FRETTING FATIGUE BEHAVIOR OF SHOT-PEENED TITANIUM ALLOY TI-6AL-4V UNDER SEAWATER CONDITIONS

THESIS

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Abstract

The fretting fatigue behavior of the shot-peened titanium alloy, Ti-6Al-4V, was investigated under a corrosive environment of synthetic seawater. Fretting fatigue tests were performed over a wide stress range to determine the effect of seawater at high and low cycle fatigue regimes. The results from this study showed: (1) seawater significantly reduces the fretting fatigue life of shot-peened Ti-6Al-4V at both high and low cycle fatigue relative to its counterpart in ambient laboratory conditions, (2) shot peening increases the fretting fatigue life of Ti-6Al-4V when tested under dry and seawater conditions relative to its counterpart of unpeened Ti-6Al-4V, (3) surface debris from samples tested under seawater conditions contained large quantities of oxide and seawater contaminants, (4) cleaning after testing removed most of the oxide and seawater contaminants from the sample.

Acknowledgements

I would like to thank my thesis advisor, Dr. Shankar Mall, for his patience, guidance, and support throughout this thesis project. I would also like to thank Dr. Hyukjae Lee for his technical support and guidance during this process. Finally, I would like to sincerely thank Captain Lewis Lietch who without which this thesis would not have been possible.

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NOMENCLATURE

BSE	Back scatter emission
SEI	Secondary electron imaging
EDS	Energy dispersive spectroscopy
N_f	Number of cycles to failure
P	Normal load
Q	Tangential load
Q_{max}	Maximum tangential load
Q_{min}	Minimum tangential load
R	Axial stress ratio
SEM	Scanning electron microscope
V	Lower applied axial load
W	Upper axial load
σ_{axial}	Axial stress
$\sigma_{axial,max}$	Maximum axial stress
$\sigma_{axial,min}$	Minimum axial stress
σ_{max}	Maximum applied stress
σ_{min}	Minimum applied stress
σ_{eff}	Effective stress

FRETTING FATIGUE BEHAVIOR OF SHOT-PEENED TITANIUM ALLOY TI-6AL-4V UNDER SEAWATER CONDITIONS

I. INTRODUCTION

Fretting induces surface damage caused by the application of a tangential oscillatory force between two contacting surfaces. Under cyclic loading conditions, this process is known as fretting fatigue. Fretting generates higher stresses at the contact surfaces resulting in surface wear and cracks. Once these cracks are initiated, the bulk stresses become concentrated on this region and accelerate crack propagation, eventually leading to component failure. Fretting fatigue is evident once these surface cracks propagate from the surface into the bulk material, which significantly reduces its fatigue strength. This phenomenon causes both a reduction in component life and an increase in maintenance costs. The United States Navy is especially concerned with fretting fatigue as it is found to be the cause of failure in many aircraft components. Figure 1 presents the blade/disk dovetail joint in gas turbine engines that frequently fails due to fretting fatigue.

Environmental factors are known to affect the amount of damage caused by fretting fatigue. This is clearly evident in corrosive environments where seawater can chemically damage material by breaking down their protective coatings. The United States Navy is especially concerned in this area due to the aggressively corrosive environments their aircraft operate in. The majority of a naval aircrafts life is spent flying in a corrosive environment, whether it is deployed on an aircraft carrier or naval base. The Navy has set up programs such as the U.S. Navy Aircraft Corrosion and

Prevention Control Program in order to stay on top of the growing corrosion problem. Currently, the Navy estimates spending $200,000 per aircraft per year on corrosion maintenance. With approximately 4,000 active naval aircraft, this estimate comes to $800 million a year [1].

The effect of corrosion on fretting fatigue varies depending on the material under consideration. Titanium alloys are widely used in aircraft component parts due to their high strength-to-weight ratio, high operating temperatures, and corrosion resistance when compared to steels and aluminum alloys. This material is widely used in gas turbine engines for disks, blades, shafts, casing, and fasteners. Ti-6Al-4V is the most common titanium alloy used in the aviation industry today. Its excellent corrosion resistance is due to an oxide film that provides it with protection from corrosive agents such as seawater [2].

Surface modifications have been used to try and adjust the mechanical properties of a material and increase its fatigue life. Shot peening is a cold-working method used to increase resistance to fatigue as well as stress corrosion cracking. Shot peening consists of bombarding the metal surface with hard, small steel shot. This method changes the surface roughness as well as introduces a compressive residual stress on the surface of the material. This compressive residual stress is known to increase the materials resistance to crack initiation thus aiding in fatigue life. Shot peening is also said to reduce and even eliminate environmental corrosive effects due to refined surface homogeneity, increased inter-granular adhesion and decreased micro-porosity [3].

In an effort to evaluate the effect of saltwater on aircraft components, this study will investigate the fretting fatigue behavior of shot peened Ti-6Al-4V under seawater conditions. Due to the complex nature of the aircraft, it was not possible to replicate the actual system in the laboratory. The geometry and loading conditions were simplified in order to properly evaluate the effect of fretting fatigue on the shot peened samples. Figure 2 shows the simplified experimental setup used in this study. The fretting fatigue pads were pressed against the specimen with a constant normal load, P, using lateral springs. The servo-hydraulic test machine was used to impose an axial stress, σ_{axial}, on the fretting fatigue specimen. This axial stress introduced a tangential load, Q, which was dependent on the coefficient of friction between the pads and the specimen and the stiffness of the springs.

In this study, synthetic seawater was applied to the specimen throughout the experiment in order to imitate the effect of seawater exposure. Figure 3 shows the experimental configuration of the seawater application system. The seawater was applied between the specimen and the pads for two seconds every minute. This resulted in a flow rate of approximately five mL a minute on each side of the specimen/pad contact surface.

The applied axial loads were varied in order to obtain data at both high and low cycle fatigue. A plot of effective stress, σ_{eff}, versus the number of cycles to failure, N_f, was established for the shot-peened specimens tested under seawater conditions. A similar study was performed by Lietch [4] with unpeened Ti-6Al-4V fretting specimens in saltwater and open-air conditions. It showed that seawater reduced the fretting fatigue life of titanium alloy in low cycle fatigue and increased it in high cycle fatigue. This study will also utilize the data from a previous study [5] performed on shot-peened Ti-6Al-4V under dry conditions in order to determine the effect of saltwater on the fatigue life of shot-peened titanium alloy.

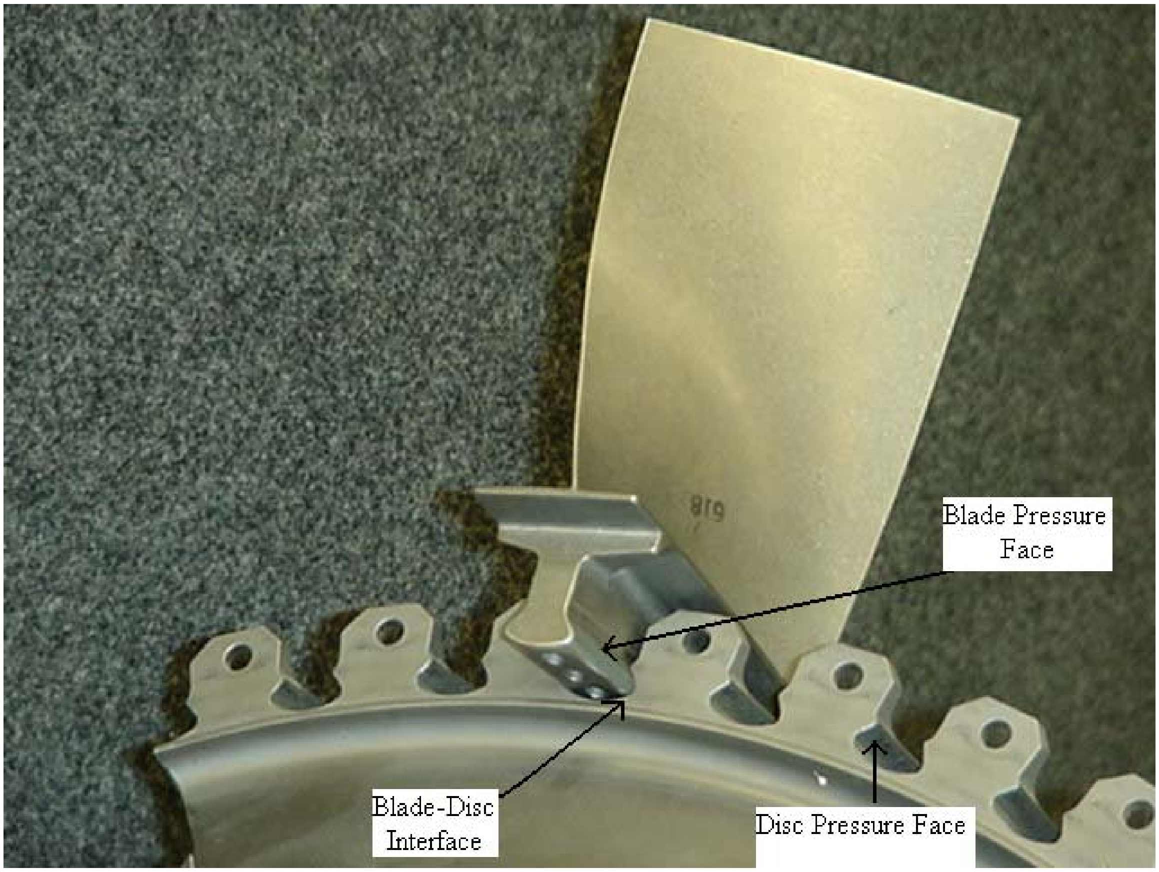


Figure 1. Blade/Disc Dovetail Joint in Turbine Engine.

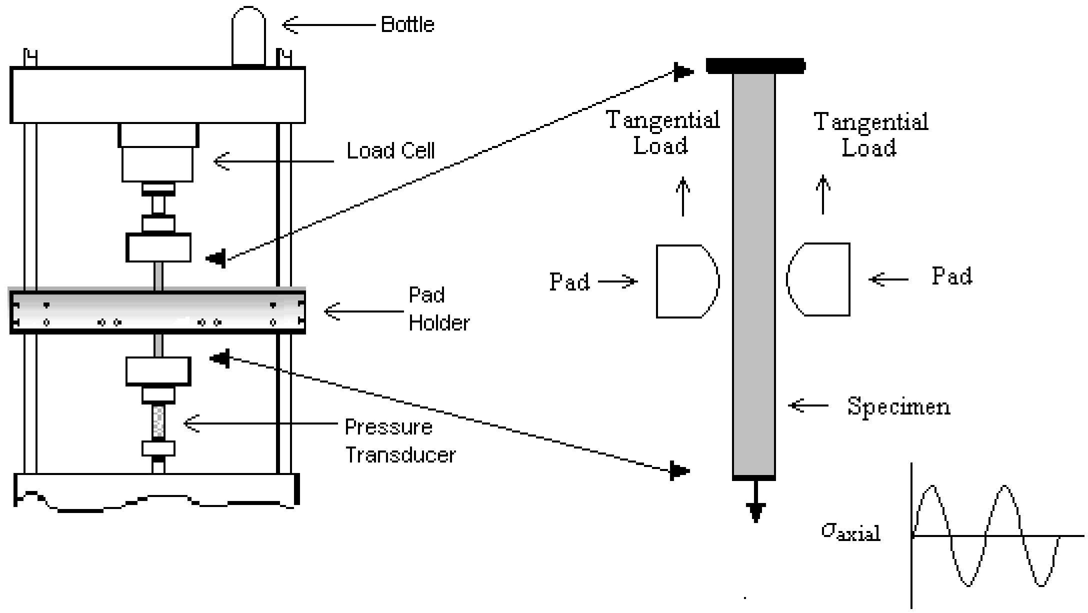


Figure 2. Fretting Fatigue Experimental Configuration.

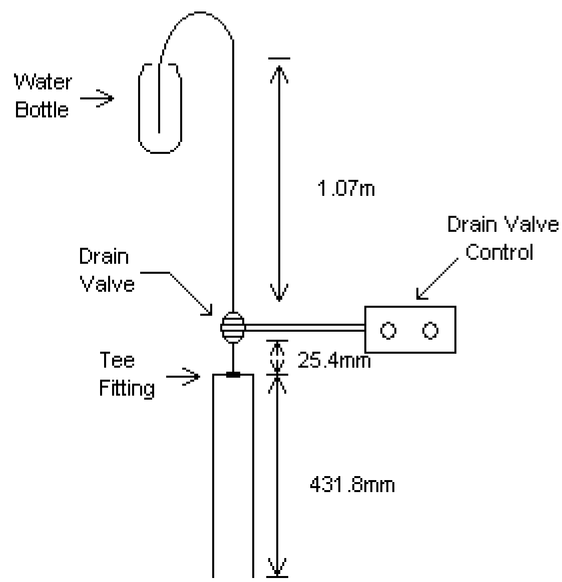


Figure 3. Seawater application apparatus schematic.

II. BACKGROUND

In this chapter, different approaches and conclusions made by the previous researchers in the field of fretting fatigue will be discussed. The mechanical, chemical and environmental mechanisms affecting fretting fatigue will be covered first, followed by the effects of shot-peening on the process. Finally, the fatigue parameters used during this investigation will be presented.

Variables affecting fretting fatigue

Originally, fretting was thought to be a purely mechanical process. In recent years, there have been many studies supporting the statement that fretting results from both mechanical and chemical processes. In a vacuum, the mechanical mechanism would be solely responsible for the damage caused by fretting fatigue. Since a vacuum is not a realistic operating environment, the chemical aspect of fretting fatigue must also be analyzed. Waterhouse [6] broke down the variables influencing fretting fatigue life into three groups; mechanical, physical, and environmental. Mechanical variables include normal load, frequency, amplitude of slip, and the number of cycles. Temperature, relative surface hardness, and surface finish make up the physical variables. The environmental variables are atmospheric conditions, humidity, and aqueous solutions such as seawater.

Poon and Hoeppner [7] state that mechanical damage is caused as soon as two clamped contact surfaces undergo cyclic loading. The asperities between the two contacting surfaces become welded together due to the high stress of the loading condition. Small particles of the metal break off and become work hardened as the process continues. These particles become extremely abrasive and damage the surface of the material by removing the protective coating.

The oxygen and water in ambient air conditions forms an oxide film on the surface of the unprotected metal. As the mechanical process continues, oxide debris is knocked off the surface and trapped between the contact surfaces where it acts as an abrasive agent further damaging the surface of the metal. As the process goes on, the oxide debris forms pits between the contact surfaces. If the pressure between the two contacting surfaces is high enough, the pits have nowhere to go but deeper into the metal. This formation of pits during fretting fatigue provides stress concentration sites where cracks can originate and significantly reduce the life of the specimen [7,14].

Which mechanism plays the dominant role in fretting fatigue? Poon and Hoepnner [7] performed fretting fatigue tests on 7075-T6 aluminum alloy in a vacuum and laboratory air. They found that the chemical factor plays the main role in reducing the life of a specimen under fretting fatigue. The aluminum alloy sample in the vacuum lasted 10-20 times longer than that tested in ambient air. Furthermore, fractographic analysis showed that no corrosion pits were formed on the surface of the specimen tested in the vacuum proving that the oxide debris resulting from the chemical process creates these pits.

Contrary to these results, it has been shown that the formation of oxide debris on the surface doesn’t necessarily decrease the fatigue life of a sample. Conner et al. [8] states that wear pits are favorable sites for crack nucleation, the mechanisms that form them have nothing to do with crack propagation and not all cracks will propagate from these sites. Once the crack is initiated, the oxide debris may enter and fill the cracks thus diverting the energy from the crack tip. An increase in the amount of oxide debris on the surface can lead to a slip condition between the contacting surfaces reducing the coefficient of friction as well as the stresses.

Environmental factors greatly influence the fretting fatigue life of a sample. It is widely known that when fatigue is present in a corrosive environment, the material experiences an increase in crack growth and a decrease in fatigue life. This may be caused by the break down of the protective oxide film under fretting conditions, allowing the corrosive agent access to the bare metal. Limited research has been done in the field of environmental influence on fretting fatigue and the results are inconsistent.

Endo and Gato [9] tested fretting fatigue of carbon steel and aluminum alloy in both humid laboratory air and dry air conditions. They determined that the environmental effect of fretting fatigue was dependent on the type of material under consideration. They found that aluminum alloy is very sensitive to water vapor since the environmental effects dominated over the stress conditions. The water vapor accelerated both fretting fatigue crack initiation and propagation. They attribute this increase in crack initiation and propagation rate to the structural changes of the surface layer due to the water vapor softening the material. However, oxygen was the cause of the increased fretting fatigue crack initiation and propagation rate in carbon steel.

When it comes to the effects of saltwater on fretting fatigue, results are extremely inconsistent. Some researchers have found that the application of saltwater under fretting fatigue increases the fatigue life of the specimen and some have found that it decreases fatigue life. The material under consideration and the amount of seawater applied are very important factors in this research. Wharton and Waterhouse [10] compared the environmental effects of fretting fatigue on Ti-6Al-4V. The environments used in this experiment include laboratory air, 1% NaCL solution, dried liquid paraffin, dry deoxidized argon and humidified argon. They found that the influence of the corrosive environment depends on the degree of adhesion to the titanium alloy. At the higher stresses, sufficient corrosion product was formed causing protective action and an increased fatigue life. At the lower stresses, the corrosion product offers no protection to crack initiation resulting in low fatigue strength.

Effect of Shot-Peening on Fretting Fatigue

It is widely known that surface modifications such as shot peening have been used to improve the fretting fatigue behavior of various materials. Shot peening introduces a compressive residual stress profile varying in depth but parallel to the surface of the material. This process changes the surface roughness and grain size of the material, as well as work hardening the surface. Mutoh et al. [22] showed that this compressive residual stress created by shot peening is the most important factor in improving the fretting fatigue behavior of a material. Shot peening has also been known to close pre-existing cracks in materials if the depth of the resulting compressive residual stress is larger than the depth of the pre-existing crack. Too severe of a compressive residual stress may result in a very brittle material with high notch sensitivity, which is detrimental to fatigue life. Another argument against shot peeing is based on the idea that the compressive residual stress applied to the material is less than the initial crack size. If this were the case, there would be no beneficial effects in the area of crack propagation.

In a previous study, Namjoshi et al. [23] attempted to determine the crack initiation location of 3.81 mm thick shot peened Ti-6Al-4V specimens under fretting fatigue conditions. They found that shot peening moved the crack initiation location from the surface of the metal to 200-300 microns below the surface. In addition, they showed that the compressive residual stress improved the fretting fatigue life of the shot-peened titanium alloy when compared to unpeened samples. They stated that:

"*the depth of the compressive zone must be greater than the depth of the region effected by compressive stresses. Therefore, a shot peening method, which produces a large compressive residual stress at the surface with a rapid fall-off, may not be appropriate to improve the fretting fatigue life. On the other hand, a method that produces a residual stress profile with a smaller gradient, so that the compressive stress goes deeper into the substrate may provide a much better improvement in the fretting fatigue life of the material*."

A similar study was performed by Yuskel [5] to determine the crack initiation location of 6.35 mm shot peened Ti-6Al-4V under fretting fatigue conditions. Yuskel showed that shot peening improves the fretting fatigue life of Ti-6Al-4V with a greater improvement in the lower stress regimes. He also found that the crack initiation location of the 6.35 mm thick specimens was on the contact surface as opposed to 200-300 microns below the surface for the 3.81 mm thick specimens. Yuskel attributed this to a smaller maximum value for the compensatory residual tensile stress as well as a higher sensitivity to stress relaxation for the 6.35 mm thick specimens. Although, he found that if the stress relaxation is small, between 20 and 40 percent, the crack initiation location may move towards a depth of 150-200 microns from the surface much like the 3.81 mm thick specimens.

Everett and Matthews [24] conducted a study on 2024 Aluminum Alloy and 4340 Steel to determine the effect of shot and laser peening on fatigue life and crack growth.

The specimens were shot peened after a crack of 0.05-inches was initiated on the surface of the material. They found that when the cracks were fairly short, the shot peened samples resulted in a crack growth life 2 to 4 times longer than the unpeened samples. At a crack length of 0.1-inches, the growth rates were nearly the same for both the peened and unpeened samples. They also found that a machining-like scratch of 0.002-inches in depth reduced the fatigue life of a 4340 steel specimen by 40%. However, the fatigue life returned to nearly 100% of the unflawed specimen when the sample was shot peened after being scratched.

Fatigue Parameters

The detection of fretting fatigue crack initiation and propagation is a very important part of component failure prevention. While an aircraft is in service, inspections on aircraft components are extremely time consuming and difficult. In most cases, the aircraft must be put out of commission for a serious of days to perform tests on the components. A number of fatigue parameters have been created in an attempt to predict the fatigue life of certain materials under a number of fretting conditions.

The parameter used in this study will predict the fretting fatigue life of shot-peened Ti-6Al-4V based on the applied or far field stress. This fatigue parameter takes into account the effect of stress ratio, calculated in Equation 1, on fatigue life. The effective stress, σ_{eff}, used in this study is expressed by Equation 2. A study by Walker [29] proposed this parameter and it was employed by Lykins et al. [30] in a study of Ti-6Al-4V utilizing various pad geometries.

$$\sigma_{eff} = \sigma_{\max}(1-R)^m \qquad (1)$$

$$R = \frac{\sigma_{axial,\min}}{\sigma_{axial,\max}} \qquad (2)$$

where, $\sigma_{axial,min}$, is the minimum axial stress, $\sigma_{axial,max}$, is the maximum axial stress, σ_{max}, is the maximum applied stress, and m is a curve fitting parameter found to be 0.45 for Ti-6Al-4V by Lykins et al. [30]. This fatigue parameter has been shown to be extremely effective in predicting the fretting fatigue life of Ti-6Al-4V in elevated temperatures, shot-peened samples, and under seawater conditions [25,5,4].

III. Methodology

All of the fretting fatigue tests were performed at room temperature in an open-air laboratory environment. A rigid fretting fixture mounted on a 22.2 kN servo-hydraulic load frame was used to create the condition of fretting fatigue. Two cylindrical fretting pads with a radius of 50.8 mm were pressed against the specimen using four lateral springs, two on each side of the specimen. These springs provided a normal load of 1334 N, which was held constant throughout each experiment. The normal load was chosen in order to maximize the normal stress on the specimen while not to exceed the yield stress of the material. A load cell was placed on each side of the specimen to determine the normal load applied prior to the experiment. The axial load at the top of the specimen was measured using two load cells attached to the load frame just above the specimen. A lightweight pressure transducer built into the servo-hydraulic machine was used to measure the axial load at the bottom of the specimen. This experimental setup can be seen in Figures 2 and 4.

The fretting pads and the specimen were machined from Ti-6Al-4V forged plates using the wire electrical discharge method. The specimens measured 4.83 mm thick, 6.35 mm wide, and 177.8 mm long giving a cross sectional area of 30.67 mm^2. Each specimen was shot-peened based on the SAE Aerospace Materials Specification 2432 standard. Computer controlled equipment with a 7 Almen intensity provided the specimen with 100% surface coverage from ASR 110 cast steel shot. The fretting pads and specimen are shown in Figure 5. Since the contact area of the fretting pads and the specimen is of great concern in fretting fatigue experiments, the alignment was checked before every test. Prior to the application of the normal load, pressure tape was pressed between the pads and the specimen to ensure that the entire surface of the fretting pads were in complete contact with the specimen during the test.

ASTM D 1141 synthetic seawater was applied to the specimen using 1.59 mm diameter Tygon plastic tubing attached to an Economatic drain valve. A 590 mL bottle was filled with seawater and place on top of the fretting fixture. A 1.1 meter length of tubing was run from the inside of the bottle to the drain valve. The tubing then ran from the drain valve to a copper tee fitting which split the flow into two separate tubes. These tubes were attached to each side of the specimen just above the fretting pads using transparent tape. The drain valve allowed the user to adjust the amount of seawater flowing from the bottle to the specimen throughout the experiment. A schematic of the seawater system is shown in Figure 3. Since this was an open system, the seawater had to be collected in order to protect the equipment from being damaged. First, the pressure transducer was wrapped with Kimwipes and plastic wrap. Next, plastic wrap was used to create a funnel just below the pads in order to drain the dripping seawater into a container placed at the bottom of the fretting machine. This collection method allowed all of the seawater to flow from the specimen directly into the container, protecting the experimental setup from corrosive damage.

Five fretting fatigue experiments were conducted on the shot peened specimens under seawater conditions. Each experiment began at 5 Hz under dry conditions. The axial loading conditions were adjusted until the desired effective stress was obtained. The tangential force and displacement were plotted in the form of a hysterises loop in order to determine whether fretting occurred in partial slip condition or the specimen was still under a gross slip condition. A sample hysterises loop at several different cycles is presented in Figure 6. Once the desired effective stress was achieved, seawater was added to the specimen at a flow rate of 5 mL per minute. The frequency was then increased to 10 Hz for the remainder of the experiment. The addition of seawater occurred no later than 2,000 cycles in each of the five tests. An experiment performed by Lietch [4] proved that an environmental effect would occur as long as the specimen surface was wet and water pooled at the contact surface between the specimen and the fretting pads. A frequency of 10 Hz was found to be a low enough frequency to maintain an environmental effect and a high enough frequency to expedite the experiment in a timely manner.

Experimental data for the five fretting fatigue experiments under seawater conditions is presented in Table 1. A typical plot of tangential load versus number of cycles is shown in Figure 7. Note that the R-value calculated using Equation 2 for this particular experiment was found to be 0.15. An attempt was made to keep a constant R-value of 0.1 for each of the five experiments. Figure 8 presents a plot of the effective stress, σ_{eff}, versus the number of cycles to failure, N_f, for the five fretting fatigue tests. Chapter 4 will compare the data from this study to previous experiments in an attempt to show the effect of saltwater on shot-peened Ti-6Al-4V under fretting fatigue conditions.

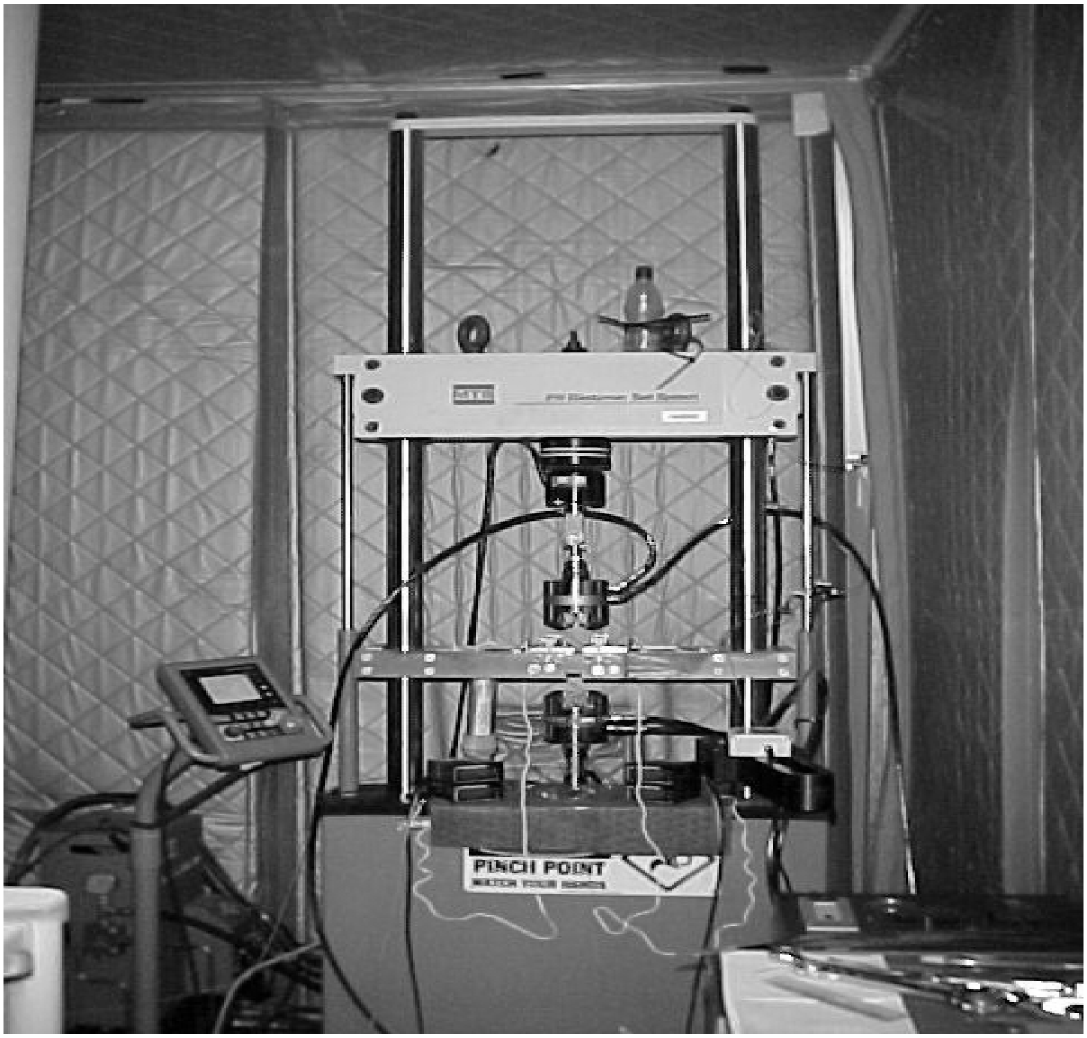


Figure 4. Servo-hydraulic uniaxial test machine with fretting fatigue apparatus.

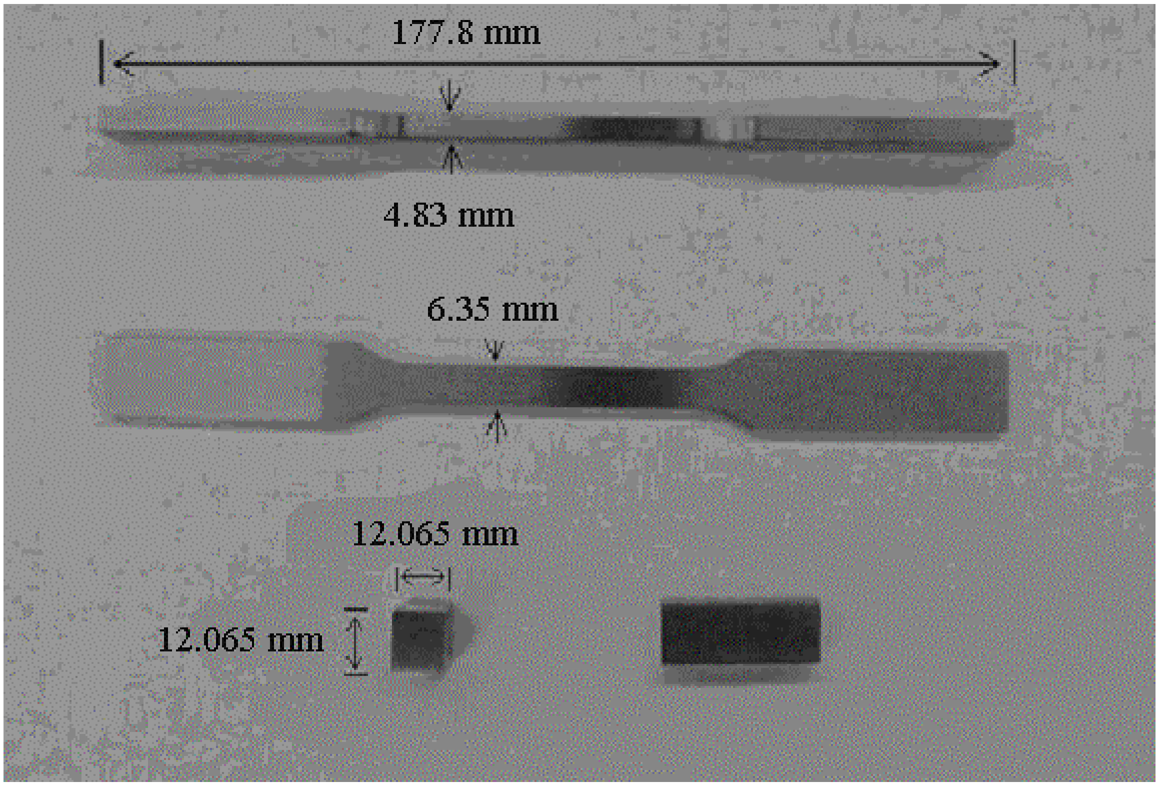


Figure 5. Fretting specimen and pad with dimensions.

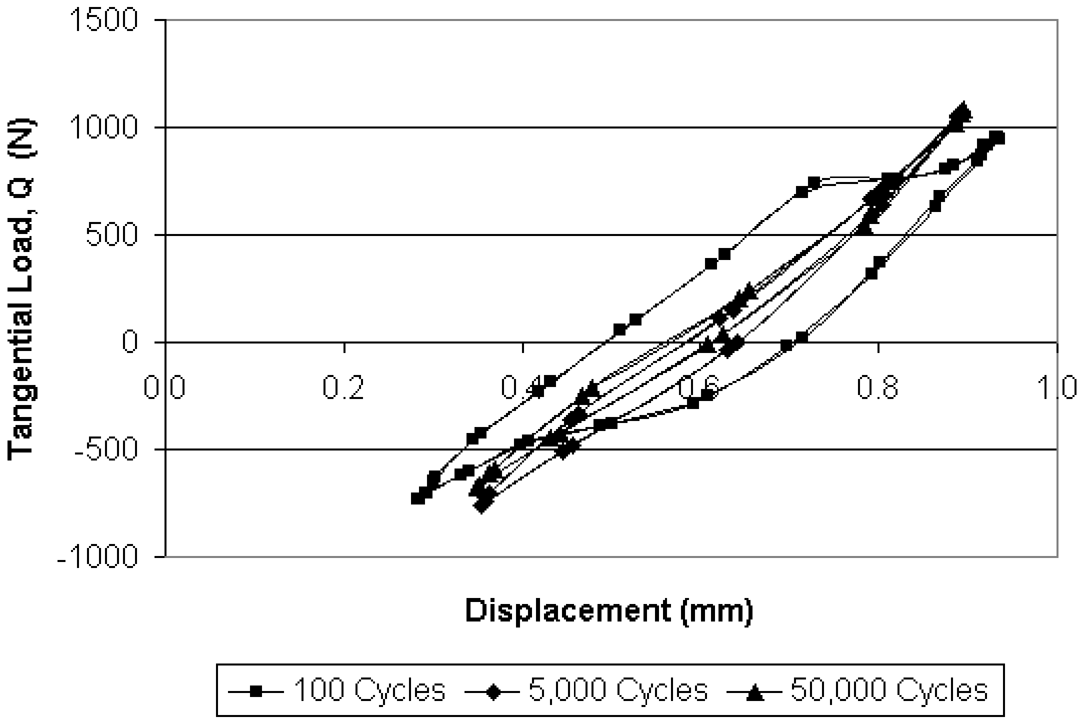


Figure 6. Hysteresis loop of Tangential Load vs. Displacement for σ_{eff} = 430 MPa.

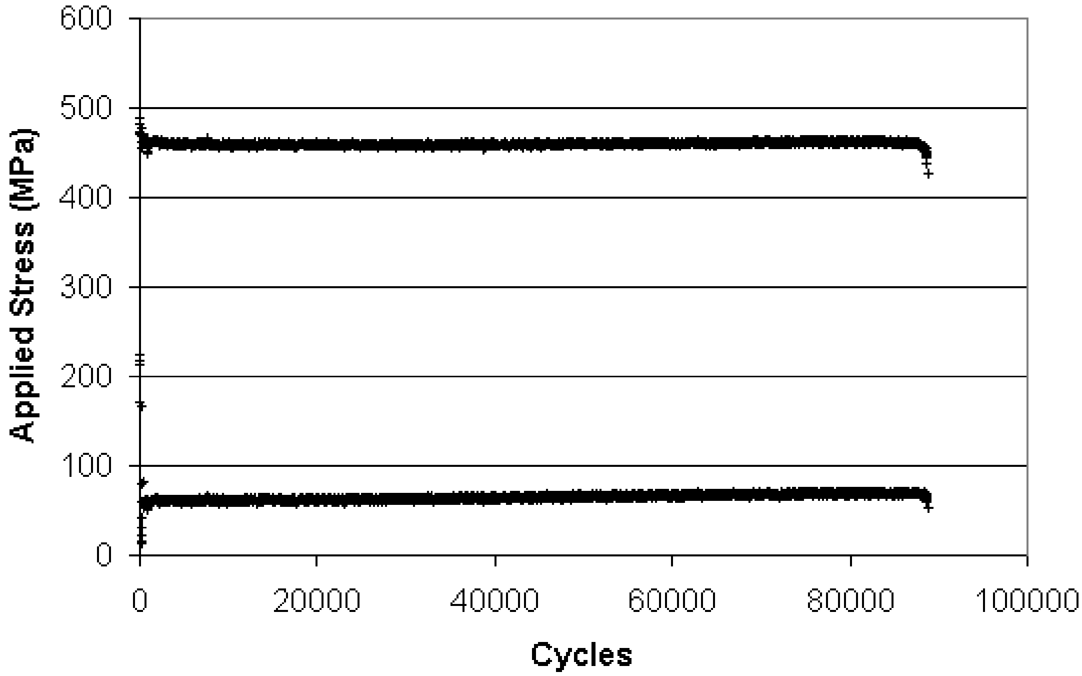


Figure 7. Applied Stress (σ) vs. Number of Cycles to Failure (N_f) for σ_{eff} = 430 MPa.

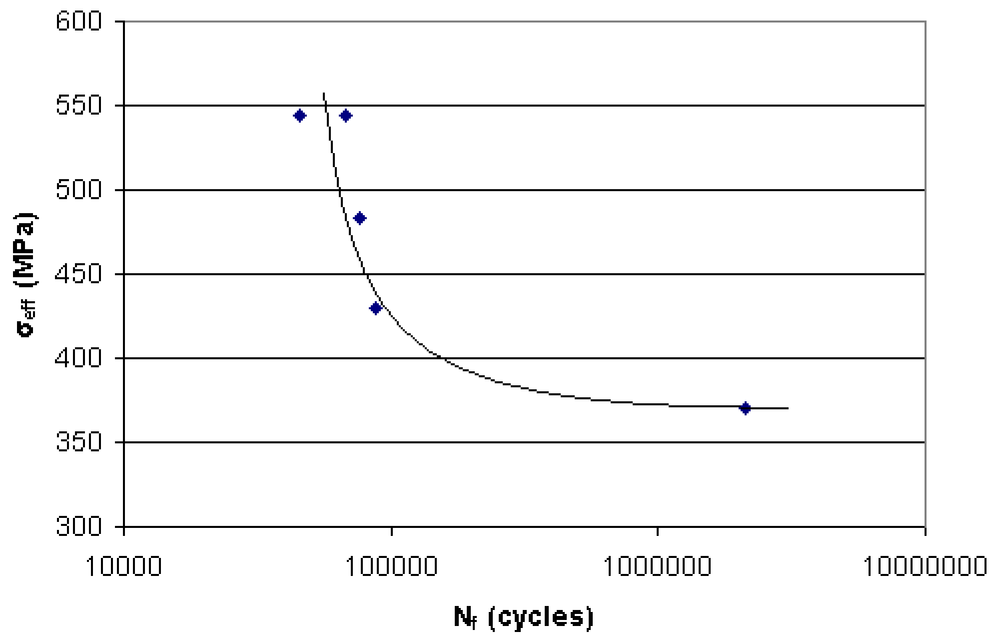


Figure 8. Effective Stress (σ_{eff}) vs. Number of Cycles to Failure (N_f) for seawater conditions.

Table 1. Experimental Data.

Test #	σ_{max}	σ_{min}	**R**	σ_{eff}	Q_{max}	Q_{min}	N_f
	(MPa)	(MPa)		(MPa)	(N)	(N)	Cycles
1	528.3	94.4	0.18	483.17	1039.95	-1003.21	76050
2	564	34.4	0.09	540.56	741.34	-1221.88	68024
3	531.3	-29.18	-0.05	544.2	1017.75	-1248.62	45274
4	461.7	67.5	0.15	430	1116.95	-780.66	88300
5	391.3	38.6	0.1	373.5	882.97	-569.93	2132325

IV. Results and Discussion

The experimental results and discussion will be presented in this chapter. Topics include the crack initiation, surface debris identification, fatigue striations, a comparison between seawater and dry shot-peened specimen fretting fatigue life, and a comparison between shot-peened and unpeened specimens under seawater conditions.

Crack Location and Surface Debris Identification

Once each specimen fractured, crack initiation location was determined by looking at the fretting scar. In theory, each specimen should fracture near the trailing edge of contact at x/a = 1.0. Figure 9 shows the location of the fretting fatigue crack initiation of the shot-peened sample tested at σ_{eff} = 490 MPa. Note that the crack initiation location is near the trailing edge of contact at x/a = 1.0. Photographs of the other samples along with the location of crack initiation are presented in Appendix A. Scanning electron microscope (SEM) images were taken of each specimen in an attempt to locate the point of crack initiation. In a previous study, Yuskel [5] found that for 6.35 mm thick shot-peened specimens, crack initiation was located on the contact surface as opposed to a depth of 200-300 microns for 3.81 mm thick shot-peened specimens. Secondary Electron Imaging (SEI), and Back Scatter Emission (BSE), was used to photograph the specimens. Figures 10 and 11 present SEI photographs detailing the crack initiation location of the shot-peened specimen under seawater conditions tested at σ_{eff} = 490 MPa. Appendix B presents SEI photographs of the other samples tested in this experiment. It is clear from the figures that crack initiation occurred at the contact surface for the shot-peened specimens tested under seawater conditions as well.

A BSE photograph of the shot-peened sample tested at a σ_{eff} = 490 MPa is shown in Figure 12. This figure shows the amount of surface debris found near the crack initiation. Energy Dispersive Spectroscopy (EDS) was used to analyze the composition of the debris particles located on the fractured surface. Figure 13 shows a broad scan of the fracture surface of one of the samples tested under seawater conditions. Notice the small traces of seawater debris shown as Na and Cl on the plot as well as oxide debris. The reason the quantities of these elements are so small is due to the EDS collecting data over the entire fracture surface, not just the area around the crack initiation. Next, the fracture surface was magnified using the SEM in order to further identify debris particles near the crack initiation. Figure 14 shows an SEI photograph of debris located on the fracture surface under extremely high magnification. A point EDS scan was used to determine the composition of the debris located in this photograph and is shown in Figure 15. Extremely large quantities of salt were found near the area of crack initiation due to the concentration of saltwater applied to the specimen during the experiment. Figure 16 shows another EDS point scan performed on a different spot locating large amounts of oxide debris near the crack initiation point. Appendix C includes both BSE photographs and EDS scans of the rest of the shot-peened specimens tested in seawater conditions.

Once all of the fractured specimens were examined under the SEM and EDS, two of the samples were cleaned and further examined. The cleaning process consisted of sonicating the specimen for two minutes in three different liquids. First, the specimen was placed in a flask full of distilled water and sonicated for two minutes. This process was then repeated with acetone and isoproponal. SEM photographs were taken of the cleaned samples and shown in Figure 17 and 18. An EDS scan was then performed on the clean specimens in order to compare them to the previous scans done on the unclean samples. Figure 19 shows a broad scan of the cleaned fracture surface. The cleaned samples showed small amounts of oxide debris and little or no sign of seawater debris when examined using EDS. This may be due to the fact that the oxide debris was embedded in the fracture surface whereas the seawater debris was close to the surface and easily washed away by the cleaning solution. It is important to note that the fracture surface shows little or no sign of surface debris after cleaning. This proves that investigators must specifically look for the environmental factors involved in fretting fatigue failure in order to see the severe damage these corrosive environments can cause.

Fatigue Striations

Striations on the surface of the fractured specimen can help to determine the degree of crack propagation. On an extremely high magnification setting, the SEM revealed these striations away from the crack initiation point. Figures 20 and 21 show the striations in specimens tested at a σ_{eff} of 490 MPa and 430 MPa respectively. These striations were then counted and compared to the effective stress in an attempt to compare the striations to the degree of crack propagation. Figure 22 shows a plot of σ_{eff} versus the number of striations per micron for the two specimens along with fatigue striation data collected by Lietch [4] for unpeened specimens tested under seawater conditions. The striations found in the shot-peened samples were more closely spaced than those of the unpeened samples. This data suggests that the shot-peened samples experienced faster crack propagation than the unpeened samples when tested under seawater conditions. Since low cycle fatigue is dominated by crack propagation, the shot-peened specimens tested under seawater conditions would see a reduced fretting fatigue life in the low cycle regime. It will be clear in the next part of this chapter that this is not the case at all. It should be noted that the difference in growth rates between the two types of samples is less than a factor of two and is only an approximation due to the surface damage shown in the images.

Discussion

Fretting Fatigue Life

This study will take into consideration results obtained from two previous studies performed in the area of fretting fatigue. They include the effects of shot peening on high cycle fretting fatigue behavior of Ti-6Al-4V performed by Yuskel [5] and the fretting fatigue behavior of Ti-6Al-4V under seawater conditions by Lietch [4]. By comparing the results from this study to the results of Yuskel and Lietch, the effect of both shot peening on titanium alloy and saltwater on shot-peened titanium alloy will be determined. Table 2 presents the data used for comparison between this experiment and that performed by Lietch [4] and Yuskel [5].

Shot-Peened versus Unpeened Specimens

Lietch tested titanium alloy under both dry and seawater conditions in order to determine the effect of seawater on the fretting fatigue life of unpeened Ti-6Al-4V. He found that seawater decreased the fretting fatigue life in low cycle fatigue but unexpectedly improved fretting fatigue life in high cycle fatigue. Lietch attributed these findings to an increase in microcracks formation on the contact surface due to the addition of seawater. He went on to say that these microcracks caused an increase in crack propagation which decreased the fretting fatigue life in the high cycle regime, but provided a shielding effect in the low cycle regime thus slowing the overall crack growth rate and increasing fatigue life. Figure 23 shows both the shot-peened and unpeened fretting fatigue data expressed as the effective stress amplitude, σ_{eff}, versus the number of cycles to failure, N_f. It is clear that shot peening increased the fretting fatigue life of Ti-6Al-4V under seawater conditions in both low and high cycle fatigue. The introduction of a compressive residual stress clearly increases the fretting fatigue life of the material by preventing microcracks from forming on the contact surface of the material. This decrease in microcrack formation allows for slower crack initiation and crack propagation thus increasing the fretting fatigue life in both low and high cycle regimes.

Dry versus Wet Shot-Peened Specimens

Yuskel tested shot-peened Ti-6Al-4V under dry conditions in order to determine the effect of shot peening on fretting fatigue. Figure 24 shows both the seawater and dry fretting fatigue data expressed as the effective stress amplitude, σ_{eff}, versus the number of cycles to failure, N_f, for shot-peened Ti-6Al-4V. Seawater clearly reduces the fretting fatigue life of the shot-peened specimens in both high and low cycle fatigue regimes. The process of fretting fatigue is known to disrupt titanium alloys protective coating, allowing the corrosive material to easily penetrate the surface of the specimen. This will cause faster crack initiation and propagation resulting in a lower fretting fatigue life in both the low and high cycle regimes. Unlike the unpeened samples tested by Lietch [4], the shot-peened samples tested under seawater conditions experienced a decrease in fretting fatigue life at both the low and high cycle regimes when compared to shot-peened samples tested in dry conditions. Lietch credited the increase in fatigue life of unpeened Ti-6Al-4V in high cycle fatigue under seawater conditions to the formation of microcracks. This phenomenon is not seen in this study due to the introduction of a compressive residual stress on the surface of the samples caused by shot peening. Therefore, the shielding effect caused by the increased number of microcracks at high cycle fatigue doesn't occur in the shot-peened samples tested under seawater conditions. This results in a decreased fretting fatigue life of shot-peened Ti-6Al-4V tested under seawater conditions when compared to its counterpart of shot-peened Ti-6Al-4V tested under dry conditions.

Figure 25 shows the effective stress, σ_{eff}, vs. the number of cycles to failure, N_f, for all four conditions; unpeened samples under seawater conditions, unpeened samples under dry conditions, shot-peened samples under dry conditions and shot-peened samples under seawater conditions. Note that the curve detailing the shot-peened Ti-6Al-4V under seawater conditions falls directly between the shot-peened specimens tested under dry conditions and directly above the unpeened specimens tested under seawater conditions. As expected, shot peening increases the fretting fatigue life of Ti-6Al-4V in both low and high cycle fatigue, whereas the addition of seawater decreases the fretting fatigue life of shot-peened Ti-6Al-4V in both low and high cycle fatigue.

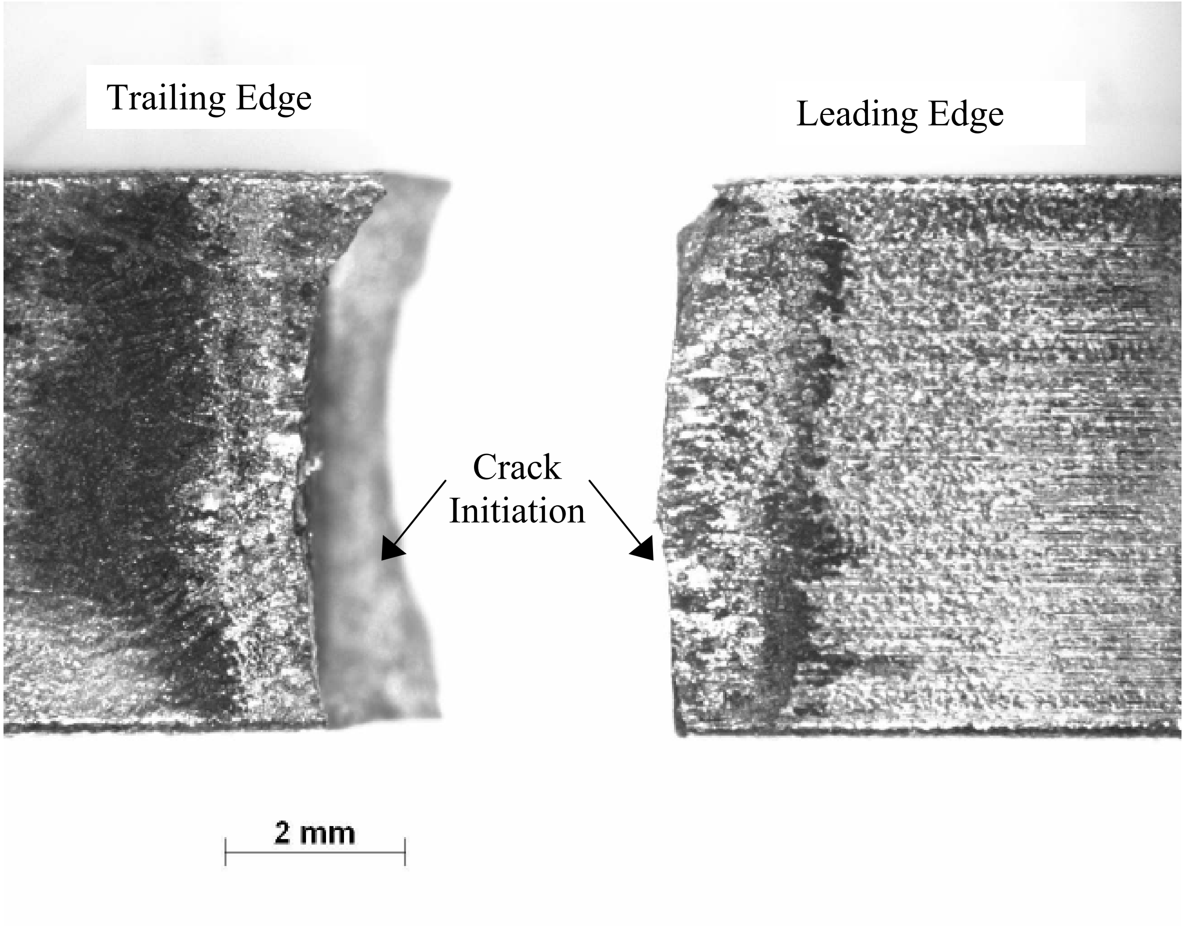


Figure 9. Crack Initiation Location of the shot-peened specimen tested under seawater conditions at an Effective Stress of 490 MPa ($\sigma_{eff} = 490$ MPa)

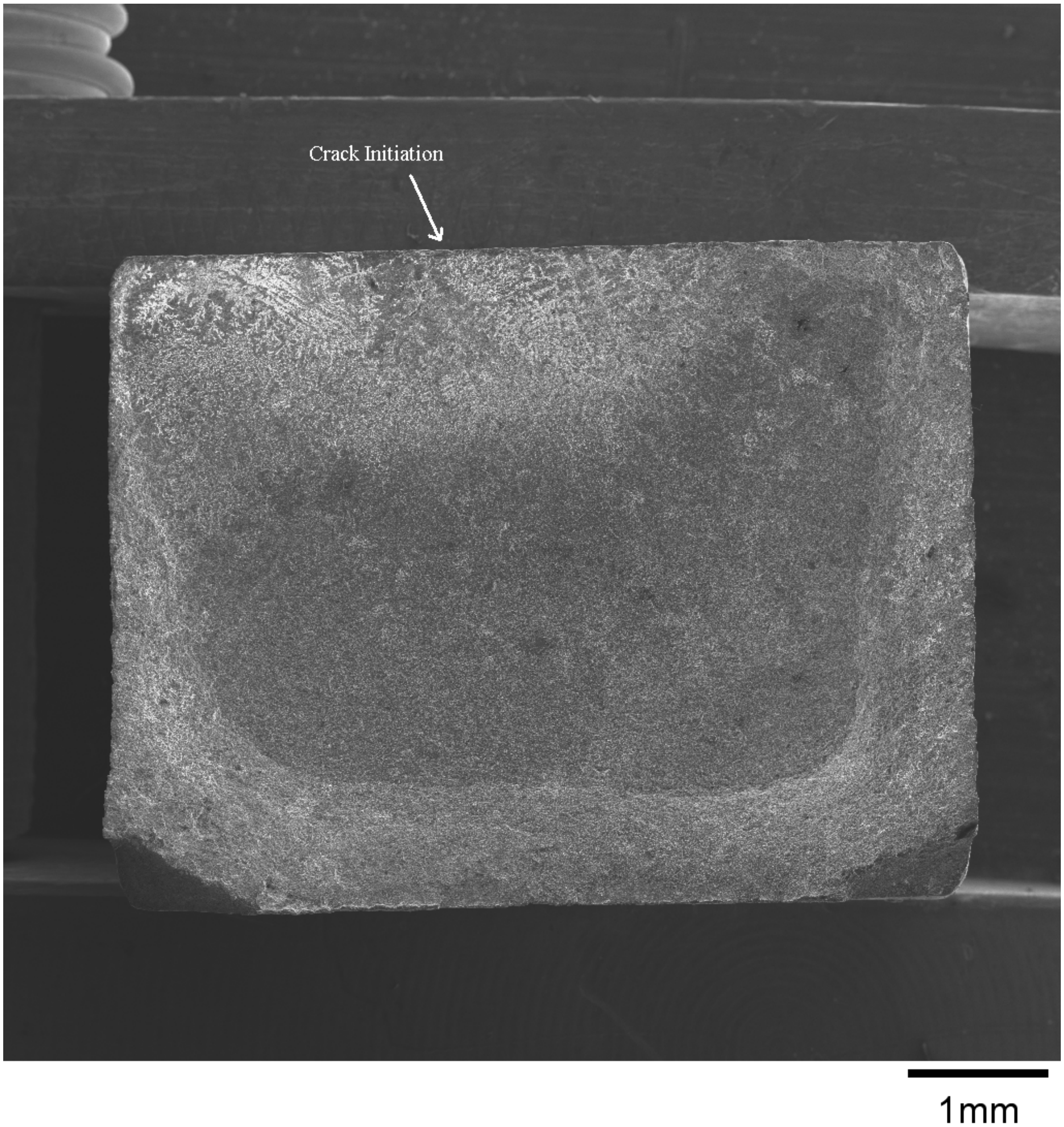


Figure 10. SEM photograph of fracture surface exposed to seawater at σ_{eff} = 490 MPa before cleaning.

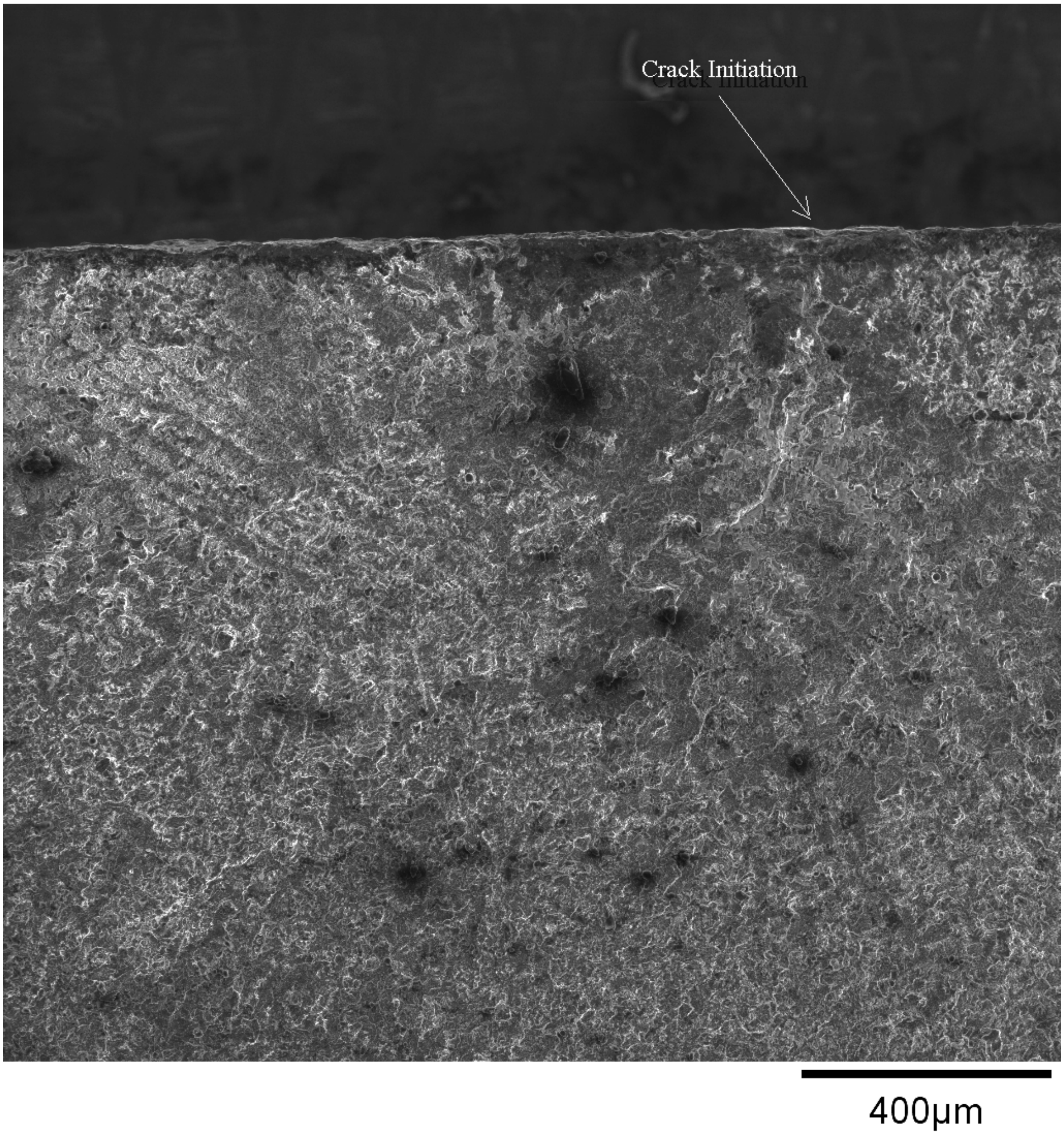


Figure 11. Magnified SEM photograph of fracture surface exposed to seawater at σ_{eff} = 490 MPa before cleaning.

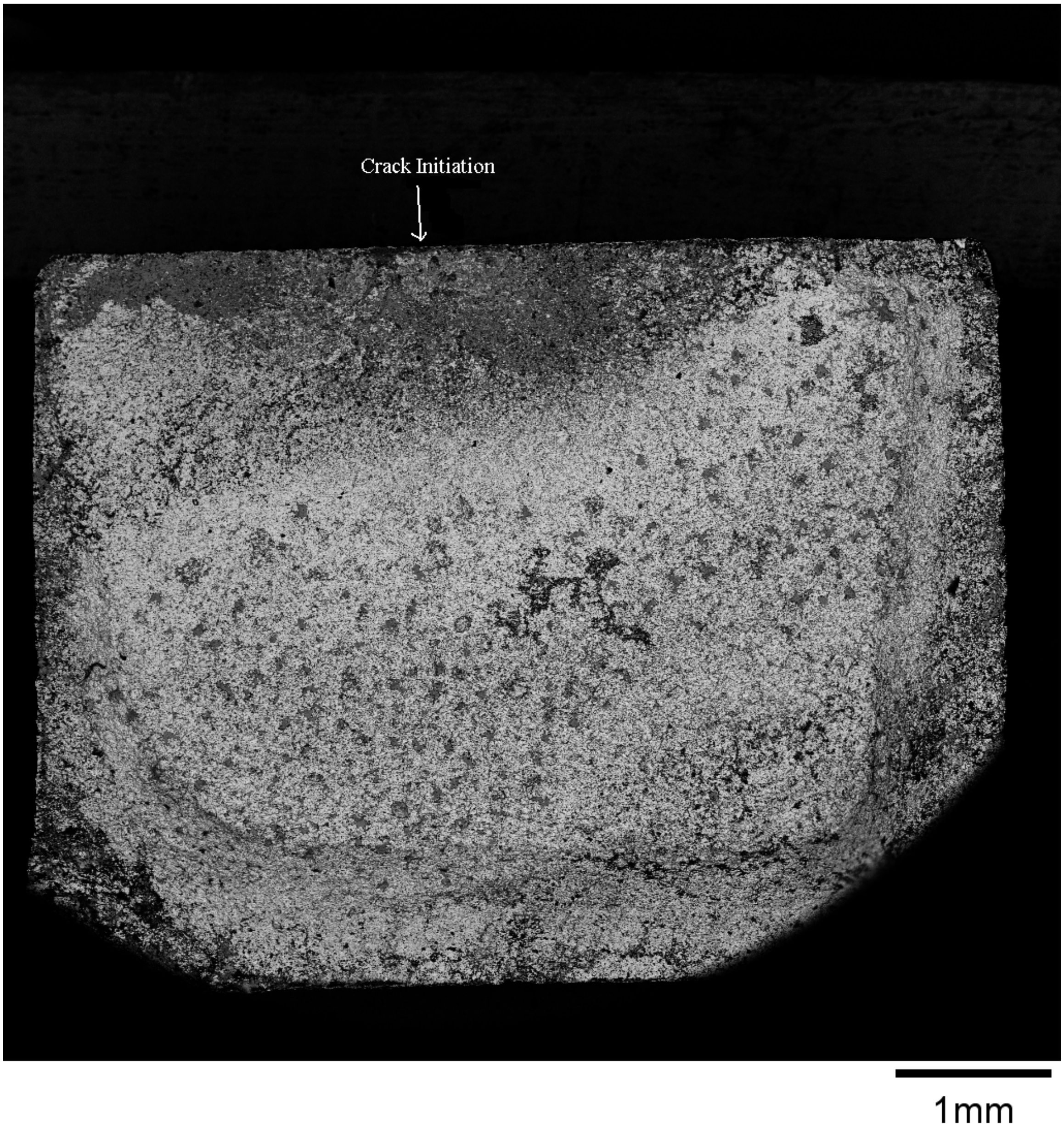


Figure 12. Back-scattered SEM photograph of fracture surface exposed to seawater at σ_{eff} = 490 MPa before cleaning.

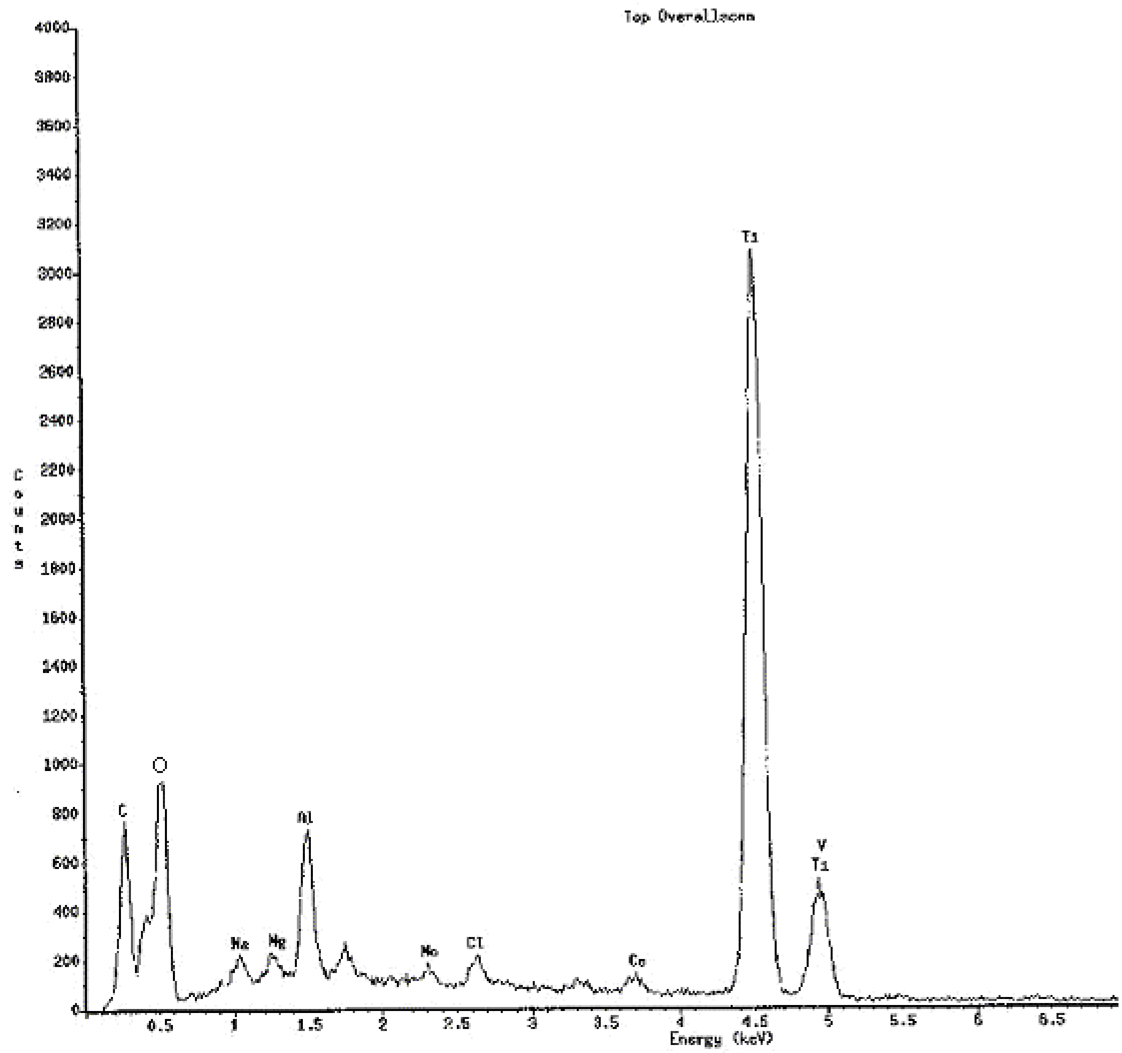


Figure 13. EDS broad scan of the fracture surface of a shot-peened specimen exposed to seawater tested at σ_{eff} = 490 MPa.

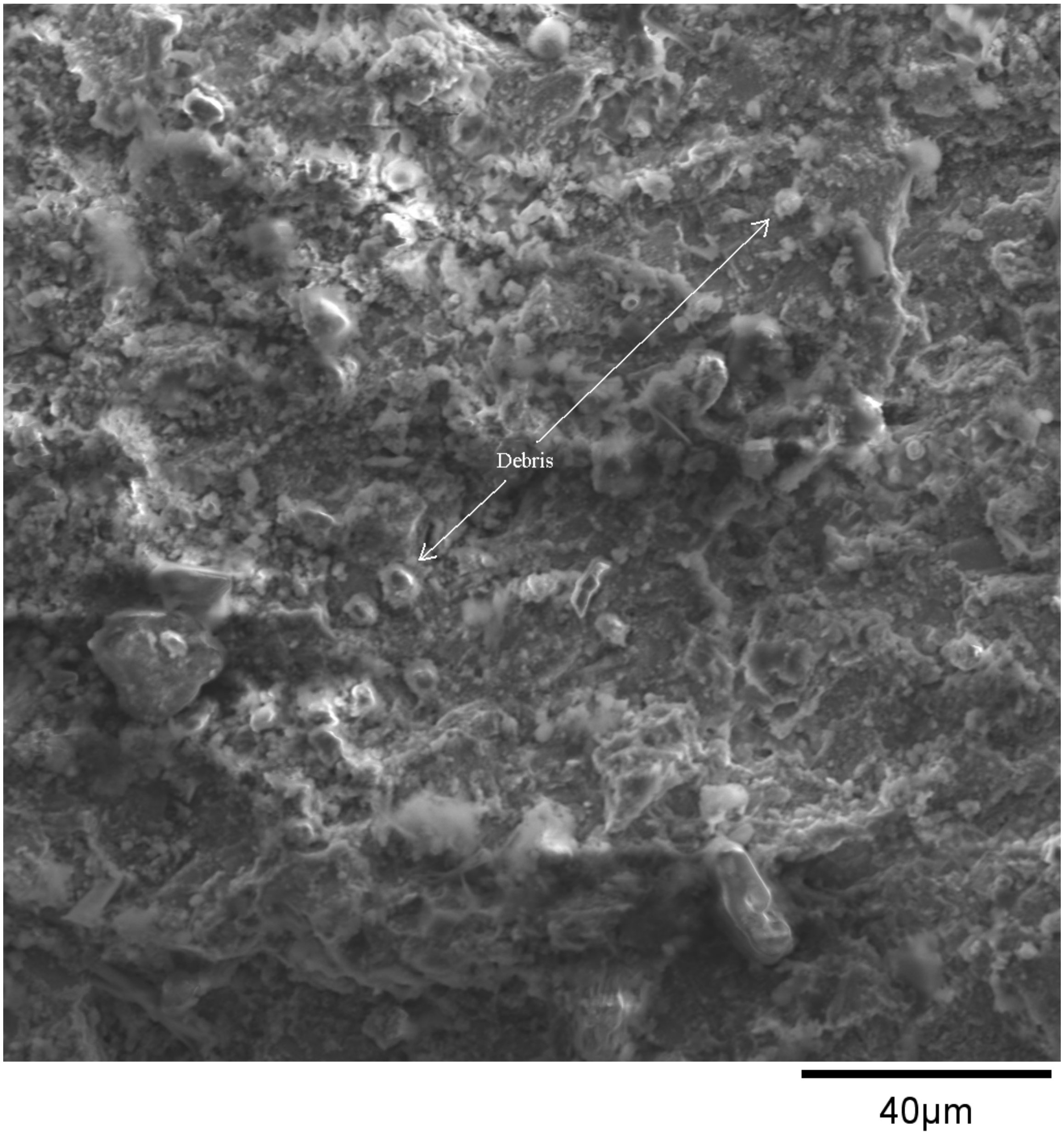


Figure 14. Magnified SEM photograph of surface debris from specimen exposed to seawater at σ_{eff} = 490 MPa before cleaning.

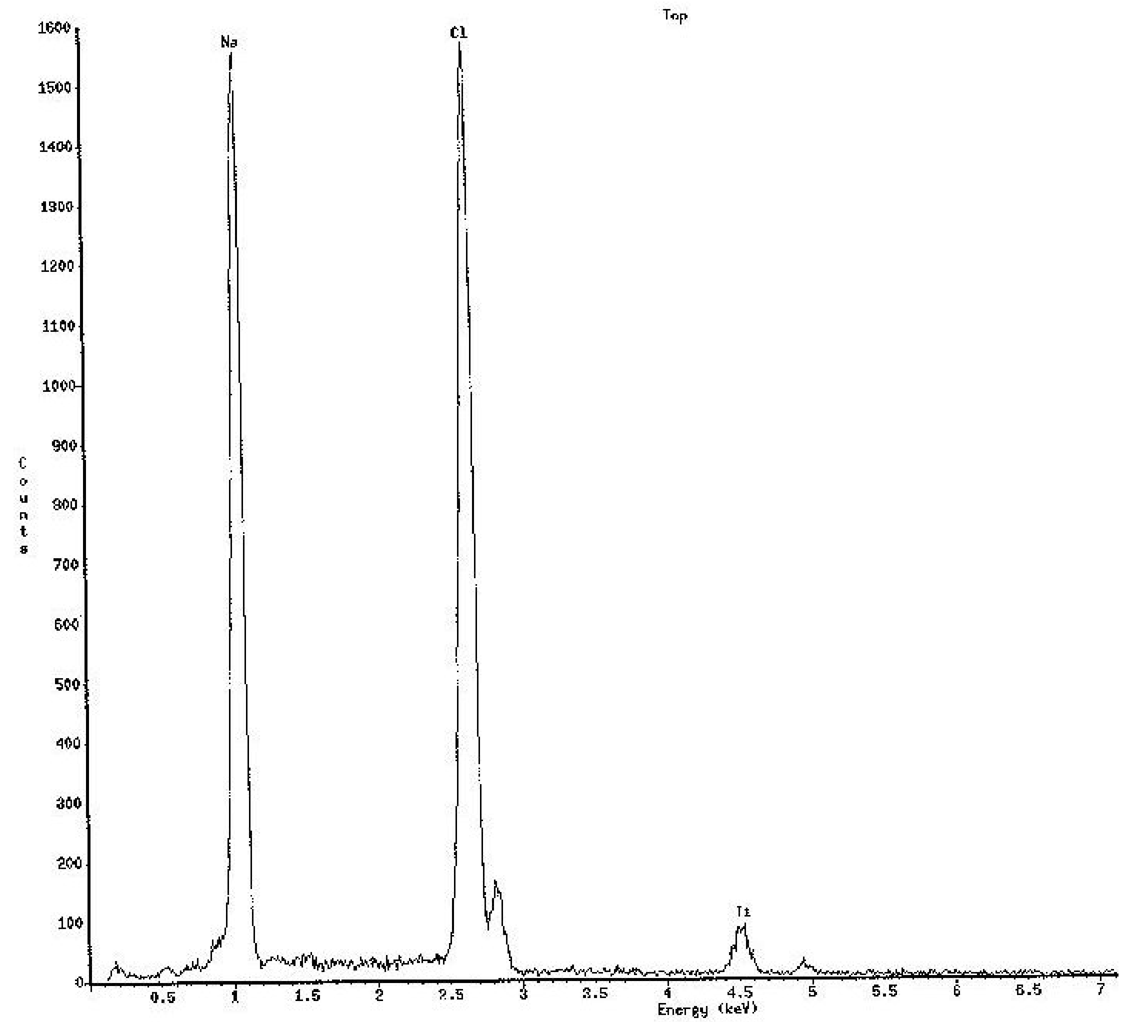


Figure 15. EDS point scan of saltwater debris formed on fracture surface of the specimen exposed to seawater at σ_{eff} = 490 MPa before cleaning.

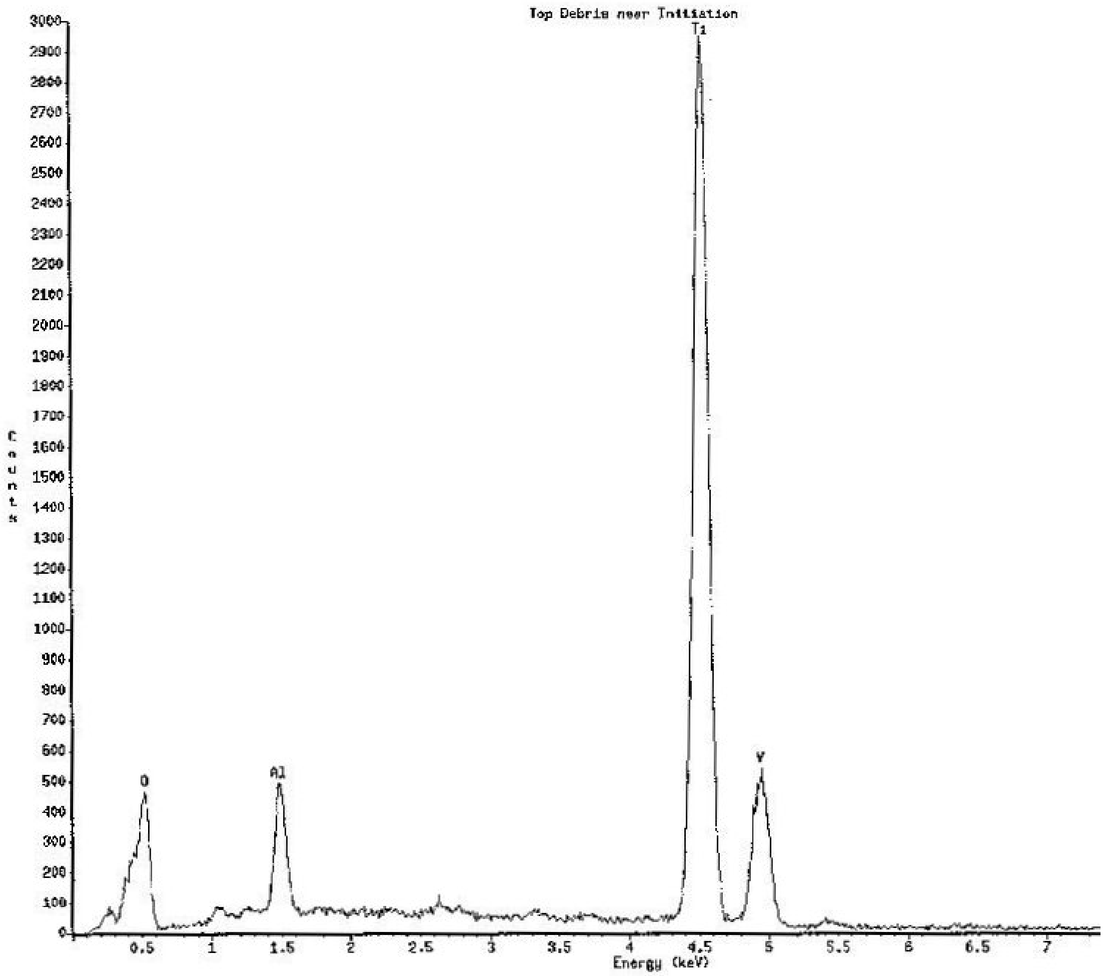


Figure 16. EDS point scan near crack initiation of a specimen exposed to seawater at σ_{eff} = 490 MPa showing oxide debris.

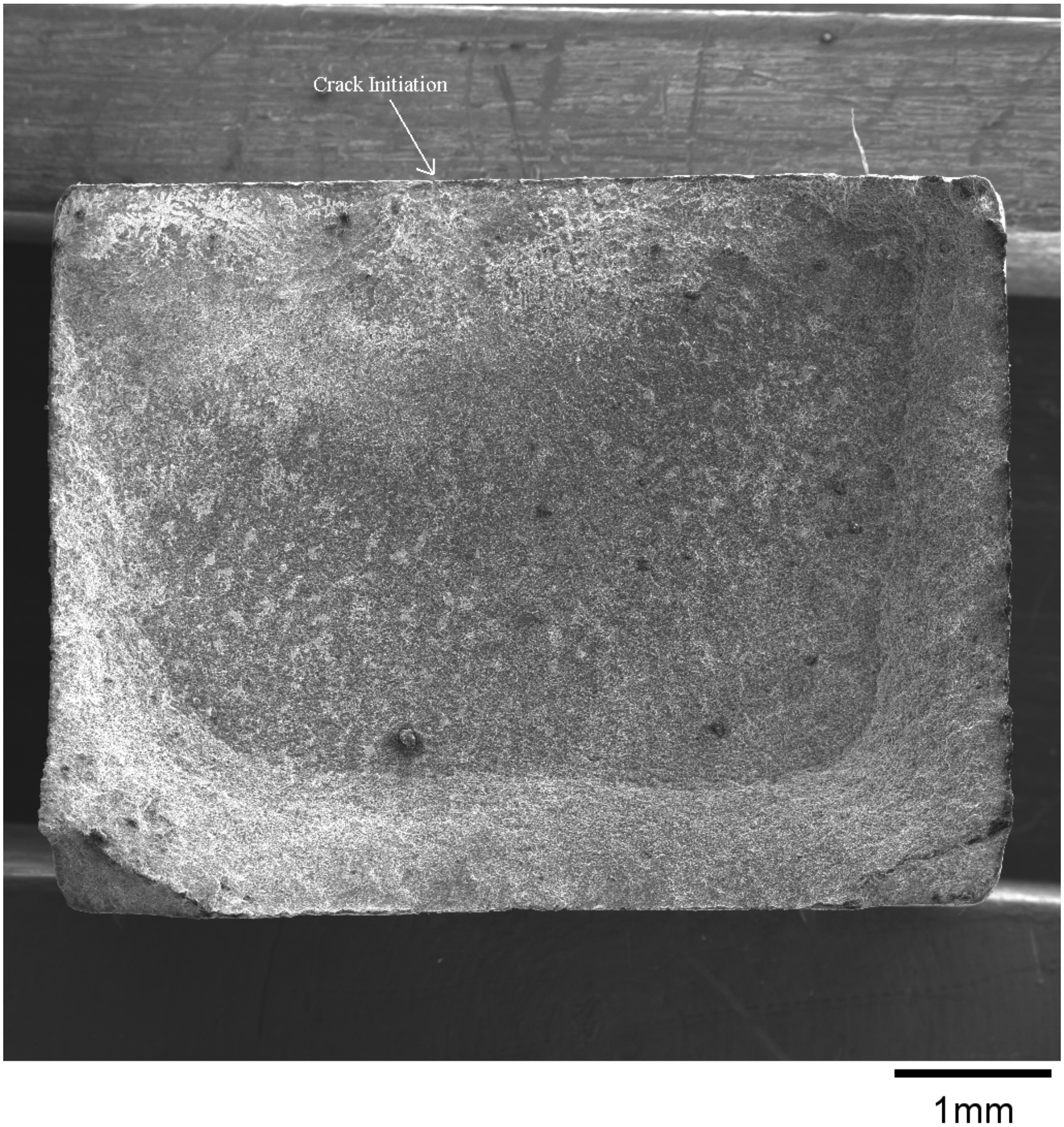


Figure 17. SEM photograph of fracture surface exposed to seawater at σ_{eff} = 490 MPa after cleaning.

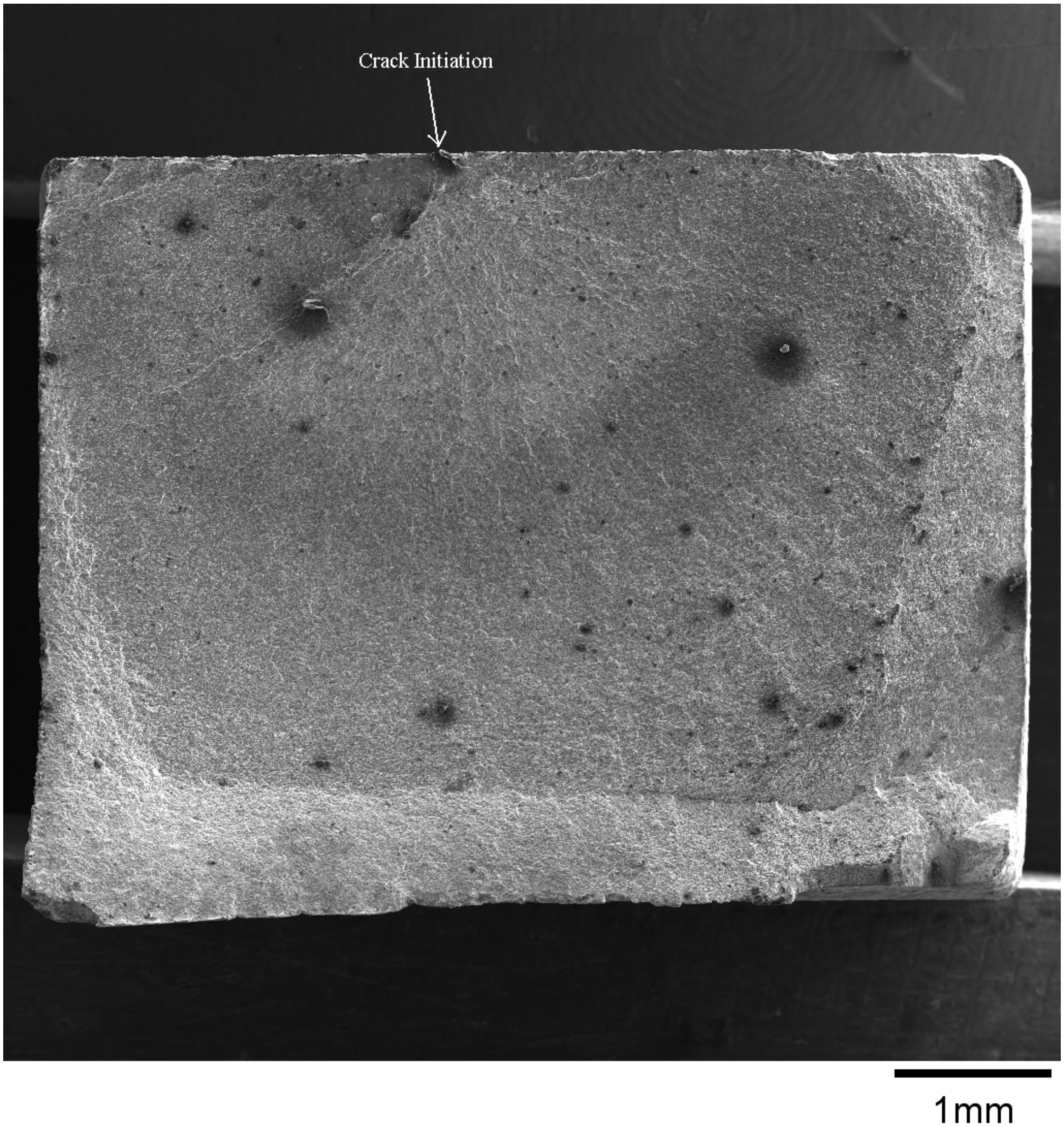


Figure 18. SEM photograph of fracture surface exposed to seawater at σ_{eff} = 430 MPa after cleaning.

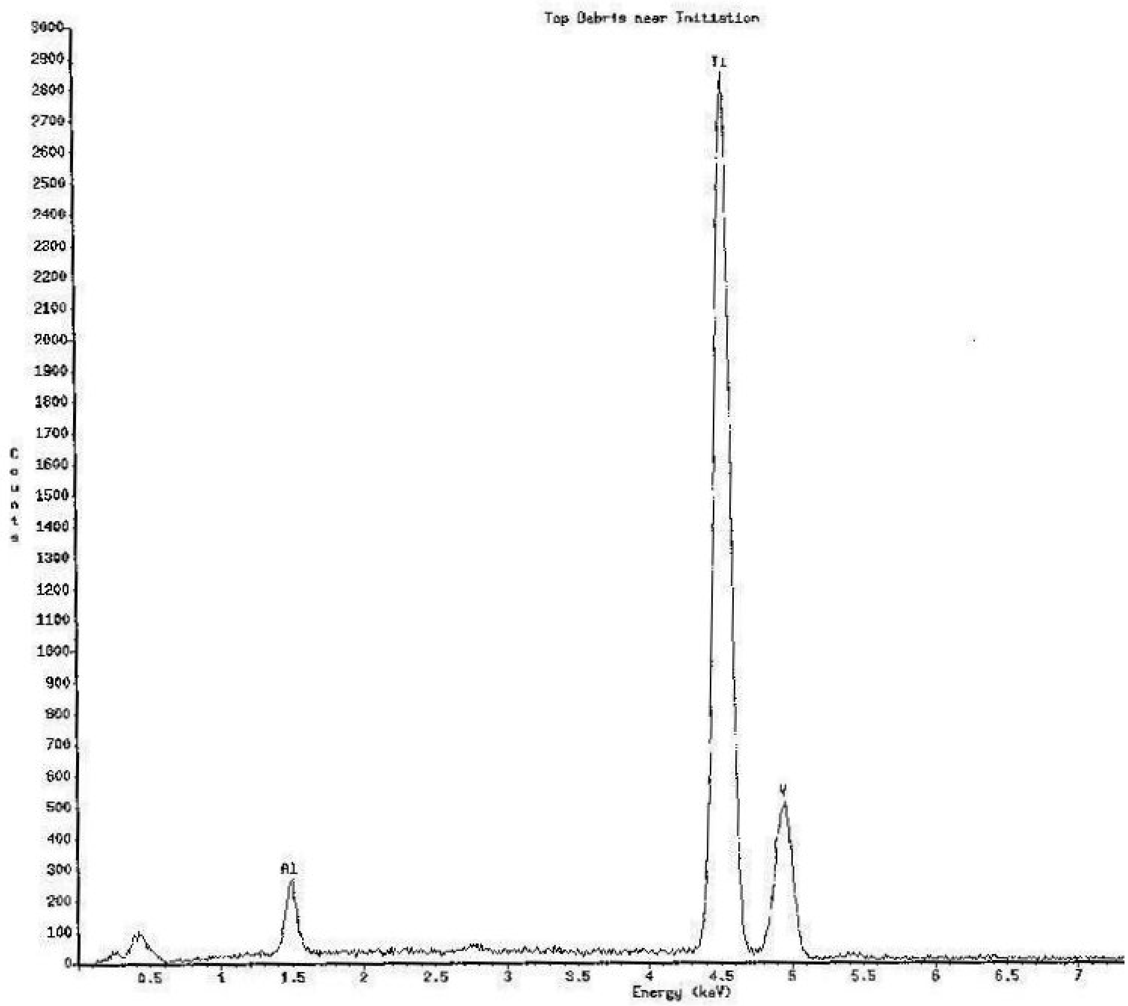


Figure 19. EDS scan near the crack initiation of the fracture surface of a specimen exposed to seawater conditions after cleaning.

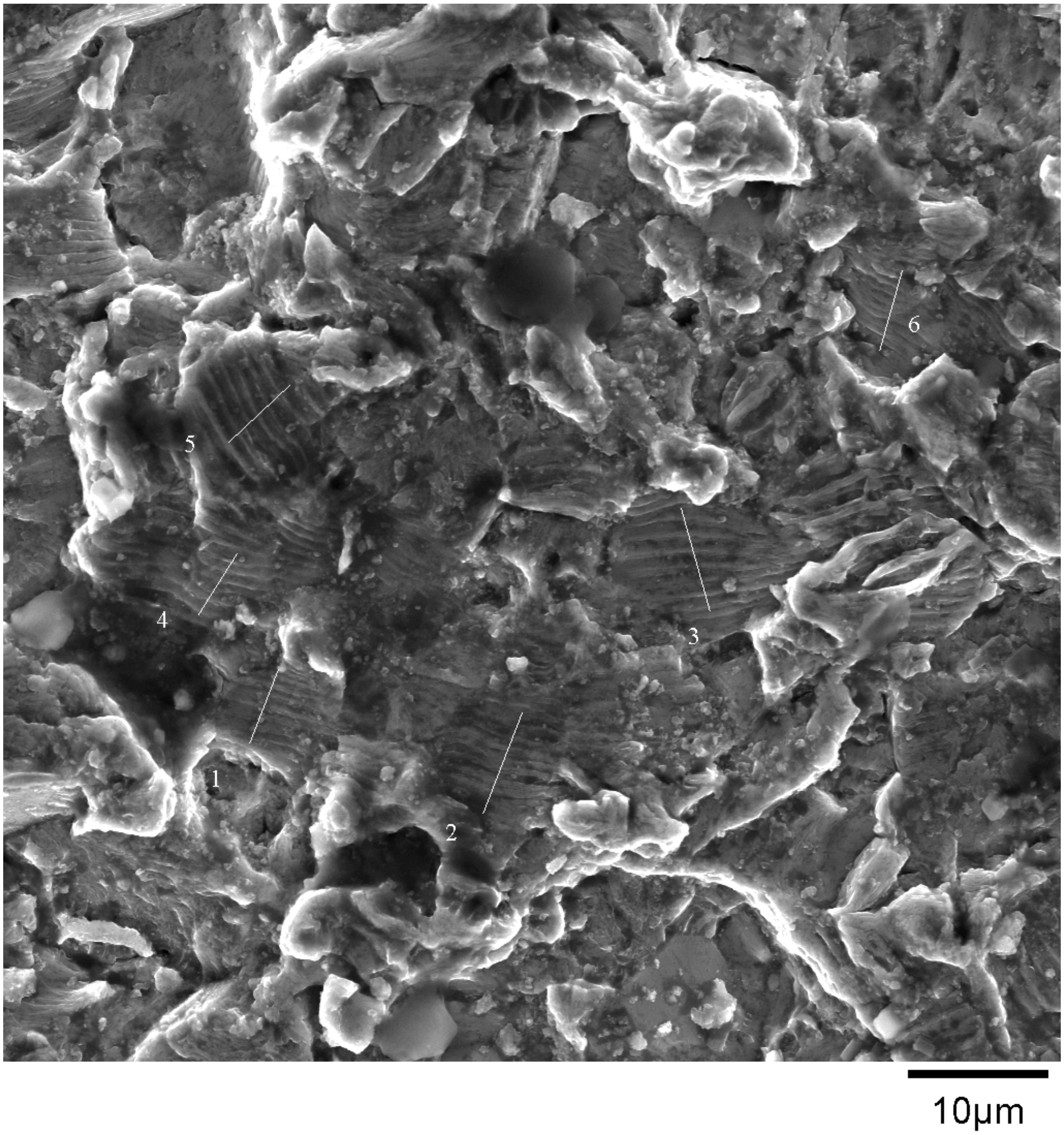


Figure 20. SEM photograph of fatigue striations in specimen exposed to seawater conditions at σ_{eff} = 490 MPa.

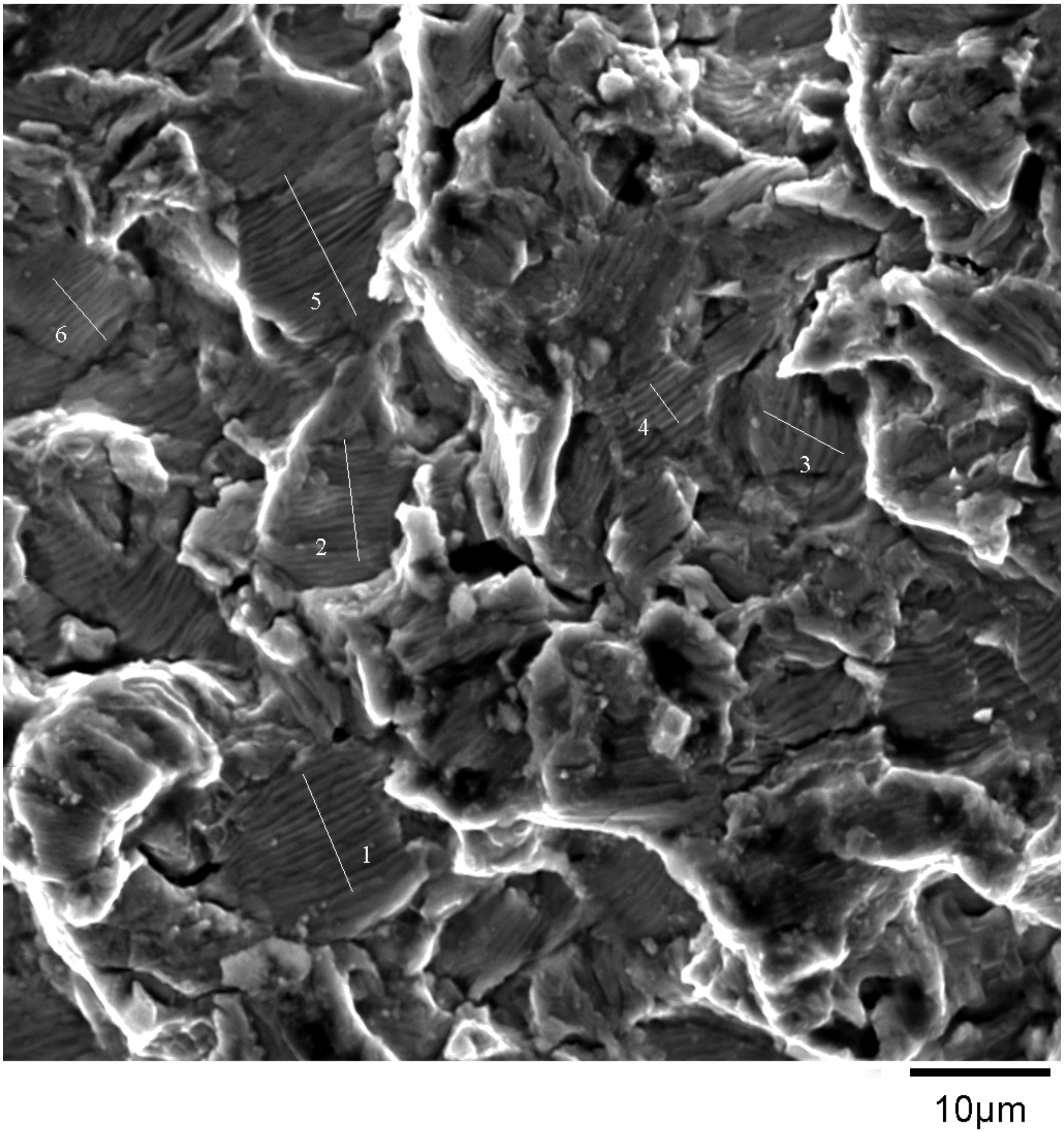


Figure 21. SEM photograph of fatigue striations in specimen exposed to seawater conditions at σ_{eff} = 430 MPa.

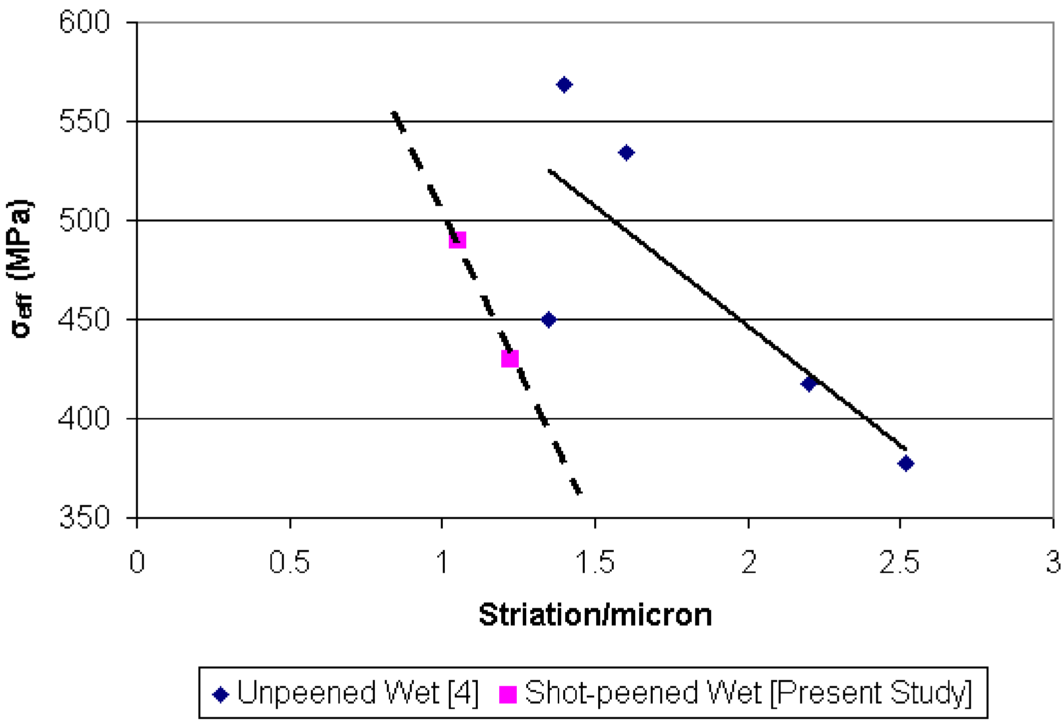


Figure 22. Effective Stress (σ_{eff}) vs. striation estimates for shot-peened samples under seawater conditions.

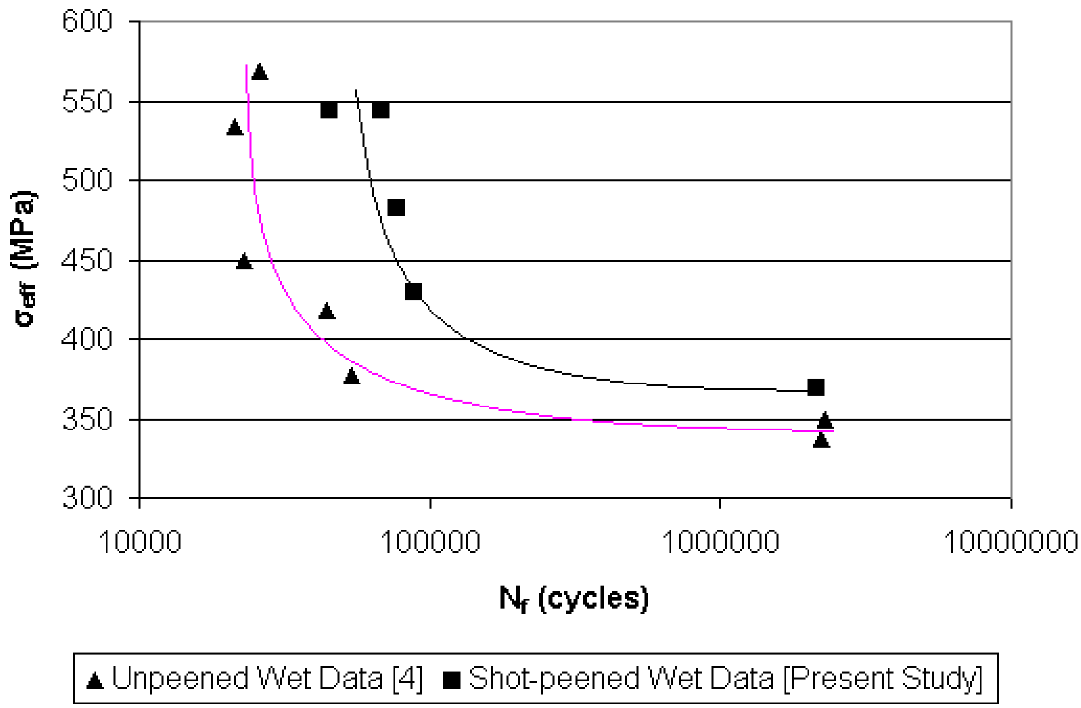


Figure 23. Comparison of Effective Stress (σ_{eff}) vs. Number of Cycles to Failure (N_f) for shot-peened and unpeened Ti-6Al-4V under seawater conditions.

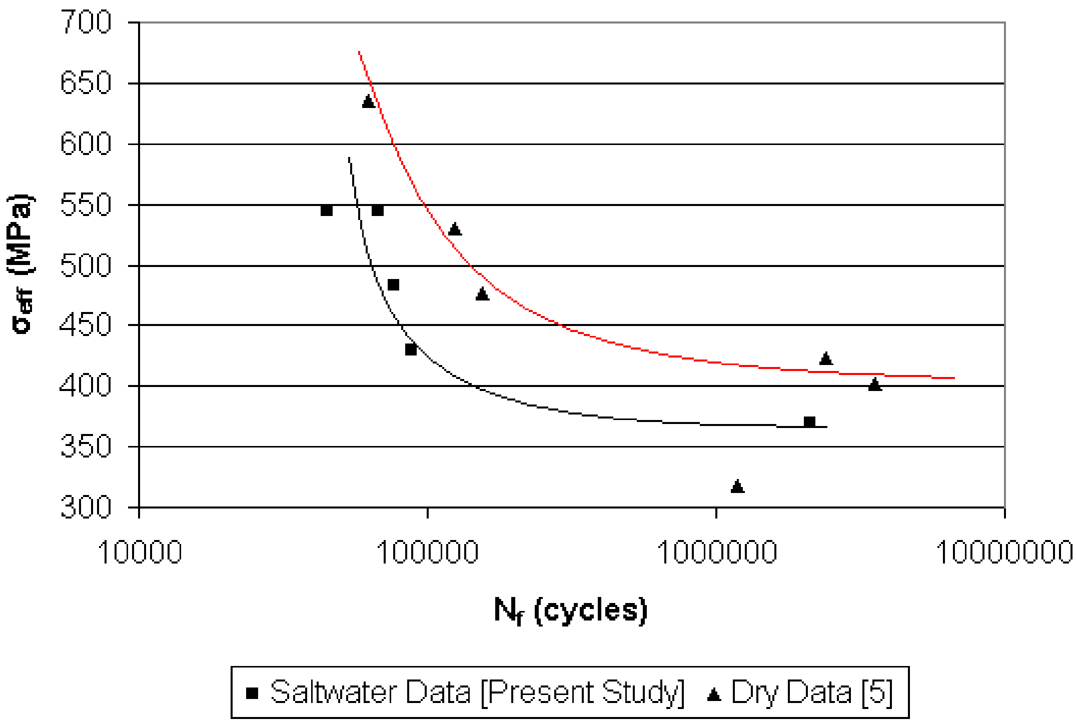


Figure 24. Comparison of Effective Stress (σ_{eff}) vs. Number of Cycles to Failure (N_f) for shot-peened Ti-6Al-4V under seawater and dry conditions.

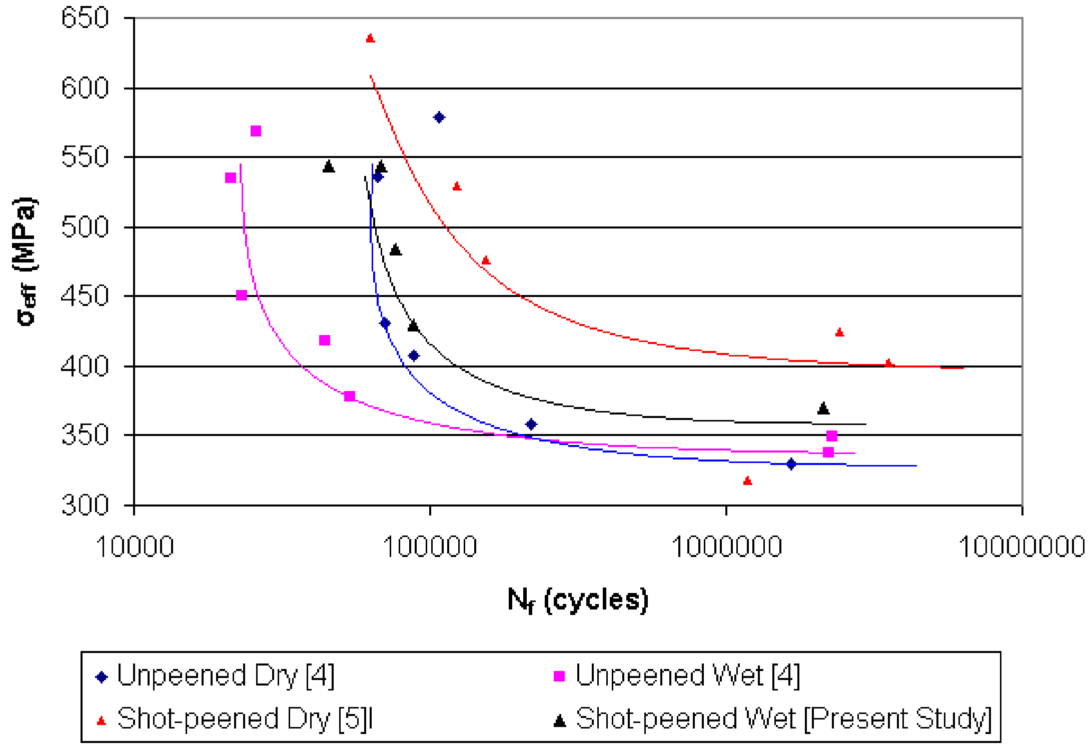


Figure 25. Comparison of Effective Stress (σ_{eff}) vs. Number of Cycles to Failure (N_f) for shot-peened and unpeened Ti-6Al-4V under seawater and dry conditions.

Table 2. Experimental Data From Previous Studies for Comparison [4,5].

Test #	σ_{max}	σ_{min}	**R**	σ_{eff}	Q_{max}	Q_{min}	N_f
	(MPa)	(MPa)		(MPa)	(N)	(N)	Cycles
Dry Shot-Peened	500	50	0.1	476.85	1130.64	-969.73	30839
Dry Shot-Peened	333.33	33.33	0.1	317.89	687.24	-714.95	1189508
Dry Shot-Peened	444.44	44.44	0.1	423.86	631.99	-483.64	2415267
Dry Shot-Peened	500	50	0.1	476.85	1482.76	-741	155545
Dry Shot-Peened	555.55	55.55	0.1	529.83	1643.35	-793.07	124222
Dry Shot-Peened	422.22	42.22	0.1	402.67	916.52	-577.16	3562668
Dry Shot-Peened	666.66	66.66	0.1	635.79	1013.29	-583.06	62501
Dry Unpeened	465.5	72.5	0.16	431.4	1201.02	-983.06	70500
Dry Unpeened	546.25	23.52	0.04	535.5	1100.53	-1138.83	66840
Dry Unpeened	586.92	18.08	0.03	578.7	1219.88	-1292.3	106687
Dry Unpeened	444.15	77.95	0.18	407.2	818.74	-740.23	87846
Dry Unpeened	383.36	107.77	0.28	330.4	759.44	-722.48	1659959
Dry Unpeened	424.77	133.2	0.31	358.6	776.75	-718.7	218329
Wet Unpeened	484.47	73.54	0.15	449.9	1183.23	-671.68	23100
Wet Unpeened	478.04	194.89	0.41	377.7	960.82	-528	54280
Wet Unpeened	424.46	170.11	0.4	337.1	711.72	-622.75	2221760
Wet Unpeened	760.08	361.29	0.48	568.6	346.96	-1205.47	25892
Wet Unpeened	687.64	295.09	0.43	534.3	1058.68	-876.3	21332
Wet Unpeened	551.58	253.73	0.46	418	889.64	-705.93	44474
Wet Unpeened	493.77	265.65	0.54	348.8	810.46	-430.45	2282108

V. CONCLUSIONS

This chapter will summarize the work done in this experiment. It will include an experimental summary, fretting fatigue life, crack initiation location and surface debris, fatigue striations, and recommendations for future work.

Experimental Summary

The purpose of this study was to investigate the effects of fretting fatigue on shot peened Ti-6Al-4V in a corrosive environment. Seawater was chosen for this experiment due to its highly corrosive nature as well as its regular contact with aircraft components. Due to the complexities of these aircraft components, simplified geometries and loading conditions were used throughout this experiment. Lateral springs pressed the two fretting pads on each side of the test specimen at a constant normal load of 1334 N for each test. Both fretting pads and test specimens were created from Ti-6Al-4V. The servo hydraulic test machine applied an axial stress on the specimen, in turn producing a tangential load. Five tests were run at various stress levels to evaluate the effect of seawater at both high and low stress regimes. Saltwater was applied at a rate of 5 mL per minute to each side of the specimen during the experiment.

Data was collected for each of the five samples and compared to previous studies in an attempt to determine the effect of shot peening surface treatment and seawater on the fatigue life of TI-6Al-4V. Once the samples fractured, a Scanning Electron Microscope (SEM) was used to analyze the fracture surface and locate the surface debris as well as locate the point of crack initiation. Energy Dispersive Spectroscopy (EDS) was used to identify the composition of the surface debris found on the fracture surface.

Fretting Fatigue Life

Fretting fatigue life data was collected for the five shot peened samples tested under seawater conditions. A plot of the effective stress amplitude, σ_{eff}, versus the number of cycles to failure, N_f, was then established and compared to its counterpart under different conditions from previous studies. When compared to shot-peened samples tested in dry conditions [5], the fretting fatigue life of Ti-6Al-4V was reduced by seawater in both high and low cycle fatigue. It has been found in previous research that high cycle fatigue is dominated by crack initiation whereas low cycle fatigue is dominated by crack propagation [10]. Therefore, this study proves that seawater increases both crack initiation and crack propagation due to the decrease in the fretting fatigue life in both regions. Fretting fatigue may disrupt the titanium alloys protective coating allowing the seawater to penetrate the specimen faster, thus increasing crack initiation and propagation.

In an attempt to determine the effect of shot peening on fretting fatigue life, the data collected in this study was compared to the data collected by Lietch (4) for unpeened Ti-6Al-4V samples tested under seawater conditions. Shot peening increased the fatigue life in both the low and high cycle fatigue regions. This further shows that the introduction of a compressive residual stress in Ti-6Al-4V increases the fretting fatigue life of the material.

Crack Initiation Location and Surface Debris

After fracture, the specimen was analyzed under a Scanning Electron Microscope (SEM) in order to determine the point of crack initiation as well as to locate surface debris. As expected, the crack initiation location for each specimen was near the trailing edge of contact at x/a = 1.0. The fracture surface was then further examined using Energy Dispersive Spectroscopy (EDS) to determine the composition of the surface debris. Once the fracture surfaces were examined, they were then cleaned using a three step process involving distilled water, acetone, and isoproponal. EDS broad scans and magnified point scans were used to determine an overall composition of the fracture surface as well as more specific debris composition. As expected, the specimens contained a large amount of seawater and oxide debris prior to cleaning. EDS scans of the specimens after cleaning showed extremely small amounts of the seawater and oxide debris, sometimes not even noticeable.

Fatigue Striations

A Scanning Electron Microscope (SEM) was used to locate striations on the fracture surface. These striations were measured in an attempt to determine the rate of crack growth in shot-peened samples tested under seawater conditions. Unexpectedly, the number of striations per micron was lower in the shot-peened samples tested under seawater than in the unpeened samples tested under the same conditions. This data shows that crack propagation is faster in the shot-peened samples than the unpeened samples when tested in seawater condition.

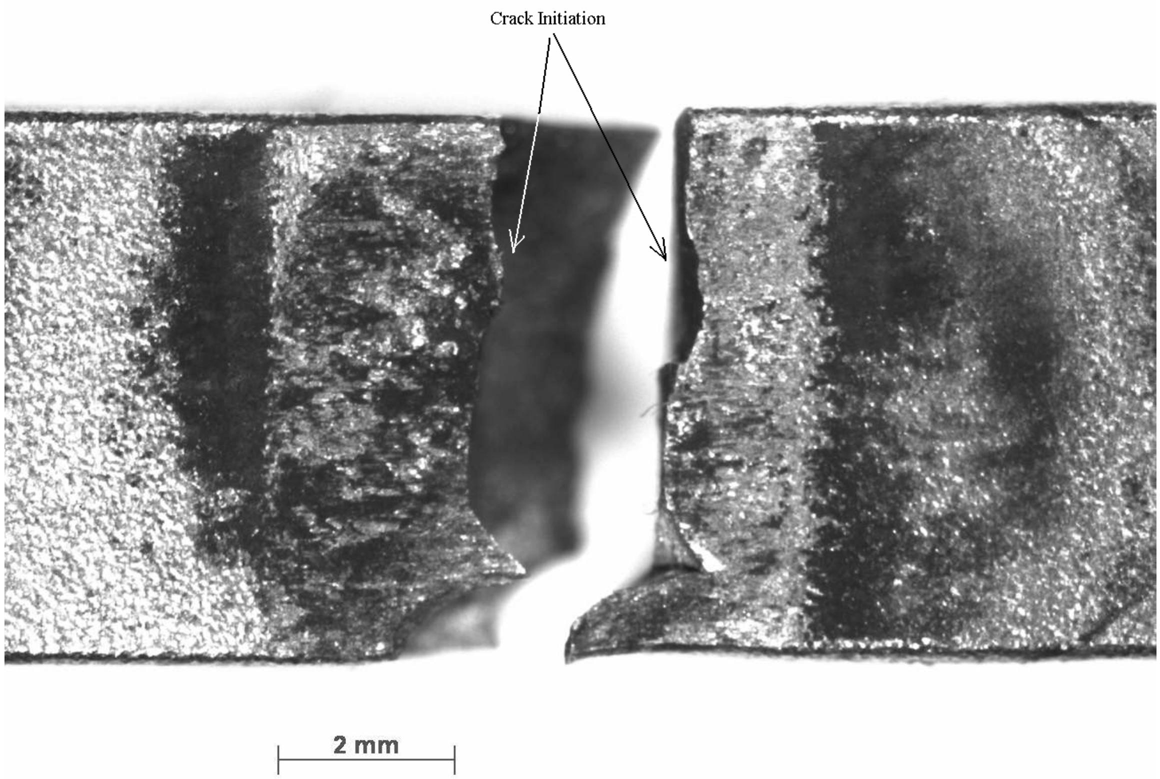
Future Work

This study performed fretting fatigue analysis on shot peened Ti-6Al-4V under seawater conditions. Many variables were held constant throughout this experiment including temperature, normal load, and the radius of the fretting pads. The effect of temperature on fretting fatigue under seawater conditions should be evaluated since most of the aircraft components that fail due to fretting fatigue are located in gas turbine engines. These components operate at extremely high temperature, which will ultimately affect their fatigue life. This future study may determine a good range of operating temperatures for aircrafts under constant contact with saltwater. Varying the loading conditions on the specimen may be helpful to determine how the fretting fatigue life depends on the various stresses at the contact surface. Different pad sizes will affect the fretting fatigue life of the sample as well. In some cases, aircraft components under fretting fatigue are made up of different materials. Measuring fretting fatigue life by varying the type of metal the pad is made from would be helpful in determining which materials complement each other.

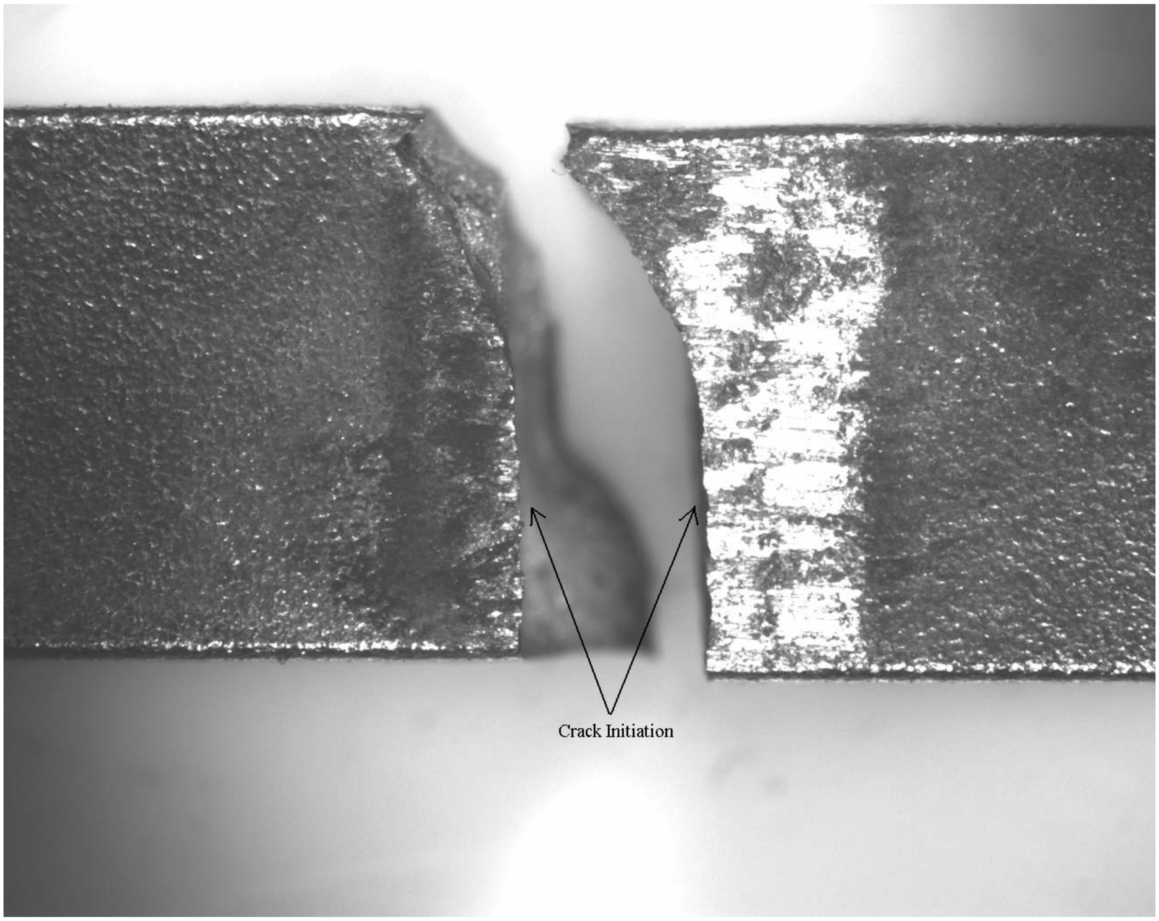
The compressive residual stresses are very important when working with shot-peened samples under fretting fatigue. Other research should include measuring the compressive residual stress profile using x-ray diffraction prior to the fretting fatigue experiments in seawater. This would allow a comparison of the stress profile with the depth of crack initiation to see just how well the compressive residual stress deters crack propagation.

Lastly, a cost comparison should be made to determine whether shot peening is a cost effective way to increase the fatigue life of Ti-6Al-4V under fretting fatigue. Comparing the cost of shot peening with the maintenance and replacement cost of these aircraft components would do this. It is possible that the use of shot peened aircraft components could save the military money by increasing the fatigue life of the components and the aircraft as a whole.

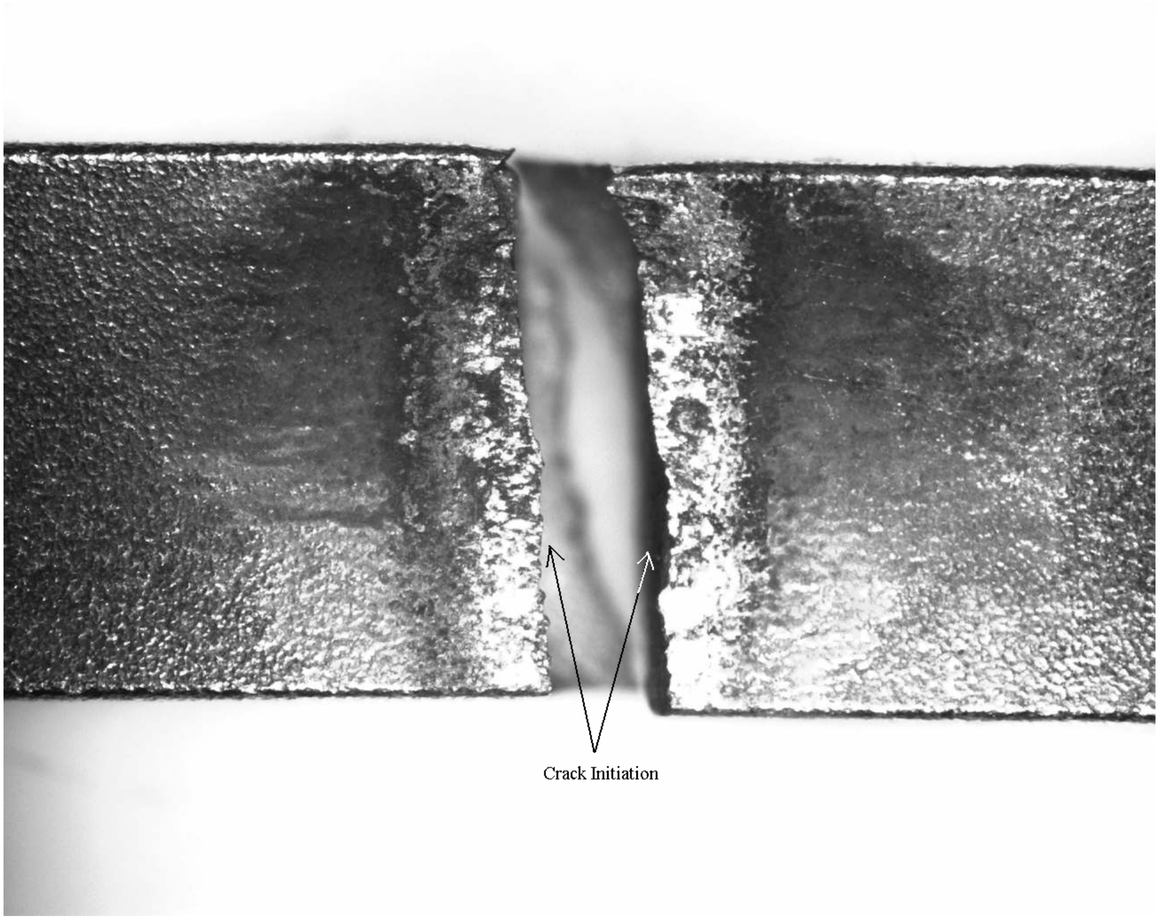
Appendix A. Digital Photographs of Specimens Exposed to Seawater Conditions Locating Crack Initiation.



A.1. Crack Initiation Location of specimen to seawater at σ_{eff} = 544 MPa.

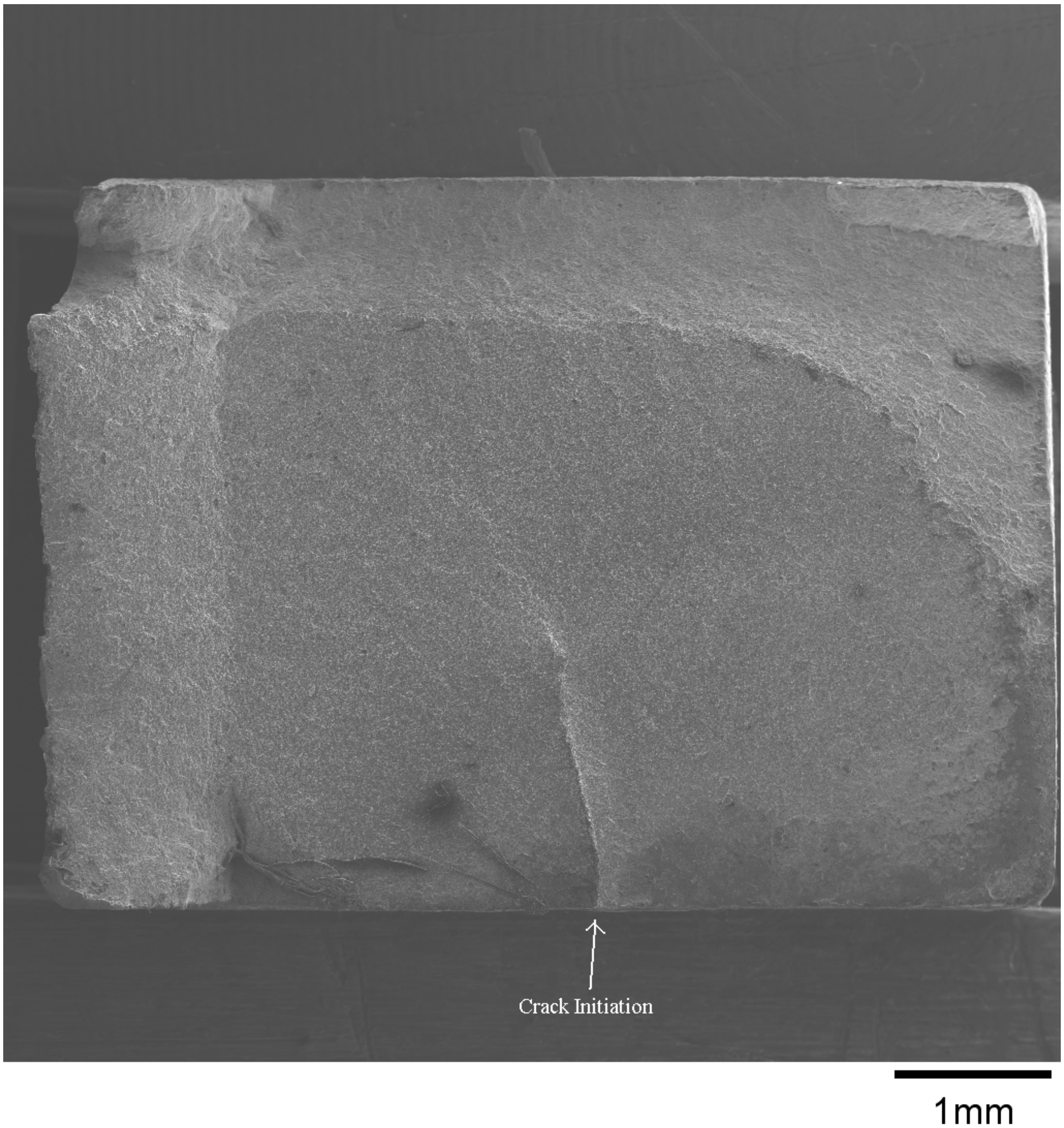


A.2. Crack Initiation Location of specimen to seawater at $\sigma_{eff} = 370$ MPa.

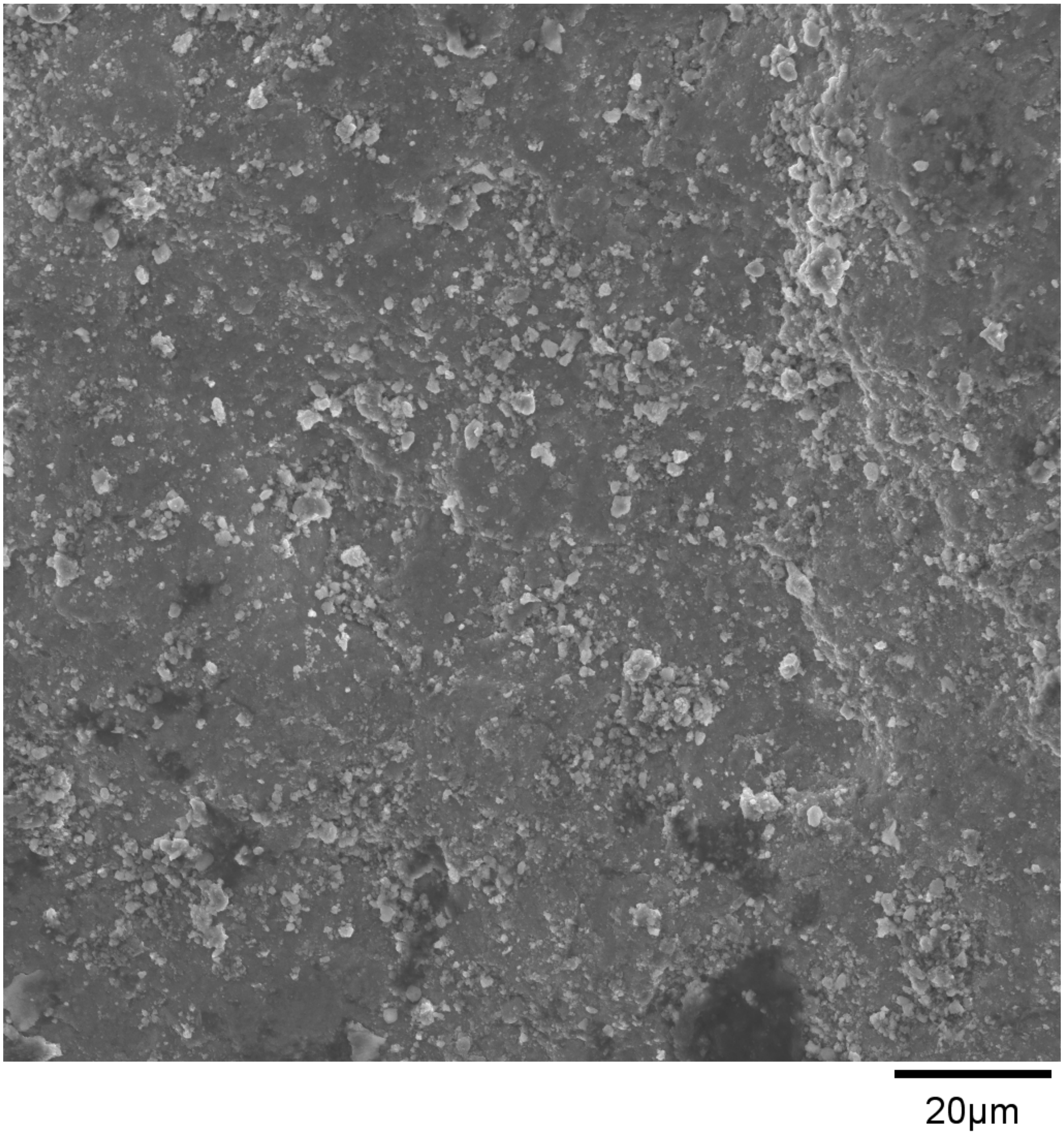


A.3. Crack Initiation Location of specimen to seawater at $\sigma_{eff} = 430$ MPa.

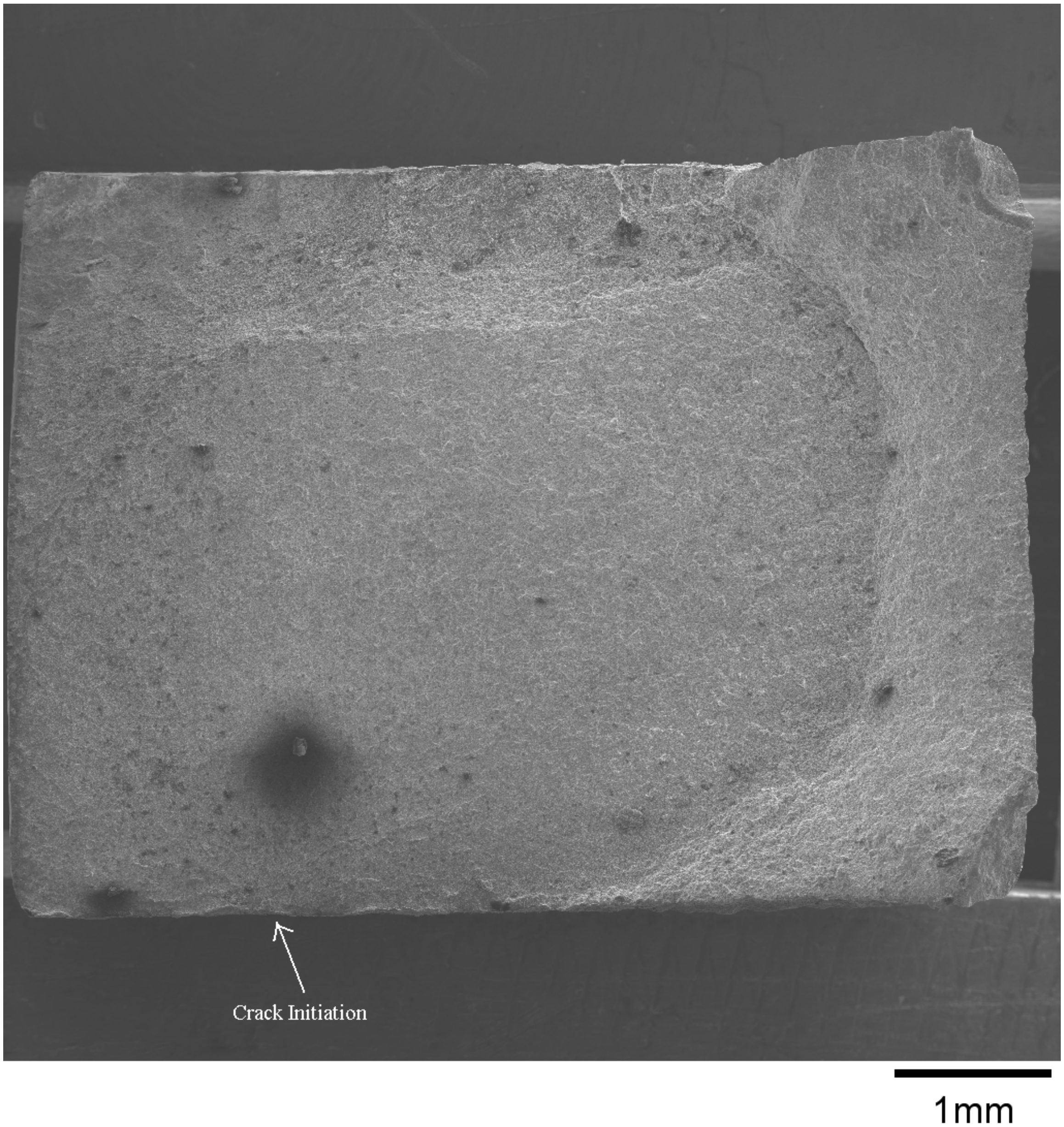
Appendix B. Secondary Electron Imaging Scanning Electron Microscope (SEI SEM) Photographs of Fracture Surfaces of Specimens Exposed to Seawater Conditions.



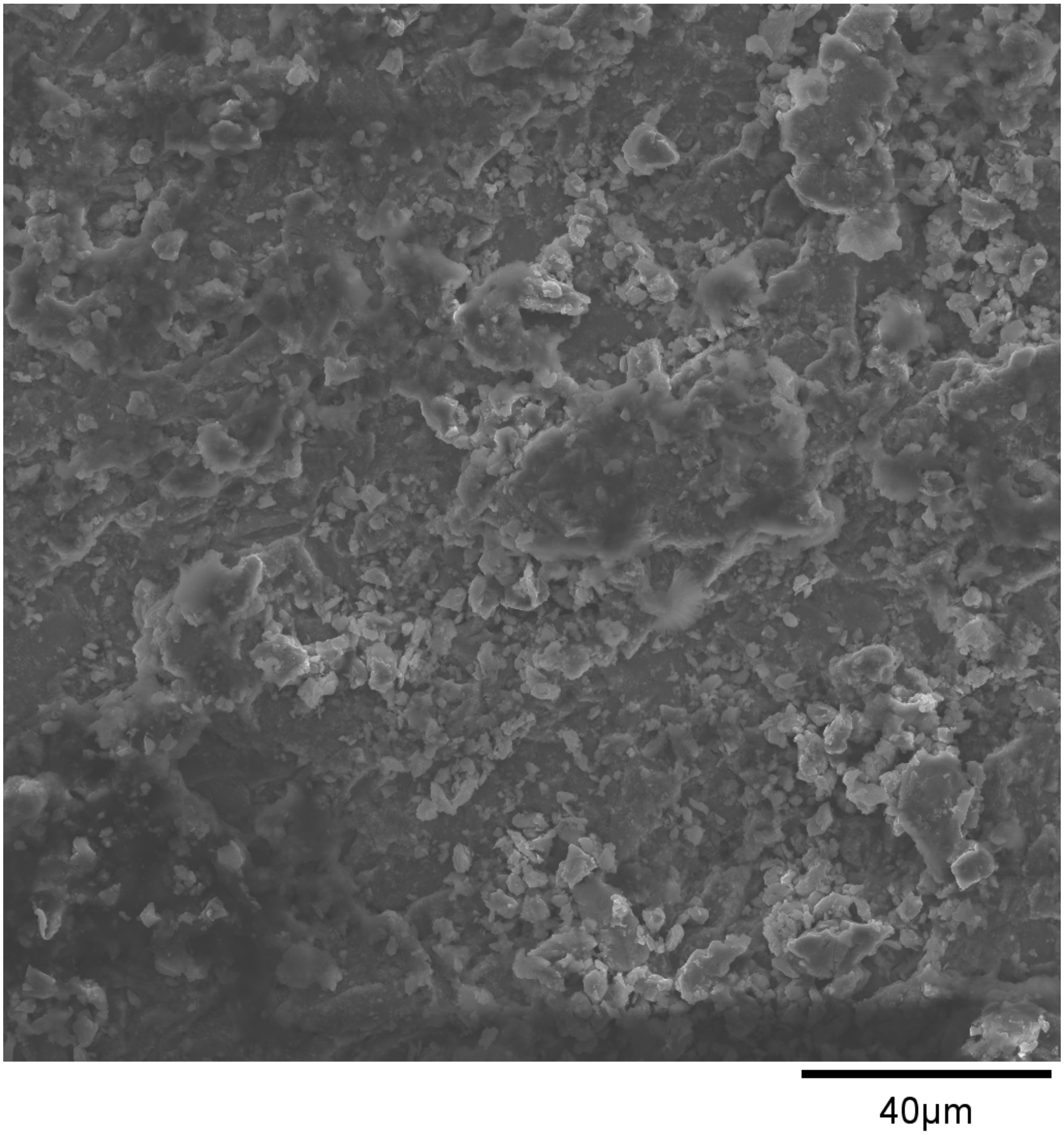
B.1. Specimen exposed to seawater at $\sigma_{eff} = 544$ MPa.



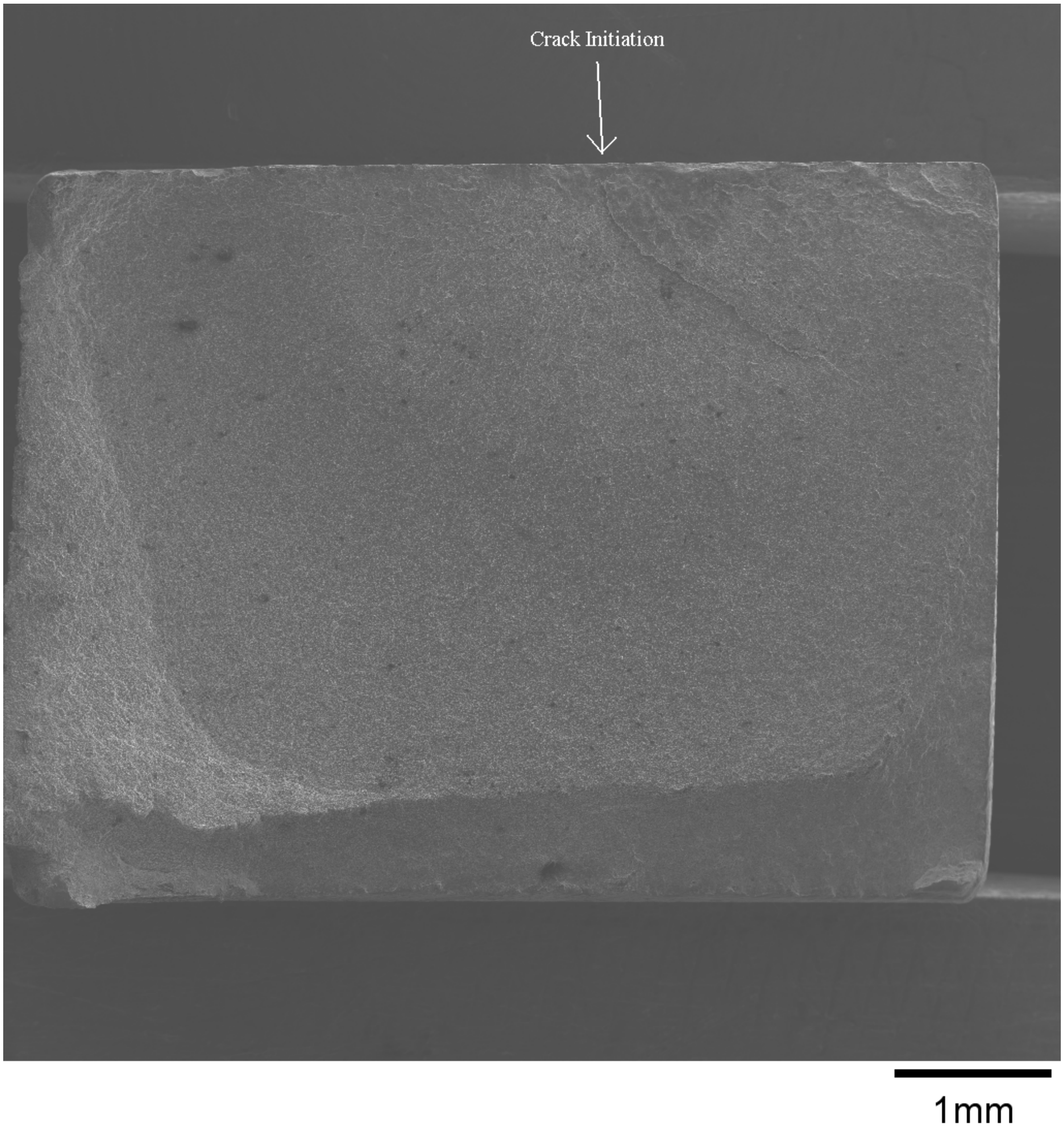
B.2. Specimen exposed to seawater at σ_{eff} = 544 MPa under high magnification.



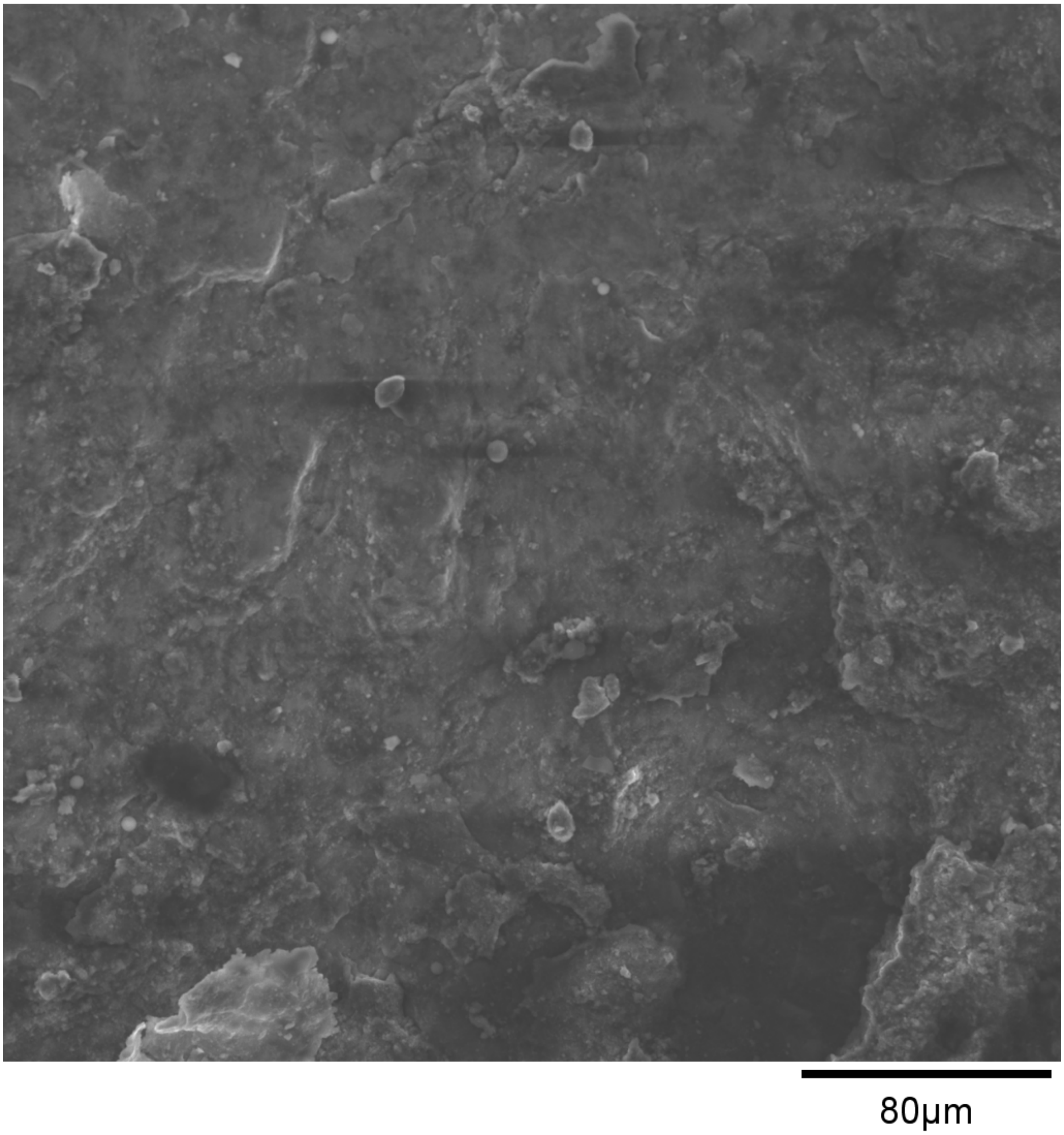
B.3. Specimen exposed to seawater at $\sigma_{eff} = 370$ MPa.



B.4. Specimen exposed to seawater at $\sigma_{eff} = 370$ MPa under high magnification.

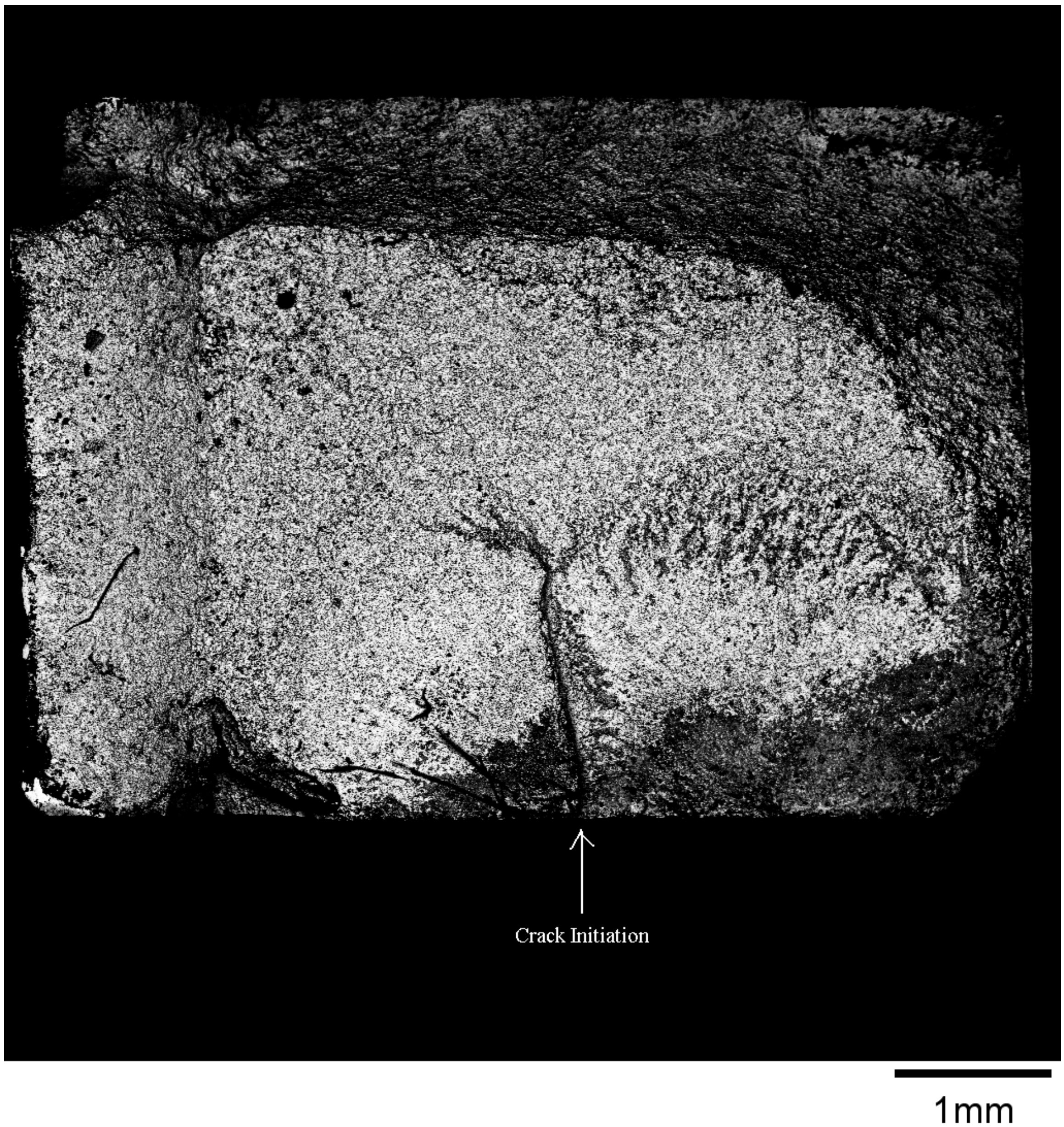


B.5. Specimen exposed to seawater at σ_{eff} = 430 MPa.

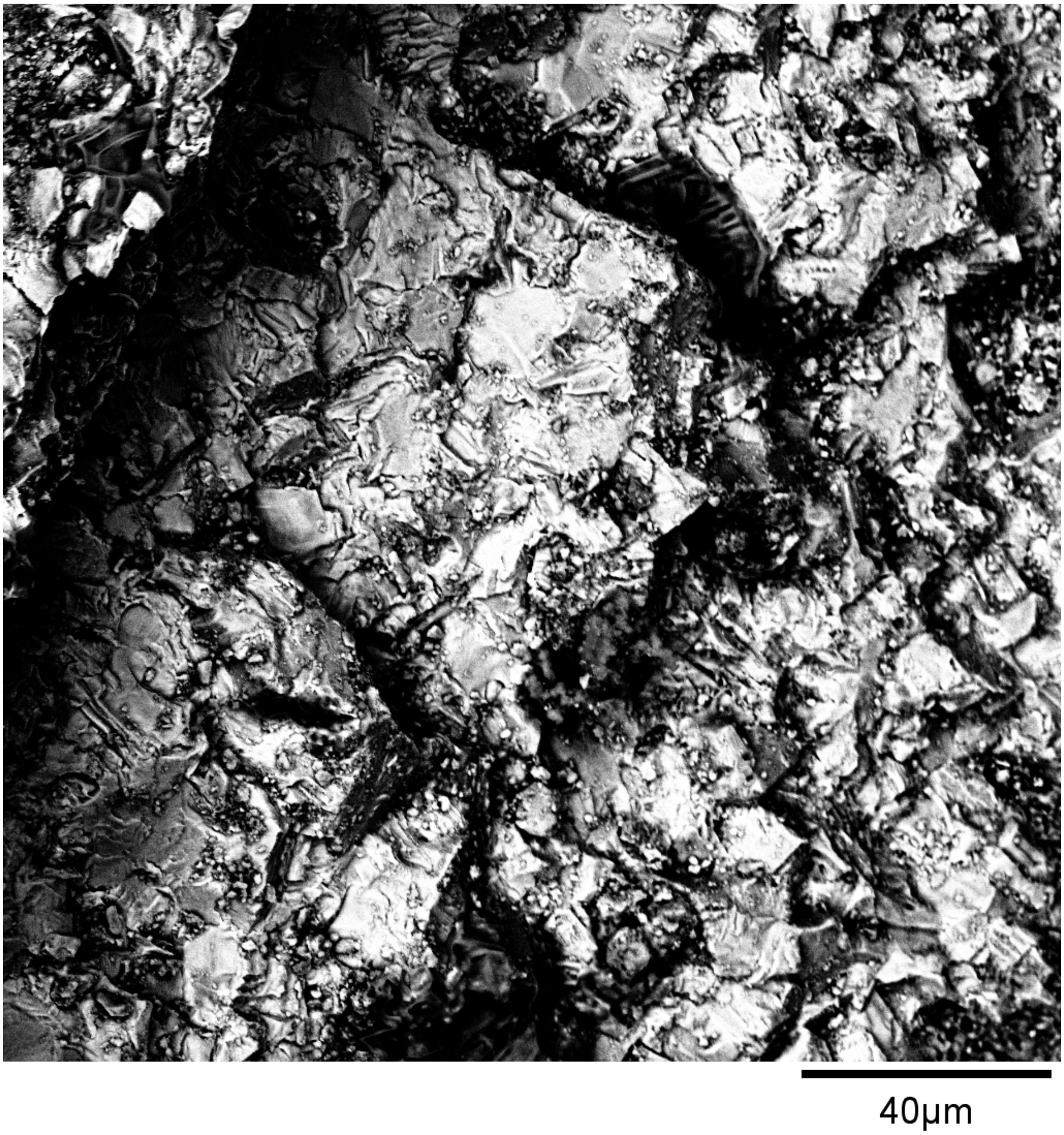


B.6. Specimen exposed to seawater at σ_{eff} = 370 MPa under high magnification.

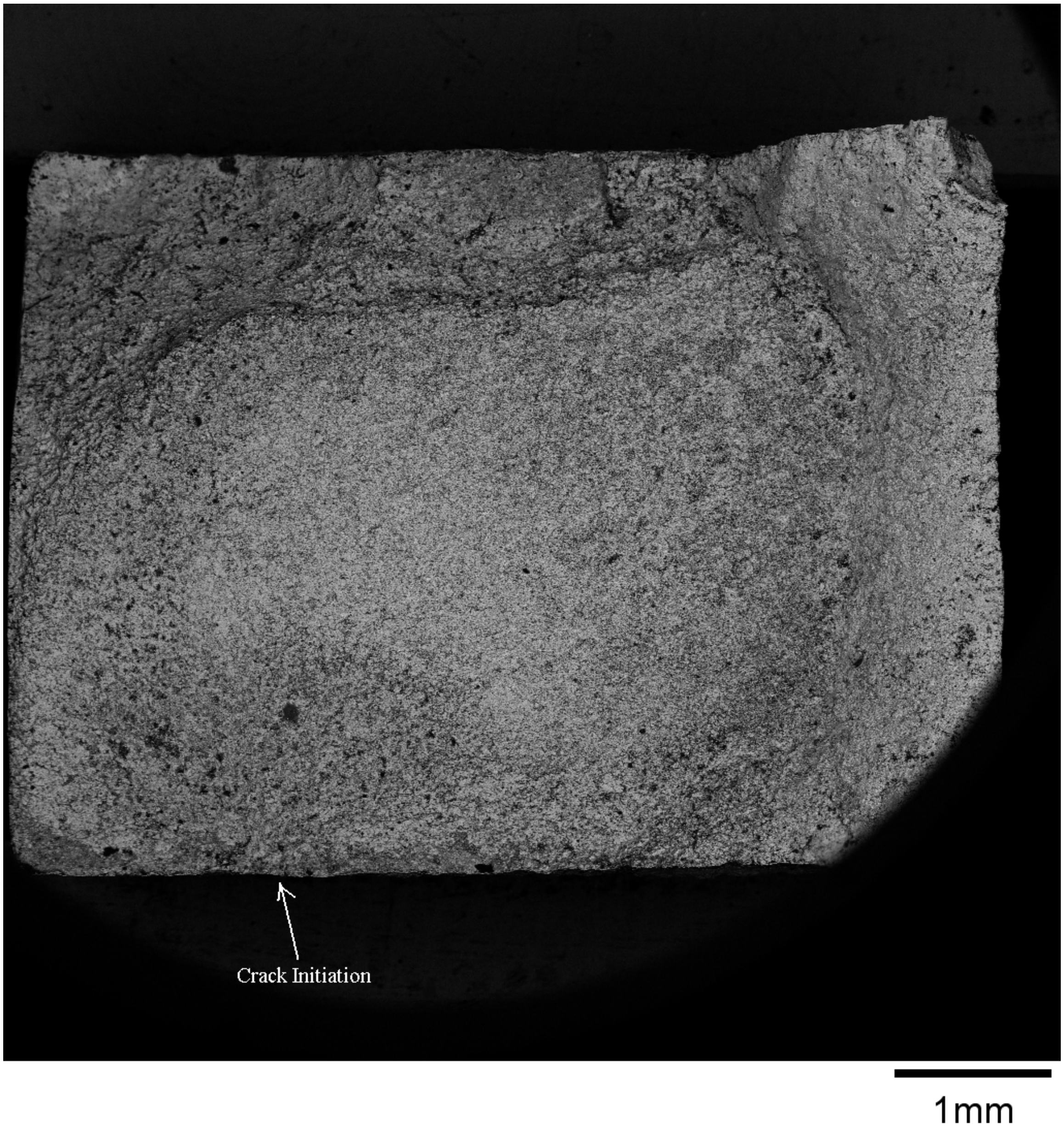
Appendix C. Back Scatter Emission Scanning Electron Microscope (BSE SEM) Photographs of Fracture Surfaces of Specimens Exposed to Seawater Conditions.



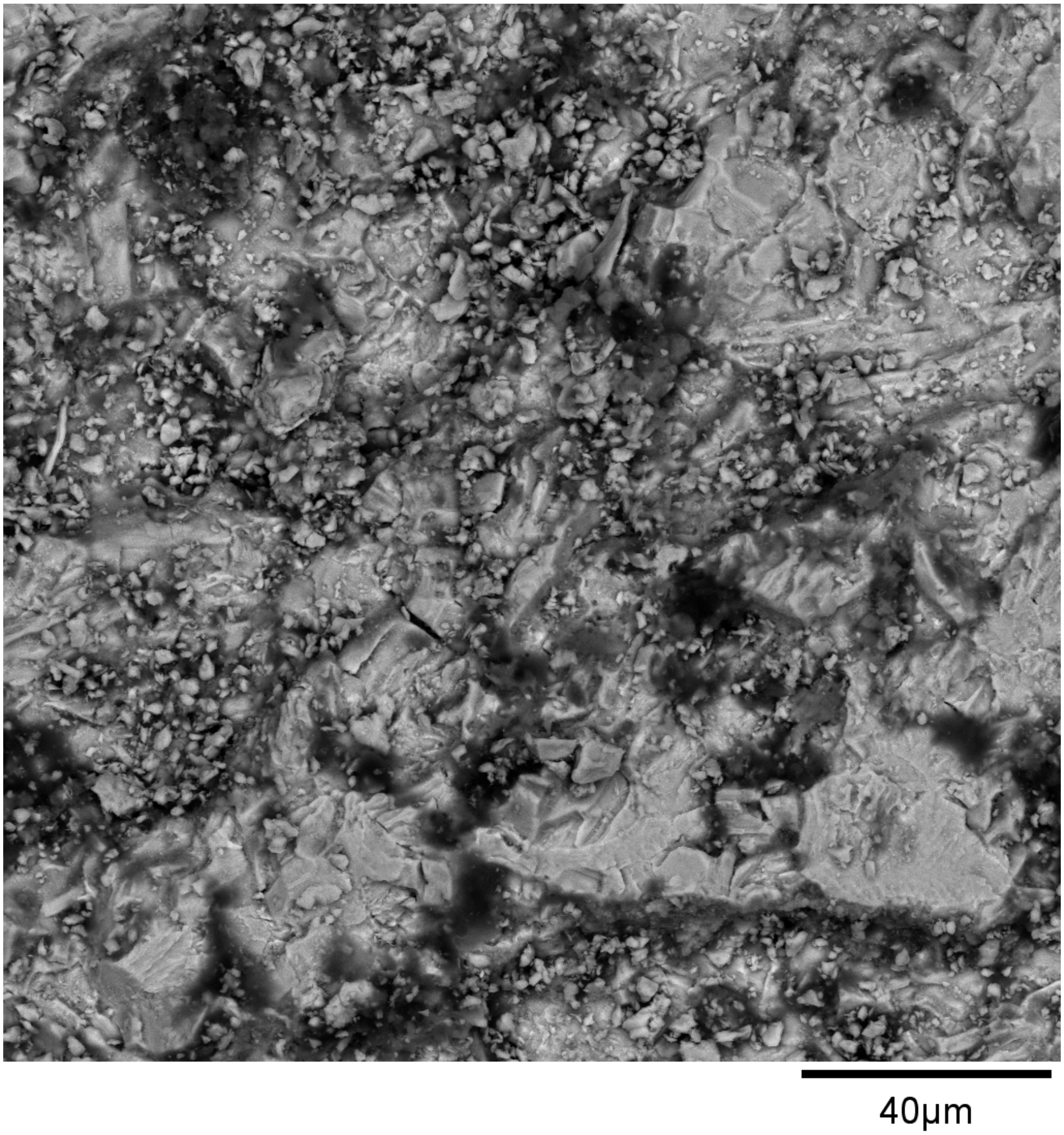
C.1. BSE SEM of fracture surface exposed to seawater conditions at σ_{eff} = 544 MPa.



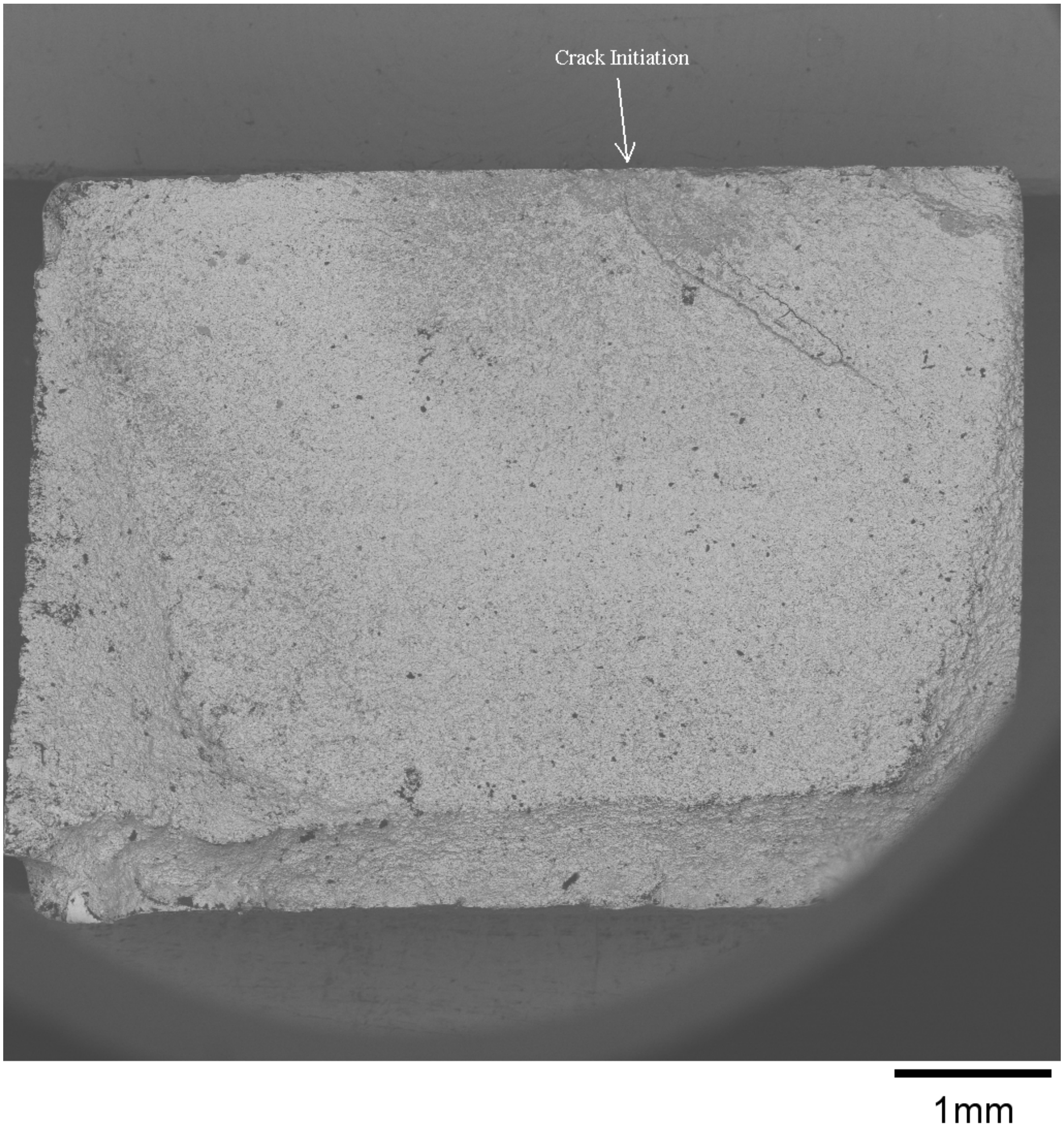
C.2. BSE SEM of fracture surface exposed to seawater conditions at σ_{eff} = 544 MPa under high magnification.



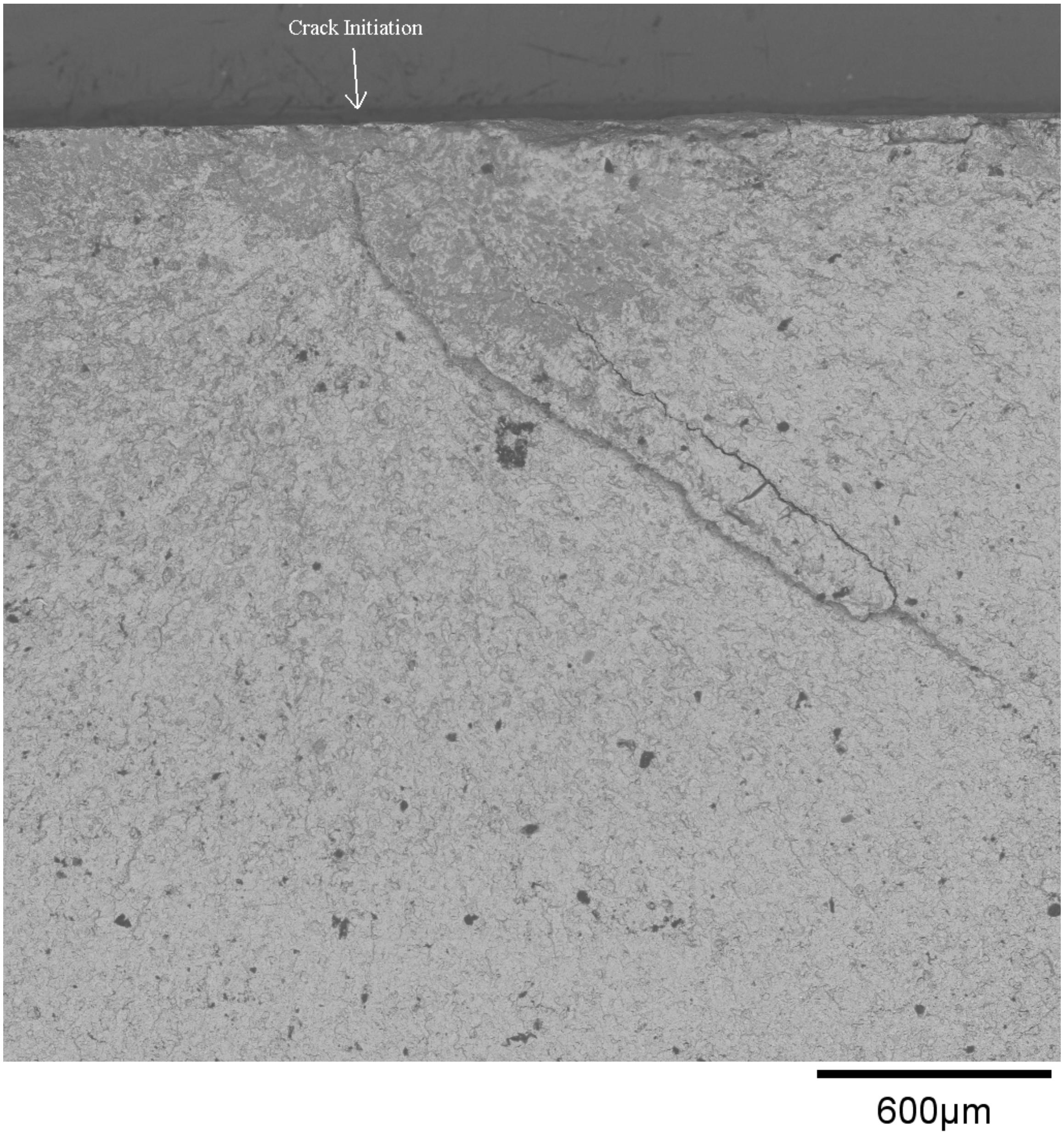
C.3. BSE SEM of fracture surface exposed to seawater conditions at σ_{eff} = 370 MPa.



C.4. BSE SEM of fracture surface exposed to seawater conditions at σ_{eff} = 370 MPa under high magnification.



C.5. BSE SEM of fracture surface exposed to seawater conditions at σ_{eff} = 430 MPa.



C.6. BSE SEM of crack initiation are of specimen exposed to seawater conditions at σ_{eff} = 430 MPa at higher magnification.

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Vita

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14. ABSTRACT
The fretting fatigue behavior of the shot-peened titanium alloy, Ti-6Al-4V, was investigated under a corrosive environment of synthetic seawater. Fretting fatigue tests were performed over a wide stress range to determine the effect of seawater at high and low cycle fatigue regimes. The results from this study showed: (1) seawater significantly reduces the fretting fatigue life of shot-peened Ti-6Al-4V at both high and low cycle fatigue relative to its counterpart in ambient laboratory conditions, (2) shot peening increases the fretting fatigue life of Ti-6Al-4V when tested under dry and seawater conditions relative to its counterpart of unpeened Ti-6Al-4V, (3) surface debris from samples tested under seawater conditions contained large quantities of oxide and seawater contaminants, (4) cleaning after testing removed most of the oxide and seawater contaminants from the sample.

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