LOCKHEED MARTIN GPS SATELLITE BRACKET – TESTING TEAM

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Abstract

Producing metal parts through additive manufacturing (AM) is a very new and innovative process to the engineering industry. In traditional manufacturing, the designer can look up known mechanical properties of a metal and then order stock materials with certified properties. However, in additive manufacturing the structure and properties of the material is altered through the 3D-printing process. In the case of this project, we are using AM to produce aluminum parts that constitute a structural bracket assembly for a Lockheed Martin Satellite. The aluminum powder used to produce the bracket is so new, there are no known mechanical properties that we can rely on while designing. Therefore, the purpose of the project was to characterize and validate the material properties of 3D-printed 6061 aluminum to ensure 3D-printed spaceflight components will not fail during launch.

The properties of the material were determined using ASTM standards. Parts were tested both as-printed and heat treated to a T6 heat treatment. In additive manufacturing, there is inherent anisotropy in the material, caused from the miniscule pores left behind between the layers of the metal as the laser melts powder on top of itself. First, density tests were conducted according to ASTM B311 to quantify the presence of porosity [1]. The averages of both the as-printed and heat-treated samples were found to be 2.73 [g/cm^3], which is the same density reported for solid Aluminum, indicated an extremely low presence of pores in the AM specimens. To determine any anisotropic influence on the strength of the metal, identical rectangular bars were printed in both vertical and horizontal orientations. Two full builds of test samples were printed on the EOS M290 machine resulting in 56 samples. One build was heat treated, according to AMS 2770 (Aerospace Material Specifications) standards, to improve the properties of the metal while the other build was left as-printed [2]. The rectangular bars were machined into a dog bone shape and tensile tests were conducted based on ASTM E8 [3]. The as-printed dog bones resulted in an elastic modulus of 54.4 [GPa] and 65.5 [GPa], yield strengths of 215.7 [MPa] and 245.8 [MPa], and ultimate strengths of 235.6 [MPa] and 259.3 [MPa] in the Z and XY orientations. The heat-treated dog bones resulted in an elastic modulus of 63.7 [GPa] and 59.3 [GPa], yield strengths of 291.6 [MPa] and 271.8 [MPa], and ultimate strengths of 325.8 [MPa] and 311.2 [MPa] in the Z and XY orientations. The variations in the different coupons tested were relatively low (as measured by variables like standard deviation). Overall, the heat-treated results were comparable to typical values of Aluminum 6061T6 and indicate this material is suitable for manufacturing.

Finally, the bracket parts were printed and tested for natural frequency using an impact hammer. Lockheed Martin required the final part to have a natural frequency greater than 100 [Hz]. Our bracket pieces had frequencies equal to 215[Hz], 242.5 [Hz], and 632.5 [Hz]. These consistencies with the manufacturer's posted properties show that the material is reliable. Initial bracket testing meets the specifications set by Lockheed Martin.

Overview

In order to ensure that our EOS M290 printer was working as expected, we needed to compare the mechanical properties from our results to the mechanical properties reported by the manufacturer of the aluminum. The values from the manufacturer that we would compare to our properties were the density $\rho = 2.73\ [\frac{g}{cm^3}]$, elastic modulus $E = 76\ [GPa]$, yield strength $S_y = 285\ [MPa]$, ultimate tensile strength $S_u = 315\ [MPa]$, and elongation percentage at fracture ≈ 13%. We were also informed by Lockheed Martin that the original design of the bracket was very stiff. To ensure that our bracket design would not fail due to vibrations during launch we needed to design a bracket with a natural frequency $\omega_n > 100\ [Hz]$.

Heat Treatment

Leaving the metal as-printed does not achieve the optimal performance from the mechanical properties of the material. By heat-treating the final parts, we are able to make the grain sizes of the metal more uniform. This uniformity of the grain sizes greatly increases the strength of the final part. To achieve the T6 level of strengths from our aluminum we had a three step heat treating process shown in Table 1.

Table 1: *Specified heat treatment process*

Process	Recipe	Furnace Class	Tolerance
Stress Relief Heat Treatment	570°F for 3 Hours	3	±15°F
Solution Heat Treatment	985°F for 2-3 Hours	2	±10°F
T6 Age Heat Treatment	350°F for 8-10 Hours	2	±10°F

For the solution heat treatment, a glycol quench is required within 15 seconds of completing the heat treatment process. The quench is required to be preheated to 150°F and has a 32% concentration with a ±2% tolerance [1].

Density Testing

3D printed 6061 aluminum is a new innovation that needs further research and testing to understand the characteristics of the materials. True density is the inherent property of the material. Dense materials are usually free of cracks; however, we assume that there might be voids or pores on the 6061-aluminum printed from the EOS M290 machine. It is obvious that aluminum is a key material widely used in aerospace industries. As a matter of fact, a spaceship launching into space has to withstand huge amounts of vibrational and mechanical forces and small pores or voids will lead to mechanical failure. In that case, a density test should be performed with a significant number of samples in order to hopefully achieve a value of 2.73 [g/cm^3] as published by Elementum3D (a material expert company that does research and development on AM materials to create more advanced metals, composites, and ceramics) and specify whether 6061 aluminum printed on the EOS M290 could be a key component used for aerospace industries [4].

The materials used for computing the density values included 32 samples in cylindrical and block shape that were printed using powdered 6061 aluminum. The print was design using a specific computer software and printed as two sets of MPS1 and MPS2 builds using the EOS M290 machine.

We did not have a well-designed apparatus to perform the density test. Instead, we used a standard formula on a self-created apparatus built from a small plastic container placed over the weighing scale, tied with thread on two stands. We ensured that the stands were completely independent of the scales. In order to compute the density of the samples, we used the density of the water. The water was poured into the container, making sure that the sample would be completely immersed in the water and that the temperature of the water was noted. The density of water at that temperature was extracted from the table given in ASTM B311 [1]. The mass of water was not an important aspect of the entire test because the container connected to the stands was not in contact with the scale. Additionally, the scale was completely tared to zero before immersing the sample into the water. Figure 1 shows the self-created apparatus.

Figure 1: *Apparatus used for density testing.*

Once the apparatus set up was completed, 32 aluminum samples that had been 3D printed at different locations and orientations on the build plates were taken for density test. Figure 2 shows the printed samples with different shapes.

Figure 2: *Variously shaped samples used for density testing.*

Some of these samples were heat-treated and some of them were as-printed. The mass of each sample was noted on a well calibrated scale before being immersing in the water. Next, each sample's mass was noted on well-tared scaled completely submerging into the water using an essentially massless string attached to the scale. This process was repeated for all the samples and density was computed using Eq. (1).

$$D = \frac{A * E}{A - F} \tag{1}$$

Where A is the mass in air in grams, F is the mass in water in grams, and E is the density of the water in g/cm^3 at the specific temperature.

Tables 2 and 3 provide the density values analyzed for the as-printed and heat treated samples, respectively. Collectively, the values obtained for both the treatments were averaged. Each treatment was computed to have an average density of 2.73 [g/cm^3] with standard error of 0.0051 for as-printed and 0.0122 for heat treated samples.

Table 2: *Density result for as-printed samples*

As Printed	**Sample #**	**Mass in Air(A) [g]**	**Mass in water(F) [g]**	**Density [g/cm3]**
Cylinders MPS 1	47	37.91	24.03	2.73
	48	37.92	24.04	2.73
	49	37.91	24.05	2.73
Blocks MPS 1	39	46.23	29.3	2.72
	42	46.28	29.32	2.72
	43	46.43	29.4	2.72

Table 3: *Density result for heat treated sample*

Heat Treated	**Sample #**	**Mass in Air(A) [g]**	**Mass in water(F) [g]**	**Density [g/cm3]**
Cylinders MPS 1	47	37.91	24.04	2.73
	48	37.76	23.97	2.73
	49	37.84	24.02	2.73
Blocks MPS 1	39	46.25	29.37	2.73
	42	46.29	29.40	2.73
	43	46.43	29.47	2.73

Cylinders **MPS 2**	44	37.84	23.99	2.73
	47	37.8	23.98	2.73
	48	37.8	23.89	2.71
	49	37.85	24.04	2.73
Blocks **MPS 2**	38	46.46	29.43	2.72
	39	46.46	29.45	2.73
	40	46.47	29.45	2.72
	41	46.47	29.47	2.73
	42	46.47	29.47	2.73
	43	46.47	29.44	2.72
Average Density				**2.73**
Standard Dev				**0.00632**

Cylinders **MPS 2**	44	37.81	24.07	2.75
	47	37.78	24.05	2.75
	48	37.94	24.04	2.72
	49	38.00	23.95	2.70
Blocks **MPS 2**	38	46.27	29.33	2.73
	39	46.43	29.36	2.71
	40	46.46	29.49	2.73
	41	46.49	29.58	2.74
	42	46.47	29.55	2.74
	43	46.49	29.57	2.74
Average Density				**2.73**
Standard Dev				**0.0129**

Figure 3 shows the results compared with the published value from Elementum3D for heat treated and as-printed samples [4]. The obtained values are compared closely with the published result.

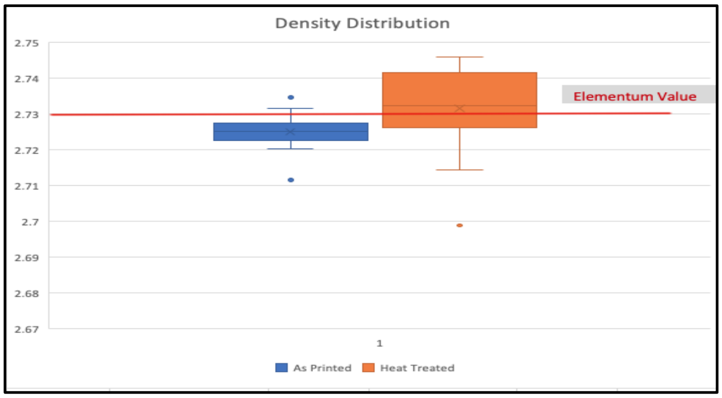

Figure 3: *Comparison of our results with published results.*

3D printed 6061 aluminum for as-printed and heated treated samples have the average value of 2.73 [g/cm^3]. This is the standard density value for 6061 aluminum published by Elementum3D [4]. The test performed for significant numbers of as-printed and heat treated samples resulted in values very close to this published result. With this, the density result shows that 3D printed aluminum is solid. The material should be able to be used for manufacturing key components.

Tensile Testing

The purpose of testing the aluminum material under tensile loading is to see whether the 3-D printed samples behave in a similar manner to the published results by Elementum3D for aluminum before putting it into production for the brackets [4]. By tensile testing the aluminum, we will determine its modulus of elasticity and strength/failure points to prove whether it will be a suitable substitute in their brackets as opposed to traditionally manufacturing them. Not only did we find the modulus of elasticity, but the yield strength, ultimate strength, and elongation at the break. The modulus of elasticity is the resistance to being deformed when stresses are applied. Yield strength is a stress at which the specific trans to the plastic regime. Ultimate strength is the maximum stress the material can take before starting the fracture process.

The materials used for this aluminum tensile test were multiple samples of dog-bone shaped aluminum, both printed as is and T6 heat treated. The measurements were taken with a calibrated pair of digital calipers. The tensile test was done using a Universal Instron machine with clamp attachments to hold the samples and an Extensometer to measure the elongation of each sample.

To conduct these tests, we used the Instron uniaxial testing machine to measure the strain/stress of the aluminum dog bone specimens. Multiple samples were tested by first determining each of the sample's geometry using a micrometer to measure its thickness and a caliper to measure its width at its smallest point. Stress is determined using Eq. (2).

$$\sigma = P/A_c \tag{2}$$

Where σ represents the stress in MPa, P represents the load in Newtons, and A_c represents the cross-sectional area in mm^2.

Before loading the samples into the machine, we adjusted the bumpers, so that the two clamps did not touch and did not exceed the maximum of the machine. Once the first sample was loaded into the Instron machine, we used the two pins on the back of the extensometer to clamp it onto the sample. We then zeroed out the extensometer on the strain scale and released the pin to begin the trials. Once the sample was taut between the grips, we zeroed and balanced out the load by clicking the zeroing/balanced button on the top of the program, Blue Hill. Once the door was closed, we ran the program with a strain rate of 0.25 [mm/min]. The strain rate was calculated by Eq. (3).

$$dL = e(L_o) \tag{3}$$

Where dL is equal to the rate of the change in length, e is the given 0.05 strain, and L_o is the original length of the reduced section in mm.

Once the strain rate was found, we plugged that number into the program and ran our as-printed samples followed by our T6 heat treated samples.

Once the tests were completed, the data was input into an Excel spreadsheet to determine the modulus of elasticity, E, ultimate strength, S_u, yield strength, S_y, and the percent of elongation, $\% E$. The modulus of elasticity was found using Eq. (4).

$$E = \frac{d\sigma}{d\varepsilon} \tag{4}$$

Where $d\sigma$ is the change in stress and $d\epsilon$ is the difference in strain in mm/mm.

The ultimate strength was found using a built in function in Excel, =MAX(), to find the maximum stress in MPa.

In order to find the yield strength of the samples, we first needed to find the stress offset, σ_{offset}, using Eq. (5).

$$\sigma_{offset} = E * (\epsilon - 0.002) + y_0 \tag{5}$$

Where ϵ is the strain and y_0 is y-intercept. The y-intercept was found using a built-in function in Excel, =INTERCEPT(), to find out where the stress and strain intercept each other. Once we had this information, we graphed the stress vs strain graph as well as the stress offset line. From here, we zoomed in on the graph itself and saw where the stress offset intercepts the stress vs strain graph. This provided the yield strength in MPa.

The last thing we found was the percent of elongation by taking the final data entry of the strain and multiplying it by 100.

All this was done for each of the samples in order to obtain the averages of each and compare them to Elementum3D's standards.

Elementum3D's standardized properties, which specified E, S_y, S_u, and % E are provided in Table 4. These values were compared with the values calculated from the tensile test [4].

Table 4: *Specified Tensile Properties of Aluminum*

E [Gpa]	**S_y [Mpa]**	**S_u [Mpa]**	**Elongation [%]**
76	285	315	13

The as-printed samples of aluminum were found to have an average E of 54.4 [GPa], S_y of 215.7 [MPa], S_u of 235.6 [MPa] and a percent elongation of 14.9% for vertically printed bars whereas there was an average E of 65.5 [GPa], S_y of 245.8 [MPa], S_u of 259.3 [MPa] and a percent elongation of 16.1% for horizontally printed bars. This data is provided in Table 5.

***Table 5**: Table of results from as-printed samples, this includes Elastic modulus, yield strength, ultimate strength, and percent elongation*

MPS [As-Printed]				
Sample Label #	**E [GPa]**	**S_y [MPa]**	**UTS [MPa]**	**Elongation [%]**
Vertical				
1	41.0	209.3	232.1	18.1
2	37.8	196.2	228.0	16.4
4	67.5	219.9	244.7	17.9
5	37.5	198.1	226.6	18.6
6	63.2	238.3	242.5	12.2
7	66.6	241.1	246.6	12.0
8	59.8	218.5	241.7	15.4
9	44.0	215.1	231.5	14.9
10	59.1	212.8	239.2	14.7
11	49.5	227.2	254.9	15.4
12	98.5	200.0	215.7	9.4
13	46.9	227.5	244.5	14.9
14	53.0	218.4	241.6	14.5
15	66.9	203.6	228.1	16.1
16	40.9	213.6	229.3	11.4
17	48.1	220.7	232.3	15.9
18	50.3	226.9	236.5	13.3
19	49.6	193.8	221.9	14.9
20	44.4	199.9	230.1	15.6
21	63.1	232.9	244.9	16.3
AVERAGE	54.4	215.7	235.6	14.9
Standard Dev	14.4	14.1	9.6	2.3
Horizontal				
22	59.7	229.1	251.9	15.1
23	41.0	231.2	247.7	19.7
24	62.3	242.9	258.6	19.5
25	65.0	242.9	245.9	18.5
26	80.6	247.5	261.3	14.3
27	54.8	232.4	246.9	14.5
29	95.2	295.0	302.7	11.3
AVERAGE	65.5	245.8	259.3	16.1
Standard Dev	17.7	22.8	20.0	3.2

The T6 heat treated samples of aluminum were found to have an average E of 63.7 [GPa], S_y of 291.6 [MPa], S_u of 325.8 [MPa] and a percent elongation of 10.8% for vertically printed bars whereas there was an average E of 53.9 [GPa], S_y of 271.8 [MPa], S_u of 311.2 [MPa] and a percent elongation of 11.5% for horizontally printed bars. This data is provided in Table 6.

***Table 6**: Table of results from T6 heat treated samples, this includes Elastic modulus, yield strength, ultimate strength and percent elongation*

MPS 3 [Heat Treated]				
Sample Label #	**E [GPa]**	**S_y [MPa]**	**UTS [MPa]**	**Elongation [%]**
Vertical				
1	39.7	298.4	331.7	12.0
2	46.3	297.0	324.4	11.5
3	49.2	318.7	350.7	11.6
4	75.5	282.5	319.6	11.9
5	48.7	295.7	329.2	11.2
6	81.7	271.4	313.0	9.0
7	73.2	277.7	307.6	10.8
8	97.1	287.0	318.2	11.8
9	66.4	299.0	326.4	11.9
10	40.4	290.8	328.6	10.9
11	58.4	299.1	332.1	9.6
12	49.4	307.0	323.5	9.8
13	70.2	274.1	313.2	11.7
14	56.0	284.9	332.8	10.2
15	57.5	297.5	325.3	10.1
16	61.1	314.6	344.5	9.6
17	102.2	283.8	318.4	9.9
18	72.7	275.6	321.9	11.7
19	51.0	298.9	328.9	13.2
20	64.4	274.3	320.9	8.6
21	76.3	295.7	331.3	9.7
AVERAGE	63.7	291.6	325.8	10.8
STND DEV	17.0	13.2	10.0	1.2
Horizontal				
22	58.3	297.6	328.3	10.2
23	71.0	308.9	344.4	10.4
24	67.3	274.4	323.7	11.2
25	62.8	275.9	319.5	11.8
26	35.9	280.3	311.5	10.0
27	58.0	271.4	301.9	12.0
28	77.5	230.7	279.9	14.8
29	43.3	234.9	280.2	12.0
AVERAGE	59.3	271.8	311.2	11.5
STND DEV	13.9	27.2	22.8	1.5

The stress-strain graph shown in Fig. 4 shows us the maximum range of the stress, maximum range of strain, and when failure occurred for the as-printed samples.

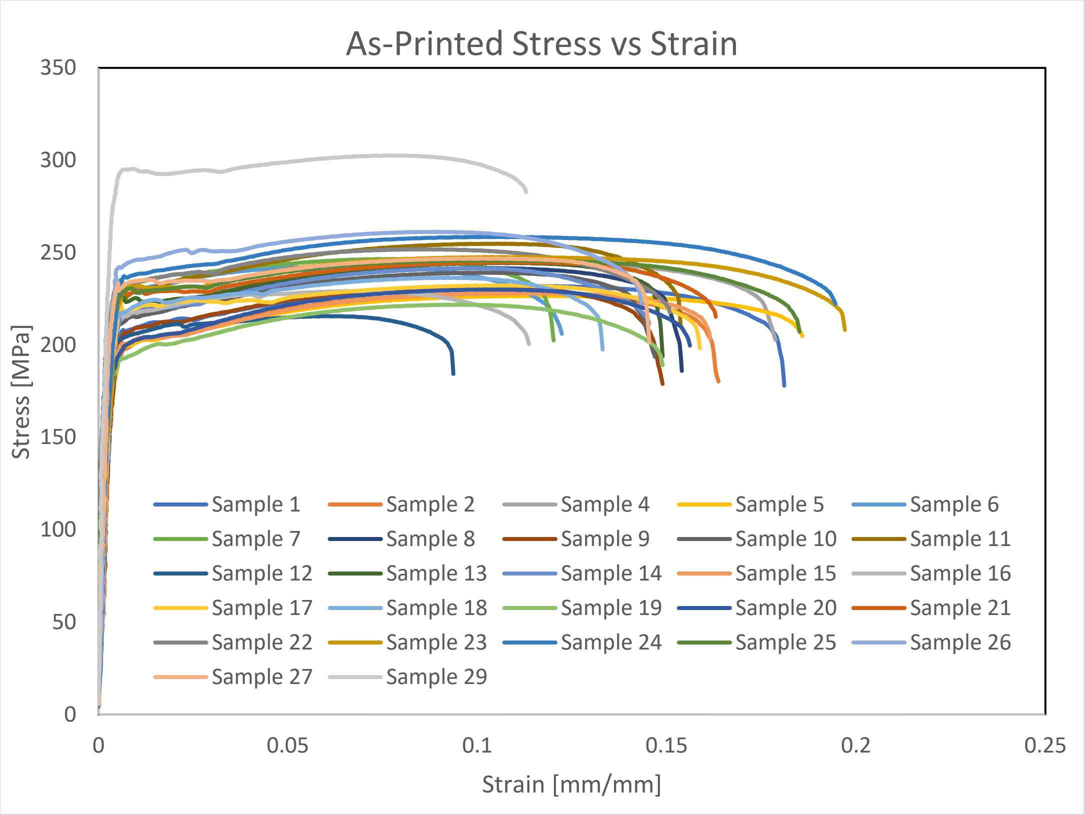

Figure 4: *Each as-printed sample, Stress vs Strain.*

The largest elongation occurred in sample 23, with a percent elongation of 19.7%. The largest yield strength occurred in sample 29, with 295.0 [MPa]. The largest elastic modulus and ultimate strength also occurred in sample 29 with 95.2 [GPa] and 302.7 [MPa], respectively. The standard deviation for elastic modulus, yield strength, ultimate strength in the vertical direction was, 14.4 [GPa], 14.1 [MPa], and 9.6 [MPa], respectively. The standard deviation for elastic modulus, yield strength, ultimate strength in the horizontal direction was, 17.7 [GPa], 22.8 [MPa], and 20.0 [MPa], respectively. One possible thing that could have happened to Sample 29 was that the grips weren't tightened entirely down, so as the Instron machine was pulling the dog bone apart, the clamps could have slipped and caused it to crack and break before the others. Another possible situation is the sample could have been bent going into the machine and there was already that torsional force in there and caused it to break before the others.

The stress-strain graph shown in Fig. 5 shows us the maximum range of the stress, maximum range of strain, and when failure occurred for the heat-treated samples.

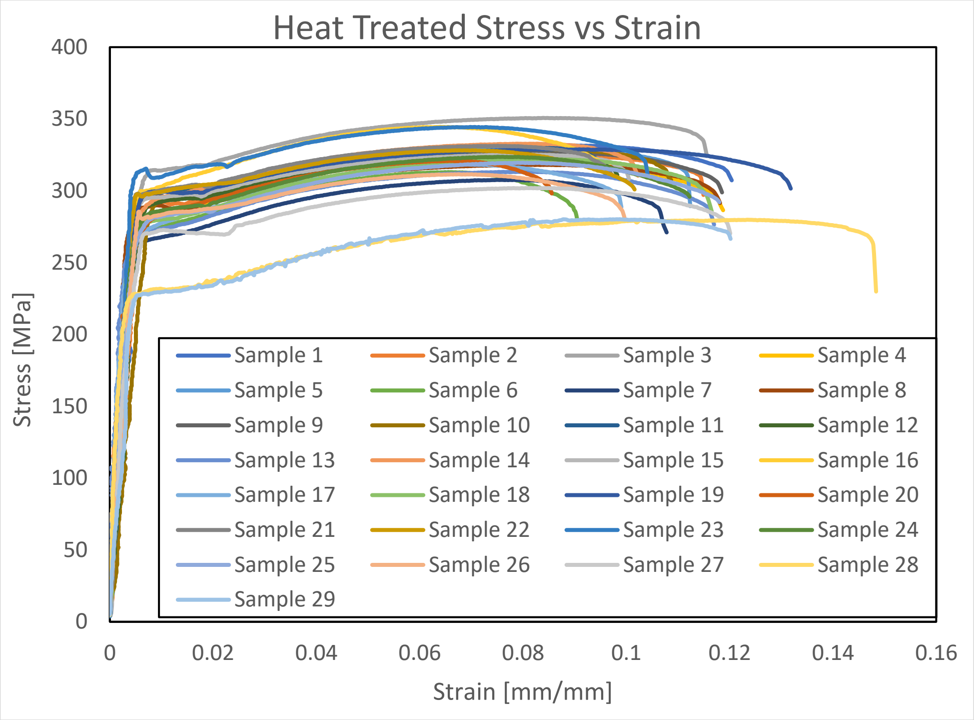

Figure 5: *Each heat treated sample, Stress vs Strain.*

The largest elongation occurred in sample 19, with a percent elongation of 13.2%. The largest yield strength occurred in sample three, with 318.7 [MPa]. The largest elastic modulus occurred in sample 8, with 97.1 [GPa] while the largest ultimate strength occurred in sample three, with 350.7 [MPa]. The average standard deviation for elastic modulus, yield strength, ultimate strength in the vertical direction was, 17.0 [GPa], 13.2 [MPa], and 10.0 [MPa], respectively. The average standard deviation for elastic modulus, yield strength, ultimate strength in the horizontal direction was, 13.9 [GPa], 27.2 [MPa], and 22.8 [MPa], respectively. Sample 28 and Sample 29 had the lowest yield strength, but also lasted the longest before breaking. Sample 3 and Sample 23 had the highest yield strength but lasted about the same as every other sample in terms of strain before breaking.

The purpose of this experiment was to test the 3-D printed samples of aluminum 6061, both as-printed and T6 heat treated, to see if the samples were up to ASTM and Elementum3D standards. The method used to test the samples, was to use an Instron machine to test the tensile stress of aluminum. The method of testing tensile stress gives the ability to find the elastic modulus, the yield strength, ultimate strength, and the percent elongation of each sample. Each sample was measured and tested. These samples did not hold up to the full standard at Elementum3D [4]. Some of these samples did meet the criteria but fell short on some of them.

Some errors in the experiment that could have accounted for the underperforming samples were that the Instron machine was not calibrated each sample. This could have been resulted in skewed data collection, the extensometer was not placed exactly leveled every time. Also, the extensometer's pin was not always secured. These errors could have resulted in skewed data, slightly.

Modal Analysis

During takeoff, a satellite may be subject to many sources of heavy vibration that can resonate with any mounted hardware. This resonance can constructively interfere repeatedly until systems eventually loosen or even fracture and catastrophically fail. Because of this it is very important to know the fundamental frequency of any payload on a spacecraft. A design criterion of having a fundamental frequency greater than 100 [Hz] on the final bracket was mandated by Lockheed Martin in order to avoid any resonance-based failure during launch. This value is best found experimentally through modal analysis. During the course of this project, each final part for the bracket was put through modal analysis with a modally tuned impulse hammer and accelerometer to determine the fundamental frequency of its first mode of vibration.

The test was performed using a PCB Piezotronics Impulse Hammer set and a National Instruments Elvis II+ for data acquisition (DAQ). The impulse hammer is recommended because of the hammer's ability to reliably provide consistent impulse curves as an input for the accelerometer. The DAQ is needed for processing the signal from the accelerometer for use in a data recording and calculation software. After a few weeks of research, it was determined that the software option with the optimal combination of accessibility, usability, and accuracy was National Instruments Dynamic Signal Analyzer. With this program it was possible to run a test, perform a Fast Fourier Transform on the time domain graph, see the results in real time, and log a text file of the raw data in both the time domain and the frequency domain. It also provided extensive control over the input and output settings. Figure 6 shows the PCB plug in attached to the Elvis II+ board.

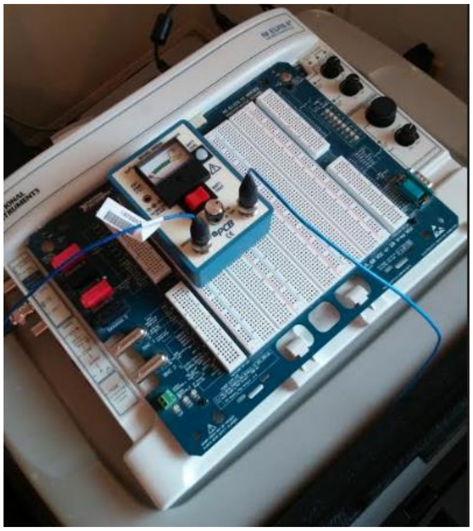

Figure 6: *Data Acquisition Tools.*

The actual hardware testing began with a set of calibration tests run on a rectangular bar made of extruded 6061 T6 aluminum. These tests were for the purposes of validating the successful operation of all the pieces in the hardware chain and determining the best software settings in the signal analyzer program. The calibration bar measured 9.88 inches in length, 6.00 inches in width, and 0.50 inches in thickness. Many tests were conducted on this bar to determine that the best settings, for a detailed and readable frequency graph giving enough information within the scope of the project, consisted of a 2000 [Hz] frequency span with a Hanning window FFT and 0.1 [V] edge triggering enabled. This setup allowed multiple frequency peaks to be prominently featured in the final frequency domain graph so that the test administrator could quickly monitor how consistent each test run on a part was and identify any hardware problems based on this information.

Once these settings were finalized a full experiment consisting of six total tests (one on each face of the sample) was performed on the calibration bar to get a value for its first fundamental frequency. This involved suspending the bar via fishing line from the ceiling to simulate a free-free vibration environment. This is the one of the best and most attainable ways to truly isolate a sample so that its intrinsic frequency response can be measured. Fishing line is an excellent analog for the extremely soft spring needed for a free-free environment and anchoring the line to an object much larger in physical size and greater in stiffness than the sample ensures that the only vibrational response recorded by the accelerometer is that of the sample itself. The results of this experiment were compared to the results of a simulation performed in SolidWorks on a model of the same bar. The SolidWorks simulation yielded a first mode frequency of 1032 [Hz] while the physical experiment measured a first mode of 1045 [Hz]. These two values were determined to be within an acceptable margin of error (1.3%), so the performance of the process and hardware was validated. Tests could be carried out on the actual bracket parts with a high degree of confidence in the data that was produced.

Experiments were run on the front mounting plate and two versions of the Chancellor vertical support piece. Each experiment consisted of six tests (one for each face of the part). This was to comply with the roving hammer method of modal analysis. In roving hammer method, a static accelerometer position is chosen, and hammer strikes are administered in several different location. This process is reversed in roving accelerometer method where a static strike position is chosen, and several tests are performed with the accelerometer in different positions. Because there was only access to one accelerometer and the wax that it came with proved to be a tricky adhesive to work with the roving hammer method was chosen to be the basis for the experiment structure. Figure 7 shows the placement of the accelerometer on one of the side pieces tested.

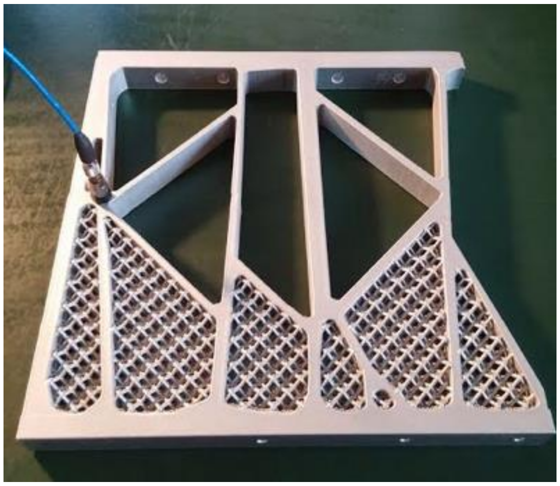

Figure 7: *Side piece tested with roving hammer method.*

Each text file that was logged from Dynamic Signal Analyzer was exported into Excel so that it could be plotted and a range of frequencies surrounding the first peak could be determined. A simple formula was used to find the maximum magnitude of the frequency response in this range (recorded in [dBVrms]) and the frequency corresponding to that magnitude value. This frequency was then reported as the fundamental frequency of the first vibrational mode for that part. A formula was set up to average the reported frequencies from each face of the part, but this turned out to be unnecessary. The data from the accelerometer was so consistent that each face returned the same value for fundamental frequency on every part tested.

For the front mounting plate, the fundamental frequency was consistently found to be 215 [Hz]. The vertical support piece with body centered cubic lattice was found to have a fundamental frequency of 242.5 [Hz] while the version with gyroid style lattice had a measured first mode of 632.5 [Hz]. Since all of these values are above the target value of 100 [Hz] it can be said with a high degree of confidence that the completed bracket will have sufficient resistance to resonance based vibrational failure.

Conclusion

After heat treating all of the samples resulted in an average density of 2.73 [g/cm^3]. This density is equal to the expected density posted by the aluminum's manufacturer. The as-printed dog bones resulted in an elastic modulus of 54.4 [GPa] and 65.5 [GPa], yield strengths of 215.7 [MPa] and 245.8 [MPa], and ultimate strengths of 235.6 [MPa] and 259.3 [MPa] in the Z and XY orientations. The heat-treated dog bones resulted in an elastic modulus of 63.7 [GPa] and 59.3 [GPa], yield strengths of 291.6 [MPa] and 271.8 [MPa], and ultimate strengths of 325.8 [MPa] and 311.2 [MPa] in the Z and XY orientations. These results were fairly consistent and comparable to the also comparable to the manufacture's claims. These material properties lead us to the conclusion that the printer is functioning as expected, and the 6061 Ram 2 aluminum will be sufficient for further use in part design. Our bracket pieces had frequencies equal to 215[Hz], 242.5 [Hz], and 632.5 [Hz]. These frequencies are all greater than the desired frequency by Lockheed, showing that current bracket designs are viable options. These current designs can be pushed forward for further testing to check against other Lockheed Martin requirements.

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