

Evaluation of Bearing Steel Corrosion in Oil Contaminated with Synthetic Seawater

Brandon W. Christoffersen

Boise State University, Department of Materials Science & Engineering
1910 University Dr., Boise, ID 83725

Abstract

Lubricant systems in military aircrafts, operating in marine environments, experience corrosion due to seawater contamination. In particular, low chromium martensitic bearing and gear steels are susceptible to pitting corrosion attack in seawater-contaminated lubricants. Therefore, the corrosion performance of two advance bearing steels was assessed in this study. The steels were immersed in oil solutions and the corrosion results were analyzed as a function of seawater content and time. Optical image analysis was used to measure the pit density/size/distribution and an optical profiler was used to measure pit depth. It was found that while the pit surface fraction (pit surface area/total area) and pit depth increased with seawater content and time, the actual chloride content in the oil might have made a greater contribution to the corrosion damage.

Keywords: Pitting, M50 steel, profilometry

1. Introduction

Stainless steels are widely used for their corrosion resistance, especially in harsh environments.^[1] Chloride contaminated environments, in particular, can cause pitting corrosion and possible failure of steel including stainless steel parts. Even in protective oil, corrosion can still occur.^[2] Information pertaining to the protectiveness of oil towards corrosion can be very useful for many applications.

In order to quantify the effects of chloride concentration on corrosion rates in oil, tests were performed on M50 steel and carburized Pyrowear 675 stainless steel (P675) (provided by Pratt & Whitney), while varying the seawater concentration and studying the corrosion at different lengths of time (1 week and 1 month). Upon test completion, each sample was analyzed by optical image software to determine pit density (pits/area), average pit size, and surface fraction of pits. This was followed by optical profilometry to determine deepest pit depth. The results of these tests show the effect of chloride concentration and time on corrosion rate.

2. Experimental Procedure

Corrosion tests were run on ten M50 samples, and four P675 samples. M50 was tested at 0 water (with 5% seasalt), 500ppm seawater, 2500ppm seawater, 5% seawater, and 30% seawater in oil for both one week and one month. Pyrowear 675 was tested at 5% seawater and 30% seawater in oil for one week and one month. The seawater used in this study had 0.6 mole chloride content. Oil-seawater mixtures were made of Exxon 254 jet oil, ASTM D 1141-52 standard seasalt, and DI water. Prior to testing, all M50 samples were mounted in an epoxy resin and polished to a 1 μm polish. P&W supplied Pyrowear 675 samples with a 1 μm surface finish and no further polishing was performed. Samples were placed in sealable mason jars, with polished side up, containing the various oil/seawater solutions. The seawater-oil solutions were added until the sample surface was located approximately 1/3 depth from the bottom (Figure 1). Upon test completion, the samples were cleansed using a DI water sonic bath, acetone, methanol, and a DI water rinse.



Figure 1. (a) 14 samples stored in 7 sealed mason jars. (b) Close-up photo with a superimposed image indicating how the sample was positioned in the solution.

Analysis began with optical digital photos and micrographs taken on a Zeiss Axiovert 200 microscope. Multiple micrographs, at various magnifications and positions were taken of each sample to provide an overall representation of the surface. Three micrographs were selected for areal analysis. Areal analysis was performed using a Scion Image Alpha 4.0.3.2 instrument. Scion Image distinguishes pits based upon a given threshold value (a sample of an analyzed micrograph with pits shown in red can be seen in Figure 2). The threshold corresponds to the pit size and comparisons of the analyzed image and optical image were used to determine the appropriate threshold value. The Scion Image program was used to quantify the number of pits and the area and perimeter of each pit. It also measured the total size of the area being analyzed. From this data, pit density, average pit size, and the surface fraction that pits covered were determined.

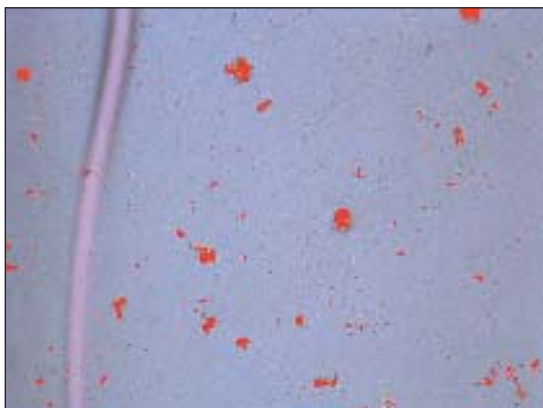


Figure 2. Analyzed micrograph of M50 sample from 2500ppm seawater in oil for 1 week

After analysis, each sample was then surface profiled on a WYKO NT1100 optical profiling system, using Vision 32 3.303 SMU4 Build 5 software by Veeco. Measurements of multiple pits were made to determine the deepest pit on each sample. The deepest pit depths were reported, not the average pit depths, in order to provide useful information regarding critical flaw size.

3. Results & Discussion

Micrographs of the samples can be seen in Figures 3-9. New oil is assumed to contain approximately 150ppm water. The amount of seasalt added is the same as the amount of seasalt that is present in the 5% seawater (0.6 M Cl) solution. This study was performed to understand what might happen if a large quantity of seawater contaminated the oil and then was evaporated off (leaving behind the salt).

As can be seen by the micrographs, only the M50 steel in 0 water, 500ppm, and 2500ppm samples can be analyzed for pitting damage. For the M50 steel, 5% and 30%, the corrosion was more severe and the pitting damage is difficult to quantify. The M50 samples displayed a filiform type of corrosion for the 2500ppm seawater samples, as seen in Figure 5.

Filiform corrosion is a type of crevice corrosion, and has mostly been observed under thin coatings of the organic type. It can most easily be described as worm-looking, with an actively corroding head and an inactive tail filled with corrosion products. Filiform corrosion is generally found to be superficial, and considered not to have a critical effect on the bulk.^[3] More study needs to be done to determine if the corrosion in Figure 5 is indeed a type of filiform corrosion, and therefore

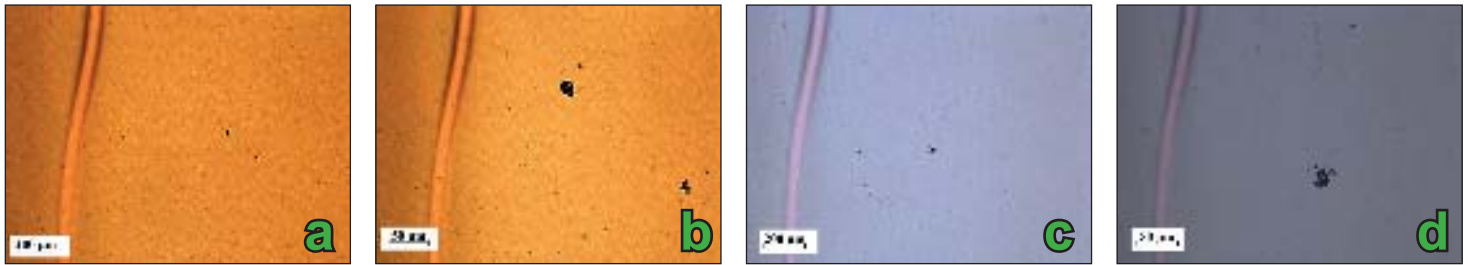


Figure 3. Micrograph of M50 in Oil with seasalt added (no water added) for 1 week, taken with Zeiss microscope (a) 1 week (b) 1 week (c) 1 month (d) 1 month

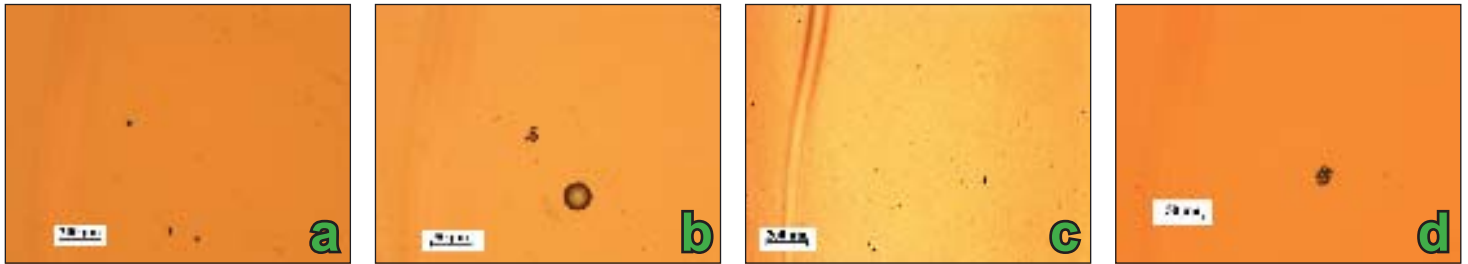


Figure 4. Micrographs of M50 in 500ppm Seawater for 1 week, taken with Zeiss microscope (a) 1 week (b) 1 week (c) 1 month (d) 1 month

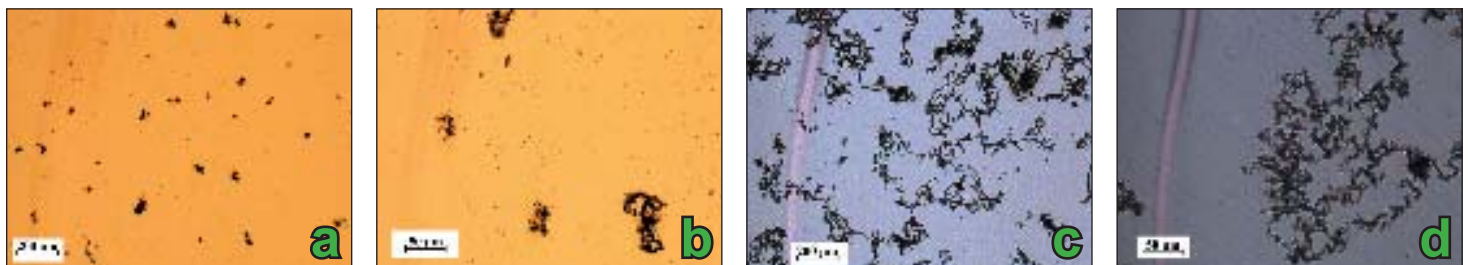


Figure 5. Micrographs of M50 in 2500ppm Seawater for 1 week, with Zeiss microscope (a) 1 week (b) 1 week (c) 1 month (d) 1 month

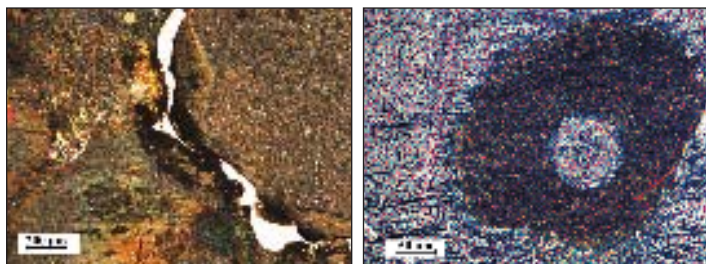


Figure 6. Micrographs of M50 in 5% Seawater for 1 week, taken with Zeiss microscope.

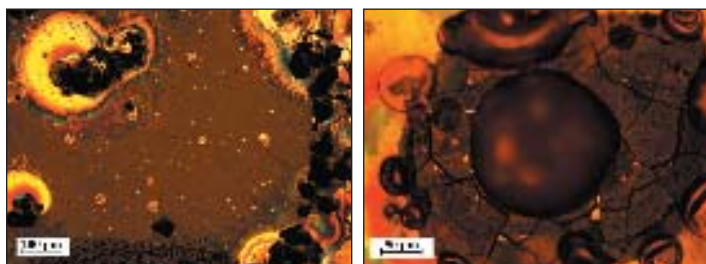


Figure 7. Micrographs of M50 in 30% Seawater for 1 week, taken with Zeiss microscope



Figure 8. Micrograph of Pyrowear 675 in 30% Seawater after 1 week, taken with Zeiss microscope

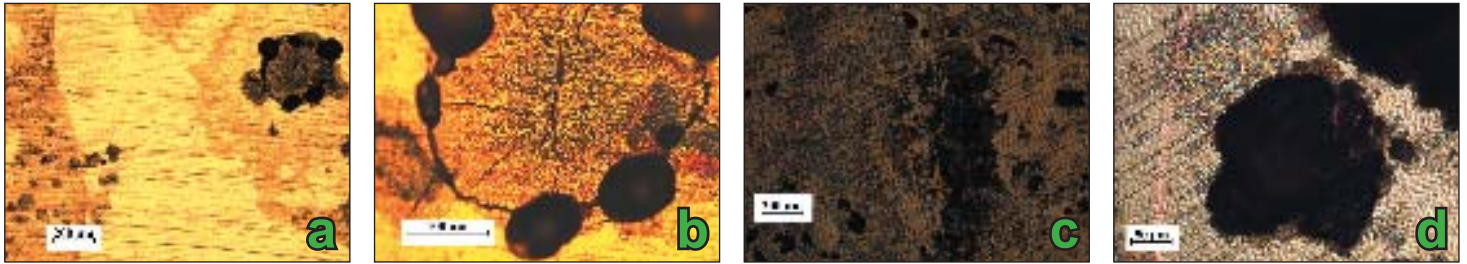


Figure 9. Micrographs showing the localized corrosion region on alloy 2 in 30% Seawater after 1 week, taken with Zeiss microscope (a) 1 week (b) 1 week (c) 1 month (d) 1 month

Seawater in Oil (ppm)	Pits per cm^2 , 1 week	Pits per cm^2 , 1 month
0	6411.7	30467
500	16977	9322
2500	26606	29173

Table 1. Pit density data collected through Scion Image analysis software

Seawater in Oil (ppm)	Average Pit Size (cm^2), 1 week	Average Pit Size (cm^2), 1 month
0	0.00359315	0.00230226
500	0.002917823	0.007781727
2500	0.00516334	0.063750395

Table 2. Average Pit sizes collected through Scion Image analysis software

Seawater in Oil (ppm)	Average surface fraction covered, 1 week	Average surface fraction covered, 1 month
0	0.0043285	0.0070152
500	0.0049357	0.0035867
2500	0.018819	0.13028

Table 3. Average surface fraction covered by pits, determined through Scion Image analysis software

determine how much or how little need for concern there is in these samples.

The transition from pitting to general/severe corrosion is suspected to be somewhere around 4000ppm, but more studies need to be conducted in that range.

For carburized Pyrowear 675 stainless steel, there was very little corrosion, as compared to M50 steel, though some pitting damage was observable. As mentioned, only the harshest conditions were studied at this point for P675 samples (5% and 30% seawater-oil solutions). Figure 8 represents the typical corrosion damage incurred on P675 samples; however P675 does display some localized corrosion phenomenon as depicted in Figure 9. Pitting was observed to initiate at grain boundaries on the samples as evidenced in Figure 9. The areas of attack are considered to be the steel matrix alloy adjacent to the chromium carbide precipitates, but further analysis is needed.

Pit density data ($\# \text{ pits}/\text{cm}^2$) has been collected and is displayed in Table 1 and Figure 10. For the 1 week immersion time, a direct correlation can be seen between seawater content

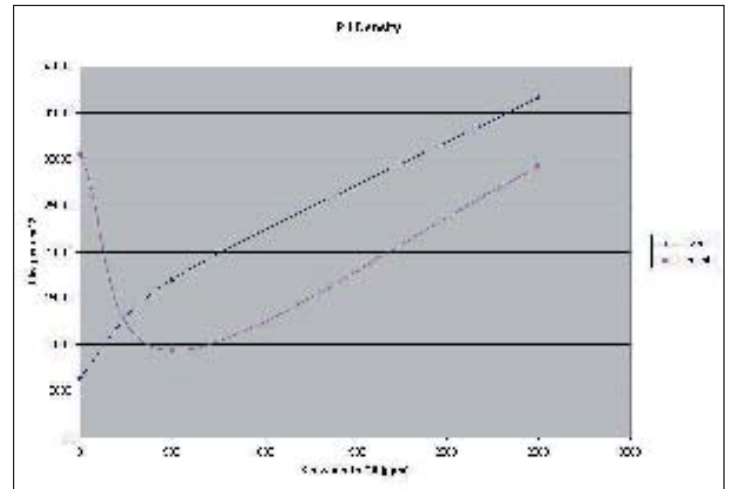


Figure 10. Number of pits per cm^2 in 0ppm, 500ppm, and 2500ppm seawater concentrations for 1 week and 1 month

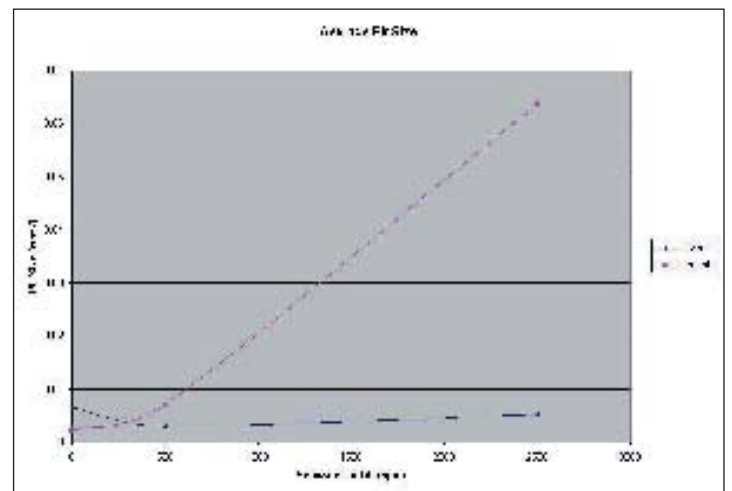


Figure 11. Average Pit Size (cm^2) at 0ppm, 500ppm, and 2500ppm for 1 week and 1 month

and pit density. For the 1 month immersion time, the correlation is not as evident due to the coalescence of pits during pit growth (i.e. the number of pits decrease as multiple pits grow to form one larger pit).

Pit size data (pit area) is listed in Table 2 and is plotted in Figure 11. For the 1 month immersion time, there is a very strong correlation between seawater content and average size of pits, but for the 1 week immersion time, a direct trend of pit size to seawater concentration is not present. This indicates that pitting is not just an effect of seawater content, but also a function of the chloride content in the seawater. This is due to the fact that seasalt (not seawater) was added to the oil for the 0 “seawater added” solution, but there is approximately 150ppm water already present in the oil from air exposure. Therefore, the chloride concentration in this solution is much greater than the others, which might explain the excess pitting for the 1 week M50 sample. More studies, which consider various chloride concentrations in seawater, will need to be carried out to verify the correlation between chloride content and pitting damage.

Taking into account the fact that pits eventually grow together, the best way to express the aerial growth of pits is by quantifying the areal surface fraction occupied by pits. Surface fraction data is listed in Table 3 and plotted in Figure 12. Over the time period of 1 week, surface fraction increases from 0.0042 to 0.0189 as seawater content goes up from 0 to 2500ppm. Over 1 month time, the correlation is even stronger. Surface fraction increases from 0.0066 to 0.1860. This means that at 2500ppm seawater content, almost 19% of the surface is covered by pits after only 1 month time.

Seawater in Oil (ppm)	Deepest Pit Depth (microns), 1 week	Deepest Pit Depth (microns), 1 month
0	2.89	4.06
500	3.61	3.28
2500	2.79	6.6

Table 4. Average surface fraction covered by pits, determined through Scion Image analysis software

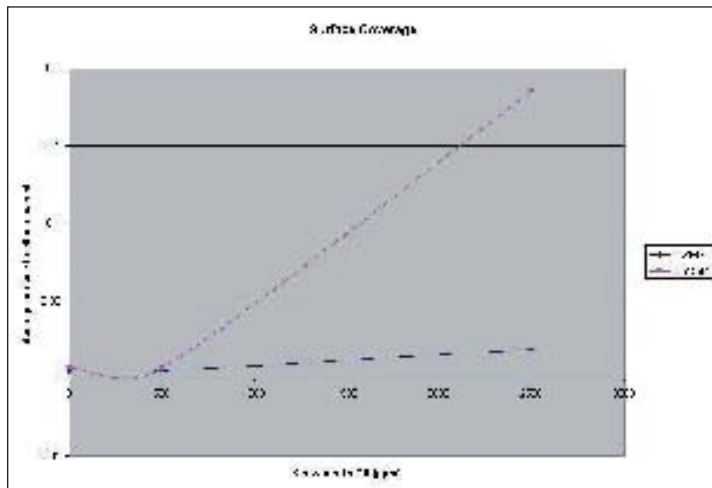


Figure 12. Average surface fraction covered by pits at 0ppm, 500ppm, and 2500ppm for 1 week and 1 month

Pit depths were measured using a WYKO NT1100 optical profiling system, using Vision 32 3.303 SMU4 Build 5 software by Veeco. The deepest pit depth data is presented in Table 4 and plotted in Figure 13. While pit depth would be expected to follow the same pattern as surface fraction, that does not appear to be the case. The pits at 0 water are much deeper than expected (around 4 microns deep). This is possibly due to the 150ppm water already present in the oil dissolving the added salt and making a very high chloride concentration seawater. This high chloride concentration seems to have as much or more of an effect on pit depth (and even pit size) than the seawater content has. For this solution, seasalt was directly added to the oil (not seawater). The amount of seasalt added is the same as the amount of seasalt that is present in the 5% seawater solution. This study was performed to understand what might happen if a large quantity of seawater contaminated the oil and then was evaporated off (leaving behind the salt).

The 2500ppm seawater content solution does not seem to cause pits to grow very deep early on but after 1 month’s time, they are as deep as 6.6 microns. Some of the optical analysis images are shown in Figures 14-16.

5. Conclusion

It has been found that surface fraction is the best way to quantify the pitting damage. Surface fraction of pitting has an obvious correlation with seawater content and time. Pit depth also shows a correlation with seawater content and time, but seawater content and time are not the only factors in pit growth. It has been shown that higher molarity of the seawater causes larger and deeper pits, and may be more crucial to pit depth

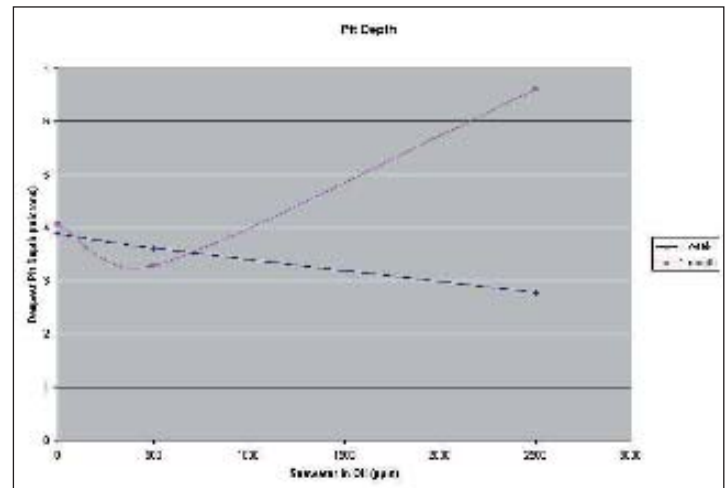


Figure 13. Deepest pit found per sample through optical profilometry

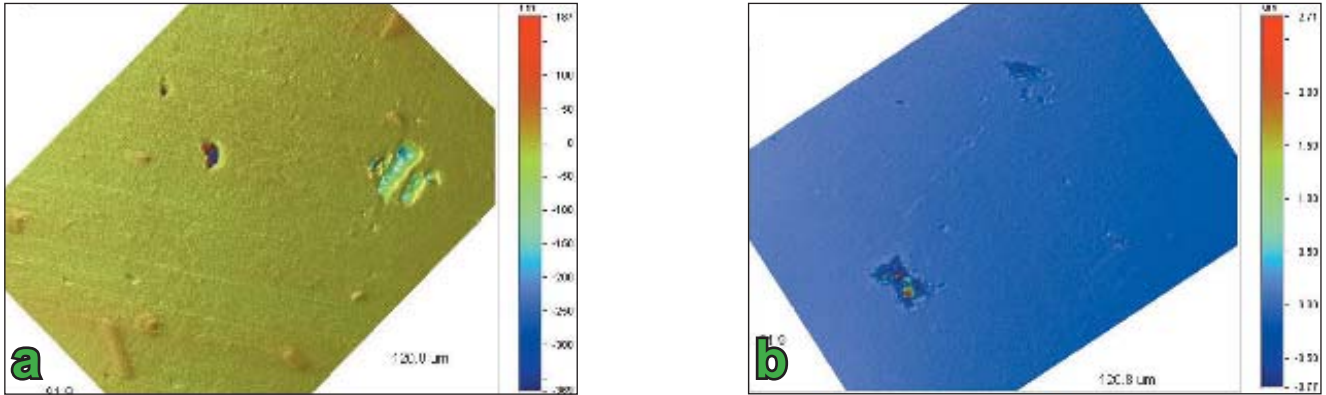


Figure 14. Optical profilometry images used to quantify pit depths in M50 after being immersed in 0ppm seawater added (≈ 150 ppm water present in the oil) for (a) 1 week (b) 1 month

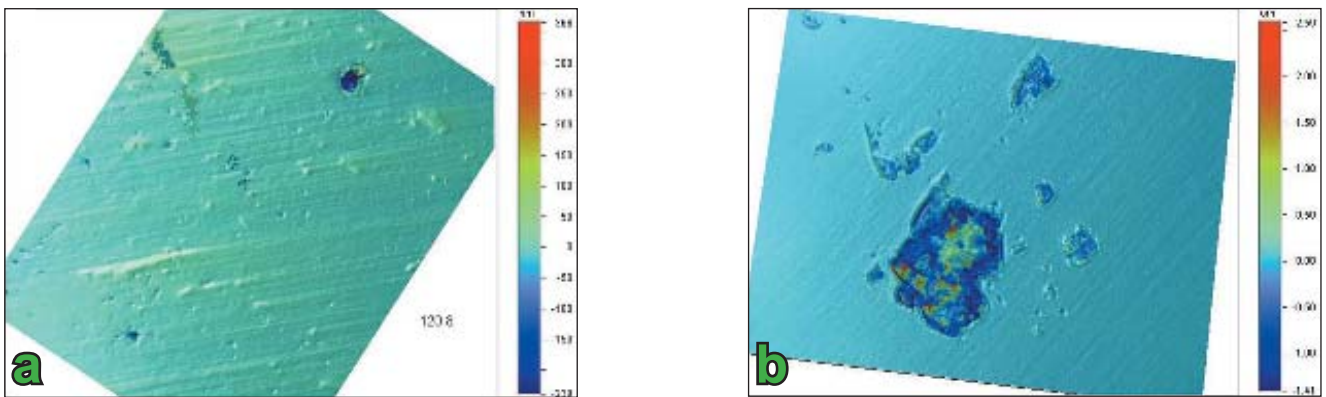


Figure 15. Optical profilometry images used to quantify pit depths in M50 after being immersed in 500ppm seawater (0.6 M Cl⁻) + oil solution for (a) 1 week (b) 1 month

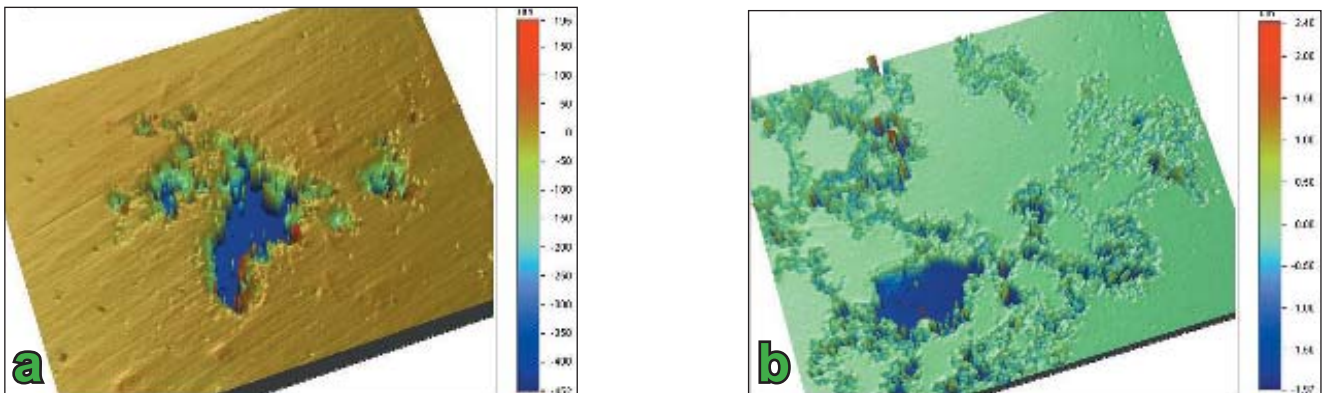


Figure 16. Optical profilometry images used to quantify pit depths in M50 after being immersed in 2500ppm seawater (0.6 M Cl⁻) + oil solution for (a) 1 week (b) 1 month

than seawater content. A note should be made that there is an obvious corrosion resistance advantage in P675 as compared to M50.

Acknowledgements

This work was done at Boise State University under supervision of Dr. Darryl P. Butt, with help from the following group members: Post Docs: Dr. Brian Marx and Dr. Abdel Salam Maklout; Students: Mathew Luke, Gordon Balfour, Brian Jaques, Patrick Callahan, and Prakash Periasamy.

Thanks to Pratt & Whitney for financial support, and special thanks to Herb Chin, Bill Ogden, and Curtis Genay of Pratt & Whitney. Thanks to Dr. Sean Donovan and Pete Miranda for help with sample preparation and optical profilometry.

References

- [1] Tsutsumi, Y.; Nishikata, A.; Tsuru, T. *Corrosion Sci.* **2007**. *99*. 1399-1407.
- [2] Lin, C.M.; Chiou, Y.C.; Lee, R.T. *Wear.* **2001**. *249*. 132-141.
- [3] Jones, D.A. *Principles & Prevention of Corrosion*. Prentice Hall: Upper Saddle River, NJ, 1996. 224-226.

About the Author



Brandon Christoffersen is currently a senior at Boise State University. He is pursuing a Bachelor's in Materials Science & Engineering and is a two-time National Science Foundation Scholar in Materials Science. He has spent the last two years doing research in the Advanced Materials Laboratory at Boise State, under Dr. Darryl P. Butt. Much of his research has focused on steel alloys and their surface behavior in marine environments. He has also done some work in nitride coatings, and powder characterization. In addition, Brandon is a captain on the Track & Field and Cross-Country teams for Boise State.