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-Technical Report-

Investigation in Friction Stir Welded Aluminum Alloy 2139-T8 for Hull Structure Applications

By:
Victor Burguess, Mechanical Engineer, Ground Vehicle Survivability and Protection
Rick Rickert, Mechanical Engineer, Ground Vehicle Survivability and Protection

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U.S. Army Tank Automotive Research, Development, and Engineering Center
Detroit Arsenal
Warren, Michigan 48397-5000

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14. ABSTRACT
2139-T8 aluminum and the use of FSW for joining of the material is understood from a quasi-static and dynamic response, however if the material is going to be used in an integrated hull structure, additional understanding is needed related to material fatigue. Military vehicles perform in very rigorous environments and use conditions. The hull structure is exposed to many different loads and cycles during its use life. This report summarizes the experimental testing and Stress-Life (S-N) curve development for 2139-T8 aluminum and FSW 2139-T8 aluminum.

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Introduction

The military has shown an increased interest in developing lightweight technology solutions for current and future platforms. A large portion of this work is related to materials. New alloys are constantly being created that show benefits from two main perspectives. The first is evaluating materials that perform the equal to the current solution at a lighter weight, and the second is materials that show an increase in performance at an equal weight. A large amount of characterization has to be performed to process, integrate, and test in order to establish design criteria for use in military applications.

There is large interest in the Defense industry for using aluminum alloys for survivability related applications because it has a low density when compared to current solutions and is relatively lower cost when compared to other lightweight armor materials such as Titanium. One aluminum alloy has proven to show a significant benefit in armor applications, 2139-T8 aluminum alloy. 2139-T8 is particularly of interest due to its ability to maintain material properties for all thicknesses. This is a significant improvement over other 2XXX and 7XXX series high strength aluminums.

There is a significant amount of data currently available that show 2139-T8's benefit with respect to survivability applications, however there is recent interest in its use for vehicle hull structures. This brings with it an increase in complexity both with respect to manufacturability and sustainment. 2139-T8 can be Gas Metal Arc Welded (GMAW) however the mechanical properties of the welds are very low when compared to the base material, in the order of 35-55% of base material properties with respect to tensile strength and elongation. As an alternative, Friction Stir Welding (FSW) can be used as an alternate method. Friction stir welding is a solid state welding process that uses a non-consumable rotating tool coupled to a high torque motor which moves along the joint of two plates resulting in a butt weld. Quasi-statically FSW has shown to maintain 75-85% of the base material properties with respect to tensile strength and increase the elongation of the material in the joint by 15-20%.

Although 2139-T8 aluminum and the use of FSW for joining of the material is understood from a quasi-static and dynamic response, if the material is going to be used in an integrated hull structure, additional understanding is needed related to material fatigue. Military vehicles perform in very rigorous environments and use conditions. The hull structure is exposed to many different loads and cycles during its use life.

This report summarizes the experimental testing and Stress-Life (S-N) curve development for 2139-T8 aluminum and FSW 2139-T8 aluminum.

Approach

Material fatigue testing is very common practice, however complications may arise in the different material states and alloys being tested. For this effort two standards were used ASTM E739 and ISO 1143.

ASTM E739 Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data was referenced to determine the required sample size to develop the Stress-Life (S-N) curve. This is based on test method, either Stress-Life or Strain-Life. Stress-Life was selected for this effort because this data will be used as design criteria for vehicle applications, thus the design requirements are Load vs. Cycles rather than a requirement for acceptable strain. For this effort, the data generated will be used as part of future research and development efforts and design criteria. For research and development efforts 6-12 specimens are required. For design allowable data, 12 to 24 samples are required. This information is caveated that if the spread is large, additional samples would be required. The amount of variance was unknown at the beginning testing so 5 specimens were created for each of the 6-12 minimum data points required for the curve development. 2139-T8 armor plate undergoes a rolling operation during development. This creates a difference in material properties parallel and transverse to the rolling direction. Therefore both directions are required for testing to determine the performance difference between the different directions. There are four test series that are required: base material longitudinal, base material transverse, FSW longitudinal, and FSW transverse. Of these 4 test series, 12 specimens are required to determine the curve and 5 specimens will be fabricated for each of the 12 points on the curve in case of a large variance. For this effort, a total of 240 specimens were fabricated to ensure enough specimens were made to conduct the testing required.

ISO 1143 Metallic Materials – Rotating bar bending fatigue testing was used for the specimen size, preparation, inspection, and testing. Rotating bar fatigue testing is a load based test that allows the specimen to be rotated a complete revolution loading the specimen fully reversing tension and compression. The size and shape of the specimen was selected based on the equipment available at the test facility. A cylindrical smooth specimen was selected. The drawing was developed directly from ISO 1143, see Appendix A.

Test Prep

Special care was required during the fabrication of the test specimens to make sure they did not get mixed up or mislabeled. A label plan was developed to track each specimen location, direction, and plate number. The base material specimens were extracted as shown in Figure 1.

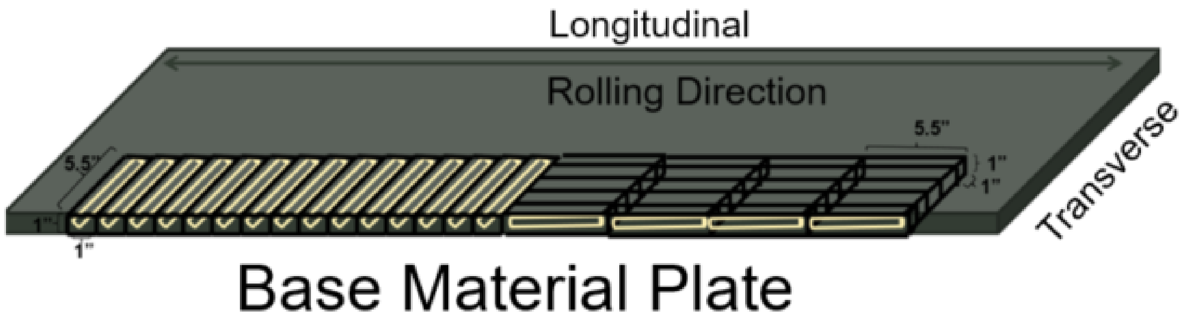


Figure 1: Base Material Specimen Extraction

The FSW specimens required additional planning. When integrated into a vehicle hull, the direction of the FSW will mostly commonly be oriented parallel to the primary rolling direction. Therefore the FSW was performed down the length of the plate and then the specimens were taken around the weld. The FSW weld performed on the plate was a single sided, fully penetrating, butt weld as this is the most common for application on a vehicle hulls due to size and access to the machine. Figure 2 shows the specimen extraction plan. The longitudinal specimens were extracted exclusively from the FSW nugget.

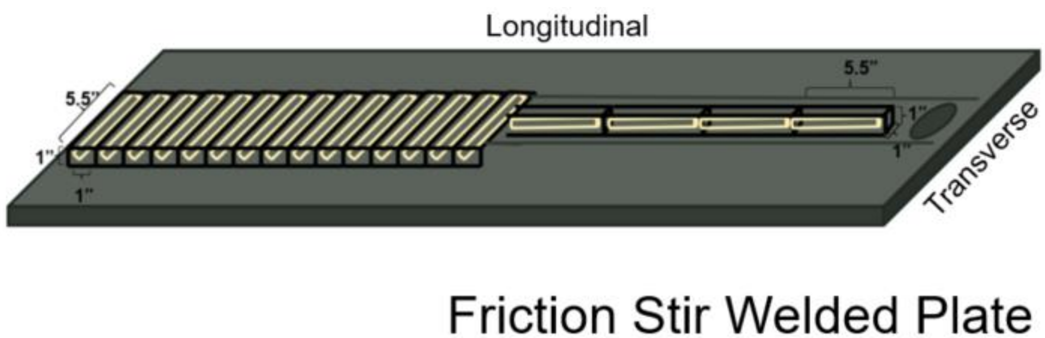


Figure 2: Friction Stir Welded Specimen Extraction

The labeling plan then outlined each specimen weld type, supplier weld ID, specimen direction, and location from FSW exit hole. An example of this is shown in Figure 3 and 4.

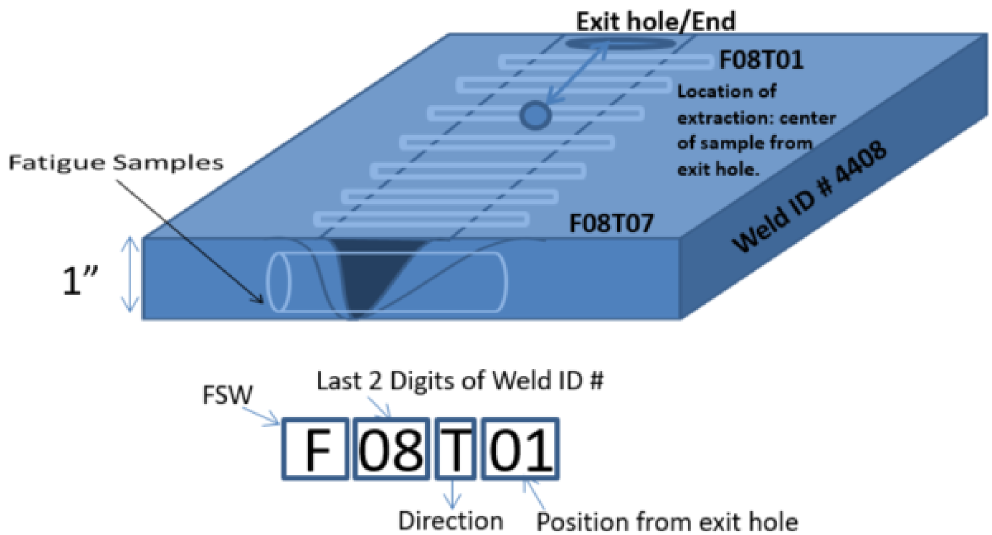


Figure 3: Specimen Identification Labeling

Test Sample	Weld Type	Last 2 # of Weld ID	Specimen Direction	Location from Exit Hole
F08T01	FSW	08	Transverse (T)	01
F08L01	FSW	08	Longitudinal(L)	01
F08T02	FSW	08	Transverse (T)	02
F08L02	FSW	08	Longitudinal(L)	02
:	FSW	:	:	:
F09T20	FSW	09	Transverse (T)	20
F09L20	FSW	09	Longitudinal (L)	20

Figure 4: Specimen Identification Example

Figure 5: Friction Stir Welded Plates prior to specimen extraction

After the labeling of the specimens was established, specimen fabrication began. Each specimen was cut out of the plate as a 5.5”x1”x1” rectangular bar out of the plates shown in Figure 5 and then transferred for machining. Figure 6 shows the specimens cut into rectangular bars.

Figure 6: Specimens after extraction prior to machining

Each specimen was rough machined, finish machined to tolerance, and the surface finish was prepared. Due to the very tight tolerances called out in ISO1143, machining was very difficult. Every time the specimens were removed and reinstalled, they would be out of tolerance. The base material specimens showed to be more consistent during machining, however the forces applied during the FSW process cause an increase in residual stress over that of a conventionally rolled plate. The FSW samples were not going to stay within specification after they had be removed from the mill. The decision was made to machine each specimen as close to the tolerance as possible recognizing that this variance would contribute to the variability during testing. During testing the specimen would be installed in the best position to keep it as close to tolerance as possible, and the runout would be recorded.

The surface finish is critical to reduce testing variability. Aluminum alloys tend to gum up during polishing. For this testing to be successful it was critical to have any striations on the surface be parallel to the specimen axis. Two test specimens were fabricated, the first was polished in the axial direction, the second was sanded. Under the microscope, the polished sample showed significant striations perpendicular to the specimen axis, this is shown in Figure 7.

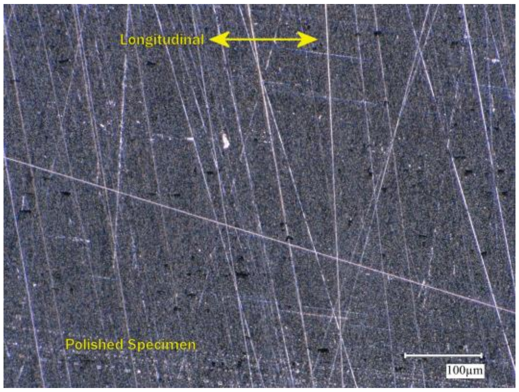


Figure 7: Microscope image of polished specimen

The sanded specimen showed a significant improvement with a uniform direction parallel to the specimen axis. This is shown in Figure 8. The sanded surface finish was selected and implemented for the specimen preparation.

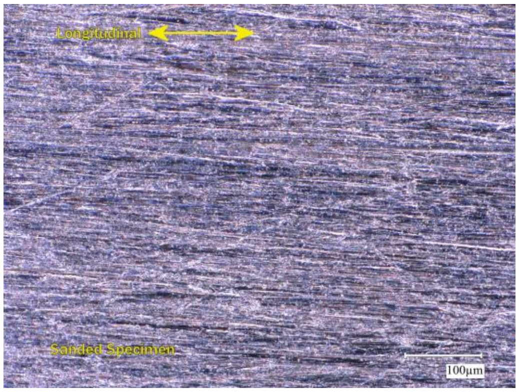


Figure 8: Microscope image of sanded specimen

Once the specimens were completed, they were sent to the testing facility wrapped in plastic tubes to prevent damage during shipping. Figure 9 shows the finished specimen ready for shipment.

Figure 9: Example of finished specimen

Testing

Once the specimens arrived at the test facility, they were cataloged and underwent an initial inspection. The inspection revealed a very large number of specimens that were out of an acceptable tolerance to test. Some of the specimens could be reworked, however some were too far out of specification. Rather than induce extra variation into the results, the decision was made to test only the specimens that were deemed within specification with the expectation that at least 12 specimens per group were tested. The inspection data for the test specimens is shown in Tables 1, 2, 3, and 4 for each material condition: transverse base material, longitudinal base material, transverse friction stir material, and longitudinal friction stir material.

Table 1: Transverse Base Material specimen inspection data

Plate configuration	Specimen Serial #	Ravg (mm)	dmin0 (mm)	dmin90 (mm)	dmin45 (mm)	dmin135 (mm)	dmin to end2 (Lo) (mm)	Specimen OAL (mm)
Drawing Specification		73.85	7.620	7.620	7.620	7.620	50.8	101.6
BMT	21	73.84	7.620	7.622	7.621	7.620	50.90	101.56
BMT	08	73.78	7.612	7.610	7.610	7.613	50.88	101.55
BMT	19	73.90	7.626	7.627	7.625	7.627	50.93	101.61
BMT	14	73.74	7.615	7.615	7.616	7.616	50.91	101.59
BMT	06	73.80	7.610	7.610	7.608	7.609	50.86	101.41
BMT	22	73.83	7.619	7.619	7.619	7.620	50.89	101.55
BMT	02	73.85	7.608	7.606	7.606	7.609	50.94	101.60
BMT	13	73.80	7.611	7.611	7.609	7.609	50.97	101.44
BMT	20	73.89	7.622	7.623	7.622	7.623	50.88	101.54
BMT	03	73.89	7.609	7.609	7.608	7.609	50.94	101.60

Table 2: Longitudinal Base Material specimen inspection data

Plate configuration	Specimen Serial #	Ravg (mm)	dmin0 (mm)	dmin90 (mm)	dmin45 (mm)	dmin135 (mm)	dmin to end2 (Lo) (mm)	Specimen OAL (mm)
Drawing Specification		73.85	7.620	7.620	7.620	7.620	50.8	101.6
BML	**10**	74.02	7.635	7.635	7.634	7.638	50.89	101.60
BML	**01**	74.20	7.646	7.649	7.647	7.650	50.87	101.67
BML	**Sndd**	73.68	7.635	7.636	7.634	7.635	50.80	101.60
BML	**04**	73.80	7.626	7.627	7.627	7.625	50.74	101.58
BML	**05**	73.85	7.636	7.636	7.635	7.637	50.86	101.58
BML	**03**	74.40	7.645	7.644	7.645	7.648	50.91	101.66
BML	**08**	73.90	7.633	7.633	7.635	7.634	50.59	101.59
BML	**07**	73.84	7.631	7.629	7.632	7.631	50.61	101.61
BML	**02**	74.10	7.618	7.623	7.616	7.615	50.92	101.65
BML	**06**	73.60	7.617	7.616	7.616	7.619	50.85	101.58
BML	**09**	73.60	7.603	7.604	7.603	7.606	51.01	101.59
BML	**12**	73.97	7.621	7.619	7.619	7.620	50.79	101.60
BML	**17**	73.96	7.633	7.635	7.631	7.632	50.83	101.53
BML	**21**	73.76	7.630	7.630	7.629	7.630	50.84	101.54
BML	**22**	74.02	7.634	7.631	7.631	7.632	50.76	101.59
BML	**23**	73.91	7.643	7.643	7.642	7.641	50.72	101.61
BML	**24**	73.91	7.638	7.639	7.637	7.637	50.87	101.63

Table 3: Transverse Friction Stir Material specimen inspection data

Plate configuration	Specimen Serial #	Ravg (mm)	dmin0 (mm)	dmin90 (mm)	dmin45 (mm)	dmin135 (mm)	dmin to end2 (Lo) (mm)	Specimen OAL (mm)
Drawing Specification		73.85	7.620	7.620	7.620	7.620	50.8	101.6
F08-T	06	74.45	7.635	7.634	7.635	7.638	50.96	101.60
F08-T	24	74.24	7.656	7.658	7.658	7.656	50.92	101.62
F08-T	13	74.39	7.682	7.681	7.682	7.680	50.93	101.58
F08-T	03	74.37	7.682	7.680	7.681	7.683	50.96	101.61
F08-T	54	74.11	7.638	7.637	7.637	7.638	50.94	101.64
F08-T	04	74.52	7.647	7.645	7.645	7.646	50.97	101.59
F08-T	02	74.55	7.680	7.678	7.679	7.677	50.94	101.60
F08-T	09	74.44	7.690	7.689	7.692	7.689	50.96	101.60
F08-T	12	74.44	7.674	7.672	7.673	7.671	50.97	101.61
F08-T	05	74.41	7.641	7.640	7.637	7.639	50.97	101.61
F08-T	41	74.57	7.657	7.656	7.657	7.656	50.97	101.64
F08-T	07	74.53	7.653	7.650	7.649	7.650	50.97	101.61

Table 4: Longitudinal Friction Stir Material specimen inspection data

Plate configuration	Specimen Serial #	Ravg (mm)	dmin0 (mm)	dmin90 (mm)	dmin45 (mm)	dmin135 (mm)	dmin to end2 (Lo) (mm)	Specimen OAL (mm)
Drawing Specification		73.85	7.620	7.620	7.620	7.620	50.8	101.6
F10-L	03	74.56	7.642	7.644	7.645	7.643	51.00	101.67
F10-L	04	74.35	7.628	7.627	7.627	7.624	50.98	101.67
F10-L	05	74.57	7.641	7.639	7.643	7.642	50.97	101.67
F10-L	08	74.43	7.625	7.626	7.627	7.626	50.99	101.69
F10-L	11	74.29	7.599	7.598	7.596	7.598	50.99	101.66
F10-L	12	74.52	7.622	7.619	7.621	7.621	51.01	101.67
F10-L	13	74.47	7.595	7.595	7.594	7.592	50.99	101.67
F10-L	14	74.65	7.632	7.631	7.631	7.630	51.00	101.63
F10-L	15	74.49	7.623	7.620	7.620	7.621	50.98	101.65
F10-L	10	74.39	7.626	7.626	7.628	7.626	51.00	101.69
F12-L	14	74.45	7.625	7.625	7.624	7.623	50.98	101.64
F12-L	08	74.40	7.607	7.606	7.603	7.604	50.97	101.66
F12-L	10	74.49	7.614	7.614	7.613	7.612	50.98	101.64
F12-L	07	74.39	7.634	7.636	7.637	7.635	50.99	101.66
F12-L	19	74.47	7.630	7.627	7.631	7.630	51.01	101.62
F12-L	11	74.54	7.622	7.623	7.621	7.622	51.00	101.66
F12-L	13	74.52	7.641	7.641	7.641	7.640	50.98	101.63
F12-L	20	74.39	7.638	7.637	7.636	7.636	50.98	101.63
F14-L	03	74.44	7.634	7.634	7.635	7.635	51.01	101.65
F14-L	02	74.54	7.652	7.651	7.651	7.649	50.99	101.64
F14-L	17	74.38	7.638	7.637	7.637	7.635	50.97	101.61

For both the base material and friction stir welded transverse direction there were only 10 and 11 respectively. For the base material and friction stir samples, it was very difficult to find specimens that were in specification. This is most likely due to the residual stress in the plate as this is perpendicular to the major rolling direction.

The testing was conducted following ISO 1143. The machined was setup to turn off at 25 Million cycles to ensure that test completed. Following the standard, the use of a R.R. Moore Rotating Beam test apparatus was used. This is shown in Figure 10 with the specimen installed.

Figure 10: R.R. Moore Rotating Beam Test Apparatus

For the specimens that did not pass inspection, they were sorted and some were re-machined into a standard ASTM E8 specimen and a quasi-static tensile test was performed. This data is used to establish the y-intercept of the S-N curves.

Results

The Fatigue testing was performed following section 10 of ISO 1143. For this testing, the maximum number of cycles was limited to 25 million cycles. If failure occurred prior to this, then the cycles at failure was recorded. If the number of cycles reached was 25 million , the machine was stopped and those samples were noted as exceeding the specified limit. All of the tests were performed at room temperature. The fatigue data is shown in Tables 5, 6, 7, and 8 for each material condition: transverse base material, longitudinal base material, transverse friction stir material, and longitudinal friction stir material.

Table 5: Transverse Base Material Fatigue Test Data

Plate configuration	Specimen Serial #	Failure Cycles (kcyc)	Actual Stress @ Failure Loc'n (MPa)	log10(kcyc)	log10(S)
BMT	21	73	293	1.86	2.47
BMT	08	198	263	2.30	2.42
BMT	19	1039	235	3.02	2.37
BMT	14	2067	208	3.32	2.32
BMT	06	4519	184	3.66	2.26
BMT	22	5910	173	3.77	2.24
BMT	02	7376	160	3.87	2.20
BMT	13	12196	159	4.09	2.20
BMT	20	15424	159	4.19	2.20
BMT	03	24422	148	4.39	2.17

Table 6: Longitudinal Base Material Fatigue Test Data

Plate configuration	Specimen Serial #	Failure Cycles (kcyc)	Actual Stress @ Failure Loc'n (MPa)	log10(kcyc)	log10(S)
BML	10	69	290	1.84	2.46
BML	01	105	276	2.02	2.44
BML	Sndd	129	275	2.11	2.44
BML	04	309	255	2.49	2.41
BML	05	935	210	2.97	2.32
BML	03	1900	171	3.28	2.23
BML	08	1945	195	3.29	2.29
BML	07	2681	164	3.43	2.21
BML	02	3045	177	3.48	2.25
BML	06	3247	172	3.51	2.24
BML	09	3728	161	3.57	2.21
BML	12	4475	148	3.65	2.17
BML	17	10304	131	4.01	2.12
BML	23	14070	140	4.15	2.15
BML	24	22042	123	4.34	2.09

Table 7: Transverse Friction Stir Material Fatigue Test Data

Plate configuration	Specimen Serial #	Failure Cycles (kcyc)	Actual Stress @ Failure Loc'n (MPa)	log10(kcyc)	log10(S)
F08-T	06	140	282	2.15	2.45
F08-T	24	264	240	2.42	2.38
F08-T	13	1229	192	3.09	2.28
F08-T	03	2014	223	3.30	2.35
F08-T	54	2507	200	3.40	2.30
F08-T	04	3500	208	3.54	2.32
F08-T	02	6183	196	3.79	2.29
F08-T	09	16906	184	4.23	2.26
F08-T	12	23430	156	4.37	2.19
F08-T	05	25000	193	4.40	2.29
F08-T	41	25000	173	4.40	2.24
F08-T	07	25774	164	4.41	2.22

Table 8: Longitudinal Friction Stir Material Fatigue Test Data

Plate configuration	Specimen Serial #	Failure Cycles (kcyc)	Actual Stress @ Failure Loc'n (MPa)	log10(kcyc)	log10(S)
F10-L	03	867	218	2.94	2.34
F10-L	04	117	274	2.07	2.44
F10-L	05	2323	198	3.37	2.30
F10-L	08	25000	180	4.40	2.26
F12-L	14	61	286	1.79	2.46
F12-L	08	357	221	2.55	2.34
F12-L	10	543	237	2.73	2.38
F12-L	07	3473	201	3.54	2.30
F12-L	19	25000	193	4.40	2.29
F14-L	03	1793	202	3.25	2.30
F14-L	02	25000	185	4.40	2.27
F14-L	17	22143	195	4.35	2.29

The data was then plotted for each case individually showing the stress-life curves for each condition, this was then repeated using a log-log plot. A logarithmic best-fit curve was used on the stress-life curves and a linear best fit curve was used on the log-log curve. The specimens that exceeded the 25M cycles are marked independently on the plots as they did not exhibit any failure during the test.

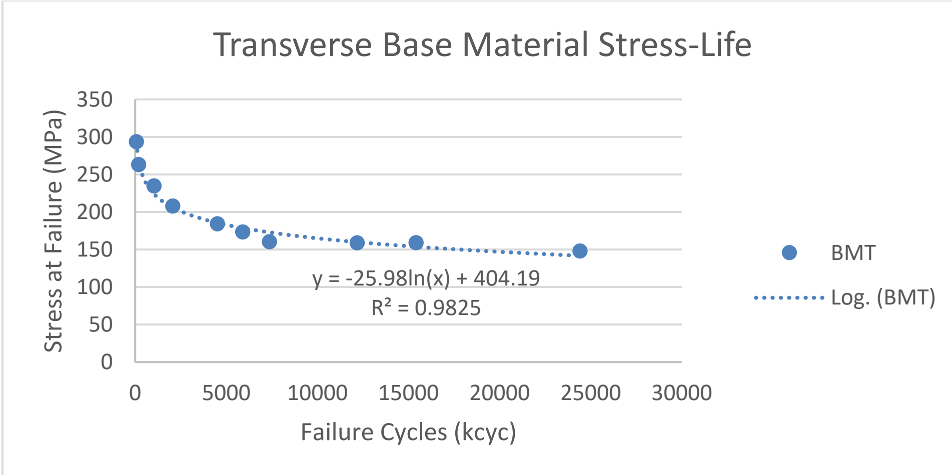


Figure 11: Transverse Base Material Stress-Life

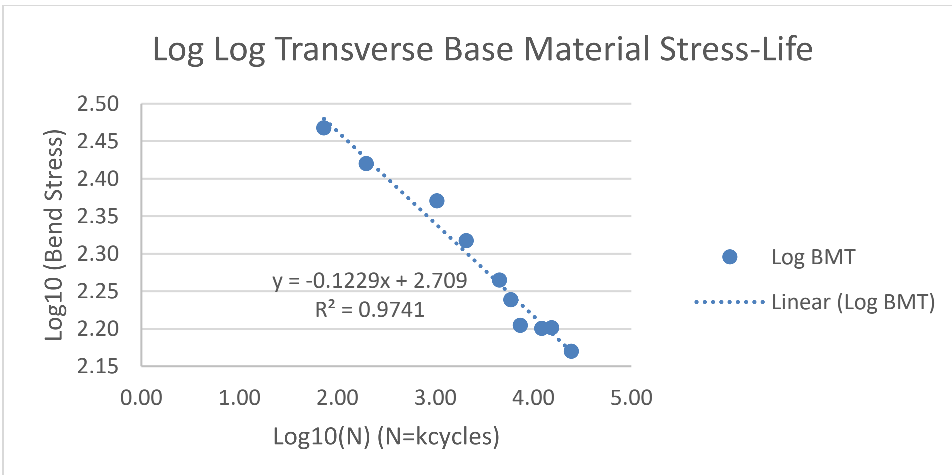


Figure 12: Transverse Base Material Stress Life, Log-Log

Figures 11 and 12 shows the transverse base material rotating beam data shown as a traditional Stress-Life and in log based format. Based on the R^2 value of the curve fit line, the data shows to be relatively consistent.

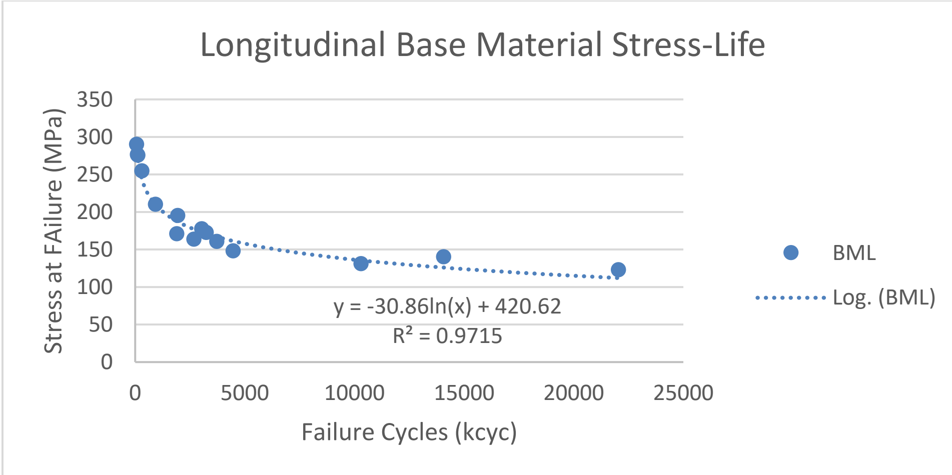


Figure 13: Longitudinal Base Material Stress-Life

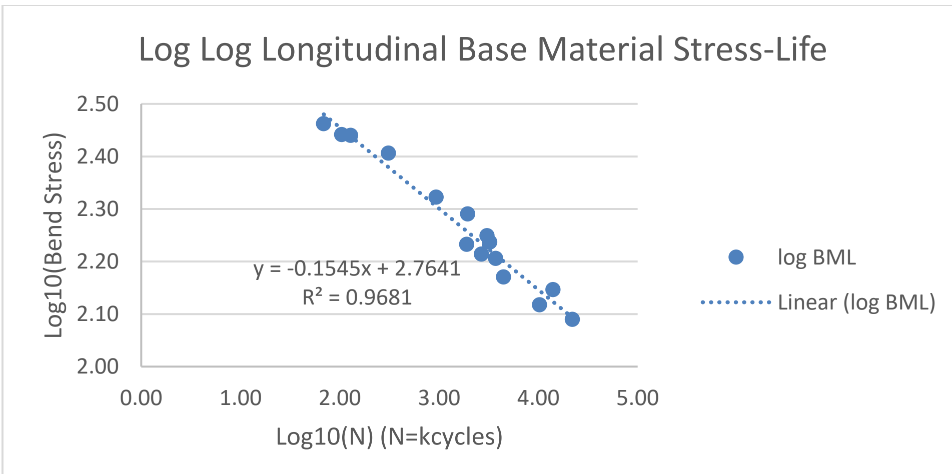


Figure 14: Longitudinal Base Material Stress Life, Log-Log

Figures 13 and 14 show the longitudinal base material rotating beam data in the Stress-Life and log based formats. Similar to the transverse base material this data shows relative consistency with respect to the curve fit R^2 values.

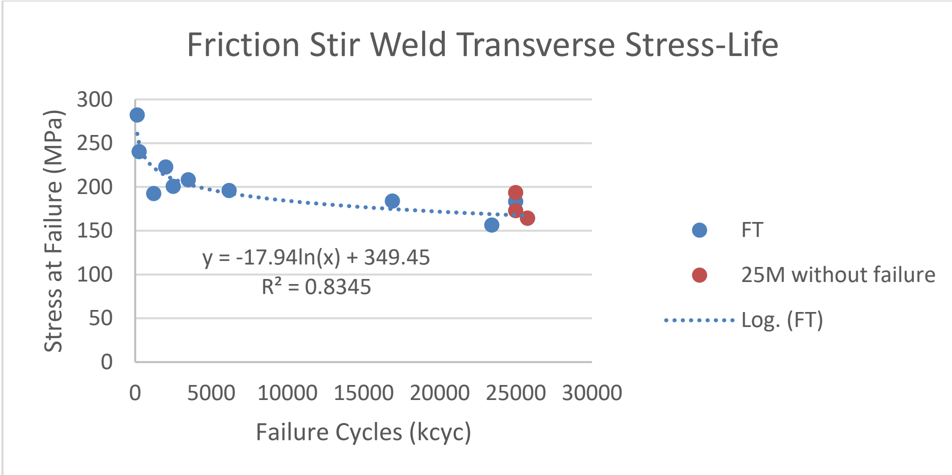


Figure 15: Transverse Friction Stir Material Stress-Life

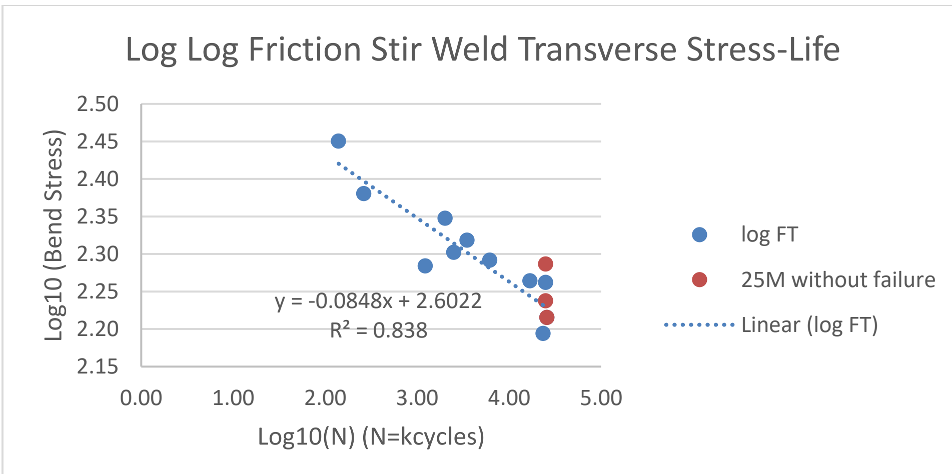


Figure 16: Transverse Friction Stir Material Stress Life, Log-Log

Figures 15 and 16 show the friction stir welded transverse data in traditional Stress-Life and log based format. There were three specimens that exceeded the 25 million cycles without failure. However as expected the data for the welds showed a larger spread compared to the base material. The curve fit data collected did not include the three specimens that exceeded the 25 million cycles as they did not exhibit failure.

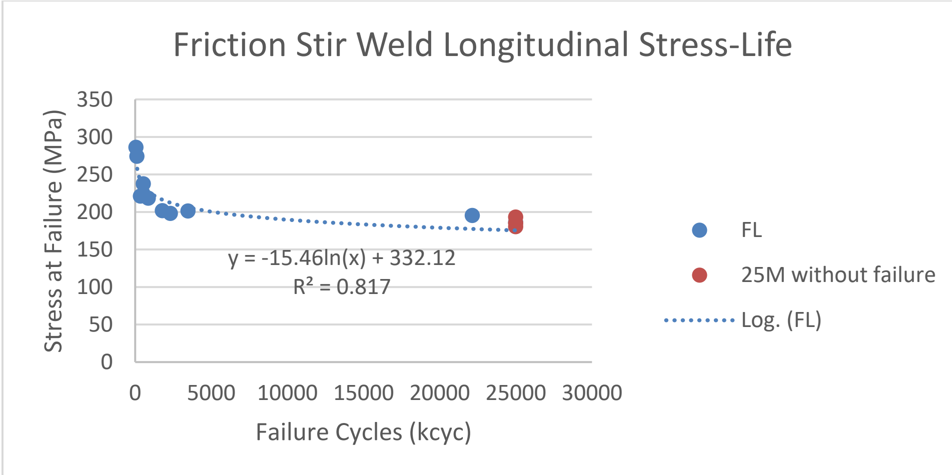


Figure 17: Longitudinal Friction Stir Material Stress-Life

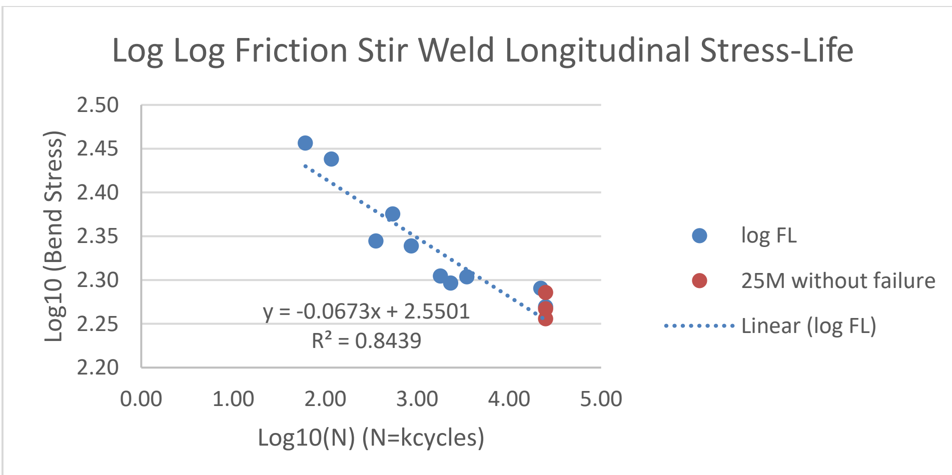


Figure 18: Longitudinal Friction Stir Material Stress Life, Log-Log

Figures 17 and 18 shows the friction stir welded longitudinal rotating beam data in both the Stress-Life and log based formats. The curve fit R^2 values show a larger spread in the data, however similar to the transverse friction stir specimens, three specimens exceeded the 25 million cycles. Similar to the transverse friction stir welded data, the three specimens that exceeded the 25 million cycles were not used in the curve fit data.

Next the E8 tensile data was analyzed. Tables 9, 10, 11, and 12 show the data recorded from the tensile tests for each specimen.

Table 9: Transverse Base Material Tensile Test Data

Plate configuration	Specimen Serial #	Yield Strength (MPa)	UTS (MPa)	Strain@Break (%)
BMT	16	452.5	496.3	12.4
BMT	1	454.4	501.9	12.0
BMT	12	452.7	502.8	12.8
BMT	5	454.6	504.8	13.6
Average		453.55	501.4225	12.695

Table 10: Longitudinal Base Material Tensile Test Data

Plate configuration	Specimen Serial #	Yield Strength (MPa)	UTS (MPa)	Strain@Break (%)
BML	13	471.0	490.35	14.134
BML	14	458.8	478.64	16.378
BML	16	459.5	479.45	15.805
Average		463.1	482.8	15.4

Table 11: Transverse Friction Stir Material Tensile Test Data

Plate configuration	Specimen Serial #	Yield Strength (MPa)	UTS (MPa)	Strain@Break (%)
F08-T	11	237.4	392.6	11.5
F08-T	14	236.7	394.1	10.7
F08-T	18	247.5	394.9	8.7
F08-T	20	245.0	392.4	12.1
F08-T	26	235.8	388.9	13.8
Average		240.5	392.6	11.4

Table 12: Longitudinal Friction Stir Material Tensile Test Data

Plate configuration	Specimen Serial #	Yield Strength (MPa)	UTS (MPa)	Strain@Break (%)
F10-L	6	274.8	430.4	21.1
F10-L	7	275.0	429.4	20.2
F12-L	17	275.8	434.3	21.0
F14-L	4	272.4	423.5	21.2
F14-L	12	270.6	431.4	21.2
Average		273.7	429.8	21.0

The average of the tensile data is then used in the fatigue data as a single cycle by recording the ultimate tensile strength as the y-intercept to the data. The data is then plotted below for the base material, shown in Figure 19.

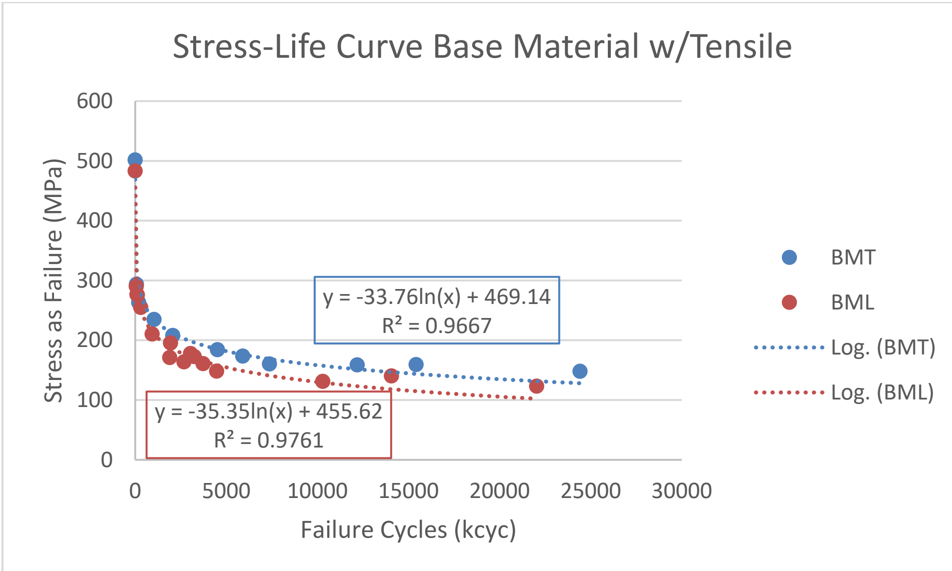


Figure 19: Stress-Life Base Material with Tensile Data

The R^2 values of the curve fit lines for both the transverse and longitudinal show relatively no change. This is a good indicator of the stability of the fatigue data.

Figure 20 shows the updated plots of the friction stir welded material to include the tensile data.

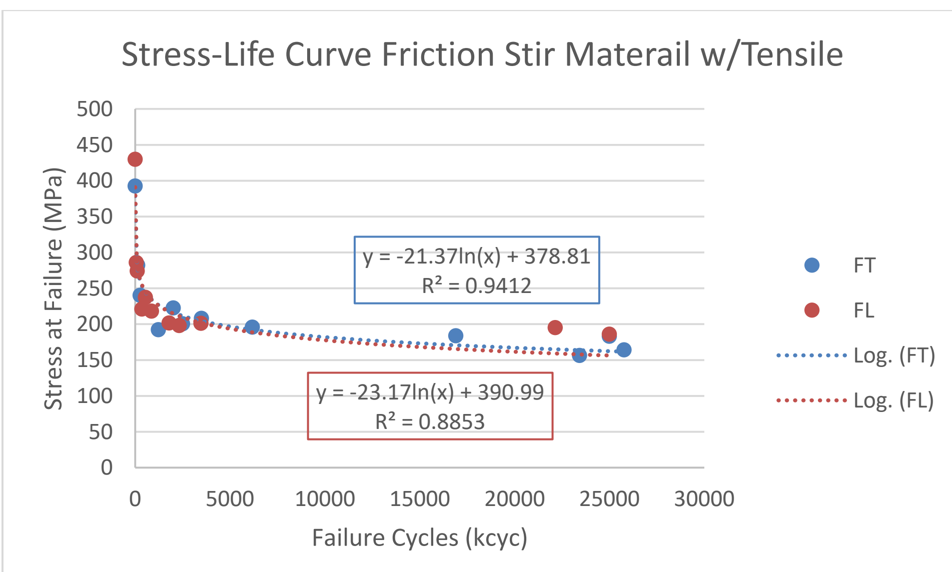


Figure 20: Stress-Life Friction Stir Material with Tensile Data

With the inclusion of the tensile data, the R^2 value of the curve fit lines showed an increase however this is still considered to be outside of an acceptable R^2 value of 0.96 for statistical significance.

Next, the Stress-Life plots were combined for the base material and friction stir materials for each plate direction, transverse and longitudinal. Figure 21 shows the transverse direction and Figure 22 shows the longitudinal direction.

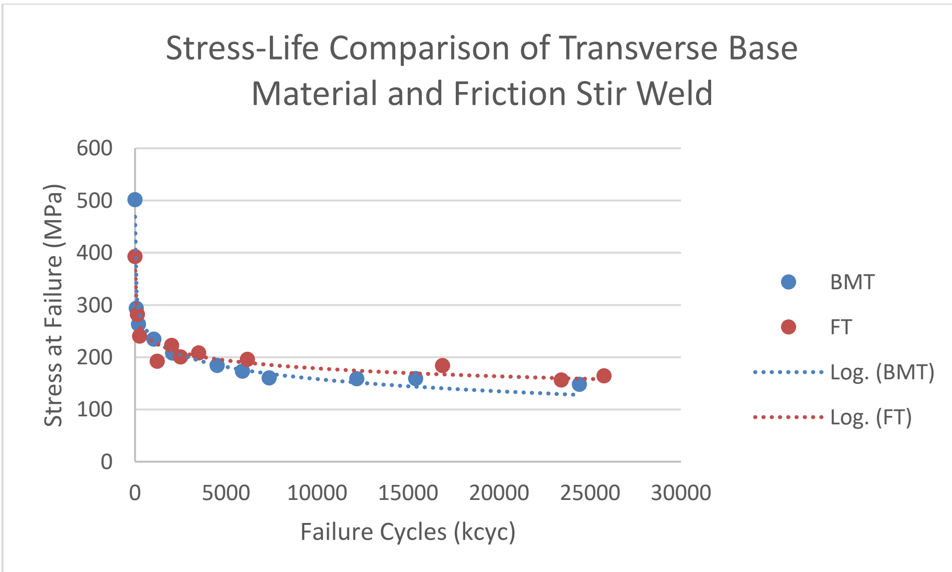


Figure 21: Stress-Life Transverse Base and Friction Stir Comparison

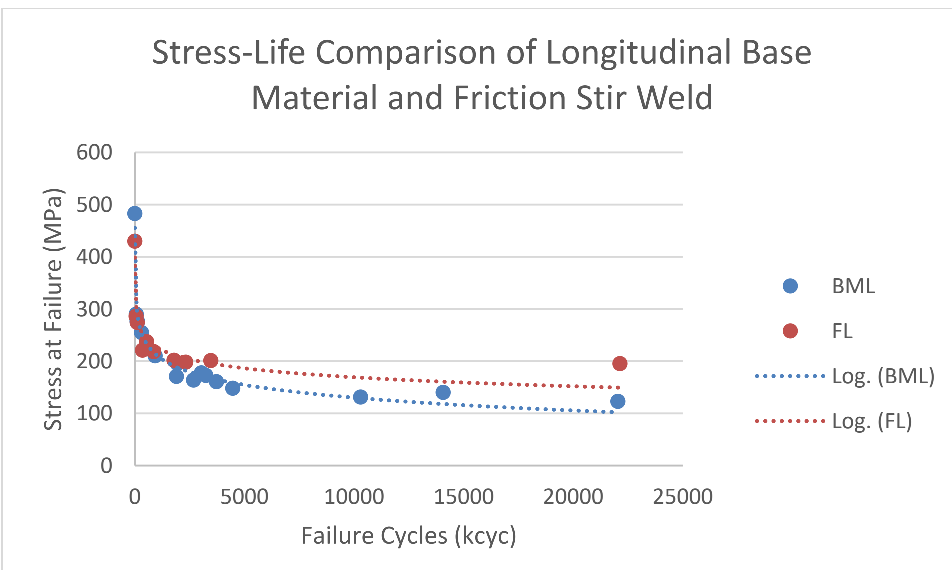


Figure 22: Stress-Life Longitudinal Base and Friction Stir Comparison

Conclusions

Fatigue data was collected for four use case conditions: base material transverse, base material longitudinal, friction stir welded transverse, friction stir welded longitudinal. The data was collected following ISO 1143 as closely as possible however it is very evident that this standard is written for ferrous materials. Non-ferrous materials like this aluminum tend to be more difficult to prepare and test. This is evident in this test series and further variances are shown in the welds. However, this data does provides an initial look at the fatigue life of 2139-T8 and FSW 2139-T8 materials. When preparing samples in the future extra special care is required for preparing the specimens. It is recommended that the fabrication and testing occur at the same location to ensure inspection process for fabrication matches the inspection process for testing and utilizes the same measurement devices. This would minimize the amount of rework and maximize the amount of useable samples.

The base material proved to be relatively consistent and predictable throughout the testing. The friction stir welded material showed a larger variance during testing. Generating data in the rage of 10-20M cycles was difficult due to the loads selected, some specimens would failure early and some would continue out past 25M cycles.

The data shows that there is a reduction in strength between the base material and friction stir welded material at low cycle fatigue, however this trend reverses at the higher cycles. The friction stir welded material shows a higher failure stress at higher cycles with an increase of 28% for transverse and 60% for longitudinal. This increase in fatigue is most like due to the increase in ductility created by the friction stir process.

Looking at the SN curves for the friction stir welded areas in both transverse and longitudinal directions, they appear to be very similar, this is an artifact of the stirring process where the grain boundaries of the material are altered by the friction stir welding process.

Future Work

Further population of the SN curve is required for use beyond research and developmental purposes. This data will provide a great baseline for replicate studies once a specific cyclic regime has been identified by the specific application.

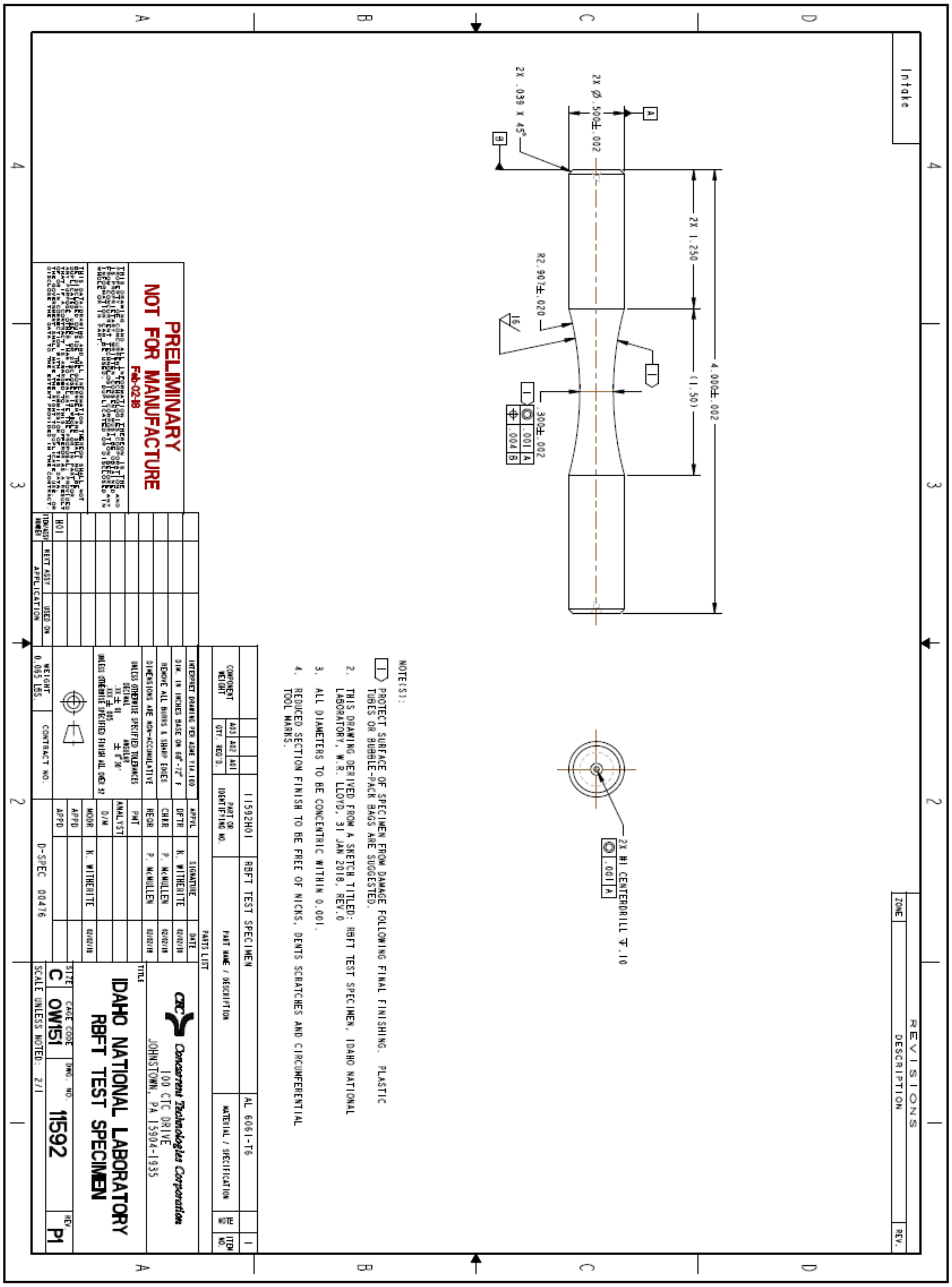
Acknowledgements

Concurrent Technologies Corporation (CTC) for the Friction Stir processing of the material and the fabrication of the specimens.

Idaho National Laboratory (INL) for conducting the fatigue testing in compliance with ISO 1143.

Appendices

Appendix A: Specimen Drawing



Works Cited

1. MIL-DTL-32341A (15 April 2015), Armor Plate, Aluminum, Alloy 2139 Weldable & Alloy 2195 and 2060 Unwelded Applique.
2. ISO-1143:2010(E), Metallic materials – Rotating bar bending fatigue testing.
3. ASTM E739-10, Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life and Strain-Life Fatigue Data.