

Lab 05

Heat Treatment of Steel

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**Lab Section: 106, Friday, 2-5
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Objectives

The experiment performed dealt with examining and understanding the effects of heat treatment of steel on the various microstructures as well as the hardness level. The time-temperature-transformation (TTT) curve for steel was also examined in great detail.

Experimental Procedures

First, the 1045 cold rolled steel sample has the thermocouple inserted into a hole in the top and is lowered into the furnace. The steel is placed in the center away from the heating coils so that it does not melt and completely inside the furnace so that the entire sample is heated evenly initially. The sample is then heated to a temperature of 1050 °C and held constant for approximately five minutes. After this time has passed, the sample is quickly dropped into the water below so that eighth of an inch is submerged in the water. The temperature is then adjusted to 900 °C and held constant for the next fifteen minutes as shown. This temperature of the steel was recorded during this heating process in Figure 1 below. After the fifteen minutes is up, the sample is then quenched by dropping it quickly into the water below.

Next, the rough sample's surface needs to be cleaned up by a process of metallographic polishing. First, the sample is placed securely in a clamp and placed on the grinder to remove the outer oxide layer that developed during the heating process; this is done for both sides. The sample is then further polished manually by rubbing it in a straight line over four decreasing grits of sand paper down to 600 grit. The sample is rotated ninety degrees between each different grit of sand paper so that the polishing process goes smoother.

Next, the sample is electroplished using an acidic solution to delineate grain boundaries, dislocations that intersect the surface, and interphase boundaries. Afterwards, the sample was rinsed with alcohol and water to help neutralize the acid and make it safe for handling. Special care was taken

into not touching the surface of the sample as it ruin the etching. Following the etching, sixteen Rockwell hardness tests were done along the length of the sample in hopes to show the effects of the cooling temperature gradient that was utilized in the experiment. The recorded values for the tests and the placement are shown below. Finally, the samples were then examined under a microscope at five different locations, taking note of the differences in grain sizes, morphology of the microconstituents, and the density of the dislocations. The location and pictures taken are shown below in Table 2.

Experimental Results

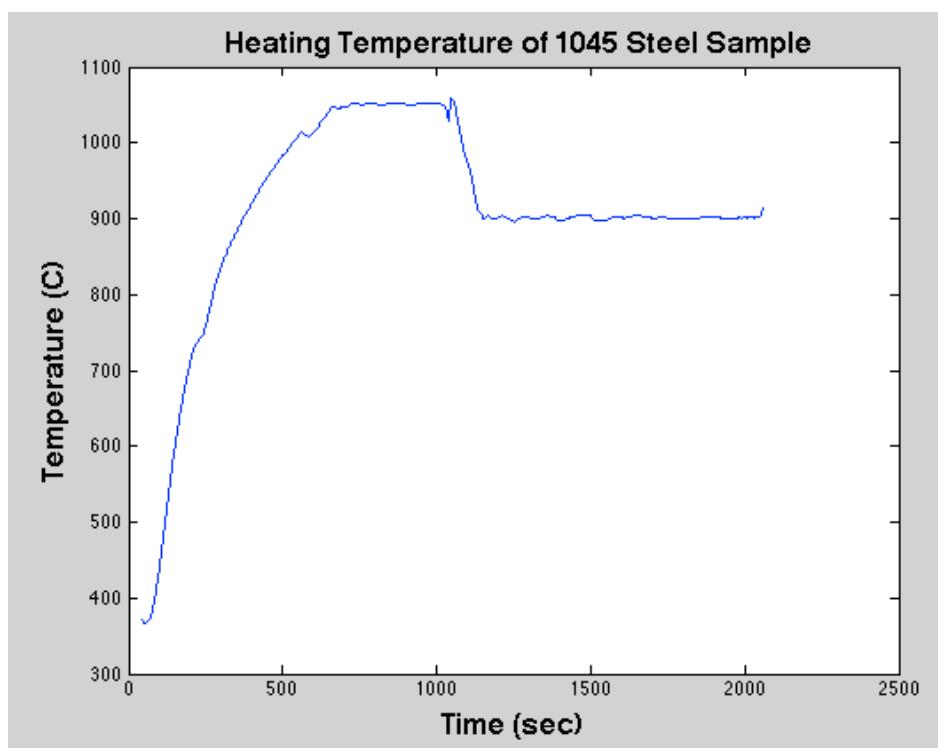
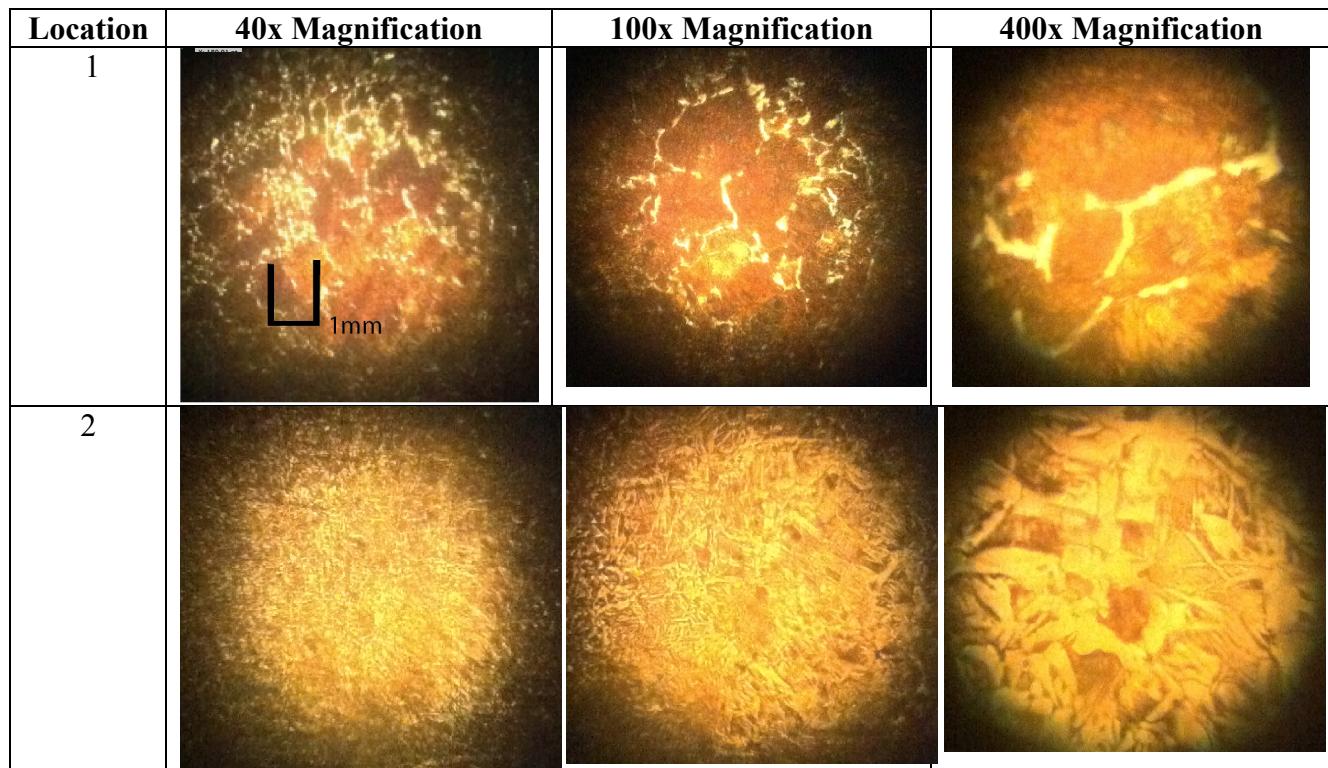


Figure 1: The figure above shows the heating treatment for the top part of the specimen

Position	Rockwell Hardness "C"
1	75.7
2	64.5
3	54.4
4	57.0
5	58.0
6	59.0
7	60.0
8	60.0
9	60.1
10	62.0
11	63.0
12	64.0
13	66.0
14	66.5
15	69.5
16	76.0

Table 1: The table above shows the hardness rating for the spots taken along the sample starting from the top where the thermocouple was inserted



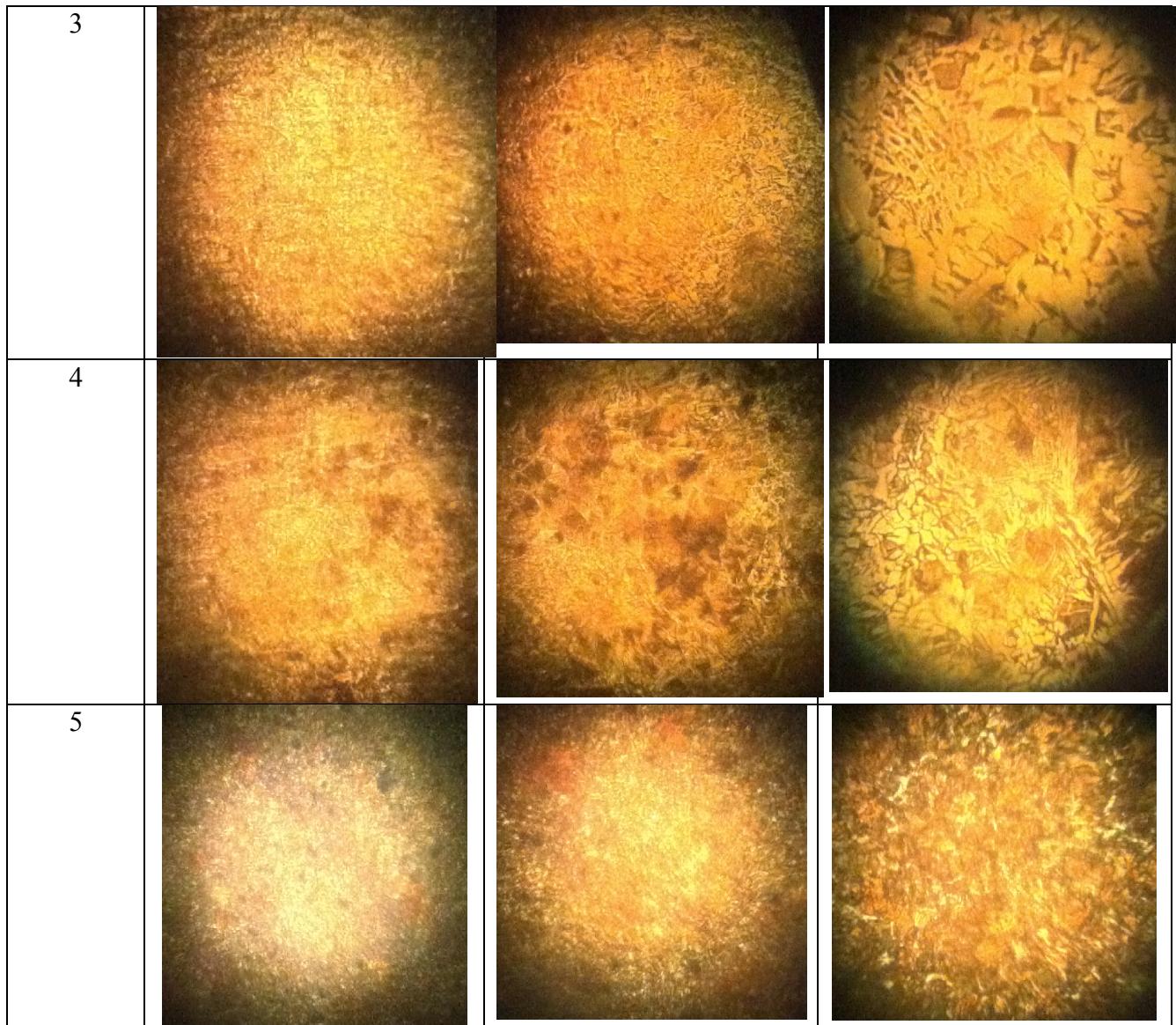


Table 2: The table above shows the different magnifications that showcase the microstructures of 1045 steel cooled at different temperatures



Figure 2: The above picture shows the 1045 steel sample after the hardness tests and electropolishing had been performed

Discussion

1. For each of the five (5) different microstructures evident in your results, draw a representative cooling curve on a TTT diagram corresponding to the thermal history associated with the specific area of the sample where the microstructure was observed. Use a separate TTT diagram for each of the five cooling curves, but show them all at the same scale. Verify the phases present in each microstructure and compare to your cooling curves. Specify the order in which the phases appeared, and refer to the phase diagram as necessary to validate your conclusions.

The first microstructure observed was that of the almost completely α ferrite phase, location 1 in Table 2. This phase had the largest grain size due to the high driving force for grain growth at high temperatures. The TTT plot that best describes this process is shown below.

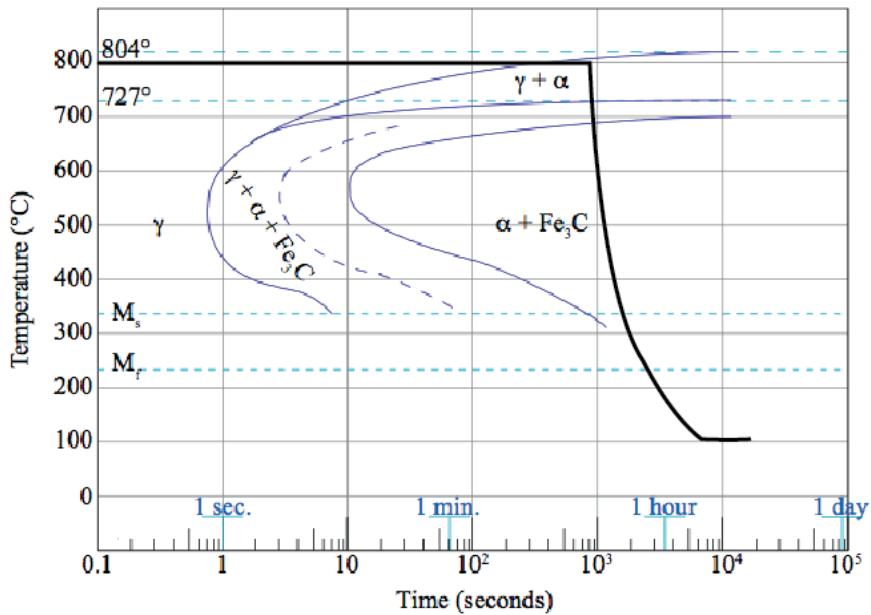


Figure 3: The TTT diagram for the formation of ferrite and cementite in 1045 steel.

As is visible this section of the sample was held close to 800 °C for 15 minutes. The α , ferrite, phase began forming as soon as the sample fell below the necessary temperature of 804°C. The ferrite formed before the other phases because the composition of 1045 steel is hypoeutectic, and looking at the phase diagram it is obvious that α phase ferrite will precipitate first because it is soluble in the liquid matrix at higher temperatures than cementite. This concept holds for all phases since the composition does not change, only the temperature. The rest of the austenite was immediately quenched leaving little portions of martensite within the large ferrite grains.

The second phase observed was coarse pearlite, location 2 in Table 2 above. Coarse pearlite formed by having the initial α ferrite phase solidify and then having the cementite bands solidify in between the ferrite grains to give it the lamellar structure of pearlite. Both of these process occurred at relatively high temperatures, thus explaining the large grain size still present. The cooling diagram for this structure is below.

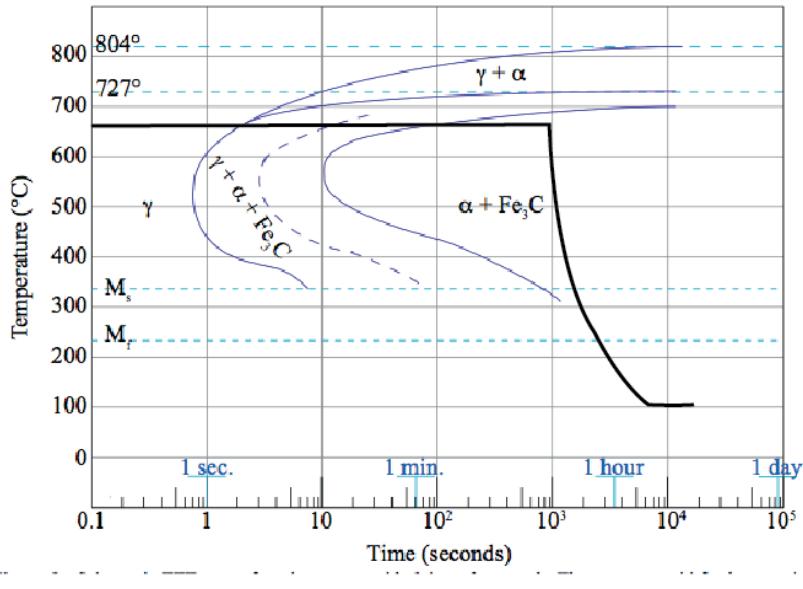


Figure 4: The TTT diagram for the formation of coarse pearlite in 1045 steel

The third phase observed in going down the temperature gradient was fine pearlite, location 3 in the above table. In fine pearlite, the driving force for grain growth is much smaller compared to that of the nucleation rate. Since the composition is hypoeutectic, α phase ferrite started to nucleate first followed by that of cementite solidifying from it in a smaller lamellar structure as seen in Table 2 at location 3. The TTT diagram below best explains the cooling process for this section.

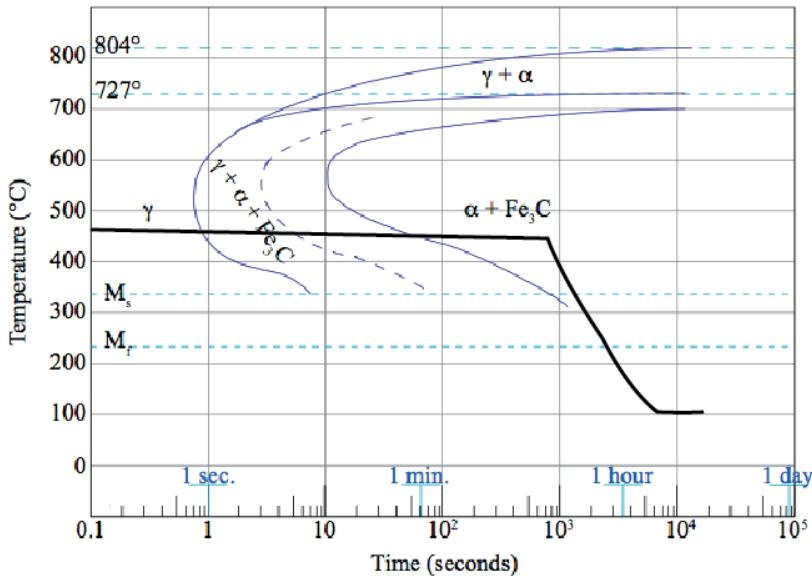


Figure 5: The TTT diagram for the formation of fine pearlite in 1045 steel

The fourth microstructure observed was bainite at location 4 in the table above. Bainite formed closer to the quenched end of the steel due to the even smaller driving force for grain growth and the rapid nucleation of many fine crystals. The dispersion of these fine crystals is very evident in the last column of the location 4 row in Table 2. The TTT diagram for bainite formation is shown below.

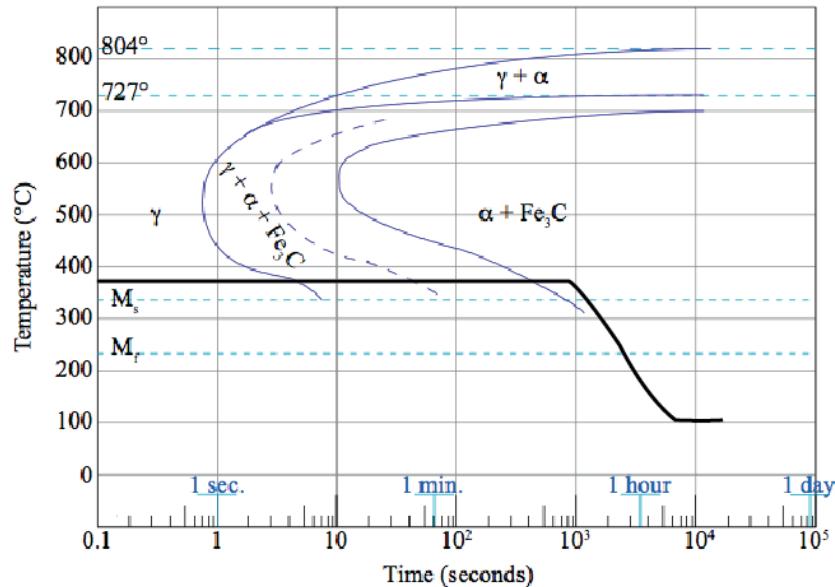


Figure 6: The TTT diagram for the formation of bainite in 1045 steel

The last phase observed was martensite at location 5. Martensite formed upon immediate quenching of the austenite at 900 °C to a much lower temperature very rapidly causing a shear transformation in the crystal structure to lock the carbon atoms in a body central tetragonal lattice of iron atoms. This process leads to very fine grains that are nearly impossible to distinguish with even 100x power as shown in Table 2 above. The numerous amounts of grains give martensite its great strength. The TTT diagram for martensite formation is shown below.

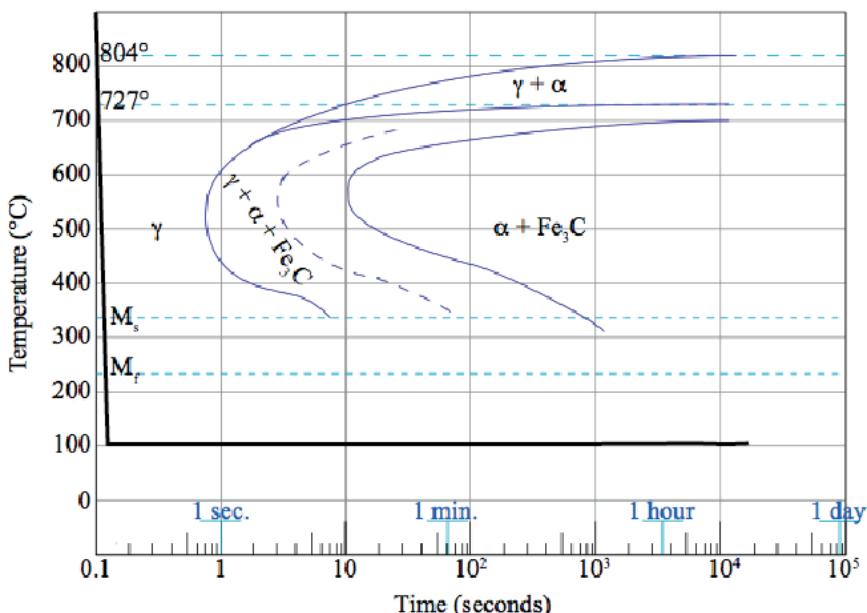


Figure 7: The TTT diagram for the martensitic transformation of 1045 steel

2. Make a plot of hardness *versus* distance from the 900°C end of the sample. Use your hardness data to rank martensite, ferrite, and pearlite from the hardest to the softest. Support your results by discussing the nature of the microstructure, crystal structure, and chemical bonding associated with all three phases (martensite, ferrite, and carbide).

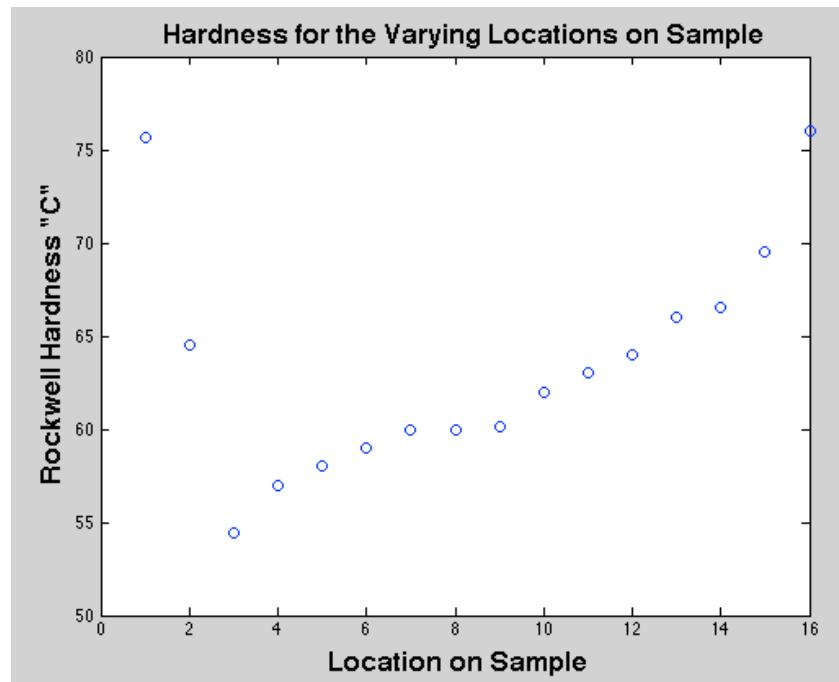


Figure 8: The figure above shows the hardness ratings for the various locations on the sample that correspond to the drawing above in Table 1

Before the hardness regions are considered, the temperature gradient that goes from 900 °C at position 1 to 100 °C at position 16 must be noted as temperature is the main factor in determining the microstructure of the steel. Looking at the figure above, the hardest regions are shown to be at both ends. The hardness steadily increases from spot 3 through 16 after a sharp drop of after the first spot. Both ends contain mostly martensite, the hardest of the steel components. Next hardest is pearlite, which forms at temperatures between approximately 504 and 727 °C and is evident in the increasing portion of the hardness plot from positions 4 to 15. Note that coarse pearlite is formed at higher temperatures due to the increase in grain growth while fine pearlite is formed at the lower temperatures where nucleation of more grains is favored. Ferrite is the least hardest out of the three and it corresponds to the very low 3 and 4 positions on the graph above since it forms best at temperatures just below 804 °C, right below the max temp of 900 °C at position 1. Examining the microstructure in more detail shows that martensite is mainly comprised of small and very fine needle like fibers consisting of carbon atoms forced in a body centered tetragonal ferrite lattice due to the rapid solidification of austenite. The fine dispersion helps to impede dislocation motion greatly, making martensite very strong. Its strength is also attributed to the fact that the body center tetragonal phase has fewer slip planes than that of ferrite, which is in an FCC crystal structure, making it more resilient to dislocations. Looking at the microstructure of pearlite, its seen to be a dispersion of ferrite and cementite crystals that vary from coarse to fine depending on the relative sizes. The fine dispersion and varying grains from each component help pearlite to be fairly strong; however, its added feature that martensite does not have is that it is more ductile because the grains can more easily slide past each other in dislocation motion. The crystal structure of ferrite is BCC while that of cementite is

orthorhombic in nature. Both these structures add to pearlite's strength and ductility. Lastly, pure ferrite is crystalline in its microstructure with grain size dependent upon that temperature of the specimen. Higher temperatures lead to more grain growth, and therefore more room for dislocations (less strength) as was shown in pearlite. As mentioned before, ferrite is in the BBC phase, but since it has large grains it is the softest of the material due to weak metallic bonds between iron atoms. This is another added factor of bonding since in cementite, Fe_3C , the bonds are covalent and much harder to break.

- 3.** Does the transformation of austenite into ferrite begin at the austenite grain boundaries and propagate inward, or does it begin inside the grains and propagate outward toward the boundaries? Include a sketch of the microstructure from the appropriate part of the specimen illustrating the answer to this question. Explain.

The transformation from austenite into ferrite begins on the grain boundary and propagates inward due to less activation energy being required for nucleation to occur. At the grain boundary, the critical radius for a new crystal to form is more easily reached since it can grow from the wall of the grain needing only half the material of that a normal crystal needs to grow. However, that is not to say that nucleation within grains does not occur, it is just less often because more energy and material is required for it to take place. The nucleation within grains is homogenous while on the grains signifies it being heterogeneous.

- 4.** How could a structure containing only ferrite and martensite be produced in a 1045 steel specimen? Illustrate on a TTT diagram.

Since ferrite begins solidifying at higher temperatures, around 804 °C for our sample^[1], a structure containing only martensite and ferrite can be produced easily by holding the sample at a temperature just below the solidifying temperature of ferrite for a couple minutes and then quenching the sample. Holding the temperature of the sample just below the solidifying range of ferrite allows the ferrite crystals to nucleate and grow in an austenite solution. After a specified amount of time has passed, the sample is quenched to convert the remaining austenite into martensite. Thus, only ferrite and martensite will be left when the sample is examined under a microscope.

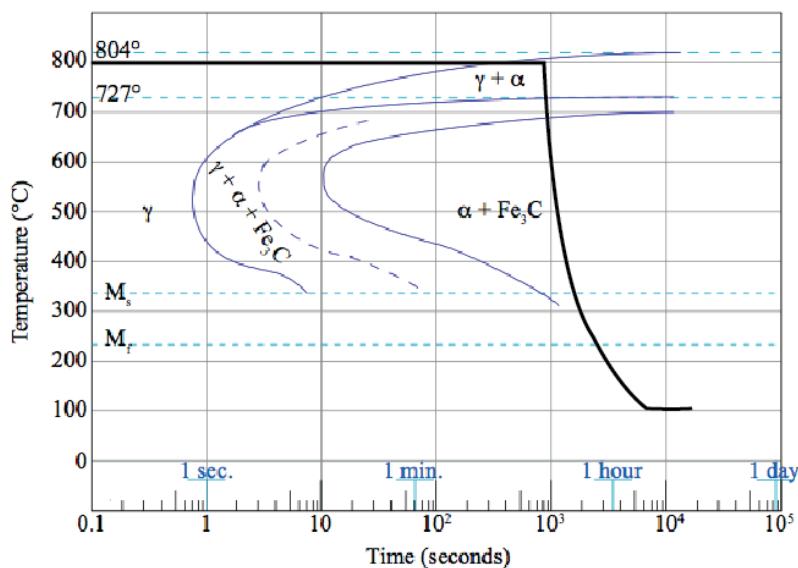


Figure 9: The above TTT diagram shows how a sample containing only ferrite and martensite can be produced

5. Could you heat treat a 1045 steel specimen so that it contains only ferrite? Describe how this can be achieved, or explain why it cannot be done.

No, a 1045 steel specimen could not be converted into only ferrite. This is mainly because ferrite is not totally soluble in the austenite phase. Looking at the phase equilibrium diagram, it is clear that a solid solution of ferrite can only exist for concentrations of carbon less than 0.22 %. Since our sample has 0.45 %, ferrite will never exist completely by itself.

6. Why isn't martensite on the Fe-Fe₃C phase diagram of Fig. 1? Why doesn't its absence from the phase diagram prevent it from being an important engineering material?

Martensite is not on the phase diagram of Figure 1 because it is a meta-stable phase, or not in equilibrium. Given time, martensite will fully convert to cementite; however, this process will take extremely long therefore making martensite an important material that can be utilized in engineering for moderate periods of time. Furthermore, the tempering of martensite is helpful to engineers as it can be tempered to showcase both very strong and more ductile characteristics.

Conclusion

As a result of this investigation, the following conclusions can be drawn. 1045 steel can be heat treated to produce an array of microstructures comprising of fine and coarse pearlite, bainite, and martensite. The amount of each phase present depends only upon the cooling method used since our composition was fixed. Fine and coarse pearlite were found to form at temperatures just below the eutectoid due to the high driving force and therefore higher nucleation rate. Martensite was found in the section of the specimen that was quenched in the water immediately after heating. Bainite was found in the specimen in areas just above the quenched portion corresponding to much lower cooling temperatures. Lastly, ferrite was found in the middle section of the specimen, since it is a component of both pearlites, because it solidifies at temperatures below 804 °C.

References

- [1] Ronald Gronsky. *E 45 Laboratory Manual*, volume 4. Materials Science and Engineering Department, 2013.