

Uniaxial Tension and Compression Testing of Materials

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3.032 Lab Report
September 25, 2013

I. Introduction

Understanding material mechanics is critical for engineering. The uniaxial tension and compression tests provide a simple and effective way to characterize a material's response to loading. By subjecting a sample to a controlled tensile or compressive displacement along a single axis, the change in dimensions and resulting load can be recorded to calculate a stress-strain profile. From the obtained curve, elastic and plastic material properties can then be determined. Therefore, to investigate material mechanics and gain experience in uniaxial testing, we performed compressive and tensile tests on alloys, pure metals, and ceramics, and calculated their Young's modulus, yield stress, ultimate tensile strength, and elastic strain energy density.

1.1 Uniaxial testing

For uniaxial tests, the displacement is typically held at a constant rate, and displacement and resulting load are recorded. The load is measured by a series of strain gages, or "load cell," while the displacement can be recorded as displacement of the crosshead, or the beam on which the specimen load frame is mounted. For more precise load measurements, strain gages or an extensometer can be directly fixed to the specimen. To make direct comparisons between materials, loading responses must be normalized against sample geometry. Therefore, the dimensions of each sample are noted to compute stress and strain from load and displacement, respectively. Engineering strain can be calculated as:

$$\varepsilon_e = \Delta L / L_0 \quad (1)$$

Where ΔL is the measured displacement and L_0 is initial sample length along a single axis.

Engineering stress can be calculated as:

$$\sigma_e = P/A_0 \quad (2)$$

Where P is the applied load and A_0 is the initial cross sectional area of the sample normal to the loading direction. In tensile tests, specimens typically have two shoulders and a gauge section in between, as so:

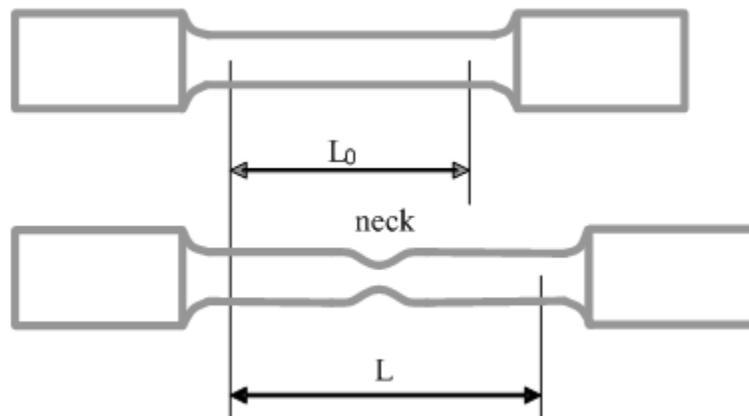


Fig. 1.1 Typical tensile testing specimen¹

The shoulders are large so that they may be gripped by the testing apparatus. The neck, as a region of reduced cross-sectional area, localizes stress and ensures that failure consistently occurs near the middle. The cross sectional area, A_0 , may be taken as that of the neck region. In compressive tests, specimens are typically cylinders.

1.2 The stress-strain profile

With the sample geometry, a stress-strain curve can then be generated from the recorded load and displacement. A typical stress-strain profile for a ductile metal resembles the following:

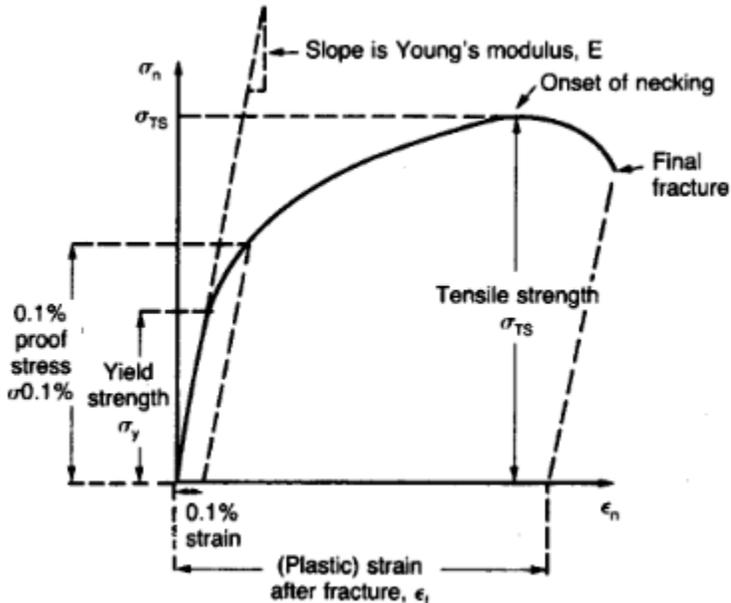


Fig. 1.2 Typical stress-strain curve of a ductile metal²

The material initially behaves in a linear elastic manner: stress and strain are linearly related, and on unloading, the deformation is recoverable. The slope within the linear elastic regime is Young's modulus, or the ratio of the engineering stress to engineering strain in the axis:

$$E = \sigma_e / \epsilon_e \tag{3}$$

E characterizes the stiffness of a material in units of force per unit area (N/m², or Pa). The area under the elastic portion of the curve therefore defines the elastic strain energy density in units of

energy per unit volume (J/m^3):

$$U = \frac{1}{2}\sigma\varepsilon \quad (4)$$

A material's maximum capacity to elastically absorb energy is then the total area under the stress-strain curve's linear elastic regime:

$$U_{\text{el}}^{\text{max}} = \frac{1}{2}\sigma_y\varepsilon_y \quad (5)$$

Where σ_y and ε_y are the yield stress and yield strain at which linear elastic behavior ceases. At larger strains, material deformation becomes irrecoverable and non-linear, or plastic. Along with σ_y and ε_y , the 0.2% offset yield stress, or the stress that corresponds to 0.2% irrecoverable strain on unloading, is used as a convention to characterize the transition. In the plastic region, the material will also exhibit its ultimate tensile stress, or the maximum load divided by the initial cross-sectional area:

$$\sigma_{\text{ult}} = P_{\text{max}}/A_o \quad (6)$$

To gain experience in uniaxial testing and better understand material mechanics, we will obtain E , σ_y , σ_{max} , ε_{max} , and $U_{\text{el}}^{\text{max}}$ of pure metals and alloys, as well as ceramics. Differences in their atomic structure will account for differences in their mechanical properties. For example, alloys typically have larger values of E than their pure counter-parts, due to the presence of substitutional atoms which impede the movement of dislocations. Ceramics will exhibit brittle

behavior and high stiffness relative to metals, due to the directionality of their covalent bonds. Covalent bonds of a ceramic will resist deformation when a force is applied, but break when the threshold is passed, whereas the delocalized nature of the bonds in metals allows for plastic deformation, or ductile behavior.

2. Materials and Methods

2.2 Uniaxial Tension

For this section of the laboratory experiment, a metal (Cu, 99.3%) and three metal alloys (α -brass [64.5% Cu, 35% Zn, 1% Pb], aluminum 6061, and steel 1045) were subjected to uniaxial tension using the Instron Model 4505. The samples were dog-bone structures to localize the point of failure to the center of the samples during testing (Fig. 2.1). The initial sample dimensions (width and thickness) were measured, and then the samples were mounted into the fixed lower base of the Instron 4505 (Table 2.1, Fig. 2.2). The gage length L between the fixed lower base and upper fixture was measured to determine the initial length of the sample undergoing uniaxial tension.

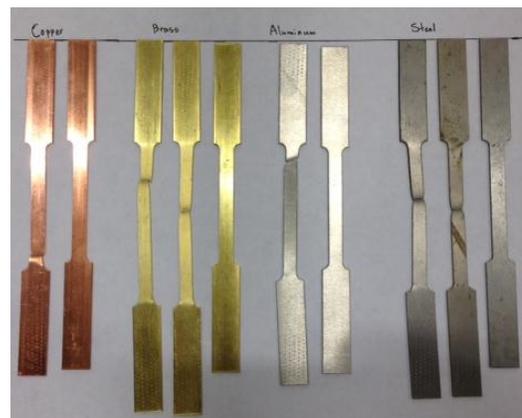


Fig. 2.1 Copper, brass, aluminum, and steel samples for tensile testing. Each set of materials contain samples before (right) and after (left) tensile testing.

Sample	Width (mm)	Thickness (mm)	Initial L (mm)
Steel	6.572	1.666	66.15
Al 6061	6.605	1.6	65.57
Cu	6.35	1.55	65.8
Brass	6.34	1.55	61.19

Table 2.1 Initial gage dimensions (width, thickness, and initial length, in mm) of the specimens.



Fig. 2.2 Brass sample between the lower base and upper fixture that had undergone uniaxial tensile testing.

Using the Instron Series IX Software, the force-displacement responses of each of the material at a displacement rate of 15 mm/min were acquired. The tests ended when the specimens fractured. After testing one sample of each material, a second round of tensile tests were performed on both the brass and steel samples to observe variations in mechanical properties for a single material.

2.1 Uniaxial Compression

This section of the laboratory experiment involved subjecting Cu (99.3%), α -brass (64.5% Cu, 35% Zn, 1% Pb), aluminum 6061, steel 1045, and alumina (porous and non-porous) to uniaxial compression using the Instron Model 4206 (Fig. 2.3). Two measurements of the initial gage dimensions of the specimens were taken and averaged to obtain the dimensions that appear in Table 2.2. The samples were then placed between the compression anvils to commence uniaxial compression testing (Fig. 2.4).



Fig. 2.3 Porous Al_2O_3 , Non-Porous Al_2O_3 , aluminum, brass, steel, copper. Each pair of materials contain samples before (left) and after (right) compression testing.

Sample	Height (mm)	Diameter (mm)
Steel	38.05	12.66
Al 6061	38.19	12.75
Cu	38.13	12.76
Brass	38.12	12.68

Table 2.2 Initial gage dimensions (height and diameter, in mm) of the specimens.



Fig.2.4 Aluminum sample between the compression anvils.

To measure the strains of the samples within the elastic range, the specimens were loaded into the Instron 4206 with the extensometer directly attached to the sample. The samples were then unloaded, had the extensometer removed, and then compressed again up to a 5 mm maximum displacement. A second limit of 100 kN was set to protect the instrument from applying a load greater than its capable load. The extensometer-loading test was not performed on the porous and non-porous alumina. Bluehill 2 Software V2.6 was used to generate force-displacement curves.

2.3 Calculation of Mechanical Properties

The force-displacement responses were re-plotted in terms of engineering stress and strain to calculate E , σ_y , σ_{\max} , ϵ_{\max} , and U_{el}^{\max} . Using the measured dimensions of the samples and Eqn. 1, 2 and 3, the Young's modulus, E , was calculated. The yield stress, σ_y , was calculated by determining the 0.2% offset yield strain, forming a line with a slope equal to the

Young's modulus with that yield strain as the x-intercept, and locating the point where this line intersected the stress-strain curve. The values for yield stress and yield strain were used along with Eqn. 5 to calculate values for U_{el}^{max} , the material's maximum capacity to elastically absorb energy. The maximum stress and strain for the uniaxial tension tests were determined by finding the local maximum of the stress-strain curve before fracture of the samples occurred.

3. Results

3.1 Uniaxial Tension

Figure 3.1 shows the measured stress versus strain data for brass, aluminum (alloy 6061), copper, and steel specimen tested under tension. Two specimens each of brass and steel were tested. The four different types of metals featured varying behaviors under tension, highlighting their different mechanical properties (Table 3.1). Brass underwent the greatest amount of necking, and accordingly its strain at failure (31.2%) was the greatest out of the four metals. Steel was found to be comparably ductile (17.6%), while aluminum (6.3%) and copper (0.5%) were more brittle. Steel was found to be the strongest of the four metals with an ultimate tensile strength of 515.8 MPa, while brass was close at 461.5 MPa. Although relatively brittle, copper's ultimate tensile strength (373.8 MPa) is greater than that of aluminum (274.5 MPa). A similar ranking was observed for the metals' behavior in yielding: steel had the highest yield strength (162.6 MPa), followed by brass (118.7 MPa), copper (95.6 MPa), and aluminum (73.0 MPa). Steel was found to be considerably tougher than the other three metals, having an elastic modulus of 74.22 GPa. Copper's toughness ($E = 53.22$ GPa) was comparable to that of brass ($E = 58.03$ GPa), while aluminum ($E = 38.16$ GPa) was found to be the most elastic of the metals. The energy stored in tension for the four metals was similarly ordered, with steel and brass

having the highest maximum stored elastic energy (121 and 128 kJ/m³ respectively). Copper tolerated a moderate amount of tensile energy before yielding (95.4 kJ/m³) while aluminum yielded under the least amount of tensile energy (74.0 kJ/m³).

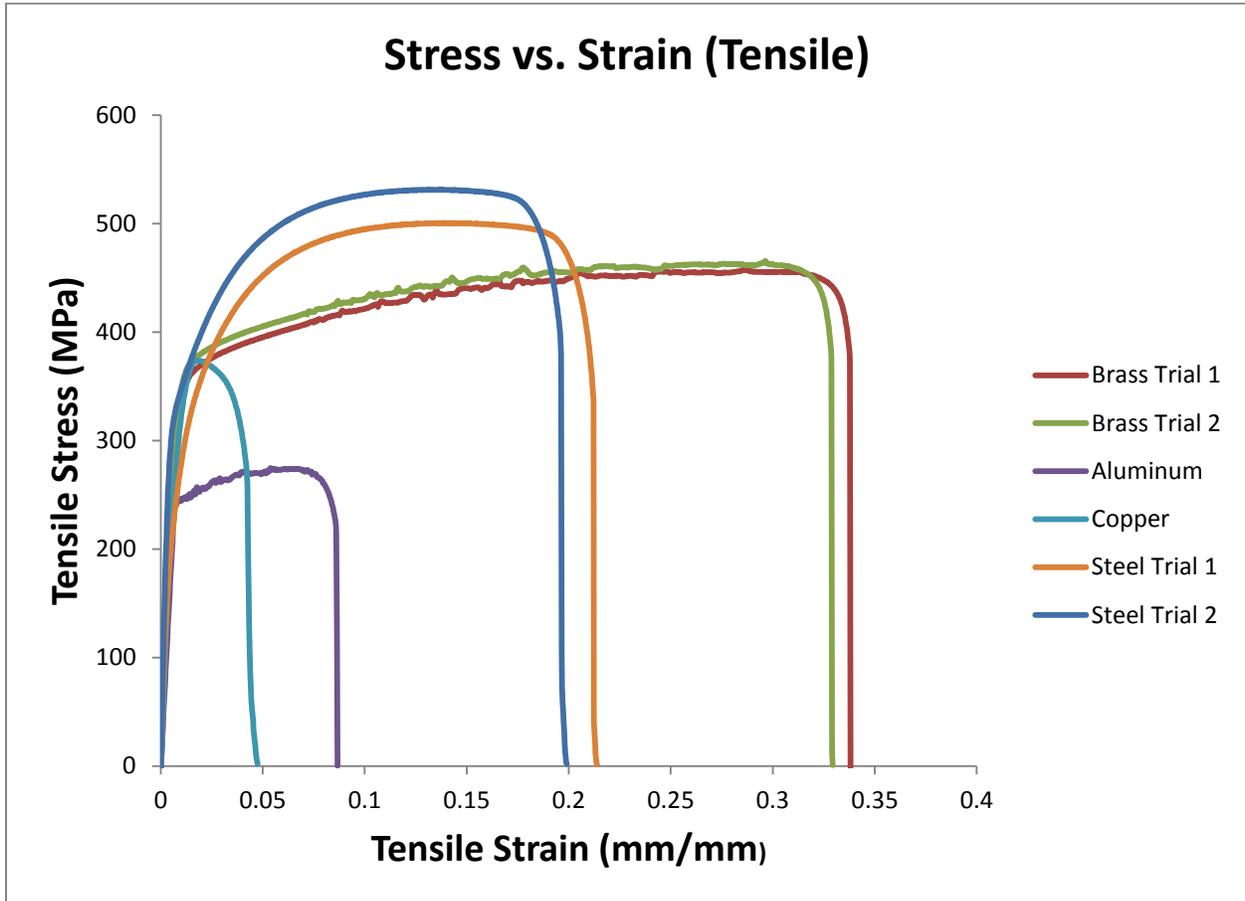


Fig. 3.1 Tensile stress versus tensile strain data as measured for 6 different specimen including brass, aluminum, copper, and steel.

Material	E (GPa)	σ_y (MPa)	UTS (MPa)	σ_{Max} (MPa)	ϵ_{Max}	U_{el}^{Max} (kJ/m ³)
Al 6061	38.16	73.0	274.5	271.5	0.063	74.0
Cu	53.22	95.6	373.8	332.5	0.005	95.4
Brass	58.03	118.7	461.5	445.9	0.312	121
Steel	74.22	162.6	515.8	508.0	0.176	128

Table 3.1 Tensile mechanical properties for aluminum, copper, brass, and steel

3.2 Uniaxial Compression

The stress-strain behavior of the four metals under compression is shown in Fig. 3.2 and Fig. 3.3, measured with and without an extensometer, respectively. Data obtained with the extensometer were subject to initial measurement error, as the reported strain values deviated below zero during the first moments of compression. The data collected with the extensometer focused on the elastic regime of deformation of the four metals, and the calculated mechanical properties under compression (Table 3.2) showed that steel was tougher ($E = 259$ GPa) than the other three metals. Brass ($E = 52.3$ GPa) and aluminum ($E = 61.3$ GPa) were the most elastic under compression, while copper was only slightly tougher ($E = 100$ GPa). Fig. 3.2 presents data from the broader regime of compressive deformation, and demonstrates that steel by far is the strongest of the four metals with a compressive yield stress of 427.6 MPa. Concordantly, steel absorbed the greatest amount of elastic compressive energy (249 kJ/m³); brass (112 kJ/m³) and aluminum (122 kJ/m³) tolerated the least amount of compressive energy before yielding, while copper absorbed 197 kJ/m³ of energy before yielding. Similarly, brass (136.4 MPa) and aluminum (165.4 MPa) were found to be the weakest, with copper being slightly stronger with a yield stress of 217.1 MPa. According to Fig. 3.2, the failure mechanism of steel appears to be more prolonged than those of the other three metals, which underwent buckling more immediately and, as evident in the lower slope of plastic deformation, offered less resistance to applied stress after yielding.

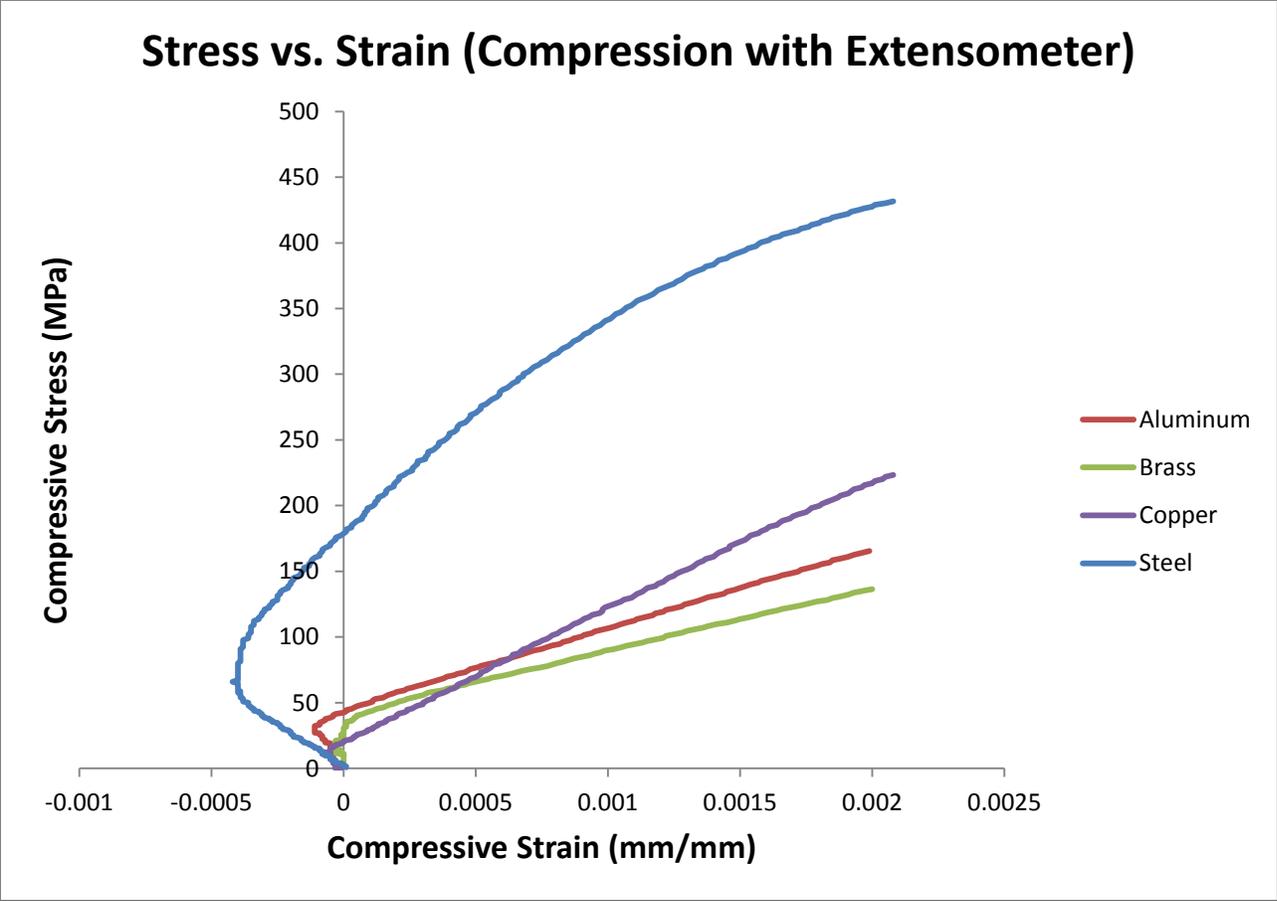


Fig. 3.2 Stress-strain behavior for the four metals as measured with an extensometer. Strain values were limited to the elastic regime below 0.2% strain.

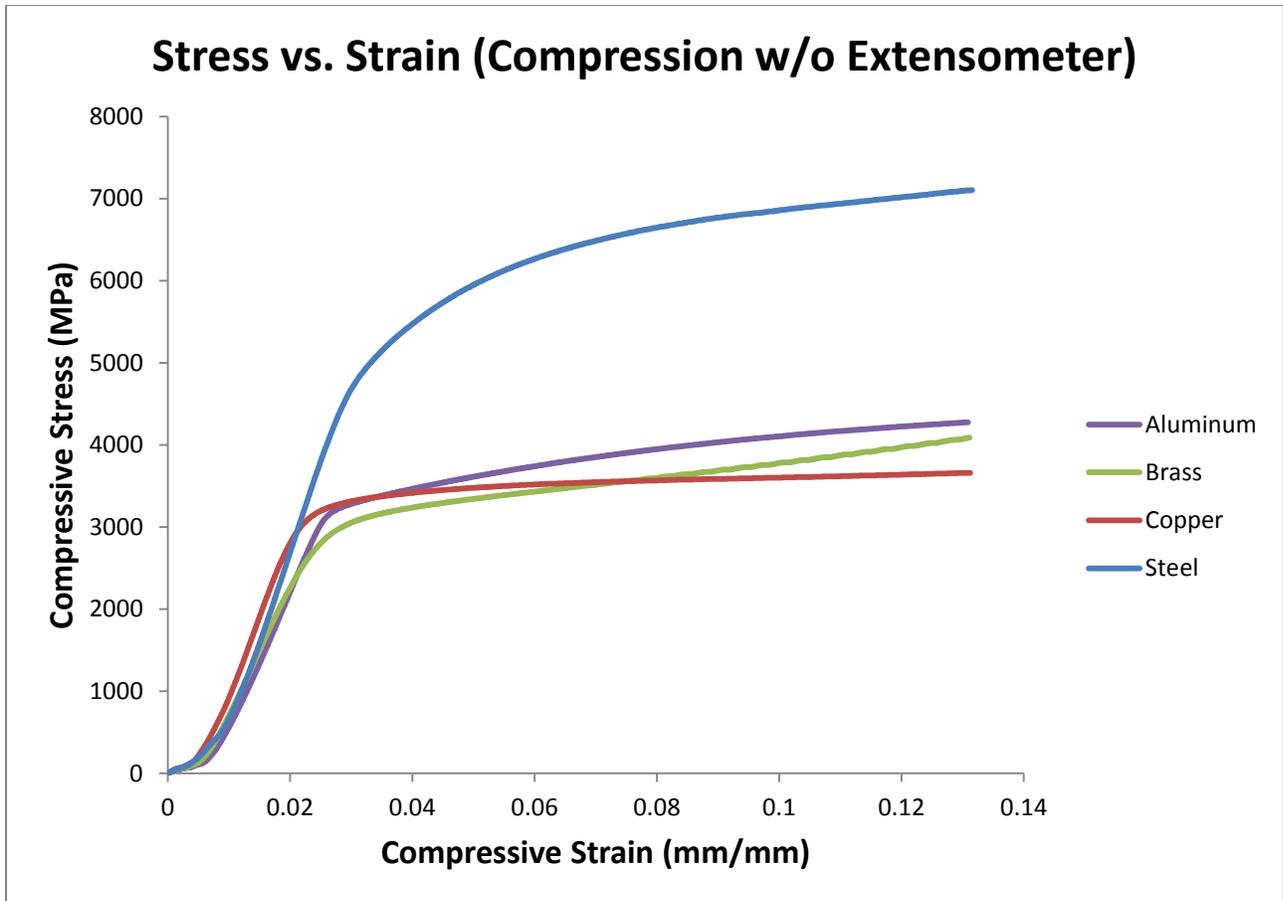


Fig. 3.3 Compression stress-strain behavior of the four different metals, measured without an extensometer and at higher values of strain.

Material	E (GPa)	σ_{yield} (Mpa)	$U_{\text{el}}^{\text{Max}}$ (kJ/m ³)
Al 6061	61.3	165.4	122
Cu	100	217.1	197
Brass	52.3	136.4	112
Steel	259	427.6	249

Table 3.2. Compressive mechanical properties for aluminum, copper, brass, and steel

4. Discussion

4.1 Trends and Analysis

For the metals, our data generated stress-strain profiles that reflect their theoretical properties, exhibiting distinct regimes of elastic and plastic behavior. Their linear elastic slopes are distinct, but the overall material behaviors are comparable: the values of E are all roughly the same order of magnitude, and the profiles look similar, reflecting the fact that the metallic bonding accounts for many of the mechanics. The accuracy of the values, however, is questionable due to various sources of error discussed later in this section.

The differences in the metals' mechanical properties are most evident the plastic regimes of the stress-strain plots, where properties including toughness, ultimate tensile strength (UTS), and fracture stress and strain are determined. The tensile data in Fig 3.1 shows clearly that the pure metals (copper and aluminum) had the lowest toughness, UTS, and fracture strain, while materials with substituted atoms (brass) or a binary phase system (steel) showed much higher values for all of these, with brass having the greatest energy absorption (toughness), and steel the highest ultimate tensile stress. This can be attributed to the fact that these alloys have an amount of substitutional atoms that are larger than the primary atom. This causes a local swelling of the crystal, areas which absorb extra strain energy and halt both slip planes and crack propagation, thus increasing the resistance to fracture.

The compressive strain data Fig 3.2, Fig 3.3 was somewhat less informative as to the specific properties, as the materials behavior was very similar, though it does show that steel, again, a binary system, was able to absorb the most energy, by a significant amount, though the noticeable area of the plot which is in the negative strain area, an artifact of the machine normalizing the stress on the inevitably uneven sample surface, may bely what would seem to be a discrepancy (to some degree) there.

4.2 Error: Theoretical Values vs Experimental values

Material	$E_{\text{calculated}}$	$E_{\text{literature}}$	%Difference	UTS _{calculated}	UTS _{literature}	Δ
Al 6061	38.1GPa	68.9 GPa	57.6%	274.5 MPa	310 MPa	12.1%
Cu	53.2 GPa	110 GPa	69.6%	373.8 MPa	210 MPa	56.1%
Brass	58.0 GPa	110 GPa	61.9%	461.5 MPa	300 MPa	42.4%
Steel	74.2 GPa	200 GPa	91.8%	515.8 MPa	585 MPa	12.6%

Table 4.1 Tensile mechanical properties for aluminum, copper, brass, and steel

From Table 4.1, it is noticeable that the accuracies of the experimental values exist mostly relative to each other, as there is a large discrepancy between any of the values and their literature counterparts³. It seems that our experimental method produces data consistently much lower than the theoretical values. The most fundamental part of this error is in the method for calculating theoretical values and the method for determining accepted literature values. Theoretical elastic moduli are calculated assuming single crystal, and the most accurate accepted values, for the sake of accuracy, are tested for using very small samples to ensure the fewest number of grains. Our test, however, used relatively large sample (~66x6.5x1.5mm) that was most certainly polycrystalline with lots of grains, decreasing the tensile strength relative to a pure, single crystal metal or ceramic. So with this in mind, we assume any testing of this sort of sample would have a lower modulus than a theoretical value. Conversely, the fact that the samples were large and polycrystalline would *increase* the toughness, though, this specific value, we did not calculate. The large number of grains and therefore grain boundaries limits the spread of crack defects (thanks to the interrupted slip planes), and thereby toughens the material overall.

4.3 Error: Sample History

Also to consider is the sample history, which for all of the samples was largely unknown. Any number of events could have occurred in the history of the sample including stress from machining,

material fatigue, or even heat cycles. It's unclear which did happen however, but we can be sure that none of them *increased* the tensile strength of the sample, as there are few ways to do that, and any would have to have been very deliberate.

One very noticeable discrepancy with our data comes from one of the steel samples, and the result suggests that this sole sample had some kind of defect that caused it to fail prematurely. Of the two samples we tested, we found that the difference between the trials was much larger than with the other repeat trials. Specifically, the two values had a standard deviation of 19, orders of magnitude higher than the other repeat trials, which had deviations of no more than 0.3. This suggests one of the two samples was very far off the norm, leading to the much larger than normal percent difference of over 90%. We believe that had the sample not failed prematurely, we would've seen a percent difference back in our range of 50-70%

4.4 Error: Sample Preparation and Machine Compliance (Instron Testing Machine 4505 and 4206)

Finally we have the machine compliance for our testing rig. The most obvious form of that is the orientation of samples as there was no self-orienting appliance in the machine. Any angle off of 90° would decrease the effective stress on the sample. The grips of the machine were intended provide entirely uniaxial stress to the sample, but the frictional elements are by no means perfect and some strain did occur outside of the length we considered. As elastic moduli are inversely proportionate to strain, any excess, ignored strain would decrease the calculated value.

All of these sources of error serve to affect a much lower calculated value than one might've expected from theoretical or literature values³, and in our case, such a depression was on the order of 60-70% across the board, but we can be confident about these values because the were consistent and accurate relative to each other. In terms of future attempts of this specific lab work, one will struggle to

find much better data without spending exorbitant amounts of money one more precise machinery made to take much smaller samples, but realistically, a level might help to ensure the stress vector is as straight as it could be, and more than one or two trials will support the consistency of the results though we are already able to see that to some extent with our small number of trials. This would of course, also allow you to calculate a distribution that quantitatively relates the aggregate of errors to percent difference from literature or theoretical values.

5. Conclusion

Despite the inaccurate values calculated for mechanical properties, the stress-strain curves from which they were generated still conform to the expected profile and mechanics of metals: an initial regime of linear elastic behavior followed by plastic deformation. Similarly, the ceramics exhibited high toughness and brittleness, as expected of the directionality of their covalent bonds. The laboratory experiment provided a more physical understanding of material mechanics, as well as significant experience in materials testing. Additionally, the process of identifying machine compliance as an explanation to the consistently low values of material properties was a crucial exercise in determining source of errors. In this respect, the data we collected was incredibly informative—testing must be designed to produce not only data but data from which artifacts and systematic sources of error may be determined.

6. Acknowledgements

We would like to acknowledge Dr. Meri Treska and Franklin Hobbes for guiding us through this laboratory module, as well as David Bono for providing technical assistance.

7. References

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