Tensile Testing and Hardness Statistics for Steel and Aluminum samples

Nick Beaver
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Dr. Ryan Smith

Abstract

Rockwell hardness testing was shown to be more precise than Vickers hardness testing. The comparative hardness of the metal alloy samples tested correlated to their comparative mechanical properties as measured via tensile testing or obtained from literature.

Introduction

Hardness and tensile testing of materials are two very important investigations into material properties in the field of materials engineering. Measuring the hardness of a material allows other useful mechanical properties of the material to be calculated, as hardness in materials is highly correlated to properties such as wear resistance, stiffness, and strength[1]. Tensile testing is an extremely common form of material testing, and yields many applicable material properties such as elastic modulus, yield strength, and ultimate tensile strength. Tensile testing and the material properties the generated data can be used to calculate are extremely useful in predicting material behavior under loading or for creating engineering designs that have to function within limits of that material behavior[2].

This report will explore hardness testing and tensile testing results for 6061 aluminum, 1040 steel, and 4140 steel. Specifically, the precision of two common hardness testing methods, Rockwell (HRB) and Vickers (HV) hardness, will be compared, while the comparative material properties of the samples are investigated via tensile and hardness testing analysis.

Experimental Procedure

All of the tests in this experiment were run on the same samples, which were prepared as standard tensile bars. The 1040 steel was air-cooled, and the 4140 steel was water-cooled. The steel samples were scrubbed with coarse sandpaper to remove any surface oxides present from heat-treating. The tensile tests were performed first in this experiment, and were done on an Instron tensile testing machine with a strain rate of 3 mm/min. The test was set up according to the ASTM E8 standard for tensile tests[3]. The raw tensile data from taken from the Instron machine was then analyzed in excel to find the elastic modulus (slope of the linear regime of data), yield strength (0.2% offset method), ultimate tensile strength, and strain hardening exponent (Ludwik-Hollomon power law).

The hardness tests done in this experiment utilized two different hardness standards. The first hardness test performed was the rockwell hardness test on a rockwell hardness testing apparatus which was set up and ran according to ASTM E18[4]. The second hardness test performed was a Vickers microhardness test with a 100 gram loading according to ASTM E384[5]. Many hardness data points were taken with both hardness standards in an attempt to create normal distributions of hardness data for statistical comparison and interpretation of the hardness of the three samples.

Hardness Testing Results

The average measured hardness results of both standards were converted to the other standard using a hardness value conversion chart[6] to compare the values given by both methods. Table 1 shows that the average HRB value for the 6061 aluminum differed greatly from its converted HV value (Table 2). This is likely due to the very high standard deviation of the 6061 HV values (Table 2). In contrast, the HRB and HV values for the 1040 steel sample seemed to convert well between each other, as the converted mean HRB value in table 1 was within one standard deviation of the measured mean HRB value for the sample. The same was true for the 1040 converted HV value in table 2. The converted mean HV value for 4140 steel was within one standard deviation of the mean HV value seen in table 2. However, the conversion from the HV value to the HRB value was not fully interpretable, as the conversion chart did not have an HRB value corresponding to 274 HV (100 is the highest value on the chart). Still, the conversion between the hardness values for the 4140 sample seemed accurate to the degree of being within 1-2 standard deviations of the mean value.

Material	**Average HRB**	**STD HRB**	**Converted Average HRB**
6061 Aluminum	49.99	7.21	84
1040 Steel	95.64	1.21	96
4140 Steel	97.59	2.06	100*

Table 1: Measured and Converted HRB values (HV to HRB)

Material	Average HV	STD HV	Converted Average HV
6061 Aluminum	160.36	75.30	95
1040 Steel	222.85	35.99	220
4140 Steel	274.27	60.845	234

Table 2: Measured and Converted HV values (HRB to HV)

None of the below histograms (figures 1-6) appear to be normal. None of them are symmetric about their mean values (from tables 1,2) due to the presence of outliers in almost every dataset (extreme outliers are seen in the 6061 HV distribution in figure 2). Another reason these distributions are not normal distributions is the lack of data points. For a sample distribution to be (approximately) normal, a sufficient amount of data points (n=30) must be used in the mean and standard deviation calculations[9]. The HV data in this experiment was more sparse due to the time it took to gather it, meaning the HV data was much more unreliable than the HRB data.

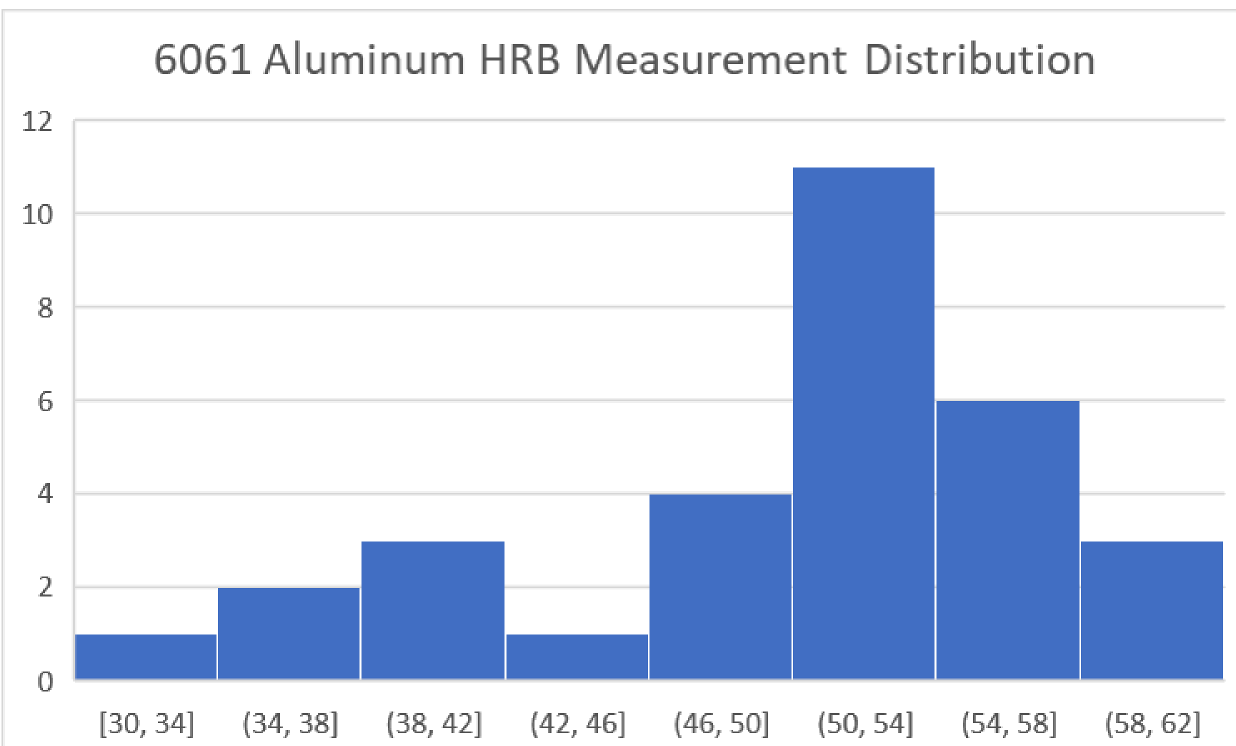

Figure 1: Histogram of 6061 Aluminum HRB values

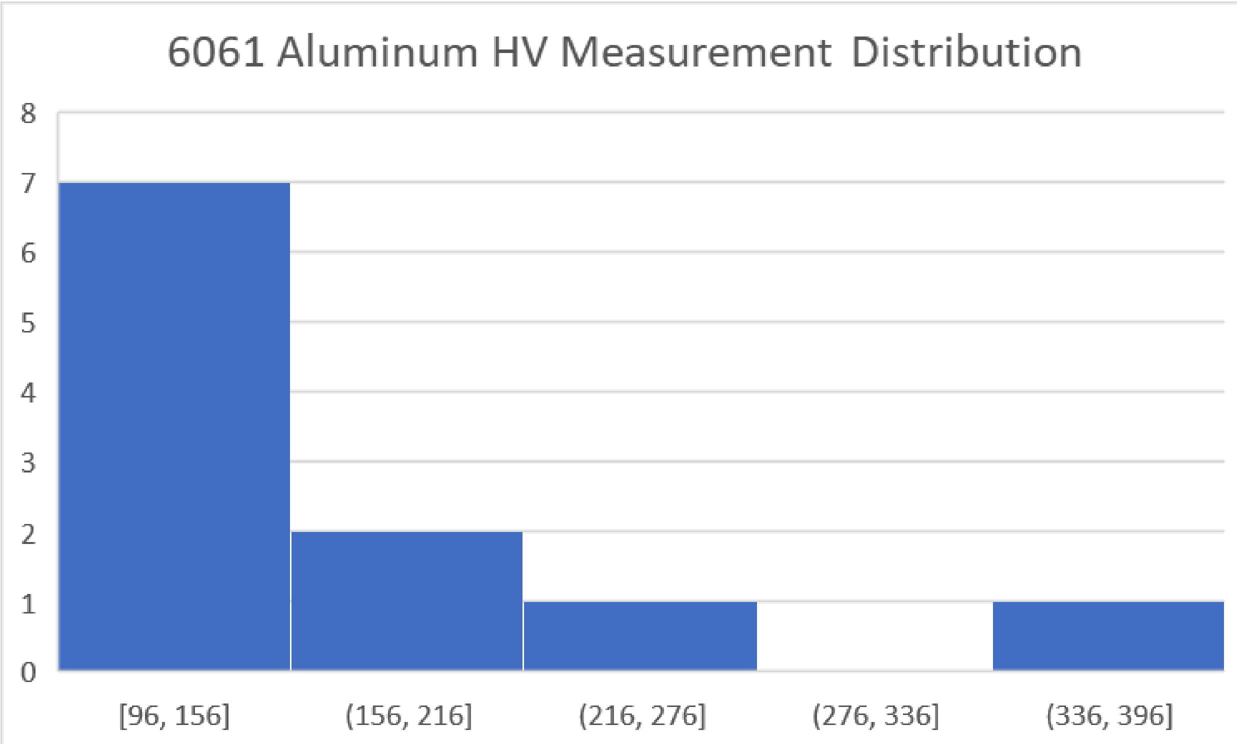

Figure 2: Histogram of 6061 Aluminum HV values

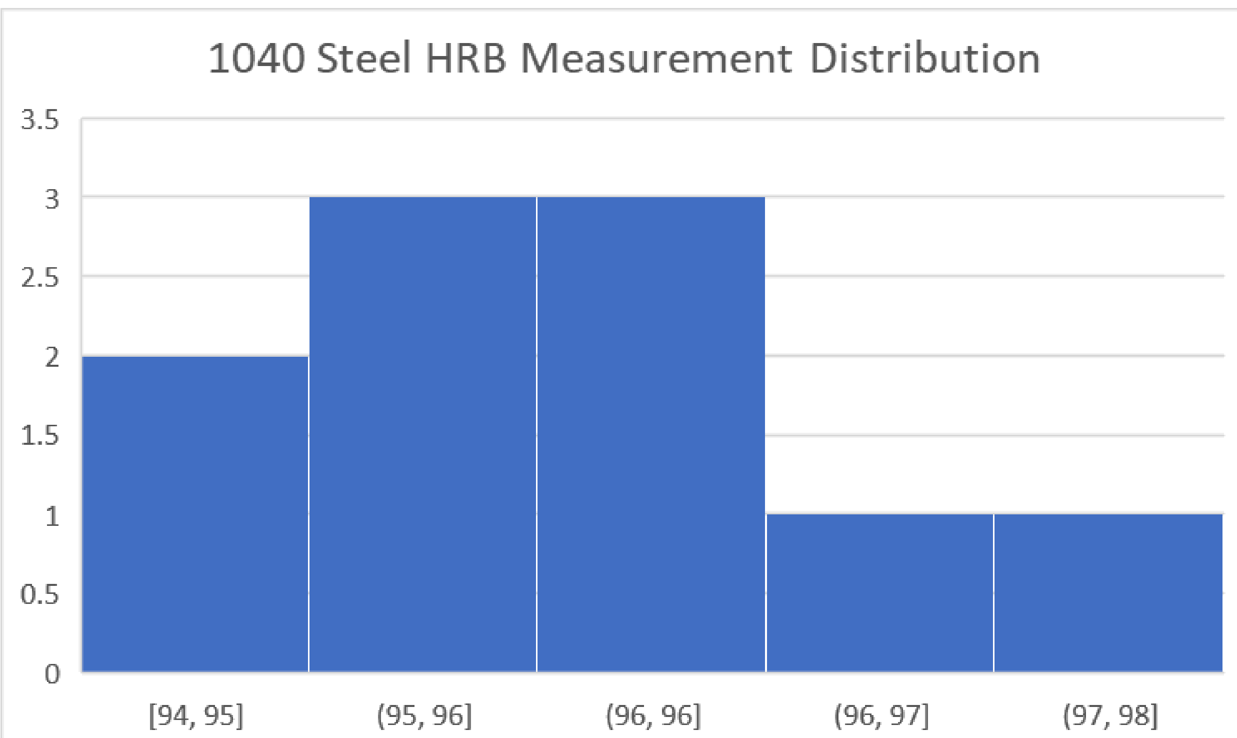

Figure 3: Histogram of 1040 steel HRB values

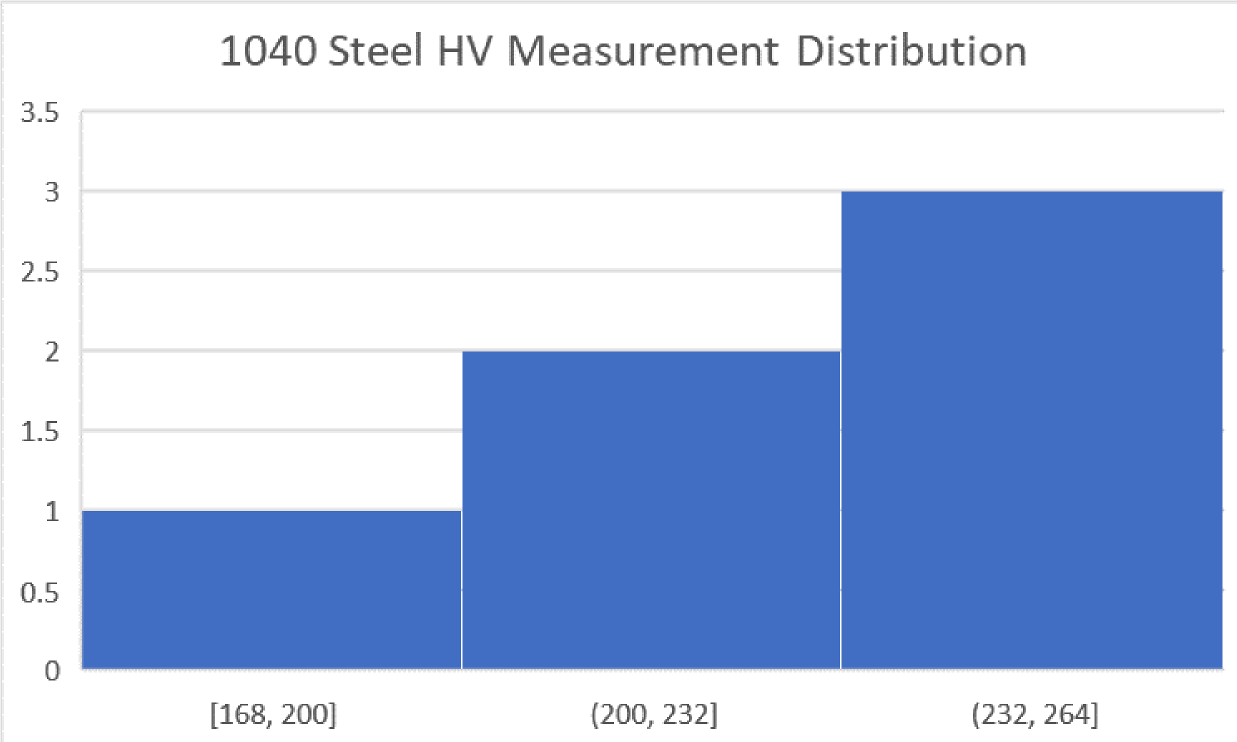

Figure 4: Histogram of 1040 steel HV values

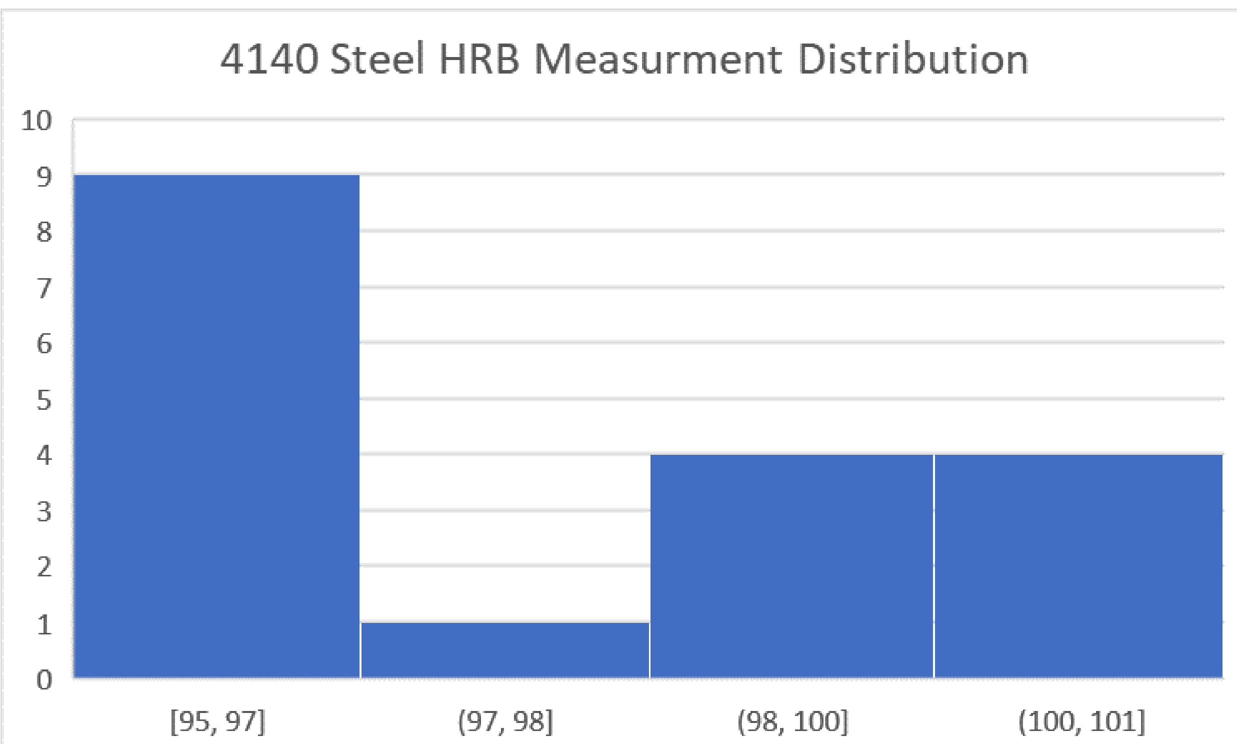

Figure 5: Histogram of 4140 steel HRB values

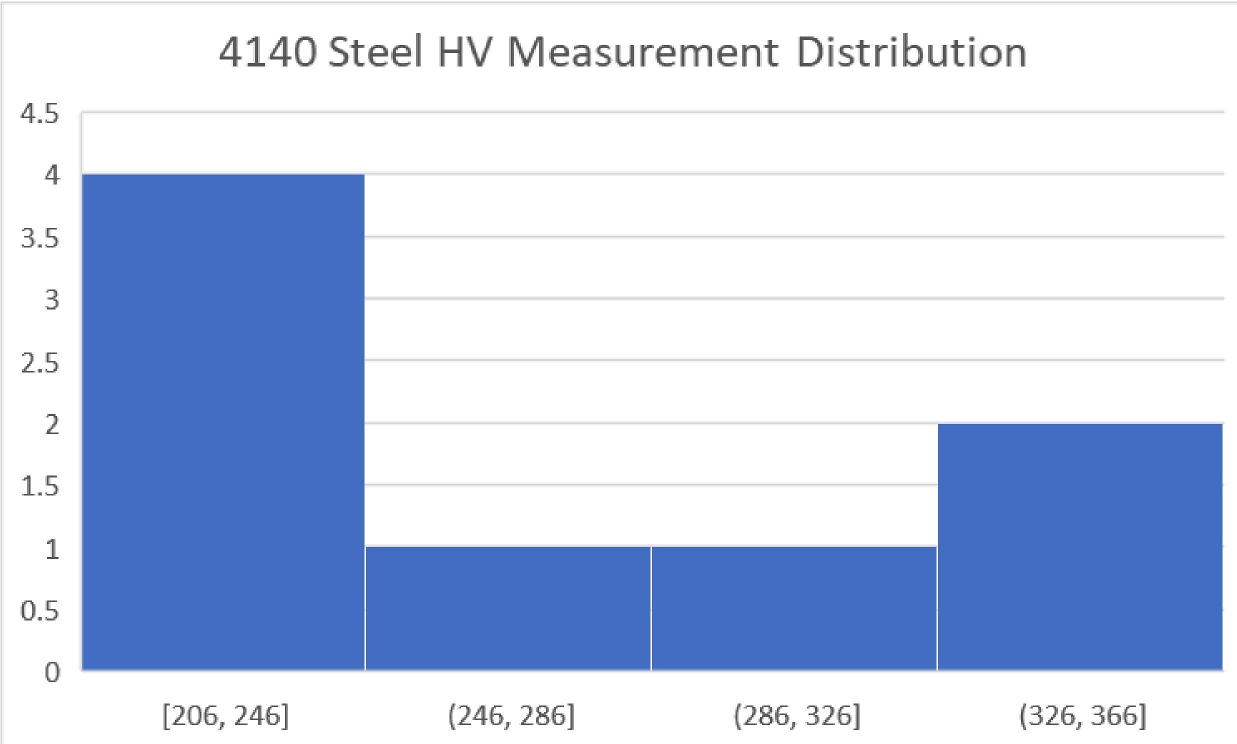

Figure 6: Histogram of 4140 steel HV values

Despite the statistical faults of this analysis, it is still possible to make some assessments of the hardness properties of the three samples. The 6061 sample was the softest of the three samples, having lower HRB and HV values than both of the steel samples. Of the two steel samples, the 4140 was harder on average. Statistically Quantifying the difference between the two samples' hardness values requires the comparison of their 95% confidence intervals about their mean hardness. In accordance with the sample mean confidence interval method[9], the 95% confidence interval for the mean HRB value of the 1040 sample was 95.64 ± 0.75, and the 95% confidence interval for the mean HRB value of the 4140 sample was 97.59 ± 0.952. Because the upper and lower bounds of the intervals do not overlap (96.4 and 96.6 for 1040 and 4140 respectively), the two mean hardness values are significantly different if the initial statistical hypothesis assumed they were in fact the same value. Based on this result, it is possible to correlate the heat treatment of the 4140 sample to its statistically increased hardness. The increase in hardness of a steel sample due to its cooling rate is due to microstructural changes such as decreased grain size, which is known to increase strength and therefore hardness in steels[10].

Based on all of the previous analyses, it would seem that Rockwell hardness is more reliable for general surface hardness testing than Vickers hardness. Human error likely played a large part in the unreliability of the collected HV data, as the imaging of the diagonal indentations could have been inaccurate or imprecise dependent on the experimenter using the Vickers machine. Additionally, it is possible that the larger size of the Rockwell indenter (which makes indents on the millimeter scale instead of the micron scale as in Vickers hardness testing) avoided measuring statistically aberrant surface structures such as scratches, oxides, or cavities.

Tensile Testing Results

The tensile testing of the 6061 aluminum sample resulted in the calculations of its material properties via a stress-strain plot (figure 7). The slope of the linear part of the true stress-true strain behavior resulted in an elastic modulus of 72.56 GPa. The Instron machine returned a value for the elastic modulus of the sample that was 86.66 GPa (figure 9). These two values are 17.7113% different, and likely are different because the Instron software used a smaller subset of the linear data to calculate the slope of the elastic behavior. Using the 0.2% offset method resulted in a calculated yield strength of 327.93 MPa. This is very close to the calculated value given by the Instron software of 323.7 MPa, shown by a small 1.3% difference between the values. Figure 7 also shows additional important material properties of the 6061 sample. The ultimate tensile strength (maximum stress) was 417.995 MPa. The true strain at fracture was 0.155, and the ratio of the percent reduction of area to the percent elongation was 16.80% (figure 9). The ludwik-hollomon plot of the plastic deformation curve of the 6061 (figure 8) showed a work hardening exponent (n) of 0.1147 and a constant (k) of 6.2687.

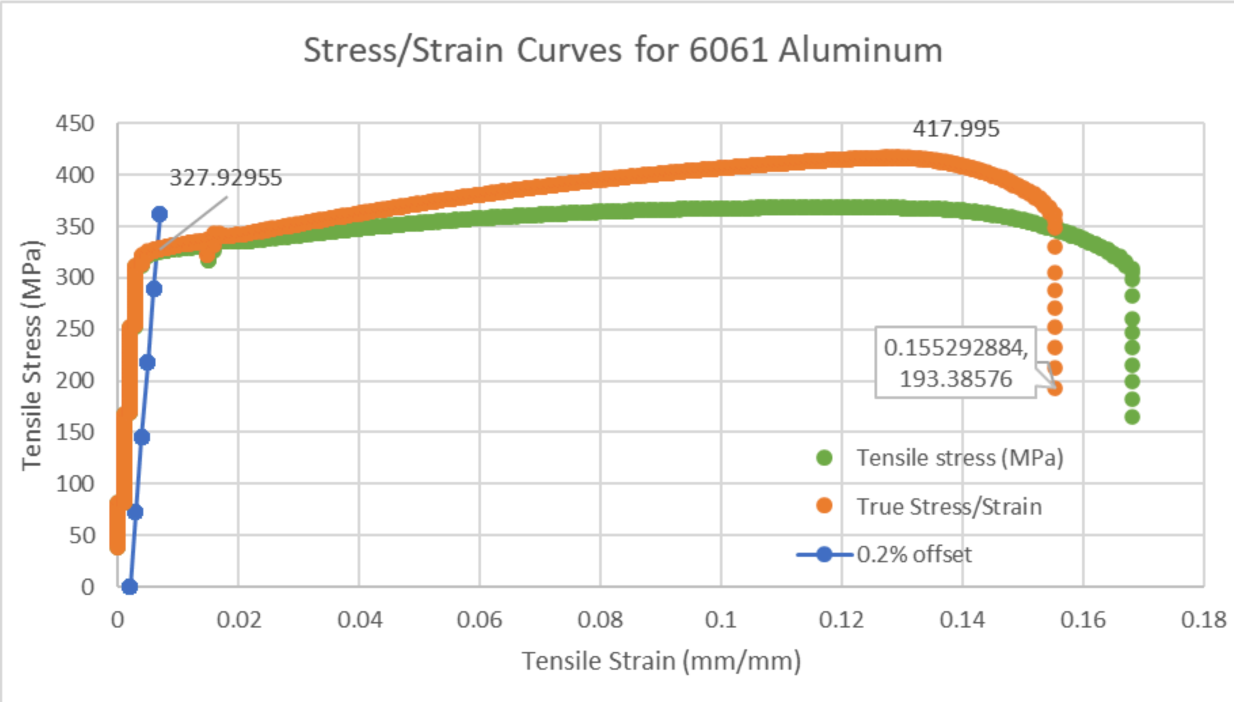

Figure 7: Stress Strain curves for 6061 aluminum sample with 0.2% offset and noted important data points

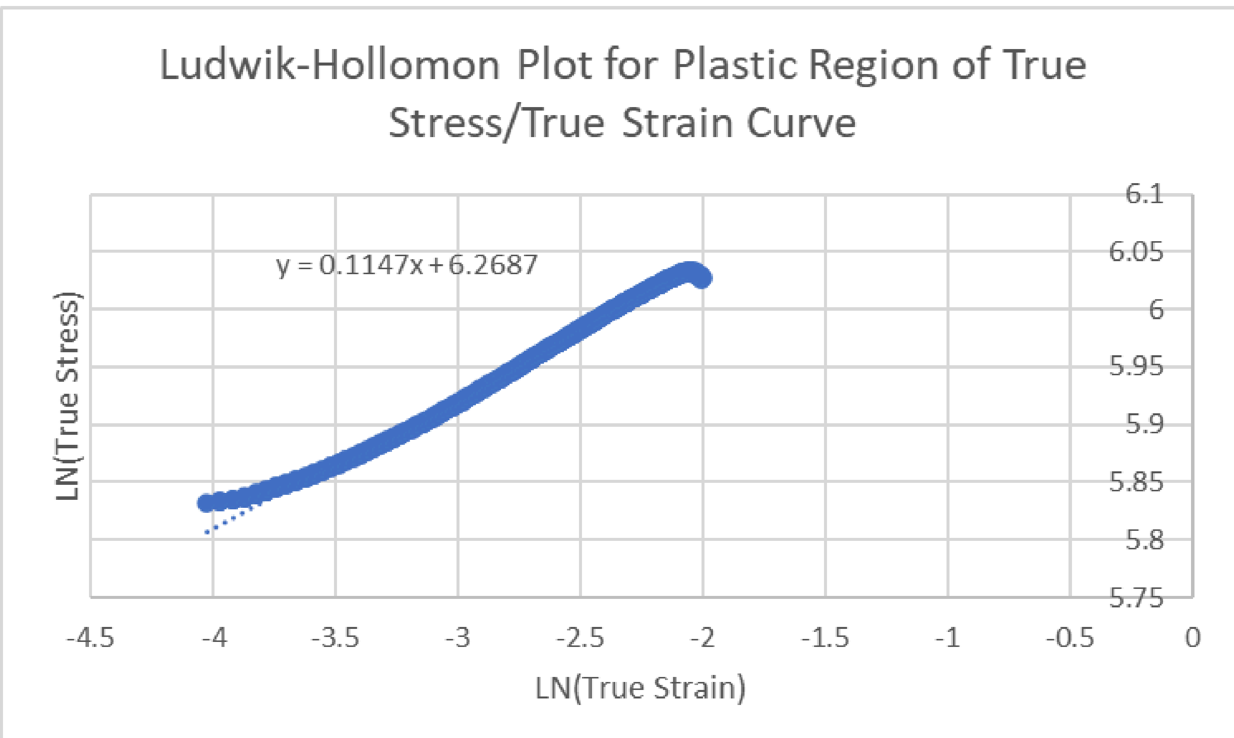

Figure 8: Ludwik-Hollomon plot for plastic region of 6061 aluminum true stress/strain

Specimen label	Modulus (Automatic Young's) [GPa]	Yield Stress (0.2% Offset) [MPa]	% Elong [%]
AL 6061T651	86.66	323.7	16.80

Figure 9: Instron machine measurements for material properties of 6061 aluminum

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Strain Hardening Coefficient
6061 Aluminum	72.56	327.93	417	0.115
1040 Steel	200	403	608	N/A
4140 Steel	205	793	931	N/A

Table 3: Material properties of tensile samples - 1040 properties from [7], 4140 properties from [8]

The material properties in table 3 show that the sample with the highest elastic modulus, yield strength, and ultimate tensile strength was the 4140 steel[8] (based on material data from similarly processed 1040 and 4140 steel). This result is an intuitive extension of the earlier result that the 4140 steel was the hardest sample tested under the given processing conditions, as hardness is a measure of deformation resistance - a higher yield strength will usually correlate to a higher hardness value[11].

Conclusion

Rockwell hardness testing is more reliable than Vickers hardness testing for general surface hardness characterization. Based on the HRB scale, the hardest sample tested was the 4140 steel. This had a direct correlation to the comparison of literature values for the mechanical properties of the three samples, as the 4140 steel (under similar processing) also had the highest yield and ultimate strength values.

References

[1] Zhai, Wenzheng, et al. “Recent Progress on Wear-Resistant Materials: Designs, Properties, and Applications.” *Advanced Science*, vol. 8, no. 11, 2021, p. 2003739., https://doi.org/10.1002/advs.202003739.

[2] “Tensile Test and Its Application to Materials.” *Infinitia Industrial Consulting*, 16 May 2022, https://www.infinitiaresearch.com/en/news/tensile-test-and-its-application-to-materials/.

[3] “Standard Test Methods for Tension Testing of Metallic Materials.” *ASTM International - Standards Worldwide*, https://www.astm.org/e0008_e0008m-22.html.

[4] “Standard Test Methods for Rockwell Hardness of Metallic Materials.” *ASTM International - Standards Worldwide*, https://www.astm.org/e0018-22.html.

[5] “Standard Test Method for Knoop and Vickers Hardness of Materials.” *ASTM International - Standards Worldwide*, https://www.astm.org/e0384-11.html.

[6] Hardness Conversion Table - Maher. https://www.maher.com/media/pdfs/hardness-conversion-chart.pdf.

[7] “AISI 1040 Steel, Normalized at 900°C (1650°F), Air Cooled, 13 Mm (0.5 in.) Round.” *Aisi 1040 Steel, Normalized at 900°C (1650°F), Air Cooled, 13 Mm (0.5 in.) Round*, https://www.matweb.com/search/DataSheet.aspx?MatGUID=117d740ede8942a5a892a05dbb81792e.

[8] “AISI 4140 Steel.” *Aisi 4140 Steel, (1 in.) Round*, https://www.matweb.com/search/datasheet.aspx?matguid=58863eb66da84888a797eb2d80ca7598&n=1.

[9] Confidence Intervals Notes - University of West Georgia | UWG. https://www.westga.edu/academics/research/vrc/assets/docs/confidence_intervals_notes.pdf.

[10] Equbal, Israr, et al. “Effect of Cooling Rate on the Microstructure and Mechanical Properties of Medium Carbon Steel.” *International Journal of Metallurgical Engineering*, 2016, https://doi.org/doi:10.5923/j.ijmee.20160502.01. Accessed 18 Mar. 2023.

[11] “What Is the Correlation between Hardness and Strength?” *Performance Alloys*, https://materion.com/about/new-at-materion/hardness-and-strength.