



Metallurgical and Corrosion Evaluation of the U.S.S. Arizona

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1. Abstract

Objectives

The purpose of this paper is to present the results of experiments conducted on selected pieces of the U.S.S. Arizona. A microstructural, chemical, and corrosion-susceptibility analysis were among the experiments performed. The knowledge gained will not only help to understand the metallurgical practices at the time the ship was built, but could provide information leading to better preservation practices of the submerged ship and other ships in the ocean. This will also help to ensure that those who lost their lives on the ship will continue to be honored.

Findings

Optical micrographs and chemical analysis of the selected pieces of the U.S.S. Arizona showed that the ship was constructed of a low to medium carbon steel. Table 1 shows the results of the carbon content analysis. Evidence of banding was found in some cases. Also, steels with higher carbon content and banding showed higher corrosion rates than those of little deformation and banding. This information is shown in Table 2.

1. Introduction

Steel pieces from the U.S.S. Arizona were received from National Park Service Submerged Resources Center (NPS). Specifically, samples from Waipio Point wreckage site were received, as well as core samples recently taken from the ship's hull. The wreckage from Waipio Point is steel that was cut off of the ship during the clean-up after the Arizona was sunk. More wreckage was also placed there when the memorial was being built in 1961. The samples from Waipio Point are pieces of plate and rivet from the site. The microstructural condition of both the Waipio Point wreckage samples and the core samples from the ship were analyzed and compared. Corrosion rates were measured on the Waipio Point

wreckage using PAP (potentiodynamic anodic polarization) testing. Also, a carbon content investigation from the Waipio Point samples was performed. Characterizing this steel will allow further understanding of the metallurgical practices that took place during the time the ship was built, and provide pertinent information to help in preserving the ship.

2. Broader Impact

On December 7th, 1941, Franklin D. Roosevelt, the 32nd president of the United States, gave his “Date which will live in infamy” address (4). The Japanese attack on Pearl Harbor occurred, and it was, without a doubt, a heartrending day. The US naval base at Pearl Harbor was nearly destroyed, and one of the largest battleships, the U.S.S. Arizona, was sunk. Over 1,000 sailors were taken to their watery grave on that ship. Their lives warrant remembrance and honor. To achieve this, the vestiges of the Arizona have been turned into a memorial. This memorial does an exceptional job of reminding visitors, especially United States citizens, the sacrifice those sailors made on December 7th. For these reasons, the Arizona must be preserved.

Understanding the materials and methods used to build the ship is a means of preserving the Arizona. The structural integrity and corrosion damage determine how long the ship will last. Because of this, research has been funded to understand the corrosion rates so the NPS can make informed decisions about further preservation plans. The following paper describes just one of the studies performed to maintain the U.S.S. Arizona.

3. Materials and Equipment

As previously stated, pieces of steel from the hull of the U.S.S. Arizona were received from NPS. Specifically, three varieties of steel plate and samples of steel rivets were received from Waipio Point.

Also, eight small core samples recently taken from the hull of the Arizona were received and analyzed. All of the samples were cut, mounted, ground, polished, and etched in a 2% nitol solution. The mounts were then viewed under an optical microscope to characterize the microstructure. PAP testing was used to obtain corrosion rate data. The steel plate and rivets were cut into the proper size and analyzed using PAP testing. All of the corrosion tests were done in accordance to ASTM Wear and Erosion; Metal Corrosion G-61, "Standard Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Iron-, Nickel-, or Cobalt-Based Alloys" (1). This standard requires a 3.56% NaCl solution (for the corrosive electrolyte) for the metal coupons to be corroded in. All of this equipment used in the experiments is located in the Materials and Metallurgical Engineering Department at the South Dakota School of Mines and Technology.

4. Metallurgical Analysis

Microscopy

After taking sections from different pieces of plate, it was found that there were three microstructural varieties of plate. A photograph showing the plate is shown in Figure 1. The different plates shown will be referred to as plates A-1, A-2, and A-3, respectively. The microstructure of A-1 shows a lower carbon condition than the rest of the plate. The matrix largely consists of ferrite (white) with some resulting pearlite (dark). The microstructural condition of A-2 indicates an acicular fine ferrite-pearlite-like matrix. The microstructure of A-3 was found to be heavily banded with a low to medium-carbon ferrite-pearlite matrix. The banding is likely the result of ingot casting solidification practices of the time. Segregated microstructures form when solidifying, and are forced into a parallel structure when rolled. Micrographs of the plates can be seen in Figures 2, 3, and 4.



Figure 1: Photograph of selected steel pieces from the U.S.S. Arizona at Waipio Point. Left: Plate A-1. Top: Plate A-2. Right: Plate A-3. Bottom: Rivet.

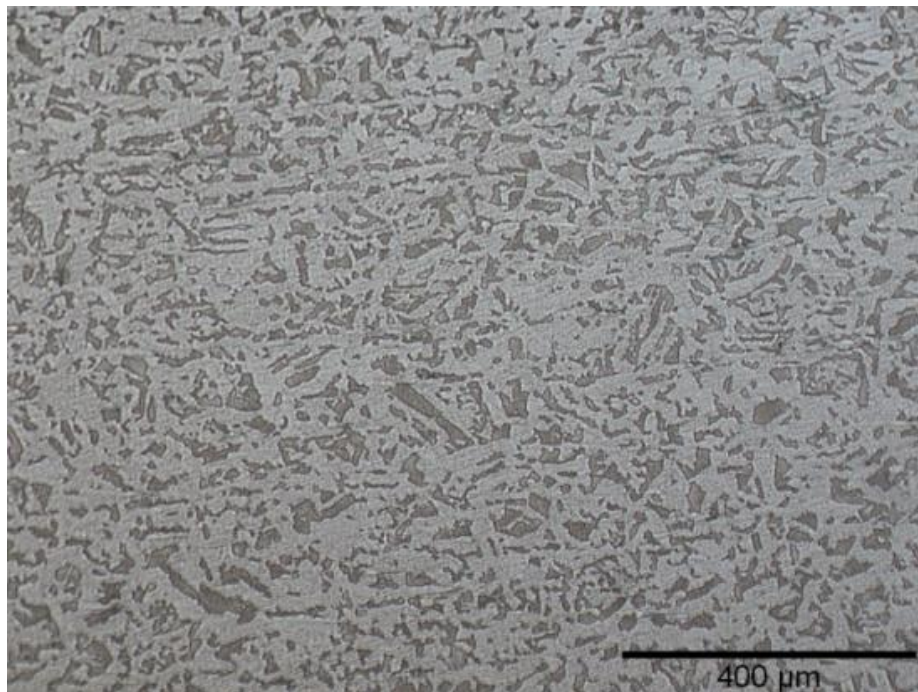


Figure 2: Microstructure of Plate A-1. 100 X.

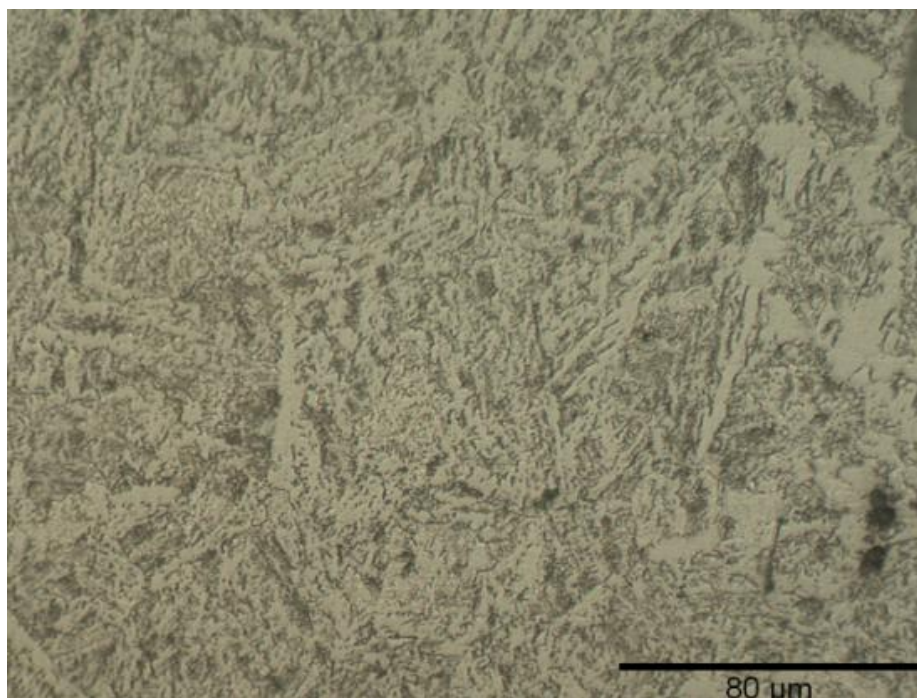


Figure 3: Microstructure of Plate A-2. 100 X.

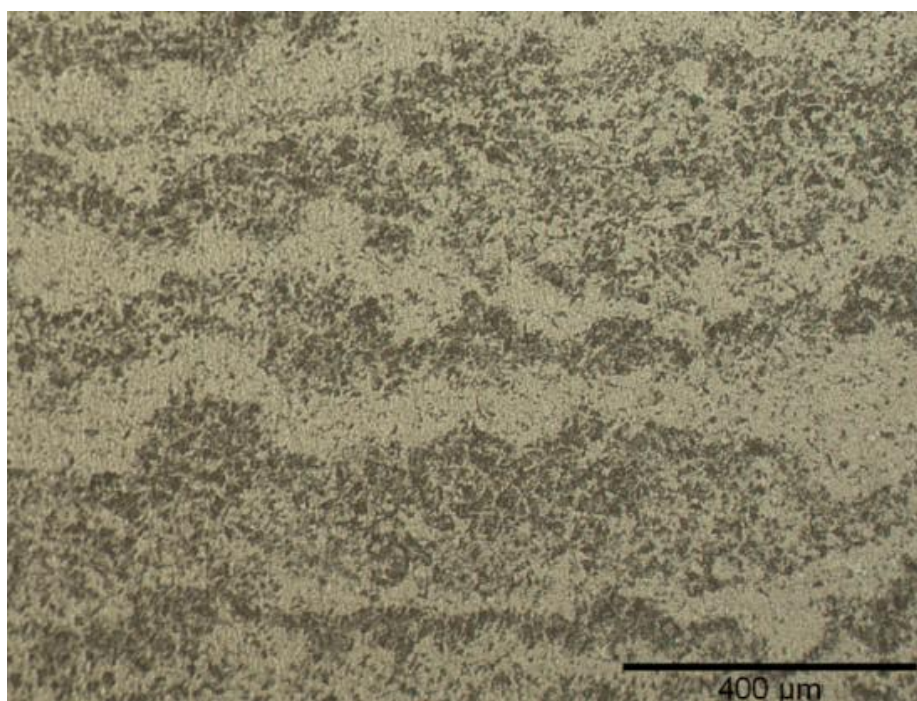


Figure 4: Microstructure of Plate A-3. 100 X

Plates A-1 and A-2 were found to be similar to those found in “Metallographic Studies of the U.S.S. Arizona”, having the banded low-carbon appearance (2). The rivets analyzed from Waipio Point were also found to have similar microstructure to the Waipio Point rivet in “Metallographic Studies of the U.S.S. Arizona.” The rivets had the appearance of being cooled quickly from austenitic temperatures, grain boundary pro-eutectoid ferrite, Widmanstätten ferrite, and fine-pearlite (2). The appearance of being cooled quickly is explained by the riveting methods of the time, where rivets are heated to red hot temperatures and forged into place. The head of the rivet, however, showed more deformation and indications of carbon loss (decarburization). The decarburization likely occurred because the rivet was heated to temperatures in which diffusion of carbon can take place. The carbon diffuses toward the surface of the part and is oxidized in the atmosphere resulting in the loss of carbon near the surface of the heated material. This is seen by the increased amount of ferrite (white) near the surface of the material. Figure 5 shows a micrograph of the rivet head.

Figure 6 shows a micrograph of the rivet shaft. A photograph of the core samples is shown in Figure 7. The core samples were found to have a similar microstructure to plate A-2, although some of the core samples indicated lower carbon content in some cases. Figure 8 shows a representative micrograph of the similar microstructure, and Figure 9 shows a representative micrograph of the lower carbon sample. The micrographs of the rest of the core samples are shown in Appendix A.

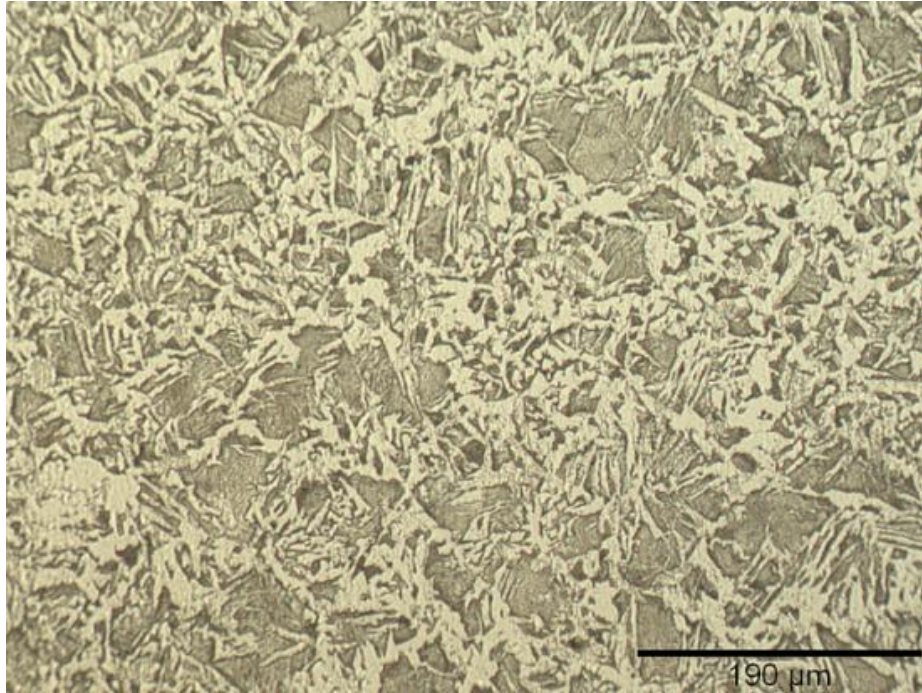


Figure 5: Microstructure of Rivet Head. 100 X.

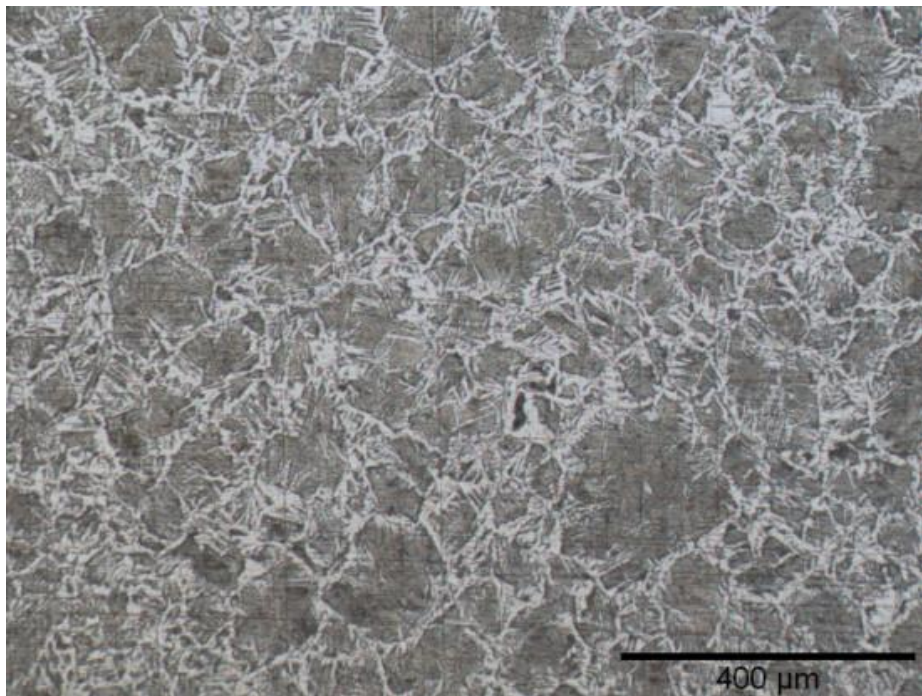


Figure 6: Microstructure of Rivet Shaft. 200 X.



Figure 7: Photograph of Core Samples from the U.S.S. Arizona. The Core Samples from Left-to-Right are: 02-001, 002, 003, 004, 007, 008, 009, and 010.

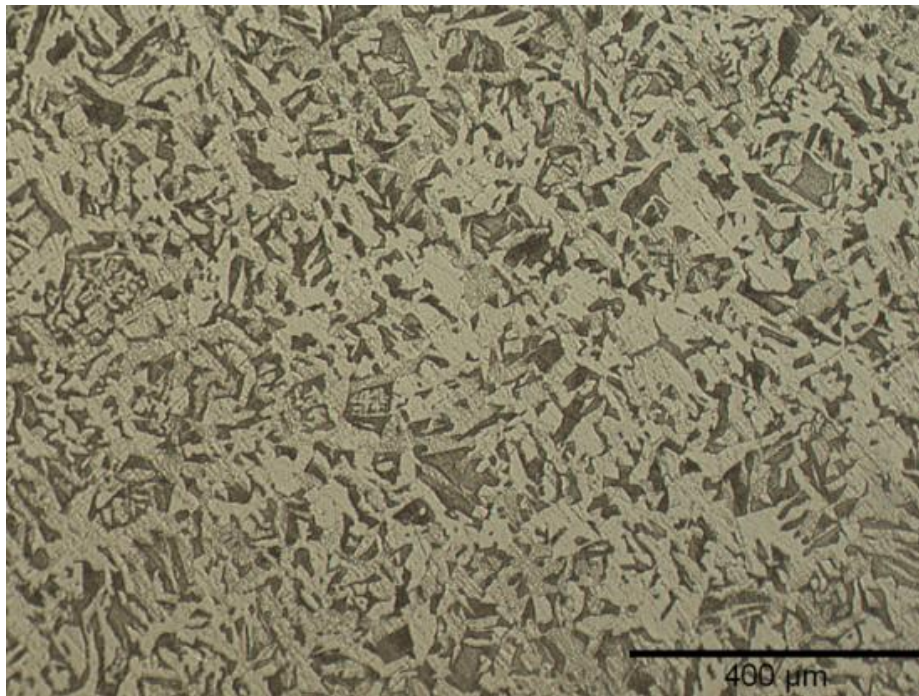


Figure 8: Microstructure of U.S.S. AZ Core Sample. 100 X.

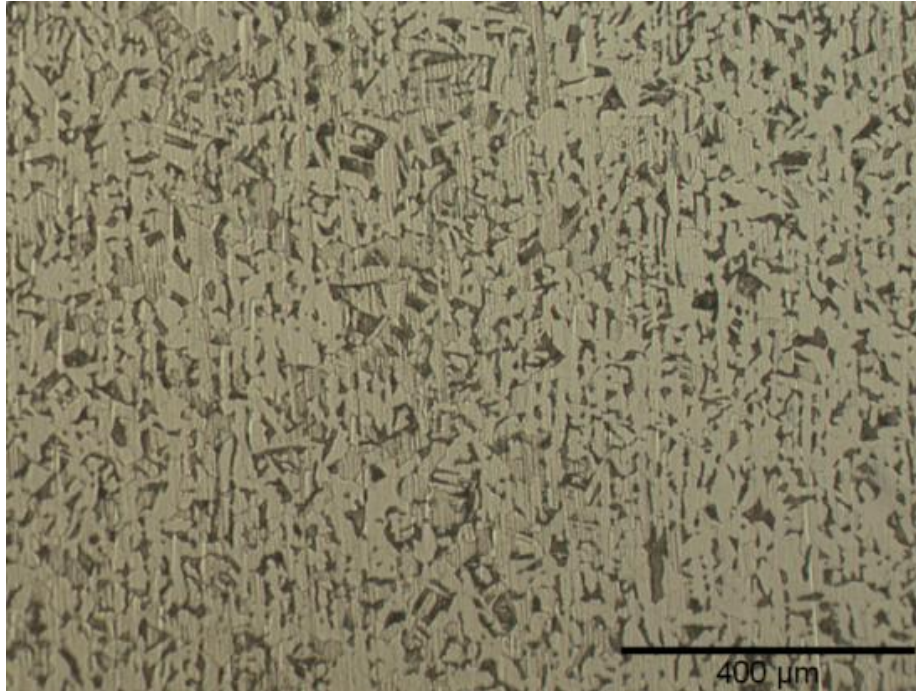


Figure 9: Microstructure of Low-Carbon Type Cutting. 100 X

Chemistry

The carbon content of the Waipio Point samples were estimated by covering the steel samples with a coating to prevent decarburization, heating them into the austenitic phase region, and slow-cooling in a furnace. The samples were then mounted and analyzed under an optical microscope. By measuring the amount of ferrite and pearlite present, the carbon content can then be back-calculated using an iron-iron carbide equilibrium phase diagram. The percent of each constituent was calculated by using an area fraction function in the software for the optical microscope that was used. Equation 1 was used to calculate the carbon content from the area fraction of pearlite and ferrite present measured.

$$\text{Weight \% Carbon} = (0.76) * (AP) + (0.022) * (AF)$$

(Equation 1)

AP is the area fraction of pearlite present, and AF is the area fraction of ferrite present. Also, this equation assumes fully saturated conditions of all ferrite present, and no other alloying elements in the

steel. This experiment was performed on all of the selected steel samples from the Waipio Point wreckage. The calculated carbon content of each sample is shown below in Table 1.

Table 1: Results of Carbon Content Experiment

Sample	Area Percent Pearlite	Area Percent Ferrite	Calculated Weight Percent Carbon Content
Rivet	22	78	0.18
Plate A-1	11	89	0.1
Plate A-2	NA	NA	NA
Plate A-3	28	72	0.23

The data obtained from this experiment compares well with the chemical analysis found in “Metallographic Studies of the U.S.S. Arizona.” Slow-cooled plate A-1 showed evidence of heavy banding. Plate A-2 showed evidence of heavy banding after the slow-cooling. For this reason, the analysis used to find the carbon content did not work well on this specimen. A micrograph of the slow-cooled plates is shown in Appendix B.

5. Corrosion Rate Analysis

Using PAP testing, corrosion rates of the plate and rivet were evaluated. A saturated Ag/AgCl KCl electrode was used as the reference electrode. Tafel plots were generated to find β_c and β_a (the cathodic and anodic slopes of Tafel plot). The Tafel slopes were then input into the linear polarization plot, and corrosion rates were obtained. The straight lines on the plot are the estimated Tafel slopes. The intersection of these lines gives E_{corr} and i_{corr} . E_{corr} is the value of the potential where the current density approaches zero. This is also found where the two Tafel slopes intersect. i_{corr} is the value of the current density where the Tafel slopes intersect. i_{corr} is used to find the corrosion rates using Equation 2:

$$r = 0.129 * \frac{A i_{corr}}{nD}$$

(Equation 2)

where A is the atomic weight of the metal corroding, i_{corr} is defined as the current density, n is the number of equivalents exchanged, D is the density of the material, and r is the corrosion rate. The rate is given in mils. (thousandths of an inch) per year or mpy. This is the penetration rate of the oxide layer. An exemplar Tafel plot is shown in Figure 9. The rest of the Tafel plots are shown in Appendix B. Table 2 shows the corrosion rates obtained from the linear polarization experiments.

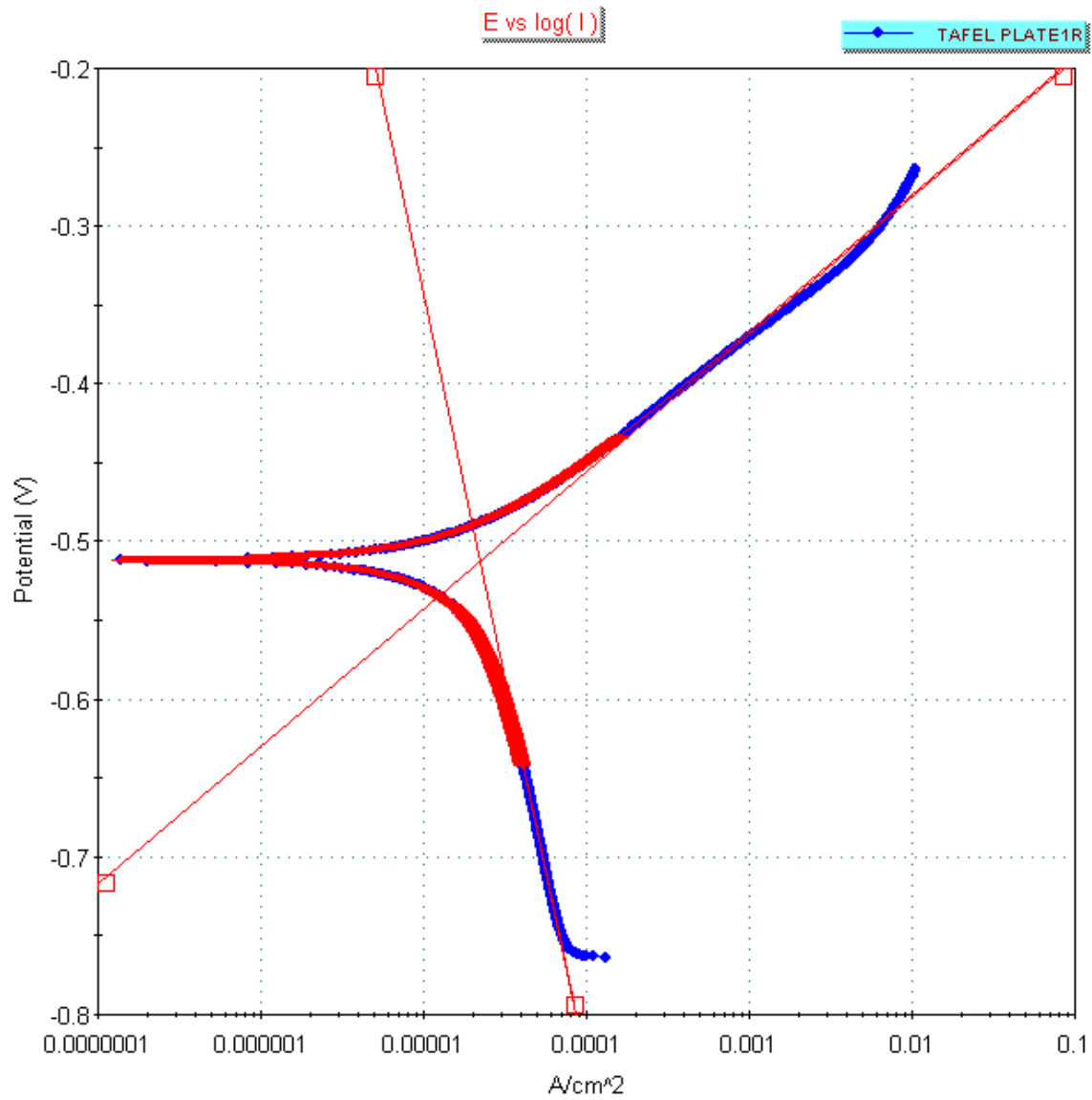


Figure 10: Exemplar Tafel Plot Showing the Results of Plate A-1.

Table 2: Corrosion Rates of the Selected U.S.S. Arizona Samples

Sample Type	Corrosion Rate (mpy)
Plate A-1	2.3
Plate A-2	4
Plate A-3	5.2
Rivet Head	5.3
Rivet Shaft	2.1

The results of the linear polarization experiments show higher corrosion rates for Plate A-1, A-3, and the rivet head. This data compares within reason to corrosion rates found in “Recent development and application of Concretion Equivalent Corrosion Rate (CECR) Methodology” (4). This research found corrosion rates from 0.5 mpy to 3 mpy. There are several possibilities of phenomena that may be causing the difference in corrosion rates. First, several different steels were used to construct the ship. Testing different steels would most certainly yield different corrosion rates for the respective steels. Also, the method of determining corrosion rates, in that paper, was by concretion chemistry analysis instead of measuring rates with PAP testing.

In general, the ocean is a much more dynamic environment than ever could be recreated in a laboratory. According to Denny A. Jones in Principles and Prevention of Corrosion, a pure water and sodium chloride solution can often times be a more aggressive corrosive environment than sea water (5). This is because there are constituents in the sea water than can lower corrosion rates. For example, calcium carbonate (CaCO_3) can deposit on the surface of the metals. This can seal the metal from the water and stop further corrosion. This means that corrosion rates for metals will be initially high, but after concretion forms the corrosion rates will dramatically lower. Many other factors may contribute to variation in corrosion rates. These factors include dissolved oxygen gradients and the presence of microorganisms.

For these reasons, it is unlikely any of the corrosion rates attained from these experiments would numerically match those found on in the ocean water. Finding metals have higher corrosion rates could indicate which metal would corrode faster given similar conditions.

6. Conclusions

Steel pieces from the U.S.S. Arizona were received from National Park Service Submerged Resources Center and were analyzed. Specifically, samples from Waipio Point wreckage site were received, as well as core samples recently taken from the ship's hull. The microstructural condition, chemistry, and corrosion susceptibility of both the Waipio Point wreckage and the core samples from the ship were analyzed and compared using an optical microscope and using PAP testing. The microstructures of some of the samples showed indications of alloy banding. Also, a carbon content investigation from the Waipio Point samples was performed. The results of the carbon content experiment indicated the steel used to build the ship was low to medium carbon steel. Corrosion susceptibility was found to be higher in steels with higher carbon, banding, and higher deformation—essentially a higher energy state. This information could prove to be important in preserving the U.S.S. Arizona and understanding metallurgical practices of the early 20th Century.

7. Acknowledgments

This research would not have been possible without the National Science Foundation funding the man-hours and supplies necessary. Also, the National Park Service Submerged Resource Center provided the steel samples from the U.S.S. Arizona. In addition, without Dr. Dana Medlin's help with directing the scope of this work, this project could not have been the work it is now. His insight and experience made it possible to aspire to excellence and fulfillment in researching this topic. Lastly, Dr. Michael West and Dr. Alfred Boysen deserve credit for their dedication to the Research

Experience for Undergraduate program that this research was a part of. This paper certainly would not have been completed without their astute input. For all of this, Thank you!

8. References

1. *1998 Annual Book of ASTM Standards; Wear and Erosion; Metal Corrosion*. (1998). West Conshohocken, PA: American Society for Testing and Materials.
2. D. L., J., W. N., W., & J. D., M. (1999). *Metallographic Studies of the U.S.S. Arizona*. *International Metallographic Society* .
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4. Johnson, D. L., Murphy, L. E., Russell, M. A., Conlin, D. L., Delagdo, J. P., & Medlin, D. J. (n.d.). *Recent Development and Applications of Concretion Equivalent corrosion Rate (CECR) Methodology*.
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6. Schumamcher, M. (1979). *Seawater Corrosion Handbook*. Park Ridge, New Jersey: William Andrew Publishing/Noyes.
7. *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*. (1989). Santa Fe, New Mexico: Southwest Cultural Resources Center Professional Papers .

Appendix A: Micrographs of Selected Core Samples from the U.S.S. Arizona

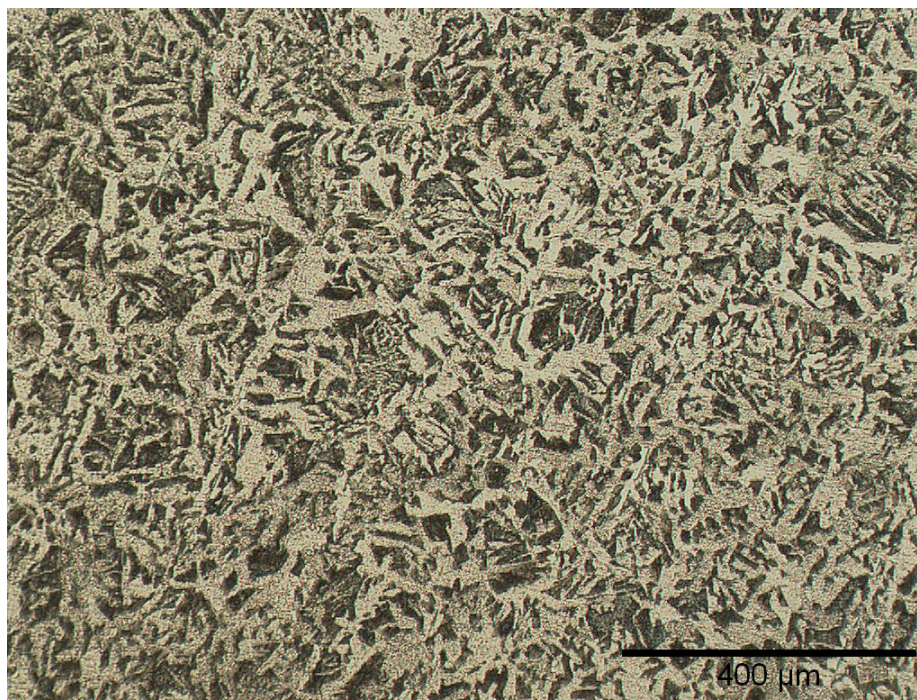


Figure A-1: Micrograph of Core Sample 02-001. 100 X.

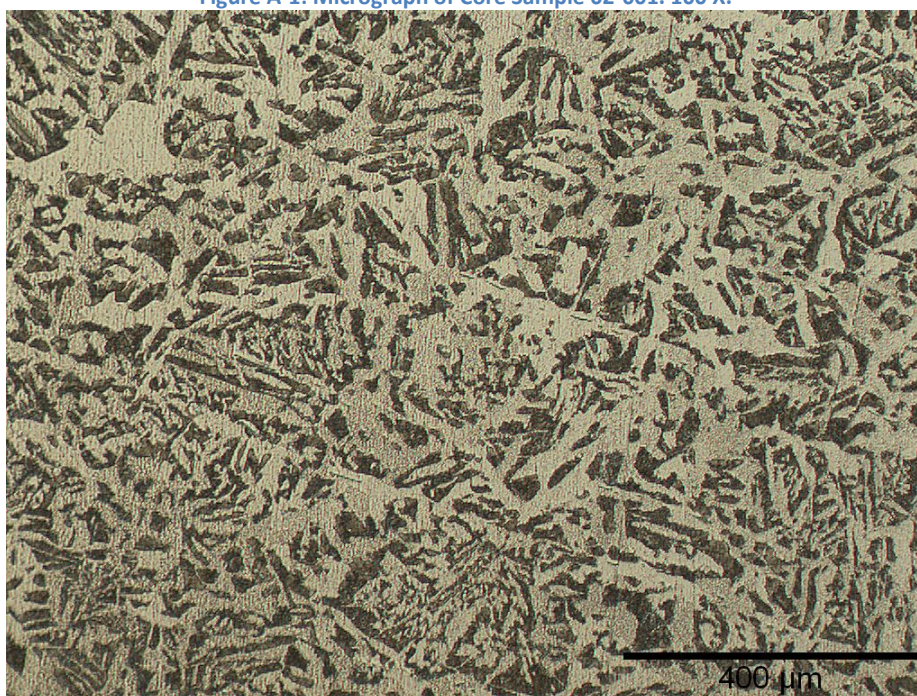


Figure A-2: Micrograph of Core Sample 02-002. 100 X.

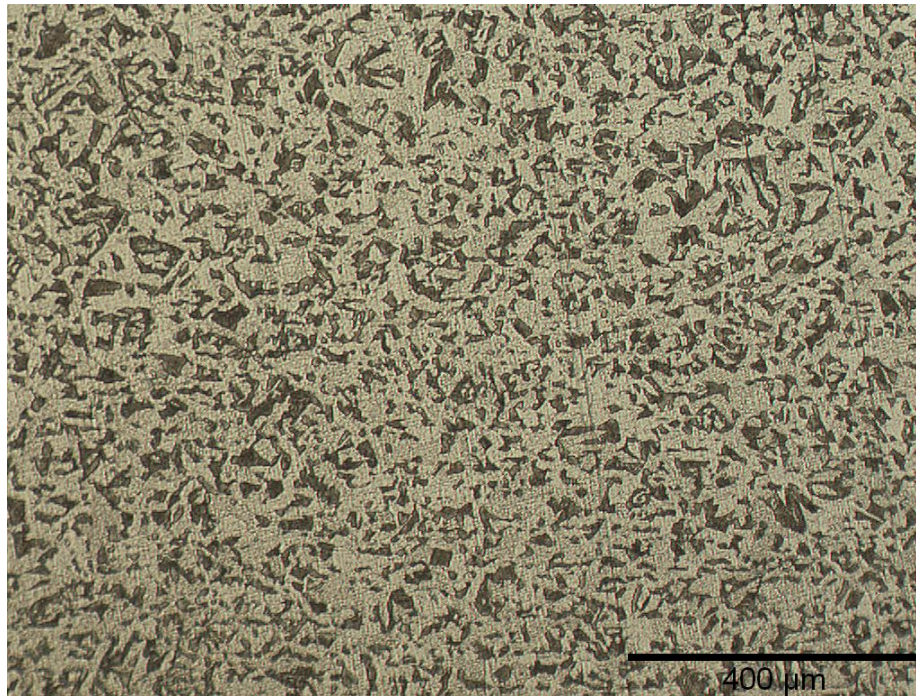


Figure A-3: Micrograph of Core Sample 02-003. 100 X.

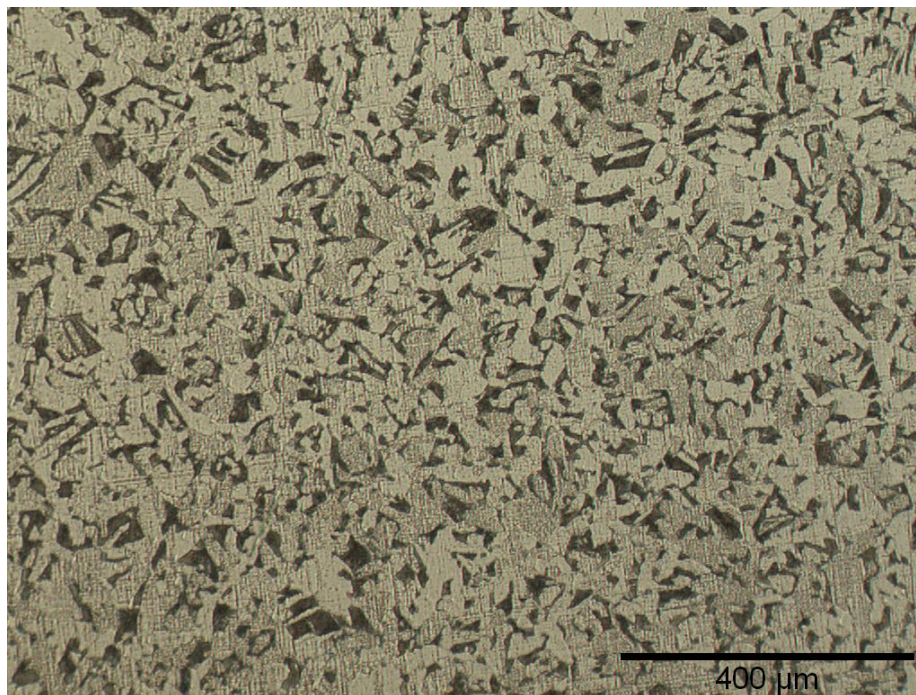


Figure A-4: Micrograph of Core Sample 02-004. 100 X.

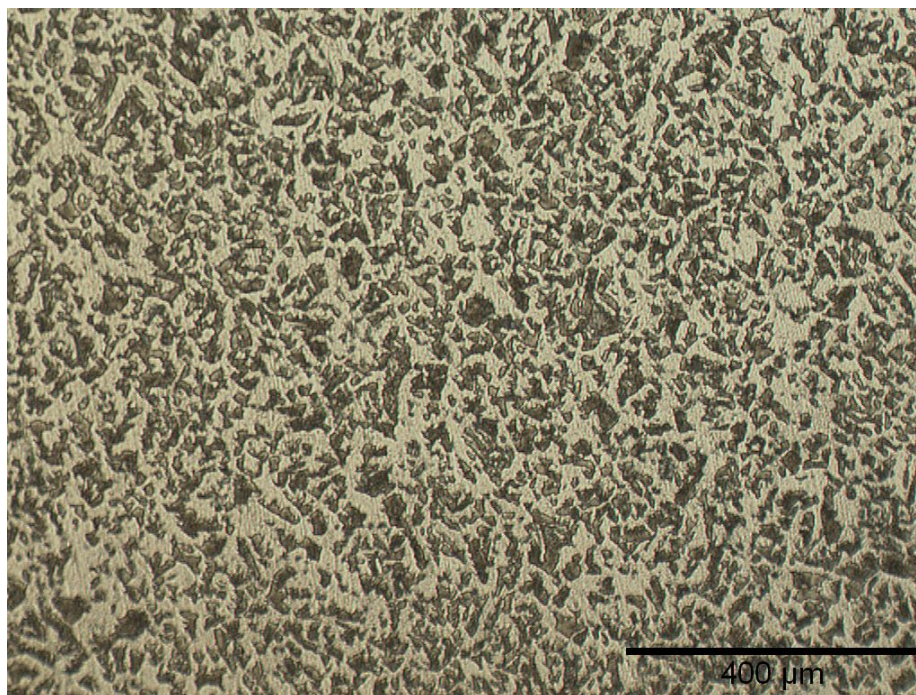


Figure A-5: Micrograph of Core Sample 02-007. 100 X.

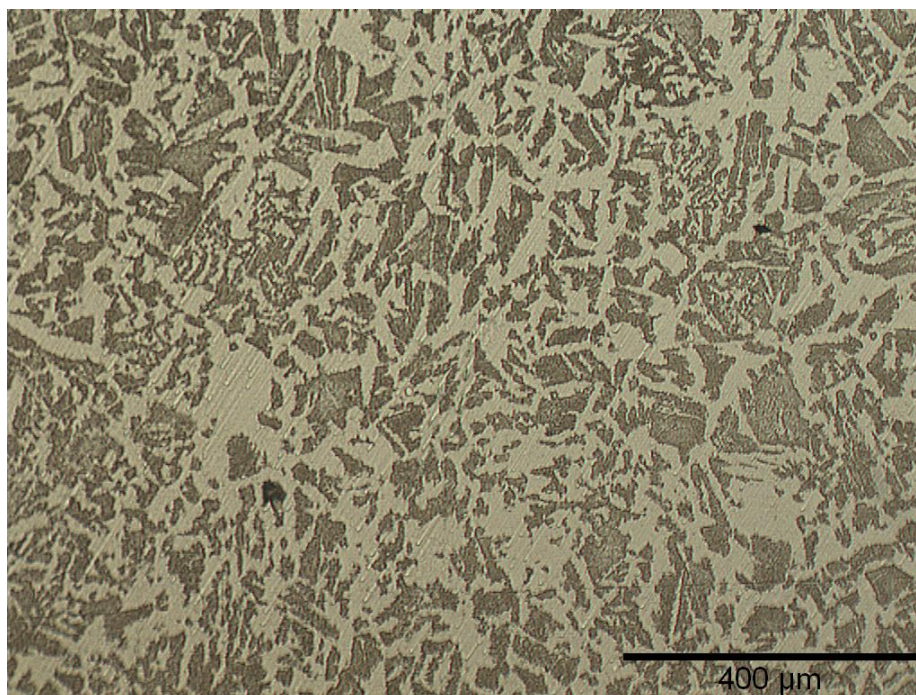


Figure A-6: Micrograph of Core Sample 02-008. 100 X.

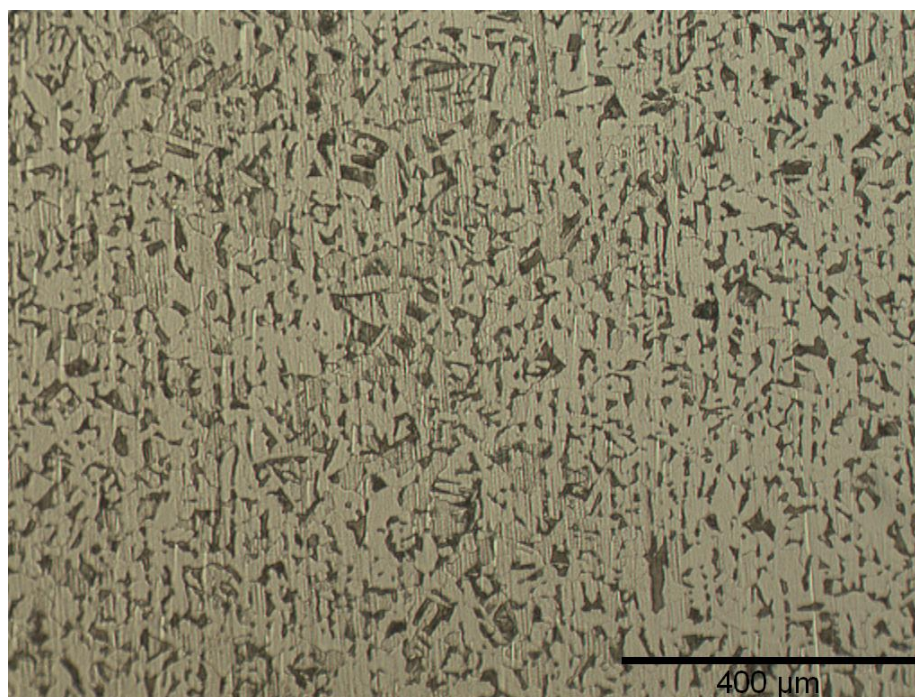


Figure A-7: Micrograph of Core Sample 02-009. 100 X.

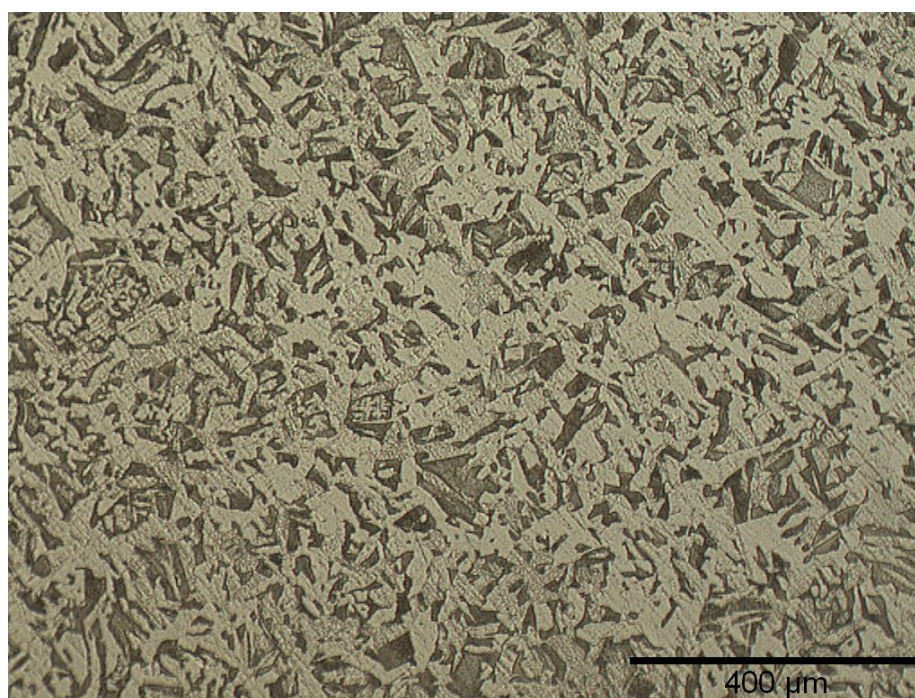


Figure A-8: Micrograph of Core Sample 02-010. 100 X.

Appendix B: Micrographs of Selected Slow-Cooled Samples

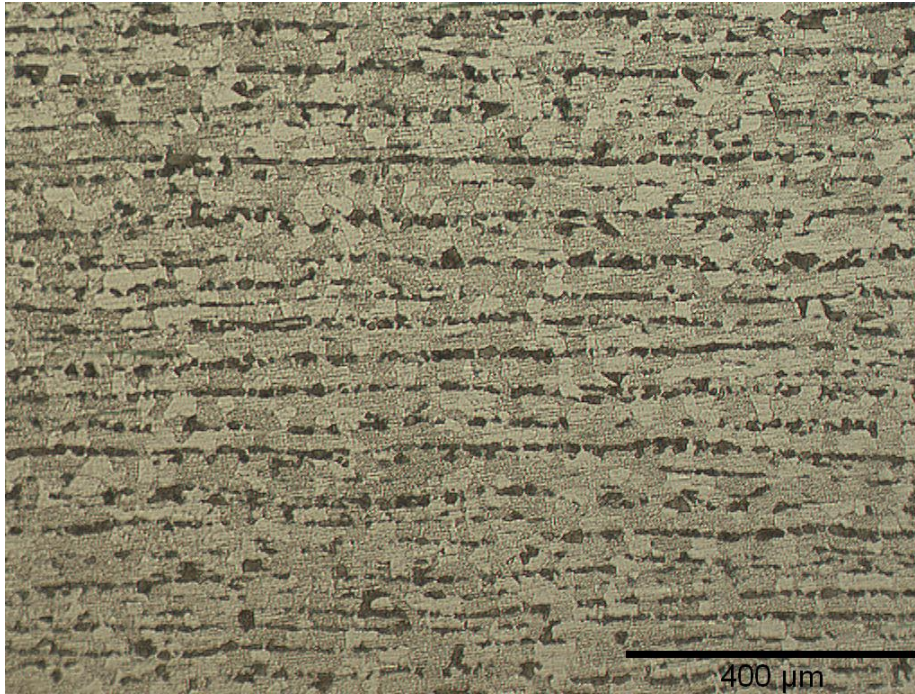


Figure B-1: Micrograph of Slow-cooled Plate A-1. 100 X.

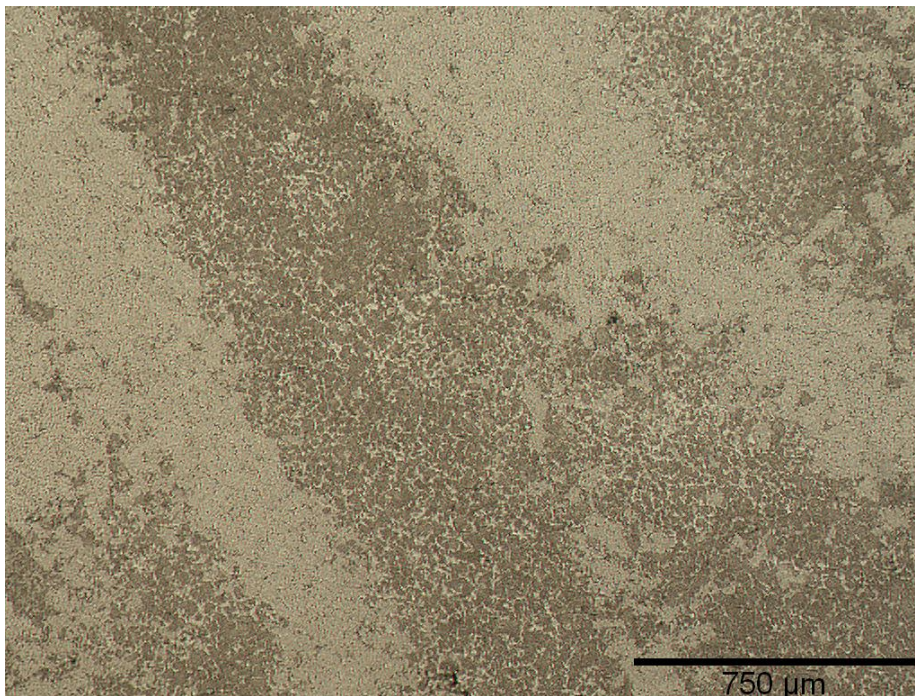


Figure B-2: Micrograph of Slow-cooled Plate A-2. 50 X.



Figure B-3: Micrograph of Slow-cooled Plate A-3. 100 X.

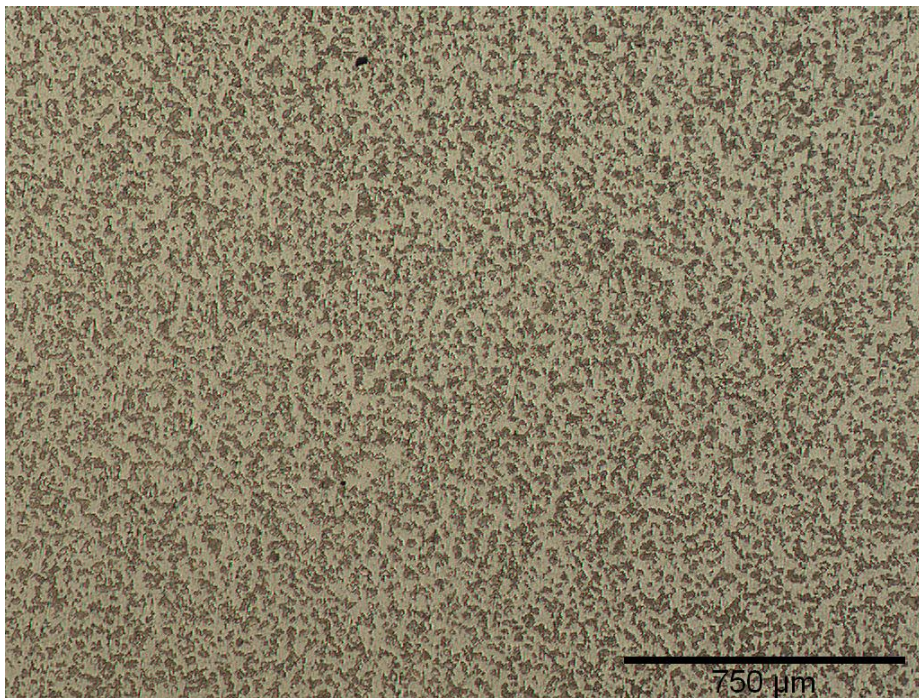


Figure B-4: Micrograph of Slow-cooled Rivet. 50 X.

Appendix C: Selected PAP Testing Tafel Plots

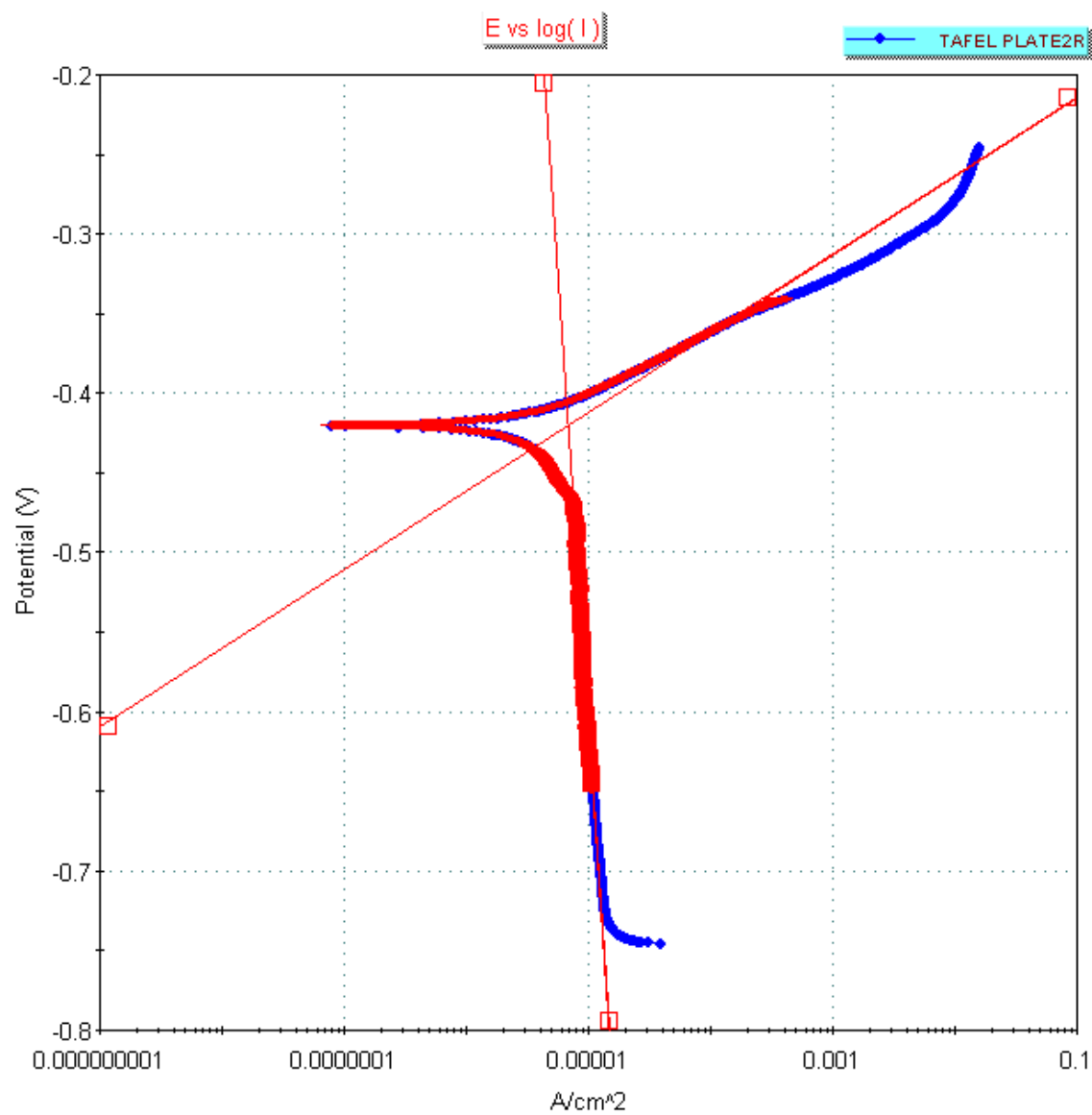


Figure C-1: Tafel Plot Showing the Results of Plate A-2.

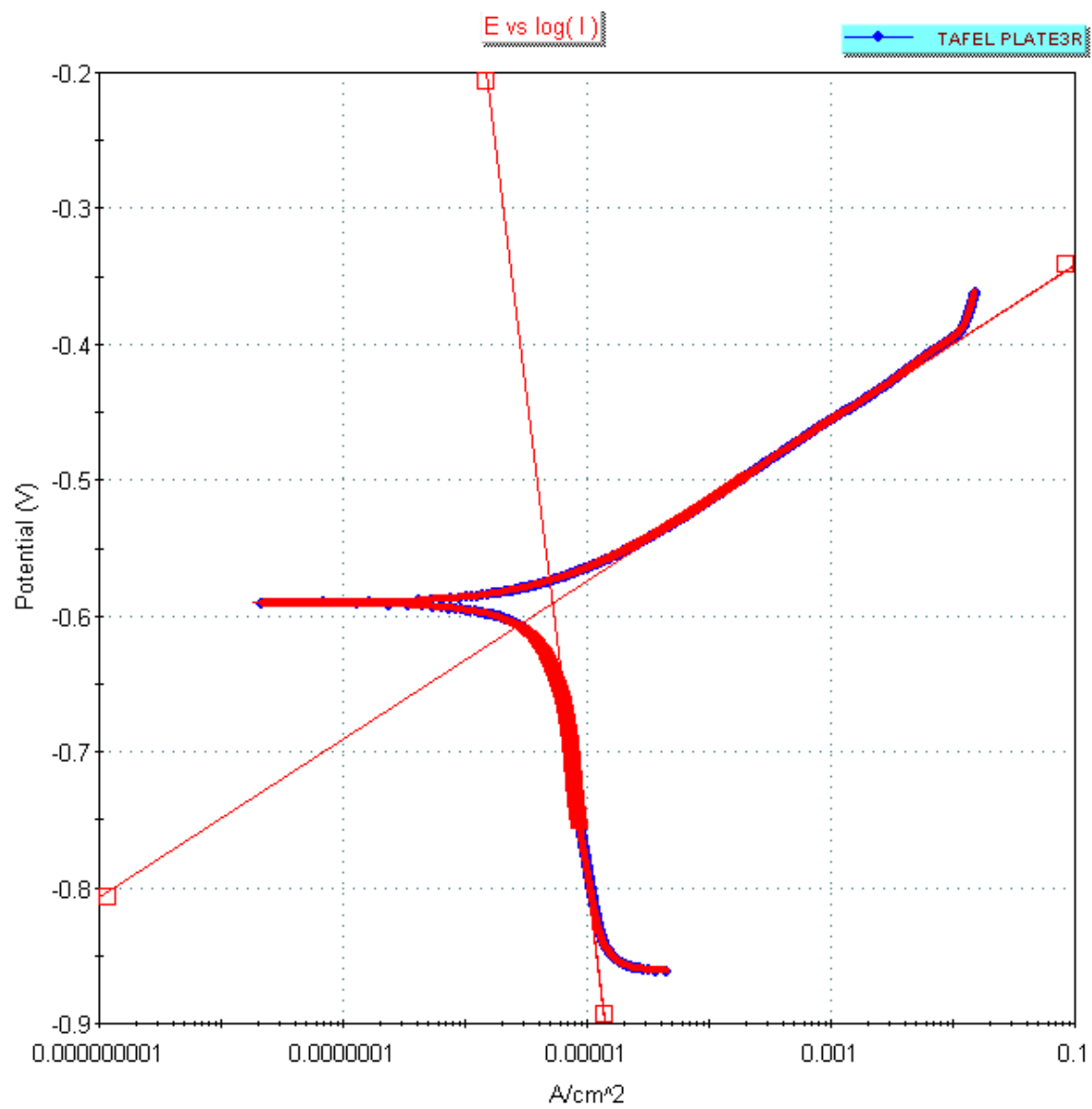


Figure C-2: Tafel Plot Showing the Results of Plate A-3.

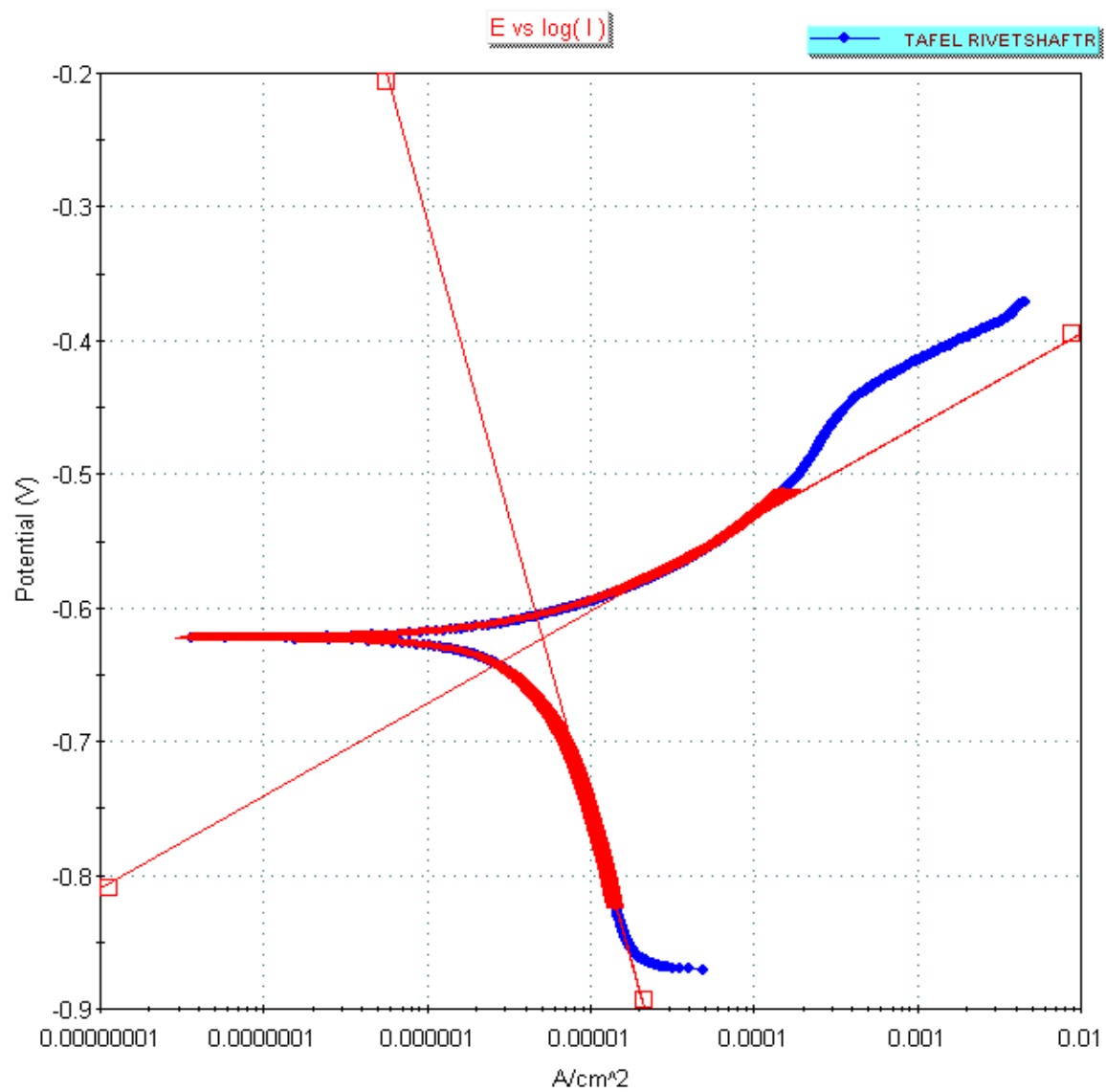


Figure C-3: Tafel Plot Showing the Results of the Rivet Shaft.

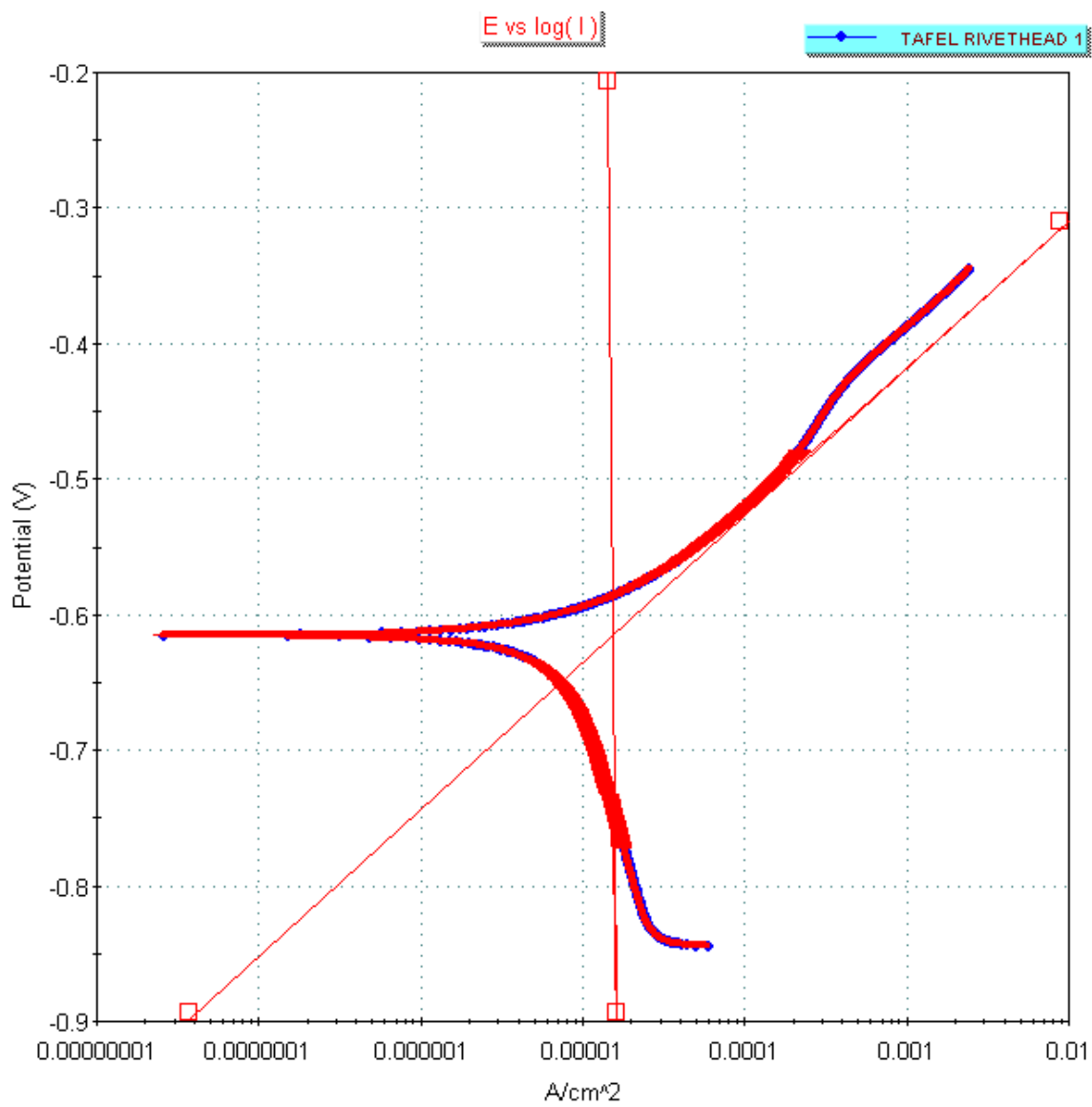


Figure C-4: Tafel Plot Showing the Results of the Rivet Head.