SOUTH DAKOTA
SCHOOL OF MINES & TECHNOLOGY

FLEXURAL BEHAVIOR AND ASSESSMENT OF ALUMINUM STIFFENERS USED ON UNITED STATES NAVY LITTORAL COMBAT SHIP (LCS).

Prepared by:
Paul Betone

Faculty Advisors:
Dr. Damon Fick
Professor, Department of Civil Engineering

Dr. Michael West
REU Program Director

Dr. Alfred Boysen
Professor, Department of Humanities

Program Information:
National Science Foundation
DMR-1157074

Research Experience for Undergraduates
Summer 2013

South Dakota School of Mines and Technology
501 E Saint Joseph Street
Rapid City, South Dakota

Table of Contents

Abstract

The United States Navy's ship structures use single angle stiffeners in the hulls of their ships to provide stiffness and strength to resist buckling from buoyancy forces from the water. The material used in the Littoral Combat Ship (LCS) is aluminum 5083; although aluminum 5083 does not have the highest ultimate strength among metallic elements, it is very light and corrosion resistant. Advantages of having an aluminum 5083 structure include a low draft, efficient speed in the water, and the ability to stay close to shore ways. Currently these stiffeners are cold-formed to a right angle perpendicular to the rolling direction of the material. As a result of this process, the minimum radius that can be obtained is about four times the thickness of the material. The typical length of the material perpendicular to the rolling direction is six feet which leads to multiple splices in the final fabricated ship hull.

A new fabrication method that includes Friction Stir Processing (FSP) has been proposed, taking advantage of the full length of the rolled sheet of aluminum by bending parallel with the grain of the metal in the FSP area. By using this process, it requires less splices, and it also results in a radius of one times the thickness of the material. The stiffeners can be created up to forty feet in length, thus reducing splices and cost of fabrication. This research focuses on the flexural behavior of the stiffeners produced with the two fabrication methods. The four objectives are to: 1) develop a four-point test for flexure and instrumentation strategy, 2) compare the response of the FSP angle to the traditional method of production, 3) evaluate the performance of a gas metal arc weld splice and a friction stir weld splice, and 4) identify any correlations with tests done previously involving tensile coupon test and compression buckling test.

Introduction

Background

The United States Navy commissioned the building of a new type of ship in May of 2004. The class of ship designated will be called the Littoral Combat Ship (LCS). Littoral meaning the zone close to shore and is shown in Figure 1. “The LCS class consists of two variants, the Freedom variant and Independence variant - designed and built by two industry teams, respectively led by Lockheed Martin and General Dynamics, Bath Iron Works” ("Littoral combat ship," 2012). Bath Iron Works will manage the contracts for General Dynamics due to over spending cost on the first build of the LCS. Each team is building ten ships and their construction of the ship will utilize the lighter aluminum alloy 5083 as stiffeners in the bulkheads and decks of the superstructures and hulls of these ships. There are many advantages to using aluminum 5083 in ships that are going to operate along the shore ways but the two most important are it’s having a low draft and it being capable of 40 knots plus.

Figure 1 LCS Freedom Class on the left and LCS Independence Class on the right.

The aluminum alloy 5083 stiffener is part of a panel in the ships structure to provide stiffness for the ridged hull and superstructures of the ship and is shown in Figure 2. It also alleviates tons of weight that a steel alloy would not be able too.

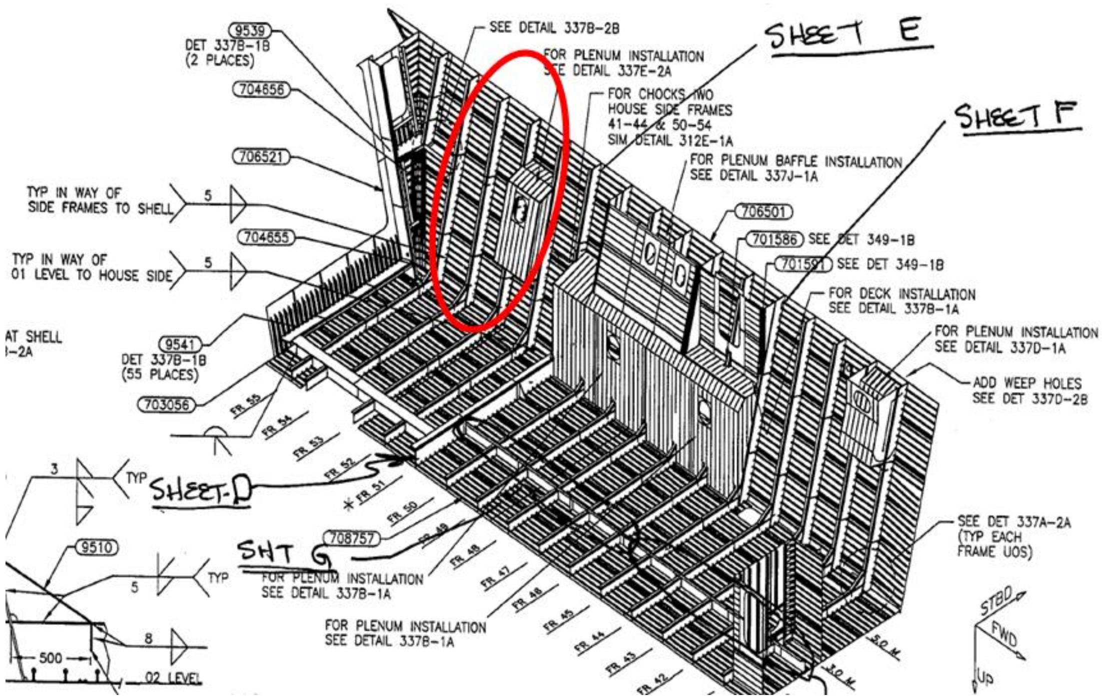

Figure 2 Typical ship superstructure modules (Smith, et al. 2009).

Currently the production of these aluminum 5083 stiffeners are cold formed with a ninety degree angle that is bent perpendicular to the rolled aluminum sheet. The stiffeners are produced from sheets of aluminum six feet wide with a length of forty to sixty feet (Figure 3).

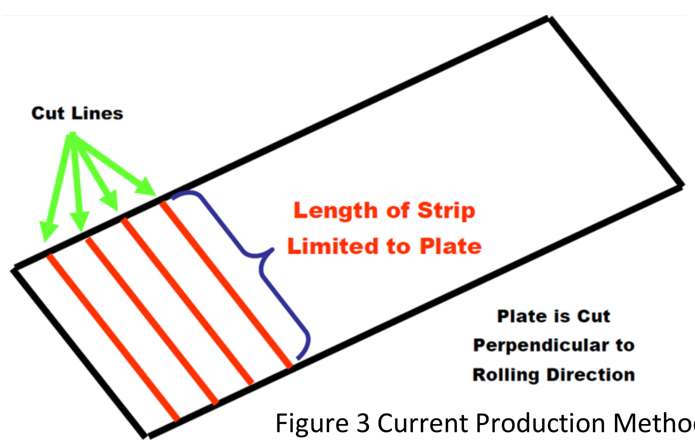

Figure 3 Current Production Method (Smith, et al. 2009)

The traditional production standard limits the lengths of these stiffeners to six feet. The reason is when the aluminum alloy 5083 is rolled out the metallic structure of the grains naturally are elongated with the rolling action of the hot rolled aluminum sheet. If the aluminum alloy were bent parallel to the 40- 60 foot sections that were created. The results would be a weakened and cracked stiffener along the bend. Another obstacle for the traditional method of production is the way a useful stiffener member is created, because the typical lengths are limited to six feet in length. If a 20 foot member was needed that would require at least three gas metal arc weld (GMAW) splices and cause frequent distortion, as Figure 4 shows. Thus a new production method is needed to help speed the production of these navy vessels.

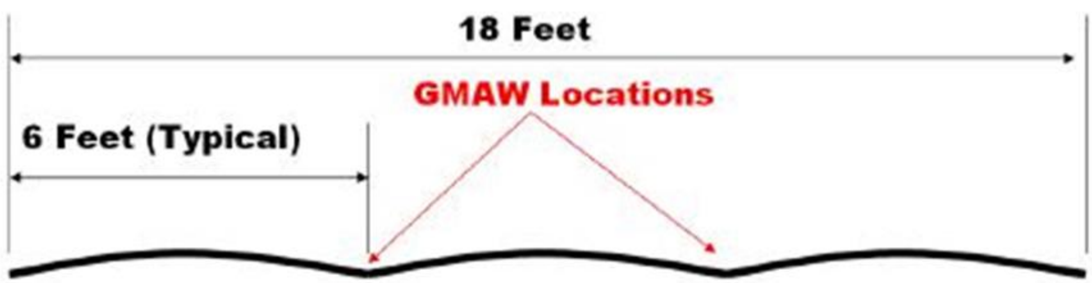

Figure 4 GMAW stiffener distortion profile (Smith, et al. 2009).

Friction Stir Process

This research focuses on the use of friction stir process (FSP) in the angles of cold formed aluminum alloy 5083 stiffeners. It's a method derived from friction stir welding (FSW) process. FSW is a technique developed in the early nineties by Wayne Thomas at The Welding Institute (TWI) to join metal alloys together with low heat and employing the use of friction to melt the metal with a pin that is pushed into the aluminum alloy and stirs the metals together to create a solid connection. It is a technique that enjoys many advantages over the traditional GMAW, by not using high heat, creating noxious fumes, using filler material to join the metals, and small voids created by the hot welds

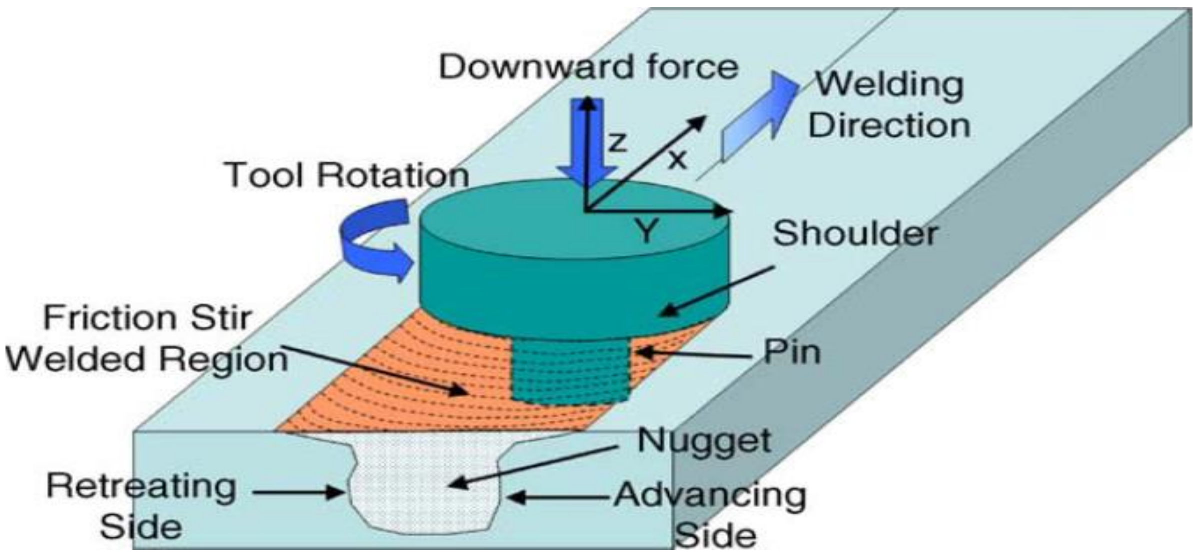

Figure 5 Schematic of friction stir welding.(Mishra and Ma 2005)

Friction Stir Processing is essentially the same as the FSW but with one difference. It is using the friction to create a zone that changes the micro structure of the alloy and creating a tighter bond of the metallic grains. Having the area changed from its previous state to its new state, the aluminum alloy 5083 is now able to be bent parallel to the rolling direction (Figure 6) creating longer members of the aluminum 5083 with less distortion in the member (shown in Figure 7).

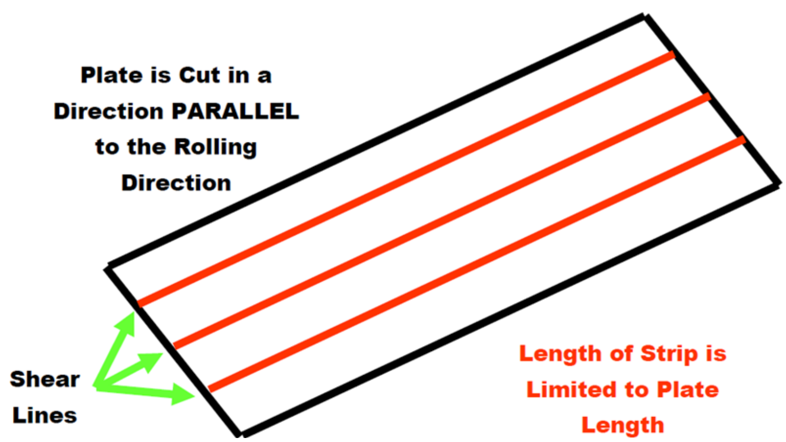

Figure 6 Cut and Bent Parallel to rolling direction.

This would allow aluminum alloy 5083 stiffener members to be created up to 40-60 feet in length with less distortion and be cut down to size for applications. This new zone is also capable of being bent into a tighter radius of one times the thickness of the aluminum alloy 5083.

Figure 7 18 feet of un-spliced material aluminum alloy 5083.

Objectives

The objectives of this research are to develop a four-point test for flexure to compare the three different types of specimen (shown in Figure 8) available for testing. The first specimen has a friction stir processed angle and has no splice in center of its span. The second specimen has a friction stirred processed angle and the center of the specimen is a friction stirred weld splice. The third is a specimen is a traditional cold formed angle and has a gas metal arc weld splice at its center span. Each specimen is 25 inches in length. After completing test and documentation of the instrumentation strategy, the response of the FSP angle will be compared with the traditional production method. The performance of a gas metal arc weld splice and a friction stir weld splice will be evaluated, and any correlations with tests done previously involving tensile coupon testing and compression buckling testing will be evaluated.

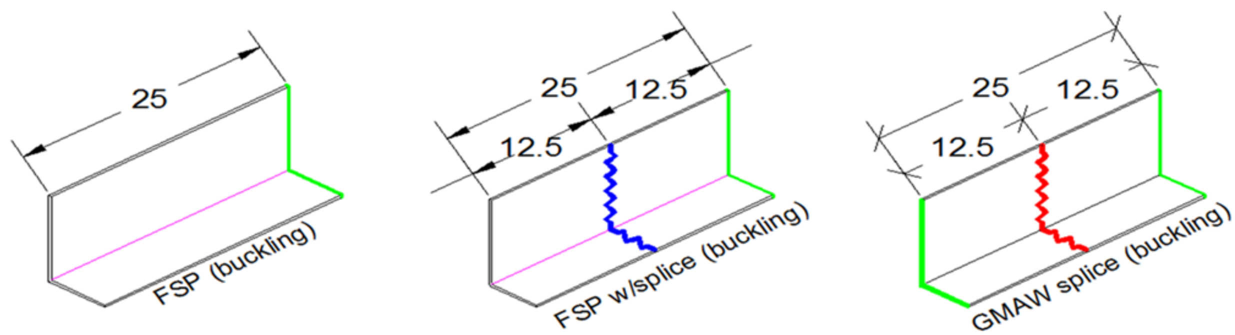

Figure 8 Three different types of specimen represented.

Broader Impact

In the future the United States Navy expects to produce a total of 60 to 70 of the LCS platform ships. With the new method in using the FSP to create the longer members of the aluminum alloy 5083 stiffener, the pace of production could speed up and the cost of building the ships could be reduced which would have a significant impact on future engineering of ship building.

Materials

Aluminum alloy 5083 a non-heat treatable alloy for strengthening panels of the hull and superstructures of the LCS. It has very good corrosion resistance, is easily welded and has good strength. Aluminum alloy 5083 is readily cold worked by conventional production methods.

Compression Specimens

The geometry of specimens that were tested in compression is shown in Fig 9 and Figure 10. below. The specimens were tested in compression using the 300 kip Tinius Olsen Load Frame. Results of the Compression tests are shown in Table 1.

Figure 9 Top Figure represents a FSP angle and bottom is a Traditional formed angle.

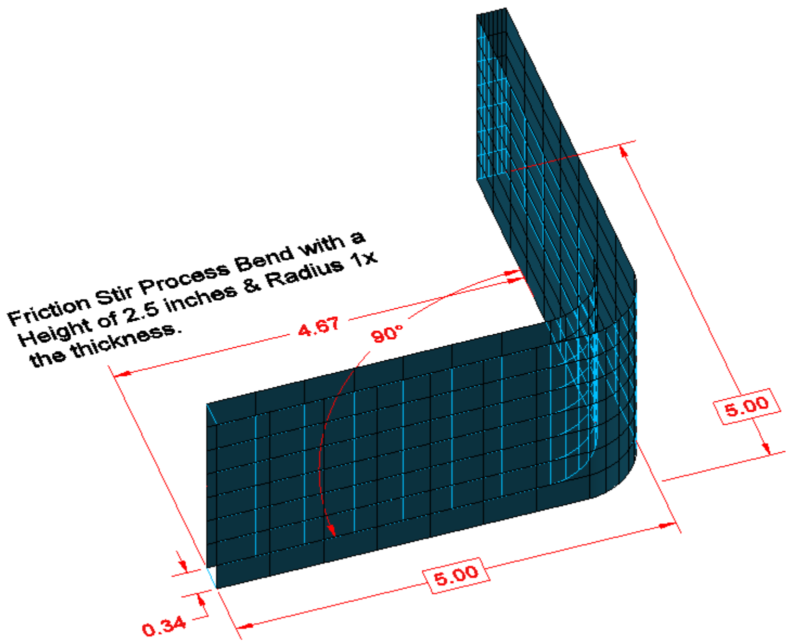

Figure 10 Aluminum 5083 Friction Stir Process corner with Radius of one times the thickness

Table 1

Corner Flexure Test Results					
Specimen Vertical	Max load	Max load Displacement	Failure Load	Failure Displacement	Angle Failure Degrees
CA1	908	1.62	729		31.6
CA2	896	.934	736	4.35	31.6
CA3	928	.915	797	4.11	34.4
FSP2	797	1.19	764	3.57	41.0
FSP3	799	1.93	795	1.98	61.6
Specimen Horizontal					
CB1	3370	.544	3360	.581	-
CB2	3680	.304	3570	.372	-
CB3	5090	.547	4800	.558	-
FSP-B1	3700	.554	853	2.58	149.6
FSP-B2	3310	.42	1020	2.76	158.8
FSP-B3	4190	.454	989	2.73	157.0

.

Tension Specimen

Coupon specimen will be tested using the MTS 810 Material Test System. Specimens to include six different samples of the aluminum alloy 5083 as shown in figure 11. The samples will include transverse and longitudinal sections of the FSW, FSP, GMAW and Parent material. To compare ultimate and yield strength, peak load, elongation, and the tensile modulus of elasticity. The center portion of the tension coupon (Figures 12, 13) consisted of parent material, friction stir processed, gas metal arc weld, and friction stir weld. Load and strain data was recorded, in addition to peak stress, stress at offset yield, and elongation for each specimen. Results are shown in Table 2. The three configurations included were parent specimens (L1-L3), Gas Metal Arc Weld (GMAW) T1-T3, FSP (center only) T1-T3, and two FSP (whole specimen) L1-L2.

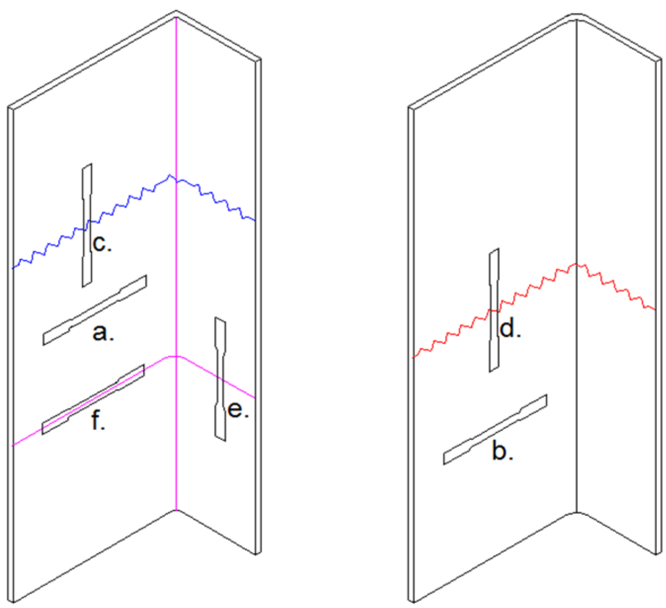

Figure 11 Coupon samples taken from stiffener (Fried, L., 2013)

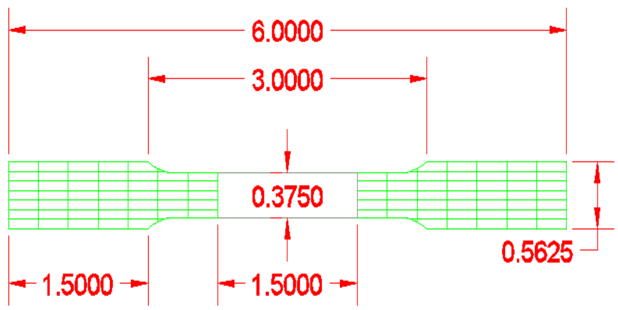

Fig. 12 Dimensions of Coupon Specimen for tensile test.

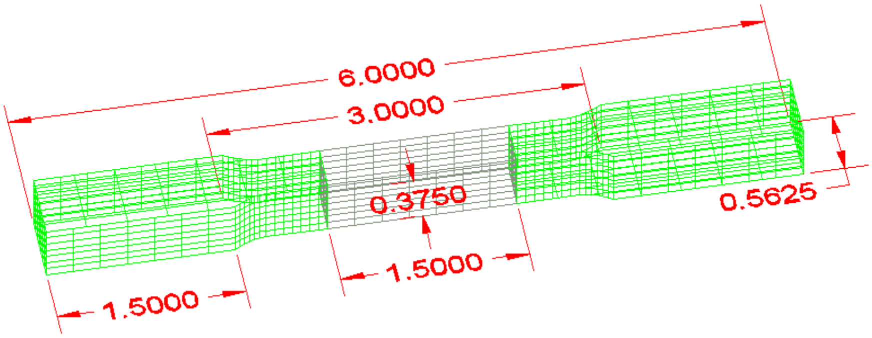

Fig. 13 Coupon specimen rotated.

Table 2, Tension Coupon Results.

Type	Area	Modulus	Stress At Offset Yield	Peak Stress	Calculated Percent Elongation
	in^2	ksi	psi	psi	in/in
Parent Longitudinal 1	0.114	10290	40481	52808	0.081
Parent Longitudinal 2	0.113	10620	42694	53091	0.081
Parent Longitudinal 3	0.110	10700	43584	54683	0.063
Parent Transverse 1	0.115	11060	38358	51691	0.093
Parent Transverse 2	0.115	10880	38046	52155	0.113
Parent Transverse 3	0.113	10920	38658	52756	0.110
GMAW Transverse 1	0.110	9560	22448	38802	0.198
GMAW Transverse 2	0.109	11720	23088	39105	0.026
GMAW Transverse 3	0.115	3930	20539	39287	0.042
FSW Transverse 1	0.111	8810	24258	45932	0.059
FSW Transverse 2	0.108	8390	24671	47328	0.233
FSW Transverse 3	0.110	9120	23715	45618	0.207
FSP Transverse 1	0.103	4510	25020	48235	0.192
FSP Transverse 2	0.110	5110	25822	49368	0.215
FSP Transverse 3	0.109	5580	25438	48507	0.252
FSP Longitudinal 1	0.112	10830	25183	46268	0.254
FSP Longitudinal 2	0.112	10400	25656	48421	0.124

Flexural Specimens

Test Set-up & Procedure

The four point test defines a material's ability to resist flexural deformation under load. The flexural strength will be reported as the loads, strains, and displacements measured at the point in which the loading fixture contacts the vertical leg of the specimen.

The American Society for Testing and Materials (ASTM) specifications, for a four point flexure test set up were used. The specimen is divided into three segments of 8 inches resulting in a span of 24 inches, as our test specimens are twenty five inches in length. The testing configuration is shown in Figure 14.

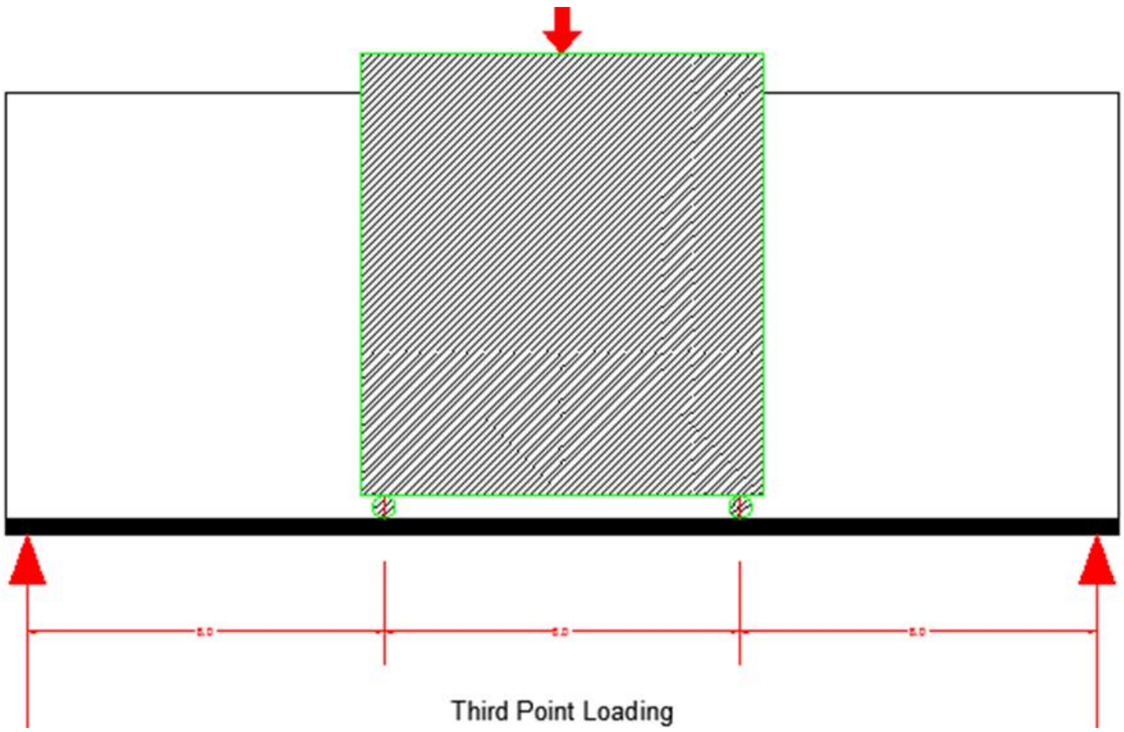

Figure 14 Diagram of Third Point loading of specimen.

Equipment

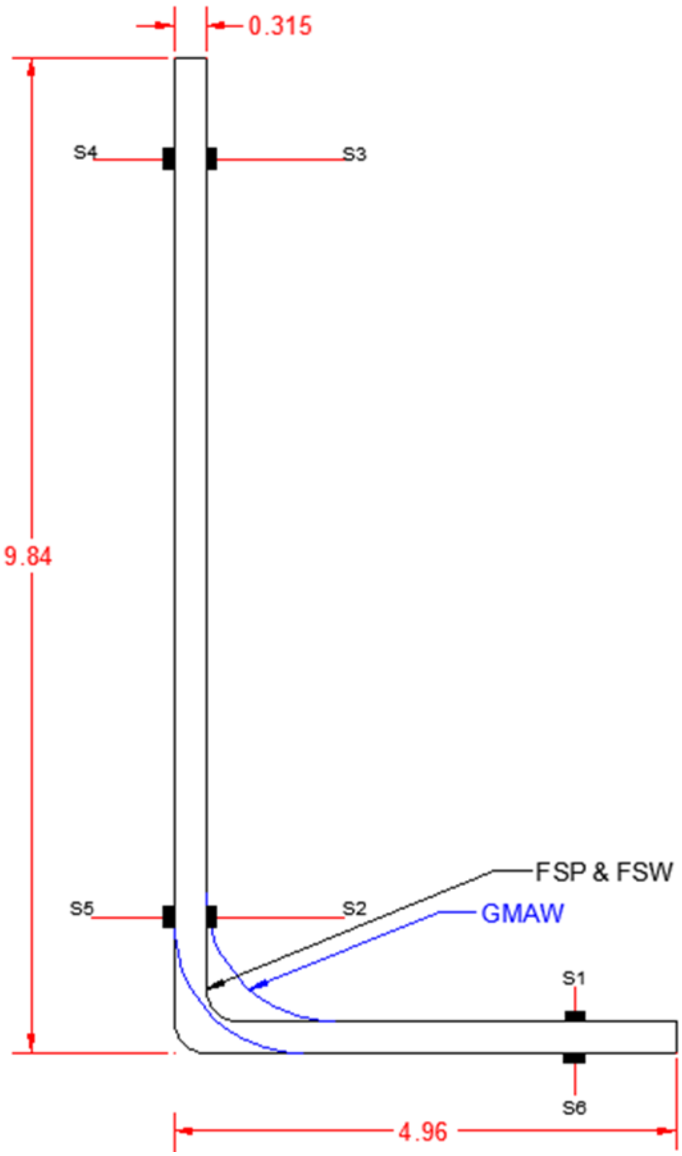

Figure 15 Strain gage placement on the specimen.

Strain Gages

A strain gage is a device used to measure the stretching or compression of an object. As the object is tested and deformed from the forces applied, the foil in the gage is being stretched or compressed, causing its electrical resistance to change. This resistance change is related to the strain by the quantity known as the gage factor.

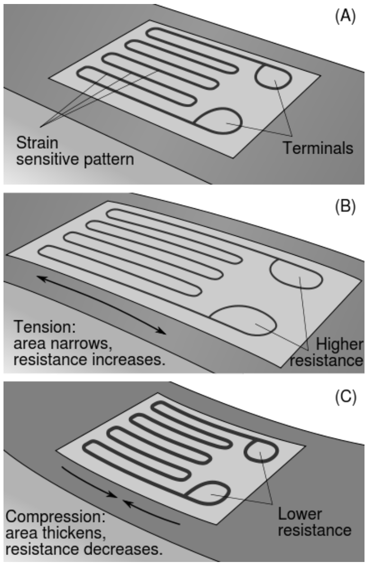

Figure 16 strain gage.

A strain gage uses the physical property of electrical conductance and its dependence on the foil's geometry. As the foil inside the gage is stretched within its limits of its elasticity such that it does not permanently deform, it will become narrower and longer, changes that increase its electrical resistance. Equally, when the foil is compressed such that it does not buckle, it will broaden and shorten, changes that decrease its electrical resistance. From the measured electrical resistance of the strain gage, the amount of applied stress may be concluded (4).

Six Electrical resistance strain gages were used to measure strains at three different paired locations along the inside and outside angle of the stiffeners as shown in Figure 15. There was an inside-outside pair located one inch in on each leg and 8.5 inches in on the long leg. One displacement transducers were located on the short leg inside angle. This research project used 120 Ohm electric resistance strain gages.

Figure 17 Tinius Olsen.

Tinius Olsen Load Frame

Flexural tests were performed on individual stiffeners using the 300 kip servo-controlled Tinius Olsen load frame shown in Figure 17.

Data Acquisition:

National Instruments (NI) SignalExpress software with strain gage and displacement collection hardware was used to gather data during the four-point flexure test. The raw data was exported to excel to be analyzed. Figure 18 below shows the data collection hardware with lead wires connected

Figure 18 NI cDAQ 9178 chassis and three modules 9235, 9219, & 9239

Table 3 NI cDAQ Chassis and Modules

NI CompactDAQ 8-Slot USB Chassis And Modules Used for Test	
NI 9235	• 8-Channel Quarter-Bridge Strain Gage Module • 120 Ω strain gage measurements • 2 V excitation • Simultaneous sampling
NI 9219	• Measured the 300 kip Tinius Olsen • 4-channel Universal Module designed for multipurpose testing • Multiple types of inputs for Measurement, Voltage Used for testing.
NI 9239	• Measured the Transducer during test for displacement • 4-channel, 24-bit analog input module • Transducer used own power supply to provide analog signal

Procedures

Each flexural specimen was tested according to the following procedures:

1. Six strain gage sensors (Figure 19) and one displacement transducer were connected to the specimen.

Figure 19 Strain Gage Placement on the inside and outside of angle.

2. Connect the leads from the strain gages to modules in the NI CompactDAQ 9178 8-Slot USB Chassis to their proper channels of the module, making sure to pay particular attention that the channels start at zero and read from left to right for the strain gages.
3. Connect the Tinius Olsen to its proper module and channel in the cDAQ-9178
4. Connect the Transducer to its own power source and proper module and channel in the cDAQ-9178.
5. Connect the Chassis to the laptop and open the Measurements and Automation program to do a self-test for the chassis and each module.
6. Use the Test Panel in the Measurements and Automation to open each channel that is connected to a measuring instrument and confirm there is a signal.

7. Open Horizon program for the Tinius Olsen and configure a 0.25 inch/minute loading rate.
8. Open NI SignalExpress program. It will automatically detect modules connected in the cDAQ 9178. Check each module and check which channels you will be using.
9. Program the SignalExpress program to output data to worksheet or excel and number of data points that are preferred per minute of testing. For this project we choose 1000 per minute.
10. Go to 'Devices', check the strain gage module box, and select all strain gage signals. Check the Calibrate button and calibrate all strain gages before each test.
11. Press record in SignalExpress program and start applying load in the Horizon program to begin experiment.

A photo of a one of the specimens during test is shown in Figure 20,

Figure 20 Specimen being tested.

Results

There is a change in slope in the stress strain plots because of the contact between the loading plate and stiffener as shown in Figure 20. This contact provided an additional bracing point resulting in an increase in stiffener stiffness, causing the abrupt change in the load-strain plots. The magnitude of the stiffness increase is larger for gages located on the compression side of the local stiffener bending (gages …).

Strain Gage 1

From Figure 19 below, the Short leg of GMAW specimens was approximately 27% less stiff than the FSP and FSW specimens in the initial linear portion of the load strain plot. The stiffness was calculated as the slope of the load-strain curves.

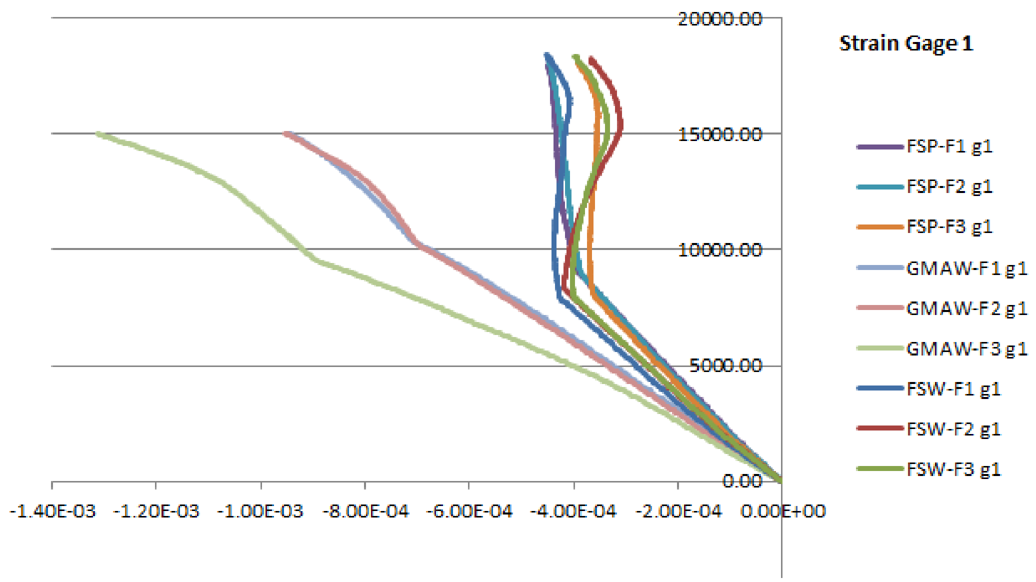

Figure 21 Strain gage 1

Strain Gage 2& 5

Strain gage #2 had a more consistent initial stiffness (slope) as shown in Figure 22 below. The friction stir processed (FSP) and gas metal arc welded (GMAW) specimens did not exhibit a reduction in strain magnitude as the loading increased as indicated by the steeper slope. The Friction Stir welded splice specimens show a flatter curve, indicating larger strains over smaller load increases.

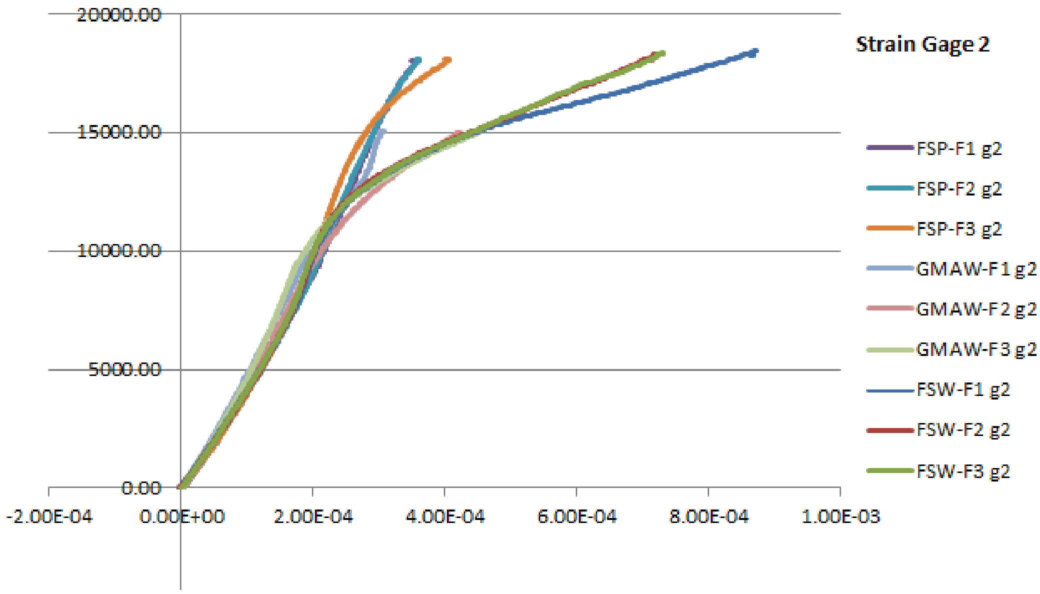

Figure 22 Strain gage 2

Strain gage #5 of the GMAW specimens show a trend towards reversal of the strain and this could be indicative of the actual strain gage 5 being placed just on the edge of its bend radius. The FSW specimen plots in the graph show a slight reversal trend. The FSP specimens show a continuous linear segment where the strain does not reverse strain action as shown in Figure 23.

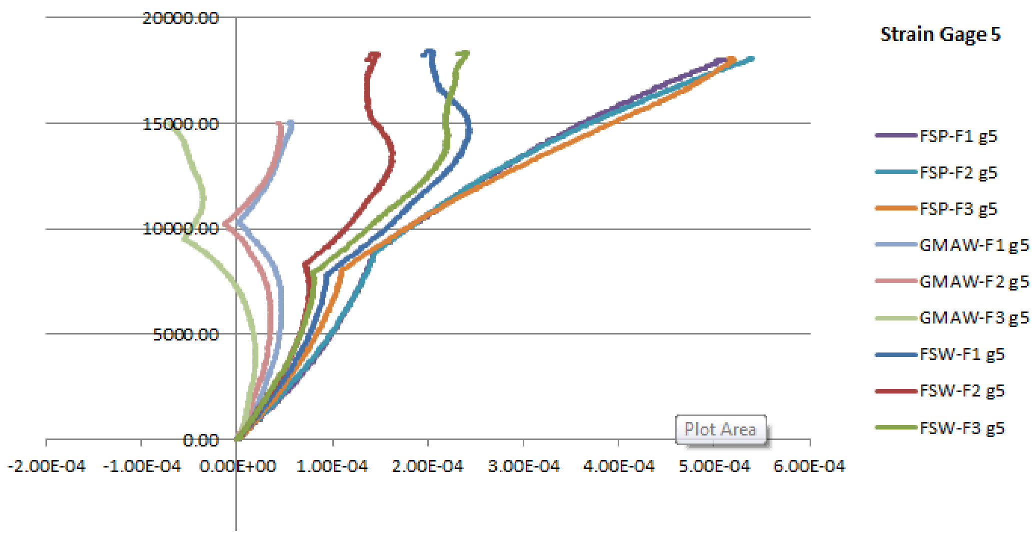

Figure 23 Strain gage 5

Strain Gage 3

Strain gage #3 which is on the inside angle of the long leg of specimens show that the GMAW specimens made contact with steel plate bearing the load at approximately 1680 lbs higher than FSP and FSW specimens as shown in Figure 24. The averages for the the FSP and FSW specimen is 8300 lbs and the GMAW approximately 10000 lbs. This gives the GMAW a 20% higher load before making contact with the steel plate.

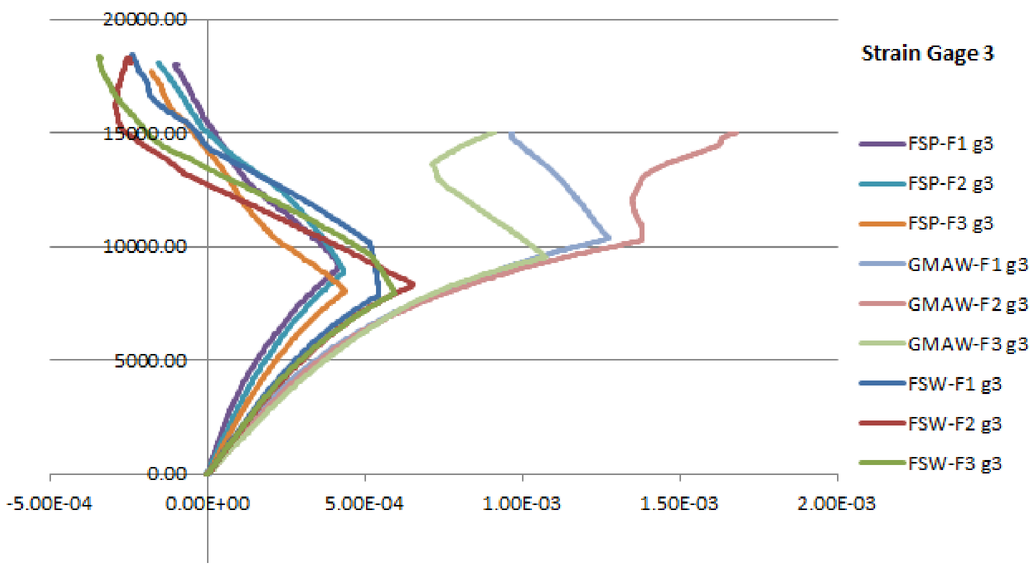

Figure 24 Strain gage 3

Discussion

In addition to the strain gage data discussed above, load and displacement data was recorded using the Horizon software from the Tinius Olsen. The Friction Stir Processed specimens with no splice show the least amount of displacement as Figure 25 shows below. Next the Friction Stir Weld specimens that have a splice show a little more displacement as they are grouped more in the center. The Gas Metal Arc Weld spliced specimens which have been the traditional method for production show the most movement as their curves would indicate in the graph below.

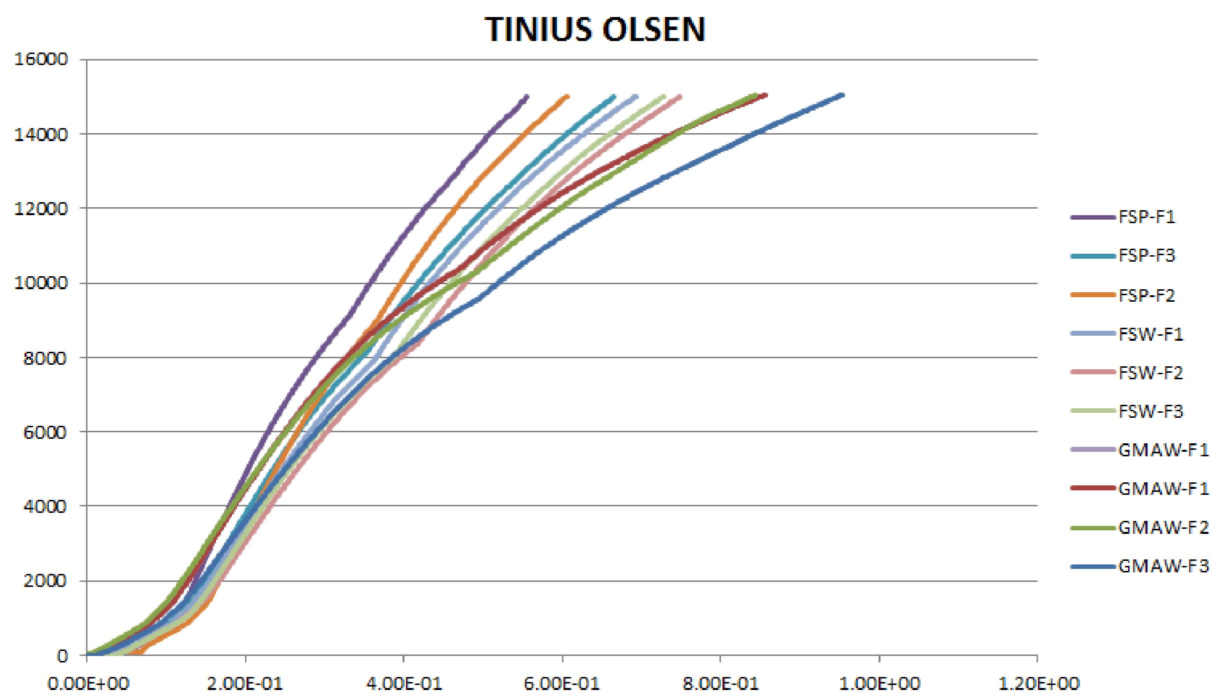

Figure 25 Tinius Olsen Load vs. Displacement

Summary and Conclusions

In this research project we developed a 4-point flexure test to characterize the flexural behavior of a single angle aluminum alloy 5083. The Tinius Olson with a loading plate and two spacers provided the loading points. It also included the implementation of strain gages and utilizing NI SignalExpress program for data acquisition.

Based on the flexural tests of the experimental program described above, present investigation, the following conclusions can be made.

1. Strain gage #3 which is on the inside angle of the long leg of specimens show that the GMAW specimens made contact with the steel plate. Bearing a higher load than the FSP and FSW specimens with about a 20% higher load.
2. Strain gage #1 which is on the short leg of GMAW specimens was approximately 27% less stiff than the FSP and FSW specimens. The stiffness was calculated as the slope of the load-strain curves
3. The Gas Metal Arc Weld spliced specimens which have been the traditional method for production show the most movement as their curves would indicate in the graph below.

Recommendations

Future testing recommended to determine Pmax and validate that the FSP and FSW specimens are stiffer. Note the top leg is going to buckle inward toward the plate and be stopped by it and cause some of the gages to reverse. Try using two points in the center of the load that has space to allow the inward buckling of the top leg. The GMAW may have approximately 20% higher load before the long leg buckled far enough and hit the leg but it’s testing was stopped at 15 kips because while it looked fine at 10 kips once it reached about 13 kips the specimen deformity caused some alarm as to maybe the plate was going to slide off. So the testing was stopped for all GMAW specimens at 15 kips. The FSP and FSW specimen held court a little longer at 18 kips before the test was halted and data collected.

References

1) AISC. (2011). Steel construction manual. (14th ed., pp. xx-xx). Chicago, IL: (AISC, 2011)
2) Littoral combat ship class - LCS. (2012, October 03). Retrieved from http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=1650&ct=4, ("Littoral combat ship," 2012)
3) Mishra, R. S., & Ma, Z. Y. (2005). Friction stir welding and processing. Reports: A Review Journal, r(50), 1-78. doi: www.sciencedirect.com. (Mishra & Ma, 2005)
4) (n.d.). Retrieved from http://www.vishaypg.com/docs/11055/tn505.pdf
5) Smith, Christopher, Rajiv Mishra, Murray Mahoney, and Cris Moen. *Material Property Testing Towards NAVSEA Approval for Use of Friction Stir Processing to Fabricate Marine Stiffeners.* Brookfield, WI: Friction Stir Link Inc., 2009.

Acknowledgments

The funding for this research came from the National Science Foundation. Thanks to advisors Dr. Damon Fick and REU site director Dr. Michael West for their direction and guidance, Professor of English Dr. Alfred Boysen for his critique in writing and speaking, and a special thanks to all of the faculty and staff at SDSM&T and the students working in the Advanced Material Processing Center for their help.