

METALS

Hardening Mechanisms

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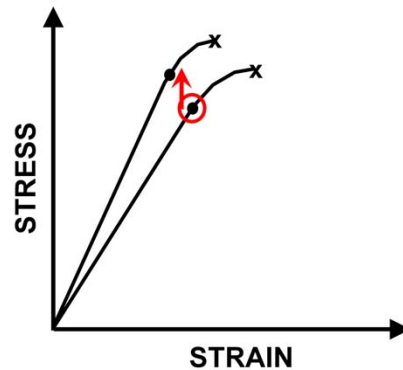
There are a variety of mechanisms which can be used to alter the hardness of materials. These are much easier to understand when considering metals.

INTRODUCTION

Definitions of hardness and hardening.

Hardness = resistance to onset of plastic deformation
= elastic limit

Hardening = increase in the elastic limit.

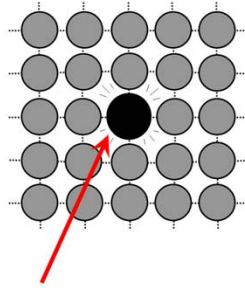


Remember that **HARDNESS** is equivalent to the elastic limit. **[CLICK]** It represents the resistance of the material to the onset of plastic deformation. What we are going to examine next is the events which may occur to increase the hardness. **[CLICK]** This process is called **HARDENING**. **[CLICK]** Quite often the same things that increase the hardness also increase the modulus and make the material more brittle as shown by the second stress-strain curve.

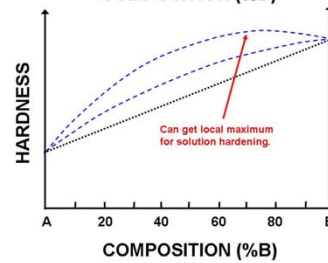
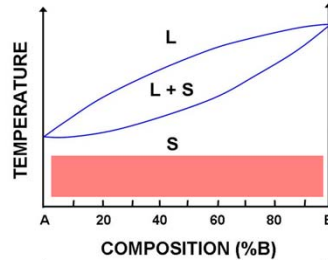
Since properties are always related to structure, a change in properties must be associated with some change in structure. Let's look at the structure in terms of 0-D, 1-D, 2-D, and 3-D mechanisms just in the same way that we looked at different levels of defects in the solid state. The major mechanisms are solid solution hardening (0-D), work hardening (1-D), disorder-order hardening (2-D), and precipitation hardening (3-D). Each of these will be discussed in detail next and then we will put them all together to examine which ones are operational for different alloy choices.

0-D MECHANISM

Solid solution hardening (atomic mechanism).



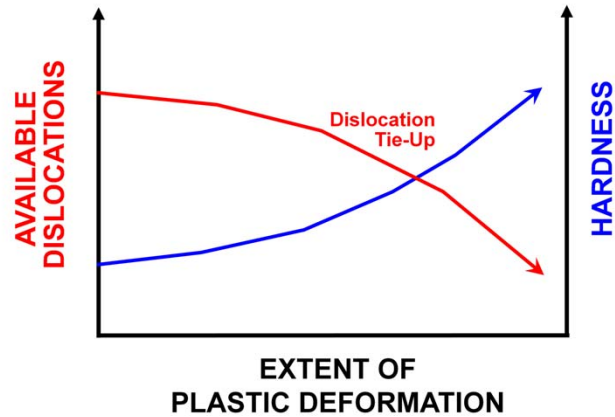
Local strain field from larger-sized atom.



Whenever a different sized atom is added to an otherwise pure material, it creates local strain whether it is bigger or smaller. **[CLICK]** This is called “solid solution hardening.” **[CLICK]** Examine the case for a “complete solid solution.” **[CLICK]** This occurs with any alloy of A-B but not with pure A or pure B. **[CLICK]** The increase in hardness can be minor or large and may produce local maximums based on the crystal structures involved. Except for pure materials, this hardening mechanism is always operational.

1-D MECHANISM

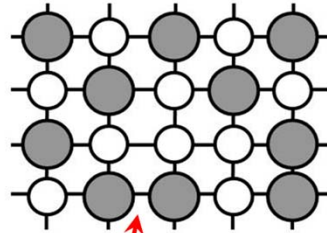
Work hardening (dislocation tie-up).



The extent of plastic deformation possible for many systems depends on the availability of dislocations that can move. **[CLICK]** During plastic deformation, dislocations can run into themselves or grain boundaries and become immobilized. While others can be generated, generally plastic deformation decreases the remaining number and decreases the ability to undergo further plastic deformation. **[CLICK]** The material becomes harder and **[CLICK]** the effect is called WORK HARDENING.

2-D MECHANISM

Disorder-order hardening.



Variations in local strains lead to less than optimal atomic packing fractions.

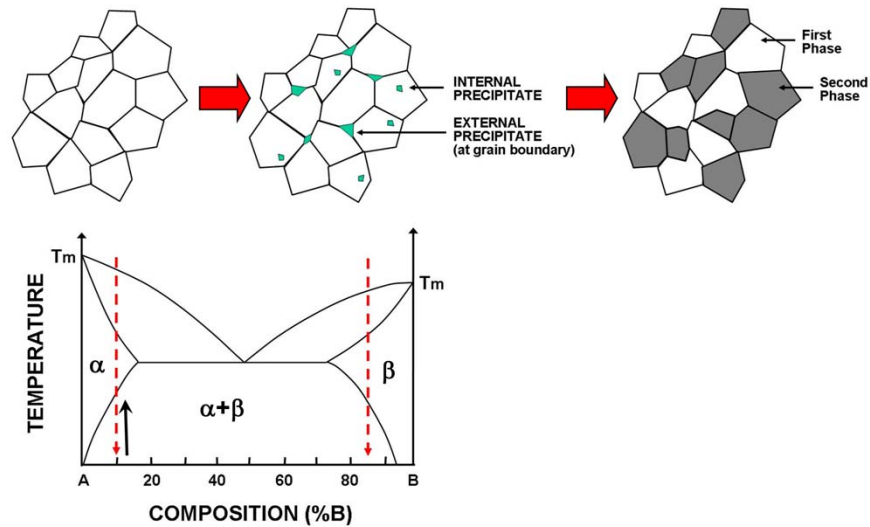


During cooling into the solid state atoms are randomly arranged (i.e., DISORDERED). **[CLICK]** Variations in local strain exist. For certain ratios of atoms, there are opportunities for some orderly arrangements to occur. For example, with equal numbers of A and B atoms, it would produce better packing if they were alternated on lattice points (i.e., ORDERED). **[CLICK]** An ordered arrangement is at a lower energy. It also produces a greater challenge for plastic deformation mechanisms such as dislocation movements. To maintain the arrangement, dislocations need to move through 2 atomic positions at once rather than just through the neighboring position. Thus the material has more resistance to plastic deformation and behaves HARDER.

For Au-Cu alloys, disorder-order hardening is an important mechanism that occurs with 50-50 alloys which are commonly in use in dentistry.

3-D MECHANISM

Precipitation hardening.



The principal mechanism of plastic deformation for many systems, particularly metals, is dislocation motion and it needs to be able to occur in all the grains in a quasi coordinated fashion. If the likelihood of dislocation motion is about the same in all grains, then plastic deformation has no special barriers. **[CLICK]** However, if a second phase is present such as with a two-phase system, the other phase may have fewer dislocations or a more difficult time for them to move through the second phase grains. Therefore, two phase systems are harder than single phase ones.

The second phase may have formed normally during solidification or may appear in a delayed manner after the initial formation of a single phase solid. We will talk more about this in a moment. With rapid cooling it is possible to get only a single phase at first when two phases would like to form. **[CLICK]** Refer to the eutectic diagram and particularly the right and left zones that show alloys that form a single phase at first and then two phases at lower temperatures. By manipulating the solid, you can allow the second phase to start forming later by heating the solid. **[CLICK]** In this case, you are precipitating the second phase from the first phase. **[CLICK]** The new second phase may form from precipitates at the grain boundaries or within in the interior of the grains.

Overall the system is becoming harder due to the appearance of this new phase. This is PRECIPITATION HARDENING. Whether the second phase forms on its own or due to your manipulation, it is called a precipitate and the process is called precipitation hardening.

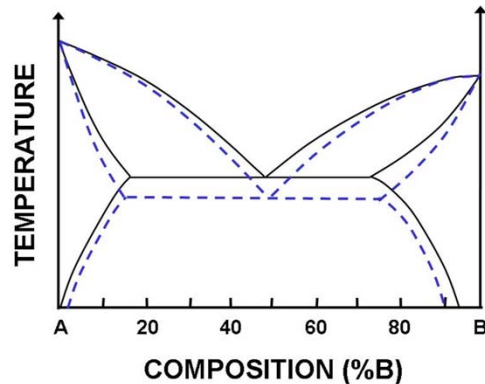
NON-EQUILIBRIUM COOLING

Non-equilibrium phases.

Non-Equilibrium Cooling = cooling too fast to allow equilibrium phases to form.

Quenching = rapid cooling (producing non-equilibrium phases).

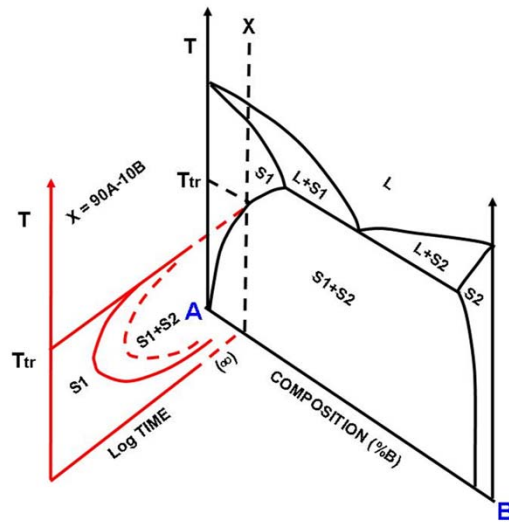
Non-equilibrium Phase Diagram = tracks non-equilibrium phases.



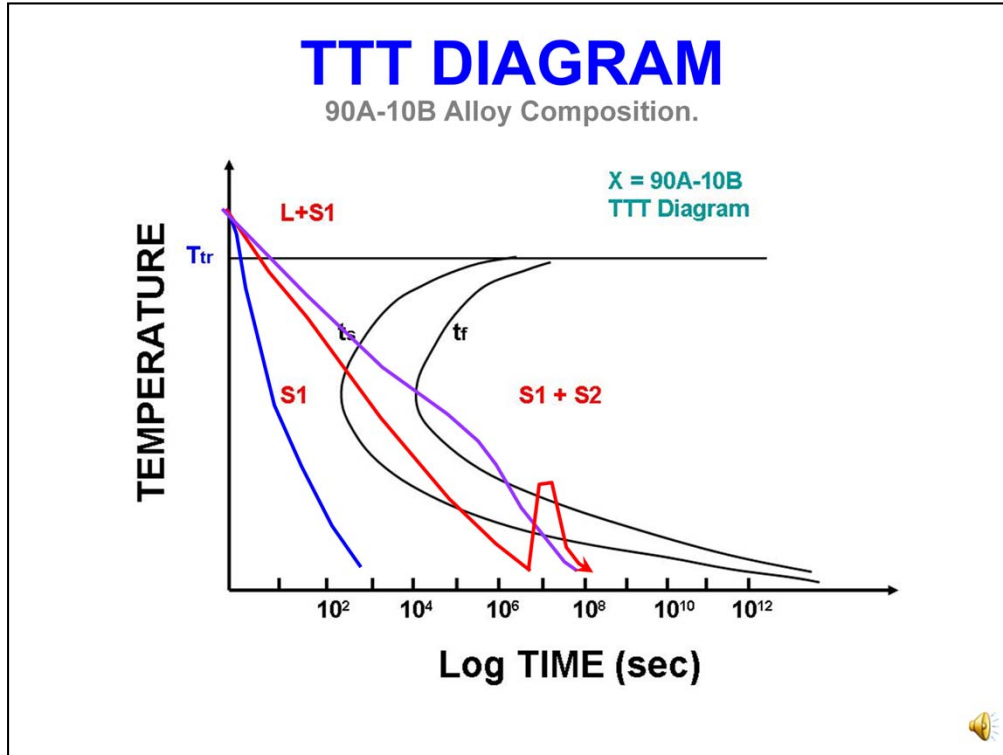
Phase diagrams are wonderful maps of the phases versus temperature. They always presume you cool slowly enough to arrive at the equilibrium phases. **[CLICK]** But what happens if you cool faster than that? **[CLICK]** Often we quench materials and arrive at non-equilibrium phases. **[CLICK]** To know what is going on, you have to create a modified phase diagram. **[CLICK]** Here is an example of one for a eutectic alloy where the dashed blue lines show the new phase boundaries for a particular cooling rate. However, if you change the rate, then you get a new diagram. It is not convenient to create a diagram for every single possible cooling rate. Therefore, instead we just look at a single alloy of interest and track it for all combinations of time and temperature. That will be considered next.

TTT DIAGRAMS

Time-Temperature-Transformation Diagrams.



TTT diagrams are time-temperature-transformation diagrams that track just a single alloy composition for all combinations of time and temperature. The image shown in RED is a TTT DIAGRAM. In this figure of A-B alloys, only the composition labeled as X is being considered. There is TTT diagram that is different for every alloy combination of A-B. The one shown is one of more interesting ones because it involves an alloy undergoing transformation on cooling from liquid (L) to liquid plus solid (L+S1) to a single solid (S1 or α) that then transforms to two solid phases (S1+S2 or $\alpha+\beta$). The most important part of this cooling path is the last transformation from one phase to two phases.



Study the diagram. Temperature is the left-hand axis. Log of time is the bottom axis. Long times (i.e., equilibrium cooling times) are represented by the far-right hand side of the diagram. Zero time is the far left-hand side of the diagram.

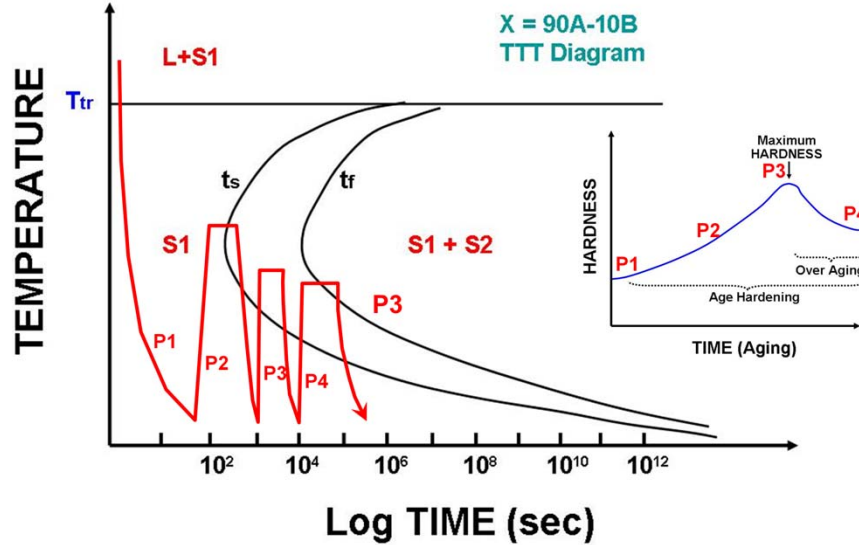
The horizontal line at the top of the diagram separates the end of cooling from L+S1 to form S1. On continued slow cooling, S1 transforms into S1+S2. Those zones are shown to the left and right separated by c-shaped curves which we call C-CURVES. The first curve represents the boundary for transformation of S1 only into S1 and some S2. The second curve represents the boundary for getting to the equilibrium amount of S1 and S2. The c-curves are labeled t_s for transformation start and t_f for transformation finish. Now let's start at the left hand side at high temperature and see what is going on for our 90A-10B alloy.

[CLICK] Shown are 3 different cooling curves. The first one to the left (BLUE) cools relatively rapidly and never crosses the t_s boundary and so no S2 ever starts to form. The second curve (RED) represents slower cooling and crosses the t_s boundary but not the t_f boundary. Some S2 forms but not the equilibrium amount. The third cooling path (PURPLE) represents sufficiently slow cooling that it crosses the t_f path and gets the equilibrium amount of S2 formed. Even though the purple curve at the end crosses back over the 2 c-curves that means nothing because the equilibrium amount of S1+S2 has already formed. It does not revert.

Finally, consider the second curve that has arrived at room temperature with only some of the S2 formed. **[CLICK]** Reheat that material up to an intermediate temperature for a short time and then allow the rest of the S2 to form.

PRECIPITATION HARDENING

Age hardening.



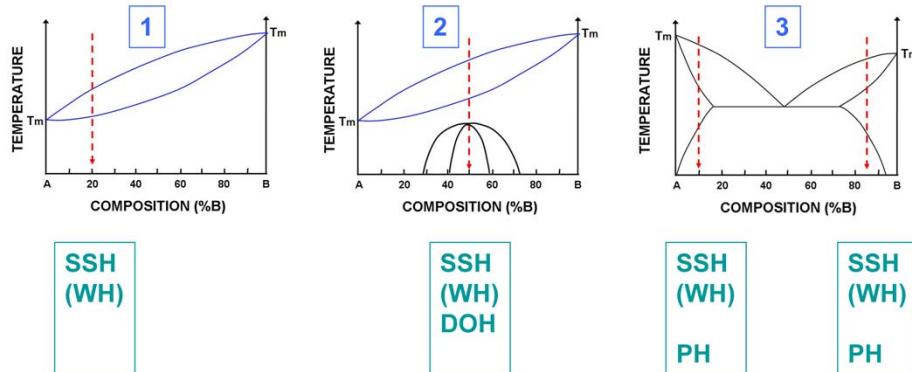
Now let's follow a complex cooling and reheating path and watch what happens. **[CLICK]** P1 represents cooling to room temperature with only the S1 phase forming. P2 represents reheating to allow some S2 to form. P3 represents further reheating to get more S2 to form. Finally P4 reheating allows the equilibrium S2 to finally be achieved. As we go from P1 to P4 we are precipitation hardening the system in a controlled manner.

Interestingly, the equilibrium amount of S2 does not produce the hardest alloy. **[CLICK]** Look at the graph of hardness versus precipitation hardening. Heating to produce property changes is often called aging or age hardening. **[CLICK]** P1's hardness represents no S2 formation. **[CLICK]** P2 represents some S2 formation. **[CLICK]** P3 represents about 60-75% conversion of the equilibrium S2 and creates the hardest system. **[CLICK]** Going beyond that maximum still yields are hardened alloy but not as hard as with P3. Going beyond the maximum is called OVER-AGING.

ANALYSIS OF ALLOYS

What type of hardening mechanisms are operating for different alloys?

SSH = Solid Solution Hardening (0-D)
 WH = work hardening (1-D)
 DOH = disorder-order hardening (2-D)
 PH = precipitation hardening (3-D)



Let's see if you can determine which hardening mechanisms are operating for different alloys (RED) on different phase diagrams (1, 2, 3). **[CLICK]** Here are the hardening mechanisms we just reviewed.

For diagram 1, the hardening mechanism is simply solid solution hardening. **[CLICK]** If you had been told that there was some deformation taking place that could have produced work hardening, then that would have been true as well.

For diagram 2, **[CLICK]** the alloy is solid solution hardened, work hardened only if you are told that it has been plastically deformed, and disorder-order hardened if it is slowly cooled or reheated to transform it. It is only a single phase and so it cannot be precipitation hardened. The small set of domes on this diagram indicate the zones where disorder-order can take place.

For diagram 3, **[CLICK]** both alloys are solution hardened and could be work hardened if plastically deformed. Both are capable of being precipitation hardened if the second phase is partly or completely formed. Neither is disorder-order hardened because of the complexity of the atomic ratios and shifting phase compositions at different temperatures.

QUICK REVIEW

Review of hardening mechanisms.

- **What is HARDENING?**
RAISING THE ELASTIC LIMIT AND MAKING PLASTIC DEFORMATION MORE DIFFICULT.
- **What are the major MECHANISMS of hardening?**
SOLID SOLUTION HARDENING and WORK HARDENING and DISORDER-ORDER HARDENING and PRECIPITATION HARDENING.
- **What diagrams are used to track NON-EQUILIBRIUM phases?**
TIME-TEMPERATURE-TRANSFORMATION (TTT) DIAGRAMS
- **What is OVER-AGING?**
PRECIPITATION HARDENING PAST THE MAXIMUM HARDNESS.
- **What are hardening mechanisms for a EUTECTIC composition alloy?**
SOLID SOLUTION HARDENING and WORK HARDENING (possibly) and PRECIPITATION HARDENING.



Here is a quick review of the concepts from this module.

[CLICK] (1) What is “hardening”?

[CLICK]

[CLICK] (2) What are the major mechanisms of hardening?

[CLICK]

[CLICK] (3) What diagrams are used to track non-equilibrium phases?

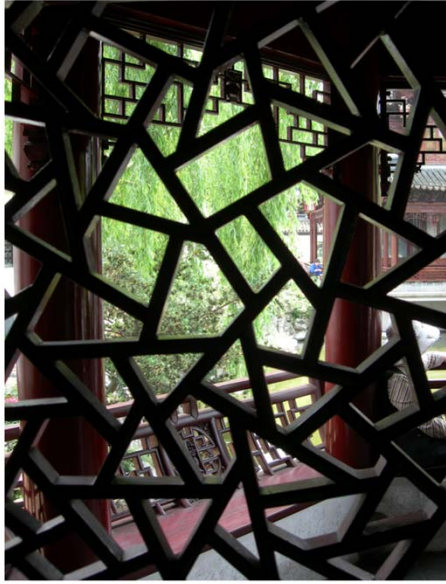
[CLICK]

[CLICK] (4) What is over-aging?

[CLICK]

[CLICK] (5) What are hardening mechanisms for a eutectic composition alloy?

[CLICK]



THANK YOU



THANK YOU.