Heat of the Moment:
Effects of Quenching Temperature and Carbon Content on Steel Hardness

Elijah Bell

5/11/24
2.671 Measurement and Instrumentation
Wednesday AM
Prof. Sili Deng

Abstract

Steels in their natural state lack the hardness and corresponding strength to be practically useful in many potential applications. To overcome this deficit, a hardening process is employed, which involves heating and then rapidly cooling (quenching) the steel, thereby altering its molecular structure and thus mechanical properties. To investigate the effect of quenching temperature and carbon content on hardness increase after quenching, three different variations of steel (1018, 1045, and O1) with 0.18%, 0.45%, and 0.85% carbon content respectively, were hardened at 5 distinct temperature set points. The samples were then analyzed through a Rockwell Hardness tester. Hardness after quenching increased with carbon content at all temperatures tested, with maximum increase from 1018 steel (0.18%C) to O1 steel (0.85%C) of about 15 HRA at 800°C. 1045 and 1018 steel both exhibited inverted parabolic behavior with respect to temperature with a maximum hardness increase at a temperature of 880-920°C. O1 steel exhibited no change in hardness increase with temperature.

Keywords:
Heat Treatment, Quenching, Mechanical Properties, Steel, Hardness

1. Introduction

Steel has become ubiquitous since the 17^{th} century, being used in projects ranging as wide as construction, tool making, and art installations. For projects such as knives, machining tools, and even railroad tracks, which need a higher hardness than steel can naturally offer, steel's hardness can be increased by heating and cooling the metal in a process called heat treatment. This process involves heating the metal and then rapidly cooling it by plunging, or quenching, the metal into a bath of liquid, typically water. The rapid temperature change alters the microscopic structure within the steel, resulting in a higher hardness and strength. It is through heat treatment that knives can stay sharp and machining tools don't dull.

To ensure the steel can be properly hardened, selecting an appropriate quenching temperature is crucial in determining the qualities of the resulting heat-treated metal. A temperature that's too high might result in too long of a cooling time, while a lower temperature might not result in enough molecular reconfiguration before the cooling. Both situations mean a lower final hardness for the steel. Additionally, the steel's final hardness is heavily affected by its carbon content, with a higher carbon content meaning a higher hardness.

To examine how the quenching temperature and carbon content affect the resulting hardness, 1018, 1045, and O1 steel were selected for their common usage in industry as well as for representing a range of carbon content, 0.18%, 0.45%, and 0.85% respectively. Each of the steels were prepared and put through the quenching procedure at different temperatures. The samples were then tested for hardness and the data was then analyzed to find the optimal temperature for maximum hardness and find how hardness varied with carbon content. The resulting fit curves could then be used to predict the hardening performance of other steels with carbon contents not tested in this study.

Given the long prevalence of steel, the literature is extensive on the various details of the molecular structure, mechanical properties, and modification of hardened steel. As such, hardness as it varies against carbon content [7] and against quenching temperature [5][6] have both been studied before, albeit separately. Additionally, information about the mechanical, thermal, and electrical qualities of a specific alloy of steel is readily available at online for reference[8]. Computer models have been designed and analyzed for forecasting the mechanical process of quenching steel, although they struggle with the complex intermolecular structures that primarily control hardness [4]. However, literature is missing specifically the quenching performance across this wide of a range of temperatures, most studies limit their zone of research to 900-1050°C. Studies also lack providing the parameters of curve fits to their equation for use in predicting untested steels within the tested range.

Using the fit curves of hardness against quenching temperature and carbon content, more informed decisions can be made in selecting or predicting the most suitable steels for a desired product or process.

2. Background

Carbon steel as an alloy which is composed of primarily iron, with a smaller addition of carbon. Within steel in its unhardened form, known as annealed steel, these elements take two forms: iron in the metallurgical form of *ferrite*, and carbide (composed of elemental carbon) in the metallurgical form of *cementite.* Cementite consists of 6.67% carbon and 93.33% iron, while ferrite is 99.97% iron and up to 0.03% carbon. Within steel, these two exist in a mechanical mixture, composed of layers, named *pearlite.* Pearlite is 0.85% carbon and 99.15% iron [1].

When steel is heated to a temperature on the range of 700 °C, the layers of ferrite and cementite within the pearlite begin to merge together, eventually forming *austenite*. If steel is heated to the point where it contains only austenite, and is then cooled down slowly, it will return to its original proportional of ferrite, cementite, and pearlite. However, if it is cooled down quickly, the austenite will begin to not separate fully and will instead form smaller and smaller layers within its pearlite. Eventually, when the cooling rate is on the order of 500°C/s, the austenite will no longer be able to fully change back to pearlite, and will instead become a new structure: *martensite*. Characterized by a much higher hardness, and relatively high brittleness, steel in martensite form becomes practical to make tools out of. By increasing the hardness from the ~60 HRA of unhardened steel to the ~80 HRA of martensite, the steel becomes significantly less susceptible to dulling. These described phase transitions are visualized within Figure 1.

The ratio of ferrite, cementite, and pearlite is controlled by the ratio of iron to carbon within the material. At the ratio where the iron and carbon are in balance and all that exists is pearlite, the steel is called *eutectoid*, this happens at ~0.85%C. When the steel has less carbon than that it is called *hypoeutectoid*, in the range $0\% < C < 0.85\%C$. When the steel has more carbon than eutectoid, it is called *hypereutectoid*, in the range $0.85\% < C < 2.5\%$. Beyond the 2.5% level are alloys like cast iron or pig iron. These steels are typically not quenched, as their high carbon content gives them a naturally high hardness, albeit a high brittleness too.

When a eutectoid steel is heated to the temperature point where it first becomes fully austenite, hypoeutectoid and hypereutectoid at the same temperature would exist as a ratio of austinite and ferrite or austenite and cementite respectively. This is because the non-eutectoid steels require a higher temperature to convert the excess non-pearlite into austenite. Since the end goal of martensite is higher hardness, eutectoid steels are thus often used for tool steels.

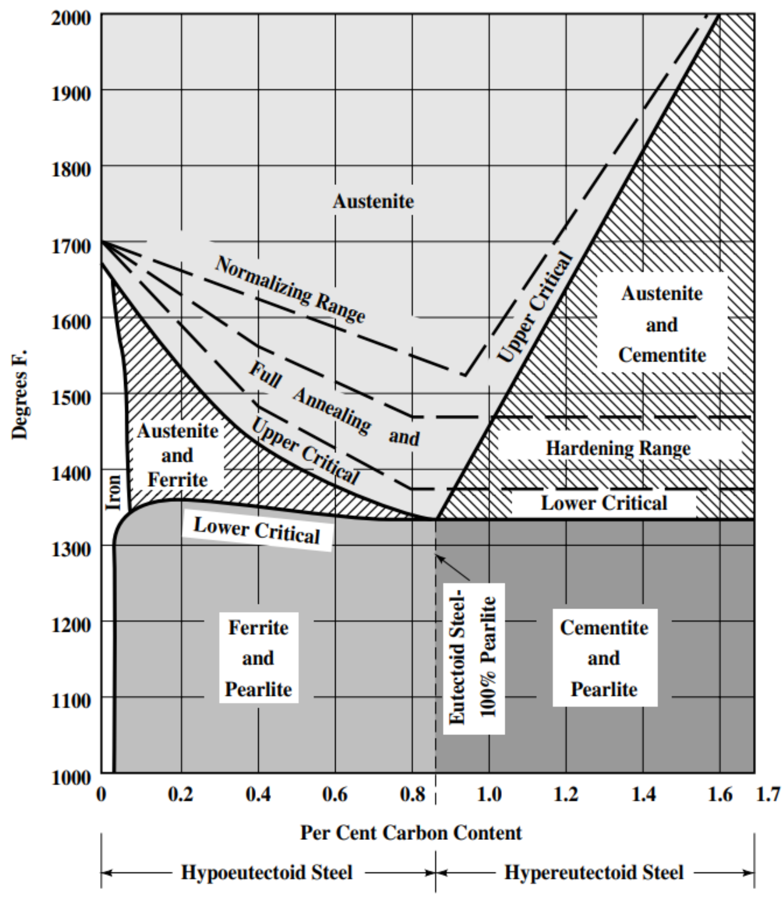

Figure 1: A Phase Diagram for Carbon Steel showing the transition points and chemical makeup as the steel is heated to certain temperatures at a given carbon content percent. **Add more to this so it makes sense as a single unit fig+caption, repeat info in paragraph above**

However, the high brittleness of fresh martensite can cause tools to chip or shatter. In order to reduce the brittleness of the martensite, the steel is then normally put through a *tempering* process where the steel is then heated up to a lower temperature ~240°C after the quenching [2]. It is then held there for considerable time, ~4 hours, before bringing it back to room temperature. By holding it at a high temperature, the internal stresses can relax and the size and distribution of the carbides withing the metal is altered. Tempering thus sacrifices some hardness for a greater decrease in brittleness, thereby increasing the ductility of the metal. In total, the treatment cycle for a piece of steel will follow a temperature-time profile as show in Figure 2.

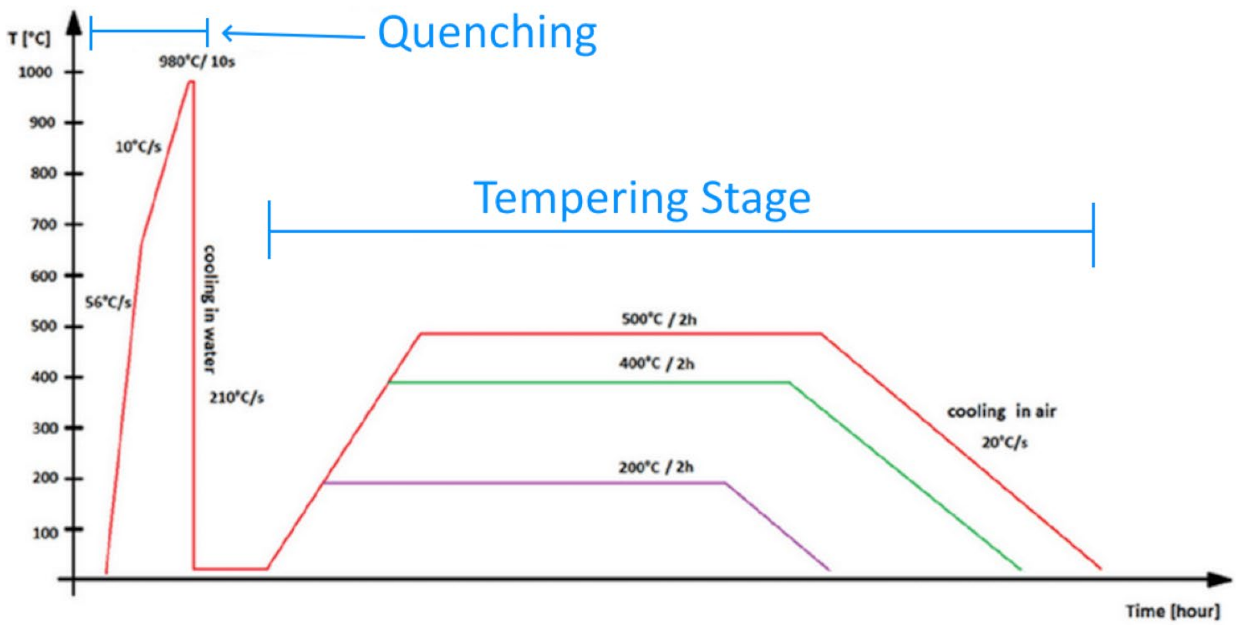

Figure 2: Temperature-time profile of the quenching and tempering process. Quenching occurs first, and heats up the steel to a high temperature before cooling very rapidly to produce a hard metal. To reduce the brittleness in the hardened steel, it undergoes a tempering where it is heated up to a lower temperature, held there for several hours, and is then cooled down slowly. Tempering sacrifices some of the hardness for useful ductility.[3]

3. Experimental Design

To analyze the hardness at different quenching temperatures and carbon contents, 6 samples each of O1, 1045, and 1018 steel were prepared from bar stock supplied from McMaster-Carr. These steels were selected for their range of carbon contents (0.85%, 0.45%, and 0.18% respectively) and their wide spread use in industry. O1 steel actually contains other alloying elements such as Mn, Cr, and W. However, it has been shown that the maximum attainable hardness of any steel depends solely on carbon content and is not significantly affected by alloy content [1]. For each of the steels, five of the samples were then heated to 800, 850, 900, 950, and 1000°C with one sample reserved as a control and was not put through the quenching process.

For each desired quenching temperature, one sample each of O1, 1045, and 1018 was heated for 10 minutes to ensure full heat penetration into the sample. After heating, the samples were quickly taken out of the furnace and quenched into a metal bucket with room temperature (20°C) water and moved in a swirling motion. They were removed from the water after being cool to the touch, roughly 10 seconds.

Each sample was then evaluated for hardness on a Clark DXT-1 Rockwell Hardness Tester by taking 4 measurements per sample, one per side. The HRA scale was used, to accommodate the high hardness of the heat-treated steels. A diagram of this full process can be seen in Figure 3.

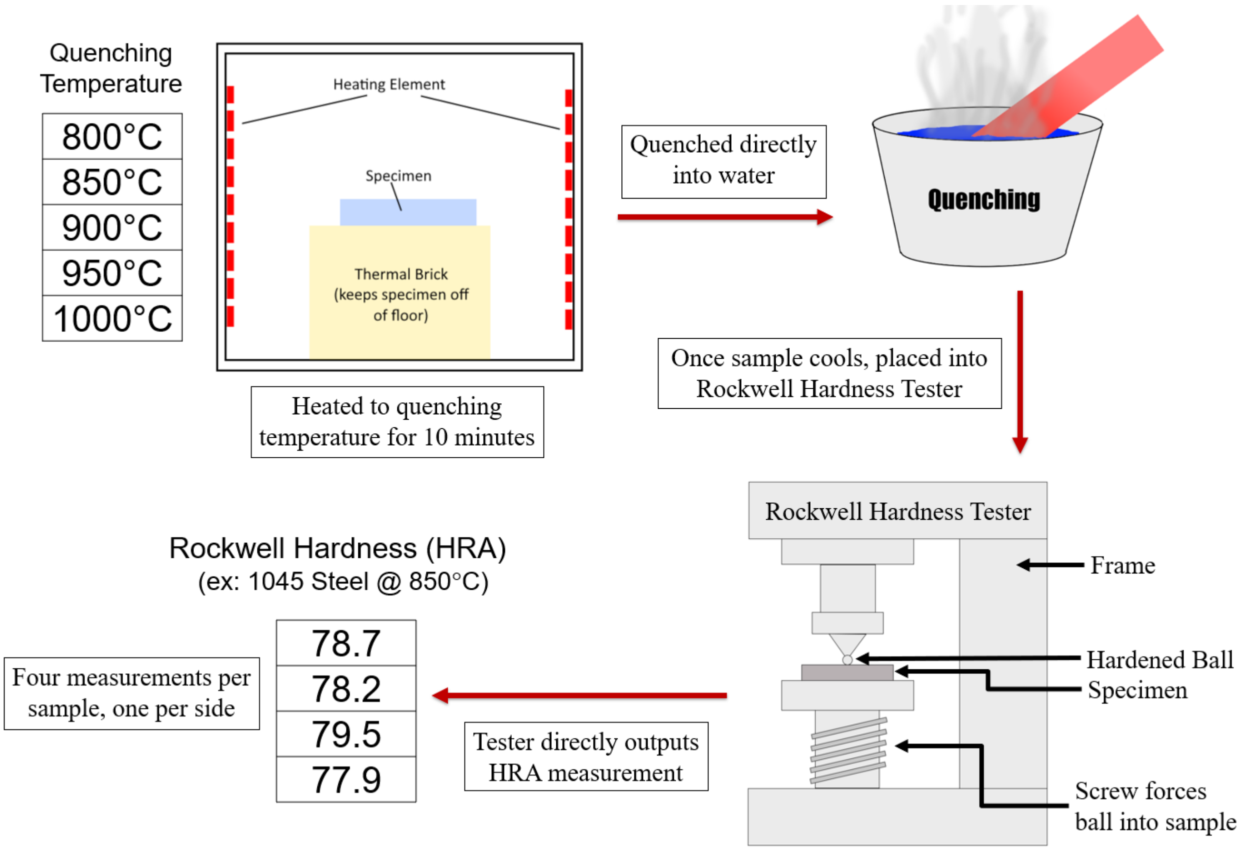

Figure 3: Each specimen is first placed into a furnace set to the desired quenching temperature and allowed to heat thoroughly over 10 minutes. It is then quenched in a bucket of water. After cooling fully, it is removed and placed into a Rockwell Hardness Tester where four measurements on the HRA scale are taken, one per side.

While the Rockwell hardness tester used directly outputs the HRA scale hardness of the tested substance, it can be useful to understand how Rockwell hardness is defined. The hardened ball shown in Figure 3 is pressed into the specimen with a specific force. That force is then released to allow for elastic deformation to reset, and then the resulting displacement is measured. The hardness rating is a function of the depth the ball travels. This procedure is presented in Figure 4, and the governing equation in Eq 1, with HRA's equation described in Eq 2.

$$H = N - hd \tag{1}$$

$$HRA\ Scale: N = 100, h = 500, F\_m = 60N \tag{2}$$

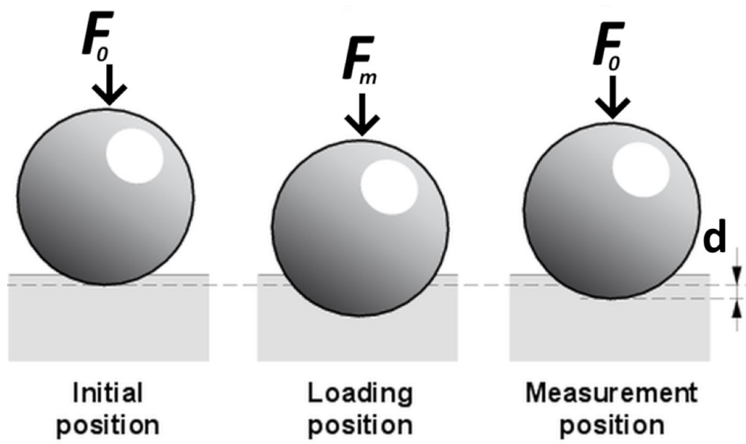

Figure 4: A zoomed-in view of the measuring process for Rockwell hardness. First elastic strain is "taken-up" with an initial force F_0, the ball is forced into the specimen with force F_m to produce a plastic deformation. After allowing to settle, the force is relaxed back to the elastic strain only F_0. The final displacement is the variable d used in Eq 1.

The Rockwell hardness scale has different scales one can select for the hardness of the object they are measuring, with HRA and HRC being the commonly used for steels. The scales set N, h, and force F_m with which the ball is forced into the sample.

The desired end observation for each test was hardness increase, which was defined as shown in Eq. 3 where $H_{initial}$ is the averaged hardness measured from the unhardened control specimen:

$$\Delta H = H_{quenched} - H_{initial} \tag{3}$$

4. Results and Discussion

Once data was collected, it was possible to then analyze the hardness for each of the steels as it varied across the studied temperature range and deduce how hardness is affected by both carbon content and quenching temperature. All steels were successfully hardened, with the hardening increase varying from $9 - 25 \pm 1$ HRA across all samples. The following table present the steels maximum hardness and the conditions under which it occurred with 95% uncertainty bounds:

Table 1: Maximum Hardness for O1, 1045, and 1018 with the corresponding quenching temperature required.

Steel Type	Carbon Content	Initial Hardness	Max Hardness Increase	Quenching Temperature for Max Hardness
O1 Steel	0.85%	57.1 ± 0.8 HRA	24.1 ± 0.5 HRA	All tested (800-1000°C)
1045 Steel	0.45%	60.6 ± 0.6 HRA	18 ± 1 HRA	888 ± 25 °C
1018 Steel	0.18%	58.5 ± 1.4 HRA	15 ± 1 HRA	915 ± 15 °C

4.1 Hardness vs Quenching Temperature

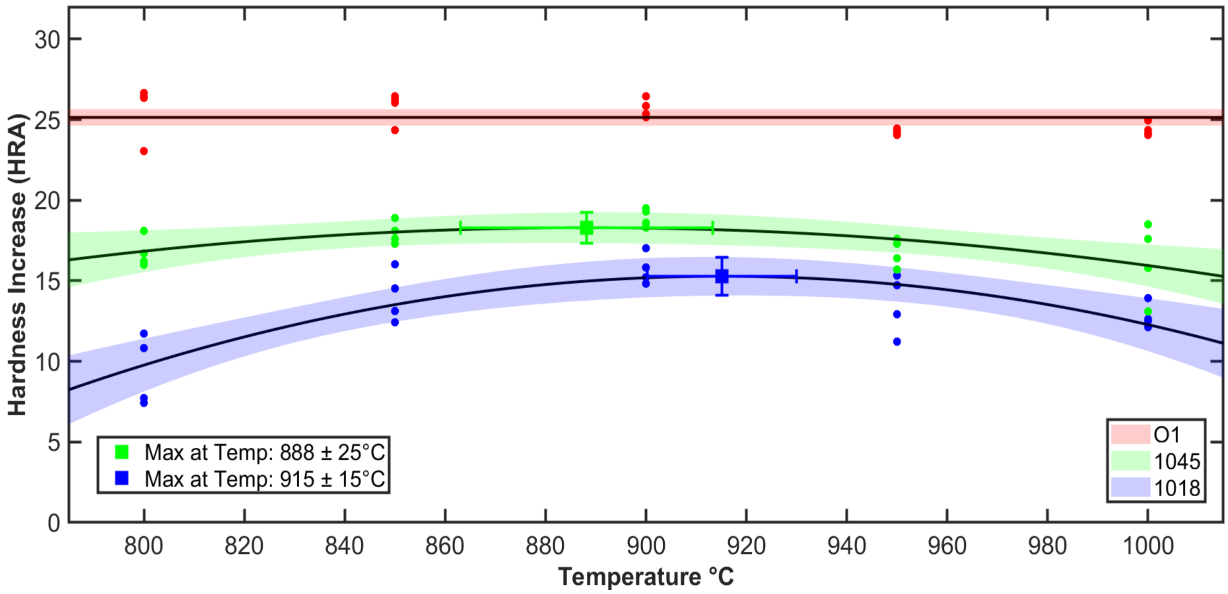

Figure 5: Hardness increase against quenching temperature for O1, 1045, and 1018 steels. A quadratic curve of best fit has been set to 1045 and 1018 with uncertainty shaded. O1's hardness increase showed no statistically significant dependence on quenching temperature, so the mean value with uncertainty is plotted instead. All parameters shown in Table 2. For 1045 and 1018, the maximum hardness reached was at 888 $\pm$ 25°C and 915 $\pm$ 15°C respectively.

The steels each showed differing relationships of hardness to temperature, with 1045 and 1018 having inverse parabolic fits while O1's hardness increase showed no statistically significant dependence on quenching temperature. For 1045 and 1018, the maximum hardness reached was at 888 $\pm$ 25°C and 915 $\pm$ 15°C respectively. Quenching temperatures beyond those points resulted in a lower hardness. The curve of fits following the equation $a * x^2 + b * x + c$ are presented with 95% uncertainty in Table 2. If a term is statistically insignificant, it is marked N/A:

Table 2: Parameters for a quadratic curve of fit for O1, 1045, and 1018 Steel hardness against quenching temperature.

Steel Type	a Term ($HRA/Temp^2$)	b Term ($HRA/Temp$)	c Term (HRA)
O1 Steel	N/A	N/A	24.14 ± 0.54
1045 Steel	$(-1.9 \pm 1.5) * 10^{-4}$	0.33 ± 0.27	-130 ± 120
1018 Steel	$(-4.2 \pm 1.9) * 10^{-4}$	0.76 ± 0.33	300 ± 150

A study into other research of steel's hardening performance at different quenching temperatures is inconclusive. Some studies report a monotonically increasing hardness as temperature increases [12]. Others report strength, which is linearly correlated with hardness, decreasing monotonically after 900°C [6]. Even more report that the hardness is inverse parabolic, but with the inflection point at a higher temperature than we observed, instead around 1000°C [13][5].

For our research, the parabolic behavior has two primary explanations: burning & cooling time.

Steel burning occurs when steel is heated to high temperatures in an environment with oxygen. The carbon within the steel at these high temperatures is able to react with the oxygen in the air and decarburize the steel, leaving a black carbon residue on the surface as a result [1]. This residue is softer than the hardened steel, and although it is rather thin, it is possible that the hardness tester was also outputting a lower hardness because it was accounting for the hardness of the film too. This would explain the trend for a lower hardness reading at higher temperatures, which when the burning happens quicker. By rerunning the experiment in an anoxic furnace, this effect would be eliminated, helping identify the cause.

The other cause is due to cooling time. As explained in the Background, in order for steel to harden it must quickly go from the austenite to martensite structures. If this process takes too long, the steel will not be able to transition into a full martensite, and instead it will have more cementite or ferrite within it. These additions will decrease the hardness of the metal, since they lower the strength of the grain structure. This also successfully explains why O1 steel has no parabolic behavior, it's a eutectoid steel. When O1 is quenched, it will not separate into martensite + ferrite/cementite, since the ferrite and cementite are in the ideal ratio to form pearlite. Thus, as long as one reaches the minimum required temperature to pass into the austenite phase, it is to be expected that any further increase will not alter the final hardening temperature.

4.2 Hardness vs Carbon Content

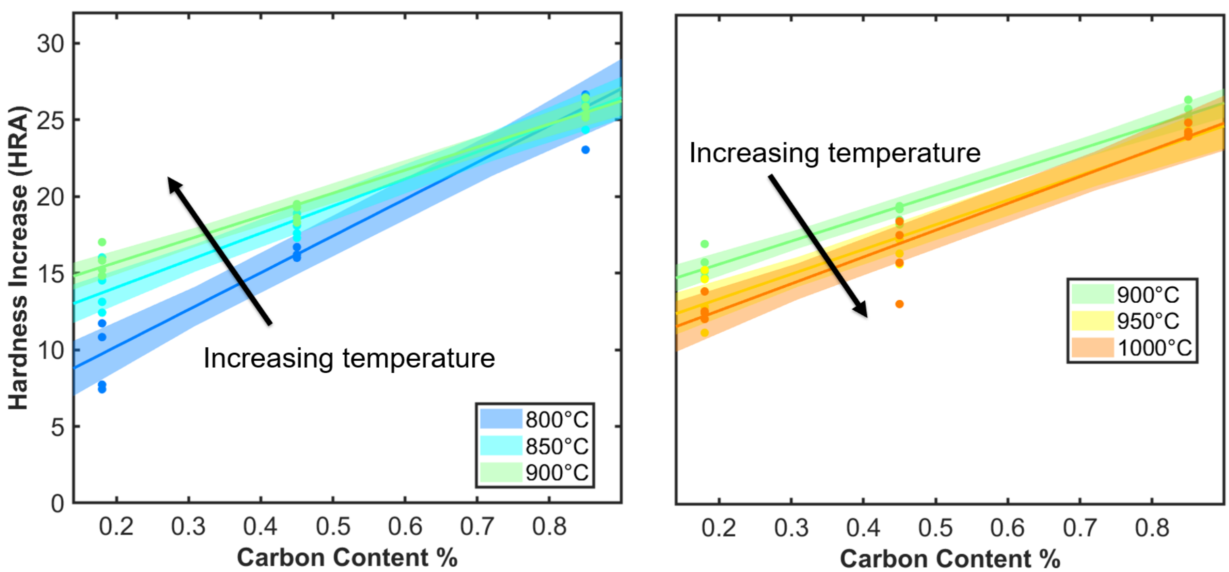

Figure 6: Hardness increase after quenching against steel carbon content. Hardness increase is shown to linearly increase with carbon content for all temperatures. The average slope for all temperatures is 17.2 ± 1 HRA/°C with individual slopes and intercepts being shown in Figure 7.

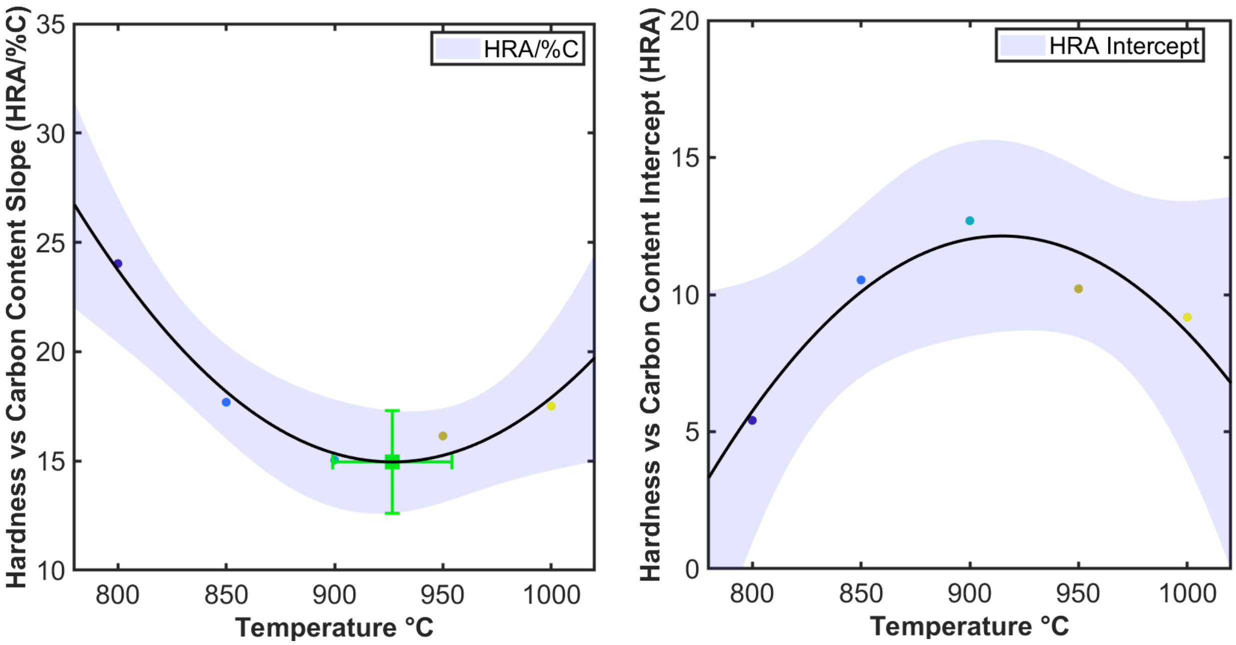

Figure 7: Plots of the slopes and intercepts of the fit curves shown in Figure 6. Both the slope and intercepts showed parabolic behavior, with slopes showing positive concavity and intercepts showing negative concavity. Minimum carbon content dependence occurred at 926°C ± 27°C. Both graphs thus had quadratic fits applied with parameters shown in Table 3.

The hardness increase as a function of carbon content was then analyzed by plotting and taking a linear line of best fit. In Figure 6, the hardness improvement after quenching is shown to linearly increase with carbon content across all temperatures studied. The average slope for all temperature fit lines is 17.2 ± 1 HRA/°C. Both the slope and intercept of the curves varied parabolically with temperature, with slopes showing positive concavity and intercepts showing negative concavity.

Both theory and published data agree that hardness should increase with carbon content. Theory holds that the higher the carbon content the more of the hard cementite will help prevent slip boundaries from occurring within the molecular lattice of the martensite. Preventing these slip boundaries from forming reduces the amount of deformation the steel experiences when a force is applied, which is definitionally a higher hardness. The data collected here agrees with published results within the range of carbon content tested (0.18%-0.85%). Although some studies show that the relationship of hardness to carbon content is logarithmic and flattens off soon after 1.0% [11][7], others show a parabolic curve with the peak at 1.0% and the hardening performance dropping off on both sides [9]. But all studies agree that for the carbon content range studied within this work[10], hardness has a positive linear increase with carbon content.

The quadratic nature of the slope and intercept can be explained by observing Figure 5. As the temperature passes out of range of the ideal quenching temperature, the hardness becomes more dependent on the carbon content being high enough to compensate for imperfect temperature. The intercept is higher at the ideal quenching temperature and lower elsewhere as it is a reviewing of the same data from Figure 5.

5. Conclusions

The highest carbon content steel, O1, (0.85% C) exhibited a constant increase in hardness of 25 ± 1 HRA, independent of quenching temperature. 1045 and 1018 steel both exhibited inverted parabolic hardness behavior with respect to temperature. The temperature at maximum hardness was 888 ± 25 °C for 1045 Steel (0.45% C) and 915 ± 15 °C for 1018 Steel (0.18% C). The maximum hardness increase for the two steels was 18 ± 1 HRA and 15 ± 1 HRA, respectively.

An increase in carbon content in steel led to a linear increase in hardness after quenching. The slope and intercept of fit lines of hardness against carbon content varied parabolically with temperature, with slopes showing positive concavity and intercepts showing negative concavity Future work could review how hypereutectoid steels perform in quench hardening as this study was limited to eutectoid and hypoeutectoid steel in the range (0.18%-0.85%).

With knowledge of steel's performance in this common range of carbon contents, it becomes possible to predict the performance of a steel not yet tested, which could be useful in developing new alloys or engineering projects. This paper contributes to a large body of work which is critical in allowing scientists and engineers work with the best materials for the job.

Acknowledgments

I would like to thank Kate Parsons, Prof. Sili Deng, and Pierce Hayward for their guidance and help in this project.

References

[1] Oberg Erik Franklin D Jones Holbrook Lynedon Horton and Henry H Ryffel. 1988. *Machinery's Handbook : A Reference Book for the Mechanical Engineer,* 23rd ed. rev. ed. New York: Industrial Press. p. 479-501

[2] Fares, M.L. & Moussa, Athmani & Khelfaoui, Y. & Khettache, Abdelkader. (2012). An investigation into the effects of conventional heat treatments on mechanical characteristics of new hot working tool steel. IOP Conference Series: Materials Science and Engineering. 28. 012042. 10.1088/1757-899X/28/1/012042.

[3] Effects of Silicon, Chromium, and Copper on Kinetic Parameters of Precipitation during Tempering of Medium Carbon Steels, Fig 1 [accessed 1 Mar, 2024]

[4] Wang, K. F., Chandrasekar, S., and Yang, H. T. Y. (August 1, 1997). "Experimental and Computational Study of the Quenching of Carbon Steel." ASME. J. Manuf. Sci. Eng. August 1997; 119(3): 257–265.

[5] Zhu, Qt., Li, J., Shi, Cb. et al. Effect of Quenching Process on the Microstructure and Hardness of High-Carbon Martensitic Stainless Steel. J. of Materi Eng and Perform 24, 4313–4321 (2015). Fig 4.

[6] Long, Shao-lei & Liang, Yi-long & Jiang, Yun & Liang, yu & Yang, Ming & Yi, Yan-liang. (2016). Effect of quenching temperature on martensite multi-level microstructures and properties of strength and toughness in 20CrNi2Mo steel. Materials Science and Engineering: A. 676. 10.1016/j.msea.2016.08.065. Fig 10a.

[7] J. L. Burns, T. L. Moore, and R. S. Archer, Transactions of American Society for Metals 26, 14 (1938).

[8] *AISI 1018 Steel, hot rolled, quenched, and tempered*. MatWeb. [accessed 5 May, 2024] https://www.matweb.com/search/datasheet.aspx?matguid=e60983fcde914b278ceffebb946995e6

[9] Litwinchuk, A., Kayser, F.X., Baker, H.H. et al. The Rockwell C hardness of quenched high-purity iron-carbon alloys containing 0.09 to 1.91% carbon. J Mater Sci 11, 1200–1206 (1976). https://doi.org/10.1007/BF00545136. Fig 5

[10] Technology Properties and Applications of Niobium Carbide Reinforced Steel and Iron Alloys- Scientific Figure. Fig 6.

[11] Heat Treatment of Plain Carbon Steels, L.H. Van Vlack 1989, http://mat_manf.tripod.com/426/lab5.htm Figure 1

[12] Microstructure and Mechanical Properties of Dual-Phase Steel/ Mikrostruktura I Własności Mechaniczne Stali Dwufazowej. Fig 5

[13] An investigation into the effects of conventional heat treatments on mechanical characteristics of new hot working tool steel. Fig 6