Hawaii National Marine Renewable Energy Center (HINMREC)

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Task 6: Supporting Studies

OTEC Heat Exchanger Program: 2015 Ultrasonic Scanning for Corrosion Monitoring Progress Reports

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May - September 2014

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OTEC HEAT EXCHANGER PROGRAM

ULTRASONIC SCANNING FOR CORROSION MONITORING

STATUS REPORT 1

Prepared For

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1. INTRODUCTION

Corrosion by seawater in Ocean Thermal Energy Conversion (OTEC) heat exchangers is an important process that affects their lifetime and efficiency. Since uniform corrosion rates for Aluminum alloys being considered are low, the primary corrosion mechanisms of concern are surface pitting and crevice corrosion at gasket interfaces. Makai Ocean Engineering is using an experimental setup which allows us to observe pit growth in-situ by both optical imaging and ultrasonic scanning. Imagery allows us to identify pitting sites and observe the buildup of corrosion product on the metal's surface. Once the corrosion product encapsulates the pit, no accurate measurements of pit size or depth can be made with imaging alone. The addition of ultrasonic scanning through the back side of samples allows us to observe the surface underneath the corrosion product and measure the 3-dimensional structure of material loss due to corrosion. With this ability, the development of pits is being monitored over time without removal and destruction of samples. Here we report on the status of our experiment.

2. Status

6 samples of three different aluminum alloys have been exposed to seawater for two weeks and some are already showing corrosion. We are able to detect pit depths in the ultrasonic scans for a couple of the samples. All samples are showing color changes to their surfaces (e.g. Figure 1). Non-uniformity of the darkening could be attributed to uneven flow characteristics since the samples are slightly recessed.

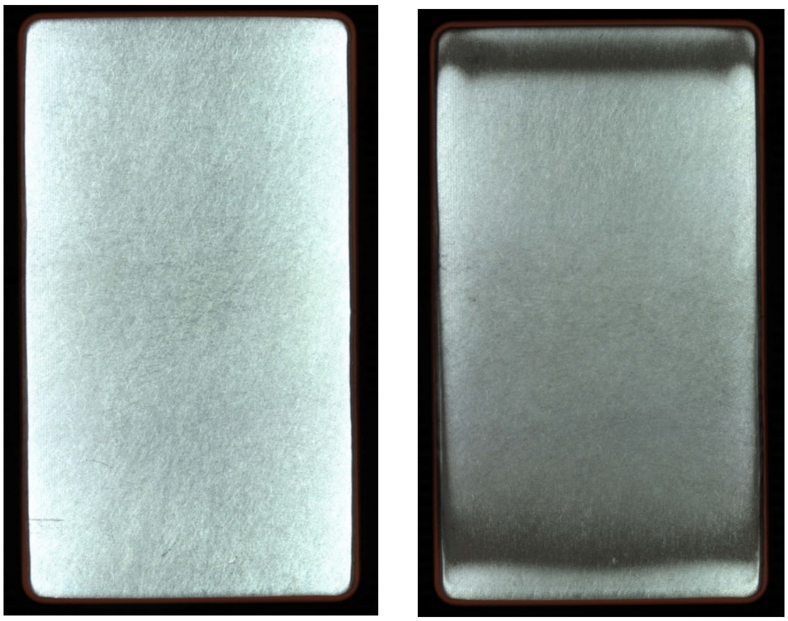

Figure 1: An Al 6061 sample exposed to flowing seawater at 1 day (left) and 15 days (right) showing surface color changes.

Neither 6061 sample has shown any corrosion, but their surfaces have darkened (Figure 1). As anticipated, the Al 2024 samples are corroding quickly and allowing us to confirm our experimental strategy (Figure 2 and Figure 3).

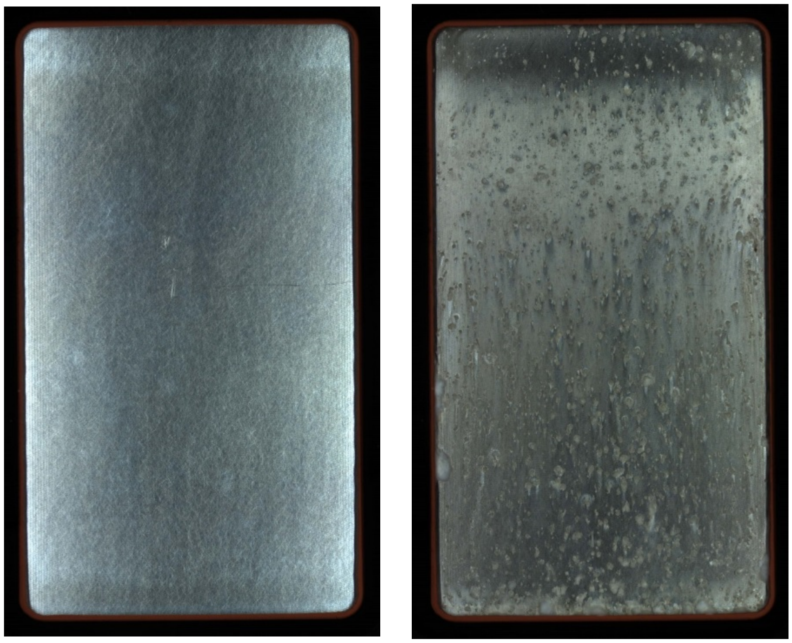

Figure 2: Corrosion development in Al 2024 sample in flowing water at 1 day and 15 days exposure.

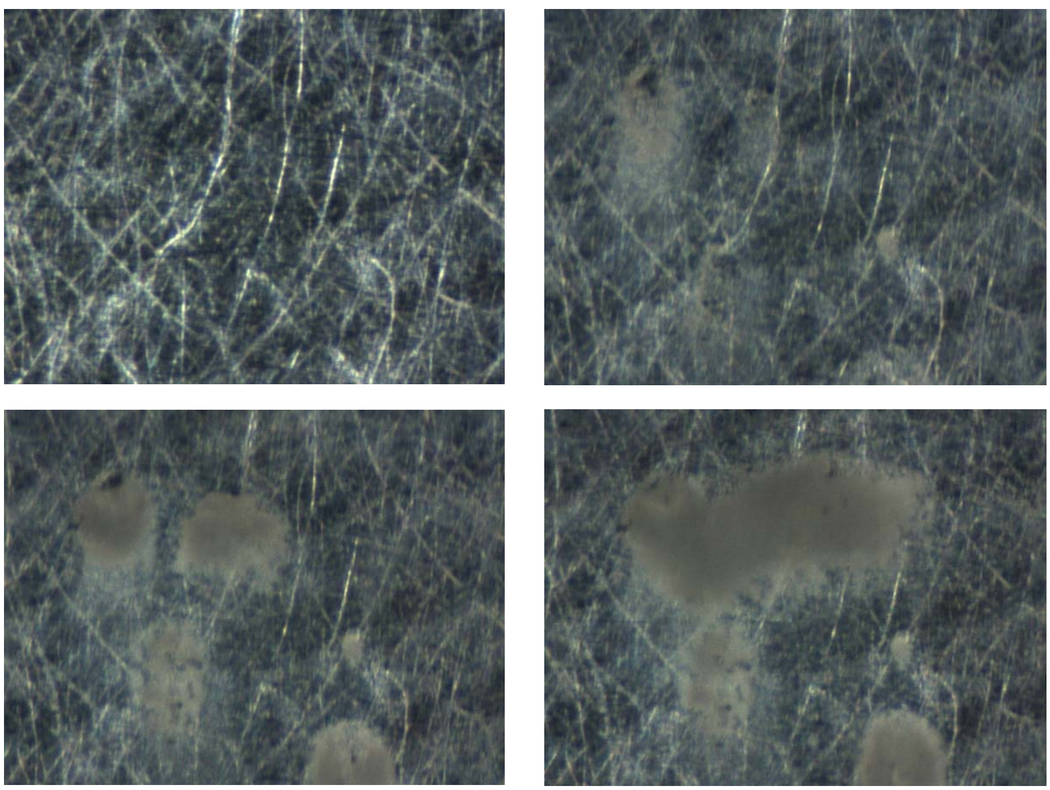

Figure 3: High magnification images (0.04” field of view) of corrosion product accumulation in Al 2024 sample in flowing water at 1, 2, 3 and 4 days exposure.

So far water flow velocity is not making a noticeable difference in the Al 2024 samples' development. We are able to detect multiple pits with the ultrasonic scanner on the Al 2024 samples with depths up to 0.013 inches (Figure 4). Most, but not all, of the pits correlate to regions of visible corrosion product build up on the sample's surface.

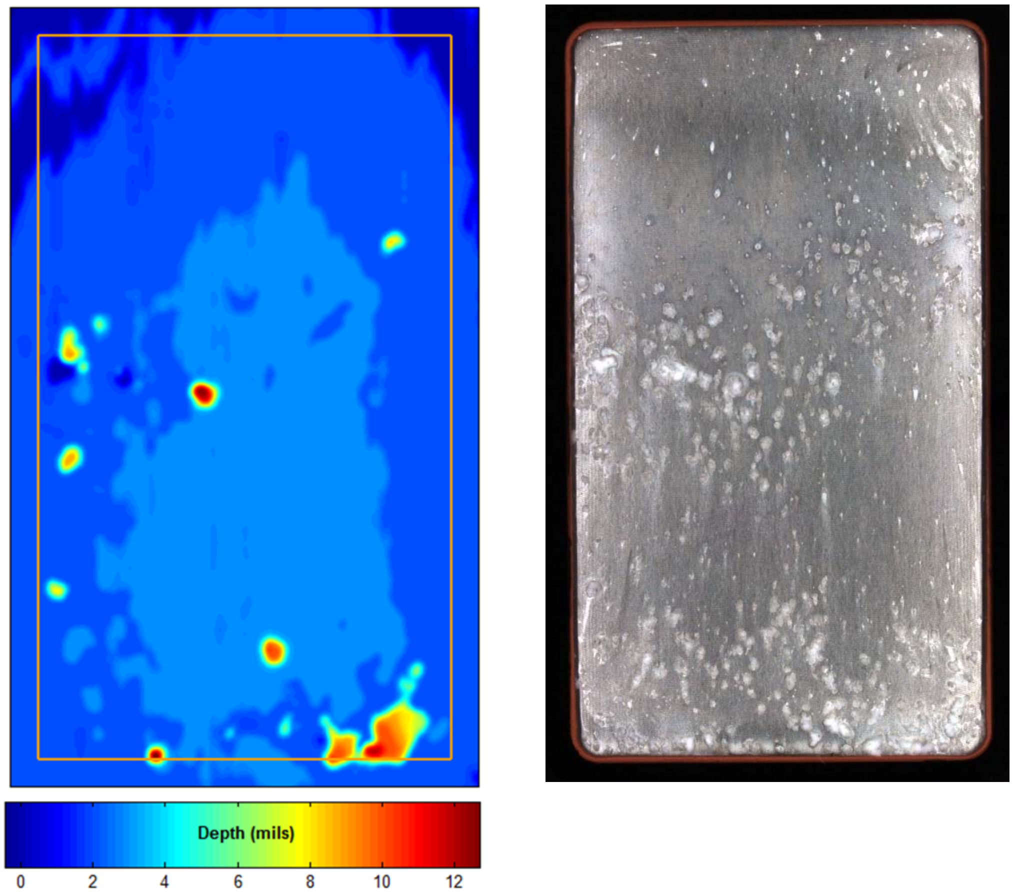

Figure 4: Ultrasonic measurements of sample thickness change (pit depth) and the surface image of the Al 2024 sample in stagnant seawater after 15 days exposure.

The Al 5052 samples are developing differently in the two flow regimes, with crevice corrosion developing on the near stagnant sample (Figure 5) and none yet appearing on the sample in flowing water. In our previous corrosion experiments we noticed that Al 5000 series is more susceptible to crevice corrosion than Al 6000 series. Ultrasonic scanning has yet to detect any pits forming under the corrosion product. Open circuit potential (OCP) measurements show that the stagnant sample has changed from about -950mV to -750mV, while the non-corroding sample has remained constant at about -950 mV. We have observed this change in OCP correlating to pit appearance in our previous studies.

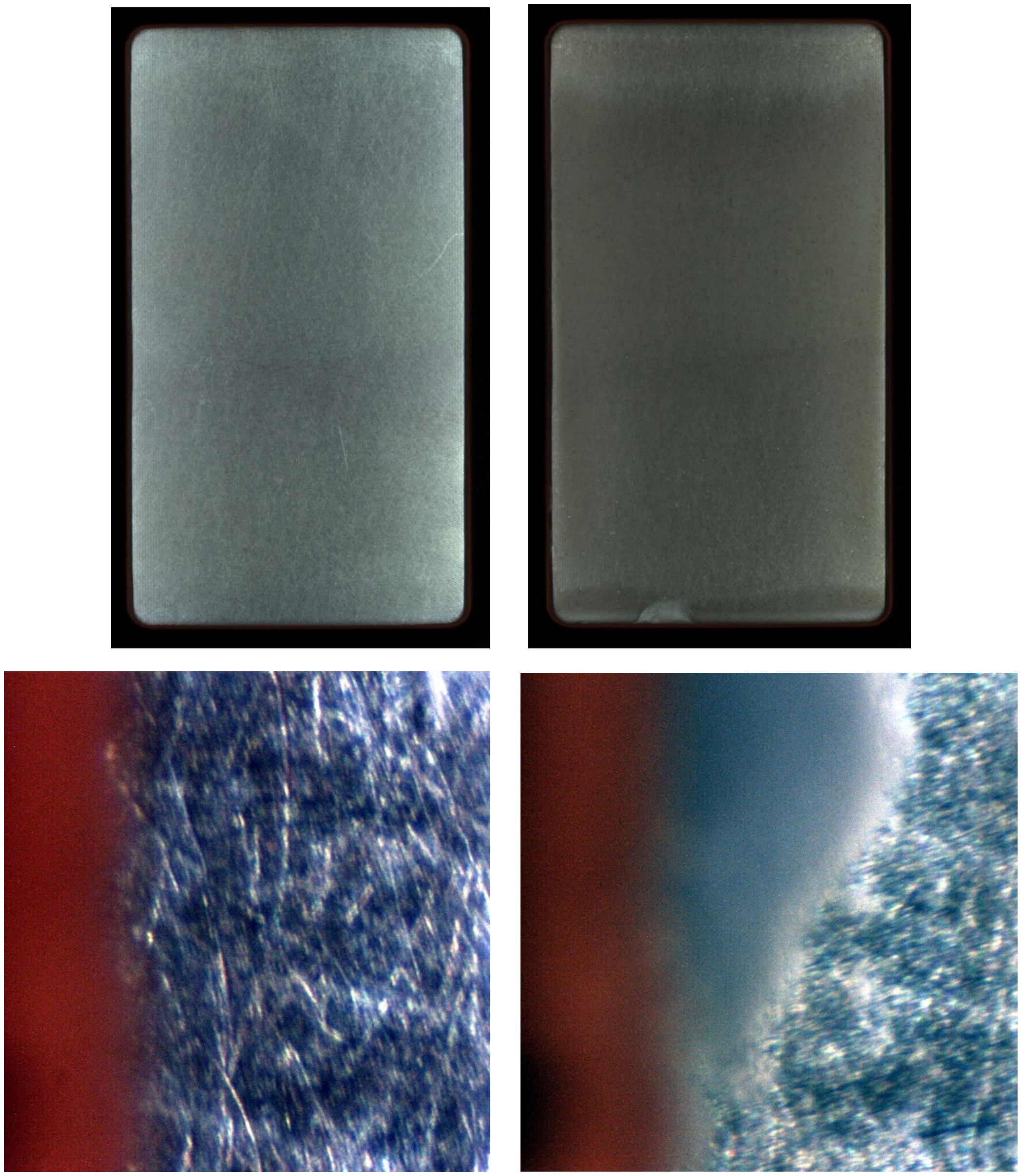

Figure 5: Crevice corrosion development on Al 5082 sample in near stagnant cold seawater. Top – sample at 1 day and 15 days, bottom -- high magnification images of gasket edge at 1 and 8 days exposure. At eight days tool marks on the surface of the sample have diminished.

Ultrasonic scans, imaging and OCP measurements will continue and the status of any corrosion development will be described in our next status report.

OTEC HEAT EXCHANGER PROGRAM

ULTRASONIC SCANNING FOR CORROSION MONITORING

STATUS REPORT 4

SUBAWARD MA140003

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1. SUMMARY

Corrosion by seawater in Ocean Thermal Energy Conversion (OTEC) heat exchangers is an important process that affects their lifetime and efficiency. Since uniform corrosion rates for Aluminum alloys being considered are low, the primary corrosion mechanisms of concern are surface pitting and crevice corrosion at gasket interfaces. Makai Ocean Engineering is using an experimental setup which allows us to observe pit growth in-situ by both optical imaging and ultrasonic scanning. Imagery allows us to identify pitting sites and observe the buildup of corrosion product on the metal's surface. The addition of ultrasonic thickness measurement from the back side of a sample allows us to observe underneath the corrosion product and measure the 3-dimensional structure of material loss due to corrosion. With this ability, the development of pits is being monitored over time without removal and destruction of samples.

After 4.5 months of exposure to deep seawater, samples of Al 2024 and Al 6061 have maximum corrosion depths of 0.78 mm and 1.22 mm respectively. After a few weeks of increasing, the maximum corrosion depth in the Al 2024 samples has leveled off, though the total corroded volume is continuing to increase. The Al 6061 samples continue to show a linear trend of depth vs. time as well as increasing corroded volume. Since the last report we have ultrasonically detected corrosion underneath the gasket in the Al 5086 sample in stagnant water. No corrosion has been observed in the sample of Al 5086 in flowing seawater. The ultrasonic scans are revealing corrosion progressing underneath several samples' gaskets, with the largest lateral penetration of ~ 4 mm and depth of ~ 0.7 mm.

2. STATUS

Corrosion samples have been exposed to both flowing (1 m/s) and near-stagnant cold, deep seawater for 4.5 months. Imaging, ultrasonic thickness measurements and electro-chemical monitoring have been performed on a regular basis.

The accumulation of corrosion product on the Al 2024 and AL 6061 samples continues, though at a slower rate than it initially progressed. Corrosion appears worse at the gaskets in the Al 2024 samples, while on the Al 6061 samples it appears as discreet sites distributed across the surface. The near stagnant Al 5086 sample has developed corrosion product at one of the gasket edges, while in flowing water no corrosion has been detected. Figures 1 – 6 show the latest imaging and ultrasonically measured depths for the 6 samples being tested. There is good correlation between areas covered in corrosion product and the corrosion location detected ultrasonically. The ultrasonic scanner's beam width (~4 mm) makes the pits appear wider in the scans relative to the images, but the corrosion depths measured are accurate to 0.03 mm.

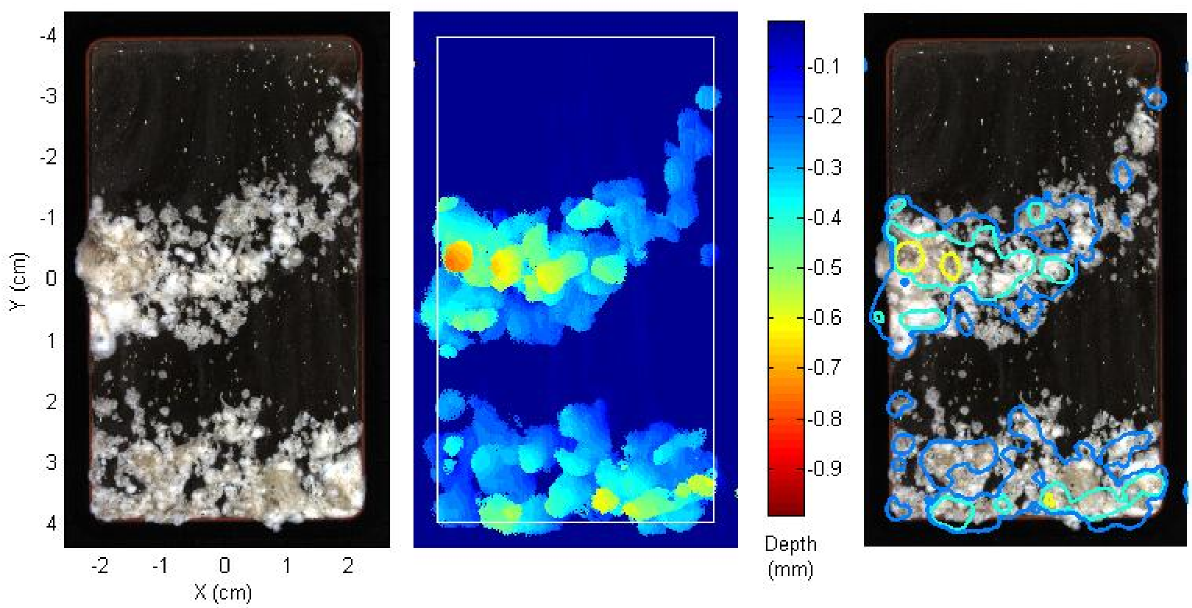

Figure 1: Al 2024 sample in near-stagnant deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images.

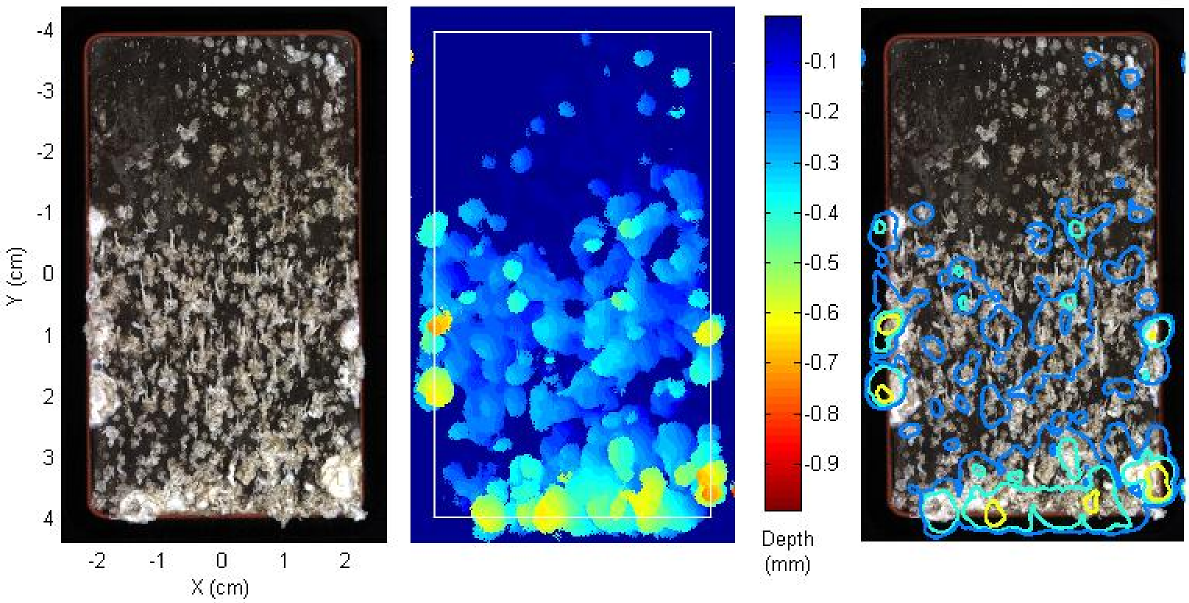

Figure 2: Al 2024 sample in 1 m/s flowing deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images.

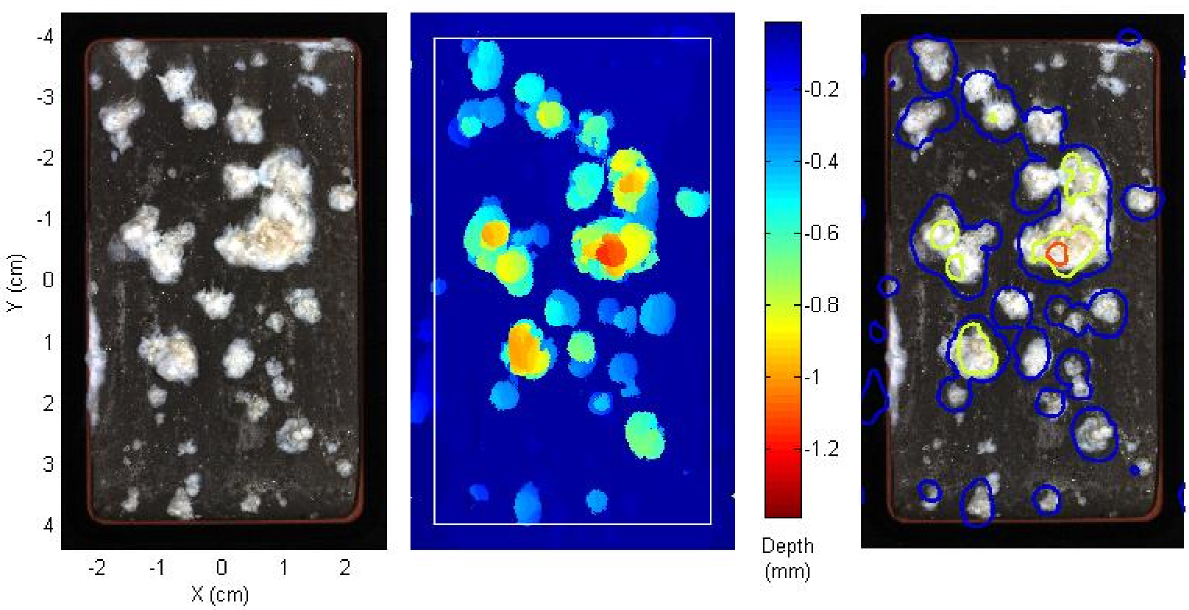

Figure 3: Al 6061 sample in near-stagnant deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images.

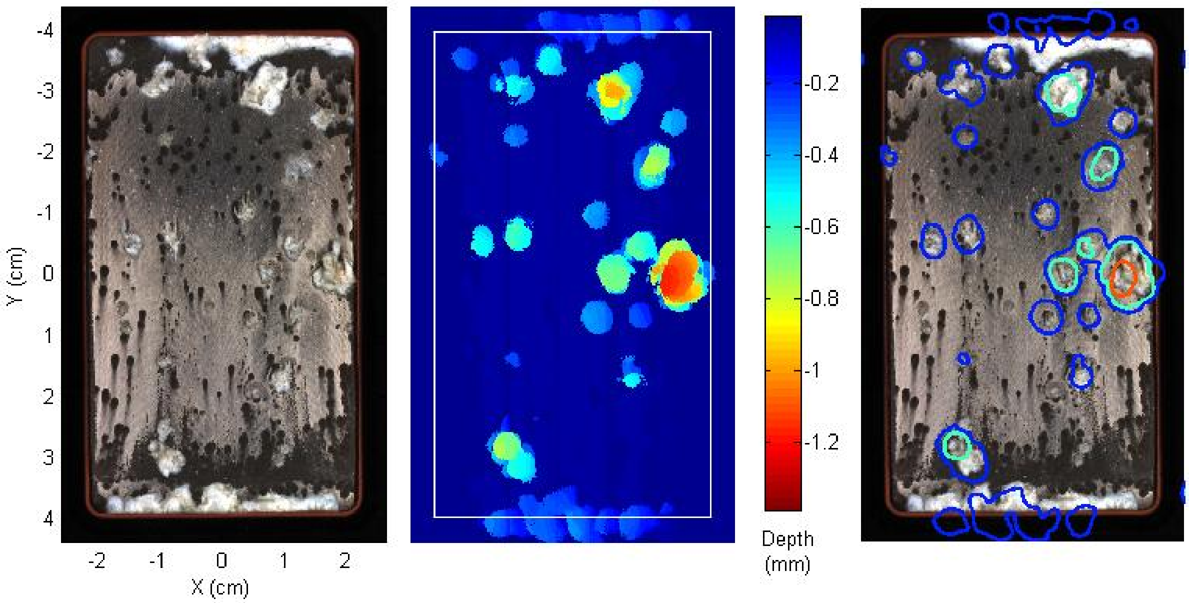

Figure 4: Al 6061 sample in 1 m/s flowing deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images.

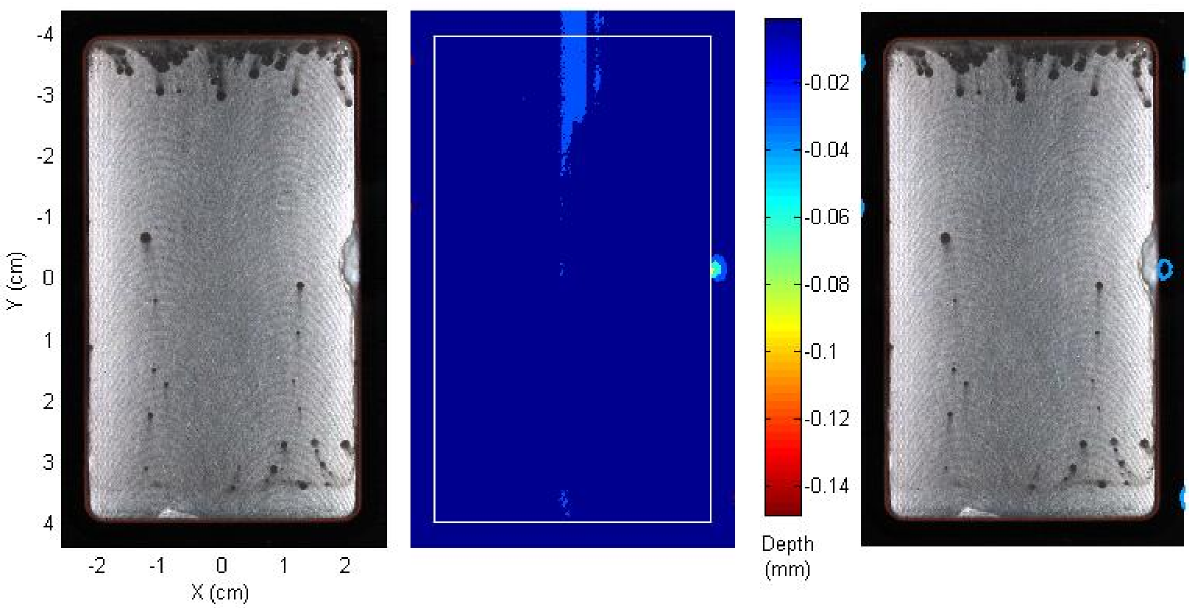

Figure 5: Al 5086 sample in near-stagnant deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images.

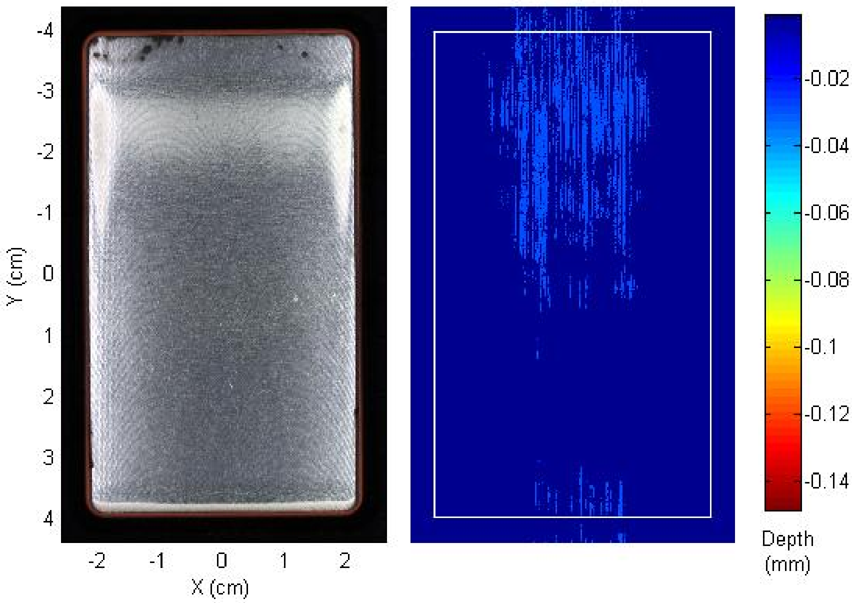

Figure 6: Al 5086 sample in 1 m/s flowing deep seawater at 4.5 months. Left - imaging, center – ultrasonically determined depths, right – overlay of the two images (not shown).

After a few weeks of rapid growth, the maximum corrosion depths in the Al 2024 samples have leveled off at ~0.8 mm. While the maximum corrosion depth is not increasing, the overall amount of corroded volume (indicated by measuring the average depth over the entire surface) is increasing nearly linearly (Figure 7). The Al 6061 samples' corrosion depths and volume are still increasing linearly and currently have maximum depths of 1.2 mm (Figure 8). We have recently detected a small amount of under-gasket corrosion in the near-stagnant Al 5086 sample which is currently 0.1 mm deep.

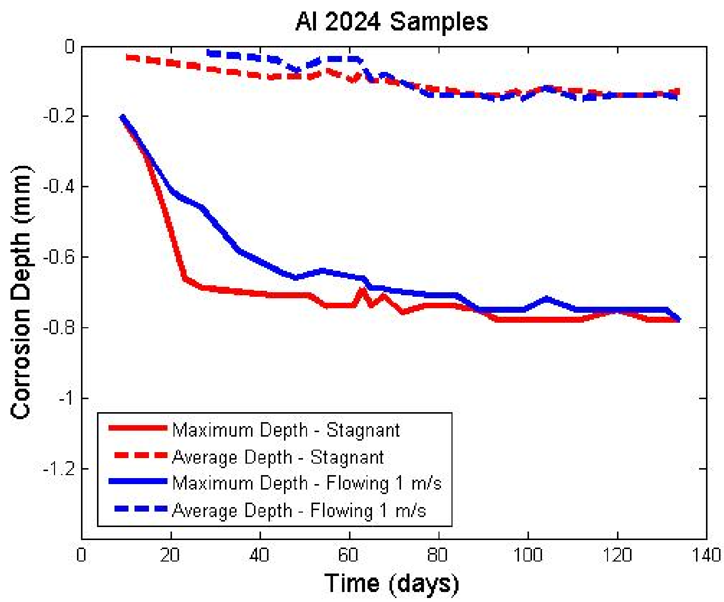

Figure 7: Maximum and surface-averaged corrosion depths measured ultrasonically in the Al 2024 samples.

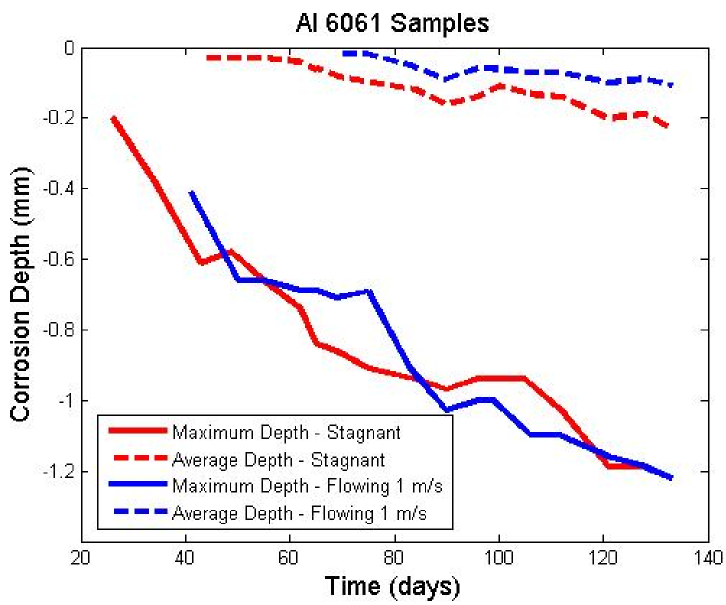

Figure 8: Maximum and surface-averaged corrosion depths measured ultrasonically in the Al 2024 samples.

The ultrasonic scanner is detecting corrosion penetration underneath the samples' gaskets. Figure 9 shows an extreme example of this penetration in the Al 2024 near-stagnant sample. The white lines indicate the location of the gasket edges, with seawater flow on the left and air on the right of the gasket. The prominent red pit seen in all frames is a pre-drilled reference hole that is used to align the images and ultrasonic scans. After day 65 another pit started growing near this hole. This may be corrosion that has penetrated all the way underneath the gasket. However no leaks have been observed in the sample. Table 1 shows the extent of under-gasket corrosion penetration for the samples.

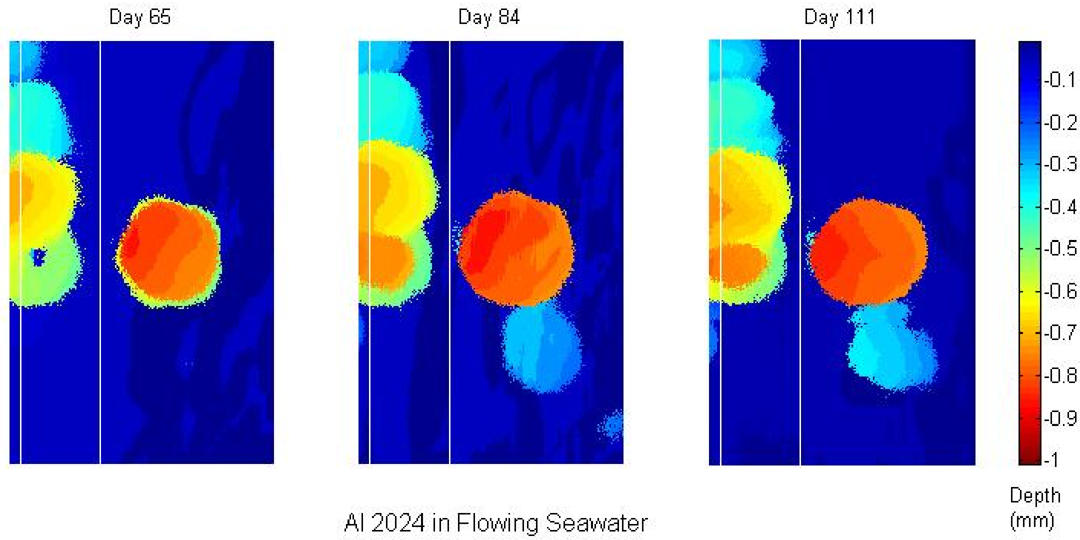

Figure 9: Corrosion appearing outside the gasket in the Al 2024 sample in flowing seawater. White lines are the edges of the gasket, water flows on its left and air to its right. The prominent red pit outside the gasket at day 65 is a predrilled reference hole. After day 65 another pit has been growing.

Source	Sample	Lateral Penetration (mm)	Corrosion Depth Underneath Gasket (mm)
Near-stagnant Seawater	Al 2024	2	-0.5
	Al 6061	3.5	-0.3
	Al 5086	1	-0.1
1 m/s Flowing Seawater	Al 2024	4	-0.7
	Al 6061	3	-0.4
	Al 5086	-	-

Table 1: Corrosion penetration underneath of the gaskets. Lateral penetration is the distance from the inner edge of the gasket to the furthest extent of corrosion.

The most recent open-circuit potential (OCP) of the samples against an Ag/AgCl reference electrode are shown in Figure 10. As noted before, the Al 6061 samples show a dramatic change in OCP when corrosion product is first observed, rising abruptly from approximately -1050 mV to approximately -700 mV. The Al 2024 samples show no such dramatic change to their OCP upon the appearance of corrosion, but are continuing to change over time. The OCP of the two Al 5086 samples are currently different by about 150 mV. It is still too early to confirm, but this may be due to the fact that one sample shows corrosion and the other does not.

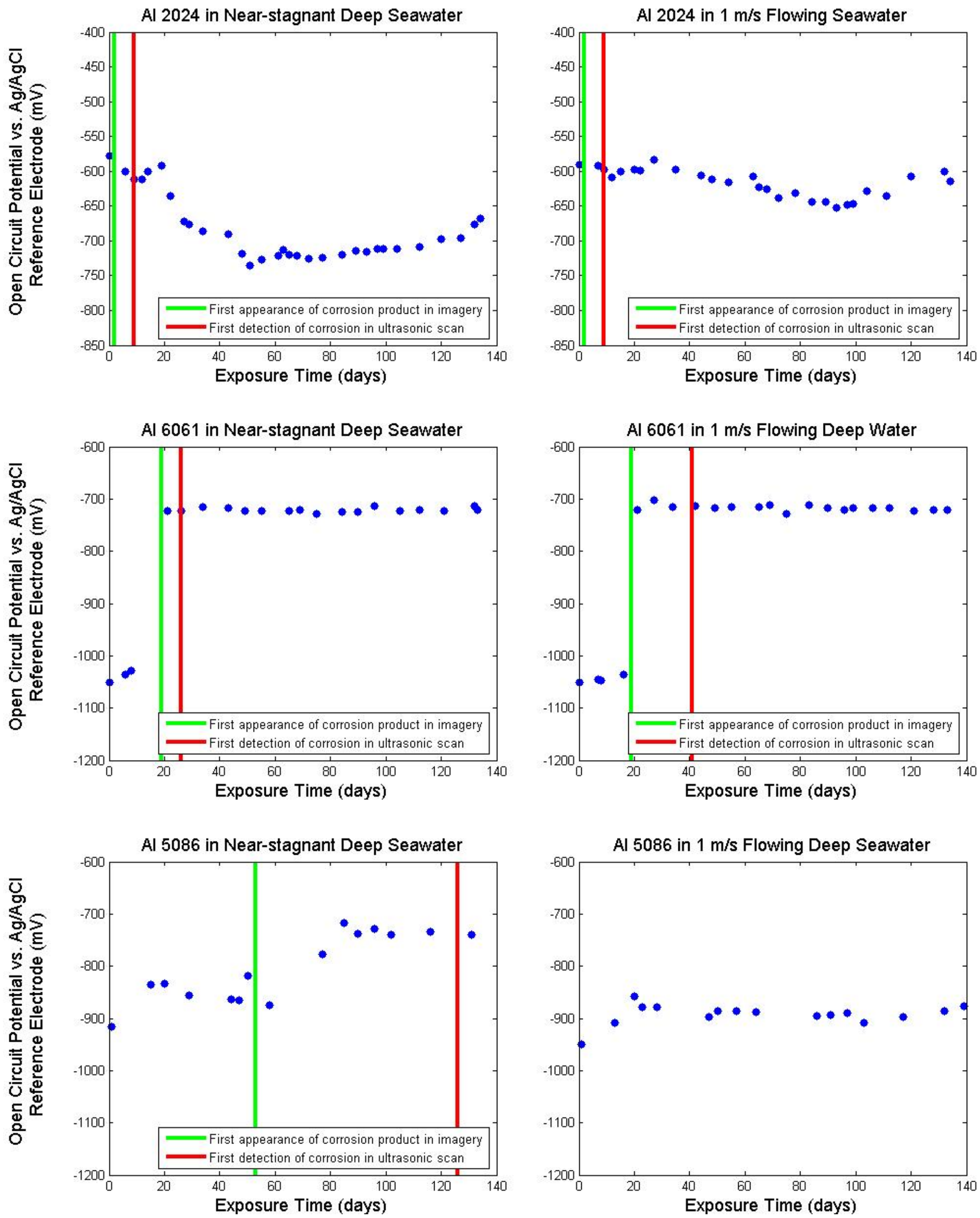

Figure 10: Open-circuit potential measurements against an Ag/AgCl reference electrode.

3. FUTURE WORK

We will continue to monitor the samples and update the current analysis. Our final report will include a complete description of our experimental setup and analysis procedures. Before this report we will remove a sample and conduct a comparison of corrosion depths determined by surface laser profilometry and ultrasonic measurements.