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Investigation of Mechanical Property Sensitivity with Respect to Processing Temperatures for A2 Steel

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Abstract

The way steel is processed through heating and cooling has a significant influence on the properties it has including flexural strength, ductility, and hardness. Processing parameters for quenching and tempering of different grades of steel are well known and are documented by ASM International, a leading materials information society. For instance, a range of quench and temper parameters associated with A2 steel, a medium alloy air-quenchable tool steel, are prescribed to demonstrate processes leading to a range of strength and ductility in the final product. The focus of this research is to observe the sensitivity of material properties with respect to processing parameters as a means to explore structure-process-properties relationships. In particular, the austenitization temperature of nine sets of A2 samples were set to three values within the prescribed band as well as six temperatures purposely set outside the prescribed band. Each sample of steel was processed by going through an austenitizing, quenching, and tempering phase. Although the austenitizing temperature was varied, methods of quench and temper as well as tempering temperatures remained constant throughout all testing. After processing, samples were tested to determine hardness, flexural strength, and flexural strain. Results suggest that samples processed with austenitizing temperatures within 50 degrees Celsius of the prescribed ASM band have similar properties to samples processed according to ASM prescription. As austenitizing temperature deviation increases, properties begin to vary significantly.

Keywords: Austenitization, Flexural Strength, Hardness

1. Introduction

1.1 Microstructure Of A2 Steel

The characteristics of A2 steel allow it to be used in tools partially because of the hardness it can obtain as a result of heat treatments. In addition to hardness, other properties of A2 steel such as strength and ductility are also affected by heat treatment. In general, heat treatments are used to change the microstructure of A2 which in turn affects its' properties. Changes in microstructure due to heat treatment are detailed in specialized references [1,2,3] which include the microstructure descriptions below. A typical "quench and temper" heat treatment of A2 steel includes a number of phases such as preheat soak, austenitizing soak, quench, and tempering soaks; figure 3 includes a schematic representation of a typical heat treatment cycle. Prior to the preheat soak, the microstructure of the specimen contains spheroidal carbides within a ferrite matrix[1]. As the specimen is heated during the preheat phase, some of the carbides break down and their carbon content diffuses into the ferrite thus supporting transformation of the matrix from ferrite to austenite. The preheat soak time is sufficient for the transformation from ferrite to austenite to be completed. Carbon from other carbides diffuse into the austenite as the specimen is soaked at the more elevated austenitizing temperature, thus enriching the austenite with carbon. When the specimen is rapidly cooled during the quenching phase, most of the austenite is transformed to martensite. The specimen is then soaked at the tempering temperature leading to a microstructure that contains ferrite and finely dispersed carbides throughout the structure. Austenite that was not transformed to martensite during the initial quench cycle may follow one of multiple paths including direct transformation to ferrite and carbides during tempering, and transformation to martensite during post-temper quenching. The specimen is tempered twice in order to spheroidize carbides that transformed directly from retained austenite, and to temper martensite that transformed from retained austenite during the first temper cycle[2]. The preceding description is relevant for a process that falls within the parameters recommended by ASM for the treatment of A2 steel. This research explores the properties of A2 steel when heated using austenitizing temperature within and without the temperature range recommended by ASM.

Heat treating parameters for A2 steel are well established. ASM International provides recommended heat treating practices for A2 steel[4]. ASM recommended practice for quench and tempering of A2 steel includes preheating the specimen at 790°C - 815°C for an hour, then austenitizing at 925°C - 980°C for 20 – 45 minutes. Heating is followed by quenching to "hand warm", about 65° C. For the case of A2 steel, a hot air blast provides a sufficient cooling rate for martensite to form. Lastly, the ASM recommends double tempering for A2 steel at 540°C.

1.2 Mechanical Testing:

Flexural and hardness tests are performed on the processed steel to observe the new properties it obtains. The test data is used to determine strength, ductility, and hardness of the samples.

1.2.1 *flexural test*

Flexural tests (also known as 3-point bend tests) are used to determine the flexural stress and strain behavior of materials. In a flexural test a sample is supported from the bottom by two supports while a load is applied between the supports by a load nose[5]-such a setup is shown in figure 1. During testing, the load nose is moved downward while the displacement of the load nose and the force applied are recorded; the amount of flexural stress and strain can be derived from load nose displacement and force as well as sample dimensions. For this study, flexural testing was carried out on an Instron 5900 series load frame. The span of the specimen between the supports is 2 inches which provides a span to depth ratio of 16:1 as suggested by ASTM International[5]. The specimen has 0.5 inches overhanging the supports at each end which is greater than 10% of the support span as the ASTM[5] recommends.

Flexural Stress (σ_f) is a measure of the tensile stress at the outer surface of a sample when undergoing a flexural test. The flexural stress is a maximum on the bottom surface of the sample, directly opposite the load nose (where the bending moment is a maximum) and is calculated using equation (1)[5]. The maximum value of flexural stress observed during a flexural test is the "flexural strength" of the sample.

$$\sigma_f = \frac{3PL}{2bd^2} \tag{1}$$

where:
P = Load applied (lbf)
L = Support span (in.)
b = Width of beam (in.)
d = Thickness of beam (in.)

Flexural Strain (ϵ_f) is the change of the specimen length. Flexural strain at breakage is related to ductility where greater flexural strain is indicative of greater ductility. The maximum flexural strain in a specimen occurs at the midpoint of the specimen opposite the load nose and can be calculated using equation (2)[5]:

$$\epsilon_f = \frac{6Dd}{L^2} \qquad (2)$$

where:
D = Deflection at midpoint (in.)
d = Thickness of specimen (in.)
L = Support span (in.)

As part of the test protocol the length, width, and thickness of each sample were measured and entered in the Instron software (Bluehill). The load cell was balanced at the beginning of each test and the load nose position was zeroed with the nose lightly touching the specimen. As the test is conducted, the Instron software records the amount of force applied at the load nose and its displacement for use in equations 1 and 2 to generate stress and strain data such as that shown in Figure 4. For the samples used in this study, the test was considered concluded when the specimen broke.

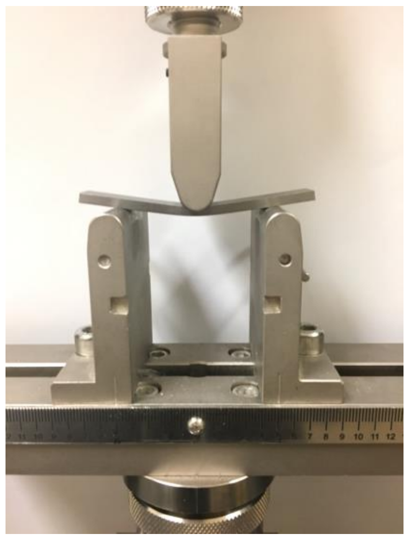

Figure 1. Flexural test

1.2.2 *hardness test*

A hardness tester capable of measuring hardness on the Rockwell C scale (Wilson Rockwell 574 Tester) was used to conduct this test. Protocol for Rockwell C testing prescribes a diamond indenter due to the anticipated material hardness. A Rockwell C test begins with an initial or "minor" load of 10 kg applied to the diamond indenter which subsequently penetrates the specimen[6]. As the test progresses, the indenter applies a secondary or "major" load of 150 kg thus increasing the depth of the indentation. The major load is then removed while the minor load is maintained. The hardness value is obtained by measuring the difference in penetration distance between the major and minor indentation which is performed by the tester.

The flexural test broke each of the samples into two smaller pieces, 10 hardness tests were conducted on each smaller piece for a total of 20 tests on each sample as shown in figure 2. Before conducting the 10 hardness tests on each piece, 3 "throw-away" tests were performed to ensure that the indenter was properly seated in the load head of the machine and the specimen was seated on the testing platform.

Figure 2. A2 steel sample with indenter marks from hardness test

2. Methodology

The purpose of this experiment was to observe the effect of austenitization temperature on material properties of quenched and tempered specimens. Of particular interest was the effect that austenitization temperatures outside the range recommended by ASM (925°C - 980°C)[5]would have on material properties. With the exception of the austenitization temperature, all other ASM recommendations were followed. Specifically, all samples in this study were preheated at 815°C, austenitized at some temperature, quenched, and then tempered twice at 540°C for one hour.

To explore the effect of austenitizing temperature on the properties of A2 steel, nine heat treatments were performed, each with a different austenitizing temperature as displayed in table 1. Six unique samples were used in each heat treatment in accordance with ASTM recommended practice[5]. Treatments 1C, 2C, and 3C are grouped within the ASM recommended austenitization band with sample 2C at 955°C representing the midpoint of the recommended temperature range. Treatments 1L, 2L and 3L were austenitized at temperatures lower than the recommended ASM austenitizing band. Treatments 1H, 2H, and 3H were austenitized at temperatures higher than the recommended ASM austenitizing band. Within both of the non-recommended groups of samples, the austenitizing temperatures varied by 50°C, 100°C, and 150°C relative to the midpoint of the recommended range.

Table 1. Summary of heat treatments

Sample	Preheat Temperature (°C)	Austenitizing Temperature (°C)	Variance from midpoint of recommended temperature range (°C)	Tempering Temperature (ºC)
1L	815	805	-150	540
2L	815	855	-100	540
3L	815	905	-50	540
1C	815	925	-30	540
2C	815	955	0	540
3C	815	980	25	540
1H	815	1,005	50	540
2H	815	1,055	100	540
3H	815	1,105	150	540

2.1 Test Specimen

All test specimens were made from purchased bars of A2, a medium-alloy air-hardening tool steel. According to the vendor (Mcmaster-Carr)[7], the composition of the purchased A2 steel meets ASTM A681[8] which includes 0.95 - 1.05 % carbon, 4.75 - 5.50 % chromium, 0.9 - 1.4 % molybdenum along with other elements. The material used in this study had dimensions of 0.125 ± 0.001 inches in thickness, 0.506 ± 0.005 inches in width, and was purchased in 3' lengths[7].

2.2 Sample Preparation

The A2 steel received from Mcmaster-Carr was cut into 3" specimens to accommodate the mechanical testing machines. An indenter was used to mark the samples with a number and a letter that correspond to the austenitizing temperature the samples will receive. The steel was washed with water and soap to remove any oils accumulated on it and was handled with pliers to avoid further accumulation of oil. To avoid oxidation of the steel during the heating process, the samples were placed in a foil bag designed for that purpose. The six samples associated with a given treatment were placed flat in the foil bag to allow even distribution of heat and the opening of the foil bag was folded to minimize the amount of oxygen available during the heating process.

2.3 Heat Treatment

The foil bag containing the batch of samples was placed in the furnace which was set to the desired preheat temperature. Throughout this project, two Thermolyne muffle furnaces were used to heat the samples. The first Thermolyne muffle furnace (FB1415M) has a capacity of 79.33 in^3, a maximum temperature of 1100°C and a temperature uniformity of ± 5 °C[9]. The second Thermolyne muffle furnace (F47925-80) has a capacity of 120 in^3, a maximum temperature of 1200°C and a temperature uniformity of ± 3.6 °C[10]. The preheat temperature used for all the treatments is 815°C. After the furnace reached the preheat temperature, the samples were left in the oven for one hour to go through the preheat soak as shown in figure 3. At the completion of the preheat soak the furnace temperature was raised to the specific austenitizing temperature assigned to the batch of samples. The samples soaked at the austenization temperature for 45 minutes to complete the austenitizing cycle. Afterwards, the samples were extracted from the furnace and quenched with hot air blast from a heat gun (Ultra Heat II Hot Air Tool SV 803). To quench the samples, the hot air from the heat gun was directed toward the steel until they were hand warm. While the samples were being quenched, the other furnace was set to 540°C which is the tempering temperature used for all the treatments. Once the samples were quenched to "hand warm" they were placed in the tempering furnace for an hour to complete the tempering phase and subsequently quenched as before. The tempering process was then repeated in accordance with ASM recommendations[11]. All treatments were tempered twice. The duration of the entire heat treatment process is about 325 minutes.

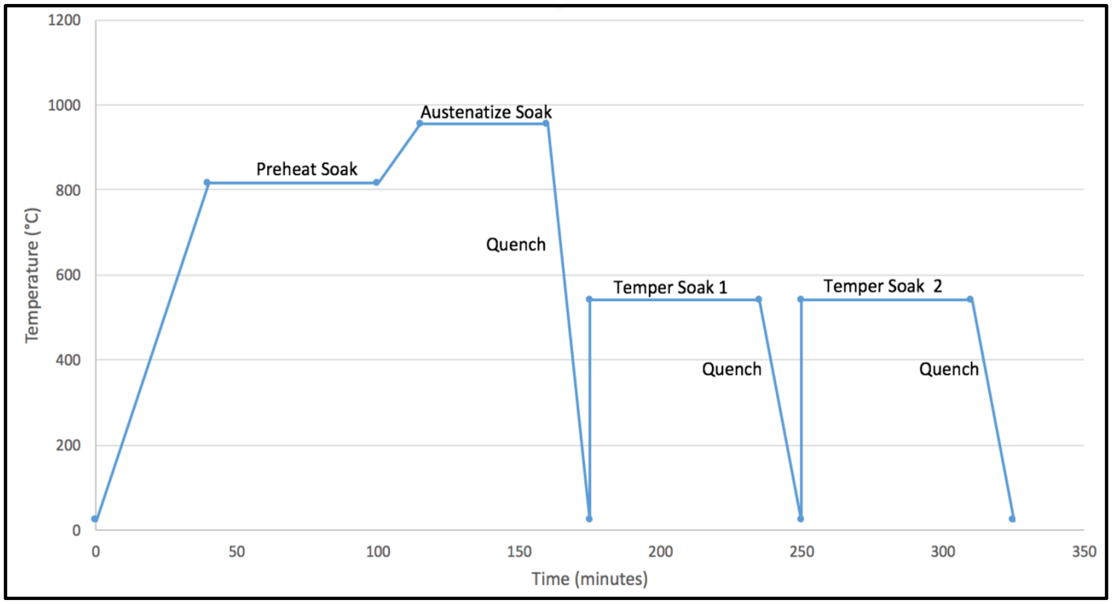

Figure 3. Phases of A2 steel heat treatment

3. Results

The data obtained from mechanical testing (flexural stress, strain, and hardness) was organized and plotted to identify some of the relationships between the properties of A2 steel austenitized at various austenitizing temperatures. More specifically, the stress and strain of each austenitizing temperatures is plotted in figure 4 to show the ductility and strength of the specimen. As discussed previously, each austenitizing temperature was performed on six samples as instructed by ASTM to ensure precision. One sample from each austenitizing temperature was plotted in figure 4 to compare the response of steel during the flexural test.

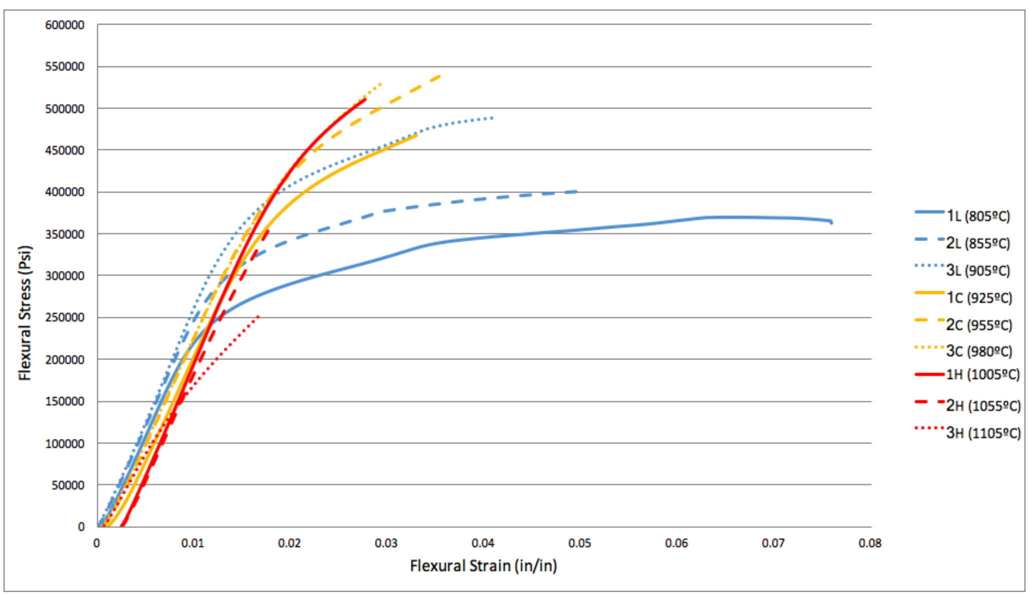

Figure 4. Flexural stress versus flexural strain

It is noted that the austenitizing temperature altered the deformation response of steel. The samples heated according to the recommended austenitizing temperature (1C, 2C, and 3C: marked in yellow) reach the point of breakage at approximately 3% flexural strain and a corresponding stress of approximately 50 ksi. The samples heated above the recommended austenitizing temperature (1H, 2H, and 3H: marked in red) demonstrate a more brittle response, with the exception of 1H whose response is on par with the samples heated according to the recommended austenitizing temperature. The samples heated below the recommended austenitizing temperature (1L, 2L, and 3L: marked in blue) demonstrate more ductile response, with the exception of 3L whose response is on par with the samples heated according to the recommended austenitizing temperature. As seen in figure 4, the point of breakage is a good proxy for the maximum stress and strain that a specimen can withstand. This is a good way to represent the strength and ductility of the samples and therefore, figure 5 shows the breaking stress and strain for all 6 samples associated with each austenitizing temperature.

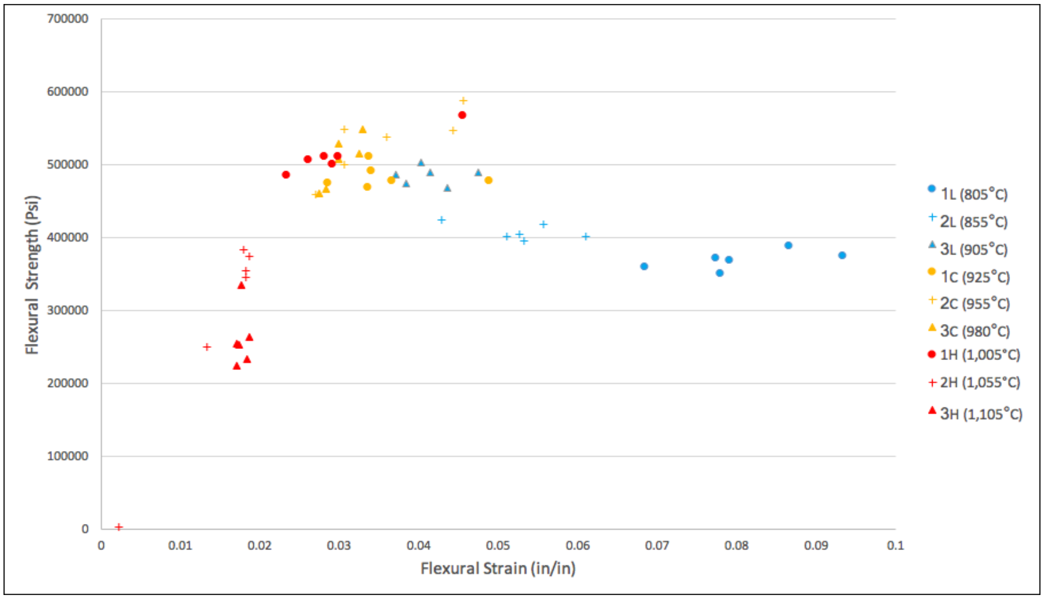

Figure 5. Flexural strength versus flexural strain of all samples

The data displayed in figure 5 represents the ductility and flexural strength of each specimen. It can be seen that the flexural stress and strain at breakage varies with austenitizing temperature. For treatments within the recommended austenitization range (1C, 2C and 3C) the samples show the highest flexural strength and a moderate flexural strain. Treatments 3L and 1H which varied from the midpoint of recommended temperature range by 50°C show similar values of flexural strength and strain. As the austenitizing temperature distanced from that recommended by ASM, the properties of steel changed. Treatment 3H which varied 150°C higher than the midpoint of the recommended temperature showed low values of flexural strength and strain indicating the embrittlement of the specimen. Contrastingly, treatment 1L which is 150°C lower than the midpoint temperature recommended showed a moderate value of flexural strength and a high value of flexural strain indicating the ductility of the specimen. To further identify the relationship between ductility and the austenitizing temperature of the specimen, figure 6 explicitly compares the two factors.

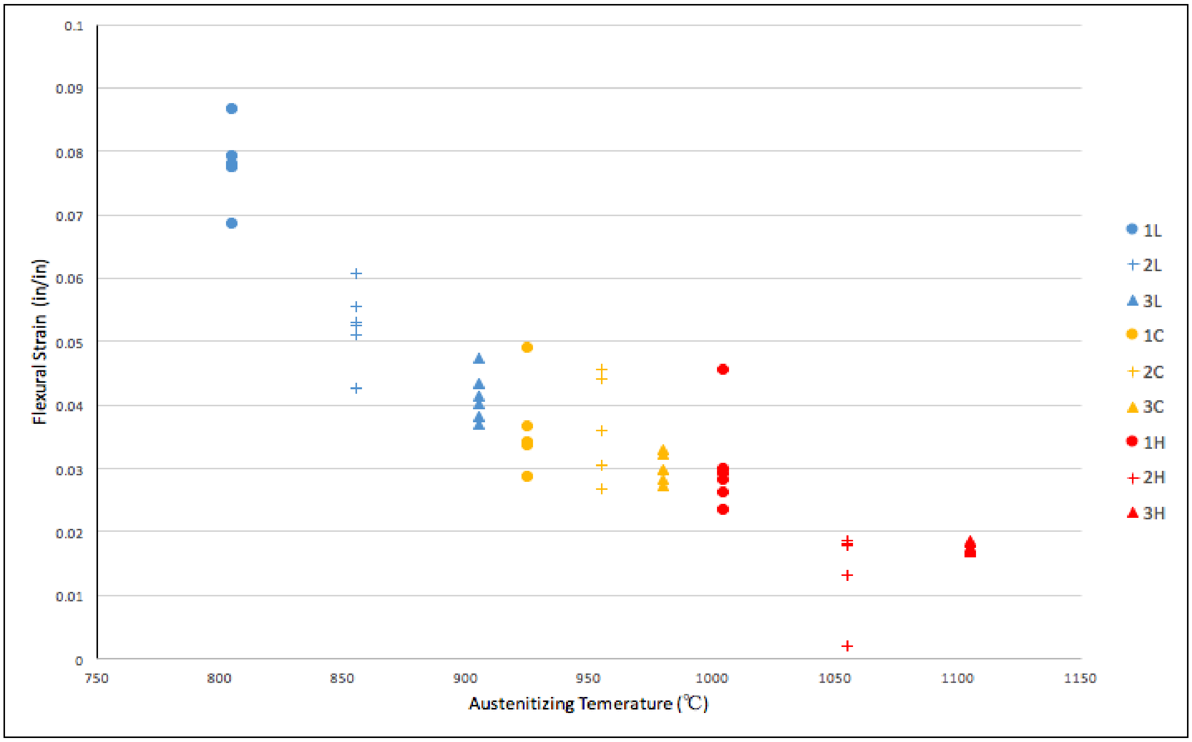

Figure 6. Flexural strain at breakage vs. austenitizing temperature

It can be noted that the relationship between flexural strain and austenitizing temperature is monotonic: as the austenitizing temperature increases, the flexural strain decreases. It can also be noted that within most treatments the value of flexural strain varied by about 0.02 in/in strain. With that said, the flexural strain measured for the treatments with austenitization temperatures closest to the prescribed temperatures are indistinguishable from the flexural strain measured for the treatments for which the austenitization temperatures followed the ASM prescription. The flexural strength at the various austenitizing temperatures responded differently than the flexural strain. The relationship between flexural strength and austenitizing temperature varied as shown in figure 7.

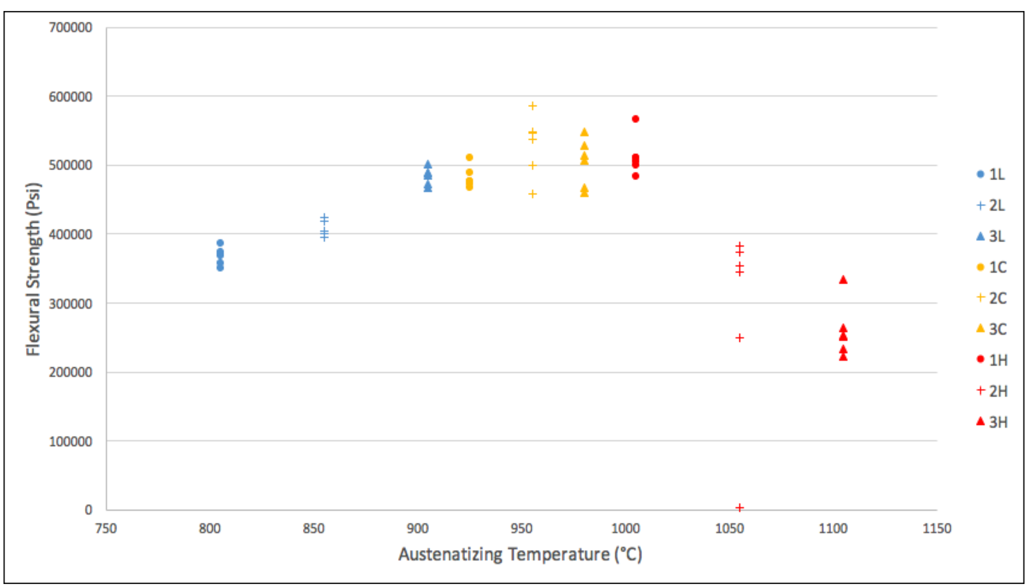

Figure 7. Flexural strength versus austenitizing temperature

The samples that were treated within the ASM prescribed temperature range attained relatively high values of flexural strength with the 955°C treatment obtaining the highest value of flexural strength at 586,000 psi which is consistent with expectations[4]. Although treatments 1H and 3L varied by 50°C from the midpoint of the recommended temperature range, the flexural strength values are indistinguishable from samples that were treated within the recommended range (1C, 2C and 3C). As the variation from midpoint recommended temperature increases, the value of the flexural strength decreases. It can be noted that treatments heated at higher temperature than that recommended by ASM obtained lower flexural strength values than those heated at lower temperatures. The lowest flexural strength value was obtained at 1100°C at a value of 223,000 psi. An explanation for this behavior is suggested in the discussion section.

Hardness is frequently used as a proxy for tensile strength[1]. The results of our tests show this to be reasonable up to a point. The hardness associated with each treatment was plotted against the flexural strength to explore the relationship between the two properties as shown in figure 8.

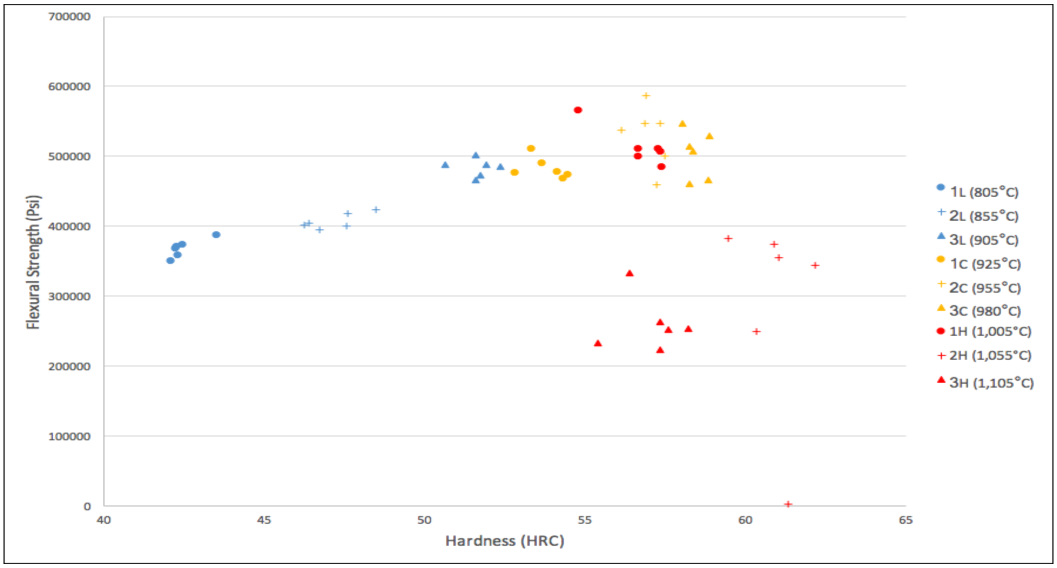

Figure 8. Flexural strength versus specimen hardness

The hardness for quenched and tempered A2 steel is anticipated to fall within the range of 57 – 62 HRC[4]. Treatment 1C, which is in the recommended austenitizing temperature range, has an average hardness value of 53.8 HRC which is slightly below the predicted range. The other two treatments within the recommended temperature range, 2C and 3C, had average hardness values of 56.9 HRC and 58.4 HRC which are consistent with prediction. Figure 8 shows treatment 3H (1105 °C) to have a hardness value that is indistinguishable from some treatments heated within the ASM recommended range (2C and 3C). Although the hardness of 3H is similar to 2C and 3C, the flexural strength value of 3H is half that of 2C and 3C. Therefore, hardness is not consistently a valid indication of the flexural strength of a treatment. The data presented shows that as the austenitizing temperature increased, the value of hardness increased as well until it reached 62 HRC and then the hardness values decreased with further increase of austenitizing temperature.

5. Discussion

As demonstrated in the results section, the properties of A2 steel change as the austenitizing temperature is varied from that recommended by ASM. The variation in properties is due to changes in structure that stem from differing austenitization temperatures. Although a metallographic study would be required to make definitive statements, we offer the following speculative explanations which we believe are consistent with the literature[1,2,3].

5.1 Specimen Austenitization Temperature Below ASM Recommendation

Heating the samples at low austenitizing temperatures reduces the dissolution of carbides leading to austenite with low carbon content relative to an ASM prescribed process. Upon quenching this will in turn lead to martensite with a relatively lower carbon content and hence less carbide precipitation due to tempering[3]. In the end, more of the carbide will remain contained in large spheroids and less carbon will exist as finely distributed particles. Less finely distributed carbide precipitates will tend to lower strength and increase ductility.

5.2 Specimen Austenitization Temperature Above ASM Recommendation

At excessively high austenitization temperatures most or all of the carbide particles will dissolve into the austenite matrix[3]; grain size is free to increase significantly in the absence of such particles. Larger grains will result in lower ductility.

6. Conclusion and future direction

Testing of quenched and tempered A2 steel that was subject to a range of austenitizing temperatures that was more broad than the range recommended by ASM demonstrates the wide range of properties attainable with A2 steel. Treatments that feature austenitization temperatures outside but close to the recommended range (± 50°C from center of recommended range) produced samples with hardness, flexural strength, and ductility properties that are indistinguishable from samples produced within ASM recommendations. Treatments that feature austenitization temperatures cooler than recommended produce samples with lower hardness, lower flexural strength, and increased ductility relative to samples produced within ASM recommendations. Treatments that feature austenitization temperatures warmer than recommended produce samples with lower flexural strength and lower ductility relative to samples produced within ASM recommendations. These samples exhibit hardness that is similar or greater than that of samples produced within ASM recommendations.

Although microstructure-based explanations are proposed for the observed behaviors, it is noted that metallography is required to produce supporting evidence. Intended future work includes metallographic study of the samples produced to date.

7. References

1. Leonard E. Samuels, Optical Microscopy of Carbon Steels (American Society for Metals, 1980).
2. George Krauss, Steels: Processing, Structure and Performance, 2nd ed. (ASM International, 2015).
3. Roberts, Krauss and Richard Kennedy, Tool Steels, 5th ed. (ASM International, 1998).
4. "Heat Treating of Specific Classes of Tool Steels", *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 734–760.
5. ASTM D790-15e2, "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials", ASTM International, West Conshohocken, PA, 2015, www.astm.org.
6. ASTM A370-17, "Standard Test Methods and Definitions for Mechanical Testing of Steel Products", ASTM International, West Conshohocken, PA, 2017, www.astm.org.
7. McMaster-Carr. Accessed May 08, 2017. https://www.mcmaster.com/#grade-a2-tool-steel/=17jm1um.
8. ASTM A681-08, "Standard Specification for Tool Steels Alloy", ASTM International, West Conshohocken, PA, 2015, www.astm.org.
9. "Thermolyne™ Benchtop 1100°C Muffle Furnaces." Thermo Fisher Scientific. Accessed May 08, 2017. https://www.thermofisher.com/order/catalog/product/FB1310M.
10. "Thermo Scientific Thermolyne 2L C1 Benchtop Muffle Furnace." McQueen Labs Discount Laboratory Equipment. Accessed May 08, 2017. http://www.mcqueenlabs.com/furnace/thermolyne-f47925-80.php.
11. B.A. Becherer and T.J. Witheford, "Introduction to Heat Treating of Tool Steels", *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 711–725.