MEEN 160

MATERIALS SELECTION IN MECHANICAL DESIGN

EXPERIMENT #6

# MECHANICAL PROPERTIES OF ANNEALED PLAIN CARBON STEELS

by

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I. Introduction

In this experiment, the hardness and tensile properties of AISI/SAE 1018, 1035, 1050, and 1095 steel annealed plain carbon steels differing only in carbon content were determined. The hardness and tensile properties of the steels being tested depended on the properties of the individual structures (proeutectoid ferrite, pearlite, and proeutectoid cementite) and their relative amounts (volume percentages). These properties depend on the carbon content of the steels. They were compared with their microstructures in order to verify the relationship between the properties, the carbon content, and the percentages of microstructural constituents associated with them.

II. Experimental Procedure

The specimen analyzed was AISI/SAE 1018, 1035, 1050, and 1095 steel. The first step in this experiment was to determine the $R_B$ hardness of the steel. This was done by making five $R_B$ hardness measurements on one side of the hardness specimen and average hardness values and the standard deviation were calculated and entered in the data sheet. Next, the Brinell hardness test was run. The indentations were made on the opposite side that the Rockwell tests were made. Five Brinell indentations were made using a 500kg load. They specimen was then placed under a microscope, and the diameters of the Brinell indentations were measured from the viewing screen. The results were recorded. Next, a tensile test was performed. The diameter of the specimen was taken five times along the bar to get an average, and the initial length of the specimen was taken. The lab instructor then ran the tensile test and load-strain and load-elongation curves were obtained. The final gage length and gage diameter of the broken tensile specimen were measured and recorded. From the load-strain curve the modulus of elasticity (E) was found and its uncertainty. From the load-elongation curve the values for the yield load and tensile load were found as well as their uncertainties. The second part of the lab included mounting the untested hardness specimen in epoxy for metallographic observation. After the epoxy hardened, the specimen was ground and polished through 1.0µm Al2)3 powder and etched for about 5 seconds with a 3% nitric acid in methanol solution. Then the metallographic specimen was examined with a light microscope at a magnification of about X500. This was done to determine the volume percent of pearlite in the microstructure by point counting. The percent of the total number of grid points falling within pearlitic areas is equal to the volume percent of pearlite. This point counting process was repeated five times to ensure accuracy. Overall, five major characteristics of the specimen were determined through this experiment: modulus of elasticity and its uncertainty, yield strength and its uncertainty, percent elongation and its uncertainty, theoretical volume faction pearlite in a hypoeutectoid steel, Brinell Hardness and its uncertainty.

III. Results

A. Data

Table 1. Nominal Chemical Composition of Steels in Weight Percent

| **AISI/SAE No.** | **Alloy Element** | | | | |
|---|---|---|---|---|---|
| | **Fe** | **C** | **Mn** | **S** | **P** |
| 1018 | Bal. | 0.15/0.20 | 0.60/0.90 | 0.040 max. | 0.050 max. |
| 1035 | Bal. | 0.32/0.38 | 0.60/0.90 | 0.040 max. | 0.050 max. |
| 1050 | Bal. | 0.48/0.55 | 0.60/0.90 | 0.040 max. | 0.050 max. |
| 1095 | Bal. | 0.90/1.03 | 0.30/0.50 | 0.040 max. | 0.050 max. |

Table 2. Hardness Measurements

| **Steel No.** | **AISI/SAE No.** | **Brinell Hardness** | | | **$R_B$ Hardness** | | **Vol. % Pearlite** |
|---|---|---|---|---|---|---|---|
| | | **d (mm)** | **$u_d$ (mm)** | **P (kg)** | **$R_B$** | **$u_{RB}$** | |
| 1 | 1018 | 2.40 | ±0.001 | 500 | 77.0 | ±0.8 | 27.2 |
| 2 | 1018 | 2.32 | ±0.001 | 500 | 79.9 | ±1.4 | 15.2 |
| 3 | 1018 | 2.44 | ±0.001 | 500 | 69.2 | ±5.0 | 33.4 |
| 4 | 1018 | 2.26 | ±0.001 | 500 | 78.7 | ±1.1 | 28.0 |
| 5 | 1018 | 2.40 | ±0.001 | 500 | 85.2 | ±2.4 | 21.0 |
| 6 | 1035 | 2.13 | ±0.001 | 500 | 87.1 | ±0.5 | 61.6 |
| 7 | 1035 | 2.04 | ±0.001 | 500 | 87.4 | ±0.3 | 22.2 |
| 8 | 1035 | 2.12 | ±0.001 | 500 | 88.3 | ±0.3 | 66.8 |
| 9 | 1035 | 2.13 | ±0.001 | 500 | 88.9 | ±1.3 | 65.2 |
| 10 | 1035 | 2.08 | ±0.001 | 500 | 88.5 | ±1.2 | 70.2 |
| 11 | 1050 | 1.98 | ±0.001 | 500 | 94.6 | ±0.6 | 80.8 |
| 12 | 1050 | 1.76 | ±0.001 | 500 | 94.8 | ±0.3 | 87.6 |
| 13 | 1050 | 1.92 | ±0.001 | 500 | 95.7 | ±0.5 | 86.6 |
| 14 | 1050 | 1.98 | ±0.001 | 500 | 97.1 | ±0.5 | 81.4 |
| 15 | 1050 | 1.92 | ±0.001 | 500 | 93.4 | ±0.4 | 75.4 |
| 16 | 1095 | 1.70 | ±0.001 | 500 | 104.1 | ±0.2 | 100.0 |
| 17 | 1095 | 1.53 | ±0.001 | 500 | 104.3 | ±0.5 | 100.0 |
| 18 | 1095 | 1.68 | ±0.001 | 500 | 105.4 | ±0.3 | 100.0 |
| 19 | 1095 | 1.77 | ±0.001 | 500 | 104.8 | ±0.2 | 100.0 |
| 20 | 1095 | 1.76 | ±0.001 | 500 | 104.5 | ±0.8 | 100.0 |

Table 3. Tensile Parameters and Properties of the Annealed Steels

| Steel No. | AISI/SAE No. | $d_0$ (in) | $u_{d0}$ (in) | Ao(in^2) | udo(in) | $P_{ys}$ (lbs) | $u_{Pys}$ (lbs) | σ ys(psi) | u σ ys(psi) | $P_{ts}$ (lbs) | $u_{Pys}$ (lbs) | σ ts(psi) | u σ ts(psi) | $d_f$ (in) | $u_{df}$ (in) | Af(in^2) | udf(in) | %RA | U %ra | $L_0$ (in) | $u_{L0}$ (in) | $L_f$ (in) | $u_{Lf}$ (in) | %EL | $u_{Lf}$ (in) | ΔP (lbs) | Δε | E(psi) | ΔE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1018 | 0.2570 | 0.0010 | 0.05184847 | 0.0004 | 2500 | 50 | 48217.4 | 194.6 | 3700 | 50 | 71361.8041 | 3443.7 | 0.136 | 0.005 | 0.015 | 0.005 | 72.00 | 0.021 | 1.804 | 0.005 | 2.360 | 0.005 | 30.8203991 | 0.005 | 800 | 0.0007 | 22042256 | 174987 |
| 2 | 1018 | 0.2469 | 0.0009 | 0.04785329 | 0.0003 | 2,450 | 50 | 51198.1 | 202.5 | 3,570 | 50 | 74603.015 | 3655.5 | 0.132 | 0.005 | 0.014 | 0.005 | 71.42 | 0.022 | 1.815 | 0.005 | 2.264 | 0.005 | 24.738292 | 0.005 | 990 | 0.0008 | 25860289 | 187293 |
| 3 | 1018 | 0.2490 | 0.0005 | 0.04867079 | 0.0002 | 2,500 | 50 | 51365.5 | 200.8 | 3,700 | 50 | 76020.9641 | 3344.6 | 0.138 | 0.005 | 0.015 | 0.005 | 69.28 | 0.022 | N/A | | | | | | 100 | 0.0001 | 41092413 | 170069 |
| 4 | 1018 | 0.2537 | 0.0021 | 0.0505255 | 0.0009 | 2,400 | 50 | 47500.8 | 197.1 | 3,600 | 50 | 71251.1551 | 4076.4 | 0.125 | 0.005 | 0.012 | 0.005 | 75.72 | 0.020 | 1.758 | 0.005 | 2.203 | 0.005 | 25.3128555 | 0.005 | 300 | 0.0002 | 29687981 | 500943 |
| 5 | 1018 | 0.2503 | 0.0008 | 0.04918032 | 0.0003 | 2,500 | 50 | 50833.3 | 199.8 | 3,700 | 50 | 75233.3444 | 2988.1 | 0.146 | 0.005 | 0.017 | 0.005 | 65.98 | 0.023 | N/A | | | | | | 770 | 0.0005 | 31313338 | 200206 |
| 6 | 1035 | 0.2560 | 0.0021 | 0.05144576 | 0.0008 | 2,700 | 50 | 52482.5 | 195.3 | 4,600 | 50 | 89414.5601 | 2584.1 | 0.157 | 0.005 | 0.019 | 0.005 | 62.39 | 0.025 | 1.729 | 0.005 | 2.074 | 0.005 | 19.9537305 | 0.005 | 960 | 0.0007 | 26657757 | 429032 |
| 7 | 1035 | 0.2222 | 0.0015 | 0.03875768 | 0.0005 | 2,650 | 50 | 68373.5 | 225.0 | 4,400 | 50 | 113525.889 | 2617.3 | 0.156 | 0.005 | 0.019 | 0.005 | 50.71 | 0.032 | 1.718 | 0.005 | 2.071 | 0.005 | 20.5471478 | 0.005 | 1,000 | 0.0007 | 34866673 | 470760 |
| 8 | 1035 | 0.2497 | 0.0001 | 0.04893698 | 0.0000 | 2,700 | 50 | 55173.0 | 200.3 | 4,500 | 50 | 91954.9994 | 2551.4 | 0.158 | 0.005 | 0.020 | 0.005 | 59.96 | 0.025 | 1.854 | 0.005 | 2.326 | 0.005 | 25.4584682 | 0.005 | 160 | 0.0001 | 32695111 | 29267 |
| 9 | 1035 | 0.2330 | 0.0023 | 0.04261687 | 0.0008 | 4,500 | 50 | 105592.0 | 214.6 | 2,675 | 50 | 62768.5777 | 2830.9 | 0.150 | 0.005 | 0.018 | 0.005 | 58.56 | 0.029 | 1.791 | 0.005 | 2.098 | 0.005 | 17.1412619 | 0.005 | 400 | 0.0002 | 40808502 | 805726 |
| 10 | 1035 | 0.2472 | 0.0008 | 0.04796965 | 0.0003 | 2,800 | 50 | 58370.2 | 202.3 | 4,500 | 50 | 93809.3062 | 2256.7 | 0.168 | 0.005 | 0.022 | 0.005 | 53.81 | 0.028 | N/A | | | | | | 700 | 0.0006 | 24320931 | 164734 |
| 11 | 1050 | 0.2498 | 0.0019 | 0.04898403 | 0.0008 | 3,460 | 50 | 70635.3 | 200.2 | 5,480 | 50 | 111873.193 | 1821.4 | 0.187 | 0.005 | 0.027 | 0.005 | 43.96 | 0.031 | 1.928 | 0.005 | 2.174 | 0.005 | 12.7593361 | 0.005 | 1,000 | 0.0009 | 24017431 | 369980 |
| 12 | 1050 | 0.2538 | 0.0023 | 0.0505494 | 0.0009 | 3,500 | 50 | 69239.2 | 197.0 | 5,420 | 50 | 107221.851 | 1881.3 | 0.184 | 0.005 | 0.027 | 0.005 | 47.42 | 0.030 | 1.624 | 0.005 | 2.076 | 0.005 | 27.8325123 | 0.005 | N/A | | | |
| 13 | 1050 | 0.2470 | 0.0011 | 0.04789207 | 0.0004 | 3,200 | 50 | 66816.9 | 202.4 | 5,400 | 50 | 112753.543 | 1417.2 | 0.212 | 0.005 | 0.035 | 0.005 | 26.33 | 0.035 | 1.750 | 0.005 | 2.070 | 0.005 | 18.2857143 | 0.005 | | | | |
| 14 | 1050 | 0.2556 | 0.0029 | 0.05128512 | 0.0012 | 3,390 | 50 | 66101.0 | 195.6 | 5,400 | 50 | 105293.704 | 1861.0 | 0.185 | 0.005 | 0.027 | 0.005 | 47.61 | 0.031 | N/A | | | | | | 223 | 0.0002 | 21741200 | 490210 |
| 15 | 1050 | 0.2501 | 0.0001 | 0.04909391 | 0.0001 | 3450 | 50 | 70273.5 | 199.9 | 5,490 | 50 | 111826.509 | 1885.4 | 0.184 | 0.005 | 0.027 | 0.005 | 45.98 | 0.029 | | | | | | | 280 | 0.0020 | 2851678 | 3526 |
| 16 | 1095 | 0.2544 | 0.0033 | 0.0508047 | 0.0013 | 4000 | 50 | 78732.9 | 196.5 | 7,400 | 50 | 145655.822 | 1147.5 | 0.236 | 0.005 | 0.044 | 0.005 | 14.23 | 0.043 | 1.528 | 0.005 | 1.696 | 0.005 | 10.9947644 | 0.005 | 700 | 0.0005 | 28704695 | 748545 |
| 17 | 1095 | 0.2549 | 0.0024 | 0.0510046 | 0.0010 | 3200 | 50 | 62739.4 | 196.2 | 7,000 | 50 | 137242.529 | 1124.5 | 0.238 | 0.005 | 0.044 | 0.005 | 12.82 | 0.040 | 1.742 | 0.005 | 1.861 | 0.005 | 6.80748479 | 0.005 | 1,000 | 0.0010 | 19035025 | 358452 |
| 18 | 1095 | 0.2472 | 0.0008 | 0.04796965 | 0.0003 | 5200 | 50 | 108401.9 | 202.3 | 7,000 | 50 | 145925.587 | 1193.6 | 0.231 | 0.005 | 0.042 | 0.005 | 12.68 | 0.038 | 1.739 | 0.005 | 1.881 | 0.005 | 8.16561242 | 0.005 | 260 | 0.0002 | 27100466 | 183816 |
| 19 | 1095 | 0.2490 | 0.0011 | 0.04867079 | 0.0004 | 4100 | 50 | 84239.4 | 200.8 | 7,225 | 50 | 148446.342 | 1193.6 | 0.231 | 0.005 | 0.042 | 0.005 | 13.94 | 0.038 | 1.734 | 0.005 | 1.843 | 0.005 | 6.28604383 | 0.005 | 630 | 0.0005 | 25888220 | 237084 |
| 20 | 1095 | 0.2480 | 0.0005 | 0.04828064 | 0.0002 | 5500 | 50 | 113917.3 | 201.6 | 7,350 | 50 | 152234.933 | 1044.0 | 0.247 | 0.005 | 0.048 | 0.005 | 0.80 | 0.040 | 1.771 | 0.005 | 1.774 | 0.005 | 0.16939582 | 0.005 | 700 | 0.0005 | 28997130 | 116997 |

Table 4. Volume Percent Pearlite in Steels

| Steel No. | AISI/SAE No. | Carbon content(wt%) | Volume percent pearlite | |
|---|---|---|---|---|
| | | | Experiemntal | Theoretical |
| 1 | 1018 | 0.175 ± 0.025 | 27.2 | 20.48 |
| 2 | 1018 | 0.175 ± 0.025 | 15.2 | |
| 3 | 1018 | 0.175 ± 0.025 | 33.4 | |
| 4 | 1018 | 0.175 ± 0.025 | 28.0 | |
| 5 | 1018 | 0.175± 0.025 | 21.0 | |
| 6 | 1035 | 0.35 ± 0.03 | 61.6 | 43.9 |
| 7 | 1035 | 0.35 ± 0.03 | 22.2 | |
| 8 | 1035 | 0.35 ± 0.03 | 66.8 | |
| 9 | 1035 | 0.35 ± 0.03 | 65.2 | |
| 10 | 1035 | 0.35 ± 0.03 | 70.2 | |
| 11 | 1050 | 0.515 ± 0.035 | 80.8 | 65.91 |
| 12 | 1050 | 0.515 ± 0.035 | 87.6 | |
| 13 | 1050 | 0.515 ± 0.035 | 86.6 | |
| 14 | 1050 | 0.515 ± 0.035 | 81.4 | |
| 15 | 1050 | 0.515 ± 0.035 | 75.4 | |
| 16 | 1095 | 0.965 ± 0.035 | 100.0 | 99.7 |
| 17 | 1095 | 0.965 ± 0.035 | 100.0 | |
| 18 | 1095 | 0.965 ± 0.035 | 100.0 | |
| 19 | 1095 | 0.965 ± 0.035 | 100.0 | |
| 20 | 1095 | 0.965 ± 0.035 | 100.0 | |

Determination of the tensile properties of the annealed steels

Please see the table 3 for values.

Calculation

Tensile stress = Tensile load/Area

Yield stress = Yield load / Area

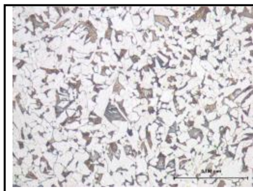
Percent elongation = Changed length/initial length X 100

Percent reduction in area = (initial area- final area)/initial area x 100

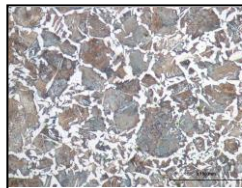
Variation of the volume percent pearlite with the carbon content

Students calculated the theoretical volume percent of pearlite in the various steels. Please see the calculation section to see the example lever rule for theoretical carbon content. Please see Table 4 to see the values of theoretical carbon contents.

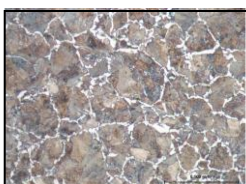
Microstructures of the Annealed Steels



AISI/SAE 1018 Steel



AISI/SAE 1035 Steel



AISI/SAE 1050 Steel

AISI/SAE 1095 Steel

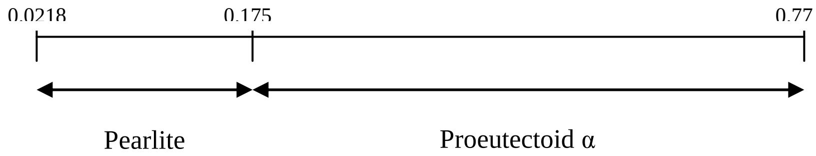
IV. Calculation

B. Modulus of elasticity (E) and its RMS uncertainty $u_E$

C. Yield Strength $\sigma_{ys}$ and its RMS uncertainty $u_{ys}$

D. Percent of elongation %EL and its RMS uncertainty $u_{EL}$

E. Theoretical volume fraction of pearlite in a hypoeutectoid steel




<Hypoeutectoid> wt%C=0.175
Assuming density of ferrite and density of pearlite are same.
Wt% α = (0.175 – 0.0218) / (0.770 – 0.0218) X 100 = 20.48%
Wt % $Fe_3C$ = (0.77 – 0.0218) / (6.7 – 0.0218) X 100 = 79.52 %
Assume 100g is the mass of pearlite

Then 20.48g of α and 79.52 g of $Fe_3C$ is in 100g of pearlite.
Volume occupied by these weights of α and $Fe_3C$
Volume of α = Mass/Density = 20.48 g / (7.86 gm/$cm^3$) = 2.61$cm^3$
Volume of $Fe_3C$ = Mass/Density = 79.52 g / (7.4 gm/$cm^3$) = 10.75 $cm^3$
Total volume occupied by 100gm of pearlite is 13.36$cm^3$
Therefore, density of pearlite equals to 100g/13.36 $cm^3$ = 7.49 g/ $cm^3$

Volume of pearlite is 20.48%.

<Hypereutectoid> wt%C = 0.965
Assuming density of ferrite and density of pearlite are same.
Wt% ferrite = (6.67 – 0.965) / (6.67 – 0.0218) X 100 = 85.8%
Wt % Cementite = (0.965 – 0.0218) / (6.7 – 0.0218) X 100 = 14.12%
Assume 100g is the mass of pearlite

Then 85.8g of ferrite and 14.12 g of cementite is in 100g of pearlite.
Volume occupied by these weights of α and $Fe_3C$
Volume of α = Mass/Density = 85.8 g / (7.86 gm/$cm^3$) = 10.92$cm^3$
Volume of $Fe_3C$ = Mass/Density = 14.12 g / (7.4 gm/$cm^3$) = 1.91 $cm^3$
Total volume occupied by 100gm of pearlite is 12.83 $cm^3$
Therefore, density of pearlite equals to 100g/12.83 $cm^3$ = 7.794g/ $cm^3$

Volume of pearlite is 85.8%.

F. Brinell hardness (BHN) and its RMS uncertainty $u_{BHN}$

IV. Discussion

1. Using calculations justify the assumption that the density of ferrite is the same as that of pearlite, which was used in the calculation of the theoretical volume fraction of pearlite.

The assumption that justifies calculations is that the density of ferrite is the same as that of pearlite which can show that the theoretical density of the pearlite is about the same as that of the ferrite(alpha phase). [2]

Calculations

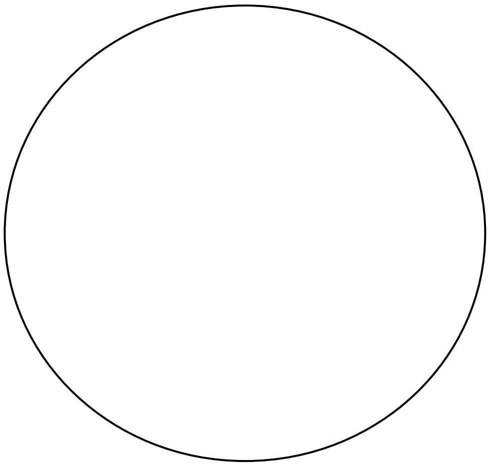
Wt % $\alpha$ = (6.7 – 0.77) / (6.7 – 0.0218) X 100 = 88.8 %
Wt % $Fe_3C$ = (0.77 – 0.0218) / (6.7 – 0.0218) X 100 = 11.2 %
Assume 100g is the mass of pearlite

Then 88.8g of $\alpha$ and 11.2 g of $Fe_3C$ is in 100g of pearlite.
Volume occupied by these weights of $\alpha$ and $Fe_3C$
Volume of $\alpha$ = Mass/Density = 88.8 g / (7.86 gm/cm$^3$) = 11.30 cm$^3$
Volume of $Fe_3C$ = Mass/Density = 11.2g / (7.4 gm/cm$^3$) = 1.51 cm$^3$
Total volume occupied by 100gm of pearlite is 12.81 cm$^3$
Therefore, density of pearlite equals to 100g/12.81 cm$^3$ = 7.81 g/ cm$^3$

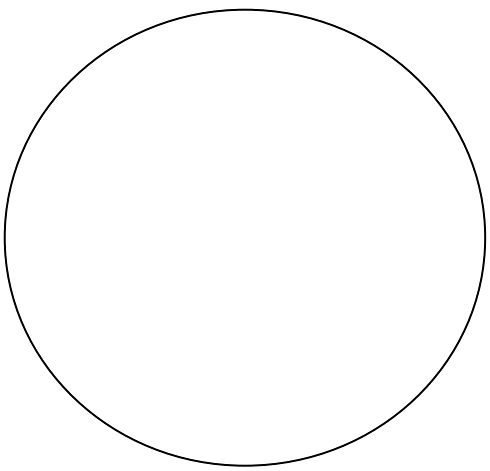
In conclusion, the density of α, 7.82gm/ $cm^3$ and density of pearlite is similar.  This makes sense because alpha phase is the most composition of pearlite.

2. Using the phase diagram to describe how the microstructure of the annealed AISI/SAE 1045 steel develops on slow cooling from 870 °C.

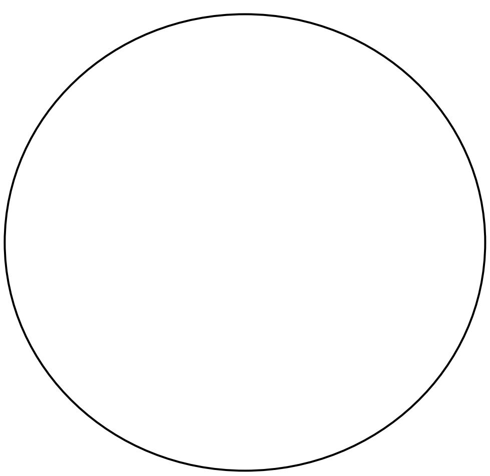
Description of microstructural changes in AISI/SAE 1045 on slow cooling. (please see the diagram of weight percent carbon vs. temperature) [1, 4]



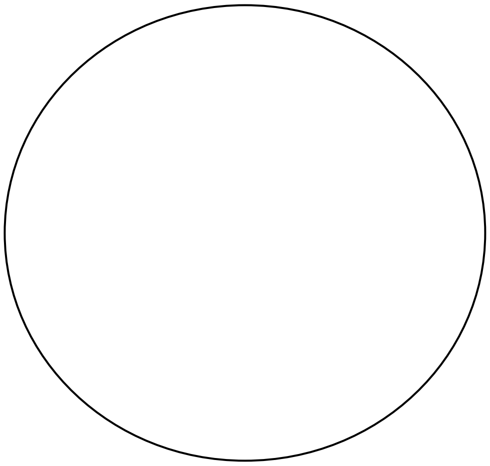
First, during the process of cooling from 900°C to just above the A3 line at 780 °C, the alloy is 100wt% gamma phase austenite.



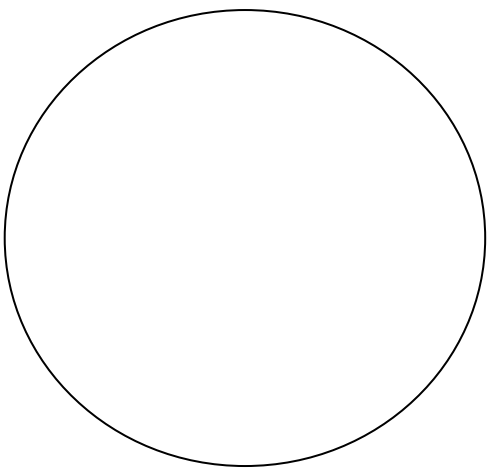
Second, during the process of cooling to just below A3 line, α phase contains less than 0.02 wt% carbon which gets starting to form on the γ phase grains.



Third, during the process of cooling from A3 line down to just above the A1 line, the amount of α phase increases.  On the other hand, the amount of γ phase decreases.  The carbon content of the α phase increases to about 0.02wt% carbon while that of the Fe3C increases the about 0.8 wt% carbon.



Fourth, during the process of cooling through the A1 line which represents eutectoid, every γ phase decreases.  The carbon content of the α phase increases to about 0.02 wt% carbon during the $Fe_3C$ increases about 0.8wt% carbon.



Finally, in the further cooling process to room temperature, the structure and phases maintain the state.  In other words, nothing changes.

3. Explain how increasing the cooling rate from 870°C by air cooling (normalizing) rather than furnace cooling would affect the microstructure of the 1045 steel.  Explain your answer.

The faster cooling rates of air cooling during normalizing results shows a finer pearlite lamellar spacing, a greater amount of pearlite (but difficult to notice), and a finer ferrite grain size than slow furnace cooling. [3]

4. Explain how increasing the cooling rate from 870°C by air cooling (normalizing) rather than furnace cooling would affect tensile strength and hardness of the AISI/SAE 1045 steel.  Explain your answer.

The smaller pearlite spacing and ferrite grain size resulting from normalizing, the higher strength and hardness because it contains more pearlite.  Because grain boundaries tend to prevent slip, decreasing the grain size (increasing the total grain boundary area) tends to retard slip and thus increases the tensile strength and hardness of the metal. [2.3]

Reference

[1] ***Metals Handbook***, 9th Ed., 9, ***Metallography and microstructures***, Amer. Soc. Metals, Metals Park, Ohio.

[2] Krauss, G., **Principle of Heat Treatment Steel**, 1980, Amer. Soc. Metals, Metals Park, Ohio.

[3] **Alloying Elements and Their Effects and Hardenability**, 1961, Republic Steel Corporation, Cleveland, Ohio.

[4] Smith, W.F., 2004, ***Foundations of Materials Science and Engineering***, 3rd Ed., McGraw-Hill, New York.