SAMPLE FORMAL LABORATORY REPORT

Fatigue Failure through Bending Experiment

Adapted from a report submitted by Sarah Thomas

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ME 498

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Professor David Bayless

Abstract

The purpose of this experiment was to observe fatigue failure using a rotating fatigue (Wohler) machine which applied a cyclical stress to samples of 6061-T6 aluminum with a neck radius of 2.50 mm. For non-ferrous metals, fatigue results in the deterioration of a material after a prolonged stress has been applied to it and the number of cycles to failure depends on the stresses applied. Several samples of the 6061-T6 material were loaded with stresses ranging from 0.9 to 0.6 of the yield strength. The resulting numbers of cycles to failure were statistically analyzed using Chauvenet's criterion and plotted as a stress vs. cycles (S-N) diagram. An estimated endurance limit of 85 MPa was extrapolated from a curve fit, based on a number of cycles to failure of $5x10^8$. Finally, a comparison was made to the known endurance limit and comparisons were made to number of cycles to failure (N) based on errors in the measured neck radius of the test specimen. The large change in N with small changes in neck radius indicates a high degree of uncertainty for the data determined in this experiment.

Introduction

All materials have different properties that result in advantages and disadvantages. Study and understanding of these properties is critical to the design of a mechanical system and the selection of the correct materials for a given part. One crucial failure mode is fatigue. Fatigue is the weakening or failure of a material resulting from prolonged stress. (Holman, 2003) Fatigue can be a result of many factors, not all of which are completely understood (Davis, 1990). However, it is understood that when a mass is repeatedly cyclically loaded at a location on the material, cracks begin to form. These cracks spread enough to eventually cause failure and break the piece at the location. Consequently, when designing a mechanical system, it is important to know these limits. (Davis, 1990) Not only could catastrophic fatigue failure cause a large loss in money due to a poor design but it could result in a loss of lives as well. Critical examples of fatigue failure range from train axles to wing cracking on airplanes (James, 1999)

To determine the level of torsional fatigue a material can withstand, testing of the number of cycles to failure is required. One of the most common procedures includes rotation of a round sample while applying a known load. As the sample rotates, the stress applied to the outside surface of the sample varies from maximum-tensile to zero to maximum-compressive and back

(Stinson, 2003). This is shown in Figure 1, where the top is in tension and the bottom is in compression, and Figure 2, where the stress applied at any point on the surface of the specimen varies as a function of rotational angle. The number of cycles until failure is counted and the data is statistically analyzed and then plotted as stress applied versus the number of cycles (S-N diagram).

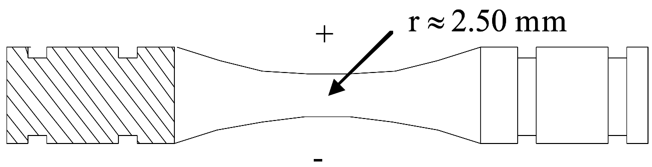

Figure 1. Schematic of the rotating fatigue specimen in tension and compression (Bayless, 2004)

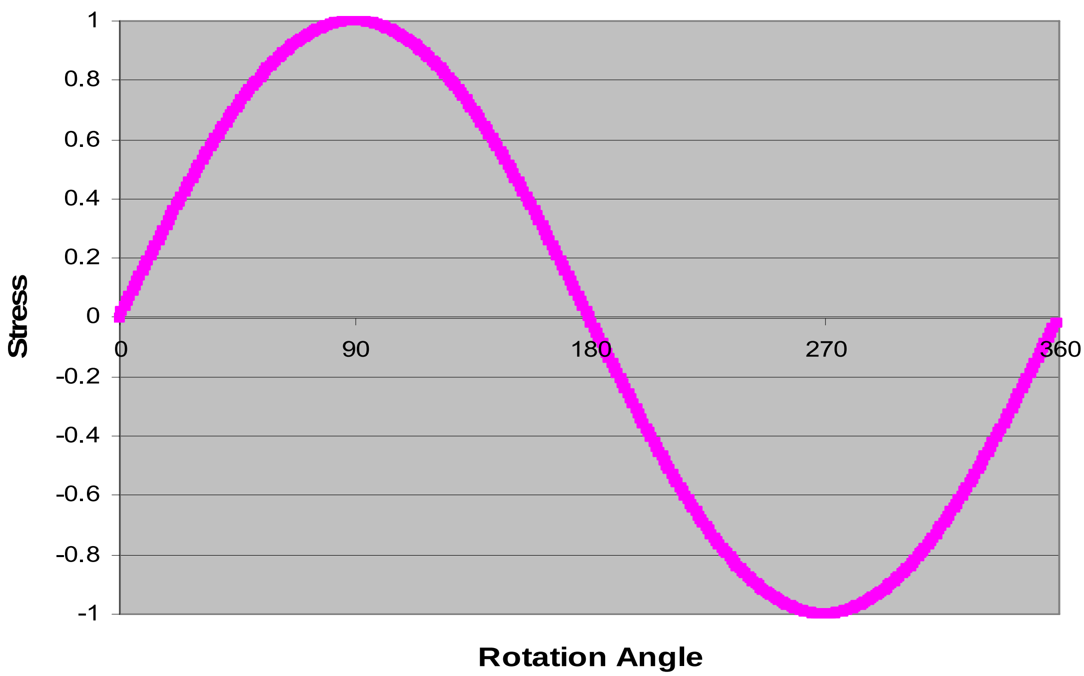

Figure 2. Stress applied at any point on a specimen as a function of rotational angle

The endurance limit is defined for ferrous (steel and iron) material as the stress level below which the material can be cycled infinitely without failure. (Shigley et al., 2003) This is very important, because the result of exceeding this point most likely will be fatigue failure. However, for non-ferrous materials, such as aluminum, there is no true endurance limit. Given enough cycles, the material will fail in fatigue. (Stinson, 2003) Therefore, for non-ferrous materials, the endurance limit is a function of a design number of cycles to failure. This is shown in Figure 3, which plots stress vs number of cycles for ferrous and non-ferrous materials, illustrating each material's endurance limit. For this experiment, we considered the reference number of cycles to be $5x10^8$.

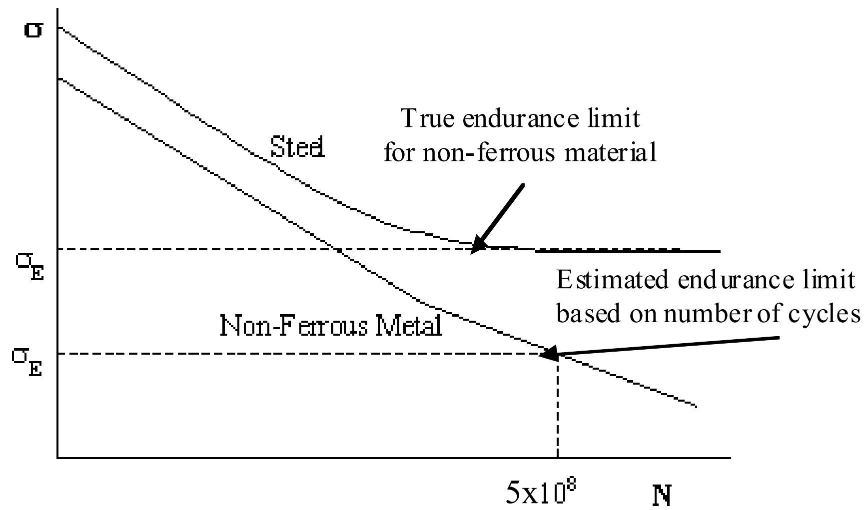

Figure 3. Stress vs number of cycles (S-N) diagram showing endurance limits for ferrous and non ferrous materials (Bayless, 2004)

To calculate the applied stress on the specimen, Equations (1) and (2) were used. The applied stress was calculated knowing the distance through which the applied weights acted on the specimen neck 9125.7 mm). and the moment of inertia (I). The loading weight (P) was calculated from equations (1) and (2) to make the applied stress to be 0.9, 0.8, 0.7 and 0.6 of the yield strength.

$$\sigma = \frac{125.7 \cdot P \cdot r}{I} \text{ (N/mm}^2\text{)} \tag{1}$$

$$I = \frac{\pi d^4}{64} \tag{2}$$

where r = neck radius (in mm)
d = neck diameter (in mm)

Equations (3) through (6) were given the in laboratory guidelines (Bayless, 2004) to find the predicted number of cycles to failure for a given applied stress. The calculated number of cycles to failure was then compared to the actual number of cycles found from experimentation.

$$X = \frac{1}{2}\log[N_{reference}] \quad (3)$$

$$b = -\frac{1}{X}\log\left[\frac{0.9\sigma_{ultimate}}{\sigma_{endurance}}\right] \quad (4)$$

$$a = \frac{0.81\sigma_{ultimate}^{2}}{\sigma_{endurance}} \quad (5)$$

$$N = \left[\frac{\sigma_{applied}}{a}\right]^{\frac{1}{b}} \quad (6)$$

where X = intermediate value based on $N_{reference}$
$N_{reference} = 5 \times 10^{8}$ cycles
$\sigma_{ultimate}$ = ultimate strength (stress) of the material
$\sigma_{endurance}$ = endurance strength (stress) of the material
$\sigma_{applied}$ = applied stress
N = predicted number of cycles to failure

Experimental Apparatus and Procedure

To begin the experiment, the weight load for each level of stress - .9σy, 0.8σy, 0.7σy and 0.6σy was determined using equations (1) and (2). The yield strength (stress) Sy for 6061-T6 is known to be 275 MPa and the ultimate strength ($\sigma_{ultimate}$) is known to be 310 MPa. (Davis, 1990). The estimated number of cycles until failure were then found using equations (3)-(6). The number of cycles increased as the yield strength level increased.

The lab was a simple procedure of loading and unloading the machine with the test specimen made of AA 6061-T6. Figure 4 shows the schematic of the testing apparatus.

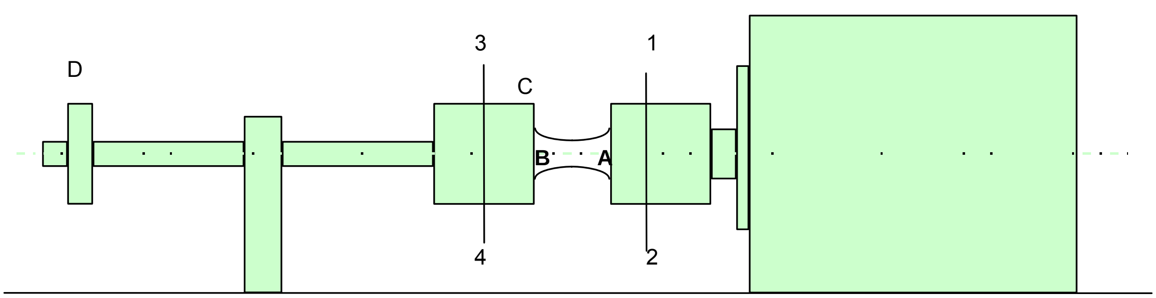

Figure 4. Schematic of Apparatus of Testing Machine (Bayless, 2004)

In the figure, points A and B are the edges of the middle section of the test specimen and were loaded to the edge of the center portion of the part. A weight was hung from the rotating bearing at point D, which applied stress through a cantilevered arm running to the specimen. Different weights loaded at D would cause different stresses.

Figure 5 shows the distinctive difference between the end and the center portions of the specimen. Only the center should be showing when loaded in the machine.

Figure 5. Test Specimen Example

The test specimen was aligned properly by using a dial gauge to check at point A with only one end of the specimen in and then after tightening the set screws (points 1 and 2), check at point B (points 3 and 4). After both sets of grub screws are adjusted, check again at point C to ensure accuracy. Once the machine was properly loaded along with the weights for the specific trial, the safety guard was put on and the machine was started. The cycles were counted on the machine and recorded for statistical use in the S-N diagram.

During this procedure, a few measurement uncertainties could affect the results. First, the dimensions pertaining to the specimen were given in millimeters, so some error in measurement of neck radius was possible. It was estimated to be an error of ±0.1mm. Also, the calculated weight (newtons) had to be converted to mass for measurement. This uncertainty in conversion was estimated to be 0.5%. The weight of the arm was to be determined and subtracted from this value to find the load for each stress level. The error in calculating the self-loading (or arm) weight was assumed to be 10g, although the technique used to find it (hanging increasing counter weights over the pulley until the arm lifted) was highly subjective and could have resulted in significantly more error, but it was impossible to determine.

Other errors could occur reading the dial gauge when calibrating the specimen in the machine. Human error and well as the accuracy of the gauge itself could cause error in loading the part. Since the equation to find the applied stress has a set value for the distance between the loaded ends of the specimen (125.7mm), improperly loaded specimens would be incorrect as well. The mass applied to the specimen depends on the certainty of the labeled weights. The specimens may vary in weight and dimensions causing variance in the results. One last possible error could be the number of cycles. The level of uncertainty of the counter could cause error as well as the person reading the cycles, but the possibility for 99 cycles to be missed always exists.

Experimental Results and Discussion

The laboratory was a collaborated effort with four levels of stress performed including $0.9\sigma_y$, $0.8\sigma_y$, $0.7\sigma_y$, and $0.6\sigma_y$. Once all the data was collected, an analysis of the different stress levels when compared to the number of cycles until failure was completed. The analysis process began by finding the average of cycles until failure at each level of stress. The standard deviation was then taken as well. Table 1 shows the number of cycles until failure received in the lab as well as the averages, standard deviation and loaded weight of each stress level.

Table 1: Statistically Analyzed Data Points

Stress	**0.9 Sy**	**0.8 Sy**	**0.7 Sy**	**0.6 Sy**
Load (g)	2332	2190	1916	1641
Trail #1	13400	64000	234600	1098700
Trail #2	67500	77000	312400	876500
Trail #3	34500	17000	369900	1110900
Trail #4	23450	87500	215700	2345600
Trail #5	27700	95300	200300	2123700
Trail #6	123800	64100	489500	2109200
Trail #7	36900	162000	204700	1720700
Trail #8	44300	218100	619900	1923300
Trail #9	86500	183300	400400	2657500
Trail #10	44600	108100	594600	564100
Trail #11	77600	241100	412800	1344900
Trail #12	43200	176100	622200	907500
Average	51954.17	124466.7	389750	1565217
Std Dev.	30086.51	66767.17	155573.4	641874.8

Due to the many areas where error could occur, not only during loading but in the variance of the material itself, some specimens significantly deviated from the expected number of cycles to failure. Chauvenent's criterion was applied to the data set in order to find any of these outlying points. The d_{max}/s value with N = 12 for a total of twelve trials per stress level was found to be 2.03 (Holman, 2003). Only one data point in the experiment's set was found to be larger than this limit when equation (7) was applied:

$$\tau_{max} = \frac{\left|(X_i - \overline{X})\right|_{max}}{S_X} = \frac{d_{max}}{S_X} \tag{7}$$

The data was then statistically analyzed again to find the new average and standard deviation with the outlying point taken out. The data was then used to plot an S-N diagram, as shown in Figure 6. This plot of the stress applied versus the number of cycles shows that an extrapolated endurance limit at $5x10^8$ cycles is 85.0 MPa. Error bars were found by taking one standard deviation of the number of cycles until failure.

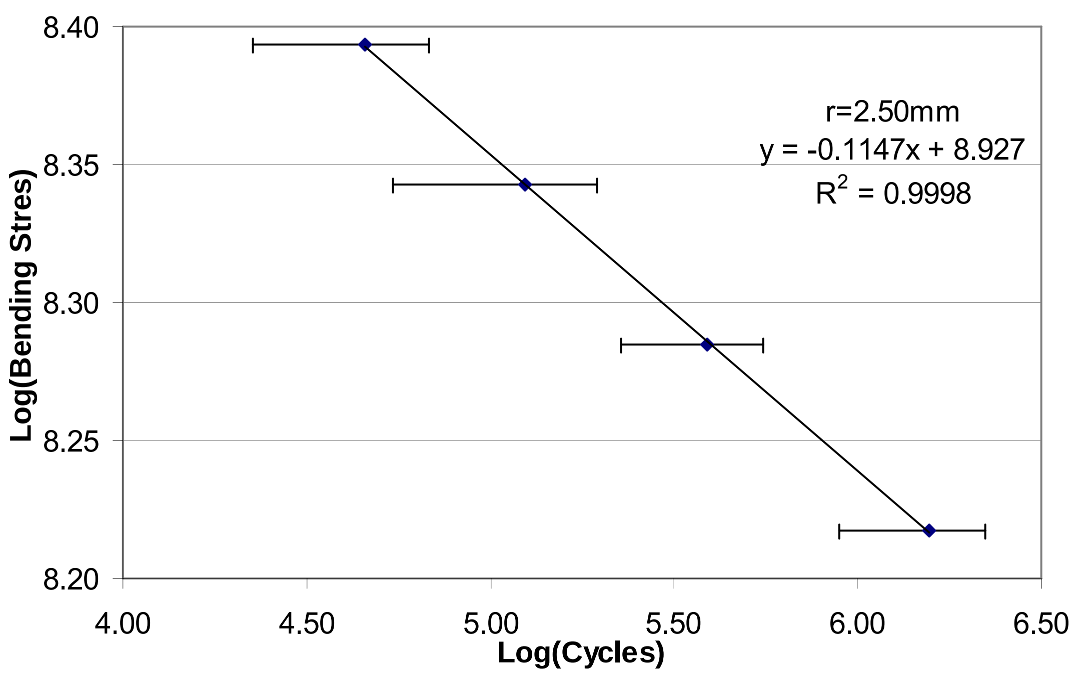

Figure 6: S-N Diagram of Laboratory Data after Chauvenent's is Applied

Comparing the original data with the data after Chauvenent's indicates that a more linear trend is observed. Even though there was only one point, it interfered with the linear relationship that defines the endurance limit. Since the material is composed of a structural AlMgSi alloy, it follows the trend of having a S-N curve that continues to fall with an increasing number of cycles. The endurance limit was found for the data assuming that N_{ref} was equal to 5 x 10^8 cycles, the value for nonferrous metals. The linear equation was used from the S-N diagram, $y = -0.1147(\log \sigma_{applied}) + 8.9269$. N_{ref} was used to find the endurance limit of 85 MPa. Further calculations are found in Appendix A.

These procedures were followed for a radius of 2.45 mm, with the original radius being 2.50 mm. The stress levels were kept the same with a new load value needed to be found. The same procedure was followed as was done originally before the lab to find the new values. The endurance limit was found for r = 2.45 mm using the linear equation of $-0.1147(\log \sigma_{applied})+ 8.9533$. The value was found to be 96 MPa. The increase in endurance limit occurs as the radii decreases. The two different radii were plotted against each other in the following figure to show the relationship of the decrease in radius size. This data is shown in Figure 7, along with a direct comparison to a neck radius of 2.50 mm.

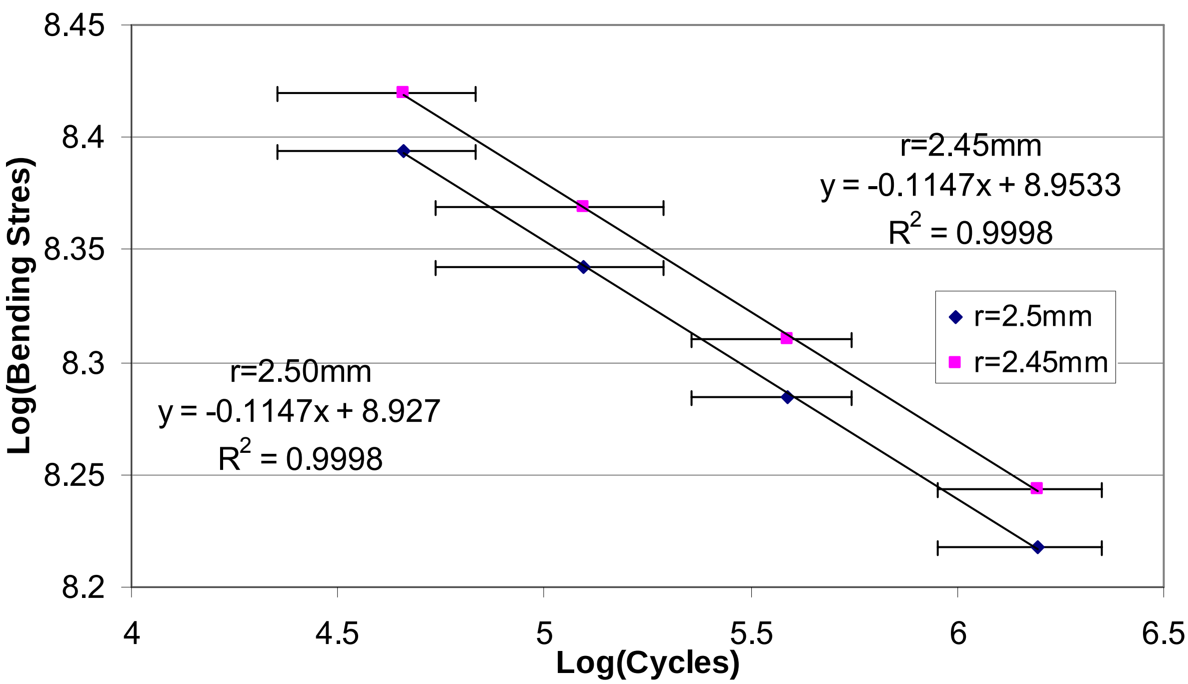

Figure 7: S-N Diagram for two possible neck radii (2.45mm and 2.50mm)

One last comparison was made to complete the analysis portion of the laboratory. The number of predicted cycles between the two radii was compared to the actual number of cycles to failure found in the lab for the actual fatigue strength of 95 MPa. These values are shown in the Table 2. The relationship is again shown that as the radii decreasing, the endurance limit increases from the data received in the lab. From the data shown in the chart, the radii have a smaller error between that found and that predicted. The predicted value is very sensitive when calculating as many values go into the final value. The number of decimals carried out in the calculations can make a significant difference.

Table 2: Number of Cycles Known versus Predicted Value

s = 95 Mpa

r = 2.50mm

	Bending Stress	N_{known}
	(Mpa)	
0.9σy	2.48E+08	45423
0.8σy	2.20E+08	124467
0.7σy	1.93E+08	389750
0.6σy	1.65E+08	1565217

s = 95 Mpa

r = 2.50mm

	Bending Stress	$N_{predicted}$	% difference
	(Mpa)		
0.9σy	2.48E+08	68101	33.3%
0.8σy	2.20E+08	203552	38.9%
0.7σy	1.93E+08	704331	44.7%
0.6σy	1.65E+08	2952049	47.0%

s = 95 Mpa

r = 2.45mm

	Bending Stress	N_{known}
	(Mpa)	
0.9σy	2.49E+08	51954
0.8σy	2.34E+08	124467
0.7σy	2.05E+08	389750
0.6σy	1.75E+08	1565217

s = 95 Mpa

r = 2.45mm

	Bending Stress	$N_{predicted}$	% difference
	(Mpa)		
0.9σy	2.49E+08	64457	19.4%
0.8σy	2.34E+08	115587	-7.7%
0.7σy	2.05E+08	400438	2.7%
0.6σy	1.75E+08	1690615	7.4%

There are many factors that can affect the fatigue life of the metal. The surface is an obvious cause as it is impossible to have a perfect, consistent surface finish. The smaller the Ra value, the better the surface is, the more consistent the surface and it will more likely take longer to cause fatigue and eventually failure. Other factors could be design and manufacturing deficiencies, heat, corrosion or secondary stresses. During the lab, the material appeared to split right in half as shown in Figure 8. Further analysis would need to be done microscopically to observe the grain structure and the surface roughness at the point of failure.

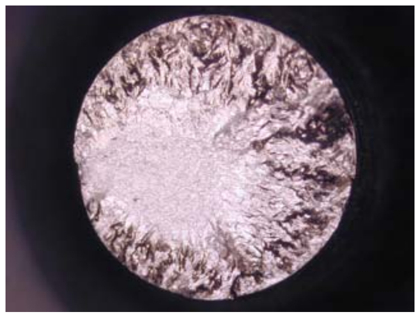

Figure 8: Specimen after Failure

Conclusions

A Wohler machine was used to producing various rotating bending stresses on known specimens of 6061-T6 aluminum. The applied rotating stress caused cracks in the material's surface that propagated to eventually cause the material to fail. The numbers of cycles to failure were recorded and analyzed using an S-N diagram. From this diagram, the endurance limit was calculated from the linear relationship when plotted on a log scale. Due to the fact the number of cycles found is not an absolute value for every run, sometimes outlying data points occur because of outside factors such as material dimensions, surface finish and incorrect loading. As a result Chauvenent's criterion is an excellent tool to eliminate these points.

The first key result to note is that there was a vast difference in the number of cycles to failure found from experimentation to the number predicted by theory. This is likely due to the fact that many different students loaded the specimens, mostly likely in their own inexact methods. This could have caused out-of-alignment conditions on the specimen and concentration of stresses far above the stress calculated using equation (1).

Next, the resulting endurance limit calculated from the data was 85.0 MPa, while a replacement calculation assuming a neck radius of 2.45 mm showed an endurance limit of 96 MPa, indicating a high degree of sensitivity to the necking radius. Further, the fact that many different students loaded the specimens, mostly likely in their own inexact methods, could have led to improper alignment of the specimens and increased stresses, thus making the data less than completely reliable. However, it appears that even with this large variation in loading techniques, there was only a 12% difference between accepted and determined endurance limits, which is far less significant than the percentage differences in number of cycles to failure.

Recommendations

There were too many possibilities for significant errors to trust the data from this lab. The initial calculations can be tricky and confusing with the various units. The first recommendation would be to do a complete sample calculation showing all units to make sure everyone calculated the same way in determining the loadings "P." Another area for inaccuracy is the material properties. The specimens are manufactured and may not have very precise properties when compared to each other. The second recommendation would be to take three or four samples and measure the neck radius, as well as the yield strength and the ultimate strength using the Instron machine. Then you would have further comparison between the various stress levels and trails. The third recommendation is to measure surface finish of the fatigue samples using something like an SRG-4000 tester to give RMS and fluctuations in finish. This information could be useful if the part fails at a sooner than expected number of cycles. The fourth recommendation would be to have one team load all the samples the same way and run three different repetitions of all four loadings. That way, the data could be directly compared to all the other teams and if one team had a less robust procedure, their data could be properly scrutinized. The sixth recommendation would be in regards to the the uncertainty of all the measurements taken. Although Chauvenent's was performed, that was for the data set. The measurements taken, such as the dial gauge, the number of cycles and weight loaded all could affect the final calculations. It is recommended to systematically investigate how each of the key measurements affect the final result to understand the sensitivity to those variables. Finally, it is highly recommended to move from the set-screw mounting system to a check system for alignment of the sample in the rotational tester. A chuck mounting system would also eliminate a lot of human error in the loading process.

References

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Holman, J., *Experimental Methods for Engineers*, McGraw-Hill, 7th ed., 2000, pp. 56-73.

James, T., *Fatigue Failure for Dummies*, Made Up Press, New York, 2nd ed., 1999, pp.23.

Stinson, K., "Fatigue Failure in Non-Ferrous Materials," *Journal of Fake Fatigue*, Vol. 65, 2003, pp. 45-51.

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Appendix A

		N to Failure							
Stress	**Predicted N**		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
$0.9\sigma_y$	68,000	**Machine #**	1	2	1	2	1	2	1
		Loaded by:							
		Mass	2337.2	2332	2337.2	2332	2337.2	2332	2337.2
		N	1238	369	443	865	446	776	432
		Recorded by:							
$0.8\sigma_y$	202,893	**Machine #**	1	2	1	1	1	1	1
		Loaded by:							
		Mass	2190	2190	2190	2190	2190	2190	2190
		N	641	1620	2181	1833	1081	2421	1761
$0.7\sigma_y$	667,690	**Machine #**	2	2	2	2	2	2	1
		Mass	1916	1916	1916	1916	1916	1916	1916
		N	4895	2047	6199	4004	5946	4128	6222
$0.6\sigma_y$	5.693×10^6	**Machine #**	1	1	2	2	1	2	1
		Mass	1641	1640	1641	1641	1640	1640	1640
		N	21092	17207	19233	26575	5651	13449	9075

Material:	Al 6061-T6

	0.9 Sy	0.8 Sy	0.7 Sy	0.6 Sy
Stress Value (Pa)	247500000	2.2E+08	192500000	165000000
Loading (g)	2332	2190	1916	1641
Predicted Cycles	68000	202893	667690	5.68E+06

Measured Cycles

Stress	**Trail #1**	**Trail #2**	**Trail #3**	**Trail #4**	**Trail #5**	**Trail #6**	**Trail #7**	**Trail #8**	**Trail #9**	**Trail #10**	**Trail #11**	**Trail #12**
0.9 Sy	13400	67500	34500	23450	27700	123800	36900	44300	86500	44600	77600	43200
0.8 Sy	64000	77000	17000	87500	95300	64100	162000	218100	183300	108100	241100	176100
0.7 Sy	234600	312400	369900	215700	200300	489500	204700	619900	400400	594600	412800	622200
0.6 Sy	1098700	876500	1110900	2345600	2123700	2109200	1720700	1923300	2657500	564100	1344900	907500

Calculations:

a	819.3789
x	4.349485
b	-0.10757

Yield strength	2.75E+08
Tensile strength	3.10E+08
$\sigma_{endurance}$	9.50E+07

Average	**Std Dev.**
51954.17	30086.51
124466.67	66767.17
389750.00	155573.43
1565216.67	641874.77

Original Data

	Mean N	*Standard Deviation*	Bending Stress (Mpa)	Log N	Log (Stress)	$N_{predicted}$	Log ($N_{predicted}$)
0.9σy	51954.17	30086.51	2.48E+08	4.716	8.394	68101.085	4.833
0.8σy	124466.67	66767.17	2.20E+08	5.095	8.342	203551.92	5.309
0.7σy	389750.00	155573.4	1.93E+08	5.591	8.284	704330.74	5.848
0.6σy	1565216.67	641874.8	1.65E+08	6.195	8.217	2952049.1	6.470

Error Bars:

log(avg+σ)-log(avg)	log(avg)-log(avg-σ)
0.198	0.376
0.187	0.334
0.146	0.221
0.149	0.229

Chavenet's

N = 12	d_{max} (Limit):	2.03

d_{max}	**(N-x)/std**											
	1.281	0.517	0.580	0.947	0.806	2.388	0.500	0.254	1.148	0.244	0.852	0.291
	0.906	0.711	1.610	0.554	0.437	0.904	0.562	1.402	0.881	0.245	1.747	0.773
	0.997	0.497	0.128	1.119	1.218	0.641	1.189	1.479	0.068	1.317	0.148	1.494
	0.727	1.073	0.708	1.216	0.870	0.847	0.242	0.558	1.702	1.560	0.343	1.025

New Data:

Stress												
0.9 Sy	13400	67500	34500	23450	27700		36900	44300	86500	44600	77600	43200
0.8 Sy	64000	77000	17000	87500	95300	64100	162000	218100	183300	108100	241100	176100
0.7 Sy	234600	312400	369900	215700	200300	489500	204700	619900	400400	594600	412800	622200
0.6 Sy	1098700	876500	1110900	2345600	2123700	2109200	1720700	1923300	2657500	564100	1344900	907500

	Average	Std Dev.
0.9σy	45422.73	22872.03
0.8σy	124466.67	66767.17
0.7σy	389750.00	155573.43
0.6σy	1565216.67	641874.77

Check Limit:

d_{max}	**(N-x)/std**											
	1.400	0.517	0.580	0.947	0.806		0.500	0.254	1.148	0.244	0.852	0.291
	0.906	0.711	1.610	0.554	0.437	0.904	0.562	1.402	0.881	0.245	1.747	0.773
	0.997	0.497	0.128	1.119	1.218	0.641	1.189	1.479	0.068	1.317	0.148	1.494
	0.727	1.073	0.708	1.216	0.870	0.847	0.242	0.558	1.702	1.560	0.343	1.025

New Data

r = 2.50mm

	Mean N	*Standard Deviation*	Bending Stress	Log N	Log (Stress)	$N_{predicted}$	Log ($N_{predicted}$)
			(Mpa)				
0.9σy	45422.73	22872.03	2.48E+08	4.657	8.394	68101.085	4.833

Error Bars:

log(avg+σ)-log(avg)
0.177

log(avg)-log(avg-σ)
0.304

0.8σy	124466.67	66767.17	2.20E+08	5.095	8.342	203551.92	5.309		0.187		0.334
0.7σy	389750.00	155573.4	1.93E+08	5.591	8.284	704330.74	5.848		0.146		0.221
0.6σy	1565216.67	641874.8	1.65E+08	6.195	8.217	2952049.1	6.470		0.149		0.229

Endurance Limit

y =	-0.1147x + 8.9269
N =	5.00E+08
Log(N)	8.70
y =	7.93
unlog(y)	8.49E+07

** Endurance Limt*

$\sigma_{endurance}$ (Pa)	9.50E+07
% Difference:	10.59

Source: www.matls.com

r = 2.45mm

	Mean N	*Standard Deviation*	Bending Stress	Log N	Log (Stress)	$N_{predicted}$	Log ($N_{predicted}$)
			(Mpa)				
0.9σy	51954.1667	30086.51	2.49E+08	4.716	8.396	64456.623	4.809
0.8σy	124466.667	66767.17	2.34E+08	5.095	8.369	115586.61	5.063
0.7σy	389750	155573.4	2.05E+08	5.591	8.311	400438.4	5.603
0.6σy	1565216.67	641874.8	1.75E+08	6.195	8.244	1690614.5	6.228

Calculations:

a	819.3789
x	4.349485
b	-0.10757

Yield strength	2.75E+08
Tensile strength	3.10E+08
$\sigma_{endurance}$	9.50E+07

Endurance Limit

y =	-0.1054x + 8.8986
N =	5.00E+08
Log(N)	8.70
y =	7.98
unlog(y)	9.59E+07

* *Endurance Limt*

$\sigma_{endurance}$ (Pa)	9.50E+07
% Difference:	0.93

Sample Calculation for Load Needed:

$$\sigma_b = \frac{125.7 \cdot P \cdot r}{I} \ (N/mm^2)$$

$$I = \frac{\pi d^4}{64}$$

Solving for P after solving for I

Example:

$$I = \pi(2.50)^4/64$$

$$I = 30.68$$

$$(0.9*275) = 125.7*P*2.50/(30.68)$$

$$P = 24.163N$$

$$P = (24.163N/ 9.81\ kg)$$

$$P = 2463\ g$$

Weight Needed =2463g -130g

2.33kg