The Effects of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

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Abstract

This research examines the effect of austenitizing and stress relieving temperatures on the Austenite grain size and hardness of martensitic stainless steel. A grade 420 stainless steel product, with controlled carbon content was examined. Samples were austenitized at four different temperature ranges from 1800°F to 1900°F. The samples were gas quenched with nitrogen and stress relieved to a range from 400°F to 600°F in increments of 50°F and held for one hour. Both ASM and ASTM standards were used to measure the hardness and the grain size. The results indicate that the grain size and hardness increase as austenitizing temperature increases. The hardness decreases as stress relieving temperature increases at any austenitizing temperature. After collecting the test results, we recommend the heat treatment of austenitizing temperature of 1825°F and stress relieving temperature of 450°F. However, our sponsor may investigate more for better heat treatment temperatures and times.
Acknowledgements

I would like to thank Professor Richard D. Sisson Jr. for his advice and guidance throughout the duration of this project. I would also like to thank Dr. Boquan Li for his assistance in ensuring that I had the necessary equipment and training to complete this project. In addition I would like to thank Yuan Lu for his assistance with the analysis of the X-Ray Diffraction for determining amount of retained austenite.
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1. Introduction

Grade 420-stainless steel is high-carbon, martensitic, stainless steel with minimum chromium content of 12%. Like any other martensitic stainless steel, grade 420 can also be hardened by heat treatment to enhance mechanical properties. It offers good ductility in its annealed state and excellent corrosion resistance properties when the metal is polished, surface grounded or hardened. Grade 420-Stainless steel has the highest hardness, 500 HV, among all the stainless steel grades with 0.15% Cabon, 12-14% chromium, 1% Manganese and Silicon. Martensitic stainless steels have high hardness and high carbon content. These steels are generally fabricated using methods that require hardening and stress relieving treatments. [1]

During this project the team investigated different methods to optimize the heat treating method to improve its mechanical properties. This will be accomplished through different austenitizing temperatures on the quenched and stress relieved metallurgical structure of the product. Furthermore, effects of the stress relieving temperatures have on the final properties such as hardness, which will effect ductility and shear strength.
2. Background

Martensitic stainless steels are alloys of chromium and carbon that have body centered tetragonal (BCT) crystal structure in the hardened condition. They are ferromagnetic, and hardenable by heat treatments and have good corrosion resistance in mild environment. Carbide (M$_2$C$_6$ & M$_7$C$_3$) may be introduced into the steel to increase wear resistance.

At elevated temperatures, Austenite is the microstructure of the martensitic stainless steels. However, at room temperature a mixture of ferrite and carbide is the equilibrium microstructure. Upon heating, Austenite (FCC) formation occurs rapidly. On the other hand, when steel is cooled rapidly from austenite, the FCC structure rapidly changes to BCT or BCC leaving insufficient time for the carbon to form pearlite.

Heat treatment of Martensitic stainless steel is essential to achieve improve strength, fracture toughness, and hardness depending on the carbon content. Martensitic stainless steels are sensitive to heat treatment variables. Before any heat treatment, prior cleaning is required to avoid contamination from oil, grease and any source of carbon. Martensitic stainless steels are hardened by heating to around 1000°F (540 °C) then austenitized to heating range of 1700-1950°F (925-1065 °C). After austenitizing, martensitic stainless steels are quenched with oil or air. [1]

The heat treatment results in high strength, Hardness, wear and corrosion resistance. Those properties make martensitic stainless steels desirable for
applications like cutlery products and some dynamic applications. Our sponsor uses
AISI 420 Stainless Steel to produce their product with different properties for
various industrial applications.
3. Experimental Plan

Our goal is to develop a stress relieving process to optimize the time and temperature it takes for stress relieving, while maximizing the quality of the part.

3.1 Current Procedure

Currently, our sponsor’s heat-treating process for the 420-Stainless steel product is listed below.

1. All parts cleaned in a solvent bath to remove all traces of oil prior to heat treatment.
2. Part placed into a vacuum furnace.
3. Preheat part to 1,450°F and hold for 45 minutes.
4. Parts are heated to 1,850°F and held for 1 hour.
5. Nitrogen quench at 4.5 bars to 150°F.
6. Stress relieve at 500°F for 3 hours.

The current process is takes place within a vacuum furnace and takes approximately 10-11 hours to complete this process. Figure 1 shows the complete process with temperature virus with time.
After discussing with our sponsor, the areas that they want us to focus on are increasing the austenitizing temperature in order to determine its effects. However, to quench the material, it must be cooled back to 1,850°F so there will not be significant warpage or cracking during quenching. Another area they want us to focus on is increasing the stress relieving temperature in order to determine its affects. However, before experiments begin, it is important to know how the material behaves during heat treatment, and how to prepare for heat treatment. This is discussed in the subsections below.

### 3.2 Cleaning and Preparation

Prior to heat treatment, it is important to clean the specimens that will be undergoing the treatment to avoid contamination of the part during heat treatment. Contamination from grease, oil, and even lead from a pencil can carburize within the material causing it to have different properties than expected. “Perspiration strains from fingerprints are a source of chloride contamination and may cause severe scaling in oxidizing atmospheres.” [1]
3.3 Pre-heating and Heat Transfer

Typically, martensitic stainless steels are heated into the Austenite range. However, due to the high amount of carbon content and low thermal conductivity, the austenitizing range can be much higher than typical carbon steels approximately 1796°F-1949°F (980°C-1065°C). Therefore, before heating the material to the austenitizing range it must be preheated first. The preheat temperature range is usually 1400°F-1454°F (760°C-790°C). If material is not preheated it can cause warpage and cracking within the part. When preheated, it is important to ensure a uniform heating to all portions of the work-piece. [1]

3.3.1 Furnaces

Furnaces are an important variable in the heat treatment of stainless steels. They can impact heating time, overall time, and price of the heat treatment. Currently, our sponsor uses a vacuum furnace, however, the other furnaces are described below. All will be taken into consideration during our experiments. [2]

**Oven or Box Furnace**

The oven or box furnace is your standard furnace. The parts are usually loaded by hand onto a rack and pushed into the furnace chamber, then heated. This furnace is a very simple method and the furnace itself is relatively cheap. However, it is a longer process because of the hand loading and unloading of the parts. In a manufacturing environment this can be a bottleneck and hurt the manufacturing process.
Retort Furnace

This furnace is a vertical furnace with a metal cylindrical retort inside in which parts can be loaded into and heat-treated. Also this furnace can be used with special gas atmospheres in order to carburize, or nitride the part. This can be a fast pace process and it can add different types of treatment to the part, such as carburizing.

Pit-Type Furnace

This is also a vertical furnace where the individual parts are loaded into a basket. Convection heating then takes place on the parts in the basket, and then lowered into a dead air space to prevent direct heating of the parts. This can be a fast pace process as well, and the prevention of direct heating can minimize warpage and cracking of the part.

Pot-Type Furnace

This furnace is used to heat treat small parts. The parts are placed in a cast alloy pot and are held in a bath of molten lead or salt and heated. This process can be relatively fast, however, diffusion of contaminated metals might be a problem during the heat treatment.

Vacuum Furnace

This is the current furnace used by our sponsor. The parts undergo a vacuum heat treatment, and then cooled via air, oil, or subzero at different pressures. This can speed up the time to stress relieve parts, as well as, save money by having it all in one step. This process will make more sense once my partner and I see the process that our sponsor uses.
3.4 Austenitizing and Stress Relieving

Typically the procedure to stress relieving martensitic stainless steels is to preheat, then heat to austenitic range, held for a specified time, and quenched to room temperature in air or oil. Stated in the ASM Specialty Handbook Stainless Steels, type 420-Stainless steel stress relieving times and estimated tensile strength and hardness. The table below can show the ranges.

<table>
<thead>
<tr>
<th>Type</th>
<th>Austenitizing Temperature (°C)</th>
<th>Quenching Medium</th>
<th>Stress Relieving Temperature (°C)</th>
<th>Tensile Strength (MPa)</th>
<th>Hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>420</td>
<td>980-1065</td>
<td>Air or Oil</td>
<td>205-370</td>
<td>1550-1930</td>
<td>48-56</td>
</tr>
</tbody>
</table>

Table 1: Stress Relieving Times and Temperatures [1]

In order to maximize the corrosion resistance and strength, a higher austenitizing temperature is required. Hardness is increased as well when the austenitizing temperature is increased. However, austenitizing stainless steels at low temperature range enhance the ductility and impact properties of the part. The figures below can show this phenomenon. [1]

Figure 2: Stress Relieving Temperature Vs. Hardness [1]
However, if heated too high for too long in the austenitizing temperature, the hardness can start to decrease due to “austenite retention and sometimes the formation of ferrite” [1]

3.6 Quenching, Soaking Times, and Subzero Cooling

Within the hardening of martensitic stainless steels it is important to have all soaking time correct because “achieving the maximum solution of chromium-iron carbides for maximum strength and corrosion resistance.” [1] If the soaking times are not correct, we risk grain growth, retained austenite, quench cracking, and brittleness. Therefore, we can develop a heat transfer equation in order to find the time it takes to heat a part or cool a part uniformly. This will be done in our experimental data.
Martensitic stainless steels have very high hardenability, as stated in the background; therefore they can be either air or oil quenched. However, when air quenching these grades of stainless steels they can lose some ductility and corrosion resistance. If cooled slowly, carbide precipitates can form around the grain boundaries of the material, which is a negative in this processing. In conclusion, we must pay attention to soaking times and quenching times.

During quenching, there might be some austenite that has still yet to transform. Therefore, subzero cooling can transform this. Immediately after quenching, the part can be cooled to -750°C in order to transform all the austenite left. This process can maximize dimensional sustainability. During our experimental procedure, we must study the microstructure, and see if it is necessary to perform subzero cooling on the part. [1]
4. Procedure

Different types of specimens will be tested using different conditions. One of the conditions will be going through different austenitizing temperatures. The other condition is to experience different stress relieving temperatures. Controlling the variables help us understanding the influence of the temperature on the heat treatment process of the product. In comparison, control tests, which are explained in characterization, will be performed on samples based upon our sponsor’s current heat treatment process. Both as quenched and stress relieved samples from the current process were analyzed for comparison with the results from our work.

4.1. Austenitizing

Our procedure during austenitizing deals with one variable which is temperature. Four different austenitizing temperatures have been selected for a one soaking time. The preheat process starts with 20 °F/min heating rate till the parts temperature reaches 1000°F, then 10°F/min heating rate to reach 1450°F. After reaching 1450°F, the heating rate needs to be set to 5°F/min till it reaches the austenitizing range of 1800-1900°F. The table below will show the number of specimens and the soaking temperatures during austenitizing.

<table>
<thead>
<tr>
<th>Category Number</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
</tr>
<tr>
<td>2</td>
<td>1825</td>
</tr>
<tr>
<td>3</td>
<td>1850</td>
</tr>
<tr>
<td>4</td>
<td>1900</td>
</tr>
</tbody>
</table>

Table 2: Austenitizing Procedure using different soaking temperatures
4.2. Quenching

After reaching the desired austenitizing temperature, all parts have been quenched with Nitrogen gas at 4.5 bar to 150°F. Quenching at 1850°F gives the material good combination of corrosion resistance and mechanical properties. However, quenching at temperature higher than 1850°F will provide high corrosion resistance; high hardness will significantly affect the properties of SS420. Our specimens have been quenched right from their highest austenitizing temperature that was reached.

4.3. Stress Relieving

During the stress relieving of the product, five different stress relieving temperatures, as shown the table and figure below.

<table>
<thead>
<tr>
<th>From Category Number</th>
<th>Temperature °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>550</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 3: Stress Relieving Procedure using different Stress Relieving temperature

The samples were placed into a standard box furnace with an Omega Type K thermocouple inside the sample in order to determine the samples temperature. Once the samples reached the desired temperature, they were held for one hour and then air-cooled. The figure below shows the process of stress relieving represented in a temperature vs. time plot. Please refer to appendix 5 for further understanding of the heat treatment procedure.
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Figure 5: Stress Relieving of Samples
5. Characterization

Each specimen went through different types of tests, like microstructure analysis, hardness, and X-ray diffraction.

5.1. Microstructure Analysis

Standard microstructure analysis procedure is followed to analyze the microstructure of our samples and control samples using an optical microscope (OMT). Each specimen was cut in both the longitudinal and transvers directions then mounted in a polymer mount cylinder.

![Figure 6: Mounted Sample](image)

After mounting, the samples were ground with silicon carbide sand paper to 120, 220, 400, 600, and 1200 grit until all scratches were parallel on the surface and turn 90° after each paper. The samples were then polished using three different polishing pads: 1 μm, 0.3 μm, and 0.1 μm in order to eliminate scratches, stains and other imperfections, also, to free the surface from traces of disturbed metal. Between each polishing step, specimens were cleaned in order to eliminate the transfer of particles. After each polishing stage, the specimens have been washed well to avoid transferring abrasive particles between the polishing steps. After polishing is over, the specimens were thoroughly cleaned. The specimens were
etched with Veilla’s Reagent (10mL HCl+1g of Picric acid+100mL of Alcohol) for 1 minute and 3 minute, see appendix 1 for further information about the etching procedure. [5] After etching, the specimens were tested using (OMT) to produce pictures of x1000 magnifying magnitude. Below are figures of as-quenched samples that were analyzed under the OMT.

Figure 7: Austenitized at 1800°F, Etched with Viella’s 3 Minute Swab.
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Figure 8: Austenitized at 1825°F, Etched with Viella's 3 Minute Swab.

Figure 9: Austenitized at 1850°F, Etched with Viella's 3 Minute Swab.
5.2. Grain Size (Hyen Intercept Method)

The first widely used methodology for measuring the average grain size is the Hyen Intercept Method. The Intercept method utilizes a randomly positioned line of a known length that is overlaid on the micrograph. Once the line is drawn, a set of rules is utilized to count the intercepts along the line. [11]

\[
\text{Average Grain Size Diameter} = \frac{\text{Total Length}}{\text{Number of Intercepts}}
\]

5.3. Micro Hardness

Micro hardness test, commonly known as Vickers hardness test, was performed on each sample. The test is normally performed on materials with a long cross section, thin, or long matrix parts. Depending on the sample that is chosen, they can fall under these categories. The test was set up to 500 g load, 10 second dwell. The Vickers hardness can then be calculated by the kilogram force load
divided by the surface area of the diamond indentation that was made on the sample. The test will follow ASTM E 384-11e1 standard procedures for Vickers hardness test. The test was conducted in a straight line across the cross section of the mounted sample. The figure below shows the sample where tests were conducted.

![Image](image.png)

*Figure 11: Hardness Test on Sample*

In the figure above, the blue dots were where the test was conducted and the red line was the path of the test. Each sample had 5 points across the red line to ensure consistency. An in depth procedure of the preparation, testing, and analysis will be explained further in the results section.

**5.4. X-Ray Diffraction Analysis**

X-Ray diffraction (XRD) test was conducted on the tested specimens to determine the phase or phases that exist in the material. Additionally, XRD identifies information about the crystal structure, the size, shape and internal stress of the crystalline regions. One of the benefits of XRD is that it’s a Non-destructive test with high accuracy. Using the figure below and data about the phases expected to be found with XRD, peaks locations were calculated to anticipate the location of
martensite, retained austenite, and carbides. [6]. The XRD machine has cannot identify retained austenite less than 5% due to its limitation.

![Figure 12: Calculated Diffraction Patterns for Various Lattices. [6]](image-url)
The martensite phase was expected to have BCC structure with lattice parameter of \( a = 2.867 \) Å instead of BCT to help us identify the preliminary locations of the peaks.

The austenite phase is FCC with lattice parameter of 3.55. [6] Carbide \( M_{23}C_6 \) is FCC and lattice parameter of 10.57-10.68 Å, and \( M_7C_3 \) is Hexagonal of lattice dimensions of \( (a = 13.98, c = 4.523 \) Å). [9]

<table>
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<tr>
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<tr>
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<td>2</td>
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<td>3</td>
<td>220</td>
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<table>
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<td>311</td>
<td>42</td>
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<td>7</td>
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<td>102</td>
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<td>5</td>
<td>110</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>103</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4: Location of the Predicted Phase Peaks

5.5. Hollomon-Jaffe Parameter

The Hollomon-Jaffe parameter, also known as the stress relieving parameter, is used during stress relieving to “define time-temperature equivalences” [12]. It gives the time-temperature correlation between long stress relieving time, low temperature, and short stress relieving time, high temperature, low temperature,
and a long stress relieving time achieves the same effect as high temperature and a short stress relieving time. [13] During steel stress relieving, the Hollomon-Jaffe parameter also describes the change in the hardness of the material [12]. The Hollomon-Jaffe equation is given below.

\[
HJP = \log(t) + C
\]

In the Hollomon-Jaffe equation, HJP is the Hollomon-Jaffe parameter, T is the stress relieving temperature in Kelvin, t is time in hours, and C is a unitless constant that is dependent on the material being stress relieved.

<table>
<thead>
<tr>
<th>Constant Value, C</th>
<th>15</th>
<th>19.5</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Content in Steels (%)</td>
<td>0.90-1.20</td>
<td>0.15-0.45</td>
<td>C-Mn and low alloy steels</td>
<td>High alloy steels</td>
</tr>
</tbody>
</table>

Table 5: Constant value C for Varying Concentration of Carbon Steel [13]
6. Results

Micro-hardness; XRD and OMT tests were conducted on each sample to determine the effect of heat treatment on the grain size, hardness, and to identify the phases exist in the final product.

6.1. Optical Microscope Test

Quenched samples from the austenitizing temperature mentioned in section 4.1 were tested under the microscope to determine the grain size. Using Heyn Intercept method and ASTM E112, the average grain size for the different samples has been calculated as in Appendix 1.

Figure 13: Microstructure of as quenched at 1800°F Austenitizing temperature
Figure 14: Microstructure of as quenched at 1900°F Austenitizing temperature

Figure 15 illustrates the relationship between austenitizing temperature and the grain size. The grain size of the as quenched samples increases as the austenitizing temperature increases. See appendix 6 for further Microstructure figures.

Figure 15: Austenitizing Temperature Vs. Grain Size for as quenched samples Plot
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

<table>
<thead>
<tr>
<th>Temperature (F)</th>
<th>Average Grain Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>6.6</td>
</tr>
<tr>
<td>1825</td>
<td>10.6</td>
</tr>
<tr>
<td>1850</td>
<td>16.8</td>
</tr>
<tr>
<td>1900</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Table 6: Grain Size Vs. Austenitizing Temperature

After stress relieving, some samples were etched to reveal the microstructure. The samples were etched with Viella’s Reagent using the same etching procedure we adopted first time. The samples were 1800°F/600°F, 1850°F/400°F, and 1900°F/450°F (Austenitizing Temperature/Stress Relieving Temperature). The samples below were selected to show the microstructure of the sample with the lowest, highest and the moderate hardness values.

Figure 16: Microstructure of 1800°F/600°F Heat Treatment
6.2. Micro Hardness

All the samples went under micro hardness testing and multiple points were tested at each specimen. It was observed that the hardness increases as the austenitizing temperature increases. The graph below illustrates the average hardness values for different austenitizing temperature.
Furthermore, the stress relieved samples were tested for hardness to determine the average hardness of the finished product. In the figure below, it was observed that as stress relieving temperature increases, the hardness decreases for any austenitizing temperature. For instance, samples with austenitizing temperature of 1800°F, the hardness average is 488HV for specimen with stress relieving temperature of 400°F while the hardness average is 470HV for the specimen with stress relieving temperature of 600°F. However, it was observed that for the sample of 1850°F austenitizing temperature and stress relieving temperature of 500°F the hardness was low and the only explanation for that is the due to problem with the processing of the heat treatment. The figure below illustrates the relationship between hardness and stress relieving temperature.
6.3. X-Ray Diffraction

X-Ray Diffraction test method was used to identify the phases and the retained austenite in the material. All as-quenched and stress-relieved samples were tested and it was found that the retained austenite percentage increases as the Austenitizing temperature increases, which is shown in the figure 21 and 22 below. Shifts in the peaks illustrates differences in the percentage of the retained austenite.

<table>
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<th>Austenitizing Temperature (F)</th>
<th>Stress Relieving Temperature (F)</th>
<th>1800</th>
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<th>1850</th>
<th>1900</th>
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<td>1.5%</td>
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<td>1.1%</td>
<td>1.9%</td>
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<tr>
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<td>1.0%</td>
<td>0.7%</td>
<td>1.4%</td>
<td>2.4%</td>
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</tbody>
</table>

Table 7: Percentage of Retained Austenite
Besides martensite and retained austenite that were identified in the X-RD analysis, some carbide was recognized. However, the structure of the carbide can’t be determined since the intensity of carbide peaks does not change with austenitizing temperature and stress relieving temperature. Also, the carbide at different temperature may change. [9] Some abnormality was found in the sample
with austenitizing temperature of 1800°F and stress relieving temperature of 450°F as a result, no retained austenite value can be provided.

The percentage of retained austenite decreases by about half after stress relieving, and continues to stay approximately the same as stress relieving temperature increases. The figure below shows the retained austenite as stress relieving temperature increases.
Figure 23: Stress-relieving Temperature Vs. Retained Austenite

6.4 Hollomon-Jaffe Parameter

Hollomon-Jaffe parameter was used to build a model that can help to achieve the desired hardness value at different stress relieving times and temperatures. A constant of \( c = 15 \) was determined through the calculation in order to have a better fit graph. The figure below shows the Hollomon-Jaffe model.
Figure 24: Hollomon-Jaffe Model
Discussion

This research showed the relationship of grade-420 stainless steel hardness to the various austenitizing and stress relieving temperatures. As austenitizing temperature increased, hardness increases, however, as stress-relieving temperature increased, hardness of the material decreased (Figure 20).

In Calliari et al paper it was shown that hardness decreases as stress-relieving temperature increases until about 600°F. On the other hand, their research indicates slight increase in hardness followed by drop as stress relieving temperatures go above 600°F, creating a secondary hardness effect. Our research was only conducted at stress-relieving temperatures up to 600°F, and our results agree with Calliari et al. [10]

This research shows that grain size increases as austenitizing temperature increases due to a higher driving force for grain growth which agrees with research done by Barlow et al. In their research they established that as austenitizing temperature increases, ASTM grain size rapidly increases at approximately 1900°F. Our research stated that the rapid increase was at approximately 1830°F. However, the temperature registered in this research is not exact, but ASTM grain size increased as expected. [7]

It can be concluded that the percentage of austenite increases as the austenitizing temperature increases despite the increase in hardness. Small percentage of austenite decomposes from 400°F to 600°F. Percentage of carbides does not change with austenitizing and stress relieving temperature, however, the
structure of the carbides may change. In general, it can be said that the retained austenite percentage decreases with stress relieving.

The research had limitations. Due to unexpected lab equipment failure and scheduling conflicts, there was only enough time to conduct experiments on one size product. Despite the need to distinguish the right temperature where secondary hardness effect starts, the procedure provided by the sponsor was not enough to reach that point. However, future research will continue the study on different size product, as well as increasing the stress relieving temperature to make the secondary hardness phase present.

While our sponsor processes their product at austenitizing temperature of 1850°F and stress relieving temperature of 500°F to get an average hardness of 535HV, our resulted average hardness following the same process was 495HV. This difference in hardness is due to the use of two different types of furnaces while processing. Our sponsor uses a vacuum furnace, whereas the furnace at WPI was a standard convection furnace. In the vacuum furnace, samples need longer time to reach the desired temperature comparing to the convection furnace that we use at WPI. As a result, the samples in the convection furnace were at the desired stress relieving temperature longer which contributed to the lower hardness.
Conclusion

This research provides basic scientific knowledge and new data about the Grade-420 stainless steel to assist our sponsor to improve their product. It was concluded that hardness of the material decreases as stress-relieving temperature increases. However, though desired, secondary hardness could not be reached. Stress-relieving temperature needs to be increased in order to acquire more data to show relationship between stress relieving temperature and the secondary hardness. Moreover, the data acquired provided new knowledge to our sponsor to help them to have better understanding of the metal they use for their product. It was determined that the austenitizing temperature of 1825°F is better that of 1850°F because the lower the austenitizing temperature has a smaller grain size and less retained austenite. Also, it is recommended to use a stress relieving temperature of 450°F since the hardness values resulted represent the mean value of hardness guaranteed by our sponsor to its client. However, our sponsor will choose the best heat treatment that will produce the best properties for the desired application. Below are conclusions that can be drawn from this research,

- As austenitizing temperature increases, the grain size increase. There is a rapid grain growth on the temperature range of 1825°F-1850°F. This has to do to the higher temperature of austenitizing, which delivers a driving force that contributes to grain growth. This experiment gives our sponsor data that they have not acquired before. The results that were gathered for the
experiments calculated an approximant grain size ranging from 6.6µm to 19.6µm (table 6).

- As austenitizing temperature increases, the hardness increases. However, as stress reliving temperature increases, the hardness decreases. This allows the user to select the stress reliving temperature to reach the desired hardness value. Raw data for hardness can be shown in the appendices 2 and 3.

- XRD concluded that the phases present were martensite with some retained austenite; which was expected. However, X-RD showed that retained austenite increased as austenitizing temperature increased. The amount of retained austenite in as quenched samples ranged from 2.5% to 4.8%, with a rapid increase in percent retained austenite at austenitizing temperatures ranging from 1825°F to 1850°F. Further, the percentage of retained austenite decreases by about 50% after stress relieving.

- The data analysis using the Hollomon-Jaffe parameter with a constant of 15 was effective to help achieve the desired hardness by increasing the temperature and shortening the time and vice versa. However, further work is essential to develop better and more accurate model to predict the desired hardness.
Appendices
Appendix 1

The following procedure illustrate step by step the ASTM grain number calculation and Hyen Intercept Method to calculate average grain size.

1. Define the picture magnification like X100, X200, etc...

2. Measure the number of grains. Grains that intercept with the pictures boarders are multiplied by $\frac{1}{2}$.

3. Calculate the area of the picture and divide that area by the square of the magnification.

4. Apply the ASTM formula of grain number $N(M/100)^2=2^{n-1}$

5. Average grain size = (Total true length/number of intercepts)
M = X1000

Number of grains = 119

True Area = \( \frac{160 \text{ mm}}{1000} \times \frac{119 \text{ mm}}{1000} = 0.01904 \text{ mm}^2 \)

\( N = 2^{n-1} \times 1 \text{ in}^2 = 0.0645 \text{ mm}^2 \)

\( N = 119 \times \frac{0.0645}{0.01904} = 403.125 \)

\( N = 1 + \frac{\log(403.125)}{\log(2)} = 9.655 \) ASTM grain number

Average grain size = \( \frac{119}{1000} = 0.00661 \text{ mm} \)
Appendix 2

Hardness values for as quenched samples:

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Appendix 3

Hardness values at different stress relieving temperatures

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Appendix 4

Sample Quenched from 1800°F austenitizing temperature

Sample Quenched from 1825°F austenitizing temperature
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample Quenched from 1850°F austenitizing temperature

Sample Quenched from 1900°F austenitizing temperature
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1800F and stress relieved to 400F

Sample austenitized to 1800F and stress relieved to 450F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1800F and stress relieved to 550F

Sample austenitized to 1800F and stress relieved to 500F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1800F and stress relieved to 600F

Samples Austenitized at 1800F and stress relieved to between 400F-600F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1825°F and stress relieved to 400°F

Sample austenitized to 1825°F and stress relieved to 450°F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1825°F and stress relieved to 500°F

Sample austenitized to 1825°F and stress relieved to 550°F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1825F and stress relieved to 600F

Samples austenitized at 1825F and stress relieved to between 400F-600F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1850F and stress relieved to 400F

Sample austenitized to 1850F and stress relieved to 450F
Sample austenitized to 1850F and stress relieved to 500F

Sample austenitized to 1850F and stress relieved to 550F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1850F and stress relieved to 600F

Samples Austenitized at 1850F and stress relieved to between 400F-600F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1900F and stress relieved to 400F

Sample austenitized to 1900F and stress relieved to 450F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1900F and stress relieved to 500F

Sample austenitized to 1900F and stress relieved to 550F
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

Sample austenitized to 1900F and stress relieved to 600F

Samples Austenitized at 1900F and stress relieved to between 400F-600F
Appendix 5

The experimental Plan

Samples

- As-Quenched at 1800°F
  - Stress relieved to 400°F, 450°F, 500°F, 550°F, 600°F

- As-Quenched at 1825°F
  - Stress relieved to 400°F, 450°F, 500°F, 550°F, 600°F

- As-Quenched at 1850°F
  - Stress relieved to 400°F, 450°F, 500°F, 550°F, 600°F

- As-Quenched at 1900°F
  - Stress relieved to 400°F, 450°F, 500°F, 550°F, 600°F
Appendix 6

Microstructure of as quenched at 1825°F Austenitizing temperature

Microstructure of as quenched at 1850°F Austenitizing temperature
The Effect of Heat Treating Process Parameters on the Hardness of a Martensitic Stainless Steel

References


