NPRE 432 Laboratory 1 - Hardness and Compression

Joseph F. Specht IV (jspecht3)

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1 Abstract

Material durability is often the first and most important characteristic investigated when selecting a material, especially a structural material, for a project. Material durability can be quantified using hardness and compression testing. Therefore, this laboratory investigated the hardness of 2024 aluminum and 4340 steel using Rockwell and Brinell hardness tests. This laboratory also investigated the effects of compression in 2024 aluminum, 1045NM steel, 1018CR steel, and PMMA (polymethylmethacrylate), which is a plastic, using uniaxial compression tests. The results of the hardness testing indicated the most important factor when measuring the hardness of a material is choosing a scale appropriate for the hardness of the specimen. The results of the uniaxial compression testing indicated the most important quality for material stress-strain curve

2 Results and Discussion

After the laboratory, the data were uploaded online for the students to download. The data were processed using a Jupyter notebook in Jupyter Lab with the Python3 (ipykernel).

2.1 Hardness Testing

During the hardness testing, each group of students measured and recorded the hardness of 2024 aluminum and 4340 steel using various hardness scales: Brinell, Rockwell B, and Rockwell C. The hardness data were then coalesced and processed to find statistically interesting quantities: the mean, the median, the standard deviation, and the coefficient of variation of the hardness measurements.

Table 1: Measures of Central Tendency of Hardness Measurements

Material:	**2024 Aluminum**			**4340 Steel**		
Hardness Test:	**Brinell**	**Rockwell B**	**Rockwell C**	**Brinell**	**Rockwell B**	**Rockwell C**
Mean	140.9	86.475	4.115	740.5	121.485	63.04
Median	138.	86.65	5.2	731.	121.55	62.85
Standard Deviation	6.172	2.927	3.033	38.124	0.977	1.495
Coeff. of Variation [%]	4.38	3.38	73.7	5.15	0.804	2.37

Where the mean, median, and standard deviation were all calculated using the numpy functions mean, median, and std, respectively. Also, The coefficient of variation was calculated by dividing the standard deviation by the mean.

As seen in Table 1, the coefficient of variation is below 5% on all measurements except two: the 2024 Aluminum Rockwell C at 73.7% and the 4340 Steel Brinell at 5.15%. The coefficient of variation of the 4340 Steel Brinell measurements is very close to the 5% being 0.15% off. The relatively low coefficient of variations on all but one data point indicate that the testing students carried out was fairly precise.

Most coefficients of variation are roughly 5%, however, there are two outliers in the coefficients of variation: 2024 Aluminum Rockwell C value of 73.7% being far above 5% and 4340 Steel Rockwell B being far below 5%. The outliers can be explained by usage of scales not suited for the hardness of the specimen. The Rockwell C scale ranges from 20 to 60 and 2024 Aluminum had a mean hardness of 4.115 – far below the minimum value of the scale.

The Rockwell B scale ranges from 20 to 100 and 4340 Steel had a mean hardness of 121.485 – markedly above the maximum value of the scale. The scales are designed in such a way that the indenter had a suitable hardness to determine the hardness of the materials in the given range. The accuracy of the scale depends on the difference in hardness between the indenter and the specimen. An extreme difference in hardnesses causes the specimen to deform with minimal resistance, which leads to a higher coefficient of variation as the material is at the bottom end of the scale, so the differences between results are more impactful in the final calculations. A minimal difference in hardnesses causes the specimen to deform minimally, which leads to a lower coefficient of variation as the material is at the top end of the scale, so the differences are less impactful.

The largest sources of variation are due to usage of a hardness scale designed for materials harder than the specimen. The converse, however, is not true – hardness scales designed for materials softer than the specimen have a lower coefficient of variation. As such, the coefficient of variation is not an accurate metric to quantify the application of a scale. Other potential sources of variation are the students setting the indenter closer than three indentation-diameters from other indentations or the indenter being set too close to the edge of the specimen.

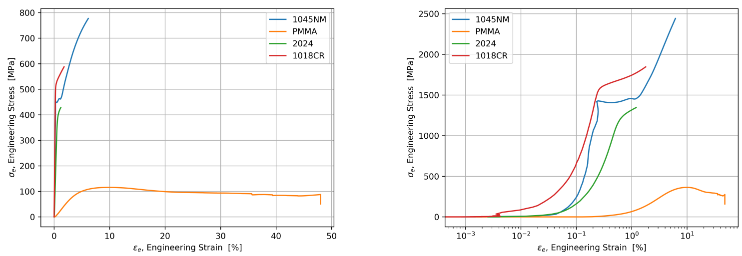
The impact of scale usage is best quantified by conversion into a single scale for comparison. The median hardness values for Rockwell B and Rockwell C will be converted into the Brinell scale using conversion charts from the laboratory manual [1] and Steel Express [2], a third-party website with conversions as the laboratory manual did not contain all requisite values for conversion. Simple linear interpolation was used when data points were not exactly given.

For 2024 Aluminum, the median Brinell hardness was 140.9 and the converted hardnesses from Rockwell B were 170.425 using the laboratory manual and 168.425 using Steel Express. The converted values agree with each other, but do not agree with the measured median Brinell hardness value. For 4340 Steel, the median Brinell hardness was 740.5 and the converted hardness from Rockwell C was 678.9 using Steel Express. The converted and measured median Brinell hardness values do not agree.

2.2 Compression Testing

During the uniaxial compression testing, each group of students experimentally determined the stress-strain curve of various materials: 2024 aluminum, 1045NM steel, 1018CR steel, and PMMA. Unlike the hardness testing, each group of students only used the data from the testing of their respective group.

The engineering stress-strain curve for all materials (Fig. 1) indicate the most influential factor varied in



(a) Linear Engineering Strain (b) $\log_{10}$ Engineering Strain Scaling

Figure 1: Engineering Stress-Strain Curve for all Materials

this laboratory was the classification of material used: metal, which refers to both metal and metal alloy, or plastic. The metals are much stiffer than the plastic and had an observable elastic deformation region and a plastic deformation region, whereas the PMMA only had a plastic deformation region.

As the metals were much stiffer, all metals had an elasticity modulus one to two orders of magnitude higher than PMMA. In order of increasing elasticity modulus value, 2024 Aluminum had a value of 73.459 -, 1045NM Steel had a value of 197.277 -, and 1018CR Steel had a value of 203.263 GPa^{-1}. The steels: 1045NM steel and 1018CR steel, had elasticity moduli roughly three times that of 2024 Aluminum – this indicates steels are generally stiffer than aluminum alloys, but both are stronger than plastics.

The yield strength of the plastic is not particularly meaningful as the is no elastic deformation. However, the local stress for early strain measurements can be approximated as linear due to any function appearing linear with a high enough magnification. For the metals, 1018CR Steel and 2024 Aluminum had similar stress-strain shapes while 1045NM Steel has a plateau region. The plateau region in 1045NM Steel is most likely due to the formation process of the steel.

The ultimate strength is only truly known for PMMA as the metals had continually were able to withstand increasing stress without reaching a maximum value. The only conclusive statement that can be made is the tested metals have an ultimate strength at least four to seven times that of PMMA.

The aforementioned values: elastic modulus, 0.2% yield strength, and ultimate strength, are tabulated below.

Table 2: Material Properties from Compression Testing

Material:	**2024 AL**	**1045NM STL**	**1018CR STL**	**PMMA**
Elastic Modulus [GPa^{-1}]	73.459	197.277	203.263	2.626
0.2% Y.S. [MPA]	401.088	453.737	521.167	61.926
Ult. Strength [MPa]	428.351	786.93	580.356	115.495

The previous analysis of the compression data used engineering stress, but true strain is another metric to quantify the stress of the material. Engineering stress normalizes the applied force by the initial specimen area while the true strain normalized the applied force by the current area.

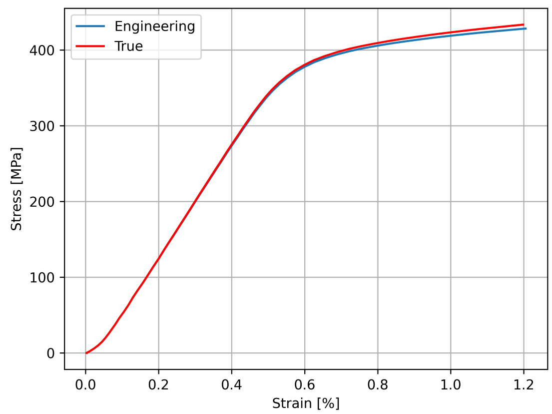


Figure 2: Engineering and True Stress for 2024 Aluminum

Figure 2 shows minimal difference between the engineering and true strain. However, when the current cross-sectional area and the initial cross-sectional area are roughly the same, the true stress simplified to the engineering stress. If a heavier load was applied, the true stress would differ more dramatically from the engineering stress.

3 Conclusions

When conducting hardness tests, the most important factor for accuracy is choosing the correct scale for the given material. If comparisons need to be made between materials of drastically different hardnesses, a single scale should be chosen that can support both measurements – conversions between scales are not reliable enough to be considered accurate. When conducting compression testing, the material property that most dictates the shape of the stress-strain curve is the material class: metal or plastic. Metallic materials have both elastic and plastic deformation regions – plastic materials only have a plastic deformation region.

References

[1] NPRE 432, Behavior of Engineering Materials.

[2] Steel Hardness Conversion Table, www.steelexpress.co.uk/steel-hardness-conversion.html. Accessed 17 Sept. 2024.