5-2012

Comparative Fatigue Analysis of Metals and Polymers for Engineering Applications

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An Undergraduate Honors College Thesis

In the

Department of Mechanical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

By

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27 April 2012

THE UNIVERSITY OF ARKANSAS

UNDERGRADUATE HONORS PROGRAM

COMPARATIVE FATIGUE ANALYSIS OF METALS AND POLYMERS FOR ENGINEERING APPLICATIONS

This thesis is approved.

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Rapid prototype polymers are becoming increasingly popular for engineering applications, particularly during the design phase as a quick check for size and fit; however they are not currently widely-used for load-bearing applications. Current research at the University of Arkansas Department of Mechanical Engineering focused on rapid prototyped polymers by doing cyclical tensile testing. The results were analyzed for strain energy and fatigue data. When cycling at lower percentages of ultimate stress, unusual strain energy patterns were observed. This research details testing of metals in order to compare strain energy patterns to those of the rapid prototype polymers.

I. INTRODUCTION

A. Background

Fabricating parts from various polymeric materials is becoming increasingly common for quick and accurate models for checking design parameters. This paper explores research conducted in response to findings from current research at the University of Arkansas of mechanical properties of rapid prototyped (RP) polymer specimens. Cyclical tensile testing was conducted to analyze the fatigue patterns of fused deposition modeling (FDM) rapid prototyped polymers. All polymer specimens were produced using the layering methods for FDM materials, made with a common RP material, acrylonitrile butadiene styrene (ABS). Both ABS and ABSplus were used to produce test specimens, using a 3D printer. The specimens varied by the direction of the layering, which was accomplished by changing the orientation in which each specimen was fabricated. The tests varied by the maximum force applied to the specimen. The first specimen was subjected to 100% of the ultimate load. Three additional specimens were subjected to 80%, 60%, and 40% of the ultimate force (Lee, 2011).

This research investigates the fatigue and strain energy patterns in three metals: copper, aluminum and steel. The purpose is to compare the data to that of the rapid prototyped polymers used for 3D printing.

B. Project Theory

Tensile tests are used to observe and analyze the fracture and failure behaviors of materials. The tensile test applies a unidirectional axial load to a specimen by means of a movable crosshead (Askeland, 2008). There are several material properties that can be determined by a tensile test. These properties include: tensile strength, yield strength, ductility, and Young's Modulus. The tensile, or ultimate, strength of a material is defined as the "stress obtained at the highest applied force." This point corresponds to the maximum stress point on the stress-strain diagram (Askeland 2008). In order to calculate the stress from the recorded force data, the cross sectional area of the specimen must be known, as $\sigma = \frac{F}{A_0}$, where A_0 is the original cross sectional area of the specimen, given by the formula $A_0 = t \cdot w$. The test software records the vertical elongation of the specimen. This data can be used to obtain the strain experienced, as $\varepsilon = \frac{\Delta l}{l_0}$, where l_0 is the original gauge length of the specimen and $\Delta l = l - l_0$. As the original dimensions of the gauge cross section and length are being used, these values are known as "engineering stress" and "engineering strain." A graphical representation of this is known as a stress-strain curve. The strain energy is determined by integrating the area under the stress-strain curve.

Cyclical testing at values lower than the ultimate force provides data to determine the fatigue patterns of the materials. A cyclical test occurs by controlling the maximum and minimum load experienced by the specimen, exposing the material to uniaxial tension and retraction. The area under the loading curves of the cycle is the strain energy stored in the material, which is reversible. During retraction, the energy released by the material is the area under the unloading curve of the cycle. (Roylance, 2001)

II. RESEARCH PARAMETERS

In order to assure consistent testing parameters, a strict set of testing procedures was developed. These procedures were applied to each set of tests for each different material. Each specimen was tested using the same *Test Navigator* cyclical program, varying only in the maximum load value. The program calls for unidirectional axial tension to the maximum force followed by unloading to zero, repeating until fracture or 10,000 cycles.

A. Experimental Setup

The University of Arkansas Department of Mechanical Engineering Materials Laboratory is equipped with a *Tinius Olsen H50KS* Tensile Test machine. The machine is comprised of a 50 kN load cell, 2 clamps, an extensometer, and a control panel, as shown in Figure 1.

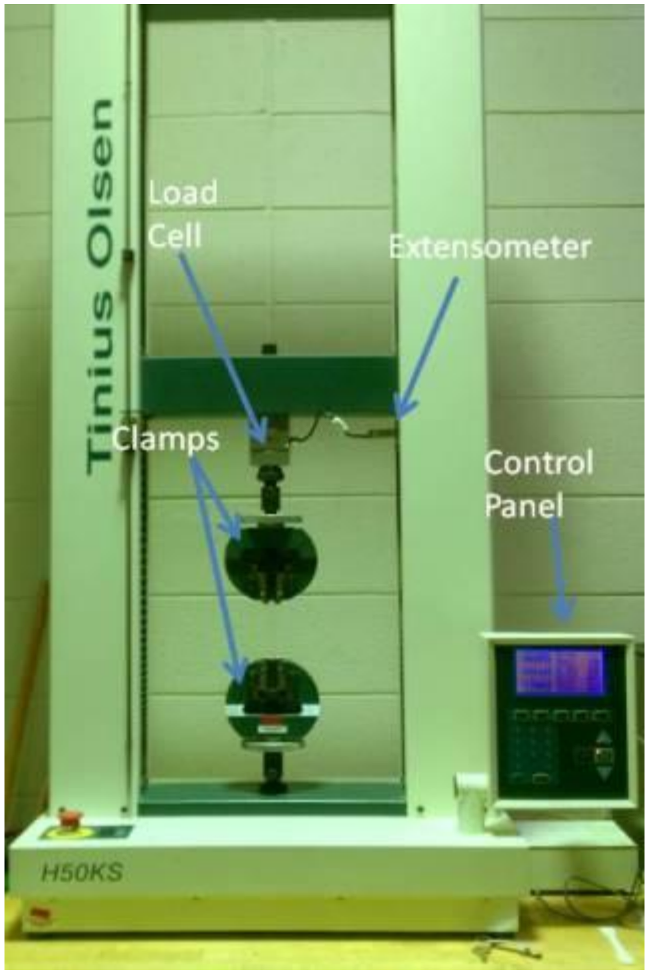

Figure 1: *Tinius Olsen H50KS* Tensile Test Machine

The tensile tester is connected to a desktop computer, and through *Test Navigator*, the data acquisition software for the tensile tester, the time of the test, force and elongation are all collected for analysis. Tests for the metals were cyclical at 90%, 80%, and 70% of the ultimate force. The tester applies the maximum load, as inputted by the user into the program interface, and then returns to zero. The maximum number of cycles allowed is 10,000, in order to prevent an overflow of data or compromise the capacity of the program. If the specimen has not failed in 10,000 cycles, the test and data collection ceases. Similarly, if the specimen fractures, data collection discontinues. The standard test settings for elongation rate are set for a pull rate of 1 inch per minute and a relaxation rate of 0.5 inches per minute.

The test specimens are "dogbone" specimens, typical of tensile tests. The gauge dimensions of the specimen are shown in Table 1. Dogbones are shown in Figure 2, both before and after fracture.

TABLE 1: Test Specimen Dimensions			
Metal	**Width (in.)**	**Thickness (in.)**	**Gauge Length (in.)**
Copper	0.373	0.123	3.295
Aluminum	0.344	0.127	3.584
Steel	0.367	0.115	3.182

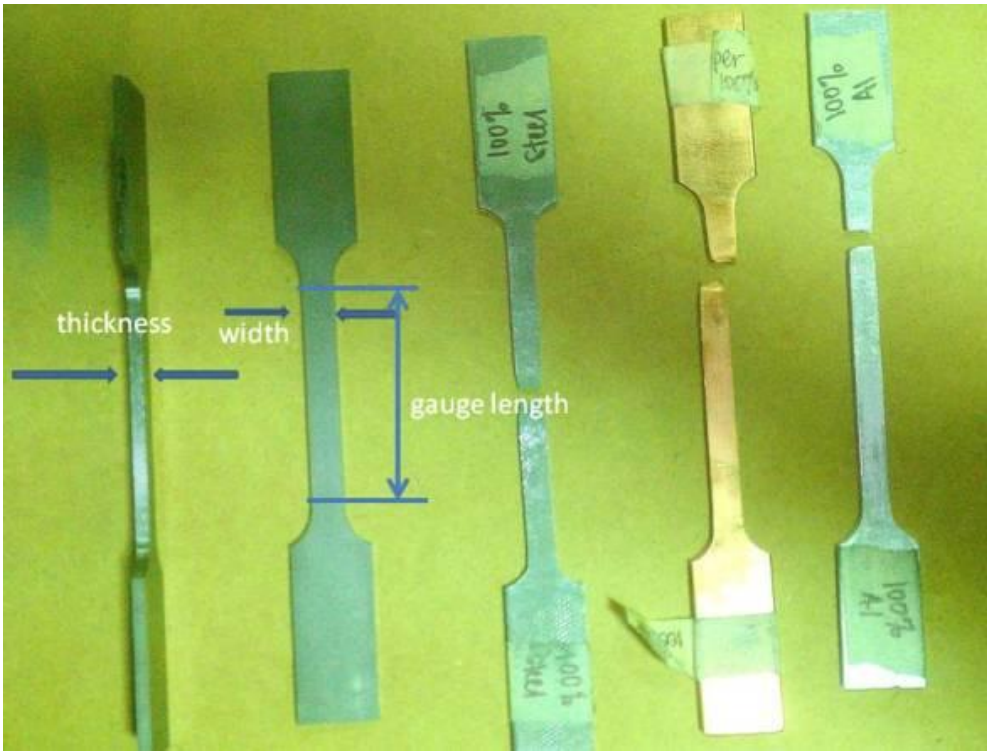

Figure 2: Dogbone Specimens before and after fracture

B. Procedure

The three metals tested are: copper, aluminum, and steel. With each metal, four different tests are done, varying by the maximum force applied per cycle. The first test is a single pull to failure done to determine the ultimate strength of the metal. This is done by setting the maximum force far above the known maximum strength. The maximum force sustained by the specimen can be determined from the data and verified by a graph of force vs. elongation, confirming the highest point on the curve. From this maximum force, the 90%, 80%, and 70% load values are determined. These values are the new maximum force input value for each of the tests. Per the program settings, the test will cease data acquisition at failure or at 10,000 cycles. If a specimen does not fail within 10,000 cycles, data will be compiled in sets of 10,000 to achieve the complete fatigue test.

Upon completion of testing, the data is analyzed using *MatLAB* programming to do calculations and produce visual interpretations of the data. *MatLAB* separates each cycle into an “up stroke” and a “down stroke”. An energy value for each stroke in each cycle is calculated. To calculate the total strain energy for the data set, the positive and negative strain energies for each cycle is summed. Another *MatLAB* script is used to count and report the number of cycles for each pull test.

III. OBSERVATIONS

There were a few oddities during testing to be noted and discussed. Firstly, when each dataset is graphed, there is a noticeable "step" in every cycle as the specimen undergoes lower loads, as shown in Figure 3.

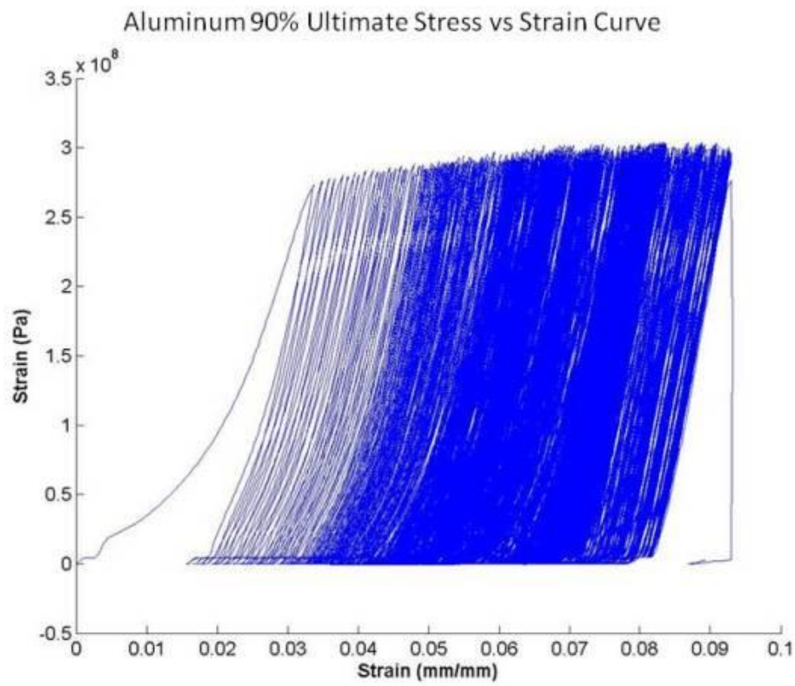

Figure 3: 90% Ultimate Stress Aluminum Cycles

This 'step' is uniform throughout each test, both single pull and cyclical. A reasonable explanation is that the specimens are slipping in the clamps each time a pull is initiated. Figures 4-a,b show the physical slipping experienced by the specimen in the clamps.

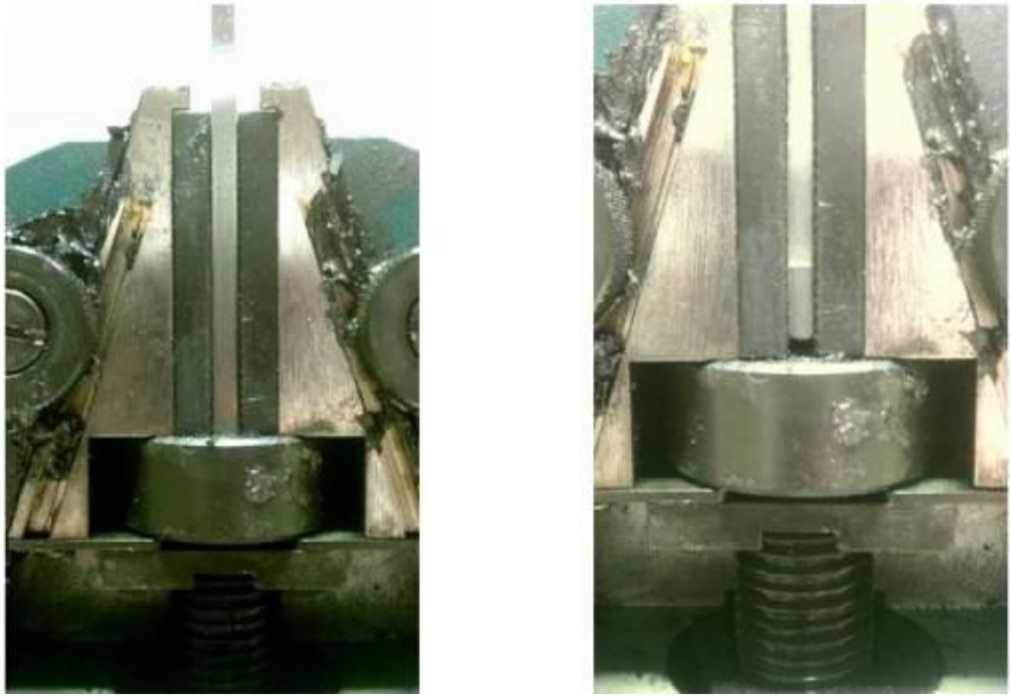

Figure 4: (a) Position of the specimen before test; (b) Position of the specimen during test

Another oddity can be observed in the single pull test for steel. Below in Figure 5, the steel stress-strain curve is shown.

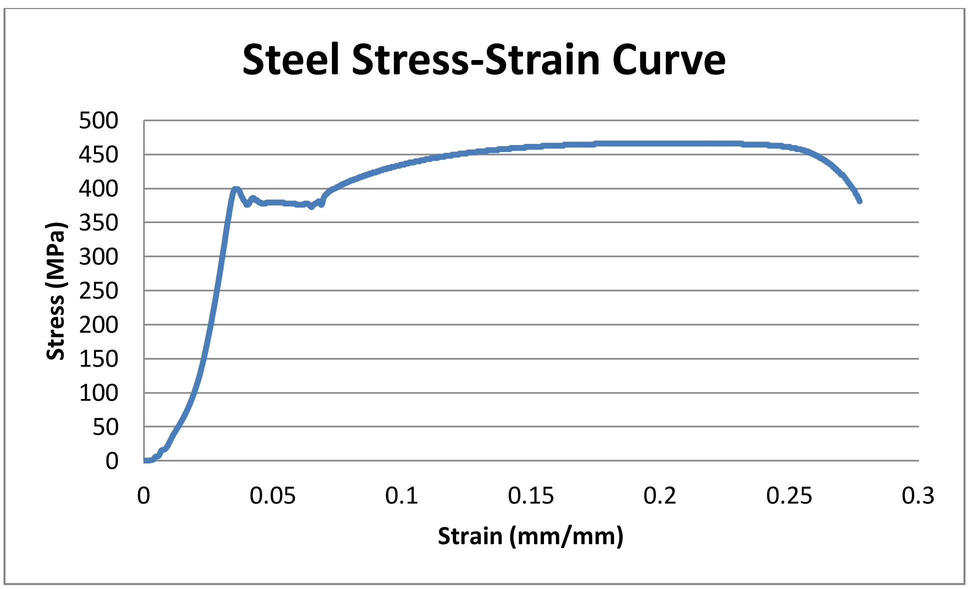

Figure 5: Actual Stress-Strain Curve for Steel

The first peak indicates the yield stress of the material. The second peak is the ultimate stress. (Askeland, 2008) Between these two peaks, a smooth dip is generally observed, due to strain hardening. However, the tested specimen experienced some turbulence during this phase. This most likely occurred as a result of the specimen slipping in the clamps during tension. The photos above (Figures 4-a,b) show the position of the specimen in the clamps before and after the test. These data points may also be explained by the residual stresses left in the material during fabrication, which affects the internal microstructure of the material.

Lastly, during the cyclical testing of steel, the specimen experienced a significant amount of torsion. Due to this torsion, the cyclical test at 90% ultimate load could not be completed.

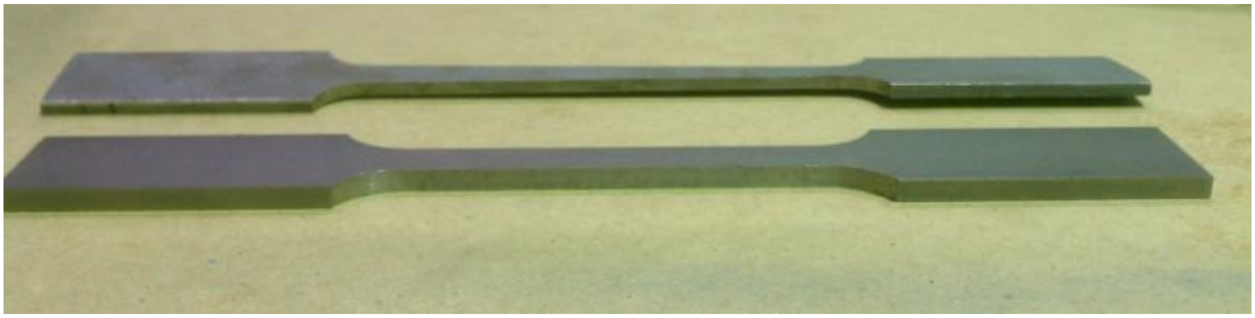

Figure 6: Steel Specimens Unaffected by Torsion (bottom) and Affected by Torsion (top)

One possible reason for this torsion relates to the fabrication of the dogbone. During fabrication of the steel, whether cold or hot rolled, there are residual internal stresses stored in the material. Additional stresses are left after machining. These internal stresses affect the way the grain boundaries slip during tension.

IV. ANALYSIS

The testing software, *Test* Navigator, outputs the data in a three column '.txt' file. The file contains measurements of force (lbf), elongation (in.), and time (seconds). Each dataset was quantitatively analyzed using *MatLAB* scripts to determine the strain energy for cyclical tests at 90%, 80%, and 70% of the ultimate load for each of the three metals. In addition to determining the strain energy, *MatLAB* was used to determine the number of cycles for each test, as well as plotting the strain and relaxation energies for each cycle.

A. Polymers

ABS and ABSplus specimens were tested using the same procedures as the metals. However, the percentages of the ultimate stress were 80%, 60%, and 40%. By integrating the area under the stress-strain curve, the strain energy for each test is determined. Figures 7-a,b show the strain energy trends when cycled at 60% and 80% of the ultimate stress. The positive strain energy (the tensile strokes) are denoted on the graph by '+', while the negative energies (the relaxation strokes) are denoted by 'o'.

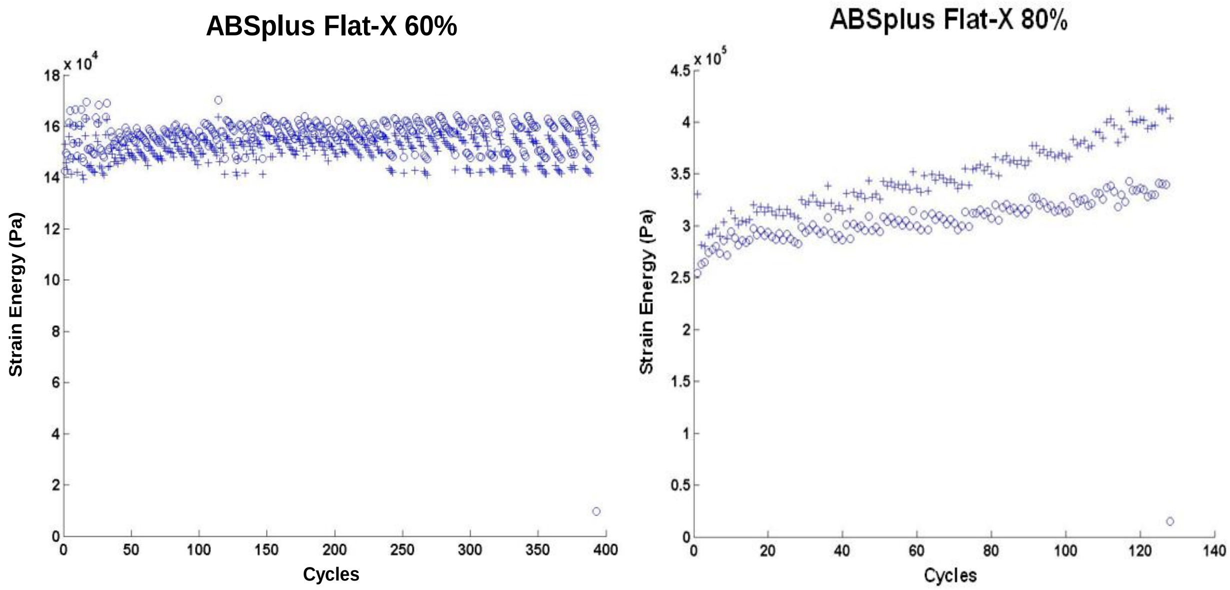

Figure 7: Strain Energy vs. Cycles (a) 60% Ult. Strength (b) 80% Ult. Strength (Lee 2011)

As shown above, the 80% cycles yielded a positive difference between the strain energy during pulling and the strain energy during relaxation, which is expected. In addition, as the number of cycles increases and the specimen stretches, the strain energies of the loading and unloading begin to diverge. The 60% cycling shows an increase in strain energy during relaxation. Further tests confirmed that as the maximum load decreased from the ultimate load, the strain energy during the loading stroke was less than the energy released during the relaxation stroke, which is the phenomenon being further investigated by testing other materials, such as metals. (Lee, 2011)

B. Metals

Upon completion of testing, each dataset was run with *MatLAB* scripts to determine the total strain energy, the number of cycles to failure, and produce a graph showing the strain energy in tension and relaxation energy for each cycle. Figure 8 below shows the relationship between the maximum stress and the number of cycles experienced by each specimen in an S-N curve.

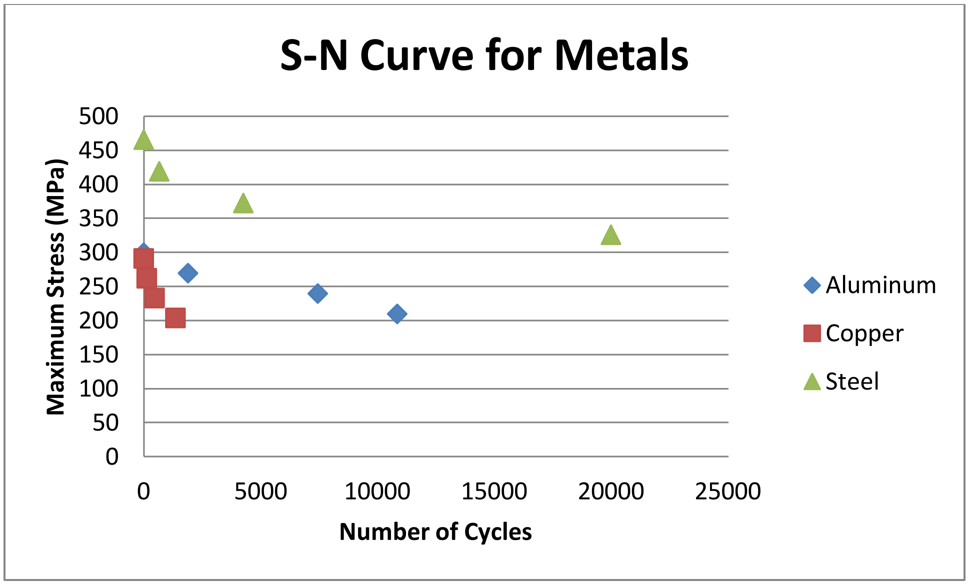

Figure 8: S-N Curves for Each Metal

The first test ran with each metal was a single pull to failure in order to determine the ultimate load for each metal. Figure 9 shows the stress-strain curves for each single pull.

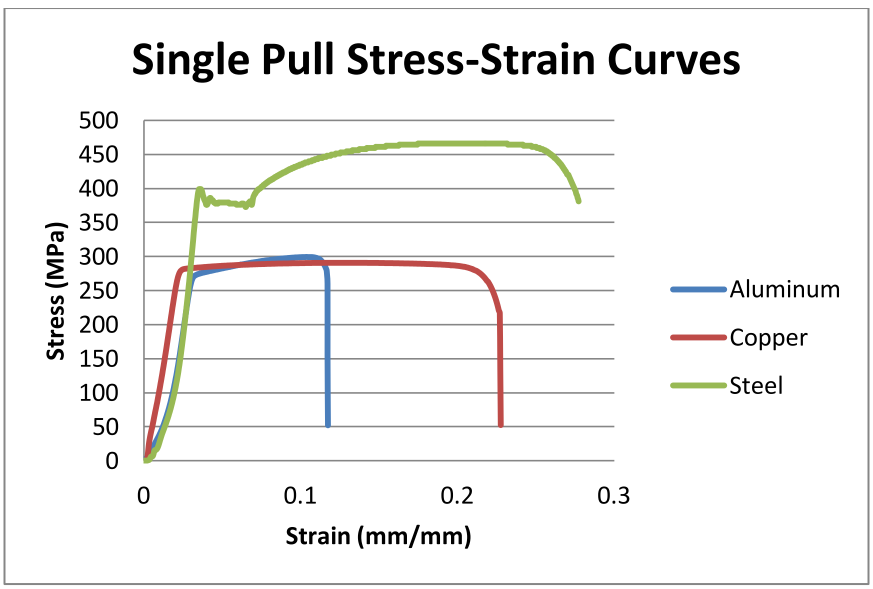

Figure 9: Single Pull to Failure Stress-Strain Curves

The highest point on each curve indicates the ultimate stress of the material. This value was used to calculate the maximum loads at which the cyclical tests were run. Table 2 shows the loads determined for each test.

TABLE 2: Testing Loads (lbf)				
Metals	**Ultimate Force**	**90%**	**80%**	**70%**
Aluminum	1897	1707.3	1517.6	1327.9
Copper	1937	1743.4	1549.6	1355.9
Steel	2850	2565	2280	1795.5

The three metals displayed comparable strain energy patterns when comparing the strain energy in tension and in relaxation. For the following graphs, '+' denotes the positive energy (strain energy in tension), and 'o' denotes the negative energy (energy released in relaxation). Figures 10-a,b present a visual interpretation of the data for aluminum.

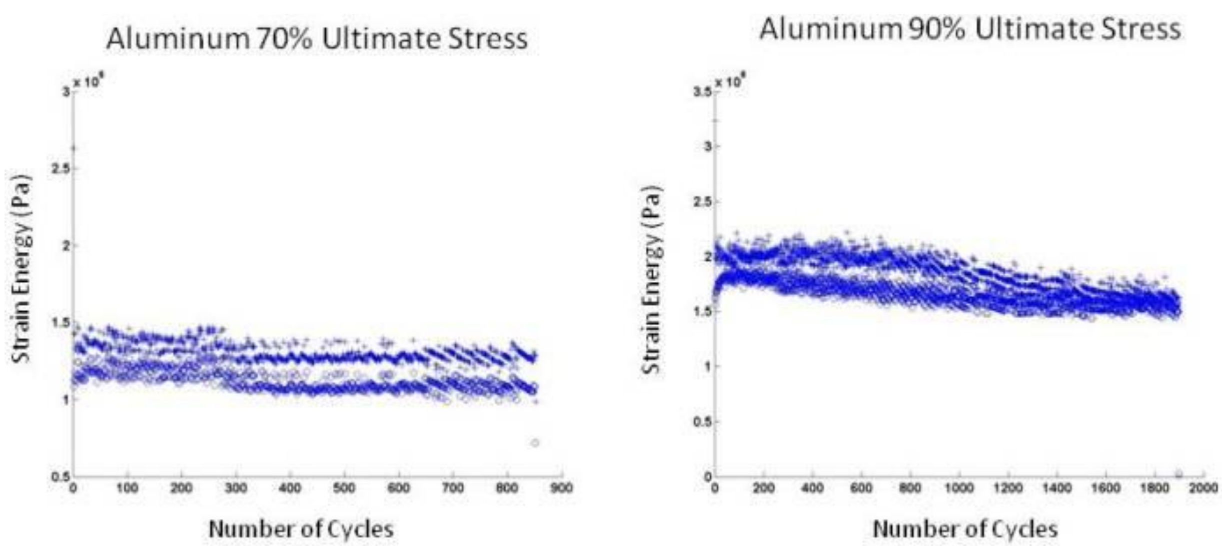

Figure10: (a) 70% Ultimate Stress for Al; (b) 90% Ultimate Stress for Al**
****Note: The 70% Ultimate Stress graphs represents cycles 10,001-10,852.**

In both cases, there is a positive difference between the positive and negative strain energies. This indicates that more energy is being stored in the material during tension than is being released during relaxation. At 70% ultimate load, the difference remains fairly constant as the specimen approaches failure. However, as the ultimate load increases, the difference between the positive and negative energies begins to converge, as shown in the 90% ultimate stress graph. Figures 11-a,b show similar datasets for steel specimens.

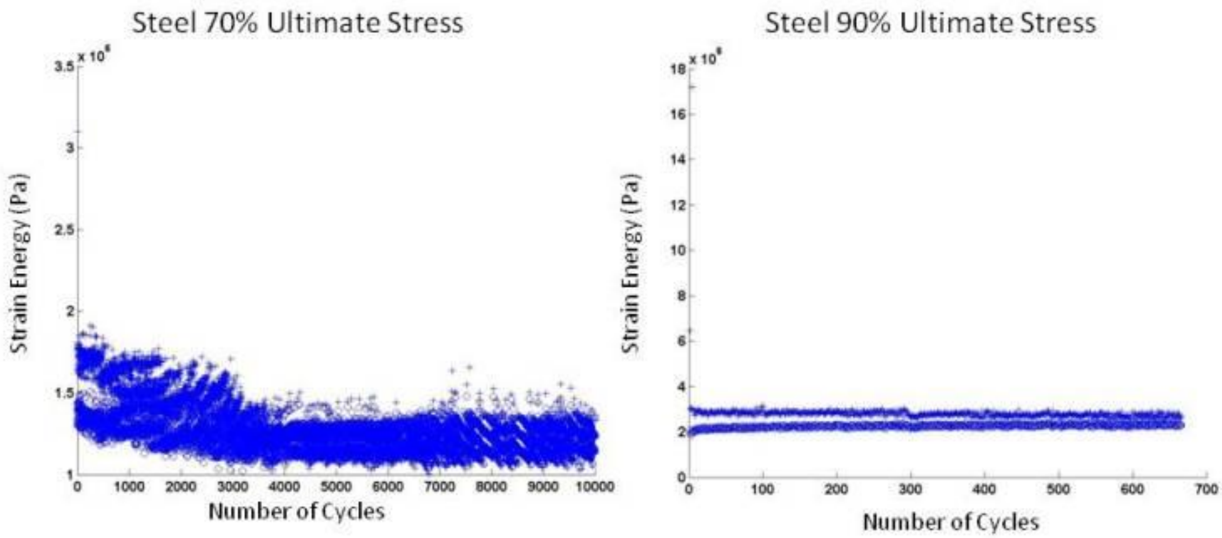

Figure11: (a) 70% Ultimate Stress for Steel; (b) 90% Ultimate Stress for Steel**
****Note: The 70% Ultimate Stress graph represents the first 10, 105 cycles. The 90% Ultimate Stress graphs represents the first 666 cycles.**

The steel specimens exhibited similar patterns as the aluminum specimens. At a lower load, i.e. 70% ultimate, the difference in energies remains positive until failure. There is no noticeable convergence or divergence at this lower load. As the maximum load increases to 90% of the ultimate, the specimen still stores more energy in tension than is released in relaxation, yielding a positive difference. However, the difference between these energies decreases as the number of cycles increases and failure approaches, as shown by the clear divergence on the graph. Figures 12-a,b show graphical representation of the data for the copper specimens.

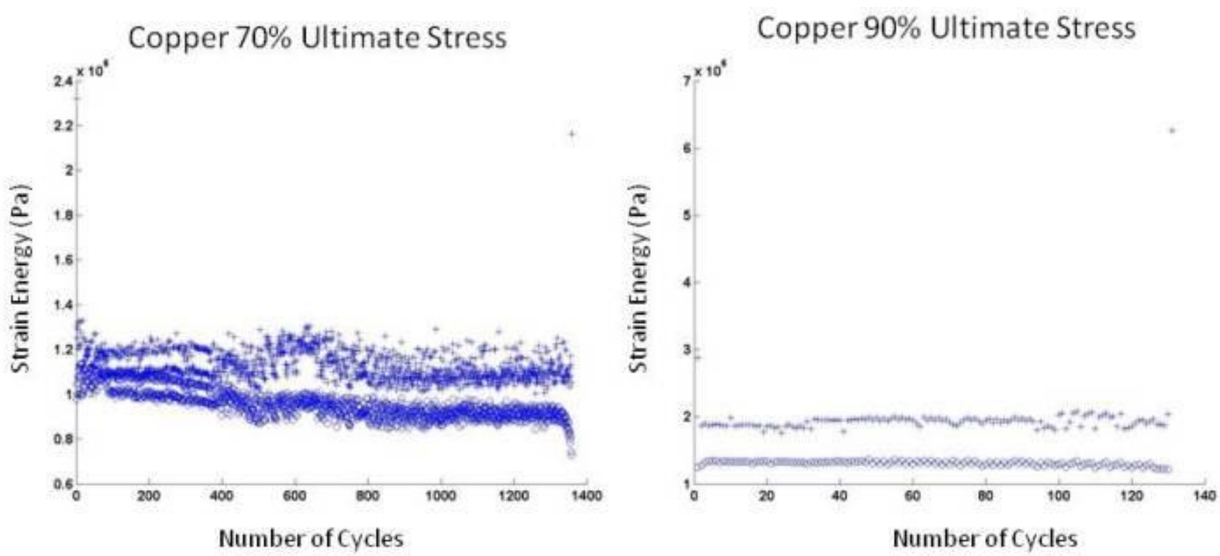

Figure 12: (a) 70% Ultimate Stress for Cu; (b) 90% Ultimate Stress for Cu

Copper was consistent with the other metals in one pattern; however, it differed in another. In both sets of data presented above, the energy stored during tension is greater than the energy released during relaxation. However, unlike aluminum and steel, at higher maximum loads, there is little to no convergence in the energy differences. At lower loads, the energy difference remains relatively constant with a slight divergence as fracture approaches.

C. Comparison

As expected from any material, the polymers and metals exhibited the same fatigue pattern. As the maximum stress applied to the specimen decreased, the number of cycles required to fracture increased.

The strain energy patterns for ABS and ABSplus polymers and the metals tester were significantly different. While the energy difference increased as the number of cycles increased in polymers, the metals, excluding copper, experienced a decreased in energy difference as the number of cycles increased. The polymers displayed negative energy differences as the load decreased to 60% of the ultimate load. While the metals were not tested at loads under 70% of the ultimate, this trend of negative energy differences was not observed.

V. FUTURE WORK

This research shows the fatigue patterns of three common metals, as cycled at 90%, 80%, and 70% of the ultimate stress. Future work on this research might include testing these metals at even lower percentages of the ultimate load to determine if a cross-over to negative energy differences occurs in metals. Further research should also include testing of additional metals and other materials, including polymers such as Teflon and Nylon. This work regarding the mechanical properties of RP polymers will be useful in many design applications. The University of Arkansas Design/Build/Fly team often uses RP polymers for 3D printed components in the competition plane each year. Further understanding and knowledge about the behaviors of these materials, particularly fatigue patterns, could potentially benefit the team when designing their plane and considering if rapid prototype parts can withstand any loads experienced by the airplane and are feasible for use.

VI. CONCLUSIONS

In conclusion, metals were tested to observe patterns in strain energy resulting from cyclical loads. The results of the tests and the patterns were compared to those of rapid prototype polymers, ABS and ABSplus. The metals did not exhibit the same strain energy patterns as the polymers. However, the metals were not subjected to loads lower than 70% of the ultimate load, while the polymers were tested at loads as low as 40% of the ultimate. Therefore, further testing at decreased loads may cause metals to exhibit these strain energy patterns.

VII. ACKNOWLEDGEMENTS

Monica Jones thanks Dr. Adam Huang for his guidance and support for the duration of this project. She would also like to thank Mr. John Lee for his guidance and instruction during the project. Finally, she would like to thank the University of Arkansas Department of Mechanical Engineering for providing the equipment and knowledge necessary for completion of this project.

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