Metallic Testing of Specimens
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Abstract

Tensile and hardness testing of annealed, quenched, and quenched and tempered A2 tool steel were performed for the purpose of material property characterization. The material properties of interest include: ultimate stress, yield stress, modulus of elasticity, and Vickers hardness. These characteristics can bring insight into the strength, stiffness, and hardness of the steel. The MTS Landmark®servohydraulic system induced tension in each specimen, and recorded the axial force applied over time, as well as the axial displacement of an attached extensometer until failure. Discernible material properties were observed for each sample size of the three heat-treated specimens. Hardness testing data showed a positive correlation between hardness and strength. The Leco LM800 microhardness tester was used to perform Vickers hardness testing. Understanding how material properties change with heat treatment is important for meeting engineering design criteria.

1 Introduction

Heat treatment of metallic substances involves energy delivery, in the form of heat, applied to the material at different rates. The cooling rate is also varied to hold the microstructure of the material in a desired configuration. The final configuration of the microstructure determines how the steel behaves on a macro-scale. Annealing of steel involves heating it to a prescribed annealing temperature, and allowing it to cool slowly. Quenching treatment consists of heating a material, then rapidly cooling it. Tempering a material consists of heating the specimen to some temperature below the critical point, then proceeding to cool it in still air. Tempering of a material is usually done after quenching. Based on these manipulations, it is expected that material properties will have noticeable differences.

The quantification of a material's strength, stiffness, and hardness can be used to aid in the mechanical design process. Tensile testing involves application of a constantly increasing displacement force applied to the specimen until failure. Values for stress (σ) and strain (ε) can be calculated from this test by knowing the forces applied and specimen dimensions. Strength and stiffness can then be determined from resulting stress and strain values. Hardness testing seeks to define the same characteristics in terms of a Vickers hardness value (HV) [1]. The hardness of a material is found by applying a constant force with a diamond indenter and measuring the geometry of the indented surface that results [5]. The determination of strength, stiffness, and hardness of annealed, quenched, and quenched and tempered A2 steel specimens should illustrate differences between the heat treatments of the material.

2 Materials and Methods

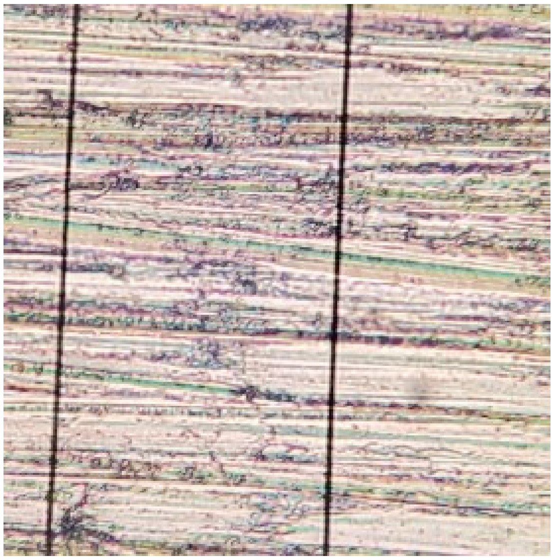
2.1 Experiment

A2 steel, acquired from McMaster Carr, was cut with a water-jet and heat treated by others prior to testing. Samples were then sanded down to remove minor surface imperfections. A load frame (Landmark®servohydraulic system, Model 370,MTS,Eden Prarie,MN) was used for tensile testing. A deformation rate of 10 $\frac{mm}{min}$ was used to collect data at a sample rate of 102.4 Hz. The sample was loaded into the frame using hydraulic grips, and an extensometer (634.31E-24 Extensometer, MTS, Eden Prairie, MN) was attached to a section of the material. The specimen was then loaded in tension until failure. Axial force (N), Time (s), and axial extensometer displacement (mm) were recorded from the load frame software. This was repeated for a total of nine trials, with a sample size of three trials per heat treatment.

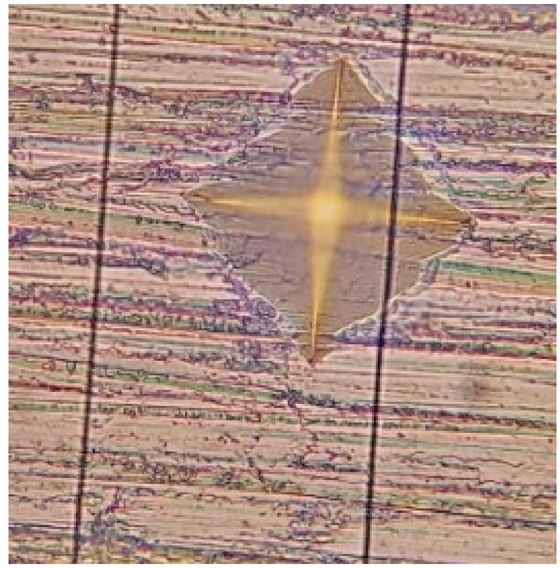
Hardness testing started with first mounting the sample in the Leco LM800at microhardness tester. Alignment of the objective lens was done to ensure that an uncontaminated part of the sample was tested. Indentation force ($F_{constant}$) was set to 500 gf of force for a duration of 10 seconds. Indentation height and width (d) were measured, as displayed in Table 2, using the hardness tester and a contact area ($A_{surface}$) was calculated. The Vickers hardness (HV) value was calculated by the hardness tester. The specimen is shown before and after indentation in Figure 1.

2.2 Data Analysis

The MTS Landmark® servohydraulic test system provided information needed to calculate material properties of the steel specimens. Axial forces (N) were recorded as well as the axial displacement (δL) of a 25.4 mm section as measured from an extensometer. Analysis of tensile forces in conjunction with extensometer readings provided data to calculate yield strength (σ_y), ultimate strength (σ_{ult}), and the modulus of elasticity (E). Stress (σ) was calculated using the force divided by the cross-sectional area of the samples, which were measured using calipers [2]. This is shown in Equation 1. Cross-sectional area data are shown in Table 1.



(a) Before



(b) After

Figure 1: Specimen surfaces before and after an indentation was made.

$$\sigma = F/A \tag{1}$$

Samples referenced in this document are labelled "A", "Q" and "T". These labels correspond with annealed, quenched, quenched and tempered respectively. It's important to emphasize that the tempered sample was quenched in addition to being tempered. Strain was determined by dividing the length change of the extensometer (δL) by the original length (L) as represented in Equation 2 [3]. Original length of the extensometer was 25.4 *mm*.

Table 1: Dimensions of specimens analyzed.

Specimen Dimensions			
Sample Label	Average Cross Sectional Area (mm^2)	Average Width (mm)	Average Thickness (mm)
A1	37.46	12.45	3.023
A2	39.23	12.52	3.124
A3	39.58	12.73	3.124
Q1	40.17	12.93	3.099
Q2	40.39	12.90	3.124
Q3	39.53	12.83	3.073
T1	32.03	12.19	2.642
T2	39.03	12.78	3.048
T3	37.24	12.70	2.946

$$\varepsilon = \delta L/L \tag{2}$$

The modulus of elasticity (E) was calculated using a linear regression of stress-strain data values encompassing a range from 5% to 35% of ultimate strength. This is within the linear elastic range and gives a reasonable prediction for E. This analysis is based on Hooke's Law as the modulus reveals a linear relationship between stress and strain within the elastic region [4]. Yield strength was determined using a 0.2% offset method. This method consists of shifting the linear regression by 0.2% on the x-axis and finding the stress at which the linear regression intersects with the stress-strain curve. Ultimate strength was determined by taking the maximum force applied to the sample and dividing by the cross sectional area. The linearity of stress described by the modulus and strain is shown in Equation 3. This relationship lends itself to a linear regression analysis.

$$\sigma = E\varepsilon \tag{3}$$

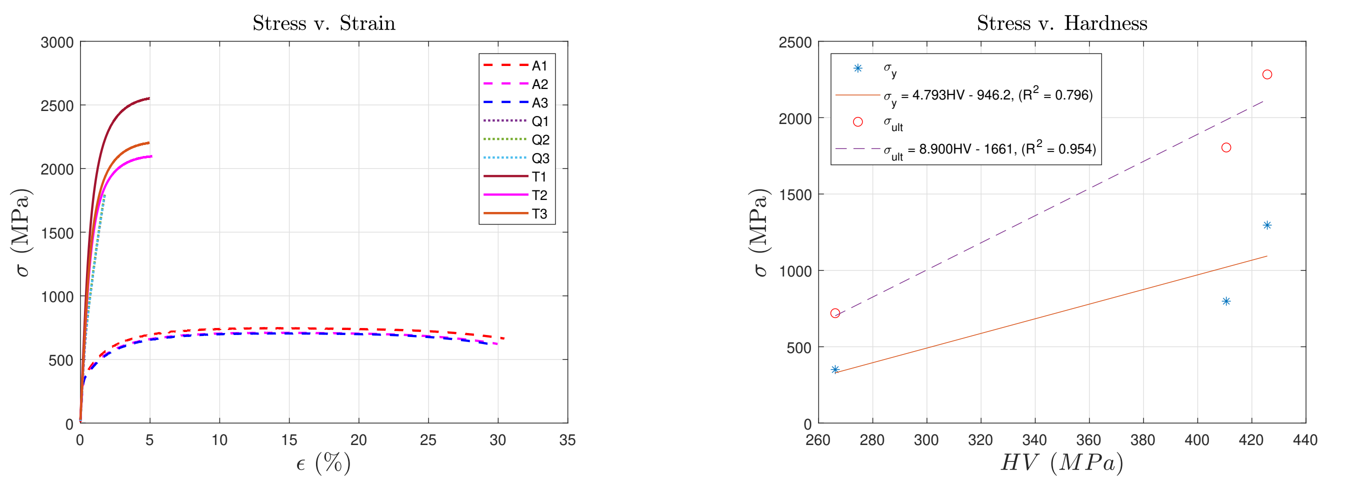
To determine if Vickers hardness is an accurate indicator of strength, a linear regression was also done by using HV values as x-values corresponding with yield and ultimate strength values. Vickers hardness was calculated by the hardness tester, but reasonable calculations can be done by hand using Equations 4 and 5. $F_{constant}$ is a constant applied force and $A_{surface}$ is the total contacted surface area of the indent. In Equation 4, d represents the average diagonal length of the indent, from corner to corner. This value corresponds with the Width column in Table 2. Vickers hardness is found by dividing the constant force ($F_{constant}$) applied by total contact surface area ($A_{surface}$). Using Equations 4 and 5 gave results that agreed with the hardness tester with an average approximate error of $\pm 3.7\%$ The collected values for tensile and hardness testing for each heat treatment gave rise to differing material properties.

$$A_{surface} = \frac{d^2}{2sin(136°/2)} \tag{4}$$

$$HV = F_{constant}/A_{surface} \tag{5}$$

3 Results

Strength and stiffness were determined for all samples, and an average was calculated for each sample size of the heat-treatments. Figure 2a shows the different stress-strain curves depending on the heat treatment used. Indentation width and height are shown in Table 2. Hardness values were averaged over the course of three trials and displayed in Table 2. Figure 2b displays plotted average yield and ultimate strength versus their hardness values, as well as a linear regression for the strengths.



(a) Stress versus strain plot of specimen base on tensile test

(b) Stress versus Vickers hardness values plotted against yield and ultimate strength

Figure 2: Stress data plotted from tensile and hardness testing, respectively.

Table 2: Hardness Test Results.

Indentation Results						
Sample Label	Width (μm)	Height (μm)	Hardness (HV)	Average Width (μm)	Average Height (μm)	Average Hardness (HV)
A1	56.43	61.25	267.8			
A2	60.93	58.15	261.6	58.71	59.36	266.1
A3	58.76	58.67	269.0			
Q1	46.92	48.77	405.0			
Q2	47.97	49.16	393.1	47.41	47.69	410.6
Q3	47.35	45.13	433.6			
T1	45.64	47.29	429.5			
T2	45.51	50.08	405.9	45.53	47.85	425.6
T3	45.44	46.19	441.7			

The highest strength was observed from quenched and tempered specimens, followed by quenched, then annealed. This was the case in both yield and ultimate calculations. Moduli, yield strength and ultimate strength calculations are displayed in Table 3.

Table 3: Calculated material properties with an average based on type.

Tensile Test Results						
Sample Label	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Modulus of Elasticity (GPa)	Average Yield Strength (MPa)	Average Ultimate Strength (MPa)
A1 A2 A3	211.1 196.4 197.2	379.2 342.3 329.7	745.0 709.1 704.6	201.6	350.4	719.5
Q1 Q2 Q3	193.6 196.2 195.1	794.8 770.0 829.5	1804 1809 2552	200.7	798.1	1805
T1 T2 T3	253.6 208.7 217.0	1420 1194 1275	2552 2096 2202	228.9	1296	2283

4 Discussion

Hardness and tension testing was performed on A2 steel specimens that were subjected to annealing, quenching, and quenching and tempering heat treatments. Axial displacement and axial force data were recorded to calculate yield strength, ultimate strength, and moduli. These calculations determined quantitative values for strength and stiffness, and were consistent within each heat treatment type. Indentation width and height were used to calculate a Vickers hardness number. Hardness testing data showed a positive correlation between material hardness and its strength. This is indicative of the relationship between surface deformation and loading deformation. The results of testing confirmed the hypothesis that steel stiffness, hardness, and strength are directly affected by the type of heat treatment used.

Annealed specimens reflected the lowest strength and hardness in comparison to quenched or tempered, indicating a slow absorption of energy applied over time. Quenched steel had significantly higher yield and ultimate strengths, with high brittleness. Tempered steel was shown to have the highest strength and hardness with minor ductile characteristics, demonstrating some ductility can be recovered after quenching. Unsurprisingly, the moduli remained relatively consistent.

A simple estimate is displayed in Equation 6 that represents yield strength as a relationship to hardness [5].

$$\sigma_y = 3HV \tag{6}$$

This equation, although not incredibly accurate, can be used to obtain data that generally agrees with the experimental results. Work hardening properties of the A2 steel is a potential reason for the limited applicability of this equation. In terms of defining ultimate strength, it is even less applicable. Yield strength may also be more predictable due to being driven by the material's crystalline structure, whereas ultimate strength is driven by imperfections in the geometric structure. The crystalline structure is less variable than geometric imperfections. Increasing the sample sizes of testing would increase the accuracy of Equation 6. Data findings in hardness testing are in agreement with the findings in tensile testing.

Different types of heat treatment methods can be used to alter material properties. Annealing will provide ductility at the cost of strength. Quenching will improve strength while increasing brittleness. Tempering, after quenching, was shown to retain minor ductile properties and improved strength. Depending on the objectives to be met, considerations of treatment methods are important to obtain a desired material property for engineering design.

References

[1] *Standard Test Method for Knoop and Vickers Hardness of Materials*. Standard. West Conshohocken, PA: ASTM International, 2010.

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