HEAT TREATMENT AND INDENTATION HARDNESS

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Abstract:

This report includes experimental hardness values of steel samples determined by a Rockwell testing system. The report also outlines the essential steps involved in the heat treatment of steel. The metal samples were identified as A36 and AISI 1045. The Rockwell test uses an indenter with a prescribed load. The numbers gathered from the test are a measurement of how far the load plastically deformed the steel sample. The test was used to identify the steel specimens we were presented with. The hardness of the original steel was compared with a heat-treated version of it. All samples were measured in both Rockwell B and Rockwell C scale. From the testing we were able to identify that the harder specimens were the A36. We concluded that the heat treatment significantly increased the hardness of the steel.

Introduction:

The purpose for this experiment was to see how the microstructure and carbon content produced changes in the hardness of steel. The experiment performed involved comparing the hardness of different steel specimens before and after heat treatment. A Rockwell test was used to measure hardness. Both Rockwell B and Rockwell C scales were used to determine the hardness of our steel specimens. We tested two types of steel: A36, which is a commonly used low carbon steel, and AISI 1045, a medium carbon steel containing around .45% carbon.

We tested samples of the metals as they came and another sample of each that had been heat-treated. For heat treatment the samples were raised up to over the eutectoid temperature, the iron changed to FCC, and it transitioned to austenite. Then, the steel was quenched to ~60ºF in water causing BCC crystals to form, which resulted in the formation of martensite, which is strong and brittle. Then the samples were heated back up and allow to air cool in a process that is known as tempering. As a result, the steel is now less hard but has improved ductility.

Samples were tested for hardness using the Rockwell testing machine. The Rockwell machine used an indenter to exert a load on the sample. Then it measured the plastic deformation to assign a number to how hard a material is. Both samples were a considerable amount harder after the heat treatment, which necessitated the use of the Rockwell C scale instead of the B scale. The Rockwell test allowed us to observe the effect of the changes made to the steel's microstructure during heat treatment.

Theory:

In this experiment we wanted to examine the effects that carbon content and heat treatment had on a material's physical properties. In order to do this we examined two steel samples, A36 and A1045, and examined the hardness of each sample before and after conducting heat treatment.

In order to under the effects of carbon, we used A36 steel which has a carbon content of .27% and A1045 which has a carbon content of .45%. The relation of carbon content to a material's physical properties comes from the crystalline structure of the material. By mixing the different atoms of carbon and iron together one is able to produce a new material that is stronger and more resilient to deformation. This occurs because of the size of carbon atoms being small relative to that of iron atoms. This size difference means that when carbon forms an alloy with iron they will be placed in areas of the iron lattice that are usually vacant. This type of defect in a lattice is known as an interstitial defect which causes the crystalline structure to be more resistant to edge dislocations [1]. Having resistance to dislocations in the material allows a material to be stronger against material deformation. Therefore, we would expect that there is a correlation between carbon content and material hardness when performing the Rockwell tests on the samples. This will be confirmed experimentally by comparing the hardness of the two alloys before and after heat treatment.

The second aspect of our experiment was to examine the effects that heat treatment would have on a materials properties. Before the heat treatment our samples have a BCC crystal structure which is in a ferrite and pearlite phase as shown in figure D. The sample is then heated and allowed to soak for a long period of time. During this time, the high temperature causes a change in the crystal structure, turning it to a FCC structure which lies in the austenite phase. At this point the alloy lattice is able to take in more carbon atoms due to the extra space in the crystal structure. Once the sample is quenched the crystal structure changes back to BCC and the additional carbons can no longer remain and wish to leave the crystal structure. However, due to the rapid nature of the cooling, the carbon atoms become trapped and form a crystal structure known as martensite [2]. The inclusion of this new crystal structure helps to increase the material's resistance to deformations at the cost of increased brittleness.

So in testing our theories we will perform a Rockwell hardness test before and after a heat treatment. The Rockwell test employs a diamond tip indenter (for scales A,D,C) or a steel ball (in for scales B,E,M,R) to gauge the hardness of a material. It does this by applying a minor load of 10kg to make a small indention which is followed by the major load, the indentation caused by this load is then measured giving a hardness reading. The hardness is calculated using the following equation:

$$HRX = M - \frac{\Delta h}{.002}$$

Where X represents the scale you are measuring with and M=100 for scales A,C, and D and M=130 for all other scales [3] Using this scale we will hope to compare the difference of deformations in order to understand impact of crystal structure on material properties.

Experimental Procedures:

The process of heat treatment required an environmental-control furnace to heat the materials at a constant temperature. The independent variables for this process were the total amount of time spent on the material and temperature for controlling the hardness of material. In this lab, the carbon steel samples were placed in the furnace for one hour with the temperature set to 850°C. We then quenched our samples in water below 170°C for 3 seconds in order to cool down. After the samples reached room temperature, bead blasted and tempered at 400°C for one hour. Once they reached the equilibrium temperature, the samples were allowed to air cool.

After the samples were cooled we were able to perform the Rockwell hardness test using a Wilson brand device. We began by calibrating our data using 4 calibration blocks two for the C scale and two for the B scale of hardness.The hardness of the blocks were 40.6 and 94.2 for the B scale while and to test these samples in the B scale we used a steel ball indenter and set the major load to 100 kg. We tested the hardness of each block 3 times each and recorded the hardness values of the analog readout. Once we completed the measurements of the calibration we began to test each of our samples. Four samples were tested: 2 sets of A36 and A1045 were used, with one of each steel type receiving heat treatment.

In testing our samples the first step was placing a specimen on anvil and finding a spot that had not being tested. The second step was applying the minor load onto the specimen by turning the capstan hand-wheel until small pointer pointed on a dot, and then setting the dual gauge to zero [3]. The next step was releasing the major load into the specimen by tripping the crank handle [3]. After the crank handle stopped to rotate, it was pulled back to its starting position, which it removed the major load on the specimen in order to get the measurement of the tester. Last step was collecting the measurements for hardness for each specimen. This procedure was repeated for the C scale blocks after adding 50 kg to the major load and changing to a diamond-tipped indenter.

Results:

The hardness of different steel samples were measured by performing Rockwell hardness tests. The full experimental results from the tests can be found in Table A1 of Appendix B. The data taken from the calibration blocks were then curve fitted to find a relationship between actual and experimental hardness data. This relationship is represented by the equations as shown in Figure A1 of appendix B:

$$HRB_a = 1.0579 * (HRB_e) - 8.0632$$

$$HRC_a = 1.0758 * (HRC_e) - 4.597$$

The full adjusted results from the experiment can be found in Table A2 of Appendix B. The Rockwell hardness numbers were then converted to Vickers and Brinell Hardness numbers using the date given in Appendix 2B of our lab manual and linear interpolating between two known points [3]. Namely, the Vickers number and Brinell hardness numbers can be found from the equations:

$$HV = HV_0 + (HV_1 - HV_0) * \frac{HR - HR_0}{HR_1 - HR_0}$$

$$HB = HB_0 + (HB_1 - HB_0) * \frac{HR - HR_0}{HR_1 - HR_0}$$

Where HR_1 and HR_0 represent Rockwell numbers above and below our experimental value, respectively, found in Appendix 2B of our lab manual [3]. The same notation holds for the Vickers number and Brinell number. Some Rockwell numbers couldn't be converted to Vickers or Brinell numbers due to the fact that Rockwell values near them were not provided in the lab manual. Ultimate strengths were found the same way, whereas yield strengths were approximated by $\sigma_y \approx \frac{HR}{3}$.

Sample	**Scale**	**Scaled Rockwell Hardness Value**	**Standard Deviation**	**HV (kg_f/mm^2)**	**HB (kg_f/mm^2)**	**Yield Strength (Mpa)**	**Ultimate Strength (Mpa)**
Steel 1045 NHT	B	89.26	0.0	181.3	181.3	592.7	607.6
Steel 1045 HT	B	112.18	0.5	N/A	N/A	N/A	N/A
Steel 1045 NHT	C	6.16	0.0	N/A	N/A	N/A	N/A
Steel 1045 HT	C	36.28	0.9	356.5	338.2	1165.5	1118.4
Steel A36 NHT	B	81.86	0.0	155.6	155.6	508.6	526.5
Steel A36 HT	B	110.42	0.9	N/A	N/A	N/A	N/A
Steel A36 NHT	C	-1.73	0.5	N/A	N/A	N/A	N/A
Steel A36 HT	C	35.21	1.5	346.9	328.9	1134.0	1086.3

Table 1: Scaled hardness Rockwell B and C of different steel specimens.

Lastly, the percent difference between non heat treated samples and heat treated samples were found showing that there is less difference between heat treated samples and non-heat treated samples.

	HR Steel 1045	HR Steel A36	% Diff
NHT B Scale	89.3	81.86	8.6
HT B Scale	112.2	110.42	1.6
NHT C Scale	6.2	-1.73 (N/A)	N/A
HT C Scale	36.3	35.21	3.0

Table 2: Percent differences before and after heat treatment

Discussion:

If we examine Table 1 in the Results section, it is clear that the heat treated specimens have a higher hardness than the non-heat treated specimens. Based on the information provided in Figure D in the Appendix, the major phase inside the specimen is pearlite and ferrite before heat treatment. Similarly if we consult Figures B and C in Appendix B, we find that after the specimen is heat treated at 850°C, and is quickly cooled to near room temperature within about 10 seconds, the major phase of the metal changes to martensite (about 95%), which is much harder. Therefore, the results we observed are congruous with theory. Beyond this, we see that the 1045 samples have a higher hardness value than the A36 samples. This is due to the higher concentration of carbon in the 1045 samples. It is also worth noting that increasing the carbon content of the steel seems to have a smaller impact on hardness than the heat treatment process.

It is worth discussing some possible sources of error that arose during the lab. Firstly, the specimens may be of a low quality, resulting in possible voids at the grain boundary. These would result in larger plastic deformation for a given load. Secondly, the specimens may not have been completely quenched to room temperature, or the cooling process may have taken longer amounts of time, both of which would result in a greater abundance of pearlite or bainite, lowering the overall hardness. Finally, the inexperience of the testers introduces possible sources of systematic error. The dials on the machine may have not been aligned correctly, or the test apparatus may have been disturbed during testing, resulting in inaccurate measurements.

Based on the data in Appendix 2B in our lab manuals, we can estimate approximate tensile strength values from our measured hardness values. Using the hardness values obtained in lab, we see that the heat treated 1045 steel has an approximate tensile strength of 1118.4 MPa. Similarly, the heat treated

A36 steel has an approximate tensile strength of 1086.3 MPa. The same chart can be used for the non-heat treated samples, and we find that the 1045 and A36 samples have tensile strengths of 635 and 565 MPa respectively. Yield strengths can be approximated converting our Rockwell hardness values to Vicker's hardness values, and subsequently dividing the Vicker's Hardness value by 3. Therefore, we obtain yield strengths of 1165.5, 1134.0, 592.7, and 508.6 MPa for 1045 HT, A36 HT, 1045 NHT, and A36 NHT respectively.

Hardness of the samples can be further improved in several ways: For on, heating the metal to higher temperature, would result in a more dramatic change when cooling the and more of the sample will transition to martensite, further increasing hardness. Alternatively, cooling it with ice water as opposed to room temperature water would conduct heat away from the sample faster, leading to a more rapid transition, and therefore a greater quantity of martensite. Finally, cold-working the specimen after heat treatment would further increase the yield strength, and consequently, the hardness.

Conclusion:

This investigation has shown that heat treating a metal results in a higher hardness. This is due to the change in the metal's major phase from ferrite and pearlite to the much harder martensite. Additionally, results from the Rockwell Hardness Tester suggest that AISI 1045 HT is the hardest sample, followed by A36 HT, 1045 NHT, and finally A36 NHT. These results are relevant because of the need for materials to be resistant to plastic deformation in practical applications. By heat treating steel, one can achieve hardness values that would otherwise only be achievable using much more expensive materials, making heat treatment an economical engineering solution.

Appendix A: References

[1] N. E. Dowling, Mechanical Behavior of Materials, 4th edn (Pearson, 2012).

[2] W. D. Callister, Materials Science and Engineering, an Introduction, 7th edn (John Wiley and Sons, 2007).

[3] K Komvopoulos, Mechanical Testing of Engineering Materials, 1st edn (University Readers, 2011).

[4] Chandler, Harry. (1995). Heat Treater's Guide - Practices and Procedures for Irons and Steels (2nd Edition). ASM International.

Appendix B: Graphs and Figures

Sample	Test 1	Test 2	Test 3	Average of three tests	Standard Deviation	Deviation from Calibration Standard	Indenter	Test Load
Calibration Test Block 40.6 B scale	46.0	46.0	46.0	46.00	0.0	5.4	1/16" ball	100kg
Calibration Test Block 94.2 B scale	96.0	97.0	97.0	96.67	0.5	2.5	1/16" ball	100kg
Calibration Test Block 26.6 C scale	29.0	29.0	29.0	29.00	0.0	2.4	diamond	150kg
Calibration Test Block 62.1 C scale	62.0	62.0	62.0	62.00	0.0	-0.1	diamond	150kg
Steel 1045 NHT B scale	92.0	92.0	92.0	92.00	0.0		1/16"ball	100kg
Steel 1045 HT B scale	114.0	113.0	114.0	113.67	0.5		1/16" ball	100kg
Steel 1045 NHT C scale	10.0	10.0	10.0	10.00	0.0		diamond	150kg
Steel 1045 HT C scale	39.0	38.0	37.0	38.00	0.8		diamond	150kg
Steel A36 NHT B scale	85.0	85.0	85.0	85.00	0.0		1/16"ball	100kg
Steel A36 HT B scale	111.0	113.0	112.0	112.00	0.8		1/16" ball	100kg
Steel A36 NHT C scale	3.0	2.0	3.0	2.67	0.5		diamond	150kg
Steel A36 HT C scale	36.0	39.0	36.0	37.00	1.4		diamond	150kg

Table A1: Raw data taken from performing Rockwell hardness tests

Sample	Test 1	Test 2	Test 3	Average of three tests	Standard Deviation
Calibration Test Block 40.6 B scale	40.6	40.6	40.6	40.60	0.0
Calibration Test Block 94.2 B scale	93.5	94.6	94.6	94.20	0.5
Calibration Test Block 26.6 C scale	26.6	26.6	26.6	26.60	0.0
Calibration Test Block 62.1 C scale	62.1	62.1	62.1	62.10	0.0
Steel 1045 NHT B scale	89.3	89.3	89.3	89.26	0.0
Steel 1045 HT B scale	112.5	111.5	112.5	112.18	0.5
Steel 1045 NHT C scale	6.2	6.2	6.2	6.16	0.0
Steel 1045 HT C scale	37.4	36.3	35.2	36.28	0.9
Steel A36 NHT B scale	81.9	81.9	81.9	81.86	0.0
Steel A36 HT B scale	109.4	111.5	110.4	110.42	0.9
Steel A36 NHT C scale	-1.4	-2.4	-1.4	-1.73	0.5
Steel A36 HT C scale	34.1	37.4	34.1	35.21	1.5

Table A2: Scaled Rockwell hardness test values, adjusting for calibration

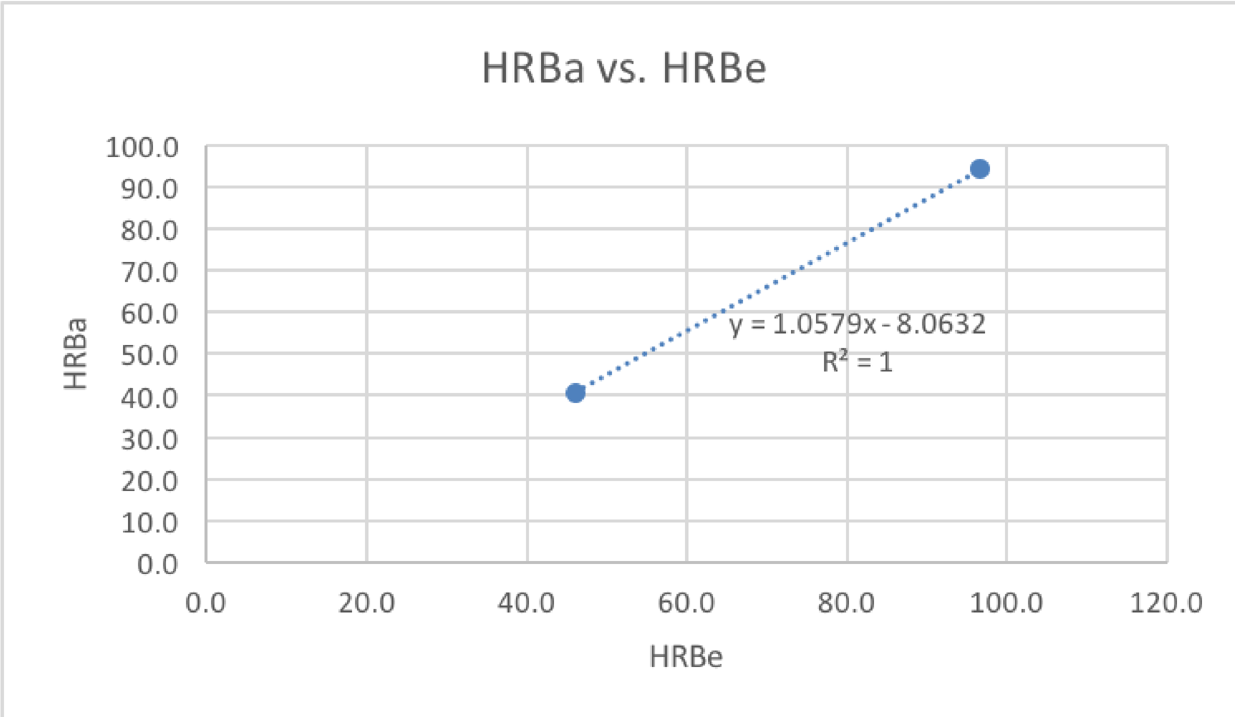

Figure A1: Actual values of B scale calibration test blocks (HRB_a) versus experimental values

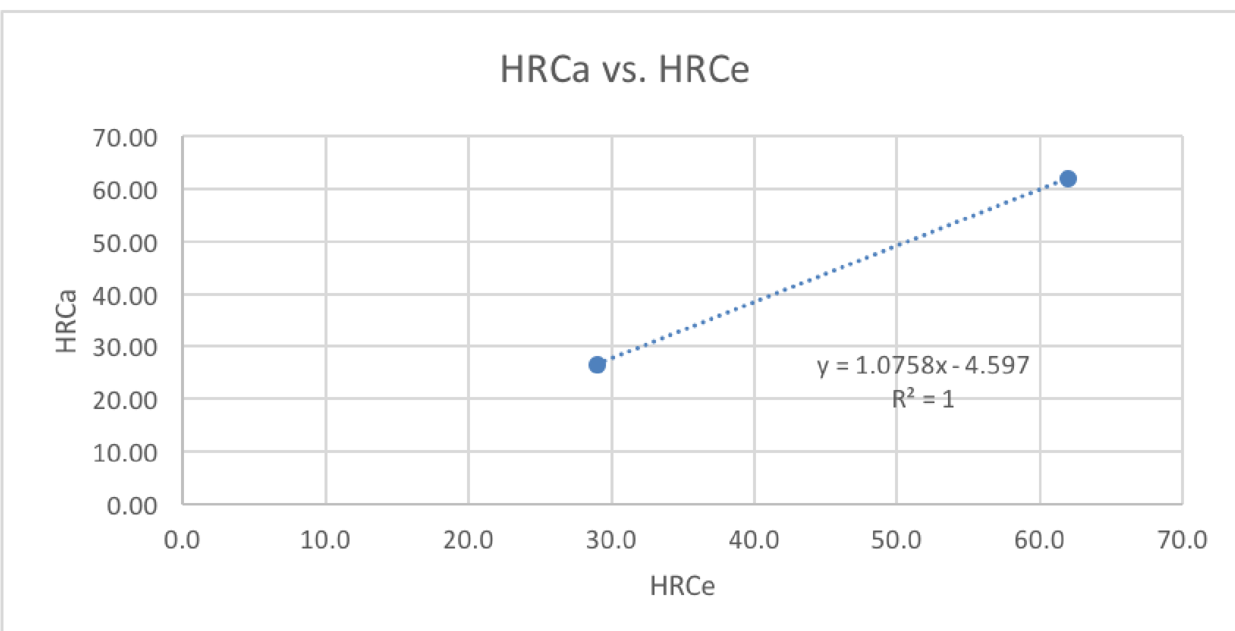

Figure A2: Actual values of C scale calibration test blocks (HRC_a) versus experimental values.

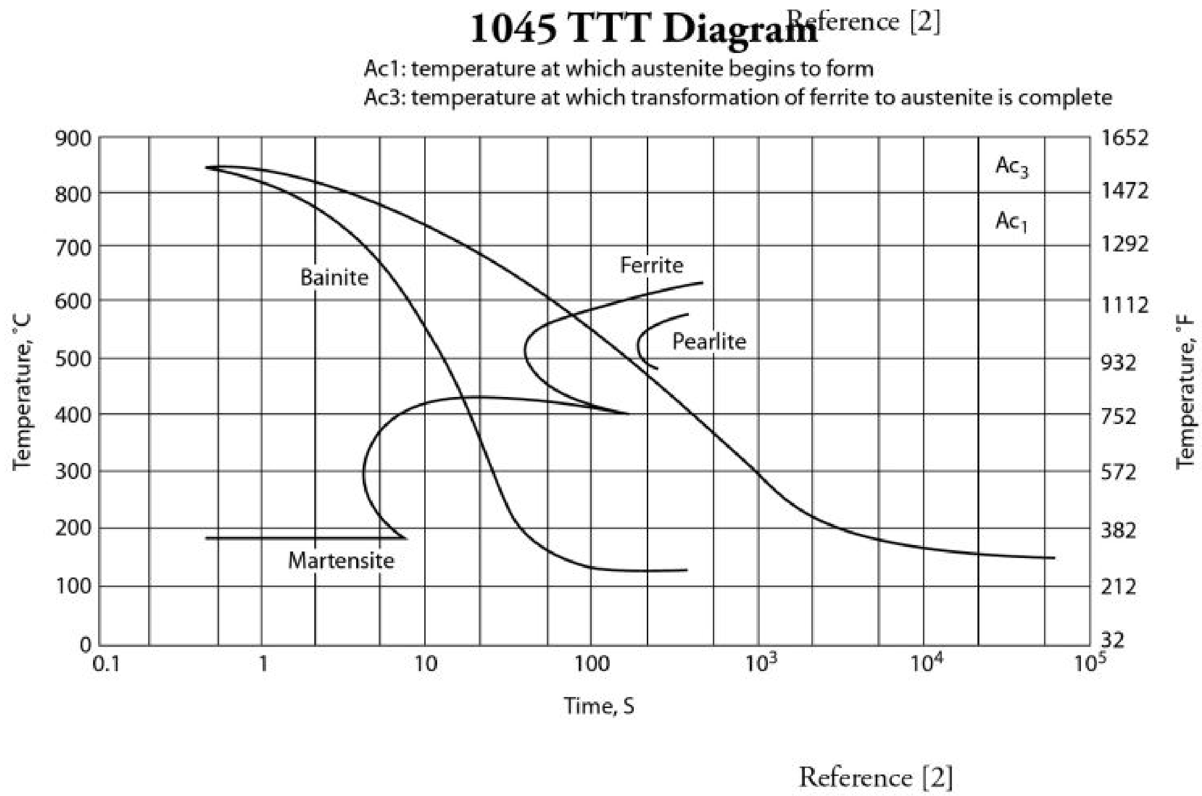

Figure B: Time, Temperature, Transformation Diagram of A1045

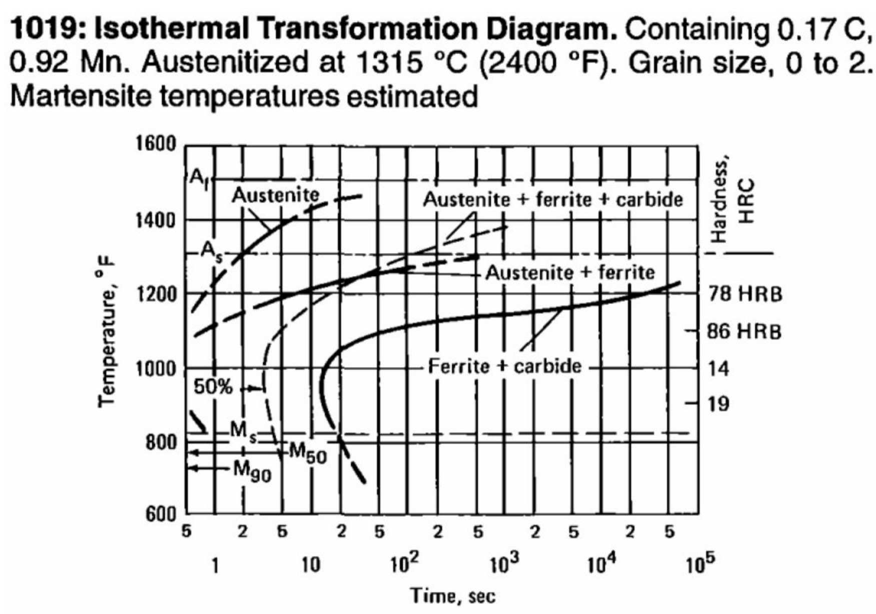

Figure C: A1019 Isothermal Transformation Diagram

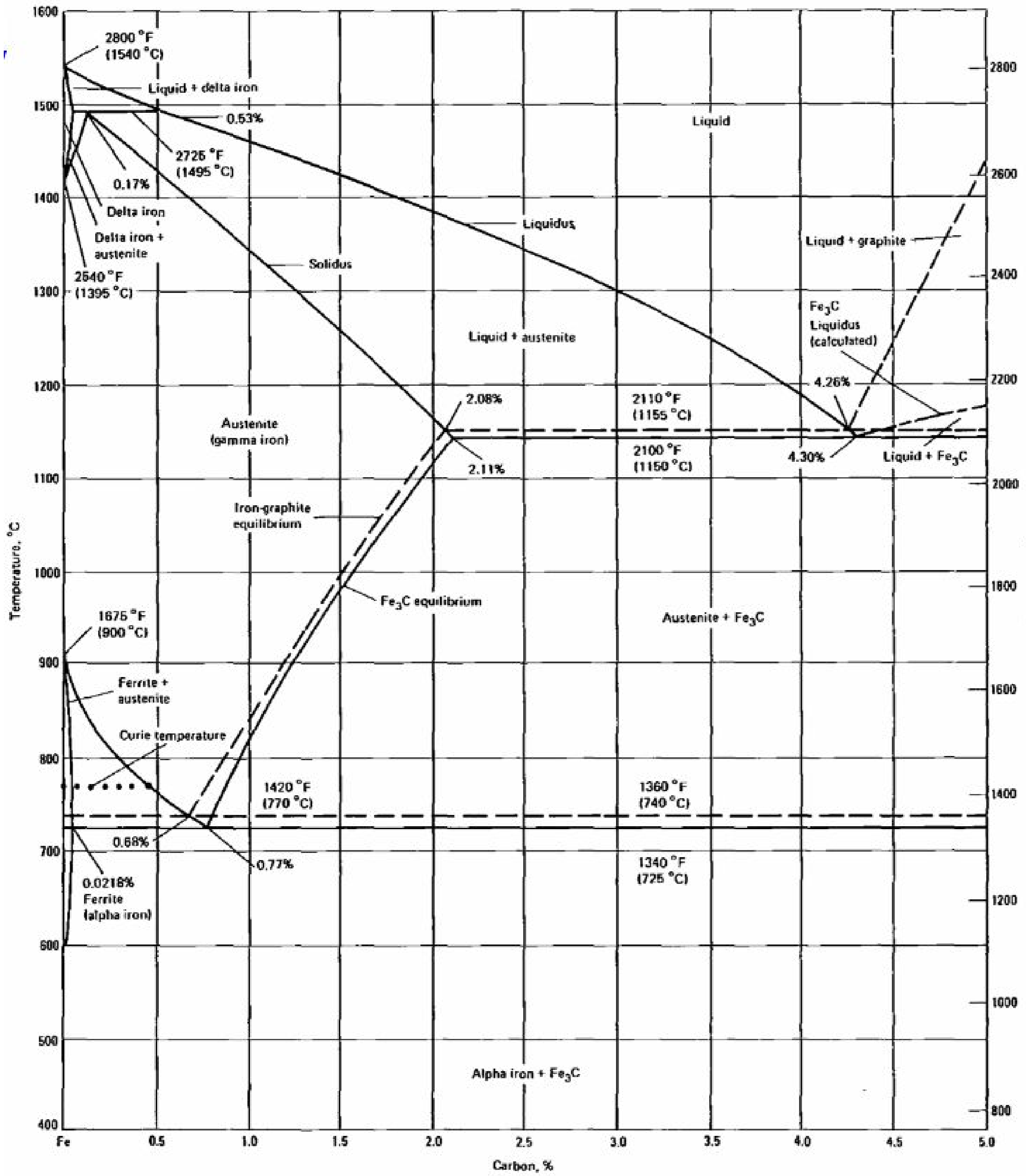

Figure D: Iron Carbon Equilibrium Chart