Material Science – ENGG*2120: Fall 2017
LAB SUBMISSION COVER SHEET
(Must be included for all group submissions)

Lab Performed: Heat Treatment of Steels
Date Performed: Friday, November 10th, 2017
Date Submitted: Friday, November 24th, 2017
Group Number: K1
GTA Name: Richard Chen

GROUP PARTICIPATION EVALUATION FORM

*****ALL GROUP MEMBERS MUST SIGN TO RECEIVE THEIR MARKS*****

By signing the cover sheet each member is stating that they made a significant contribution to the writing of this lab report and that the distribution of sections completed is accurate.
One form is required for each group report submitted. One report is to be submitted **per group.**
All submissions to be submitted electronically to the dropbox in Courselink by **NO LATER THAN** 4:00 p.m., two (2) weeks after the assigned experiment is performed (unless otherwise indicated in the course outline).

Group Members		**Sections Completed**
Name (Printed)	**Signature**	
Noah Montag		Summary, Experimental Apparatus and Procedures, Discussion Questions 3,9
Melissa Hardy	MHardy	Conclusion, Discussion Questions 4,5,7
Daniel Sherman		Results, Discussion Questions 2,6,8
Bilal Ayacche		Introduction and Discussion Question 1

HEAT TREATMENT OF STEELS

November 24th, 2017

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*ENGG*2120*

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Summary

This lab report tested several different heat treatment methods of two different types of steel. The different methods used were; no treatment at all, air quenched with no temper, oil quenched with no temper, water quenched with no temper, oil quenched with a 20-minute temper, water quenched with a 20-minute temper, oil quenched with a 40-minute temper, and water quenched with a 40-minute temper. The steels tested were AISI-1045 plain carbon steel and AISI-4140 plain carbon steel. The purpose of this report is to show what heat treatment process produces the hardest steel and to help understand what changes inside of samples to cause the differences in hardness.

The softest material is AISI-1045 air quenched steel with no tempering done to it. The hardest material was AISI-4140 water quenched steel with no tempering. Tempering makes materials more ductile but it is at the cost of some of its hardness. Chromium and molybdenum improve the hardness of steel when they are added to it because of their ability to form martensite more easily. Quenching steel also improves its hardness. The rapid cooling doesn't give it enough time to form cementite or pearlite and the more martensite is formed. Water has a higher quenching velocity than oil and that's why it creates harder steel than oil quenching does. The harder a steel is the more brittle it is, that is why tempering is done. The steel becomes more ductile at the cost of some hardness.

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Introduction

Steel is one of the most commonly used metals because of its wide range of applications which ranges from construction materials to medical tools and industrial. Steel alloys are primarily made from carbon and iron but sometimes have additional alloying elements such as Si, Mn, Cr, and Ni. These additional alloys affect the mechanical properties of the alloy. Mechanical properties such as formability, machinability, wear and corrosion resistance, and ductility get affected by the addition of the elements. Heat treatment of steels is a process in which the microstructure of steel is manipulated for the purpose of changing the material's property, such as, hardness, ductility and brittleness. Hardened steels can withhold more stress and are commonly used as kitchen knives, cutting tools, and drill bits. The process of heat treatment involves heating the material to the point in which the solubility of the carbon in the structure changes. The structure of the material transfers from BCC to FCC. This allows iron carbides to form a homogeneous austenite phase. As the sample cools down back to its BCC temperature range, excess carbon is expelled from the material's surface forming an iron carbide. As the samples cools down into the BCC temperature range, excess carbon is expelled from the sample which results in the formation of iron carbide. The rate at which the sample cools down affects the material differently. If sample cools down slow enough, the cementite, a carbide is formed which obtains a moderate ductility, hardness and strength. On the other hand, if the sample was cooled quickly through quenching in water or oil, the carbon does not have enough time to produce cementite, therefore martensite forms instead. The BCC structure of the sample then deforms into a body-centered tetragonal structure. Although The structure formed is very brittle, it becomes exceptionally hard which makes it suitable for different applications. Tempering is a secondary process in heat treatment in which previously hardened or normalized steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate. This is to allow the carbon to diffuse back to BCC from the BCT structure to form ferrite and cementite. This is primarily to increase ductility and toughness at the cost of a slight reduction in strength. It is important for the manufacturer to know and understand the mechanical properties that can be achieved through different heat treatment processes and use that information to select or create the best material for any given application.

Experimental Apparatus & Procedures

Equipment

- 8 samples of AISI-1045 plain carbon steel
- 8 samples of AISI-4140 plain carbon steel
- 2 Furnaces
- 1 container of oil with device that lifts materials and mixes oil
- 1 container of water with device that lifts materials and mixes water
- Rockwell hardness testing machine

Experiment Procedures

1. Sand the faces of every steel sample you have.
2. Measure and record the hardness of a 1045 steel specimen and a 4140 steel specimen.
3. Heat all other samples at 800 °C for 30 minutes in a furnace.
4. Take a 1045 steel sample and a 4140 steel sample out of the furnace and place it onto a porcelain plate so it can be air cooled. Measure and record its hardness 20 minutes after it was removed from the furnace.
5. Oil quench and water quench three of each steel type.
6. Measure the hardness of 1045 water quenched, 1045 oil quenched, 4140 water quenched, and 4140 oil quenched samples.
7. Temper the remainder of the samples in a furnace at 400 °C.
8. Remove one of each type after 20 minutes and let them cool for 10 minutes before measuring and recording their hardness.
9. Remove the remaining samples after 40 minutes and let them cool for 10 minutes before measuring and recording their hardness.
10. Put all of the samples under the digital microscope after etching and polishing them.

Note: Lab manual instructions and all safety precautions were strictly followed and no additional changes were made to either.

RESULTS

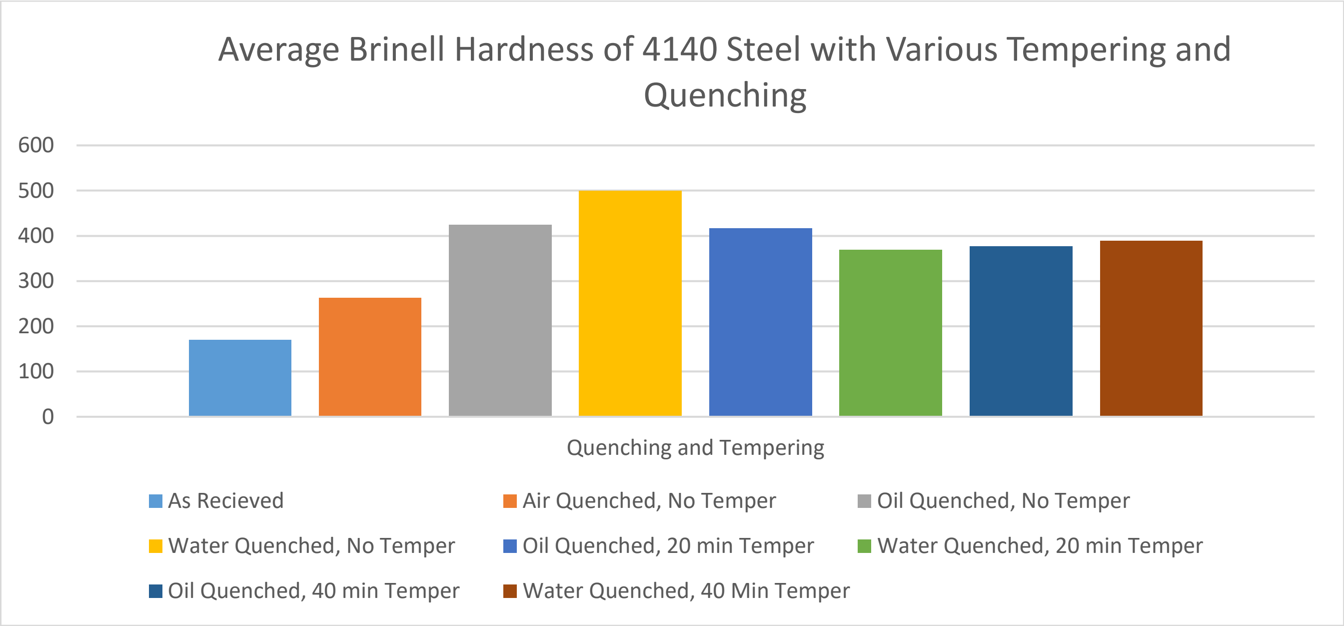

Figure 1: Average Brinell Hardness of 4140 Steel

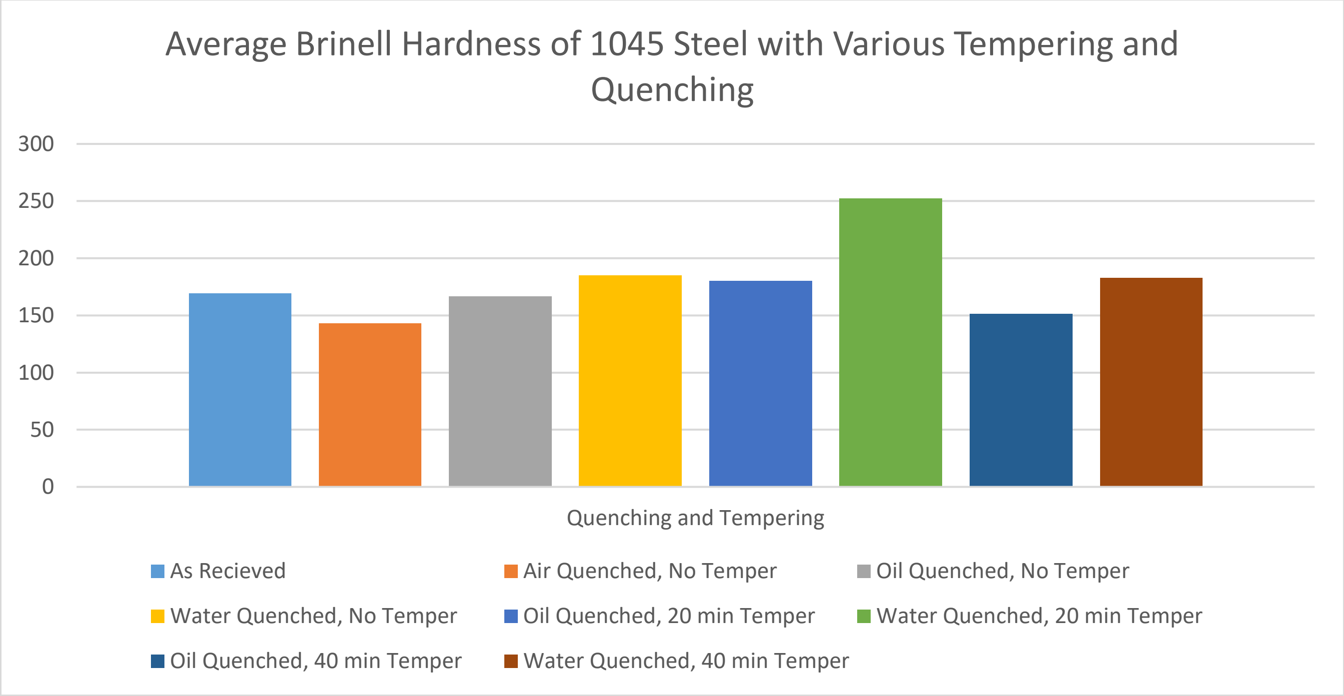

Figure 2: Average Brinell Hardness of 1045 Steel

	4140		*1045*	
Trial #	**Rockwell B**	**Brinell**	**Rockwell B**	**Brinell**
1	90.66	183	85.7	163
2	85.14	163	85.77	163
3	85	163	89.96	183
Average	86.93333333	169.6666667	87.14333333	169.6666667

Table 1: Hardness Values of Materials (As Received)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell B**	**Brinell**
1	29.45	271	80.18	147
2	28.6	264	78.58	141
3	26.27	255	77.84	141
Average	28.10666667	263.3333333	78.86666667	143

Table 2: Hardness Values of Materials (Air Quenched, No Temper)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell C**	**Brinell**
1	40.6	373	4.56	163
2	50.24	469	7.15	170
3	46.43	430	6.29	167
Average	45.75666667	424	6	166.6666667

Table 3: Hardness Values of Materials (Oil Quenched, No Temper)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell C**	**Brinell**
1	63.46	681	12.12	186
2	50.73	486	12.47	186
3	55.9	572	10.84	183
4	44.23	415	-	-
5	41.76	388	-	-
6	48.54	456	-	-
Average	50.77	499.6666667	11.81	185

Table 4: Hardness Values of Materials (Water Quenched, No Temper)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell B**	**Brinell**
1	42.19	388	89.87	183
2	45.86	430	86.19	167
3	46.35	430	92.43	191
4	-	-	89.25	180
Average	44.8	416	89.435	180.25

Table 5: Hardness Values of Materials (Oil Quenched, 20-minute Temper at 400°C)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell C**	**Brinell**
1	40.58	373	23.5	245
2	35.98	331	24.66	250
3	43	402	26.92	262
Average	39.85333333	368.6666667	25.02666667	252.3333333

Table 6: Hardness Values of Materials (Water Quenched, 20-minute Temper at 400°C)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell B**	**Brinell**
1	37.24	341	74.28	131
2	40.48	373	86.6	170
3	43.84	415	81.6	154
Average	40.52	376.3333333	80.82666667	151.6666667

Table 7: Hardness Values of Materials (Oil Quenched, 40-minute Temper at 400°C)

	4140		*1045*	
Trial #	**Rockwell C**	**Brinell**	**Rockwell C**	**Brinell**
1	43.57	415	10.36	180
2	37.66	348	11.52	186
3	43.48	402	11.17	183
Average	41.57	388.3333333	11.01666667	183

Table 8: Hardness Values of Materials (Water Quenched, 40-minute Temper at 400°C)

Softest Material:

1045 (Air Quenched, No Temper)

Hardest Material:

4041 (Water Quenched, No Temper)

Alloy Content

Alloying elements are added to steels mainly for the purpose of increasing hardenability, which refers to the ease at which a steel can produce martensite. Plain carbon steels typically have very low hardenability and can only produce martensite under very rapid cooling rates. On the other hand, high carbon steels (or alloy steels) have high hardenability and can produce martensite more readily.

Hardenability

In general, adding alloying elements improves the hardenability of steel. In no way does it refer to the actual hardness, it is a measure of how easily a steel can produce martensite. Plain carbon steel has a low hardenability as it can only produce martensite through rapid quenching, which can be done with quenching in water. High carbon steels have high hardenability and can produce martensite through slower cooling methods, like quenching in oil or even air.

Hardest/Softest Steel

The hardest steel that was produced was cooled very quickly. It was quenched in water and then was tempered for 20 minutes. The softest steel that was produced was cooled the slowest, it was only air quenched. To harden a steel, the idea is to produce as much martensite as possible. To do this, one must cool steel at non-equilibrium rates, so the martensite does not dissolve away to form pearlite or austenite.

Tempering Time

Tempering is used to increase ductility, which decreases hardness and strength. This is done after quenching, and this process is to decompose martensite. Based on this, it was predicted that there would be a loss in hardness of the steel with a long enough tempering time. This was seen in the lab. For the 1045 sample was tempered for more than 20 minutes, the hardness dropped off significantly. For the 4140 sample, any tempering decreased the hardness significantly.

Micrographs

In general, the longer a sample of steel has to cool, the less martensite will retain in the metal. Because of this, the longer a sample has to cool, the more time martensite has to transition. Looking at the micrographs, the one for water quenching 4140 (the shortest cooling time) had the most dark, granular, martensite that was visible. The next shortest cooling time, oil quenching, had less dark granules, but more than the micrograph for air quenching, the longest cooling time.

Please see the Appendix for the Iron-Carbon Phase diagram

Discussion

1. Referencing to the micrographs in the results section above, there are 4 different phases that are applicable to the samples that were tested in this experiment. Referring back to the Iron-Carbon phase

diagram in the appendix both samples, 4140 Steel and 1045 steel are in the α(ferrite) which is a BCC Structure at room temperature. In the ferrite state the solubility of carbon is lower than in other states. As shown in the Iron Carbon phase diagram, as samples are heated above 750°C, the steel transforms into the α + y (ferrite + austenite) phase. During this transition, the crystal structure changes to an FCC which makes the solubility of the carbon increase, allowing the carbon to dissolve into the FCC iron. At 800°C the 4140 steel remain in the α + y phase while the 1045 steel enters the Austenite phase, which causes all of the cementite to dissolve into austenite. During the quenching process, the samples were cooled too quick. This caused the carbon to reform into cementite and form martensite. The martensite caused the BCC iron to distort into a body-centered tetragonal crystal (BCT). This formation caused the samples to become very hard and brittle. After quenching, tempering allows some of the carbon to diffuse from the BCT structure, which reduces residual stresses and in turn returns some ductile properties. By increasing either tempering time or tempering temperature, more residual stresses can be relaxed and more ductility can be regained.

2. The hardest steel that was produced was made from water quenching 1045 steel, then tempering it for 20 minutes. Before heat treatment, 1045 steel consists of Ferrite and Pearlite, making it moderately strong, and ductile (Ibrahim and Mayuti, 2015). After heat treatment, the 1045 steel becomes much harder, as martensite forms in the steel, which is much harder than Pearlite or Ferrite (Ibrahim and Mayuti, 2015). However, the newly hardened 1045 is much more brittle than before, due to the martensite.
3. The softest steel that was produced was 1045 steel when it is air quenched and not tempered. Air quenched 1045 steel has alternating layers of ferrite and cementite, or pearlite, because it is slow cooled. As a result, it has moderate strength and good ductility.
4. Chromium (Cr) is commonly found in stainless steel as it provides anti-corrosive properties as well as resistance to oxidation at high temperatures. It also promotes a ferritic microstructure, as does molybdenum (Mo), improving hardenability. Molybdenum also improves pitting resistance (Outokumpu 2017). Hardness of steel is generally determined by its martensitic content and hence it's hardenability (a material's ability to form martensite) (Clemmer 2017), therefore both Mo and Cr increase the hardness of the steel they are added to.
5. The purpose of quenching is to reduce the cooling time of a material such that it does not have enough time to form cementite or pearlite, only martensite. The faster the cooling process, the

more martensite is formed and thus the harder (and more brittle) the steel will be. Due to the higher quenching velocity of water, it has a greater cooling efficacy and consequently produces a harder steel than that produced by oil quenching (lower quenching velocity). However, since ductility is inversely proportional to hardness, steels that are water-quenched tend to be much more prone to fracture (less tough) and brittle than oil-quenched steels (Clemmer 2017), thus the latter tend to be used more often in industry (where wear resistance and safety are high priorities).

6. Tempering in necessary in the hardening process because after quenching and increasing the hardness, the material becomes very brittle due to the martensite that was formed. Tempering alleviates some of the stresses, making the steel more ductile. The benefits of hardening the material first is that one can achieve a much harder steel than if ductility was increased first. Afterwards, one can temper the steel to the requirements of use to make sure the steel can be as tough as they would want. A disadvantage in quenching first is that quenching too much or too fast can create a lot of stress in the steel, making it more brittle due to a large buildup in carbon in the surface of the steel.
7. Based on previous knowledge that quenching and tempering increase the hardness of steel, it can be inferred that heat-treated, steel components should be quenched and tempered after being brazed in effort to strengthen the material used to braze the two components together. Moreover, since the components are already heat-treated, it would be redundant to quench and temper them again before brazing, because in no way would this affect the hardness or strength of the joint. Nonetheless, welding would be a better fabrication method than brazing in most cases, as it produces the strongest joints, however it requires partially melting (and thus possible distortion) of the two components, and thus brazing may be more preferable in applications that require minimal effects and maintained integrity of the two base metals (Mraz 2016).
8. Alloy steel can be used for automotive parts and for construction purposes. Their high strength makes them a good choice as they can handle a lot of stress without failure. They have better weldability and formability than plain carbon steel (Clemmer, 2017).
9. The results for this lab are pretty accurate. It is known that when metals are slow cooled they are not as hard as when they are quenched, and the results show that for both types of steels.

When steel is fast cooled, or quenched, it becomes harder but also very brittle, so it is heated again, or tempered, to make it more ductile. When steel is tempered to become more ductile, it loses some of its strength. The results for 1045 steel differ from this, showing that when it is tempered for 20 minutes it is harder than when it is not tempered. Possible sources of error for this are that 20 minutes was not enough time for 1045 steel to be tempered, the hardness testing machine went into a previous indent in the sample, the samples could get mixed up somehow, the hardness testing machine could be too far away or too close to the sample (pushing against the sample already), not enough hardness tests were run so they featured anomalies that weren't accurate, and the samples given were somehow not 100% what they were supposed to be.

Conclusion

In conclusion, materials with the highest martensitic content were the hardest (as seen in Tables 1-8). Based on previous knowledge about the formation of martensite, it makes sense that the water-quenched, no-temper 4041 steel was the hardest, as it would consequently have the highest content of martensite of all the samples. Moreover, because 4041 steel has added alloying elements, such as chromium and molybdenum (which also improve hardenability), it is logical that the water-quenched, no-temper 4041 steel sample was harder than that of the 1045. For the reasons above, it is also logical that the softest material was the air-quenched (no martensite), no temper 1045 steel sample.

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APPENDIX

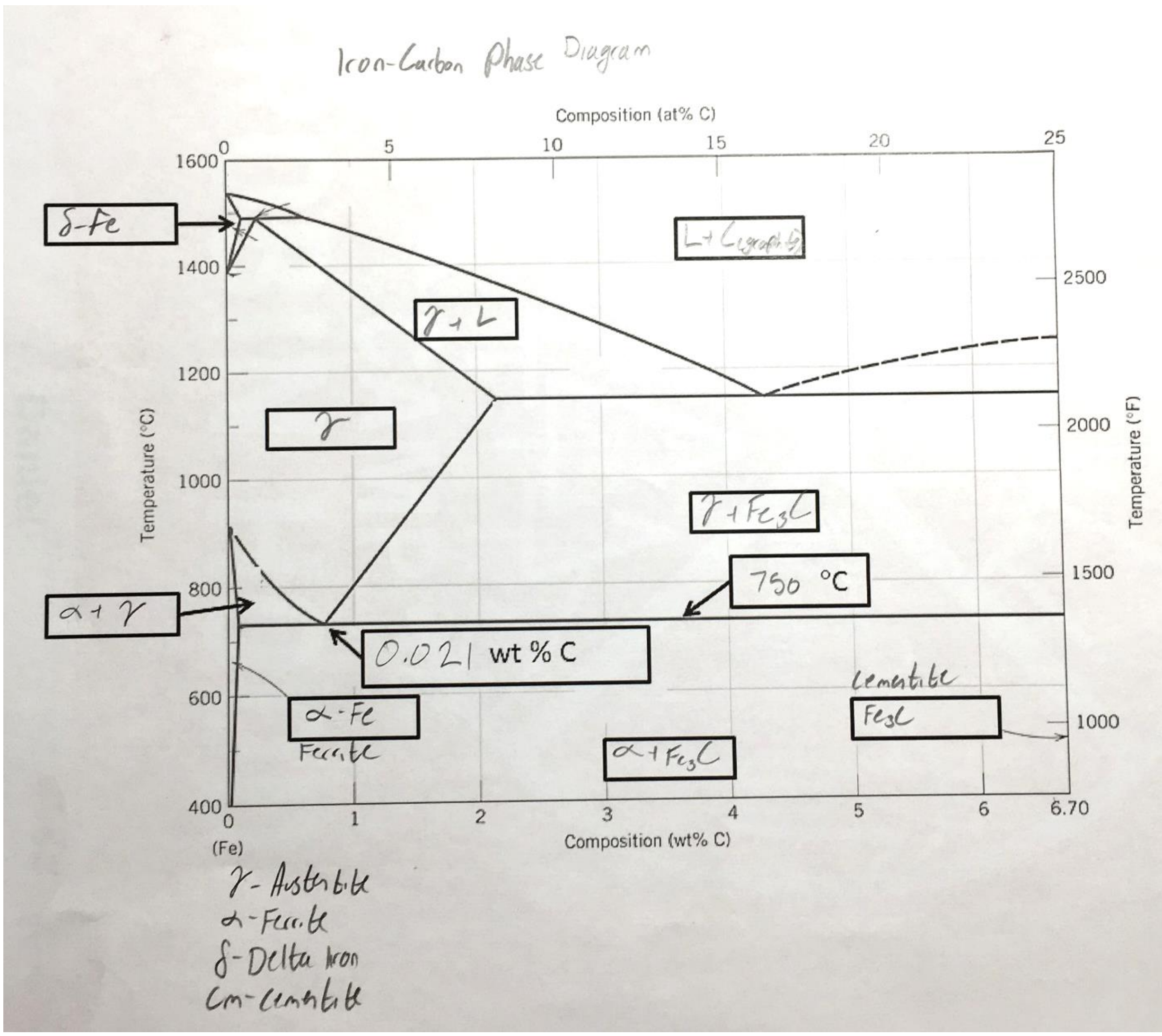

Figure 3 Iron Carbon Phase Diagram