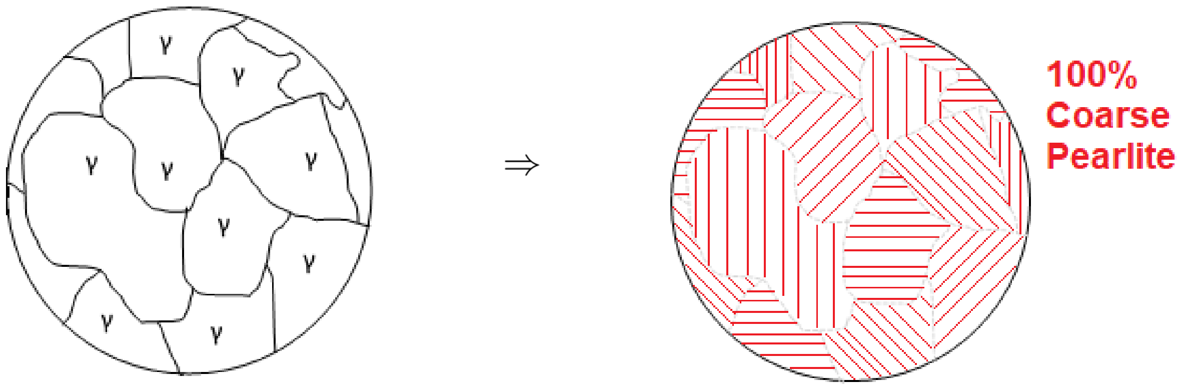
(a) [4 *pts*] $C_0 = 0.42\%\ C$ (by wt).

830°C **726°C**



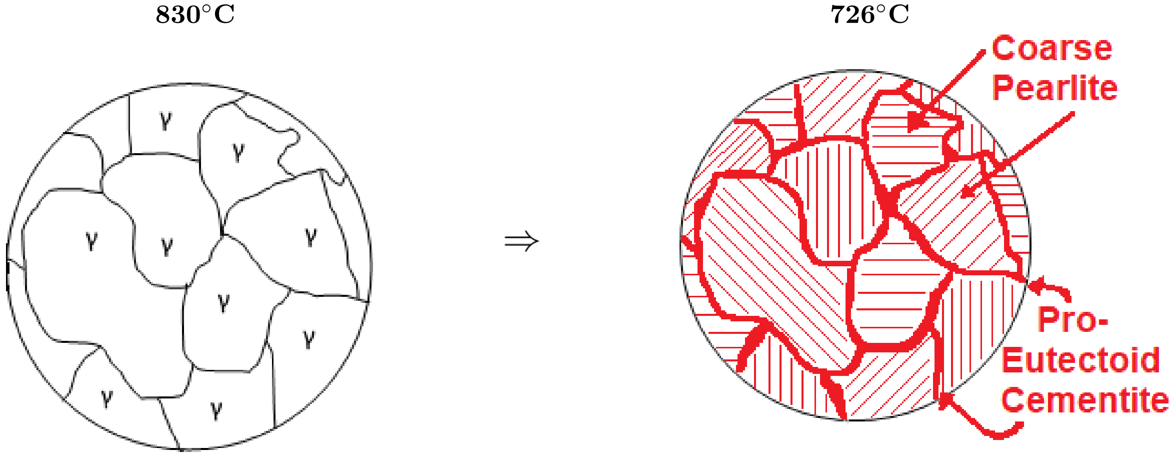
(b) [4 *pts*] $C_0 = 0.80\% \, C$ (by wt).

830°C **726°C**



(c) [4 *pts*] $C_0 = 1.05\% \, C$ (by wt).

830°C **726°C**



(d) [7 *pts*] For the composition of part (c), $C_0 = 1.05\% \, C$ (by wt), calculate the fraction of the solid that is pearlite at $726°C$.

$$W_{pearlite} = W_{\gamma \; at \; 728°C} = \frac{C_{Fe_3C} - C_0}{C_{Fe_3C} - C_\gamma} = \frac{6.67\% - 1.05\%}{6.67\% - 0.8\%} = \underline{\underline{95.74\% \text{ Pearlite}}}$$

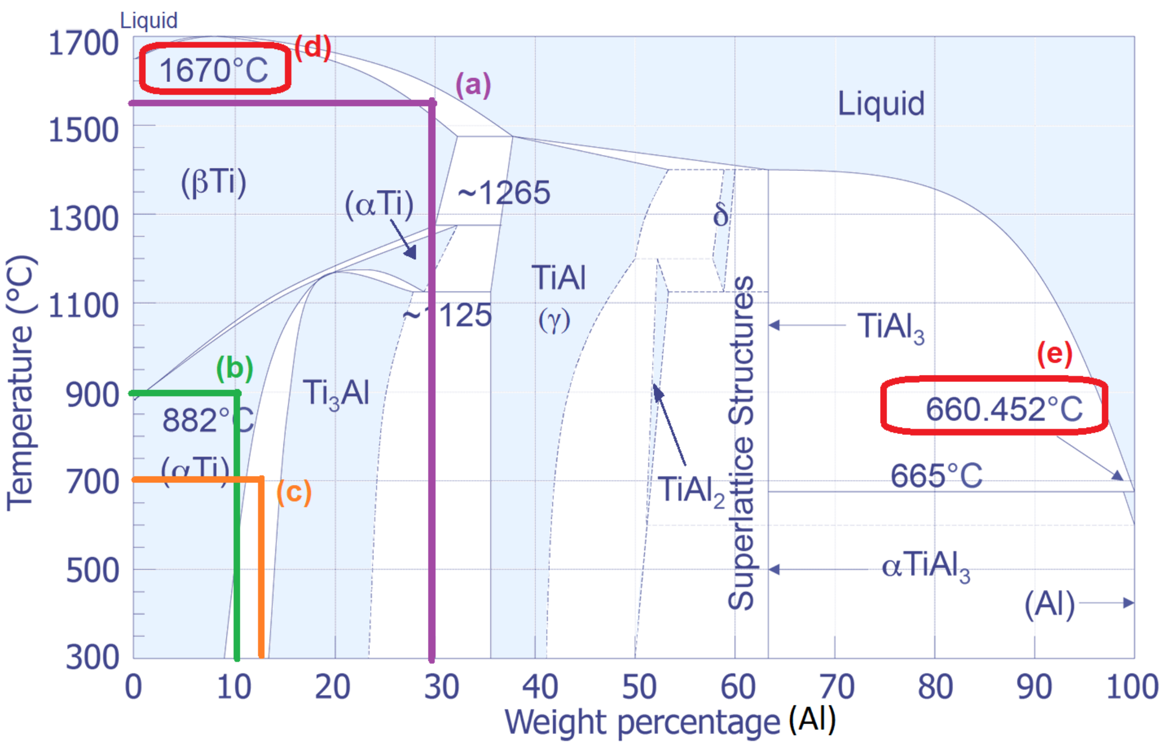
2. [11 *pts*] Write in the correct term for each of the following related to carbon steels[1 *pt* each] (terms will be used exactly once):

This material features carbon content in excess of 2.0% and is known for its excellent hardness, wear resistance, machinability and castability.	Cast Iron
This plain carbon steel composition contains 0.8% concentration Carbon by wt.	Eutectoid Steel
This plain carbon steel composition contains $< 0.8\%$ concentration Carbon by wt.	Hypo-eutectoid Steel
This plain carbon steel composition contains $> 0.8\%$ and $< 2.0\%$ concentration Carbon by wt.	Hyper-eutectoid Steel
This term describes a phase (such as α or Fe_3C, for steel) that is formed before undergoing a (i.e. at higher temperatures than) single-solid-phase-to-multiple-solid-phases transformation.	Pro-eutectoid
This cabon steel phase is present at elevated temperatures and takes the FCC crystal form.	Austenite (γ)
This carbon steel phase is present at room temperatures and takes the BCC crystal form.	Ferrite (α)
This unstable carbon steel microstructure only forms at temperatures below $\approx 205°C$ and takes the BCT (Body-Centered-Tetragonal) crystal in needle-like microstructure (with α).	Martensite
This carbon steel microstructure features distorted, plate-like formations.	Bainite
This carbon steel microstructure features alternating bands (called lamella) of α and Fe_3C.	Pearlite
This is the name of the intermetallic compound (carbide) comprising three moles of Iron to each mole of Carbon.	Cementite

Cementite	Austenite (γ)	Pro-eutectoid	Eutectoid Steel
Pearlite	Bainite	Ferrite (α)	Martensite
Cast Iron	Hypo-eutectoid Steel	Hyper-eutectoid Steel	

Binary Alloys.

3. [25 pts] Below is the (excessively busy!!!) Titanium-Aluminum ($Ti - Al$) Binary Phase Diagram. Fear not - you have all the tools you need to draw some insights on this alloy system. Note: where possible, shading has been added to single phase regions of the diagram for clarity.



(a) [2 pts] List the equillibrium phase(s) present at 30% Al and 1550°C. Liquid + $\beta\, Ti$

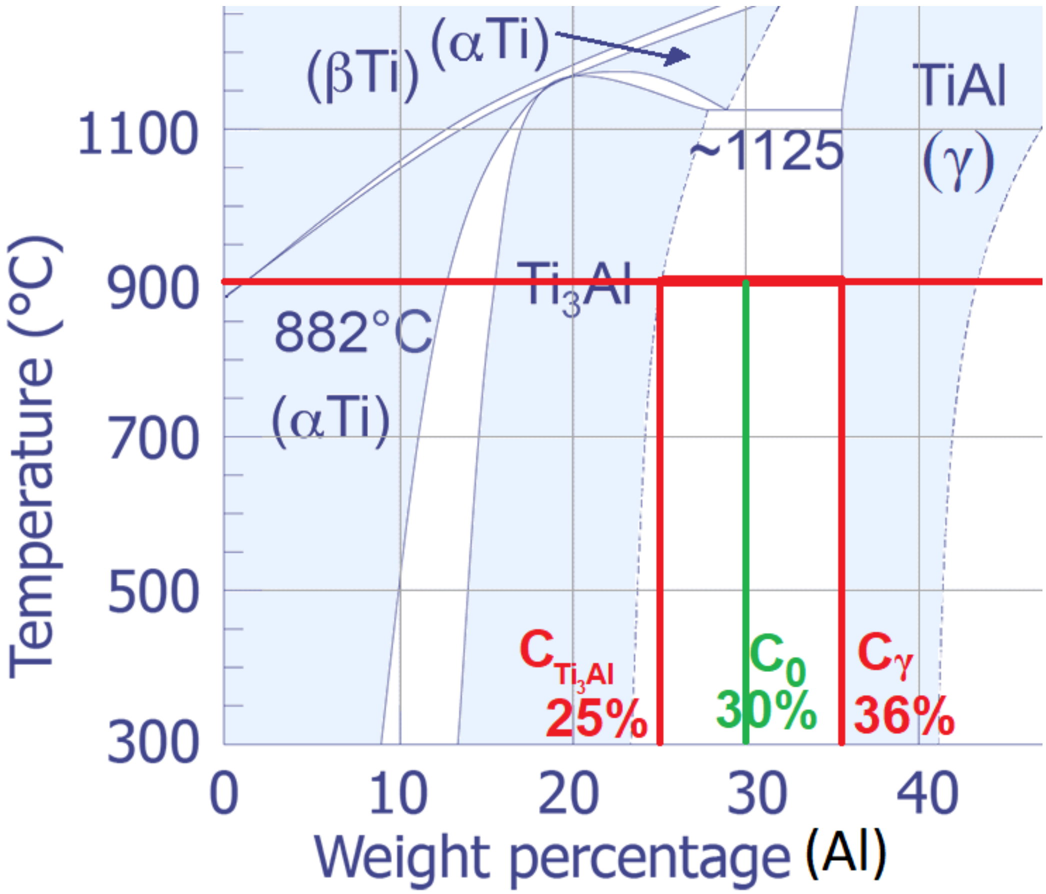
(b) [2 pts] List the equillibrium phase(s) present at 10% Al and 900°C. $\alpha\, Ti$

(c) [2 pts] List the equillibrium phase(s) present at 12.5% Al and 700°C. $\alpha\, Ti + Ti_3Al$

(d) [2 pts] What is the melting point of pure Titanium? 1670°C

(e) [2 pts] What is the melting point of pure Aluminum? 660.452°C

(f) [15 *pts*] 70% Ti (by weight) is held at 900°C for a *very* long time to produce a mixture of $TiAl\,(\gamma)$ and Ti_3Al phases. Answer the following (and mark up the below *enlarged* phase diagram to show your work).



i. [2.5 *pts*] What is the Aluminum content (% by wt) of the $TiAl\,(\gamma)$ phase at this temperature?

$C_\gamma = 36\%$

ii. [2.5 *pts*] What is the Aluminum content (% by wt) of the Ti_3Al phase at this temperature?

$C_{Ti_3Al} = 25\%$

iii. [5 *pts*] What fraction of the solid is in the $TiAl\,(\gamma)$ phase?

$$W_\gamma = \frac{C_0 - C_{Ti_3Al}}{C_\gamma - C_{Ti_3Al}} = \frac{30\% - 25\%}{36\% - 25\%} = 45.45\%$$

iv. [5 *pts*] What fraction of the solid is in the Ti_3Al phase?

$$W_{Ti_3Al} = 1 - W_\gamma = \frac{C_\gamma - C_0}{C_\gamma - C_{Ti_3Al}} = \frac{36\% - 30\%}{36\% - 25\%} = 54.55\%$$

Crystalline Structure.

4. [10 pts] For elemental Gold (Au), $r = 0.144\,nm$, find:

   (a) [2pts] The lattice constant, a in [nm] (Au takes the FCC crystal structure at room temperature).

$$a_{FCC} = \frac{4r}{\sqrt{2}} = \frac{4 \cdot 0.144\,nm}{\sqrt{2}} = \underline{\underline{0.4073\,nm}}$$

   (b) [2 pt] The cell volume, $\forall_{cell}$ in [nm^3].

$$\forall_{cell} = a^3 = (0.4073\,nm)^3 = \underline{\underline{6.7565 \times 10^{-2}\,nm^3}}$$

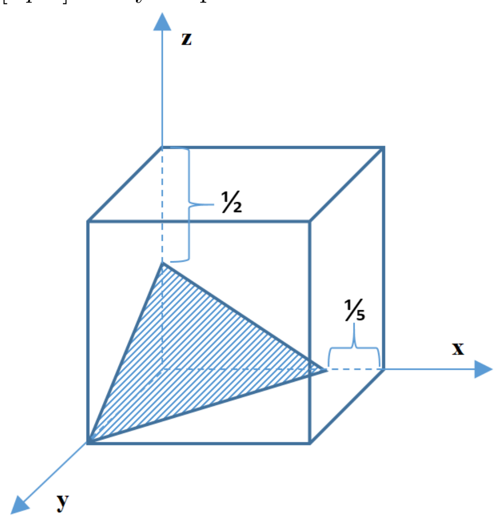
   (c) [2 pts] The number of atoms in the unit cell (show your work!).

   For FCC, we have: $\frac{1}{8}$ atom at each of 8 corners + $\frac{1}{2}$ atom at each of 6 faces: $\frac{1}{8} \cdot 8 + \frac{1}{2} \cdot 6 = \underline{\underline{4\,\frac{atoms}{cell}}}$

   (d) [4 pts] The atomic packing factor, APF.

$$APF = \frac{\forall_{atoms\ in\ cell}}{\forall_{celll}} = \frac{\#_{atoms/cell} \cdot \frac{4\pi r^3}{3}}{a^3} = \frac{4_{atoms/cell} \cdot \frac{4\pi(0.144\,nm)^3}{3}}{6.7565 \times 10^{-2}\,nm^3} = \underline{\underline{0.74}}$$

5. [5 *pts*] A crystal plane of interest in a cubic structure is depicted below.



What are the Miller Indices for this plane (show your work)?

Plane doesn't pass through origin

Intercepts:

x	y	z
$\frac{4}{5}$	1	$\frac{1}{2}$
Take reciprocals:		
$\frac{5}{4}$	1	2
Simplify (multiply by LCD = 4):		
5	4	8
Place in parentheses:		

$\underline{\underline{(\,5\,4\,8\,)}}$

Material Processing

6. [10 pts] Describe in your own words:

   (a) [3pts] The fabrication processes of casting and forging. Which produces a part with more uniform mechanical properties? Which results in a tougher part?

   In casting, we pour molten metal into a mold to form the desired shape.

   In forging, we heat up the solid metal and beat/hammer/press the material into its final shape.

   Casting allows for more uniform cooling resulting in more uniform mechanical properties.

   Forging makes for a tougher part as a result of selectively strengthing some, but not all, of the material.

   (b) [2 pts] Why we case harden low carbon steel (what is the advantage). What is the relationship between diffusivity, D, and the required processing time, t?

   Case hardening improves hardness (a surface property) without significantly changing/sacrificing ductility and toughness in the bulk of the material (at depth).

   From Fick's law: $Dt = constant \Rightarrow$ as $D \uparrow, t \downarrow$ (these parameters are inversely proportional).

   (c) [5 pts] A 2 in plate is *cold rolled* to 35% $C.W.$ Calculate the final thickness, t_f.

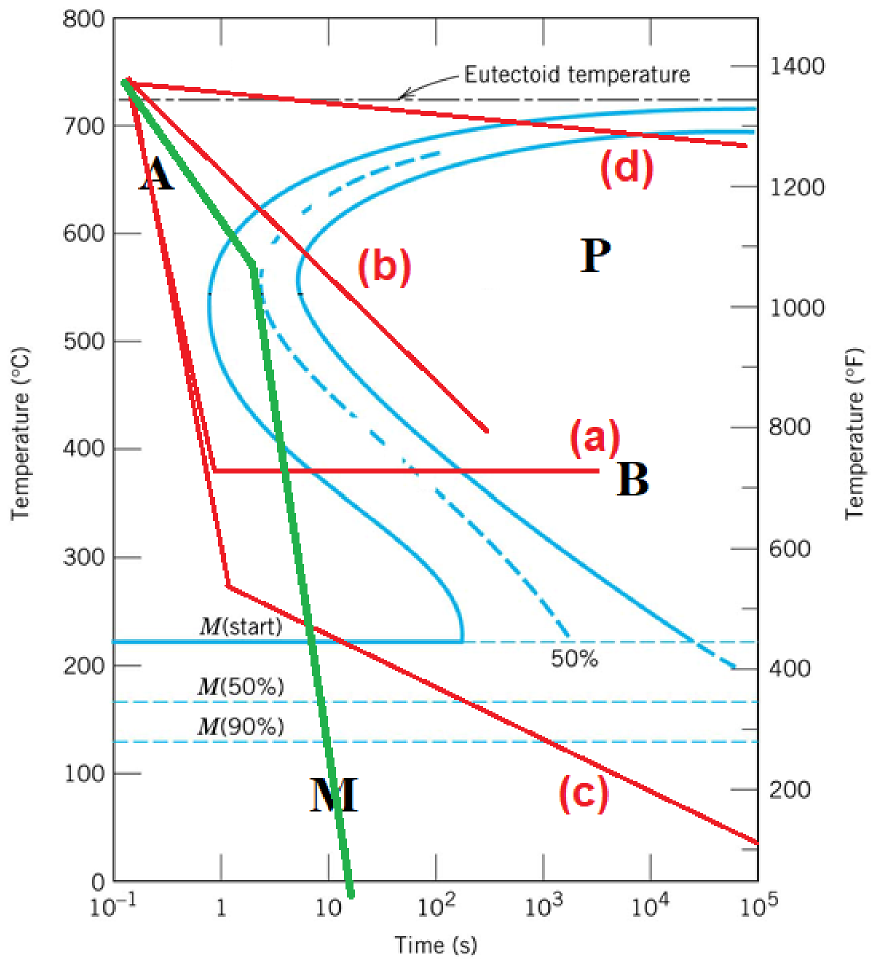
$$Given: \quad \%\,C.W. = 35\%, \quad t_0 = 2\,in$$

$$Find: \quad t_f$$

$$Relationships: \quad \%\,C.W. = \frac{\Delta t}{t_0} = \frac{t_0 - t_f}{t_0}$$

$$\rightarrow t_f = t_0 - \%\,C.W. \cdot t_0 = 2\,in - 0.35 \cdot 2\,in = \underline{\underline{1.3\,in}}$$

7. [10 *pts*] The TTT Diagram below is for a 1080 steel.



(a) [2 *pts*] What is the name for heat treatment (a)?

Austempering

(b) [2 *pts*] What is the resulting microstructure for heat treatment (b)?

Fine pearlite

(c) [3 *pts*] Why does heat treatment (c) change cooling rates at $\approx 275°C$ (what is the main advantage processing in this way)? What is the name for this heat treatment?

Slowing the rate of transformation of the austenite (γ) into martensite reduces the warping present in the finished part.

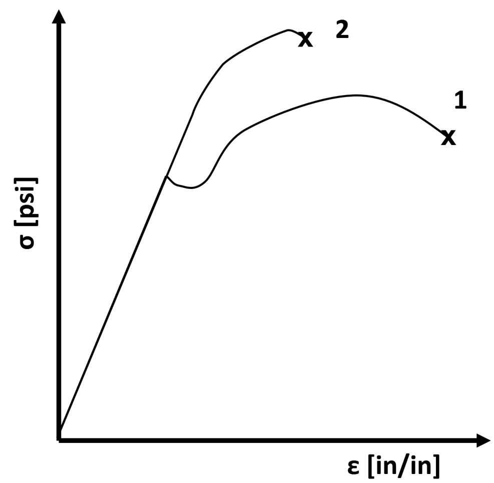
This process is Marquenching/Martempering.

(d) [3 *pts*] On the TTT diagram, draw a new cooling curve that would produce a microstructure of 50% fine pearlite + 50% martensite (start at $\approx 750°C$). Curve shown in green.

8. [10 *pts*] Use the stress strain curves below to answer the following:

(a) [2 *pts*] If the stress-strain curves (1 and 2) at right represent the same material having undergone cold rolling, which curve has been processed the most?

(2)



(b) [2 *pts*] If the stress-strain curves (1 and 2) at right represent 1025 and 1045 plain carbon steel (with the same mechanical processing and heat treatment), which curve is which?

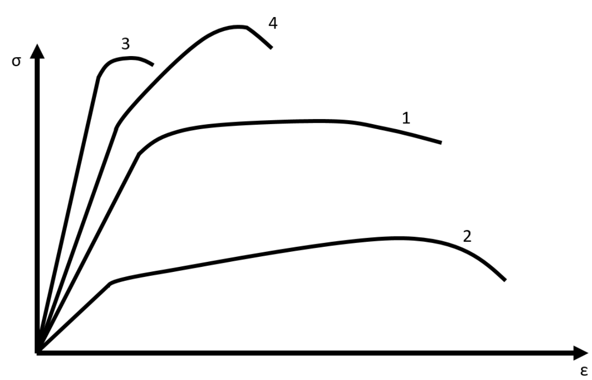
(1) – 1025

(2) – 1045

(c) [2 *pts*] If the stress-strain curves (1 and 2) above represent 1060 carbon steel having undergone different cooling treatments, which curve's material experienced the more rapid cooling rate?

(2)

(d) [4 *pts*] Which material shown at right is:



i. [1 *pt*] Strongest (based on UTS)? (4)

ii. [1 *pt*] Most ductile? (2)

iii. [1 *pt*] Toughest? (1)

iv. [1 *pt*] Stiffest? (3)

XC [10 pts] A crankshaft fabricated from 1020 plain carbon steel is to be case hardened by placing it in a furnace under a methane (CH_4) environment. If the carbon diffusivity at this temperaure is $D = 3.3482143 \times 10^{-11}\ \frac{m^2}{s}$ and the surface carbon concentration in the furnace is 1.25%, calculate the carbon concentration at a depth of 0.3 mm after 70 minutes of carburizing. What microstructure will result when the shaft is removed from the furnace to quench in air (be specific)? Show your work!

1020 steel $\rightarrow C_0 = 0.20\%\, C, \quad x = 3\, mm, \quad t = 70\, min, \quad D = 3.3482143 \times 10^{-11}\ \frac{m^2}{s} \quad C_{surf} = 1.25\%$

$$\frac{C_{surf} - C_x}{C_{surf} - C_0} = erf\,(\overbrace{\frac{x}{2\sqrt{Dt}}}^{z}) \Rightarrow z = \frac{x}{2\sqrt{Dt}} = \frac{0.3 \times 10^{-3}\ m}{2\sqrt{3.3482143 \times 10^{-11}\ \frac{m^2}{s} \cdot 70\ min \cdot \frac{60\ s}{1\ min}}}$$

$$z = 0.400000$$

Interpolating is not required as z falls exactly on the table values

$$\Rightarrow erf(z) = 0.4284$$

$$\Rightarrow \frac{C_{surf} - C_x}{C_{surf} - C_0} = 0.4284 \rightarrow C_x = C_{surf} - (C_{surf} - C_0) \cdot 0.4284 = 1.25\% - (1.25\% - 0.20\%) \cdot 0.4284$$

$\underline{\underline{C_x = 0.800\%\, C \text{ which is the eutectoid composition}}}$

Quenching 0.800% C in air (normalizing) will produce 100% fine pearlite

Error Function (Tabular)

z	erf (z)	z	erf (z)	z	erf (z)
0.000	0.0000	0.550	0.5633	1.300	0.9340
0.025	0.0282	0.600	0.6039	1.400	0.9523
0.050	0.0564	0.650	0.6420	1.500	0.9661
0.100	0.1125	0.700	0.6778	1.600	0.9763
		0.750	0.7112	1.700	0.9838
		0.800	0.7421	1.800	0.9891
		0.850	0.7707	1.900	0.9928
				2.000	0.9953
				2.200	0.9981
0.400	0.4284			2.400	0.9993
0.450	0.4755			2.600	0.9998
0.500	0.5205			2.800	0.9999

Interpolating Unnecessary!

z = 0.400

erf(z) = 0.4284