California State University, Long Beach
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Characterization of Microstructure and Mechanical Properties of 6061 Aluminum and AISI 1018 Steel Dissimilar Weldments using Aluma-Steel Electrodes

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Introduction & Motivation

The ability to join aluminum to steel has opened up many new possibilities in the field of engineering. The lightweight engineering applications are boundless. However, due to the dissimilar metallurgical properties, the joining process is not conventional and requires special techniques, such as Cold Metal Transfer developed by Fronius [1]. Such techniques are not commonly available to the average welder. However, new TIG electrodes and processes developed by Aluma-Steel offers a simple, cost effective way to weld aluminum to steel [2]. The aforementioned TIG rods are used with a conventional arc welding machine and by following the simple instructions laid out by Aluma-Steel. The significance of this product is its ability to join aluminum to steel by the means of a commonly available method such as TIG welding. There are two welding processes being tested in this research. The first process involves a single electrode known as Aluma-Steel #1. The second process involves a two electrode method where Aluma-Steel #1 and Aluma-Steel #2 are utilized together. The characterization of these electrodes and processes will provide valuable information that can be used to determine the capabilities and best application of these electrodes. Also, it could provide insight to optimize the processes in order to achieve high quality welds. By characterizing the electrode's weld properties, this product can be utilized in new designs of joints not easily achieved before.

Objective & Problem Statement

Aluma-Steel electrodes are a relatively new product and have not yet been tested and properly documented for its full capabilities and limitations. These electrodes are cost effective and can be used with conventional arc weld machines. The electrodes can create a new way dissimilar metals are joined in the future. The characterization of the electrodes' mechanical properties is an important step to achieve this goal.

The research being conducted aims to characterize the properties of the welded joints, of both the single and double electrode processes, by performing tensile tests, shear tests, hardness tests, microstructure analysis of the fusion zones, and possible methods for heat treating the welded samples. However, this particular report is only regarding the hardness tests and heat treating of the samples.

Literature Review & Technical Background

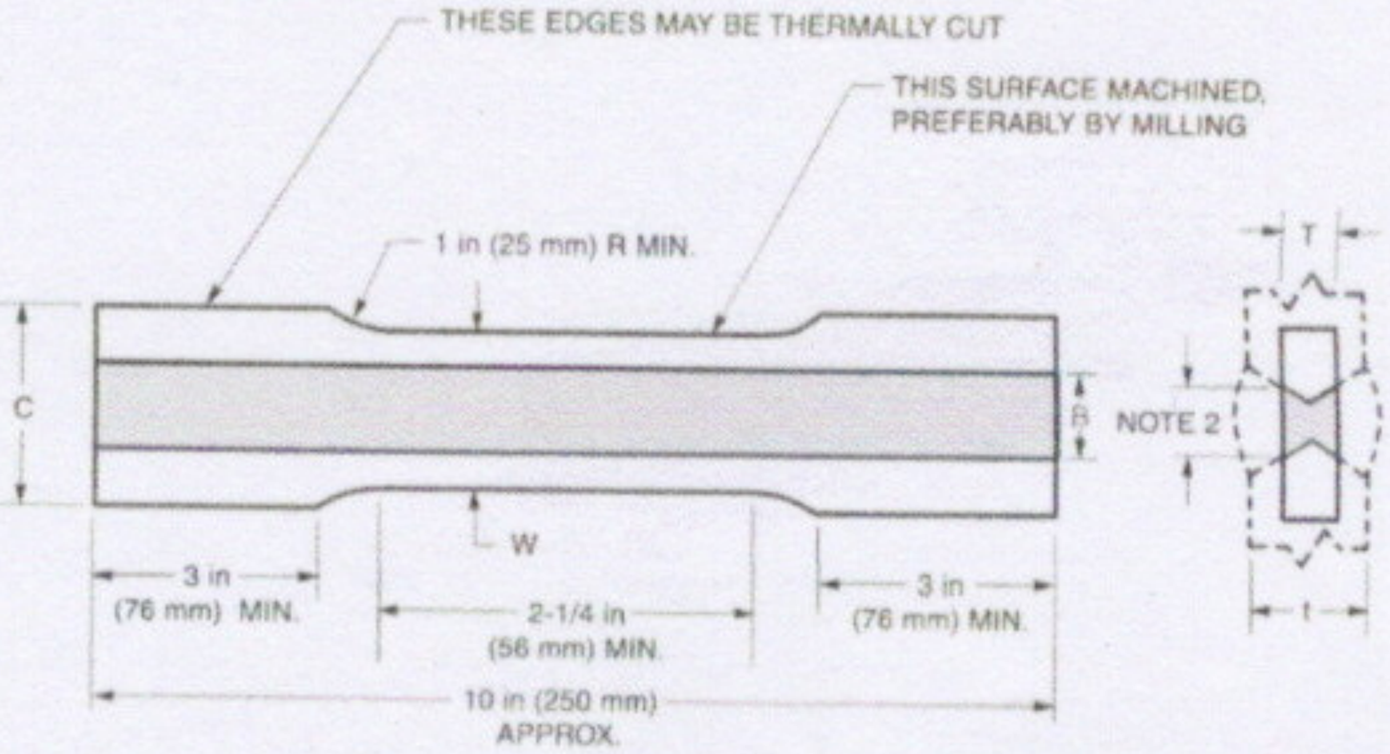
Currently, manufacturers use the conventional and cost effective method of spot welding aluminum to galvanized steel. However, the dissimilar properties of the materials can have a negative effect on the strength and quality of the weld. The quality and strength of the weld depends on the intermetallic phase that is formed when welding. The intermetallic phase is brittle which leads to issues such as pores and cracking. In order to achieve a proper joint, automotive supplier Magna Steyr discovered that the intermetallic phase should not exceed ten micrometers [1]. The key is temperature control, keeping the temperature above the melting point of aluminum and below the vaporization point of the zinc layer on the steel. Such high control of temperature is very difficult with arc welders,so the Cold Metal Transfer (CMT) technique was developed by Fronius. CMT uses a digital process control which decreases heat input, resulting in an intermetallic phase less than ten micrometers. CMT allows the mechanical properties of the joint to meet all the requirements placed on it (usually by the automotive industry), and improves on the cost-effectiveness compared to conventional methods.

The article "Characterization of Microstructure and Mechanical Properties of Inconel 625 and AISI 304 Dissimilar Weldments" by K.D. Ramkumar, et. al, demonstrates similar research [3]. In this research, the weldments were characterized by optical microscopy as well as hardness and tensile testing to characterize the mechanical properties. Due to the various chemical compositions of the welded bimetallic joints, macro and microstructure analyses were performed on areas termed as "composite regions", which covered the entire weld zone. The "composite regions"of the weld were polished to a mirror like finish using sandpaper ranging from 220 to 1000 grit. Electrolytic etching (10% oxalic acid solution; 6V DC supply and 1 A/Cm2) was utilized to examine the microstructure of Inconel 625, whereas glyceregia was used for AISI 304 side. Tensile test coupons were cut out and the weldments were made as per ASTM E80 standards. Three trials were conducted on the weldments to check for reproducibility of the results. The fractured samples were then characterized for SEM analysis to determine the mode a fracture. Hardness measurement was carried out on the composite region of the weldment using Vicker's Micro-hardness tester with a load of 500 gram-force for a dwell time of 10 seconds at regular intervals of 0.25 mm. The photographs and the macrographs show that the joints are free from defects such as lack of fusion, incomplete penetration, and macro level cracks. The micrographs of the composite region show the formation of secondary phases at the weld interface of AISI 304. The grains were found to be coarser in the heat affected zone of the AISI 304 in the case of GTA weldments when compared to PCGTA. Hardness studies were carried out over the cross section of the dissimilar weldments. It is observed that the hardness across the weldment is fairly uniform. The average hardness of the weldment is slightly higher than that of the heat affected zone and the parent metal, AISI 304. Typical stress-strain curve graphs were obtained from the transverse tensile tests. It was observed that the fracture occurred at the parent metal of AISI 304 in all the weldments for both GTA and PCGTA. The SEM fractographs revealed the formation of micro-voids and small dimples which were dispersed at the fibrous fractured zone.

The article "Characterization of Gas Metal Arc Welding welds obtained with new high Cr-Mo ferritic stainless steel filler wires" by V. Villaret, et al., describes the characterization of new filler wire [4]. The new wire contains 19% Cr and 1.8%Mo, which is equivalent to the base metal K44X, but with varying titanium and niobium contents. This research utilized tests such as microstructure analysis and tensiles tests, among other tests. For microstructure testing, cross sections of welded samples are cut, polished up to grade 4000 SiC paper, and prepared with Marble reactant (4g $CuSO4$ - 20 ml HCl - 20 ml $H2O$). The tensile tests were carried out with tensile specimens with reduced width and non-standard geometries with transverse welds. The tests were performed at room temp, 850°C, and 950°C. Tensile tests were achieved with a strain rate of 0.005 min^{-1} up to 0.45% strain, and 0.02 min^{-1} after this strain value. The microstructure results show that when the weld zone contains low titanium content (<0.1%), the grains are large and columnar. The opposite is observed, where a high titanium content (>0.15%) in the weld zone produces finer and more equiaxed grains. A transitional grain structure, coarse and columnar to finer and equiaxed, exists between titanium content of 0.1% and 0.15%. Niobium showed to have little to no effect on the grain structure of the fusion zone. This element's purpose it to only improve high temperature properties.The tensile test results show that despite the the equiaxed grain structure, the as-welded fusion zone possess rather low ductility compared to the base metal. This could be due to the segregation phenomenon during solidification, which promote the formation of brittle compounds in the intergranular spaces. An aging treatment of 100 hours at 950°C improves the ductility, which however is remains lower than the base metal. The ultimate strength at room temperature is sensibly equivalent to the base metal and does not change after aging. At high temperatures, the mechanical properties of the ferritic stainless steels are dependent on the niobium content. Two different niobium contents on two fusion zones (0.2% and 0.5%) are tested at 850°C, where the base metal contains 0.6% niobium. In the as-welded condition, the two fusions zones show a higher ultimate strength compared to the base metal, but have lower ductility. After an aging process of 100 hours at 950°C, the two fusion zones showed a decrease in strength possibly due to the homogenization of the segregation zones. The ultimate strength was lower for the fusion zone containing less niobium (0.2%), which confirms the positive effect of niobium on the high temperature strength. The results of the tensiles tests carried out at 950°C displayed the same results as 850°C. The 950°C test showed an increased strength in the fusion zones compared to the base metal, but lower ductility. The results also showed a similar decrease in strength and increase in ductility after aging for 100 hours at 950°C. High temperature transverse tensile tests on as-welded samples confirm the higher strength of the fusion zones, due to the failure always occurring in the base metal. The the characteristics of the aged samples indicate the homogenization of the behavior of both fusion zones, low and high niobium content. The aging reduces stress concentrations in the weld seam and improve the fatigue lifetime of assemblies.

Experiment Methodology

The metals used in this experiment were aluminum 6061 T6 and AISI 1018 carbon steel. These were selected because Aluma-Steel recommends using 6061 or A356 aluminum with a cold rolled low carbon steel. These started as 1" x 10" x 0.25" rectangular bars. A 30 degree bevel (**A8**) was machined using a mill on one of the long ends of each bar to allow for better weld penetration when butt welding the aluminum to the steel. A reduced width section of 2.25" in length with a radius of 1.66 inches was then cut into each piece as to create a stress concentrator, **Figure 1**. Three welded specimens were made using the single electrode method and three were made using the two electrode method. Unfortunately, these specimens developed a warp when they were welded, which can be seen in the appendix **A1** and **A2**. The warping of the pieces can be avoided by starting with larger plates and then cutting the coupons after welding. Due to time constraints and access to machinery, the coupon dimensions were cut before welding, which lead to warping. For the hardness tests samples, two of the warped pieces, a single rod and a double rod sample, were cut shorter using a cut-off saw. The welds were then machined to remove the weld reinforcement using a carbide fly cutter on mill, **A3**. One sample of each welding method were polished to a mirror finish using 240-1200 grade sandpaper to prepare them for hardness tests, **A5**. The hardness test was performed using Rockwell B and A scale on a United Tru-Blue II hardness test machine, **A4**. Three rows of fifteen data points were taken at 2 mm increments across a 30mm width of each of the samples, with the center of the weld being the origin, in order to get a map of the hardness across the steel, the welded section, and the aluminum, **Figure 2** and **Figure 3**. It was found, however, that the aluminum had lost almost all of its hardness characteristics during the high heat involved in the welding process. It order to increase the hardness of the aluminum a two step heating process was used. The welded samples were first heated in an oven at 280℃ (536℉) for one hour and then air cooled. They were then heated again at the same temperature for another hour however, this time they were quenched in water after heating. This process ended up making the aluminum softer and further heat treating will be required in future tests.



Dimensions		
	Specimen 1 in (mm)	Specimen 2 in (mm)
W = width	1 ± 0.05 (25 ± 1.25)	1-1/2 ± 0.125 (38 ± 3)
B = width of weld	1/2 (13) approx.	3/4 (19) approx.
nominal C = width of grip section	1-1/2 (38)	2 (50)

Figure 1 - Dimensions of tensile test coupon

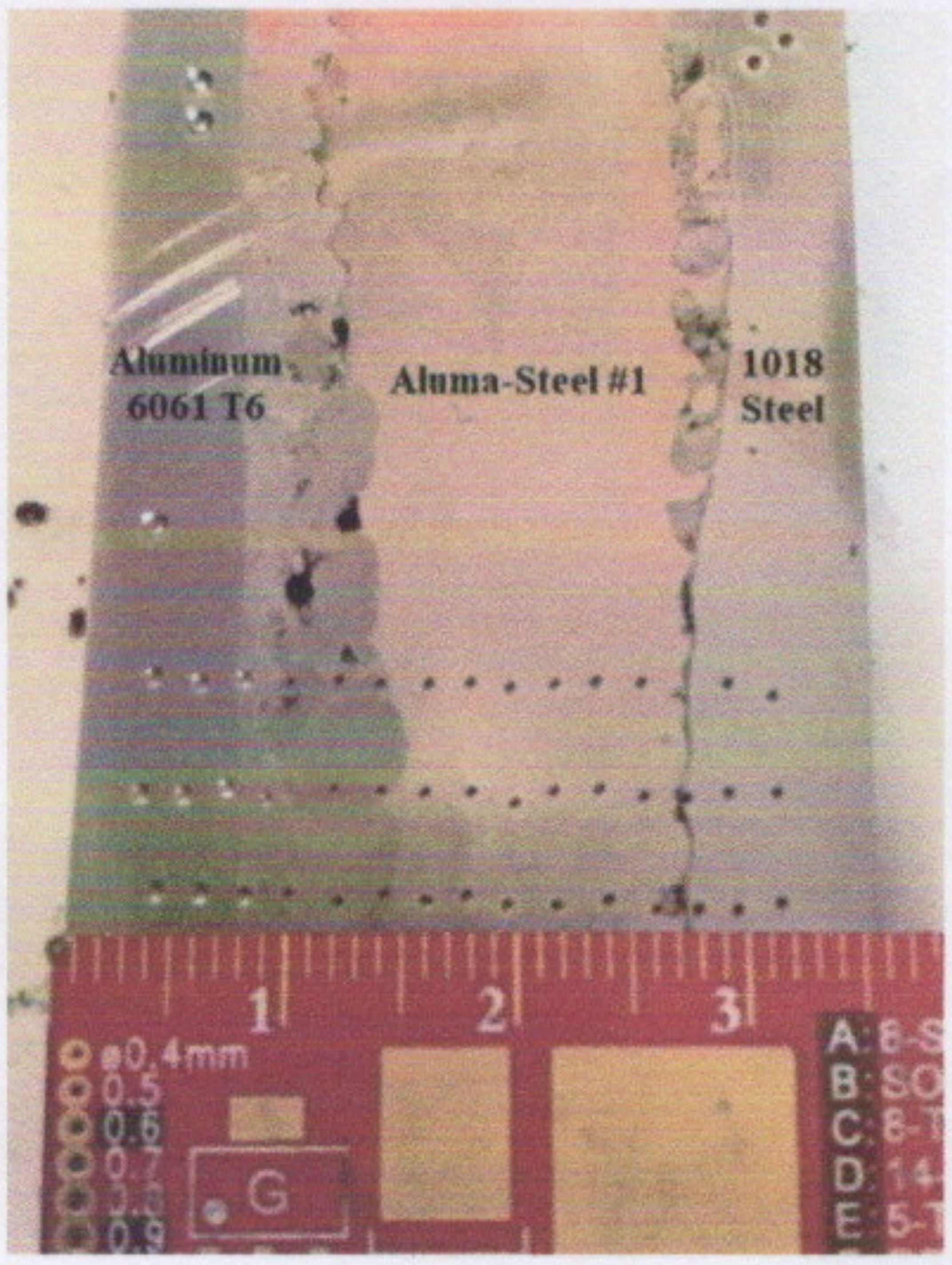


Figure 2 - Rockwell Hardness indentations of the single rod weldment sample

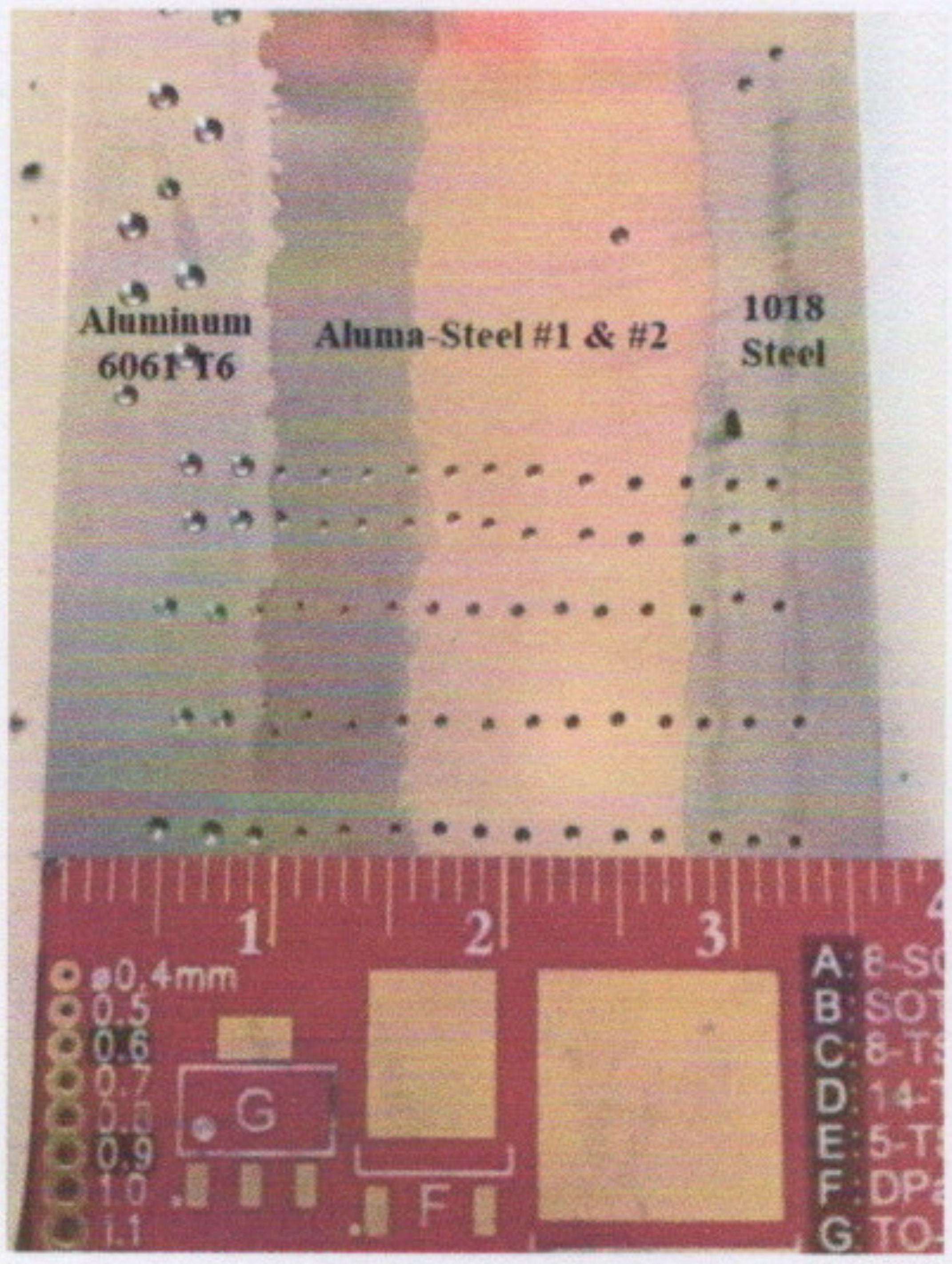


Figure 3 - Rockwell Hardness indentations of the double rod weldment sample

Test Results

Theoretical Hardness 6061 T6	
HRBW	HRA
60	40

Theoritcal Hardness 1018	
HRBW	HRA(Converted)
71	51

Table 1 - Theoretical Hardnesses of Aluminum and Steel

Raw Data 6061 T6 Unwelded	
HRBW	HRA
59.8	40.2
61.1	40.3
61.4	39.6

Raw Data 1018 Steel Unwelded	
HRBW	HRA
91.5	54.1
91.7	54.8
91.7	54.4

Table 2 - Hardness of Unwelded Samples

In order to have data to compare the hardness results to, raw data was taken on unwelded pieces of aluminum and steel as seen in **Table 2**. Rockwell A and B scales were both used. It cannot be explained, however, the large difference between the theoretical and raw data hardnesses for the 1018 Steel.

1 Rod Weldement Sample Data				
Location (mm)	HRA Hardness			Average HRA
14	56.3	56.5	56.4	56.4
12	55.9	56.1	56.4	56.1
10	63.2	51.3	53.4	56.0
8	52.1	52.7	58.3	54.4
6	47.7	49.3	50.0	49.0
4	53.4	52.0	53.2	52.9
2	55.7	55.4	55.0	55.4
0	53.3	54.3	54.5	54.0
-2	48.8	53.6	50.5	51.0
-4	56.3	57.3	58.7	57.4
-6	59.3	61.4	60.8	60.5
-8	60.0	44.2	58.8	54.3
-10	23.4	19.8	22.0	21.7
-12	17.5	14.1	15.3	15.6
-14	13.6	12.6	11.7	12.6

Table 3 - Hardness results of Aluma-Steel #1 rod welded sample

2 Rod Weldment Sample Data				
Location (mm)	HRA Hardness			Average HRA
14	54.9	54.8	55.1	54.9
12	52.4	54.0	54.8	53.7
10	51.0	51.2	51.3	51.2
8	43.7	47.8	45.0	45.5
6	41.0	41.8	42.2	41.7
4	42.0	41.5	41.5	41.7
2	42.3	42.4	38.1	40.9
0	44.5	45.6	43.4	44.5
-2	45.5	45.6	44.1	45.1
-4	54.8	51.4	42.9	49.7
-6	54.2	55.7	56.0	55.3
-8	55.1	55.9	56.4	55.8
-10	37.5	53.9	24.2	38.5
-12	5.7	7.1	8.5	7.1
-14	5.3	8.4	7.0	6.9

Table 4 - Hardness results of Aluma-Steel #1 and #2 welded sample

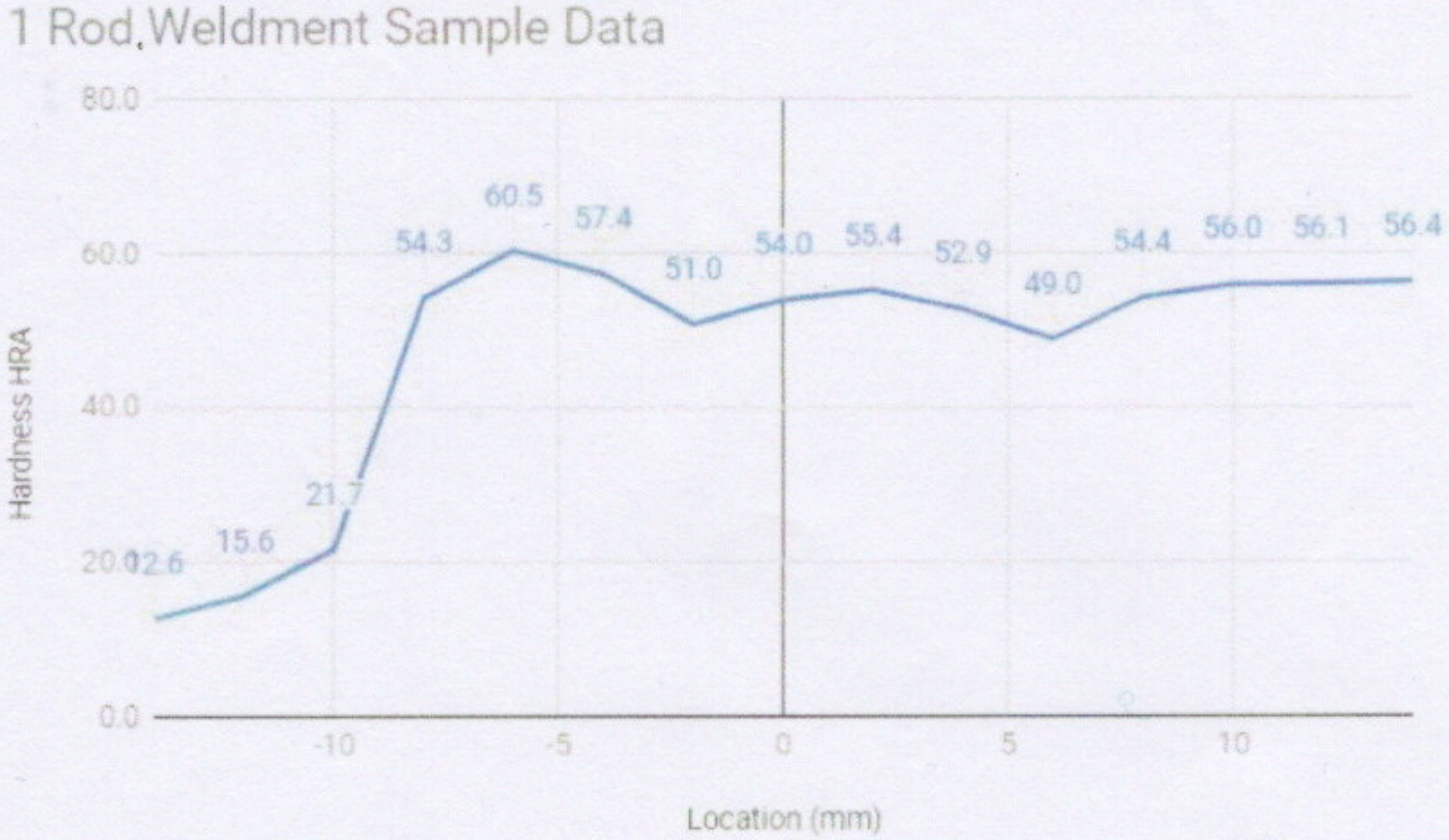
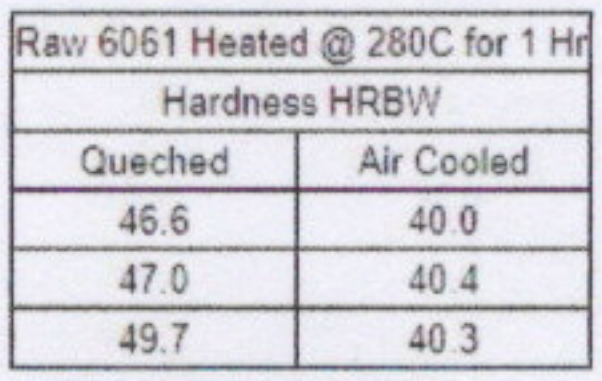


Figure 4 - Graphical data of the single rod hardness across the weldment.

Figure 5 - Graphical data of the double rod hardness across the weldment.

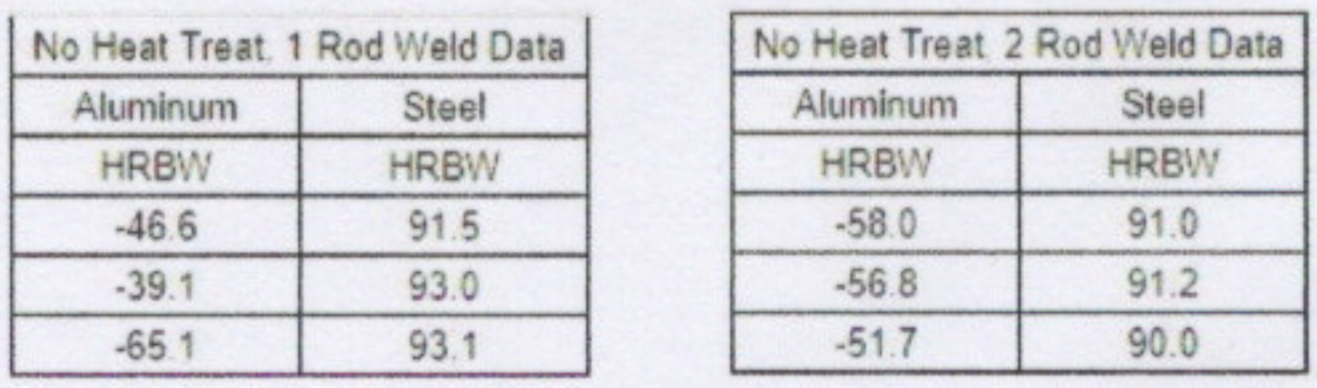
Table 3 and **Table 4** show the hardness results of samples welded with the single and double rod methods, respectively. **Figure 4** and **Figure 5** show the graphical representation of the hardness the hardness results of samples welded with the single and double rod methods, respectively. Three rows of fifteen data points were taken at 2 mm increments across a 30mm width of each of the samples, the the center of the weld being the origin, in order to get a map of the hardness across the steel, the welded section, and the aluminum, **Figure 2** and **Figure 3**. From the graphs, it can be seen that the single rod welded sample stays relatively the same across the steel and weldment, but drastically drops once the aluminum is reached. The double rod methods shows a slight drop in hardness in the weldment compared to the steel. However as the data points move along to the left, the hardness rises again briefly and then drops when the aluminum is reached. The different hardnesses across the 2 rod weldment reflects the different hardness of the 2 electrodes used. When comparing the results it can be seen that the average hardnesses across the one rod method are higher than those of the two rod method. Another significant finding was that in both methods there was a huge drop in the hardness of the aluminum (around -10 mm to -14 mm). In the single rod method the hardnesses dropped from 54.3 HRA to 12.6 HRA. In the double rod method the hardnesses dropped from 55.8 HRA to 6.9 HRA. This was likely due to the great amount of heat produced during the welding process. As a result, it was determined that the welded samples should be heat treated to increase the hardness of the aluminum.



Raw 6061 Heated @ 280C for 1 Hr	
Hardness HRBW	
Queched	Air Cooled
46.6	40.0
47.0	40.4
49.7	40.3

Table 5 - Hardness results of heat treated, unwelded aluminum sample pieces

For reference small aluminum sample pieces were heat treated, the results can be seen **Table 5**.



No Heat Treat. 1 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-46.6	91.5
-39.1	93.0
-65.1	93.1

No Heat Treat. 2 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-58.0	91.0
-56.8	91.2
-51.7	90.0

Table 6 - HRBW hardness results for as-welded samples

the hardness results of samples welded with the single and double rod methods, respectively. Three rows of fifteen data points were taken at 2 mm increments across a 30mm width of each of the samples, the the center of the weld being the origin, in order to get a map of the hardness across the steel, the welded section, and the aluminum, **Figure 2** and **Figure 3**. From the graphs, it can be seen that the single rod welded sample stays relatively the same across the steel and weldment, but drastically drops once the aluminum is reached. The double rod methods shows a slight drop in hardness in the weldment compared to the steel. However as the data points move along to the left, the hardness rises again briefly and then drops when the aluminum is reached. The different hardnesses across the 2 rod weldment reflects the different hardness of the 2 electrodes used. When comparing the results it can be seen that the average hardnesses across the one rod method are higher than those of the two rod method. Another significant finding was that in both methods there was a huge drop in the hardness of the aluminum (around -10 mm to -14 mm). In the single rod method the hardnesses dropped from 54.3 HRA to 12.6 HRA. In the double rod method the hardnesses dropped from 55.8 HRA to 6.9 HRA. This was likely due to the great amount of heat produced during the welding process. As a result, it was determined that the welded samples should be heat treated to increase the hardness of the aluminum.

Raw 6061 Heated @ 280C for 1 Hr	
Hardness HRBW	
Quenched	Air Cooled
46.6	40.0
47.0	40.4
49.7	40.3

Table 5 - Hardness results of heat treated, unwelded aluminum sample pieces

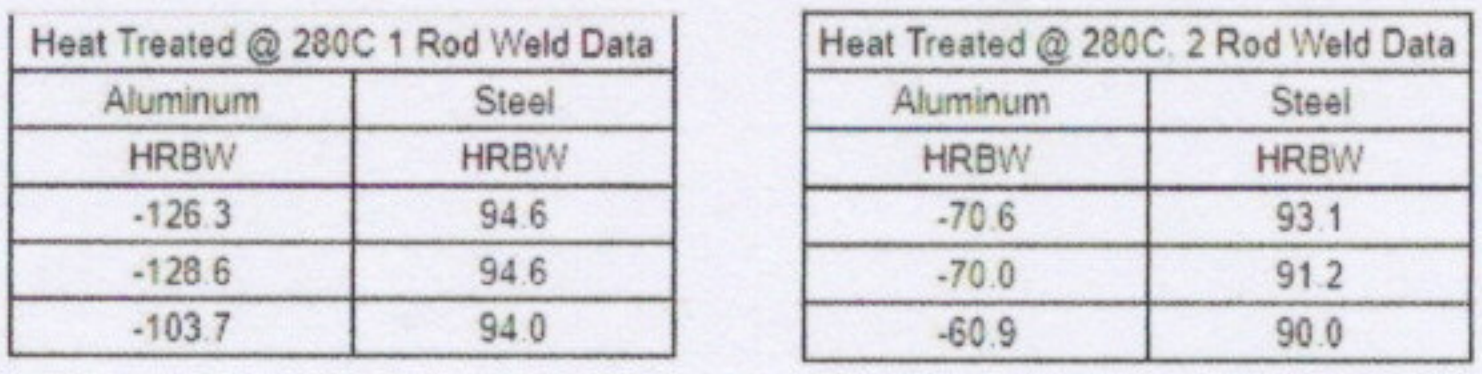
For reference small aluminum sample pieces were heat treated, the results can be seen **Table 5**.

No Heat Treat. 1 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-46.6	91.5
-39.1	93.0
-65.1	93.1

No Heat Treat. 2 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-58.0	91.0
-56.8	91.2
-51.7	90.0

Table 6 - HRBW hardness results for as-welded samples

The HRBW hardness of aluminum and steel parts of the as-welded samples were taken before the heat treatment for later comparison. The hardness results for the aluminum were negative because the indenter went past its limits and left a deep indentations in the material, **Figure 5** and **Figure 6**. This means that the material is too soft for the scale used, which was HRBW.



Heat Treated @ 280C 1 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-126.3	94.6
-128.6	94.6
-103.7	94.0

Heat Treated @ 280C. 2 Rod Weld Data	
Aluminum	Steel
HRBW	HRBW
-70.6	93.1
-70.0	91.2
-60.9	90.0

Table 7 - Hardness results after heat treatment

In order to increase the hardness of the aluminum, a two step process heating was used. The welded samples were first heated in an oven at 280 °C (536 °F) for one hour and then air cooled. They were then heated again at the same temperature for another hour, but were quenched in water after heating. When comparing the hardness data from **Table 6** and **Table 7,** the heat treating process seemed to have opposite intended effect on the aluminum, however the steel was unaffected from the heating processes. Rather than increasing the aluminum hardness, it decreased it. In the one rod method the aluminum dropped from average hardness of -50 HRBW to an average hardness of -120 HRBW. In the two rod method the aluminum dropped from average hardness of -55.5 HRBW to an average hardness of -67 HRBW. This is likely due to the fact that the aluminum did not reach its recrystallization. In future heat treatments, a higher temperature of around 400°C (750°F) will be used for 2-3 hours along with controlled air cooling.

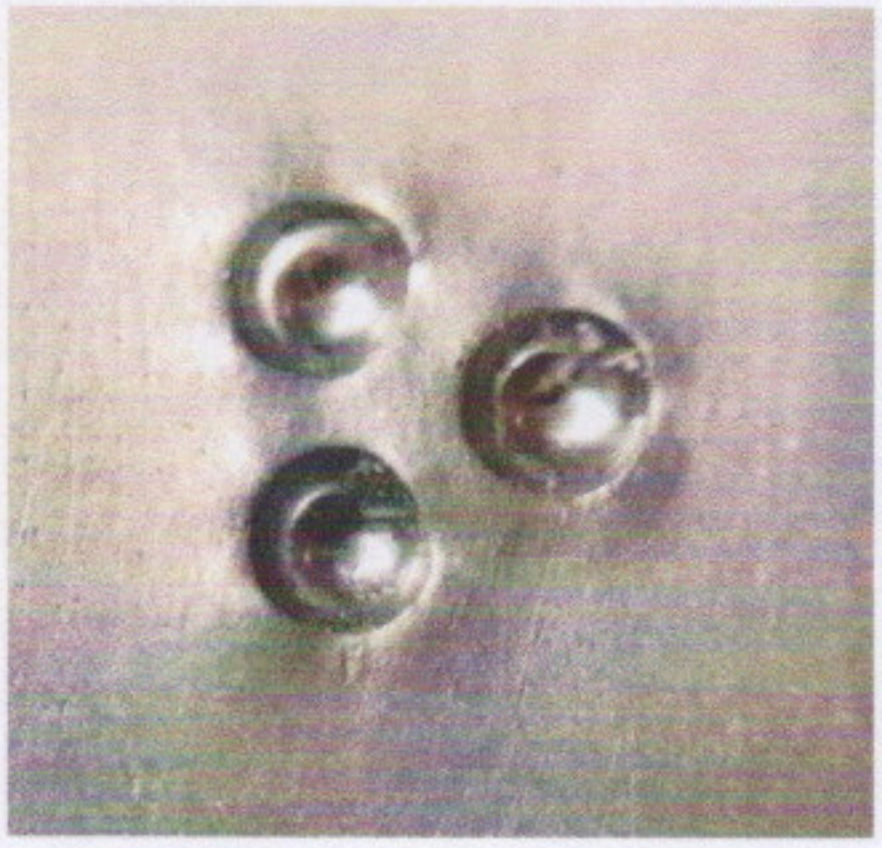


Figure 4 - Indentations of the 1 rod welded sample

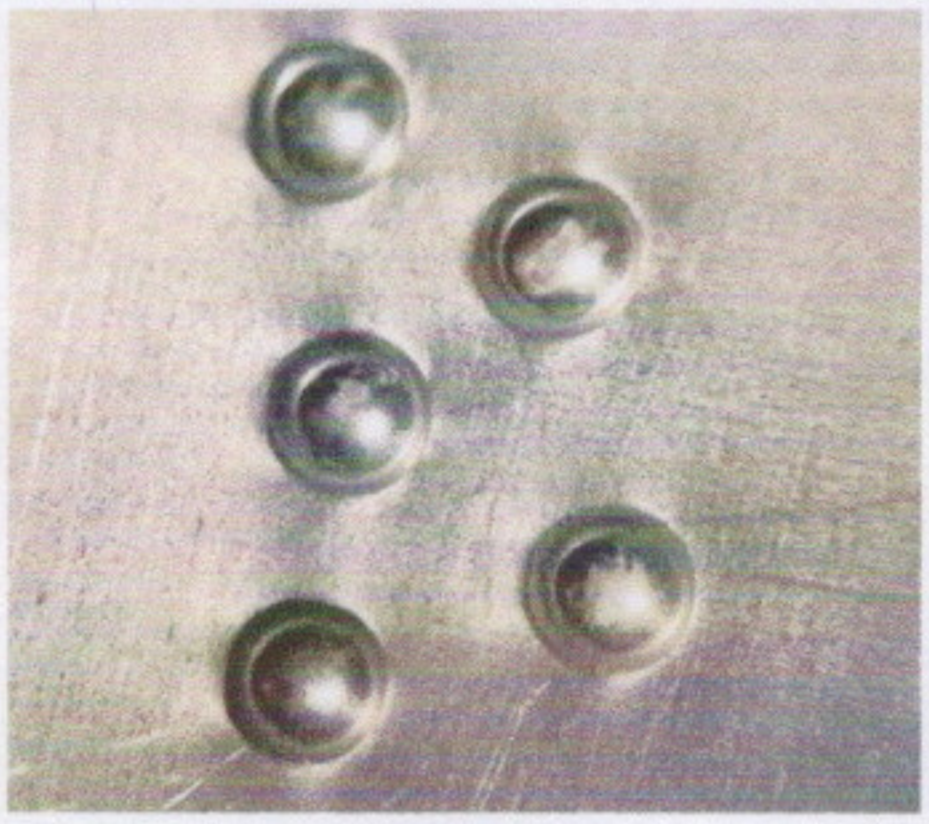


Figure 5 - Indentations of the 2 rod welded sample

Future Scope of Work

The hardness tests performed in this experiment are just one step in the process of characterizing the mechanical properties of the Aluma-Steel electrodes. The next step for the future is to tensile test as-welded samples in order to get baseline data and determine the yield strength and the modulus of elasticity of the welded joint. Then, would be to optimize the heat treatment processes in order to restore the aluminum properties while having little to no effect on the strength of the steel. After heat treatment, the welded samples can be used for tensile tests to compare to the as-welded samples. Shear tests will be used to determine the shear modulus of elasticity. In addition to these mechanical tests a microstructure analysis will done on the weld fusion zones of the samples. By these tests and analyses we hope to fully characterize the mechanical properties of Aluma-Steel so that it can be used for joining dissimilar metals in the future.

Conclusions

The welding of dissimilar metals such as aluminum and steel is a fairly complicated task due to the different metallurgical properties of each material. Aluma-Steel TIG rod, may offer a simple and cost effective way to join aluminum and steel. The purpose of this research is to fully characterize the welded joints created by Aluma-Steel by the means of tensile tests and microstructure analysis. The next goal is to optimize the heat treatment process in order to fully discover the characteristics of this product and determine suitable applications. The scope of this particular report, however, only involved the hardness tests of the samples and the heat treatment of the welded samples in order to restore some of the aluminum's strength. Through testing, it was found that the hardness of the aluminum had drastically decreased due to the high temperature of the welding process. In order to restore the aluminum's strength, the welded samples were heat treated at 280℃ (536℉) for 1 hour, air cooled, and then reheated at the same temperature for another hour and quenching the samples in water. The results, however, were opposite of the intended goal. The aluminum seemed to have gotten softer. In the one rod method the aluminum dropped from average hardness of -50 HRBW to an average hardness of -120 HRBW. In the two rod method, the aluminum dropped from average hardness of -55.5 HRBW to an average hardness of -67 HRBW. This is likely due to the fact that the aluminum was not subjected to enough heat nor enough time for recrystallization to occur. In future heat treatments, the higher temperature of approximately 400℃ (750℉) will be used for 2-3 hours along with controlled air cooling. Despite the setbacks in the beginning, the outcome of the projected future tests of this research will be an important contribution to the engineering of joining dissimilar metals.

Acknowledgements

We would like to thank the Department of Mechanical and Aerospace Engineering for everything they have done. We would like to especially thank Dr. Surajit Roy for his consistent help and advice throughout this project. We would also like to thank Mike Fritz, Filipe Coelho, and Steve Sandoval with helping us machine test samples for our project. In addition, we would like to thank Dr. Shamim Mirza and Dr. Ehsan Barjasteh for their assistance with the materials laboratory and their guidance during the hardness tests and heat treating. We would like to thank Ray Cota and Alex Barrios for providing the materials used in these experiments and taking the time to weld the samples needed for testing. Finally, we would like to thank Derek Franklin of Aerotec Alloys for allowing the use of the company work space for welding. Without the continued help of everyone, we would not have been able to complete this step of the ongoing project.

Appendices

Sources

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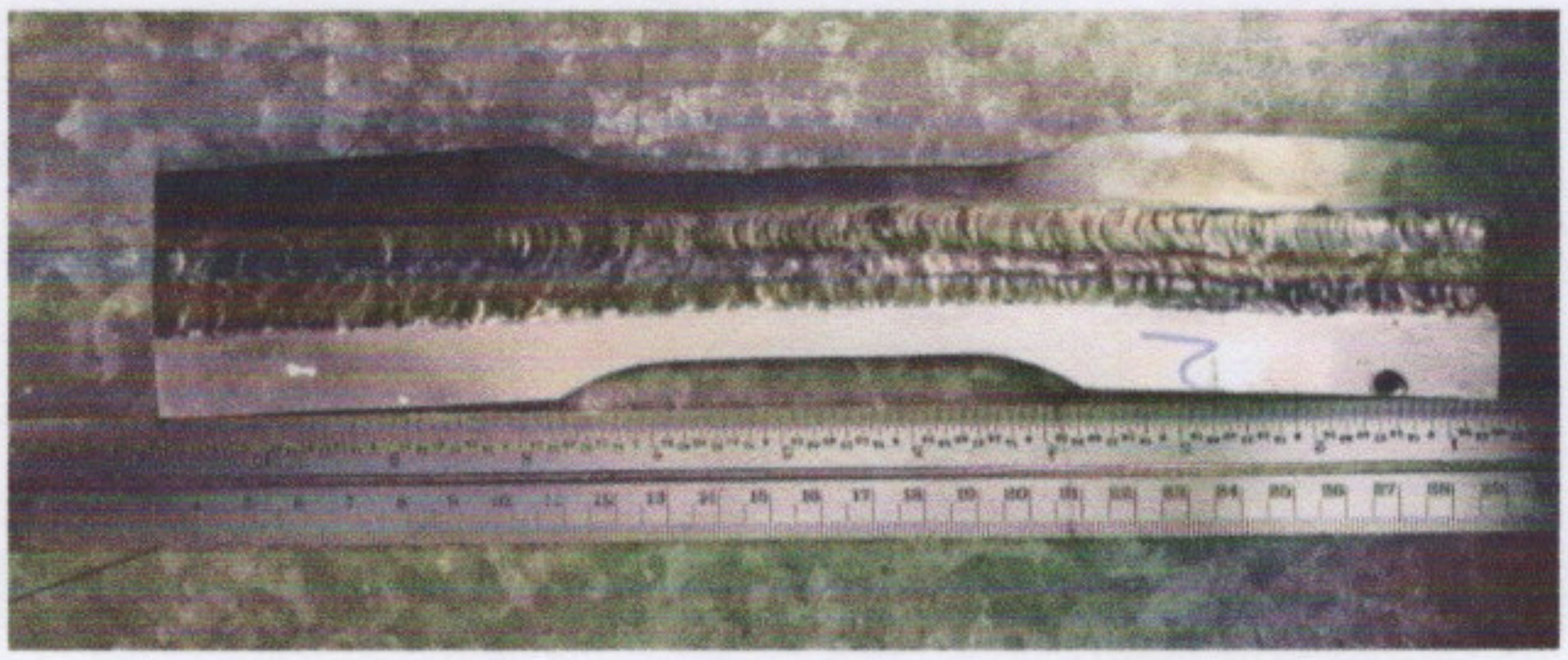
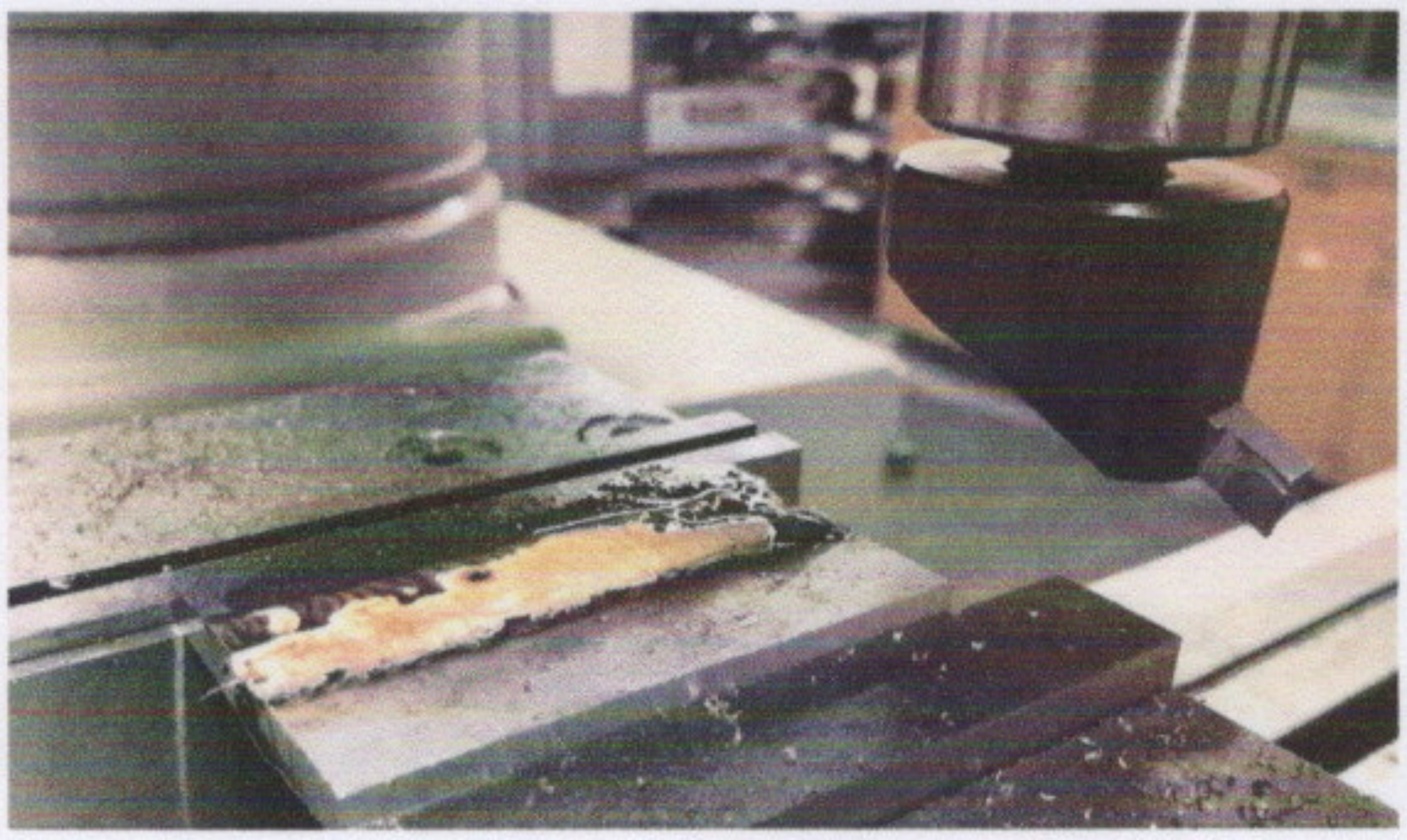
Additional Pictures

A1 - Warped Single Rod Welded Sample



A2 - Warped Double Rod Welded Sample



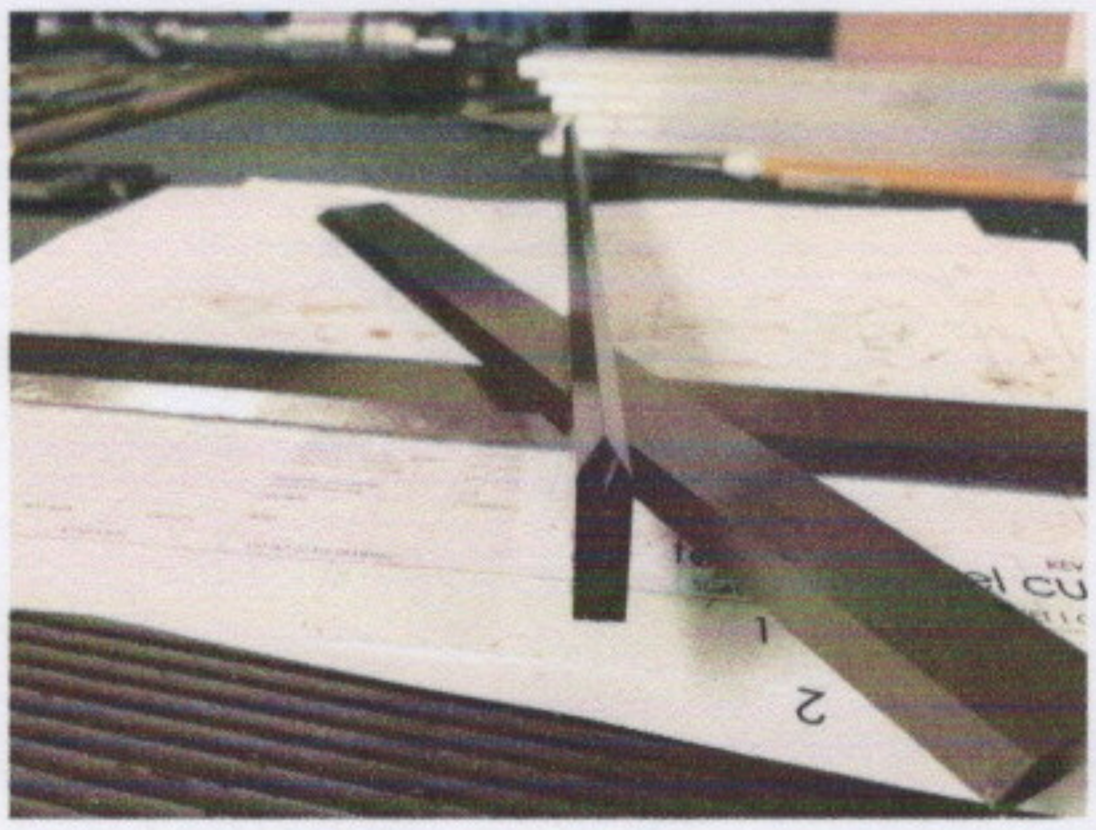
A3 - Carbide fly cutter used to remove weld reinforcement

A4 - United Tru-Blue II Test Machine

A5 - Hardness Testing Process

A6 - Close-up of machined double rod method

A7 - Humboldt oven used for heat treating



A8 - Steel sample with 30° bevel