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NONDESTRUCTIVE EVALUATION (NDE) EXPLORATORY DEVELOPMENT FOR AIR FORCE SYSTEMS

Delivery Order 0001: Quick Reaction NDE and Characterization--Effects of Chemical Etching after Pre-Inspection Mechanical Cleaning on Fluorescent Penetrant Indications of Fatigue Cracks

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Universal Technology Corporation

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14. ABSTRACT
A study was conducted to gather data on the ability of etching to recover FPI crack indications degraded by mechanically cleaning cracked specimens made of Ti-6Al-4V and Inconel 718. The data showed that minimal etching does not sufficiently overcome the deleterious effects of certain mechanical cleaning methods to provide for a subsequent reliable fluorescent-penetrant inspection, and the amount of etching required to recover some crack indications would not be allowed on critical rotating engine parts.

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nondestructive inspection, (NDI), fluorescent penetrant inspection, (FPI), etching, mechanical cleaning

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J. Edward Porter, Universal Technology Corporation - Conducted all fluorescent penetrant inspections (FPI) of cracked specimens, measured and recorded the brightness data for FPI indications, provided digital photographs of all crack indications, and archived the digital data.

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Robert Ware, AFRL/RXSA - Provided SEM images and interpretation thereof. Provided SEM spectrographic data to identify foreign material in or around cracks.

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1. SUMMARY

Mechanical cleaning involves physically removing surface contamination or coatings by directing a stream of small particles under pressure at a surface. The particles can consist of plastic, glass, abrasives, water or other material. The process cleans metal parts efficiently, but it also may disturb the surface to the degree that metal moves and covers discontinuities open to the surface.

A previous study produced data that supported the premise that mechanically cleaning aircraft engine parts adversely affects the ability of subsequent fluorescent penetrant inspection (FPI) to detect pre-existing cracks.[1] In fact, mechanical cleaning obliterated 76 percent of the FPI crack indications detected in Ti-6Al-4V and Inconel 718 specimens.

The objective of the study reported herein was to gather data on the ability to recover FPI indications by etching the mechanically-cleaned, cracked specimens to remove smeared metal covering crack openings. Prior to etching examination of mechanically-cleaned specimens with an optical microscopic confirmed that all impinging media, except for urea plastic (Type II), disturbed the surfaces of the specimens to the extent that smeared metal covered many of the crack openings so that liquid penetrant could no longer enter cracks to produce reliably detectable indications. In addition, foreign material was observed embedded in the cracks and in some cases was identified as cleaning media (e.g., plastic).

The specimens were etched to remove 0.2 to 0.4 mils of stock and then re-inspected with fluorescent penetrant. These etch/inspection cycles were repeated until the respective FPI crack indications recovered at least 40 percent of the brightness measured before mechanical cleaning.

The first etch recovered 11 percent of the obliterated FPI indications. After successive etches resulted in a total stock loss of 1.0 to 1.2 mils, only 45 percent of the indications were recovered. Removing up to 3.0 mils improved the recovery rate to 62 percent. In most cases the recovery rate was better for indications on titanium specimens. Unfortunately, on some specimens the etching attacked the crack surfaces so aggressively that the cracks became too wide to retain enough penetrant to produce good indications.

The results indicate that etching does not sufficiently overcome the deleterious effects of certain mechanical cleaning methods to allow a subsequent fluorescent-penetrant inspection to be effective. After minimal amounts of stock were removed with etching, the recovery rate for FPI crack indications was unacceptable. Etching beyond the minimal amount not only removes more stock than dimensional tolerances allow but also recovers far less than 100 percent of the FPI indications lost due to mechanical cleaning.

Since etching produced the quickest recovery of indications on specimens cleaned with the water jet, modification of that technique may allow it to be an effective pre-FPI cleaning method. There may also be other cleaning media available that would not affect the FPI indications so severely.

2. BACKGROUND

For the previous study mill-annealed Ti-6Al-4V plate and Inconel 718 extruded bar were used to fabricate test specimens, nominally 6 inches long by 1 inch wide by 0.25 inch thick. A low-cycle fatigue (LCF) crack was produced in each specimen by applying three-point cyclic bending loads. Each crack length was optically monitored during growth. All crack lengths are tabulated with the respective fluorescent penetrant inspection data in the Appendix.

There were nine groups of five specimens each for both alloys. Eight different mechanical cleaning methods had been applied to respective groups of each alloy. A ninth group of each alloy, designated as a control group, had not been subjected to any mechanical cleaning but was always inspected along with the other groups to monitor the repeatability of the FPI process.

The mechanical cleaning had been conducted at the USAF Oklahoma City Air Logistics Center (OC-ALC).[2] The methods used are shown in Table 1.

Table 1. Mechanical Cleaning Methods

Dry plastic media (Type II)
Water jet (50 ksi)
Dry glass bead (Size 13)
Wet glass bead (Size 13)
Dry Al_2O_3 (60 grit)
Dry Al_2O_3 (150 grit)
Dry Al_2O_3 (240 grit)
Wet Al_2O_3 (150 grit)

3. CHEMICAL ETCHING

3.1 Overview

The recipes for the etchant solutions were taken from the USAF NDI procedure manual for General Electric engine parts (T.O. 33B-1-11). The objective was to remove 0.2 to 0.4 mils (0.0002 to 0.0004 inch) of stock per surface with etching, perform fluorescent penetrant inspection (FPI) and evaluate the recovery of crack indications. Then, as necessary, the intention was to repeat the cycle until all the crack indications were recovered. When less than half of the indications were recovered after removing 1.0 to 1.2 mils of stock, exposure to the etchant solutions was increased in order to remove 0.4 to 0.6 mils of stock per etch cycle, because at that point the amount of stock removal already exceeded the allowable tolerance for some engine parts.

3.2 Etchant Solution (Titanium Alloy – Class B) for Ti-6Al-4V

Water: 496 mL

Nitric Acid (69-71 percent): 280 mL

Hydrofluoric Acid (48 Percent): 24 mL

3.3 Etchant Solution (High Chromium Super Alloy – Class G) for Inconel 718

Water: 180 mL

Hydrochloric Acid (36-38 percent): 593 mL

Nitric Acid (69-71 percent): 28 mL

Ferric Chloride ($FeCl_3$ $6H_20$): 180 grams

3.4 Etch Rate Test Tabs

Etch rates are commonly determined by measuring stock removal from test tabs, which are precisely dimensioned parts with simple geometry made from the same alloy being etched. For this study six tabs were cut from 0.047-inch thick annealed Ti-6Al-4V sheet and six tabs were machined from the same Inconel 718 bar stock from which crack specimens had been made. The titanium tabs measured 3.5 by 2 by 0.047 inches ±0.001. This configuration is typically referred to as the standard test-tab configuration where the combined top and bottom surface-area-to-thickness ratio is greater than 100 to 1, allowing the surface area of the edges to be ignored in the etch-rate calculations.[3] The Inconel tabs measured 3.5 by 1.0 by 0.5 inches ±0.001. This configuration is typically referred to as non-standard and all surface areas have to be included in the etch-rate calculations.[3]

3.5 Etch Protocol and Stock Loss Calculation

A common method of determining stock loss is by measuring etch tab thicknesses with a micrometer before and after etching. However, that method is very inaccurate due to variations in micrometer closing pressures and changing tab-surface topography with repeated etching. Therefore, in this study etch rates and stock loss were determined from equations found in the literature.[3] To determine the etch rate for the thin, flat Ti-6Al-4V tabs, the known tab dimensions and precisely measured weight losses were inserted into Equation 1.

$$R = \frac{(W_O - W_F)}{2 \cdot 454 \cdot (lwd) \cdot (t_e)} \qquad \textbf{(1)}$$

Where

R = etch rate (inches lost per surface per minute)

W_O = original tab weight before etching (grams)

W_F = final tab weight after etching (grams)

l = tab length (inches)

w = tab width (inches)

d = alloy density (pounds per square inch)

t_e = etching time (minutes)

The number 2 reflects the fact that there are two (top and bottom) surfaces of a tab being etched; (the surface area of the edges is ignored where surface-area-to-thickness ratio is greater than 100 to 1)

The number 454 is the approximate number of grams in a pound

Equation 2 was used to determine the etch rate for the Inconel 718 thick, flat, non-standard tabs.

$$R = \frac{(W_O - W_F) \cdot lwT}{2W_O \cdot (lw + Tw + lT) \cdot (t_e)} \tag{2}$$

where

R = etch rate

T = tab thickness (inches)

Equation 3 was used to determine the etch time required to remove 0.1 mil of stock, where the etch rate was based on stock removed from tabs during previous etch cycles.

$$t = \frac{0.0001}{R} \tag{3}$$

Then the total etch time needed for a group was obtained by multiplying t by the desired number of tenths of a mil to be removed.

The actual stock lost per surface (λ_{st}) from a group of crack specimens during an etch cycle was calculated from Equations 4 and 5 for titanium and Inconel respectively.

$$\lambda_{st} = \frac{(W_O - W_F)}{2 \cdot 454 \cdot (lwd)} \quad \text{for titanium} \tag{4}$$

$$\lambda_{st} = \frac{(W_O - W_F) \cdot lwT}{2W_O \cdot (lw + Tw + lT)} \quad \text{for Inconel} \tag{5}$$

Initially the etch time was calculated from etch rates that were empirically determined by exposing multiple tabs of the respective alloys to the appropriate etchants for various times. Based upon a comparison of the calculated stock loss for the first group etched with the intended loss, the etch time for the next group was adjusted as necessary to obtain the desired stock loss. This iterative adjustment to the etch times continued for each subsequent group. A new batch of each etchant solution was mixed at the beginning of each etch cycle. However, it was soon apparent that the etch rate for titanium decreased rapidly over time, so a new solution was mixed after etching only four groups. The solution for Inconel generally became more aggressive with each successive group, so a single batch could be used to etch all eight groups if necessary. The etch-rate changes were not linear, so plotting etch rate versus the total etch time for each solution provided a means to recognize patterns of rate change and predict the proper etch time for the subsequent etches.

The five crack specimens of each group were etched together along with one test tab of the respective alloy. The calculated stock lost per surface of the test tab became the stock lost per surface from each specimen of the respective group. The setup used for etching is shown in Figure 1. Since AFRL/RXSA does not have standing etch tanks, a one-liter beaker was chosen to accommodate a group of five specimens and one test tab while keeping the amount of etchant solution to a minimum. Placing the beaker on a magnetic stirring device to agitate the etchant by means of an encased ferromagnetic pellet in the beaker was found to provide a more uniform and predictable stock loss. The heat control of the device was turned off. The cracked specimens were mounted on a metal rod, separated by pieces of plastic tubing. The test tab was immersed first so that it rested on the bottom of the beaker completely submerged. The specimens were then suspended in the etchant solution so that the cracks were submerged at least one inch. For consistent exposure to the etchant solution the sequence of immersing the specimens immediately after the tab was followed. After the prescribed exposure time, the tab and the specimens were removed in the same sequence and put into a beaker of plain water. A rinse under running water followed immediately.

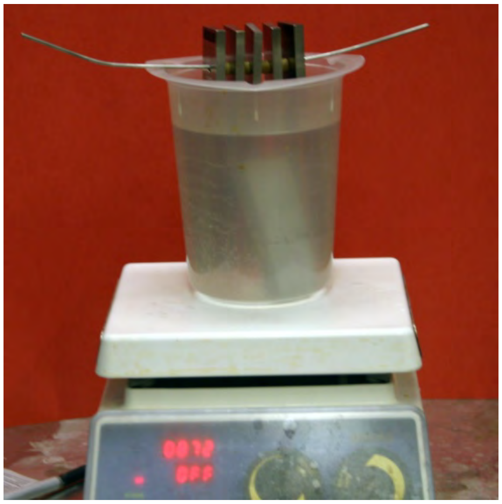


Figure 1. Etching Apparatus

To roughly verify the consistency of the etching among the specimens and the test tab, the stock losses from the cracked specimens were also calculated directly. Since the thicknesses of the cracked specimens varied, the etch-rate equations for the non-standard tabs had to be applied to each specimen individually using the dimensional measurements of the submerged volume and the measured weight loss of the specimen. The stock losses of the five specimens in a group were averaged and compared to the stock lost calculated for the respective test tab. Despite the approximations involved with the dimensional measurements of submerged lengths of the cracked specimens, the resulting calculations were consistent with the test tab calculations.

4. FLUORESCENT PENETRANT INSPECTION

4.1 Overview

The fluorescent penetrant inspection (FPI) process consisted of pre-cleaning the specimens, processing the specimens with the penetrant system and developer, measuring the brightnesses of the crack indications, photographically documenting the indications, and post-cleaning the specimens. Since the object of the etching was to recover the FPI indications, which mechanical cleaning had prevented from forming, the FPI process was repeated after each etch cycle on groups of five specimens at a time. Initially the grouping coincided with the methods of mechanical cleaning. However, to maintain processing efficiency as etching was terminated for specimens with recovered indications, some groups included specimens from a mixture of methods. The control (un-etched) groups also underwent FPI once per etch cycle along with the etched specimens of the respective alloys.

4.2 Cleaning

4.2.1 Equipment and Materials

- Custom rack for specimens (Figure 2).
- Acetone.
- Container to accommodate acetone and the custom rack with specimens.
- Ultrasonic cleaner, Lewis Model 1209-SH, with continuous ultrasonic output power of 800 watts RMS.
- Sink with warm running water.
- Parts-cleaning brush with soft fiber (no metal) bristles.
- Mild dishwashing soap.
- Container for dishwashing-soap and water solution.

4.2.2 Pre-cleaning

1) Place the specimens into the custom rack in S/N sequence.
2) Place the rack into the container with sufficient acetone to completely immerse the specimens, and cover the container.
3) Place the covered container into the ultrasonic cleaner filled with water according to the manufacturer's instructions.
4) Turn on the ultrasonic cleaner for 5 minutes.
5) Turn off the ultrasonic cleaner and allow the specimens to remain immersed in the solvent for an additional 10 minutes.
6) Remove the holder with specimens from the solvent and place it in the recirculating oven at 135 ± 5°F (21 ± 3°C) for 30 ± 5 seconds to flash off any remaining acetone.
7) Visually examine the specimens under both UV-A radiation and white light to verify that there is no residual fluorescent indication of any crack and the specimens are clean and dry.

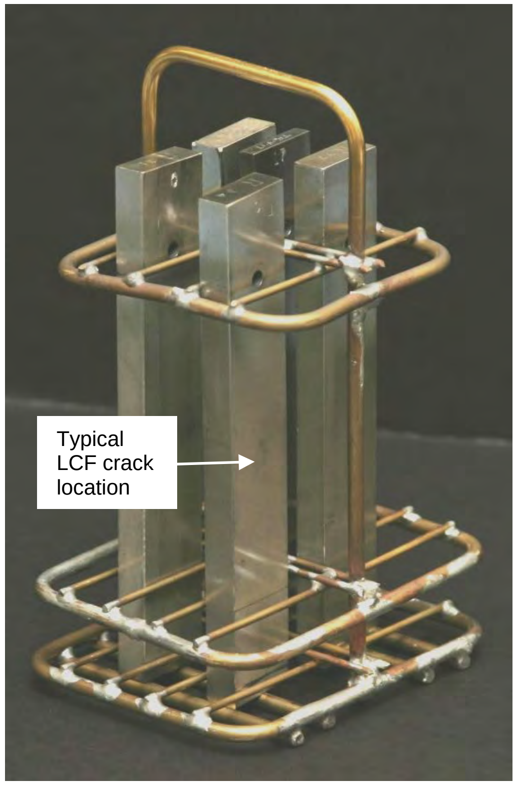


Figure 2. FPI Custom Specimen Rack

4.2.3 Post-cleaning

1) Transfer the specimens to the sink.
2) In S/N sequence dip the first specimen into the soap-and-water solution.
3) Dip the parts brush into the soap-and-water solution and brush the surfaces of the specimen to remove the developer. Brush the cracked surface parallel to the crack only.
4) Rinse the specimen under warm running water and place it on end against a support on a workbench to drain.
5) Repeat steps 2 through 4 for the remaining four specimens in sequence.
6) Dry the first specimen with a clean, soft, dry paper towel and place the specimen into the rack. Repeat for the remaining four specimens in sequence.
7) Place the rack into the container with sufficient acetone to completely immerse the specimens, and cover the container.
8) Place the covered container into the ultrasonic cleaner filled with water according to the manufacturer's instructions.
9) Turn on the ultrasonic cleaner for 5 minutes.

4.3 Penetrant System and Developer

A Level 3, Method D, Type 1 penetrant system used at OC-ALC was selected for processing the cracked specimens: Met-L-Chek FP-95A(M) fluorescent liquid penetrant and E-58D hydrophilic emulsifier mixed at a 20% concentration. A dry powder developer, Magnaflux ZP-4B, although not used at OC-ALC, was selected for this study because experience at AFRL/RXSA has shown it to provide the most repeatable indications of low-cycle fatigue cracks in specimens processed multiple times for evaluating the sensitivity of penetrant materials in accordance with the SAE Aerospace Material Specification, AMS 2644, *Inspection Materials, Penetrant*.[4]

4.4 Penetrant System and Developer Processing Parameters

The variables of the penetrant inspection process were minimized by conducting the inspections at AFRL/RXSA using the tightly controlled processes developed for testing the sensitivity of candidate penetrant materials for inclusion on the SAE Qualified Products Database, QPD AMS 2644, *Inspection Materials, Penetrant*. Table 2 contains the penetrant system and developer processing parameters. Each step was closely timed, and the water and oven temperatures were closely monitored. For process control during critical steps, a group of five specimens were processed simultaneously as a set whenever possible. To maintain process control when it was necessary to process specimens individually (e.g., dipping into penetrant and applying developer), the specimens were always processed in the same sequence and the timer for the respective step was started after the last specimen was processed.

Table 2. Penetrant System and Developer Processing Parameters

Penetrant Dwell	Dip, drain for 30 minutes ± 10 seconds.
Prewash[1]	Method D: Spray for 30 ± 5 seconds with water.
Emulsification	Method D: Immerse for 2 minutes ± 5 seconds, no agitation.
Wash[1]	Method D: Spray for 1 minute ± 5 seconds with water. Remove dripping water: one light wipe with clean towel.
Dry[2]	5 minutes ± 10 seconds in oven.
Developer	Form a: dip, agitate, remove and tilt to let developer slide off specimen. Dwell for 5 minutes ± 10 seconds before measuring indication brightness.

[1]Water: 25 ± 2.5 psi (172 ± 17 kPa) and 70 ± 5°F (21 ± 3°C)
[2]Oven: 135 ± 5°F (21 ± 3°C)

Figure 3 shows the custom wash apparatus used to simultaneously wash the five specimens in a group. Wash time is controlled by opening and closing a quarter-turn ball valve in the water supply line. Figure 4 shows a close-up of the wash-apparatus fixture with the removable holder for transferring specimens to and from the container with hydrophilic emulsifier. After the wash following emulsification, specimens are transferred back to the custom rack (Figure 2) for drying.

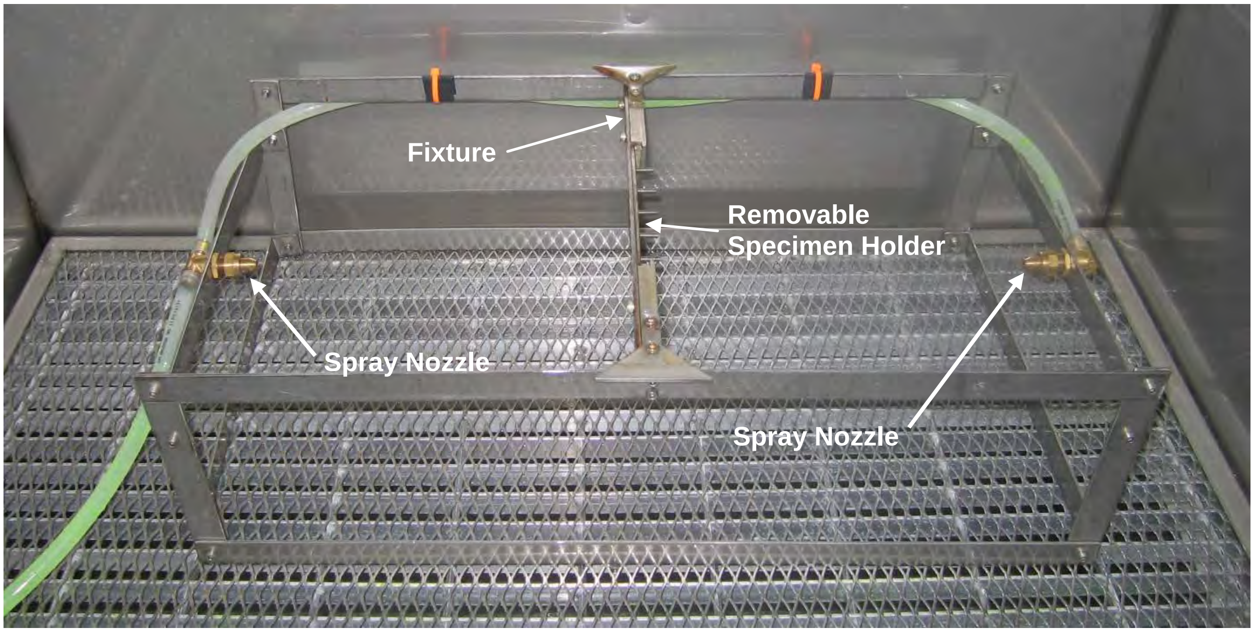


Figure 3. FPI Wash Apparatus

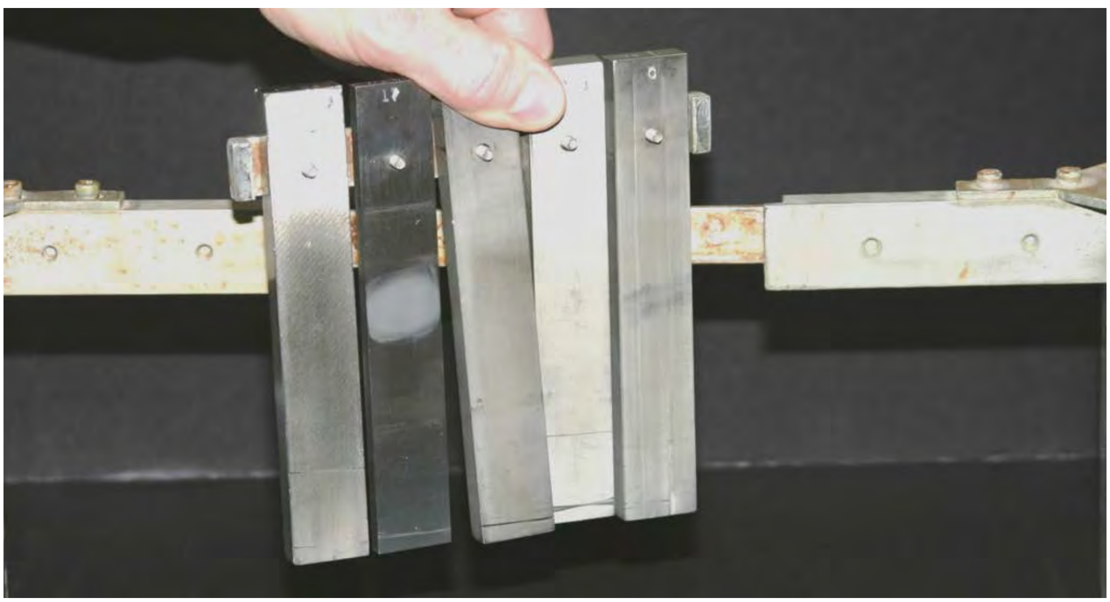


Figure 4. FPI Wash-Fixture Removable Holder for Fatigue-Crack Specimens

4.5 Brightness Measurement of Penetrant Indications

A photometer, Photo Research Model PR-1500 Spotmeter® with a ¼-degree aperture and an MS-55 macro lens, was used to measure the brightness of the penetrant indications. An internal photopic filter simulated the response of a typical human eye. The configuration of the measurement station is shown in Figure 5. With this setup the field of view at the specimen surface was approximately 0.060 by 0.020 inch; the long axis of the elliptical area was aligned along the length of the crack indication being measured. The UV-A intensity at the specimen surface was 2200-2400 $\mu W/cm^2$. Before each group measurement sequence the intensity of the UV-A light was checked with a radiometer, and the self-calibration of the Spotmeter® was accomplished. UV-A lamp tubes were cleaned or replaced as necessary to maintain consistent intensity.

In the same sequence followed during penetrant processing one specimen at a time was placed on the movable stage mounted to the jack stand, and the stage was adjusted to place the indication within the field of view of the photometer. The value of the indication brightness displayed on the Spotmeter® digital display was recorded after subtracting the brightness of the fluorescent background adjacent to the crack. The latter was measured by moving the crack indication out of the field of view of the photometer.

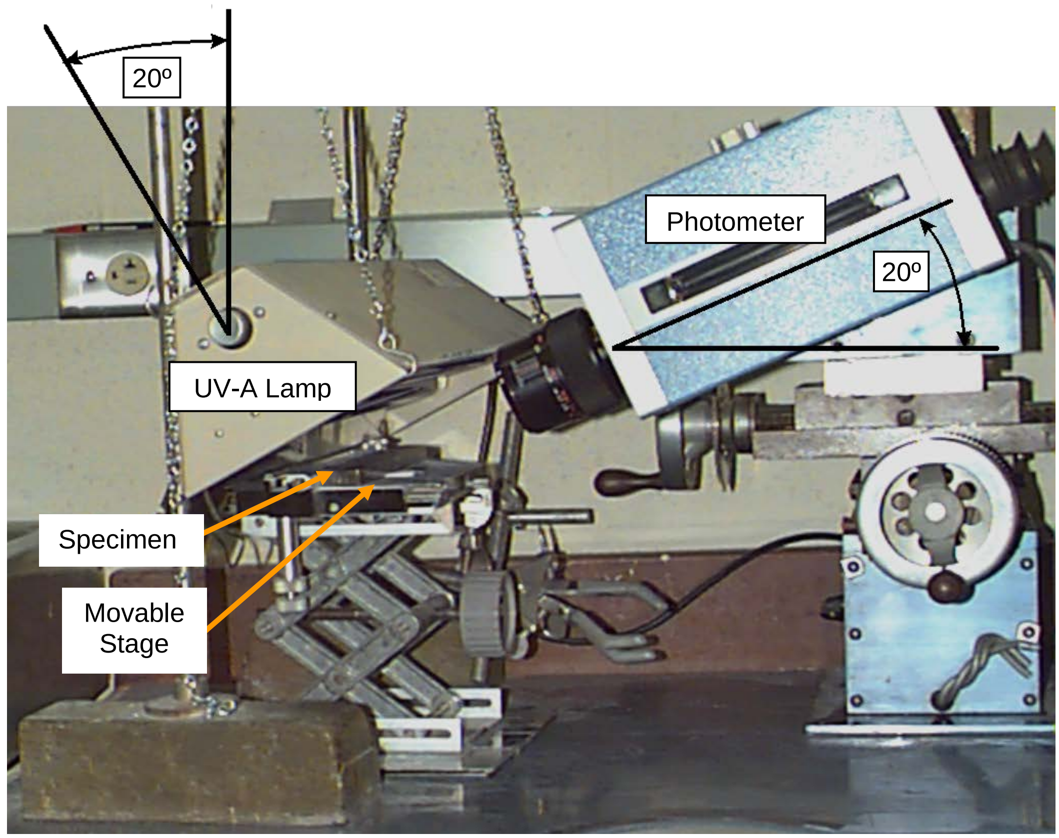


Figure 5. Equipment Configuration for Measuring Brightness of Crack Indications

5. MICROSCOPIC EXAMINATION

Optical microscopes and a scanning electron microscope (SEM) were used to examine the specimen surfaces containing the cracks. The objectives were to 1) visualize the effects of the various methods of mechanical cleaning, 2) analyze the effects of etching on the smeared metal covering cracks and on the cracks themselves, and 3) attempt to correlate the FPI indications with the crack-opening physical characteristics.

At the onset of the study one specimen from each group of mechanically cleaned specimens was selected for SEM examination. A limit of one specimen was set because the time to pump down the SEM vacuum chamber and examine one specimen was not inconsequential, and the availability of SEM was limited. Selected specimens had crack lengths ranging from 0.060 to 0.0100 inch. The thinking was that longer cracks would have the best chance of being seen, even after mechanical cleaning. Images were recorded of each specimen at a minimum of two magnifications: 50X to enable the entire length of the longest cracks to be seen on a single image and 200X to show more detail of the mechanically cleaned surfaces and the cracks without limiting the field of view to a very small area. Images were recorded at higher magnifications to investigate a feature of interest or the interior of a crack. If foreign material was detected inside a crack, the spectroscopic analysis feature of the SEM was employed in an attempt to identify the material. Most of the SEM images in this report are made from secondary electron emission, which provides the most realistic picture of the specimen surface. Electron backscatter, which provided a shadowing effect, was used to image cracks that were difficult to detect.

After two rounds of etching the sixteen specimens initially examined with the SEM were re-examined. Images were recorded as before to document changes that occurred due to etching, including any new features that were uncovered. In addition, nine other specimens not selected before etching were examined because of an interesting trend noted in the FPI data or a marked difference in the FPI data for two cracks of similar lengths. Some of the specimens in the control groups were also examined to provide baseline images of cracks in specimens that had not been mechanically cleaned.

After all etching was completed, optical microscope images were recorded for all specimens at 50X and 200X magnification. Crack lengths were also measured at the highest magnification that allowed the entire crack to be seen in one image.

6. RESULTS AND DISCUSSSION

6.1 Review of FPI Results after Mechanical Cleaning

All mechanical-cleaning media adversely affected FPI crack indications. However, on specimens cleaned with dry plastic media all five cracks continued to produce indications with brightnesses greater than 40 percent of that obtained before mechanical cleaning (pre-MechClean). Table 3 summarizes the previously reported post-MechClean FPI results.[1] The threshold of 40 percent of Pre-MechClean brightness represented was easily detectable and was achieved by all the crack indications on specimens cleaned with plastic media. Therefore, in practice titanium and Inconel parts cleaned with Type II plastic media would not have to be etched prior to FPI.

Table 3. FPI Results after Mechanical Cleaning

	FPI Indications (% of cracks)			
	Ti-6Al-4V		Inconel 718	
Cleaning Media	Any Brightness	Brightness > 40% of Pre-MechClean	Any Brightness	Brightness > 40% of Pre-MechClean
Dry plastic media (Type II)	100	100	100	100
Water jet (50 ksi)	60	60	80	40
Wet glass bead (Size 13)	40	20	20	20
Dry Al_2O_3 (150 grit)	0	0	60	0
Dry Al_2O_3 (240 grit)	40	0	40	0
Wet Al_2O_3 (150 grit)	0	0	40	20
Dry glass bead (Size 13)	0	0	0	0
Dry Al_2O_3 (60 grit)	0	0	0	0

6.2 FPI Results after Etching

In general, etching was most effective at recovering indications on titanium specimens. A recovery rate of 80-percent was achieved after removing small amounts of stock from titanium specimens cleaned with two media: 0.3 mil from specimens cleaned with water jet and 0.2 mil from specimens cleaned with wet glass bead. In both cases the cracks that did not recover were less than 0.030 inch long. Eventually 100 percent of the indications for five titanium groups and 80 percent for the other two groups were recovered with etching. In all cases the last cracks to recover were less than 0.050 inch long. On Inconel specimens the highest recovery rate was 80 percent, and that was only for the group cleaned with water jet after 0.6 mil of stock was removed.

Although precautions were taken to control the etching process and verify the amount of stock removed with each etch cycle, the process did not exhibit the desired predictability with respect to the anticipated FPI indications. Successive etches did not always result in increased indication brightness. In fact, brightnesses decreased after some etch cycles and did not always recover to the previous level. The behaviors of some FPI indications may have been due to observed differences in the physical activity (i.e., bubbling) and the corresponding etch rates between etchants and between successive etch cycles of both etchants. Perhaps using small batches of etchant contributed to the variations. In addition, characteristics of the specimens themselves, such as the compressive stresses at the crack openings, may have influenced the amount of etching that occurred within the cracks themselves, which certainly would affect the FPI indications.

The FPI results seem to indicate that the effects of mechanical cleaning and subsequent etching are neither consistent nor predictable. Furthermore, the state of the crack (i.e., crack opening and volume) not only affects the FPI indication but also may influence the effect of mechanical cleaning and etching. A secondary finding of this study was that viewing cracks under magnification does not consistently provide information that allows a correct prediction of the nature of an FPI indication.

Table 4 summarizes the recovery rates for FPI indications degraded by mechanical cleaning. An indication was considered recovered after etching when its brightness exceeded 40-percent of its pre-MechClean brightness. Media groups are listed in order of decreasing effectiveness of etching in recovering indications. In ranking the media both alloys were considered together, and more weight was given to recovery achieved with the least amount of stock removal. However, beyond the first two listed media adjacent rankings could easily have been reversed by using slightly different criteria in judging the data.

Table 4. Summary of FPI Indication Recovery

	Ti-6Al-4V			Inconel 718		
Cleaning Media	**Indications above Recovery Threshold (%)**	**Stock Removed[1] (mil)**	**Total Stock Removed[2] (mil)**	**Indications above Recovery Threshold (%)**	**Stock Removed[1] (mil)**	**Total Stock Removed[2] (mil)**
Dry plastic media (Type II)	100	0	n/a	100	0	n/a
Water jet (50 ksi)	100	1.0	n/a	100	1.5	n/a
Wet glass bead (Size 13)	100	1.4	n/a	60	1.2	2.4
Dry Al_2O_3 (150 grit)	100	1.4	n/a	60	1.7	2.9
Dry Al_2O_3 (240 grit)	100	2.0	n/a	40	0.5	1.9
Wet Al_2O_3 (150 grit)	80	2.1	2.1	40	0.8	2.0
Dry glass bead (Size 13)	80	2.0	2.0	40	1.9	2.6
Dry Al_2O_3 (60 grit)	100	1.6	n/a	20	2.2	2.7

[1] Amount of stock removed to achieve recovery percentage listed in previous column.
[2] Total amount of stock removed in unsuccessful attempts to improve recovery percentages.

Figure 6 presents the data graphically, showing recovery rate for each etch cycle. The post-MechClean results relative to the recovery threshold are also included. Two post-MechClean indications in Inconel specimens, one each cleaned with wet glass bead and wet 150-grit Al_2O_3, suffered significant reductions in brightness after the respective initial etches, only to recover brightnesses equal to or much greater than their post-MechClean brightness after additional etching. Etching sometimes degraded FPI indications, but usually not to this degree.

Additional data is provided in the Appendix. For each mechanical cleaning method a chart presents FPI indication brightnesses (as percentages of the pre-MechClean brightnesses) obtained after mechanical cleaning and after each etch cycle. Recoverd indication brightness greater than 100 percent of pre-MechClean values are indicated numerically in the appropriate places. On the horizontal axes of the charts pre-MechClean indication brightnesses and crack lengths are provided along with respective specimen numbers. The chart legends indicate accumulated amounts of stock removed. Photographs are also presented of pre- and post-MechClean FPI indications, post-etch FPI indications, and post-etch optical or scanning-electron microscope images of cracks. To optimize the contrast of the post-etch photographs of FPI indications and provide an image that more accurately reflected what was observed visually, a yellow filter was added to the camera lens to block the UV-A radiation and the visible (blue) light emitted by the UV-A lamp.

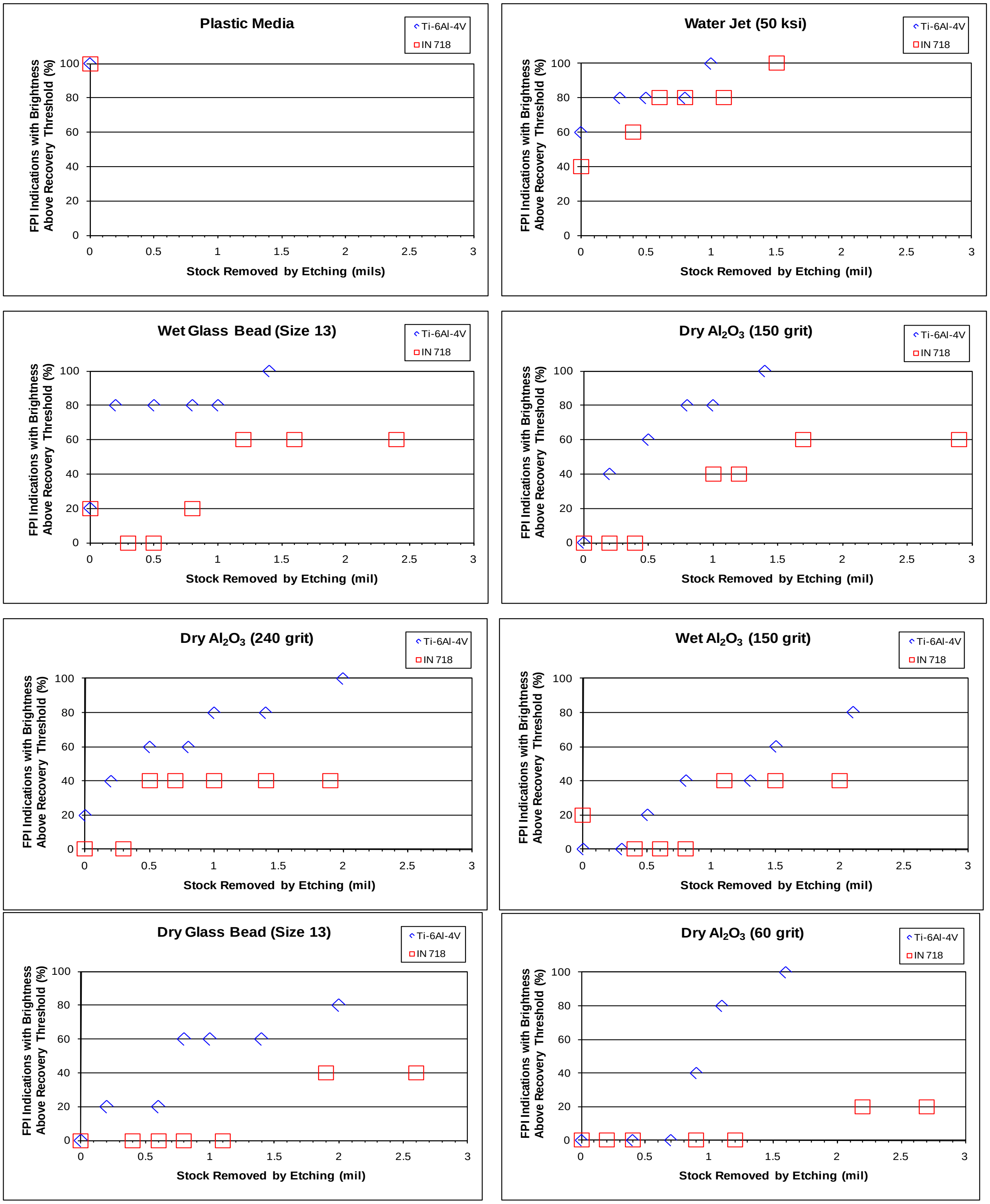


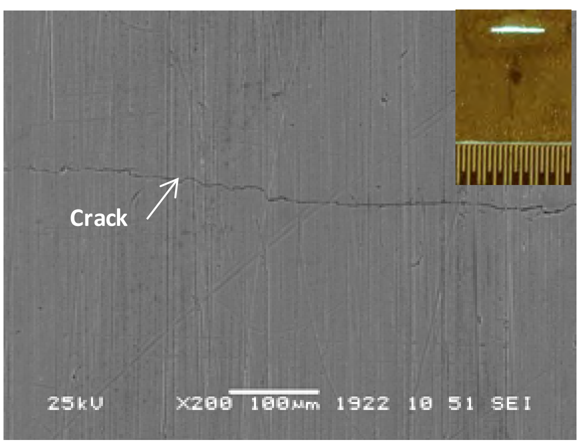
Figure 6. Post-Etch FPI Indications with Brightness above 40 Percent of Pre-MechClean

6.3 Supporting Microscopic Examination Vis à Vis FPI Results

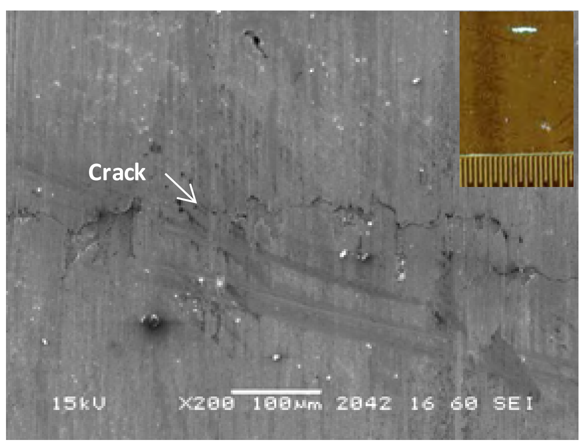
The SEM examination of selected specimens prior to etching provided the following data: 1) typical pre-MechClean surface topography of Ti-6Al-4V and Inconel 718 as exhibited by the control specimens, 2) images of the surface topography produced by the various mechanical cleaning methods, and 3) images of cracks that were still visible after mechanical cleaning regardless of whether they produced FPI indications or not. Post-etch examination with both the SEM and the optical microscope revealed that most cracks in the Inconel specimens appeared to be tighter and much more difficult to detect than the cracks in titanium.

Since the control specimens were not mechanically cleaned, SEM images of two of those specimens (Figure 7) provide examples of the as-manufactured condition of the surfaces. Some features created by the manufacturing process are evident, e.g., linear machining marks on both alloys and smeared metal on Inconel. These features provide one way to qualitatively gauge the effects of mechanical cleaning, and as will be shown later, they were visible after mechanical cleaning only on specimens cleaned with the water jet and plastic media. In addition, being able to discount some metal smearing as caused by manufacture was helpful in understanding the different degrees of smearing produced by the various mechanical cleaning methods.

Figure 7 also contains superimposed images of the respective FPI indications. The 0.098-inch long well-defined crack in the titanium specimen T-43 produced an indication with a brightness of 67 fL. The 0.047-inch crack in the Inconel specimen 626-31 produced an indication with a brightness of 27 fL despite appearing to be partially covered by smeared metal. The brightnesses are considered average for the respective crack sizes. Cracks of similar sizes in as-manufactured specimens have produced FPI indications both brighter and dimmer. Experience has borne out this trend for all sizes of cracks, making it difficult to make predictions about FPI indications based on crack length or on other features observed by microscopically examining a crack. Adding the effects of mechanical cleaning and etching the specimens compounds the difficulty.



a) Ti-6Al-4V Specimen T-43



b) Inconel 718 Specimen 626-31

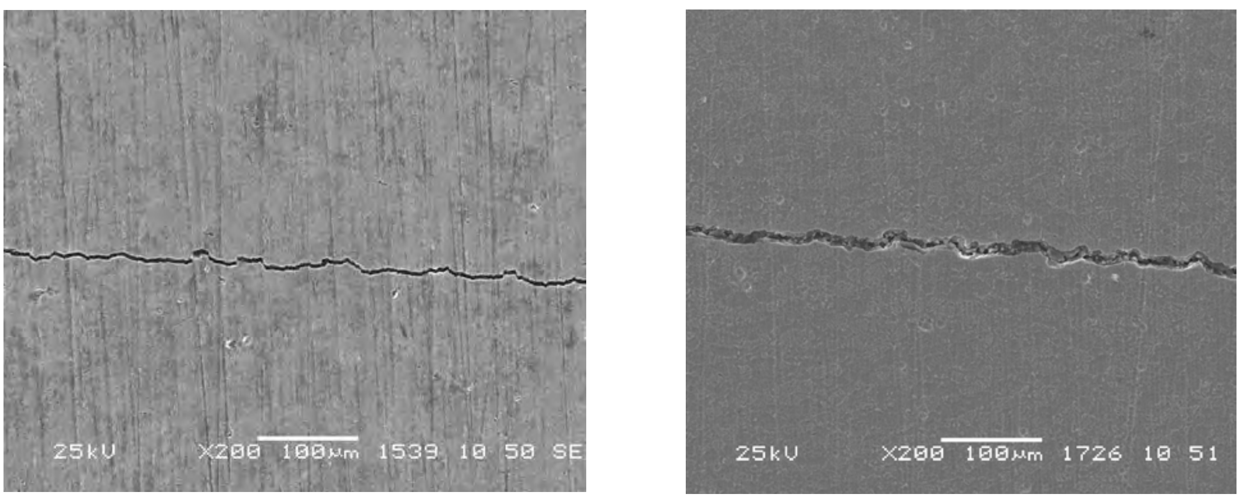
Figure 7. SEM Images of Two Control Specimens and the Respective FPI Indications

6.3.1 Specimens Cleaned with Dry Plastic Media (Type II)

Titanium (FPI data and additional post-etch microscope images in Figures A-1 through A-6)

Cleaning with Type II dry plastic media produced no effect on the specimen surfaces that was visible under 200X examination. Machining marks were still quite evident and there was no metal smeared over any parts of the cracks. Etching away 0.5 mil of stock blended away machining grooves on specimen surfaces to varying degrees and increased the crack width on the specimen that had been examined with the SEM both before and after etching. Embedded plastic media was visible in the crack as well. The FPI results were mixed: indications for three cracks became brighter than their pre-MechClean indications and two became dimmer. Post-etch optical microscope images of this and the other cracks in the group showed well-defined cracks but provided few clues to explain these results.

The pre- and post-etch SEM images for specimen 625-17 (Figure 8) show that the crack width increased with etching and provided a better view of plastic media embedded inside. The images also revealed the smoothing effect that etching had on the machining grooves. Post-etch optical images of this crack (Figure A-6) and two others (Figures A-2 and A-5) reveal hardly any evidence of grooves, whereas Figures A-3 and A-4 have evidence of grooves that were diminished less.



a) 625-17 Post MechClean b) 625-17 Post Etch-2

Figure 8. SEM Images of Titanium Specimen 625-17 Cleaned with Dry Plastic Media

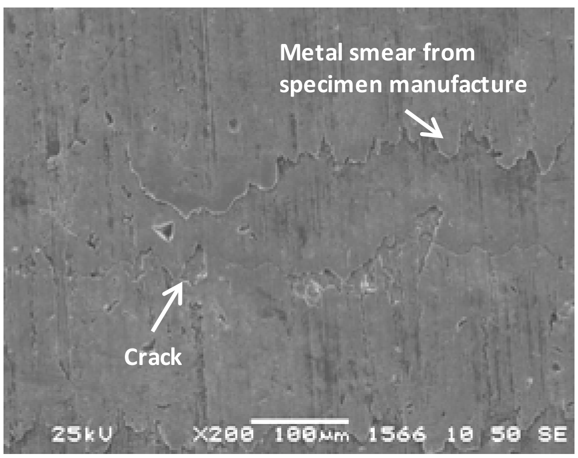
The indication brightness for the crack in 625-17 increased with each etch, reaching nearly three times the post-MechClean brightness (Figure A-1). However, it was impossible to determine if the increase in indication brightness was due to just the fact that the crack opening was wider or that some plastic media was removed from the wider crack during the pre- and post cleaning steps of the FPI process.

The post-MechClean brightness of the T-04 indication decreased 81 percent after the first etch but recovered to just above the recovery threshold after the second. The short length (0.021 inch) of the crack could have contributed to this erratic behavior. The post-MechClean indication T-20 was the only one brighter than its pre-MechClean indication, but with etching the brightness continually decreased until it was only eight percent of its pre-MechClean level. The overall behavior of the

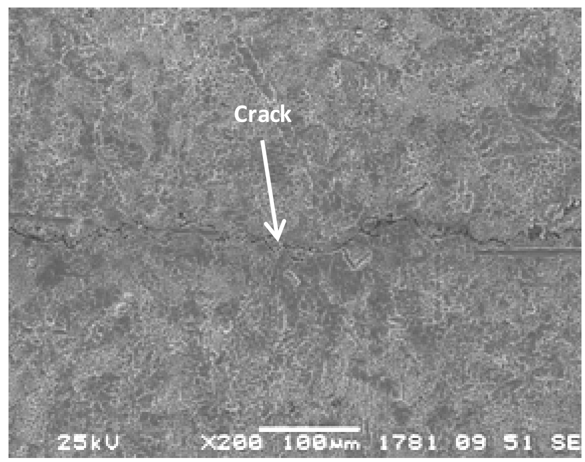
T-20 indication is an example of the sometimes baffling nature of FPI indications. The crack lengths for T-20 and 625-60 measured the same (0.059 inch), but the pre-MechClean FPI indication brightness of T-20 was less than half that of 625-60. The post-etch microscope pictures for both cracks looked similar (Figures A-3b and A-4b respectively), but upon closer examination of Figure A-3b, the crack in T-20 appeared shallower and slightly wider. The shallow depth could explain the dimmer pre-etch indication brightness and, when combined with the increased width after etching, could have reduced the capability of the crack to retain sufficient penetrant to produce a good FPI indication.

Inconel (FPI data and additional post-etch microscope images in Figures A-7 through A-12)

Type II plastic media blasting had little visible effect on Inconel as well. The post-MechClean image in Figure 9a still shows evidence of machining marks. However, etching away 0.5 mil of stock completely obliterated machining marks and metal smear (Figure 9b), indicating the etchant for Inconel was more aggressive. Etching these specimens improved the brightness of only one FPI



a) 626-52 Post MechClean (200X)



b) 626-52 Post Etch-2 (200X)

Figure 9. SEM Images of Inconel Specimen 626-52 Cleaned with Dry Plastic Media

indication (626-55) by a small amount (Figure A-7). The pre- and post-etch SEM images for Inconel specimen 626-52 (Figure 9) show that etching increased the crack-opening width. However, in both instances the crack was much tighter than the one in the titanium specimen 625-17 shown above in Figure 8. Plastic media was still able to enter the crack in 626-55, but it took a 5000X magnification to see evidence of the embedded media inside the crack (Figure 10). All cracks in the Inconel specimens appeared to be very tight and difficult to detect during post-etch microscopic examination (Figures A-8b through A-12b), a trend that would continue for most Inconel specimens. The different colors of the specimen surfaces in those pictures are

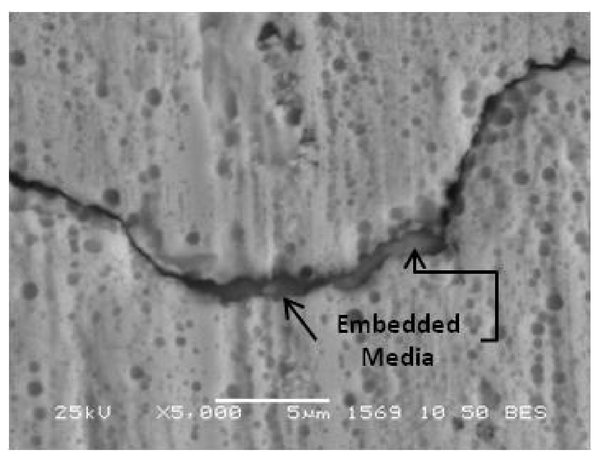


Figure 10. Post-MechClean Image of Specimen 626-52 (5000X)

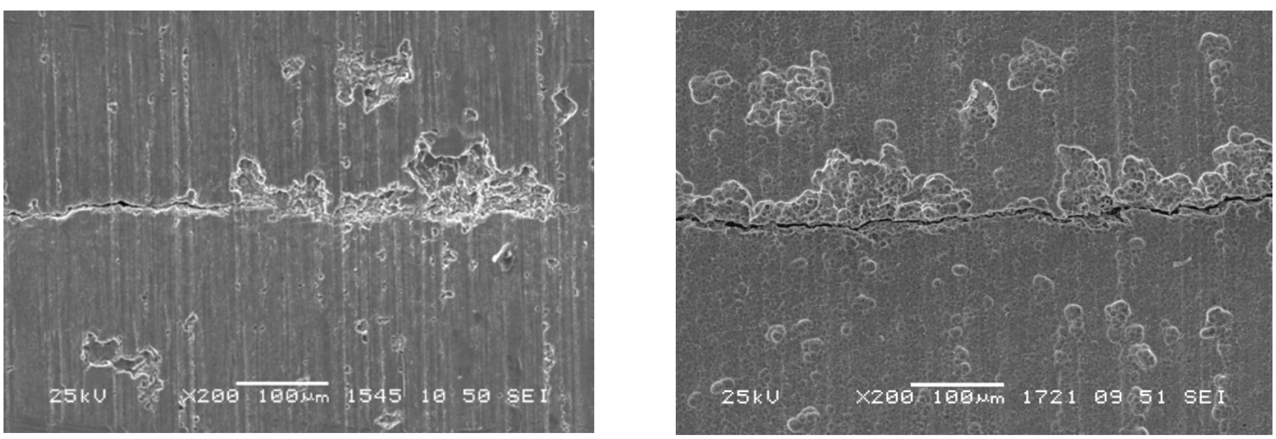
due to variations made in the angle and intensity of the incident light when trying to optimize the crack images.

6.3.2 Specimens Cleaned with 50 ksi Water Jet

Titanium (FPI data and additional post-etch microscope images in Figures A-13 through A-18)

Post-MechClean SEM examination revealed scattered eroded/pitted areas on the cleaned surfaces (Figure 11a). Smeared metal, partially closing the crack opening, was also noted in pitted areas that straddled a crack. This was somewhat unexpected since a cleaning process engineer had developed the water-jet technique allowing for no surface pitting. However, magnification had not been used to visually examine the cleaned surface and verify that no etching occurred at the conclusion of the development process. Sixty percent of the cracks had post-MechClean indications above the 40-percent recovery threshold. One etch that removed 0.3 mil of stock improved 80 percent of the indications on titanium specimens cleaned with water jet, including the one on 625-33 that did not exist after mechanical cleaning (Figure A-13). However, all of the recovered indications suffered partial losses in brightness after the second etch.

Post-MechClean SEM examination of specimen 625-58 at 200X Figure 11b shows that after etching removed 0.5 mil of stock from 625-58, the edges of the pits were noticeably rounded, and the crack opening appeared a little wider, especially where the crack traversed pitted areas. The post-MechClean SEM examination at 1000X revealed that there was a fine crack through the pitted areas even though at 200X the crack appeared smeared over (Figure 11a). These observations may explain the reasonably bright post-MechClean FPI indication, the minor brightness increase after Etch-1 and the small brightness decrease after Etch-2.



a) 625-58 Post MechClean b) 625-58 Post Etch-2

Figure 11. SEM Images of Titanium Specimen 625-58 Cleaned with 50-ksi Water Jet

Figure A-13 shows that the successive FPI indications for the crack in specimen 625-07 followed a trend in relative brightness similar to that for 625-58. However, the crack in specimen T-05 produced a bright indication only after four successive etches removed a total of 1.0 mil. The microscope image in Figure A-14b reveals that the crack in T-05 was nearly completely surrounded by pitting, which may have affected the surface opening of this short (0.018 inch) crack more than it did on longer cracks.

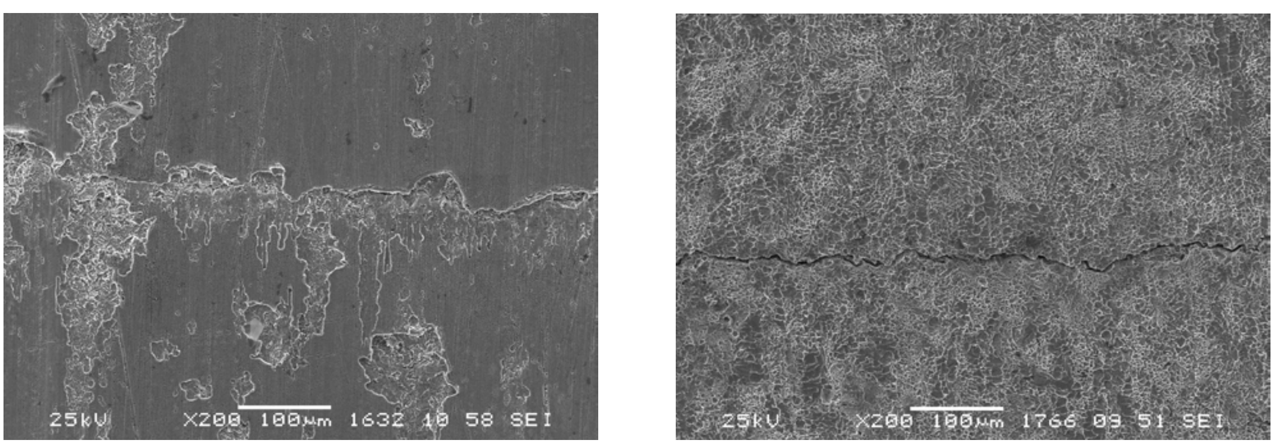
Inconel (FPI data and additional post-etch microscope images in Figures A-19 through A-24)

The water jet caused more pitting on Inconel than it did on titanium. This observation correlated the relatively higher amounts of FPI background observed on the Inconel specimens. The general appearance of the etched surface indicated that the action of the etchant on the Inconel again appeared to be more severe than on titanium. Other than recovering one crack indication that did not exist after mechanical cleaning, the first etch had little significant effect. The second and third etches improved some indications and degraded others.

Figure 12a is an example of the greater amount of pitting observed on Inconel specimens compared to titanium (Figure 11a). This caused the relatively higher number of post-etch FPI background indications on Inconel specimens can be seen in Figures A-20a through A-22a and Figure A-24a compared to the lesser amounts on the titanium specimens (Figures A-14a through A-18a). Little fluorescent background is evident in Figure A-23a because specimen 626-63 endured twice as many etches as the other four, so most of the pitting caused by the water jet was removed.

Even though there is significant pitting on 626-63, there is still evidence of the original machining marks in Figure 12a. After Etch-2 (Figure 12b) the surface lacks any evidence of machining marks but does have a high population of dimples typical of an etched surface and much more evident than on titanium (Figure 11b).

The FPI results for the first three cracks charted in Figure A-19 illustrate the unpredictable nature of crack indications. The short (0.029 inch) crack in 626-16 produced a very bright (62.9 fL) pre-MechClean indication, which was matched (100-percent recovery) after three etches. At 78 percent of pre-MechClean brightness the post-MechClean indication was bright as well. The slightly larger cracks (0.040 inch) in 626-56 and 626-32 had significantly smaller pre-MechClean indications (5.1 and 30.8 fL respectively). The even larger crack (0.070 inch) in 626-63 produced the smallest pre-MechClean indication (17.2 fL) that didn't get significantly better with etching, which is surprising given the crack image after Etch-2 shown in Figure 12b. Additional SEM examination revealed small amounts of foreign material in the crack but not enough to explain the relatively low brightness of the FPI indications. The large brightness increase (271 percent) occurring for 626-56 was due to the pre-MechClean brightness being so low.



a) 626-63 Post MechClean b) 626-63 Post Etch-2

Figure 12. SEM Images of Inconel Specimen 626-63 Cleaned with 50-ksi Water Jet

6.3.3 Specimens Cleaned Wet Glass Bead (Size 13)

The surfaces of both titanium and Inconel specimens cleaned with wet glass bead exhibited a dimpled (peened) appearance. However, compared to specimens cleaned with dry glass bead (discussed in Section 6.3.7 below) the disturbed metal surrounding dimples produced with wet glass bead had smoother edges.

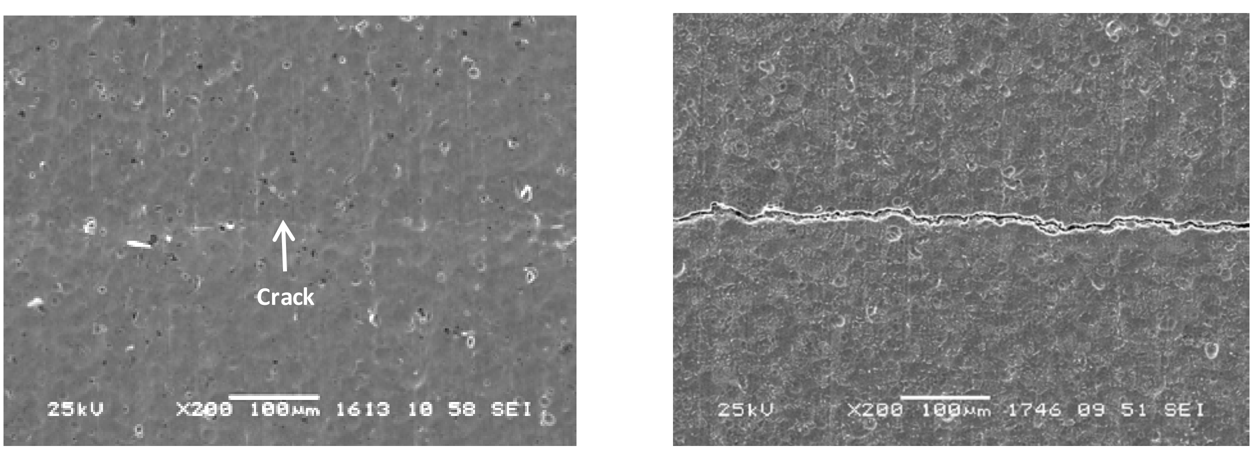
Titanium (FPI data and additional post-etch microscope images in Figures A-25 through A-30)

The survival and recovery of FPI crack indications for titanium specimens cleaned with wet glass bead were nearly as good as for titanium specimens cleaned with water jet. Fewer indications survived the cleaning with wet glass bead, but 80 percent of the indications were above the recovery threshold after removing only 0.2 mil of stock. Before etching the cracks were hardly visible, but two etches effectively removed the metal smear that had covered the crack openings. The crack openings remained narrow, a characteristic that usually led to a good FPI indication.

The crack in specimen 625-41 can barely be seen in the post-MechClean SEM image in Figure 13a, whereas the crack is easily visible in the post-Etch-2 image in Figure 13b. This, along with the FPI results (Figure A-29a), indicates that the metal smear was effectively removed by the etching, which removed only 0.5 mil of stock after two etches and did not widen the crack excessively. The dimpled appearance of the surface due to the wet glass beads is still in evidence in Figure 13b also.

After mechanical cleaning the crack in 625-61 had an FPI indication brightness equal to 83 percent of its pre-MechClean value. Two subsequent etches did not alter the indication brightness significantly. Three other cracks (625-28, 625-03 and 625-41) recovered at least 40 percent of their FPI indication brightness after single etch, and 100 percent or more after a second etch.

The brightness of the crack indication in T-33 remained around 20 percent until the fifth etch when it jumped to nearly 100 percent of its pre-MechClean brightness. The brightness took a much larger jump (to 1310 percent) after Etch-6. As seen in Figure A-26 the crack in T-33 is an exceptional example of a crack with a relatively wide opening producing a good FPI indication after several etches. The much narrower widths of the other four cracks in the group (Figures A-27b through A-30b) are more typical of those that produced good FPI indications.



a) 625-41 Post MechClean (200X)　　b) 625-41 Post Etch-2 (200X)

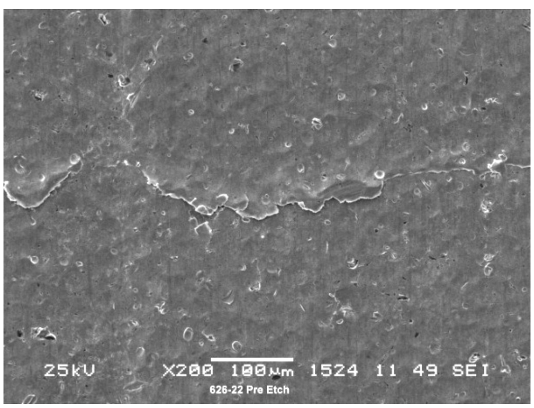
Figure 13. SEM Images of Titanium Specimen 625-41 Cleaned with Wet Glass Bead

Inconel (FPI data and additional post-etch microscope images in Figures A-31 through A-36)

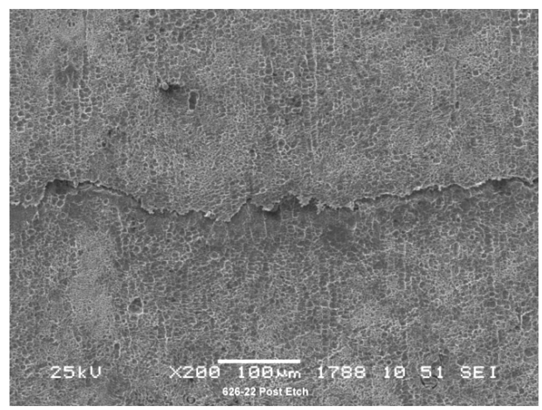
The survival and recovery of FPI crack indications in Inconel specimens cleaned with wet glass bead were far worse than for titanium specimens. One crack was covered with metal smear both before and after etching, but the smear did not prevent an indication from forming. Post-etch examination with an optical microscope found the cracks difficult to detect. Both SEM and optical-microscope images showed evidence of etchant attack on Inconel surfaces than on titanium.

Figure 14 shows the smeared metal that appears to be covering the crack in specimen 626-22 both before and after etching. However, some portions of the smeared metal do not appear to be held tightly against the specimen surface. This might be the reason why the FPI indication immediately after mechanical cleaning was 60 percent of the pre-MechClean brightness (Figure A-31). The reason for the drastic reduction of indication brightness after the next two etches before nearly recovering to its previous level is unknown. This crack was one of the most visible in the group during post-etch examination with the optical microscope (Figure A-33b), although the crack is not sharply defined.

The crack indication on 626-58 eventually recovered 114 percent of its post-MechClean brightness (Figure A-31). However, the FPI indication is relatively dim (3.5 fL), so the difficulty in detecting the obscured crack in the microscope image (Figure A-32b) is not unexpected.



a) 626-22 Post MechClean (200X)



b) 626-22 Post Etch-2 (200X)

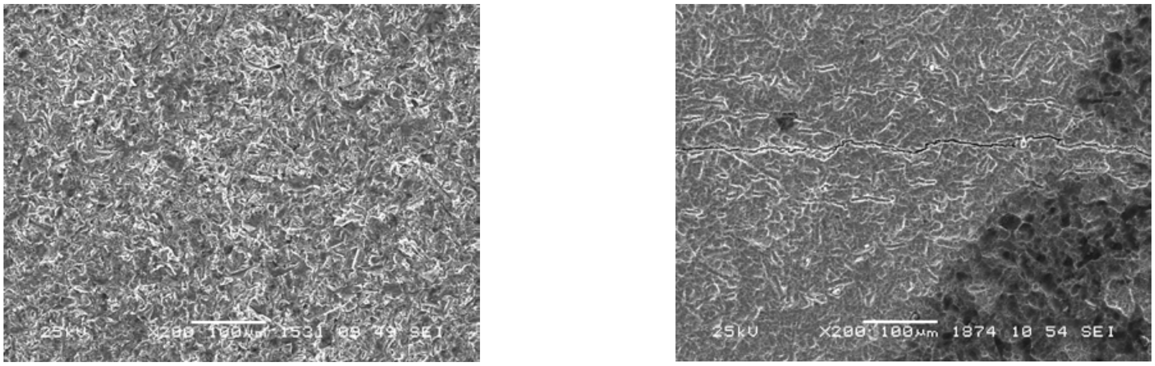
Figure 14. SEM Images of Inconel Specimen 626-22 Cleaned with Wet Glass Bead

6.3.4 Specimens Cleaned with Dry Al_2O_3 (150 grit)

Titanium (FPI data and additional post-etch microscope images in Figures A-37 through A-424)

The surface roughness produced by the 150-grit media was more severe that that produced by any of the media discussed above. Embedded media particles were evident as was the smoothing effect of multiple etches on the sharp features of the metal upset by the media blasting. Sixty percent of the indications exceeded the recovery threshold after 0.5 mil of stock was removed and all indications but the one from the smallest (0.038 inch) crack recovered after 0.8 mil was removed. No distinct trends in the FPI were obvious since the results were mixed: successful recovery of FPI indications was achieved from cracks of different widths after various amounts of etching.

Figure 15a illustrates the surface roughness produced by the 150-grit media that completely obscured the crack and the extent of embedded media particles (black spots). Figure 15b shows the smoothing effect of multiple etches; the dark area at the right of the image is an artifact from a marker used to facilitate locating the crack for SEM examination.

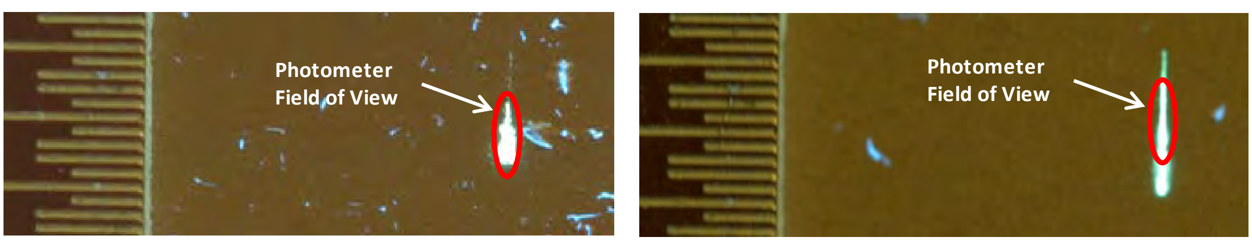


(a) 625-02 Post MechClean (b) 625-02 Post Etch-2

Figure 15. SEM Images of Titanium Specimen 625-02 Cleaned with Dry Al_2O_3 (150 grit)

The FPI data in Figure A-37 and the microscope images in the five figures that follow provide an interesting mix of results indicating successful recovery of FPI indications from cracks of different widths after various amounts of etching. The crack in 625-35 was so tight that the optical image showed only a slight depression but not visible crack, so a follow-up 200X SEM electron-backscatter image of the tight crack was substituted into Figure A-39b.

The indication for the crack in titanium specimen T-03 recovered 59 percent of its pre-MechClean brightness after a single etch which removed just 0.2 mil of stock (Figure A-37). The subsequent drop-off in brightness is deceiving, especially in light of the significant post-Etch-2 indication shown in Figure A-40a. This is an anomaly caused by the limited field of view of the Spotmeter™ and the area of the crack indication selected for measurement. After the first etch of T-03, only the brighter, lower part of the FPI indication (Figure 16a) was measured (44 fL) because it was mistaken for the entire indication. However, after the second etch the center portion of the indication was measured (Figure 16b), resulting in a lower brightness measurement (17 fL).



(a) T-03 Indication after Etch-1 (b) T-03 Indication after Etch-2

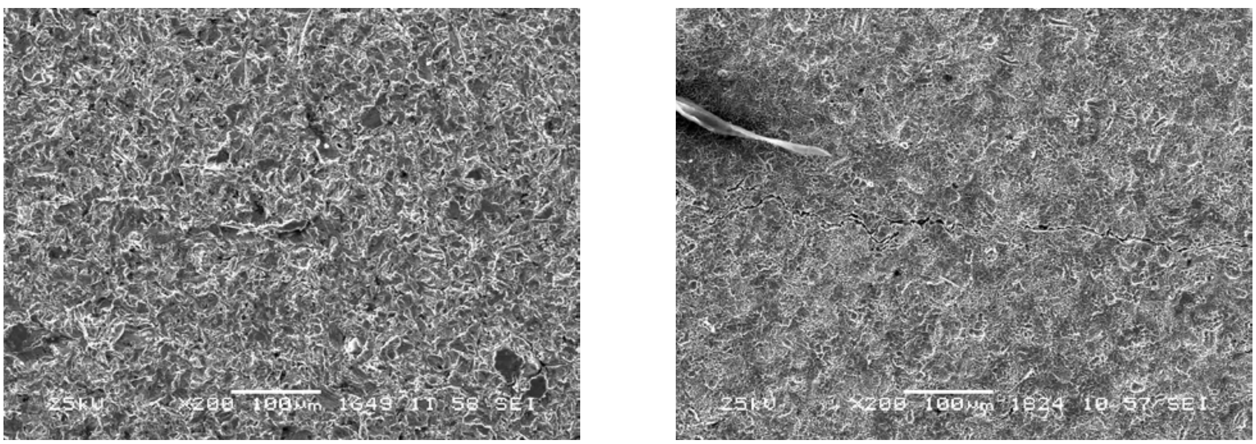
Figure 16. FPI Indications for Titanium Specimen T-03

Inconel (FPI data and additional post-etch microscope images in Figures A-43 through A-48)

The pre- and post-etch Inconel surfaces appeared similar to titanium surfaces cleaned with 150-grit dry Al_2O_3. After two etches the crack on one specimen examined with the SEM was not as visible but another one was. Three dim post-MechClean indications were detected, as opposed to none on the titanium specimens, but etching the Inconel specimens was ineffective at adjusting the surface conditions to permit the FPI indications to recover until at least 1.0 mil of stock had been removed.

Figure A-43 shows that only one FPI crack indication (626-57) regained 100 percent of its pre-MechClean brightness. In fact, after the sixth etch the indication brightness jumped to 756 percent of its original value. That high percentage is a little deceiving because the pre-MechClean brightness was only 1.7 fL. It is not unprecedented for a crack 0.068 inch long to have such low indication brightness, but generally one would expect a higher value. For example, the pre-MechClean brightness of the 0.078-inch crack in 626-50 was 79.6 fL. Therefore, although the indication for 626-57 exceeded the 40-percent recovery threshold after Etch-3, this specimen was etched six times to see if the indication brightness would improve significantly. Indeed, this occurred, but the final indication brightness was only 13.1 fL, only slightly brighter than the pre-MechClean indication for the 0.049-inch crack in 626-38.

Figure 17 contains SEM images of two specimens. After Etch-2 the SEM examination could not detect the crack in 626-50, so an image of the crack in 626-06 was substituted.



a) 626-50 Post MechClean b) 626-06 Post Etch-2

Figure 17. SEM Images of Inconel Specimens Cleaned with Dry Al_2O_3 (150 grit)

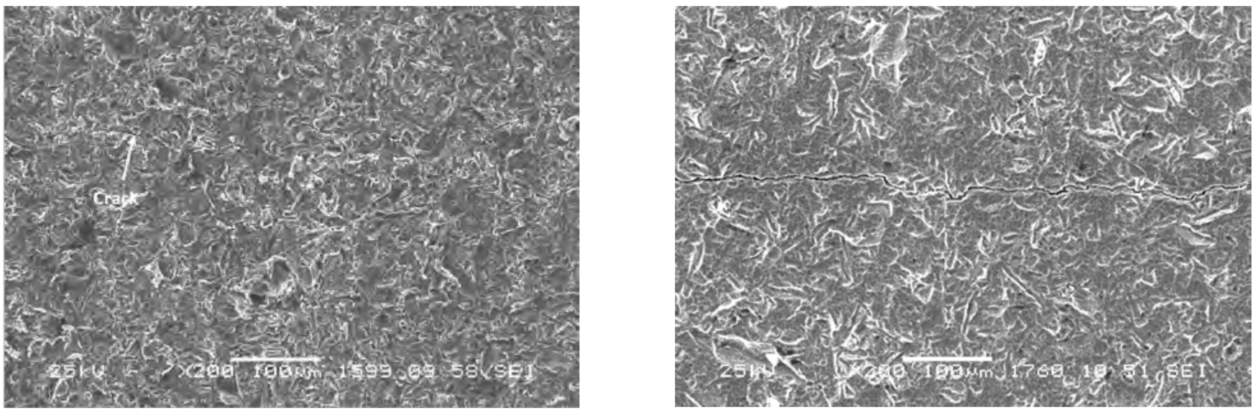
Microscope images of the cracks in this group offer little in the way of clues to explain the FPI data. As with other Inconel specimens the cracks were difficult to resolve. A 600X SEM backscatter image was substituted in Figure A-48b because good optical image for 626-53 of the crack could not be obtained. In Figure A-46c a higher magnification, optical-microscope image of 626-06 shows the angular nature of the surface roughness remaining after six etches hints of foreign material inside the crack, probably cleaning media. Similar images were obtained for other specimens cleaned with the different Al_2O_3 media. Thorough evaluation of the composition of the material was beyond the scope of this effort.

6.3.5 Specimens Cleaned with Dry Al_2O_3 (240 grit)

Titanium (FPI data and additional post-etch microscope images in Figures A-49 through A-54)

As expected the surface roughness due to cleaning with 240-grit Al_2O_3 is less severe than when 150-grit was used. However, it was still difficult to detect cracks with pre-etch SEM examination, and any FPI indications that did appear were very dim. All crack indications recovered with etching, two after removing only 0.2 mil and a third after 0.5 mil of stock was removed. The cracks are clearly defined in the optical-microscope images shown in Figures A-50b through A-54b. In this group it was clear that the crack-opening widths increased with increasing amounts of etching, as one might expect, and wide cracks as well as narrow ones produced bright FPI indications. Generally, successive etches improved the FPI indications.

Figure 18a shows the barely visible crack on the roughed surface of 625-40, which give credence to the dim, spotty post-MechClean FPI indication (Figure A-54a). However, after two etches removed 0.5 mil of stock, the corresponding SEM image (Figure 18b) depicts a clearly defined crack as does the optical-microscope image (Figure A-54b). The recovered FPI indication is shown in Figure A-54a.



a) 625-40 Post MechClean b) 625-40 Post-Etch-2

Figure 18. SEM Images of Titanium Specimen 625-40 Cleaned with Dry Al_2O_3 (240 grit)

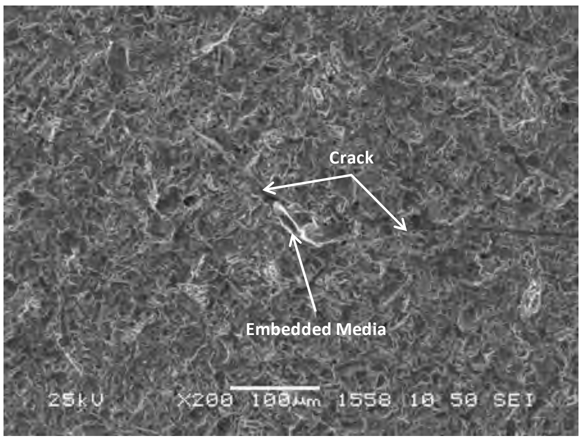
If the pre- and post-MechClean crack indications on 625-19 (Figure A-53a) are compared, it appears the post Etch-2 indication should have recovered more than 50 percent (Figure A-49). However, the large bleed-out of pre-MechClean indication produced a very high brightness measurement (118 fL) for such short crack (0.024 inch). Nevertheless, it did recover after removing only 0.5 mil. The last two cracks in the group also recovered but only after significantly more stock was removed: 1.0 mil for T-19 and 2.0 mils for T-13. For its relatively large width after six etches, the crack in T-13 (Figure A-50b) produced a surprisingly bright indication.

Inconel (FPI data and additional post-etch microscope images in Figures A-55 through A-60)

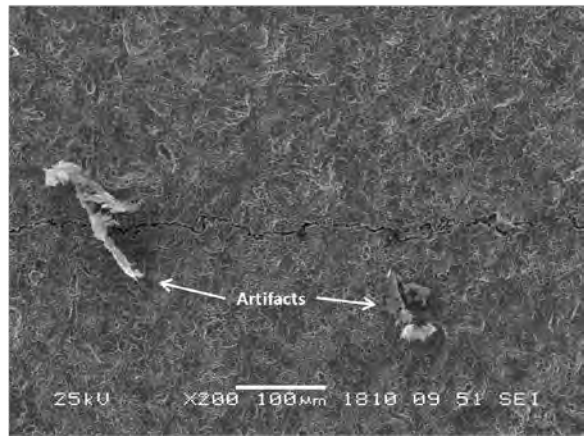
The surface roughness of Inconel due to cleaning with 240-grit Al_2O_3 looked similar to that on titanium, and it was equally difficult to detect cracks with pre-etch SEM examination. Any pre-etch FPI indications that did appear were very dim also. Etching was less successful on Inconel: only two cracks recovered their brightnesses after two etches removed 0.5 mil total. For three of five specimens successive etching improved the FPI indications. Initially etching helped one other but caused still another to disappear. The post-etch optical microscope pictures (Figures A-56b through A-60b) are similar to many others taken of Inconel specimens, i.e., cracks are not well defined and the edges of the crack openings are rounded.

Figure 19a shows the difficulty seeing a crack on the cleaned surface of 626-14. Figure 19b shows a well-defined crack after Etch-2 even though the FPI indication was only four percent of its pre-MechClean brightness. After six etches the indication recovered only 38 percent of its brightness, even though the photograph in Figure A-59a shows a good indication. This is another example of the limitations of the photometer measurements and the difficulty duplicating the human eye response with an instrument.

The FPI indication for 626-18 recovered 146 percent of its brightness (Figure A-55), but this is another example where a dimmer than expected pre-MechClean indication for the length of the crack (0.051 mil) showed a high percentage of recovery for a small improvement in brightness.



a) 626-14 Post MechClean



b) 626-14 Post Etch-2

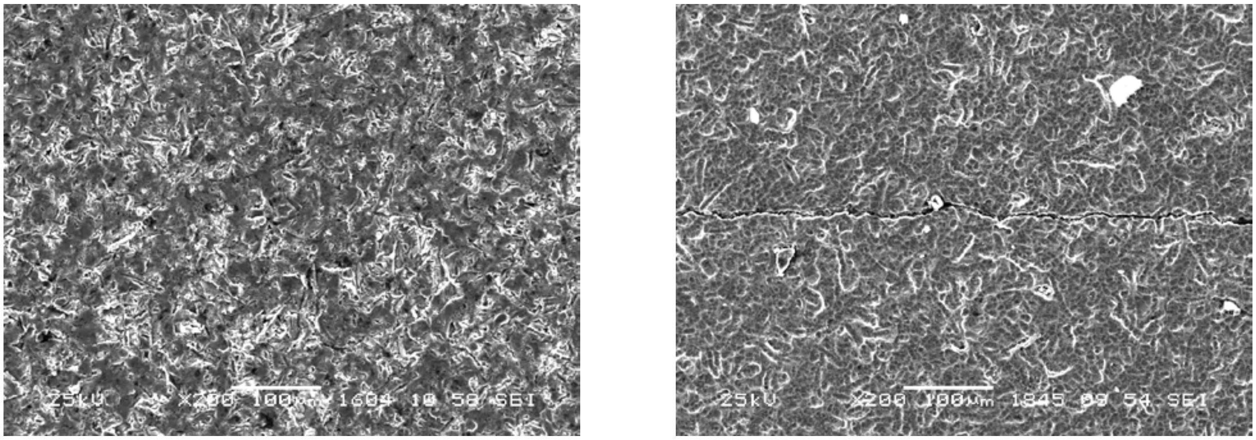
Figure 19. SEM Images of Inconel Specimen 626-14 Cleaned with Dry Al_2O_3 (240 grit)

6.3.6 Specimens Cleaned with Wet Al_3O_2 (150 grit)

Titanium (FPI data and additional post-etch microscope images in Figures A-61 through A-66)

Before etching the post-MechClean specimen surfaces were too rough to allow positive crack detection with the SEM. Recovery of FPI crack indications began after 0.5 mil of metal was removed with two etches. However, only one indication qualified as having recovered its pre-MechClean brightness. After the two etches SEM examination of two specimens revealed evidence of etch activity (metal erosion) along the edges of the crack and into the crack openings of both cracks.

Figure 20a illustrates the rough post-MechClean surface of specimen 625-21, on which the longest crack (0.098 inch) of the group was not visible. Figure 20b shows the crack after the second etch. It produced a reasonable FPI indication that was 27 percent of pre-MechClean brightness (Figure A-61). After one more etch the indication recovered 45 percent of its pre-MechClean brightness, a percentage that probably would have been higher if the photometer field of view had been large enough to encompass the entire crack since the ends of the indication were brighter than the center (Figure A-66a). The crack in the other specimen (T-27) examined with the SEM after Etch-2 appeared slightly wider than the one in 625-21 but produced a barely detectable indication (Figure A-61). In Figure A-65b the crack in T-27 appears significantly wider after it had been etched six times, but its indication recovered its brightness. A third, relatively short (0.035 inch) crack in specimen 625-10 recovered 93 percent of its pre-MechClean brightness after Etch-2, more than enough for it to be considered a recovered indication. Like the crack in 625-21, it was also quite narrow (Figure A-63b).



(a) 625-21 Post MechClean Surface (b) 625-21 Post Etch-2

Figure 20. SEM Images of Titanium Specimen 625-21 Cleaned with Wet Al_2O_3 (150 grit)

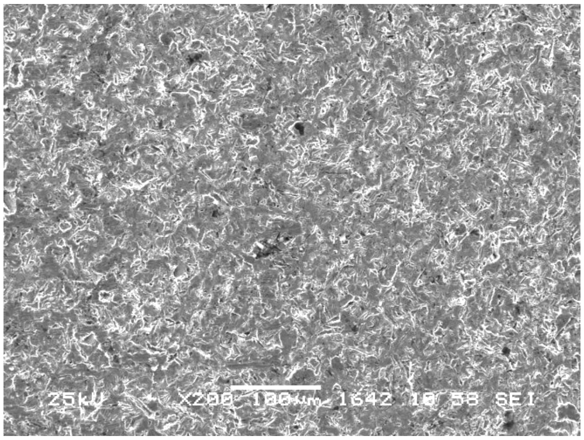
After the fifth etch the brightness of the FPI indication for the 0.040-inch crack in T-10 recovered to 85 fL, 586 percent of its pre-MechClean brightness. The large percentage increase in brightness was due to a relatively low initial brightness (16 fL), which actually is not inappropriate for the short crack length. After five etches the crack at that point was quite wide (Figure A-64b), proving that wide cracks can produce bright indications also. The crack in T-38 also grew to be quite wide after Etch-6 (Figure A-62b), but it was so shallow that the penetrant was probably flushed out during the wash cycle of the inspection process causing the indication to disappear after a partial recovery following previous etches. The seemingly inconsistent indications relative to the crack widths for this group illustrate the difficulty in correlating FPI indications with crack topography.

Inconel (FPI data and additional post-etch microscope images in Figures A-67 through A-72)

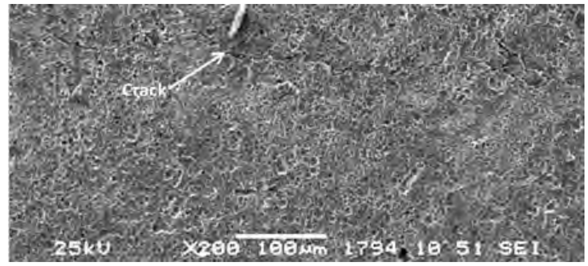
Of the two alloys cleaned with wet Al_2O_3 (150 grit) the Inconel surfaces appeared less rough. However, the rough Inconel surface examined with the SEM still obscured the crack from view prior to etching. Etching was not very productive with regard to recovering FPI indications, and it even initially degraded the one post-MechClean indication that was detected. After Etch-2 cracks in each of two specimens were found with SEM examination. The openings of both cracks had inconsistent widths and were still partially covered with metal smear. In addition, they were narrower than the ones in the titanium specimens cleaned with the same media.

Figure 21a shows the rough surface of specimen 626-08 where the crack is supposed to be, and Figure 21b shows part of the narrow, intermittent crack opening that was barely visible after Etch-2. Figure 21c shows one end of the crack, which had a wider opening that contradicts the FPI indication obtained after the third etch (Figure A-71a). That indication was bright enough to be considered recovered, but the brightness was concentrated over a small portion of the crack, which does not appear to be at either end. The etching seemed to act aggressively on only a localized part of the crack. The corresponding microscope image in Figure A-71b shows that the crack was still narrow, which may explain the lack of a complete indication, but does not provide a topographic feature that would explain the concentrated area of brightness in the FPI indication.

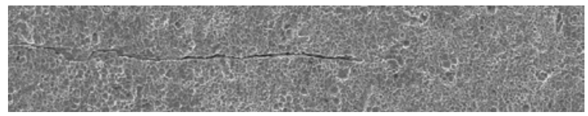
The post-etch optical microscope image of the crack in 626-17 (Figure A-68b) belies the fact that the FPI indication did not recover well. Similarly appearing well-defined cracks produced brighter indications.



a) 626-08 Post MechClean Surface



b) 626-08 Post Etch-2 (center of crack)



c) 626-08 Post Etch-2 (one end of crack)

Figure 21. SEM Images of Inconel Specimen 626-08 Cleaned with Wet Al_2O_3 (150 grit)

The FPI indication for the crack in Inconel specimen 626-20 retained 41 percent of its brightness after mechanical cleaning (Figures A-67 and A-70a). However, for an undetermined reason the brightness dropped to zero after the second etch, even though a crack is visible in an SEM image shown in Figure 22. After Etch-3 the indication brightness jumped to 219 percent of the pre-MechClean value. This FPI indication (Figure A-70a) was very broad, as was the indication before MechClean. The post-etch microscope image of the crack in Figure A-70b shows a clearly visible, relatively wide crack opening, unlike most cracks in Inconel specimens.

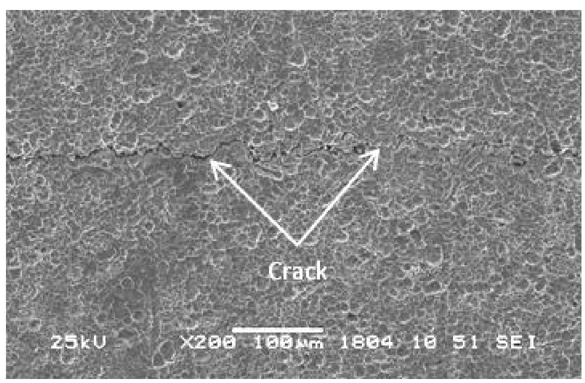


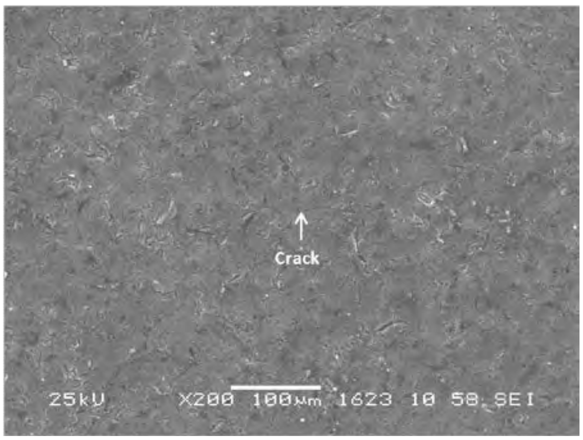
Figure 22. Post-Etch-2 SEM Image of Inconel Specimen 626-20 Cleaned with Wet Al_2O_3 (150 grit)

6.3.7 Specimens Cleaned with Dry Glass Bead (Size 13)

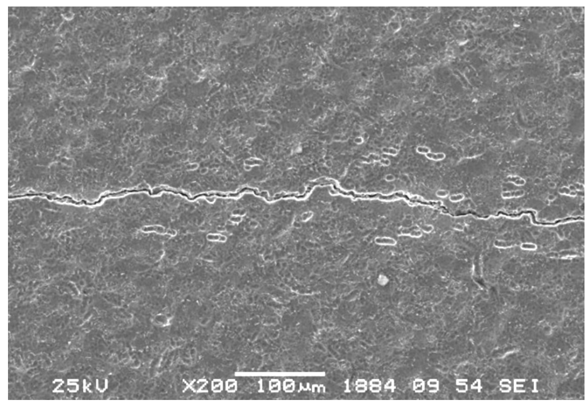
Titanium (FPI data and additional post-etch microscope images in Figures A-73 through A-78)

Cleaning with dry glass bead effectively peened the treated surface, creating a dimpled appearance. Cracks were difficult to detect with microscope examination. Etching softened the peening features, and opened up the cracks but did not always lead to immediate recovery of FPI indications. Only one crack had recovered its pre-MechClean brightness after 0.6 mil of stock had been removed.

In the Post MechClean SEM image of titanium specimen 625-14 (Figure 23a) the 0.071-inch crack is barely visible, having been obliterated by the dry glass bead media that imparted a peened appearance to the surface. After the second etch the peening features were softened and the crack appeared to have opened up (Figure 23b), but no FPI indication was detected. On the other hand the indication for a shorter crack (0.051 inch) in 625-52 recovered after Etch-1 and was still detectable after Etch-2 even though it still looked partially closed (Figure 24). When viewed with an optical microscope after all etching (Figures A-76b and A-75b respectively), the cracks look similar; the crack in 625-14 appears slightly wider, probably because it was etched one more time than 625-52. Figure A-73 contains a chart of the FPI indication brightness data.



a) 625-14 Post MechClean



b) 625-14 Post Etch-2

Figure 23. SEM Image of Titanium Specimens 625-14 Cleaned with Dry Glass Bead

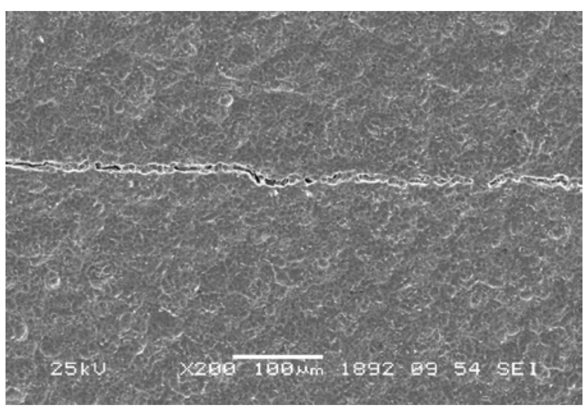
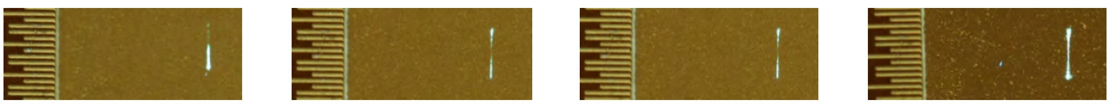


Figure 24. Post Etch-2 SEM Image of Titanium Specimen 625-52 Cleaned with Dry Glass Bead

Photographs of FPI indications for 625-50 are shown in Figure A-77a. The high recovery rate (1258 percent of its pre-MechClean brightness, Figure A-73) was due in part to its low pre-MechClean brightness (6.8 fL), especially for a crack 0.076 inch long. However, the length of the indication (0.045 inch) is still shorter than the measured crack length and is another example of etching apparently acting differentially along a crack.

Figure A-77b shows that the 625-50 crack opening remained narrow, comparable to that in 625-52 (Figure A-75b). Except for needing 0.8 mil of stock removed before the indication was recovered, specimen 625-50 is an example of a desirable etching result: the metal smear was removed and the recovered FPI indication was more typical of a 0.076-inch crack.

Another 0.079-inch crack (T-40) had indications more comparable to its measured length (Figure A-78a), but it recovered only 16 percent of its pre-MechClean brightness after the third etch (Figure A-73). FPI indications after additional etches exhibited a reduction in brightness followed by a return to the 16-percent level. In this case, the reductions can be explained by looking at pictures of successive FPI indications (Figure 25). Since the field of view of the Spotmeter™ was only 0.060 inch long and was always centered on an indication for a measurement, it didn't always encompass the brighter parts of the indication. This is another case where the brightness measurements do not reflect the actual visibility of an indication.



a) T-40 Post Etch-3 b) T-40 Post Etch-4 c) T-40 Post Etch-5 d) T-40 Post Etch-6

Figure 25. FPI Indications of the Crack in Specimen T-40

The optical-microscope pictures of the crack in T-40 in Figure A-78b reveal a relatively wide crack opening, probably too wide to produce a good FPI indication. The small crack (0.030 inch long) in T-35 also had a wide opening (Figure A-74b) that contributed to its dim (0.3 fL) post-etch indication, but even its pre-MechClean brightness was very low (0.2 fL). For these two cases the threshold for an effective etch may have been exceeded, illustrating that an optimum etch is difficult to achieve given the variables in crack topography.

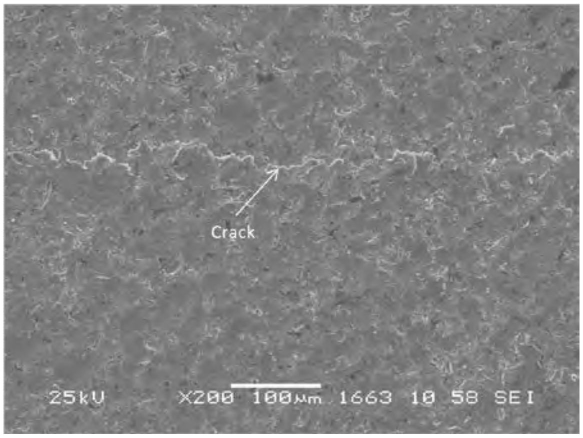
These results for the titanium group cleaned with dry glass bead is representative of the results encountered for all groups and seem to indicate that the effects of mechanical cleaning and subsequent etching are neither consistent nor predictable. The limited microscopic examination did not provide definitive information to help predict the nature of an FPI indication. Furthermore, the state of the crack (i.e., crack opening and volume) may influence the effect of mechanical cleaning and etching as well as the FPI indication.

Inconel (FPI data and additional post-etch microscope images in Figures A-79 through A-84)

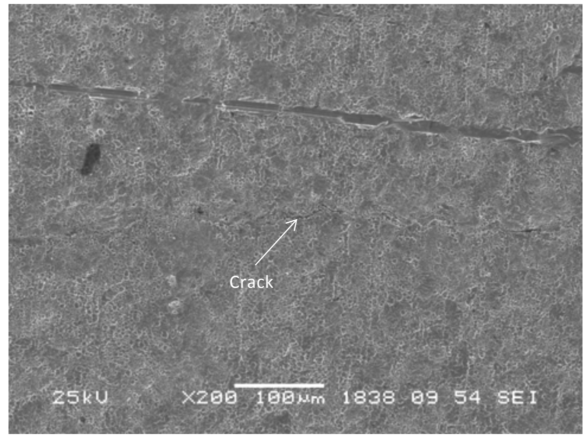
Like the surfaces of titanium specimens cleaned with dry glass bead the surfaces of Inconel specimens were also peened. Even after etching the cracks were not easily detectable with microscopic examination. Only two cracks recovered their FPI indications, and that was only after an unacceptably large amount of stock (1.9 mils) was removed.

The SEM images of specimen 626-54 in Figure 26a and Figure 26b provide a clue to the reason why none of the post-MechClean FPI indications for the Inconel specimens cleaned with dry glass bead recovered well (Figure A-79): the cracks were very tight. The post-MechClean surface of Inconel specimen 626-54 shown in Figure 26a is similar to that of the titanium specimen 625-14 shown in Figure 23a. Although the crack is slightly more visible in the Inconel specimen, two etches did not open the crack significantly (Figure 26b) as they did for the titanium specimen (Figure 13b). Even at

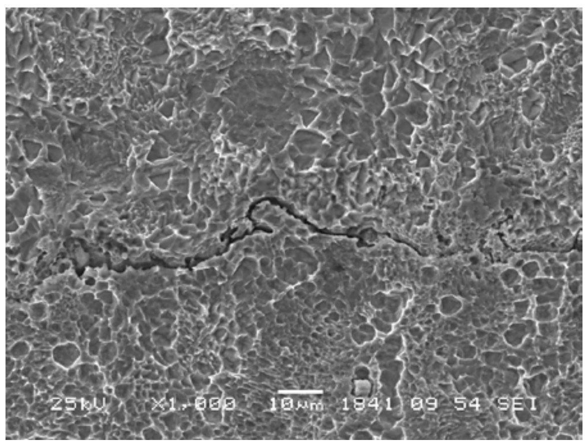
1000X the crack opening on Inconel specimen 626-54 still appears quite narrow (Figure 26c). The crack is even less obvious in the optical microscope image shown in Figure A-83b.



a) 626-54 Post MechClean (200X)



b) 626-54 Post Etch-2 (200X)



c) 626-54 Post Etch-2 (1000X)

Figure 26. SEM Images of Inconel Specimen 626-54 Cleaned with Dry Glass Bead

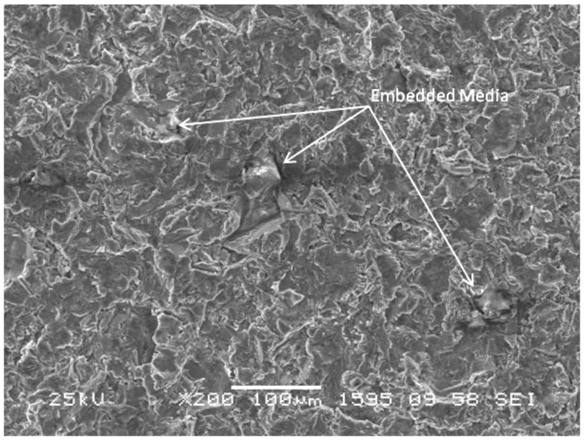
The optical-microscope examination of 626-33 did not produce a good image of the crack, so a SEM image was substituted in Figure A-80b. At 100X magnification the crack is not well defined. In Figure A-80a the post-etch FPI indication appears to be easily detectable even though its brightness (2.4 fL) is only 13 percent of the post-MechClean brightness. Apparently the six etches attacked the crack as well as the specimen surface, leaving a less than optimum reservoir for a good FPI indication.

6.3.8 Specimens Cleaned with Dry Al_2O_3 (60 grit)

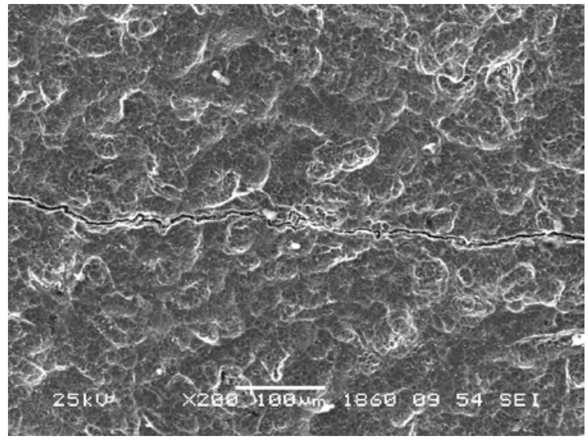
Titanium (FPI data and additional post-etch microscope images – Figures A-85 through A-90)

Cleaning with 60-grit Al_2O_3 severely roughened the surfaces and hides cracks. Media particles were also embedded in the surfaces. The first post-etch FPI indication was not detected until 0.7 mil of stock had been removed. Although it did not qualify as being recovered at that point, the crack was easily detected with SEM examination, and noticeable smoothing of the sharp surface deformations had occurred. After an additional stock loss of only 0.4 mil, 80 percent of the cracks had recovered.

Figure 27 presents pre- and post-etch images of a surface cleaned with 60-grit dry Al_2O_3. Although the surface was still rough after two etches, the smoothing effect that etching had on sharp surface-roughness features of 625-29 is visible in Figure 27b. The crack appears well defined and re-opened to the surface, a fact confirmed by the FPI indication that was detectable even though it had recovered only 32 percent of its brightness. Two more etches didn't significantly change the indication. However, after the fifth etch raised the total stock removed to 1.6 mils, the indication brightness jumped to 132 percent, and the optical microscope image obtained showed a relatively wide crack (Figure A-89b).



a) 625-29 Post MechClean (200X)



b) 625-29 Post Etch-2 (200X)

Figure 27. SEM Images of Titanium Specimen 625-29 Cleaned with Dry Al_2O_3 (60 grit)

FPI indications for two other cracks (625-57 and 625-46) also had sudden increases in brightness after the fifth etch to 175 and 328 percent of their pre-MechClean brightnesses respectively (Figure A-85). The optical microscope images in Figures A-86b and A-87b do not suggest any reason for the large increases in brightness.

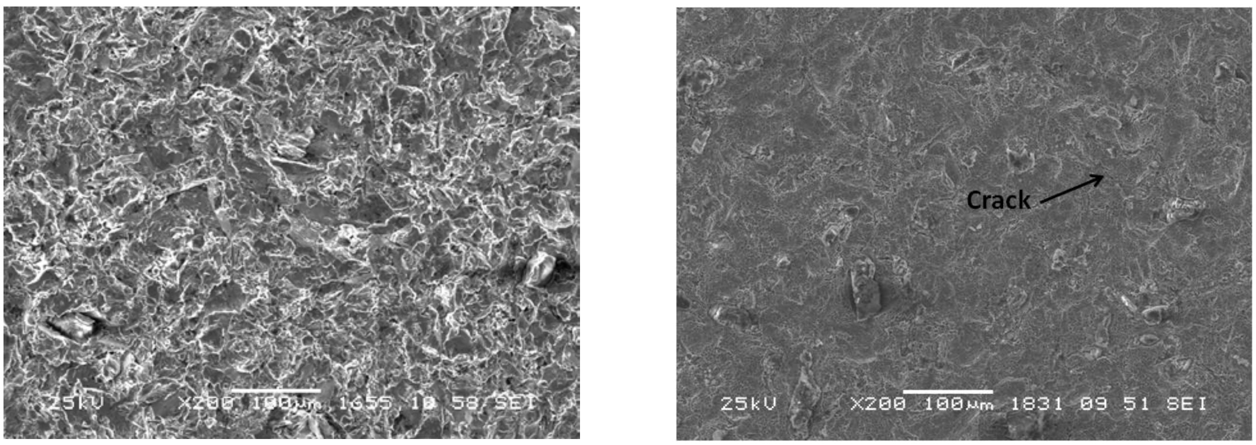
Before mechanical cleaning the FPI indication for 625-34 was barely visible (0.4 fL). After mechanical cleaning no indication was detected until after the fourth etch when the brightness increased to 28,865 percent of its pre-MechClean value, an unusually large percentage increase, but one that raised the brightness to 106 fL, which is not unusual for a 0.081-inch crack. SEM examination of 625-34 revealed that one end of the crack (approximately one-third of the length) had very little opening visible. The transition from closed to relatively open is shown in Figure A-90c. The crack obviously was very tight when manufactured and etching opened up only a portion of the crack, as confirmed by the FPI indication in Figure A-90a. In the 200X optical microscope image in Figure A-90b the barely visible portion of the crack probably corresponds to the wider end at the bottom of Figure A-90c. The various colors in the image are due to light highlighting different topographical features of the rough surface.

Again, brightness measurements of FPI indications may do not always correlate directly with the apparent detectability of that indication because of different penetrant bleed-out patterns for the same crack at different times. The pre-MechClean indications for 625-06 and 625-29 were broad and produced high brightness measurements. The brightest portion of the indication was a narrow irregular line directly over the crack, while a thinner (less bright) layer of penetrant bleed-out broadened the indication to contribute significantly to its brightness. The post-etch indications had different shapes and were more uniformly bright. All indications were easily detectable, but post-MechClean recovery required excessive stock loss.

Inconel (FPI data and additional post-etch microscope images in Figures A-91 through A-96)

The surface roughness resulting from cleaning with the 60-grit media was quite evident, and although removing 0.4 mil of stock smoothed the roughness to some degree, cracks were still hardly detectable with a microscope and no FPI indications were produced. This group of specimens had the worst recovery rate; just one crack recovered only after 2.2 mils of stock was removed.

The surface roughness resulting from cleaning with the 60-grit media was quite evident in the SEM image of 625-29 in Figure 28a. There was only a hint of a crack after Etch-2 (Figure 28b), which correlated to the lack of any FPI indication. Embedded media particles were evident both pre- and post-etch.



a) 626-13 Post MechClean b) 626-13 Post Etch-2

Figure 28. SEM Images of Inconel Specimen 626-13 Cleaned with Dry Al_2O_3 (60 grit)

Contrary to the results for other groups only the indication for the shortest (0.029-inch) crack (specimen 626-27) recovered at least 40 percent of its pre-MechClean brightness (Figure A-91). Even after six etches removed 2.7 mils of stock from the other four specimens, brightness recovery was less than 10 percent in all cases. After the etching was completed, optical-microscope examination was barely successful in imaging the cracks (Figures A-92b through A-96b). The crack openings resemble shallow gullies, hardly sufficient to hold much penetrant. In Figure A-93b an SEM electron-backscatter image was substituted to provide better image of the crack in 626-09. It appears either shallow or filled with foreign material.

7. CONCLUSIONS

Etching Ti-6Al-4V and Inconel 718 does not consistently nor sufficiently overcome the deleterious effects of certain mechanical cleaning methods to allow a subsequent fluorescent penetrant to be effective. This conclusion is based upon the assumption that recovering 100 percent of the crack indications degraded by mechanical cleaning is required with a minimal stock loss (0.2 to 0.4 mil). Under these criteria, only Type II plastic media (of the eight media evaluated in this study) should be used for pre-FPI mechanical cleaning of Ti-6Al-4V and Inconel 718 parts.

If detecting cracks less than 0.030 inch long is not necessary, water jet and wet glass bead are two other cleaning media that could be used for titanium parts. Refinement of the water-jet cleaning process may eliminate this limitation by reducing the degradation of crack indications on both titanium and Inconel, because specimens cleaned with that method retained the highest number of indications of any method except dry plastic media.

Sometimes etching to remove more than 0.2 to 0.4 mil enabled crack indications to recover brightnesses comparable to those obtained before mechanical cleaning. However, this additional stock loss was more than dimensional tolerances of rotating engine parts allow. Furthermore, the additional etching recovered far less than 100 percent of the FPI indications lost during mechanical cleaning.

Etching appeared to affect the surfaces of Inconel specimens more severely compared to titanium. This was especially evident for specimens cleaned with plastic media and water jet. Those two media disturbed the surfaces of both alloys to a relatively minor degree, so the effects of etching were more easily observed with microscopic examination. On the other hand, etching enabled indication recovery on Inconel specimens to a lesser degree than on titanium specimens.

Etching did not produce the anticipated predictable effects of etching on the recovery of FPI crack indications. Due diligence was observed in the performance of the etching in the laboratory. Small batch etching was thought to provide a degree of control not available with large tanks in an Air Force depot setting. Nevertheless, some uncertainty was generated by the sometimes unpredictable behavior of the etchant, which may have been caused by the very thing thought to provide control: small batch etching. In any case, iterative recalculation of etch rates controlled the stock removal to the desired amount in a high percentage of cases.

There is always variability in the brightness of FPI crack indications with repetitive processing of the same crack. However, no explanation is forthcoming for the sharp decrease in indication brightness after an etch cycle followed by a sharp increase in brightness after one or more subsequent etches. The much lower degree of variability in indications produced with repetitive FPI of the cracks in the control specimens provided confidence that FPI process was under control.

Characterization of crack topography with microscopic examination was difficult due to the surface disturbances caused by the mechanical cleaning and the compounding effects of etching. It was also impossible to detect any trend that enabled consistent correlation of microscopic observations of cracks with the character of respective FPI indications.

8. RECOMMENDATIONS

If mechanical cleaning is performed with any media other than Type II plastic media prior to inspecting for fatigue cracks in Ti-6Al-4V and Inconel 718 engine parts, use a nondestructive inspection method other than FPI.

Evaluate refined water jet and possibly the wet glass bead cleaning processes as potential additional cleaning methods, especially for Ti-6Al-4V.

Investigate the use of other cleaning media, such as CO_2 pellets or plant-seed hulls, for use prior to performing fluorescent penetrant inspection for fatigue cracks. Conduct initial screening of candidate mechanical cleaning methods by performing surface analysis of material coupons exposed to the candidate cleaning method to assess the potential to disturb surface material.

Evaluate other NDI technology (e.g., wide-field eddy current, sonic infrared) as alternatives to FPI on mechanically cleaned parts.

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[2.] Oklahoma City Air Logistics Center Process Order 76PMXG 79-007, "Basketizing and Cleaning of Engine Parts."

[3.] Glass, William L., "Measurement of Pre-penetrant Etch Rate," *Materials Evaluation*, **66**, Dec 2008, pp 1234-1240.

[4.] SAE AMS 2644, "Inspection Materials, Penetrant," SAE International, Warrendale, PA, 2006.

APPENDIX

FPI AND OPTICAL-MICROSCOPE DATA

List of Figures

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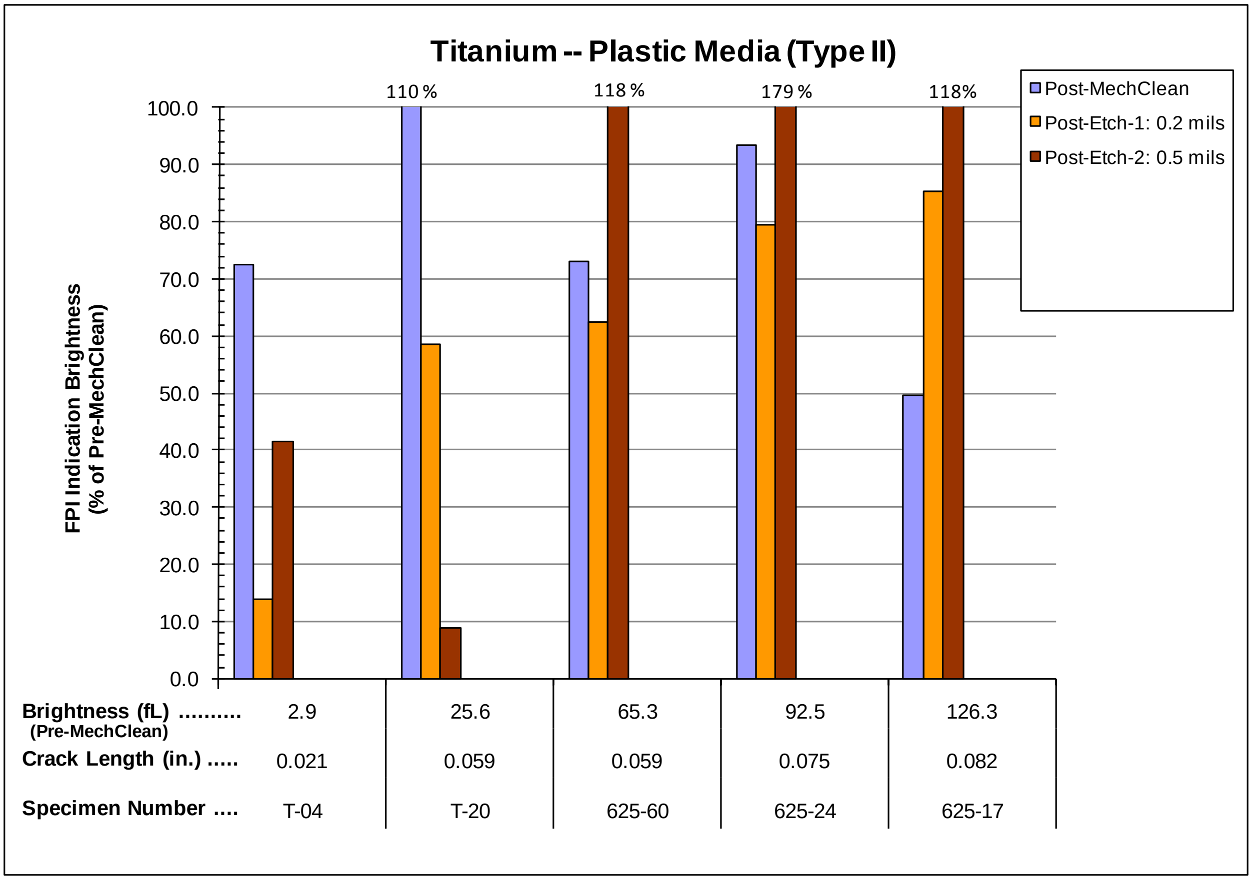


Figure A-1. FPI Data for Ti-6Al-4V Specimens Cleaned with Plastic Media (Type II)

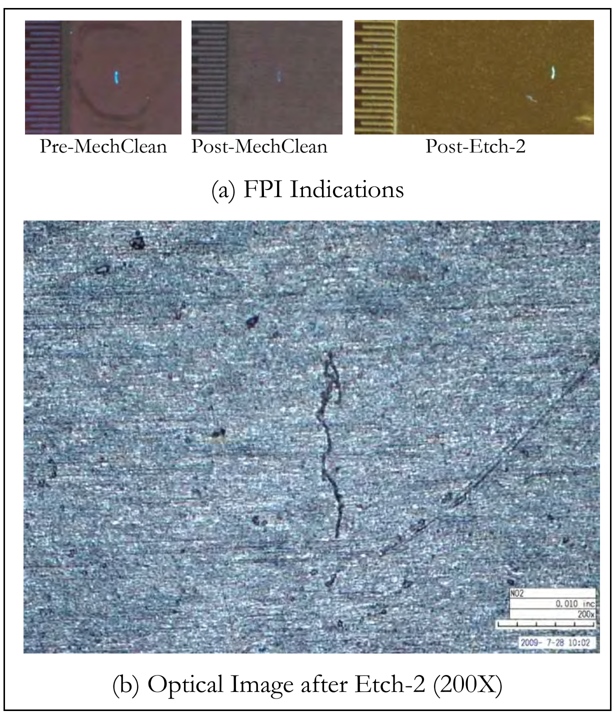


Figure A-2. Specimen T-04 Crack Images

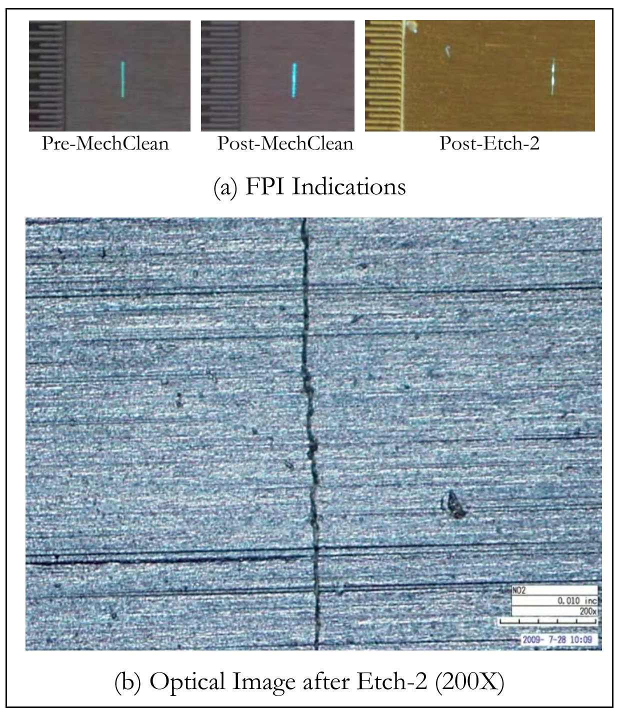
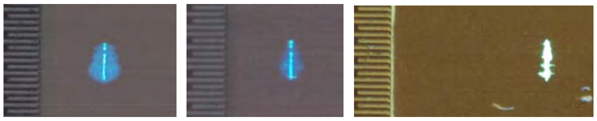
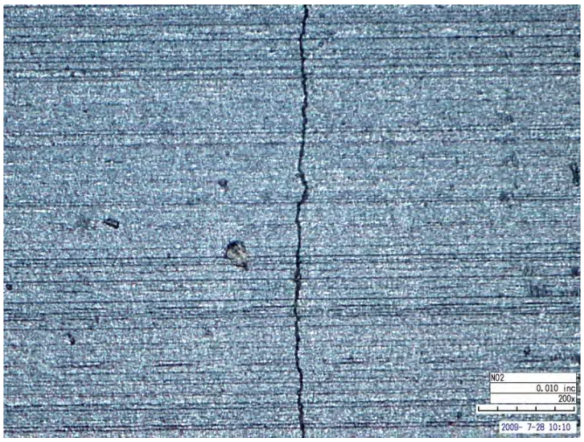


Figure A-3. Specimen T-20 Crack Images



Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications

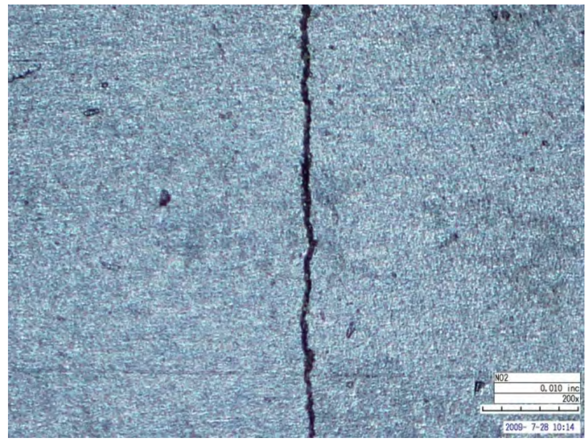


(b) Optical Image after Etch-2 (200X)

Figure A-4. Specimen 625-60 Crack Images

Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications

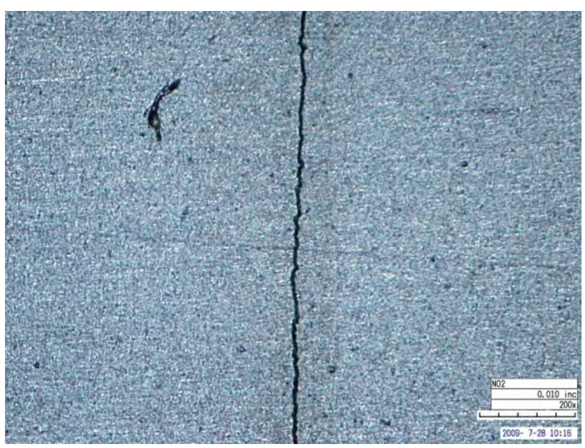


(b) Optical Image after Etch-2 (200X)

Figure A-5. Specimen 625-24 Crack Images

Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications



(b) Optical Image after Etch-2 (200X)

Figure A-6. Specimen 625-17 Crack Images

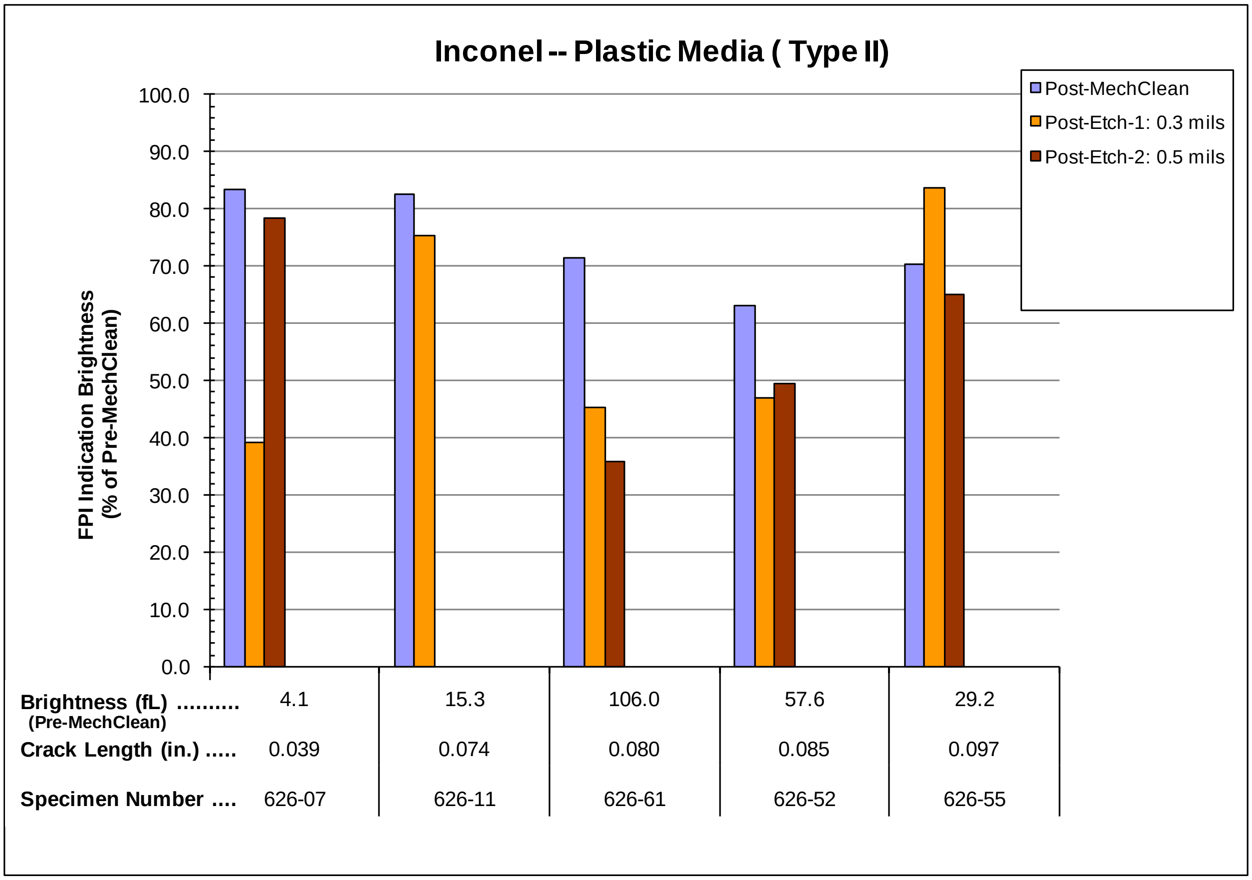
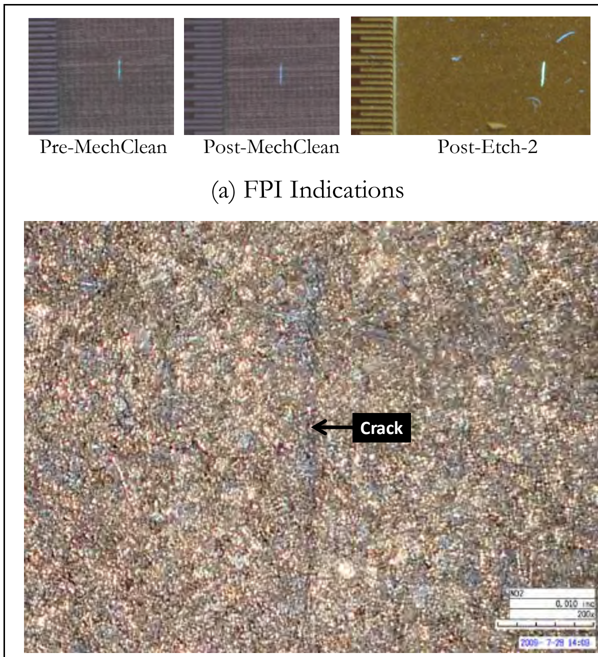
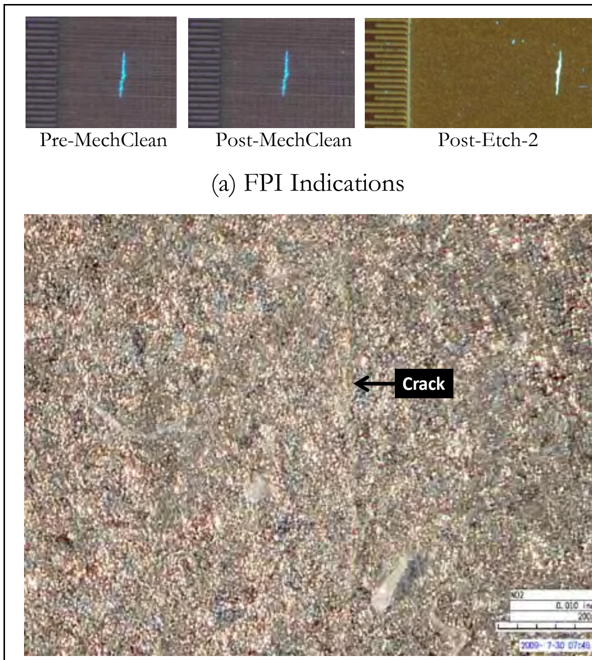


Figure A-7. FPI Data for Inconel 718 Specimens Cleaned with Plastic Media (Type II)



(b) Optical Image after Etch-2 (200X)

Figure A-8. Specimen 626-07 Crack Images



(b) Optical Image after Etch-2 (200X)

Figure A-9. Specimen 626-11 Crack Images

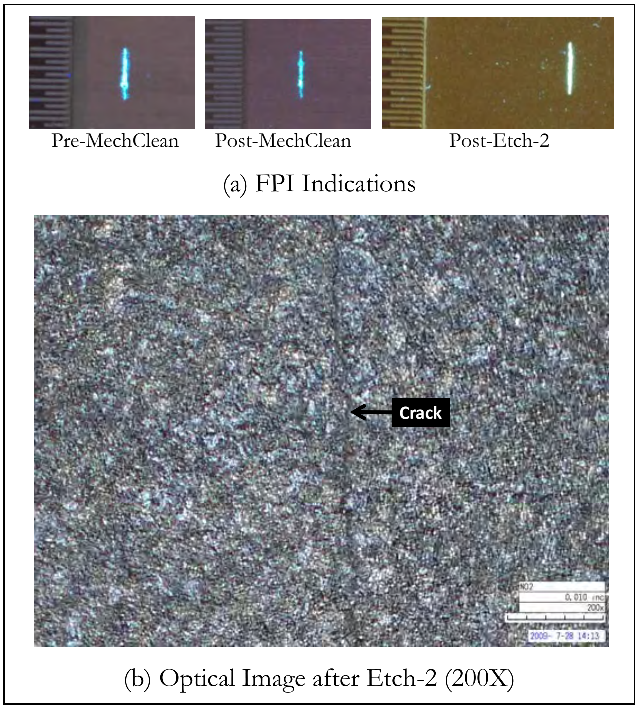


Figure A-10. Specimen 626-61 Crack Images

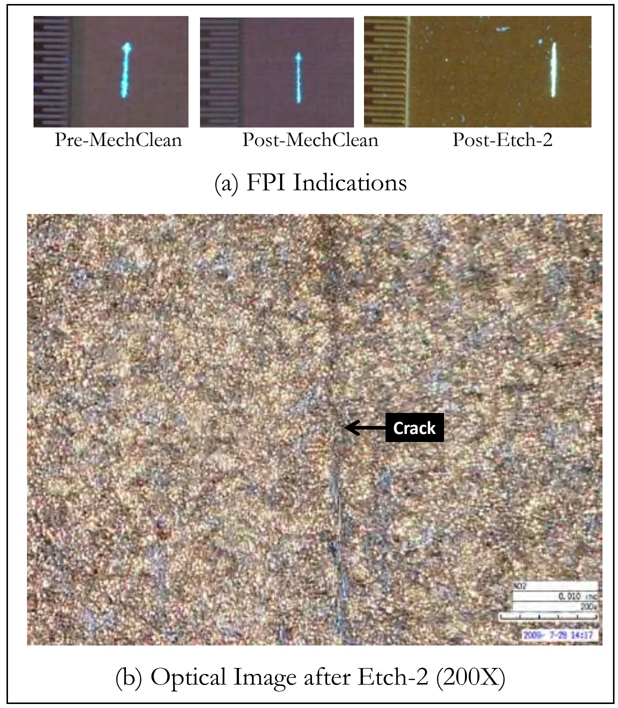


Figure A-11. Specimen 626-52 Crack Images

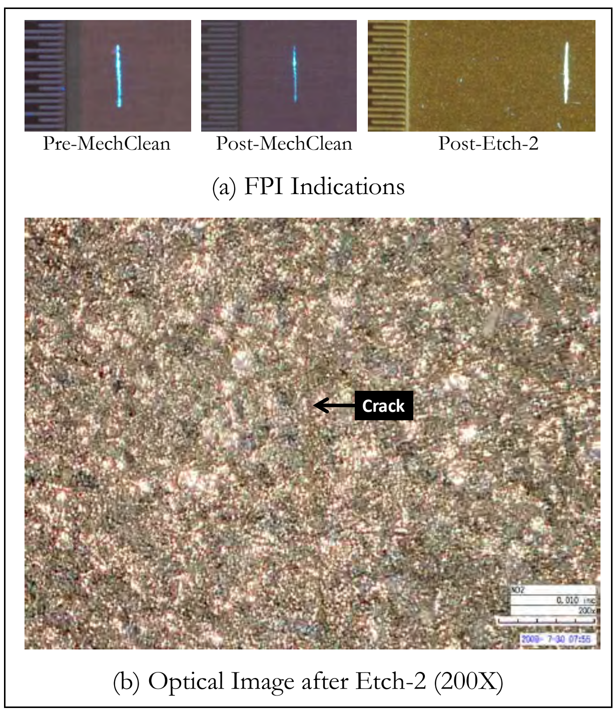


Figure A-12. Specimen 626-55 Crack Images

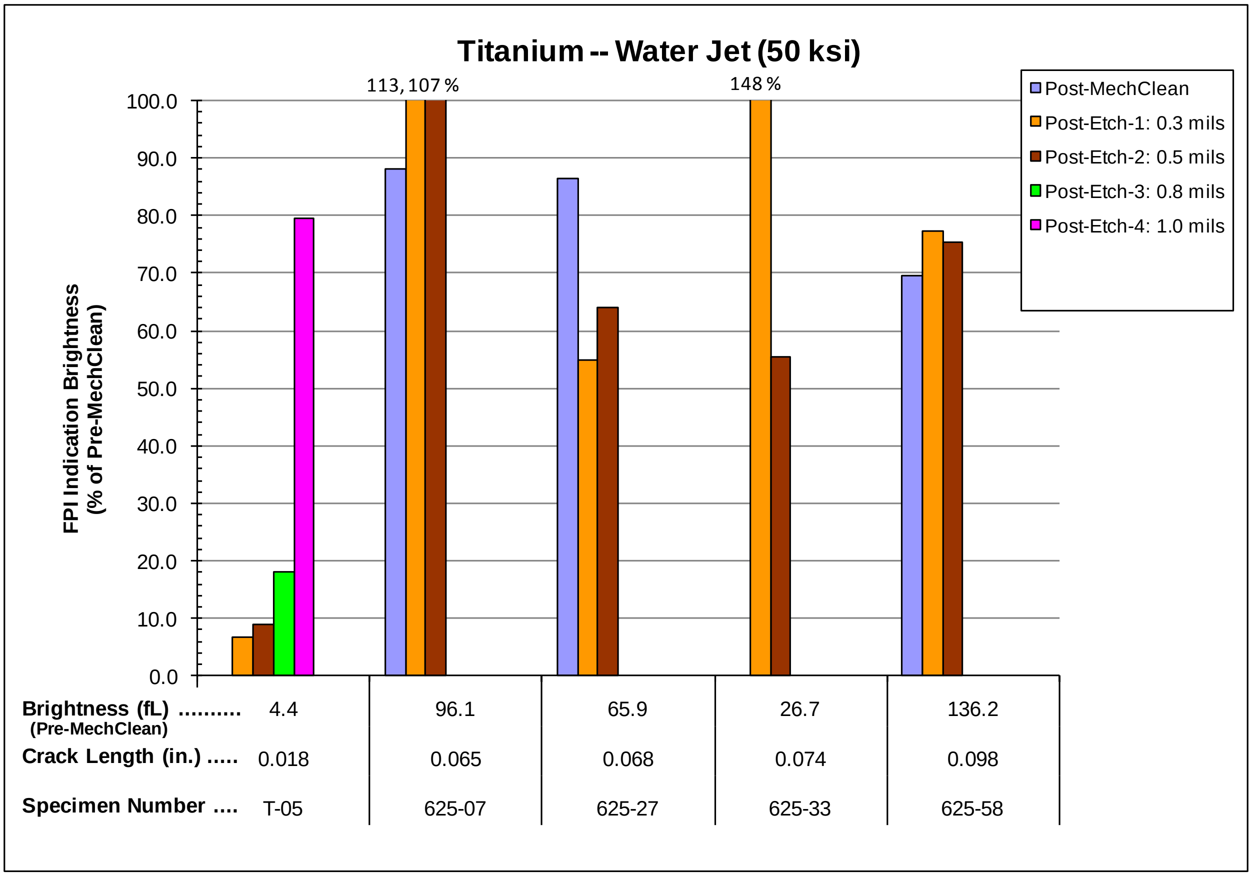


Figure A-13. FPI Data for Ti-6Al-4V Specimens Cleaned with Water Jet (50 ksi)

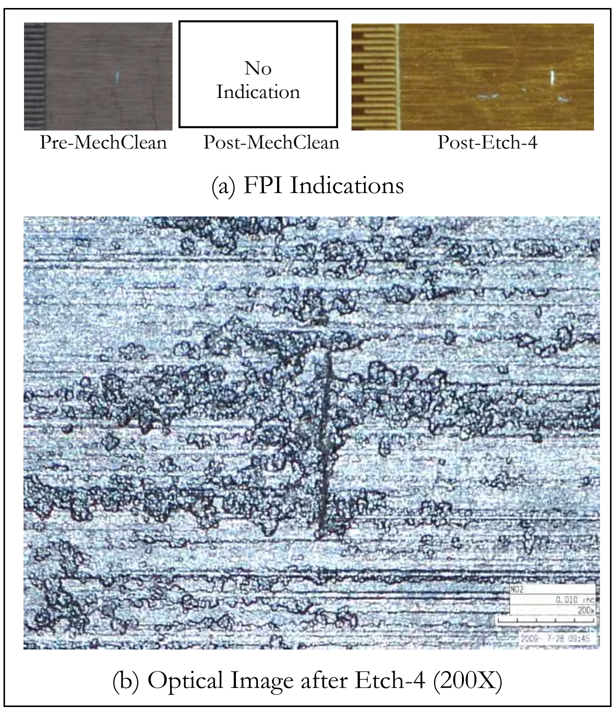


Figure A-14. Specimen T-05 Crack Images

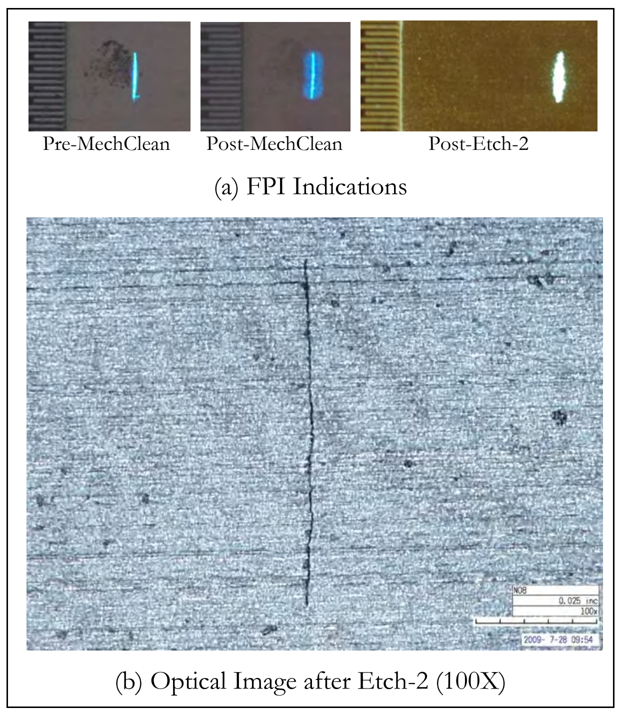


Figure A-15. Specimen 625-07 Crack Images

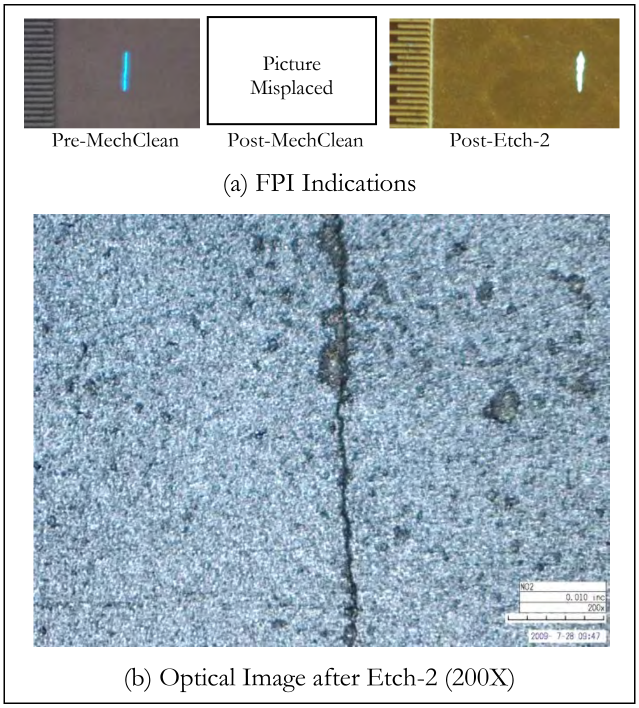


Figure A-16. Specimen 625-27 Crack Images

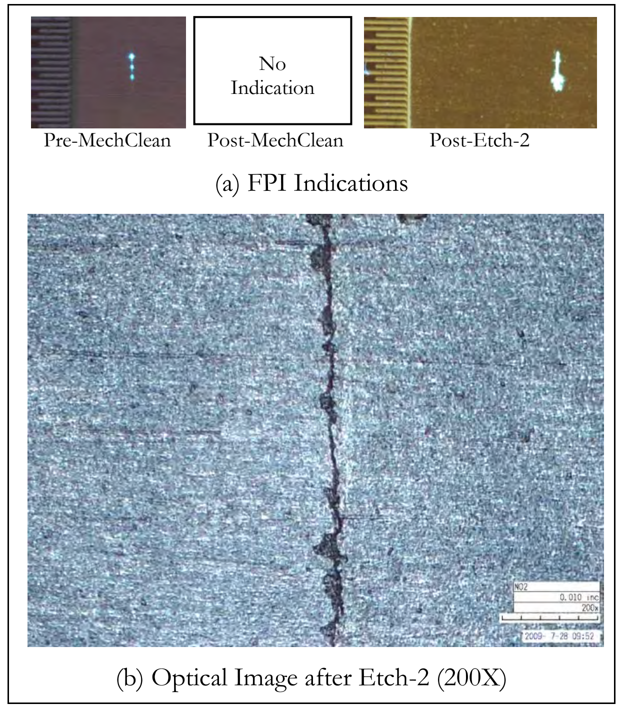


Figure A-17. Specimen 625-33 Crack Images

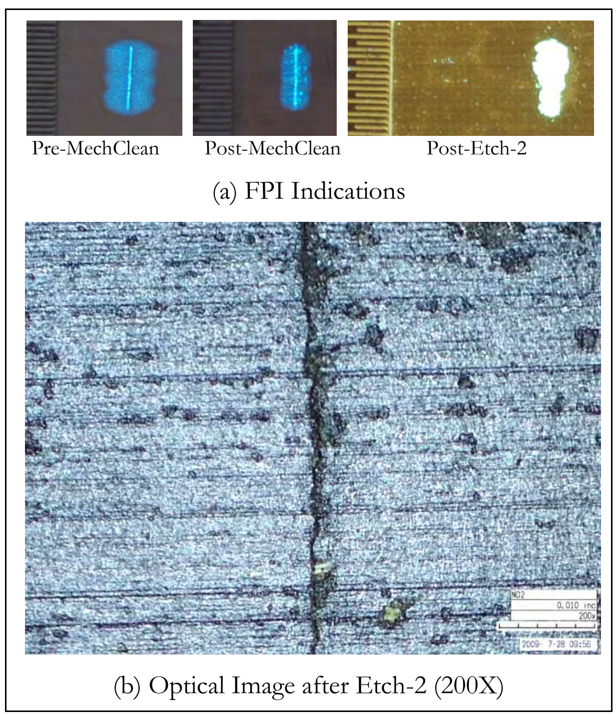


Figure A-18. Specimen 625-58 Crack Images

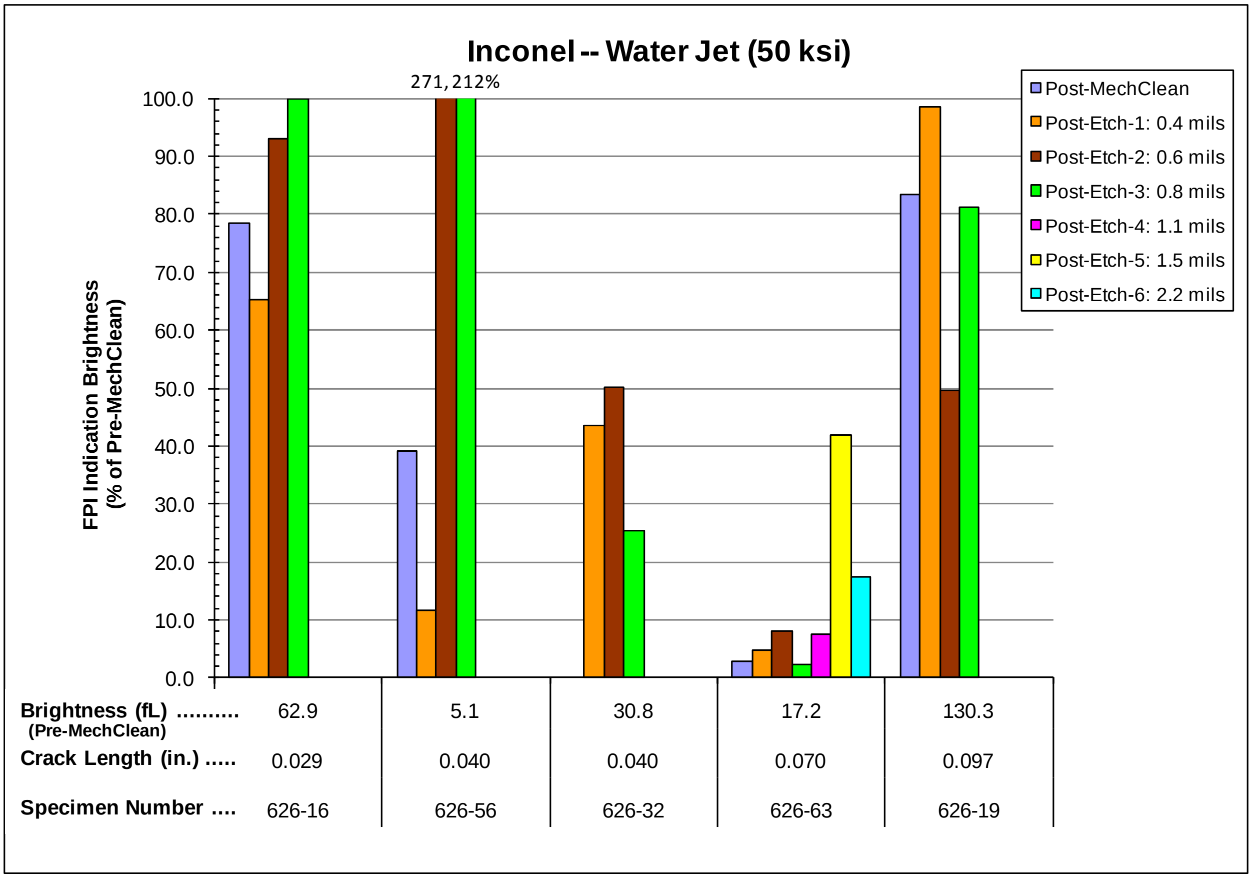
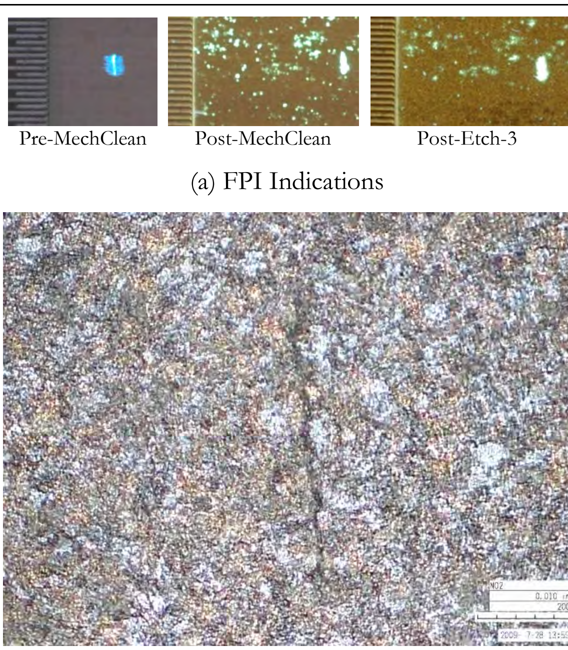


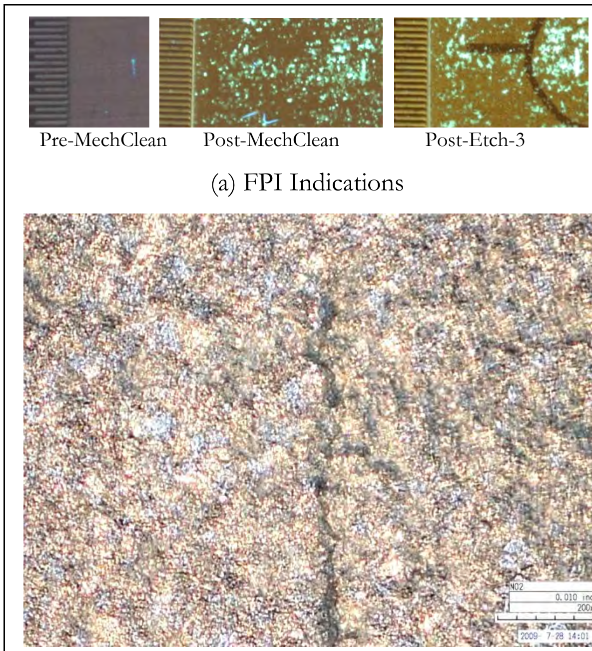
Figure A-19. FPI Data for Inconel 718 Specimens Cleaned with Water Jet (50 Ksi)



(a) FPI Indications

(b) Optical Image after Etch-3 (200X)

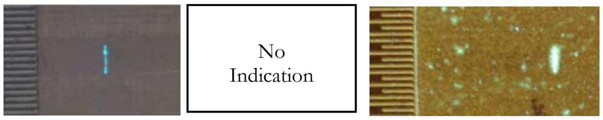
Figure A-20. Specimen 626-16 Crack Images



(a) FPI Indications

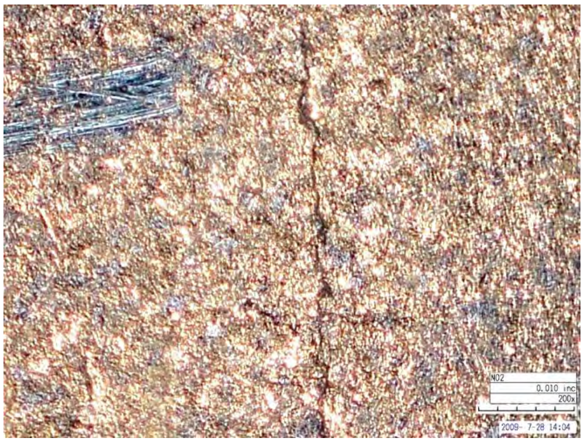
(b) Optical Image after Etch-3 (100X)

Figure A-21. Specimen 626-56 Crack Images



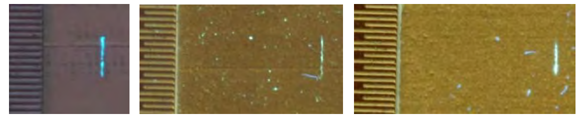
Pre-MechClean Post-MechClean Post-Etch-3

(a) FPI Indications



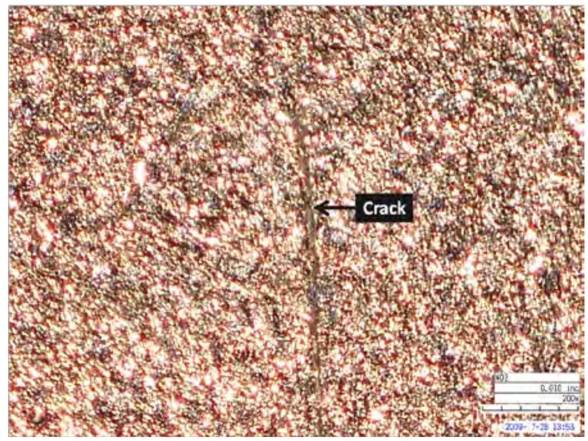
(b) Optical Image after Etch-3 (200X)

Figure A-22. Specimen 626-32 Crack Images



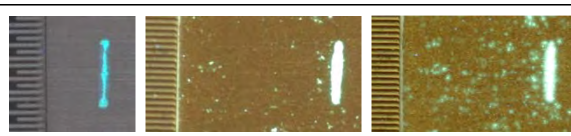
Pre-MechClean Post-MechClean Post-Etch-6

(a) FPI Indications



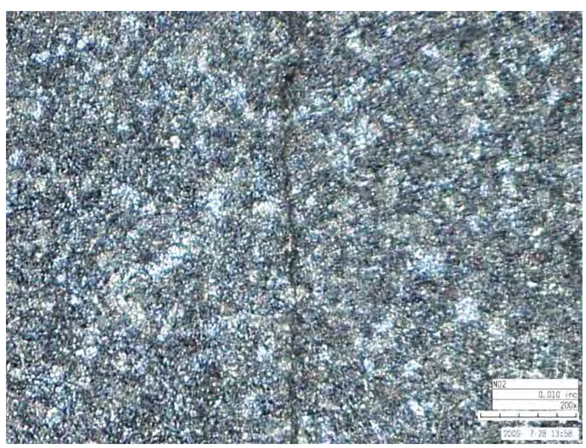
(b) Optical Image after Etch-6 (200X)

Figure A-23. Specimen 626-63 Crack Images



Pre-MechClean Post-MechClean Post-Etch-3

(a) FPI Indications



(b) Optical Image after Etch-3 (200X)

Figure A-24. Specimen 626-19 Crack Images

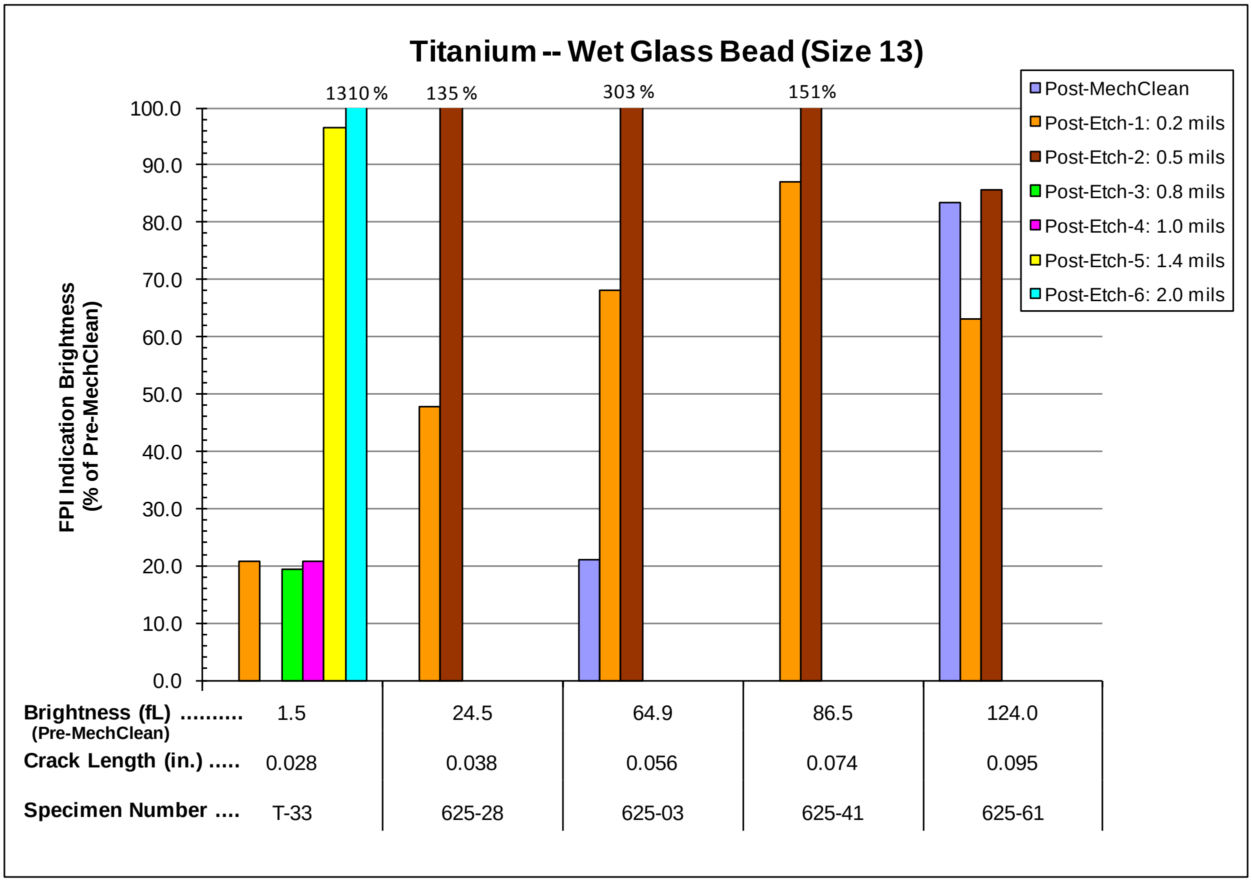
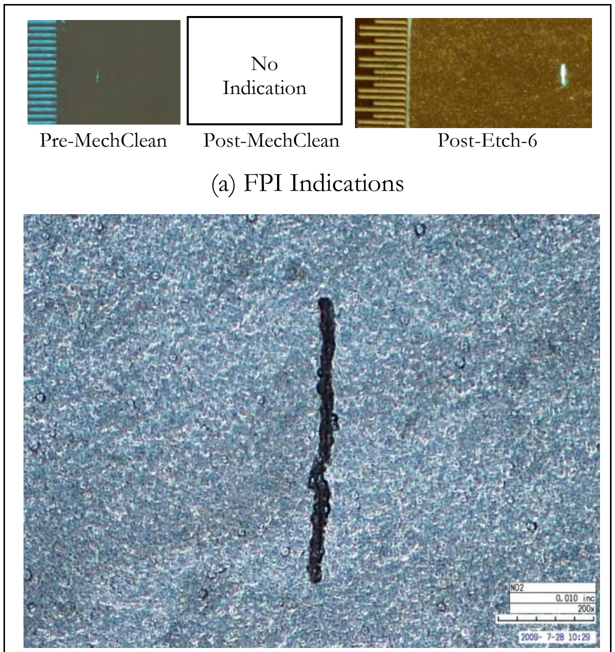


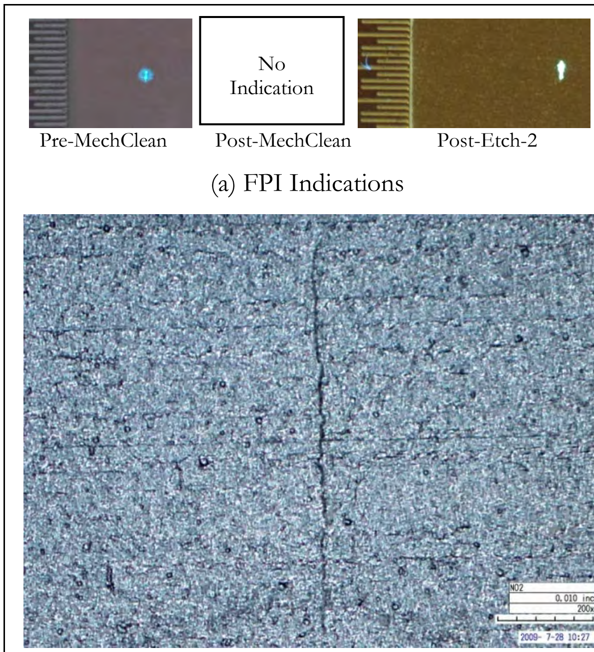
Figure A-25. FPI Data for Ti-6Al-4V Specimens Cleaned with Wet Glass Bead (Size 13)



(a) FPI Indications

(b) Optical Image after Etch-6 (200X)

Figure A-26. Specimen T-33 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-2 (200X)

Figure A-27. Specimen 625-28 Crack Images

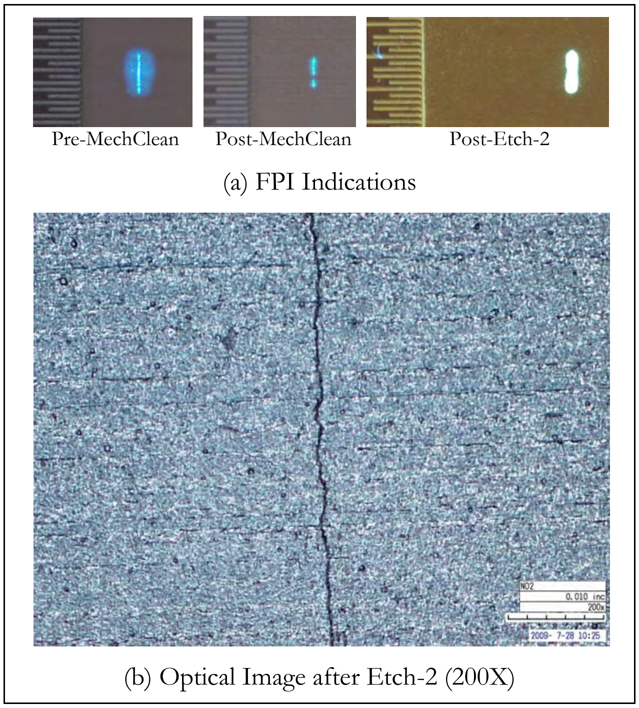


Figure A-28. Specimen 625-03 Crack Images

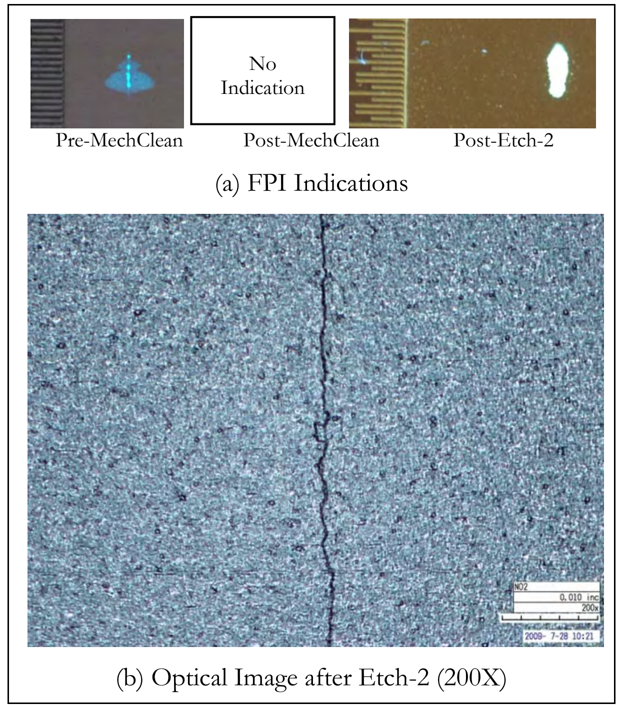


Figure A-29. Specimen 625-41 Crack Images

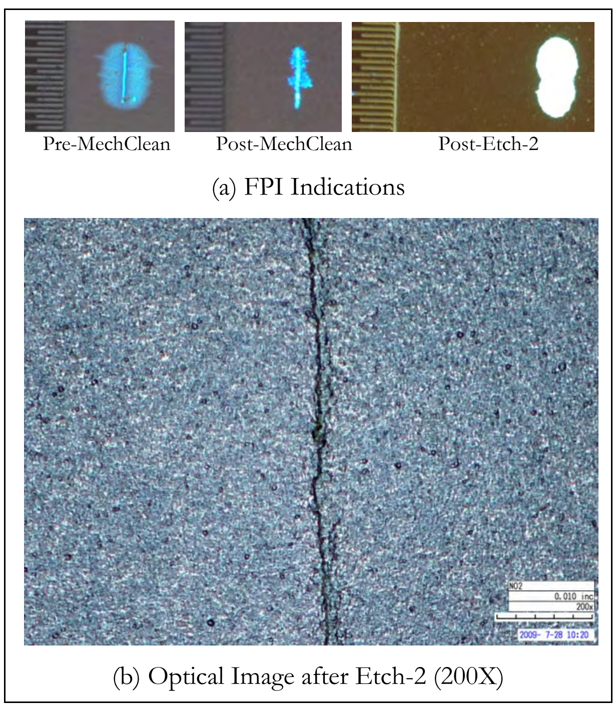


Figure A-30. Specimen 625-61 Crack Images

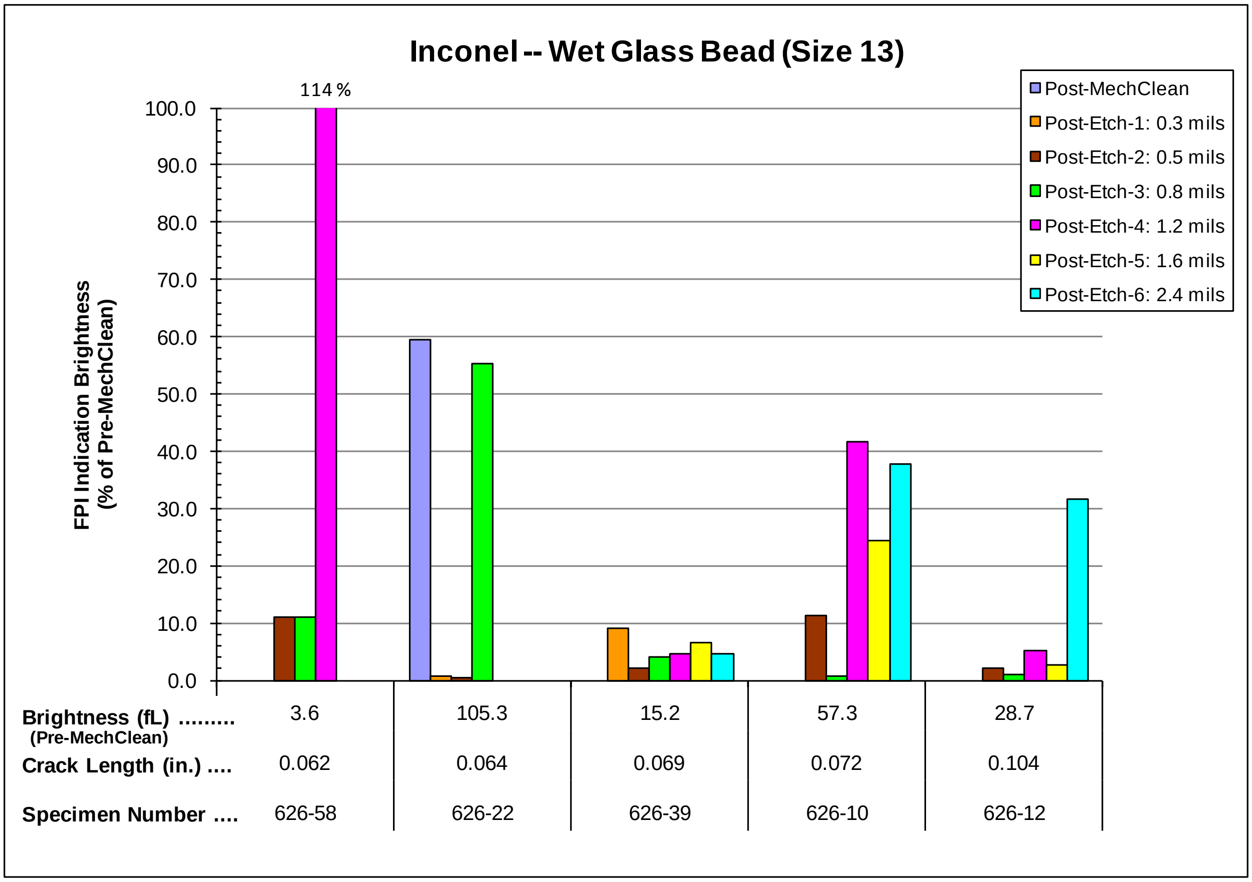
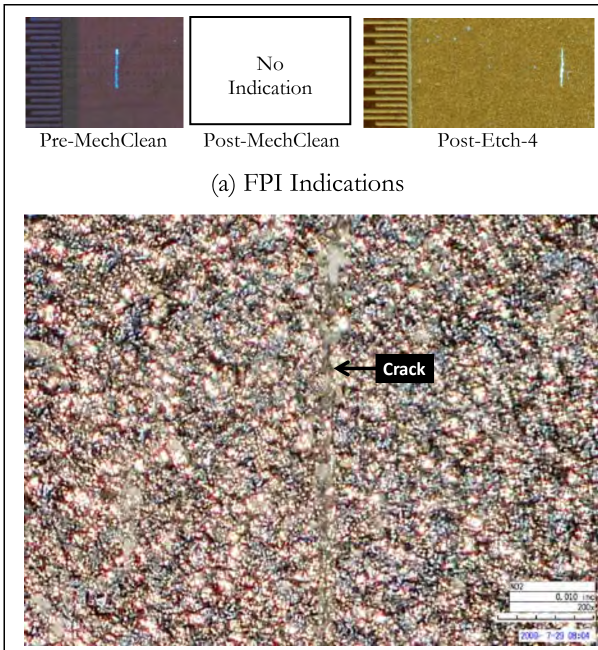


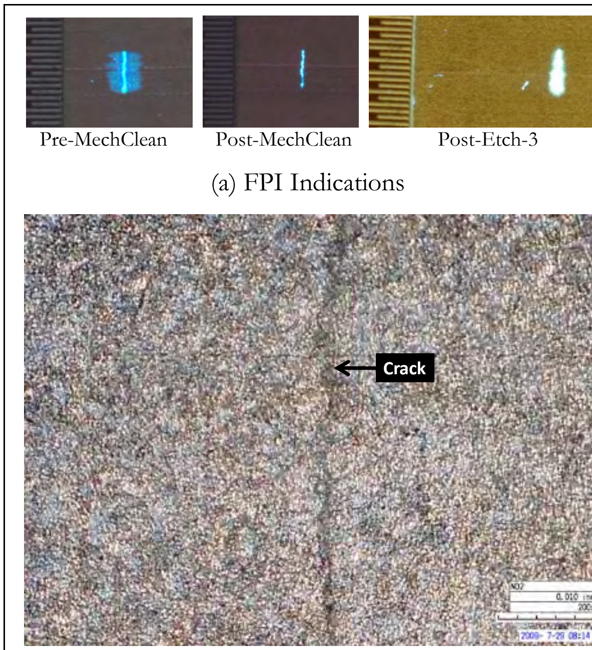
Figure A-31. FPI Data for Inconel 718 Specimens Cleaned with Wet Glass Bead (Size 13)



(a) FPI Indications

(b) Optical Image after Etch-4 (200X)

Figure A-32. Specimen 626-58 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-3 (200X)

Figure A-33. Specimen 626-22 Crack Images

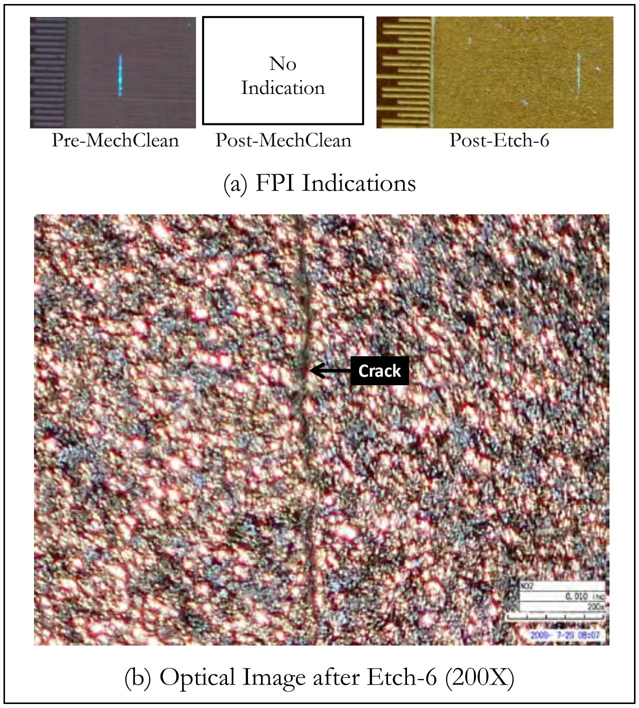


Figure A-34. Specimen 626-39 Crack Images

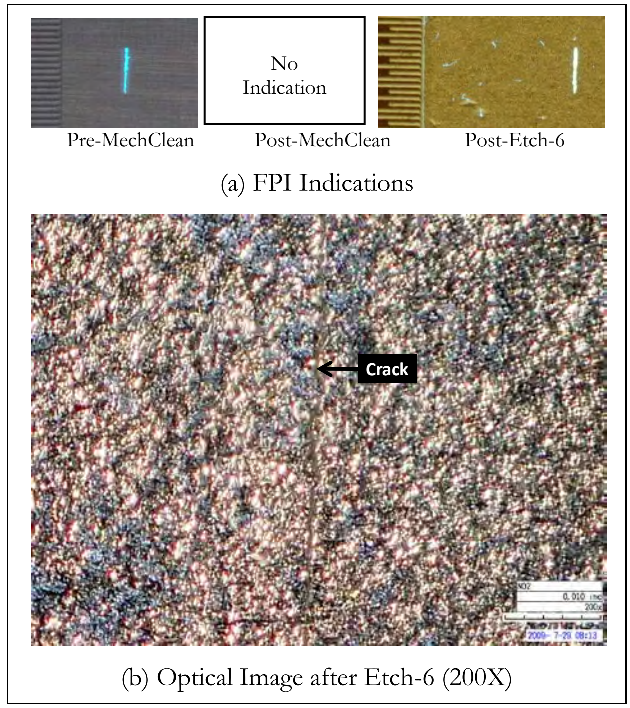


Figure A-35. Specimen 626-10 Crack Images

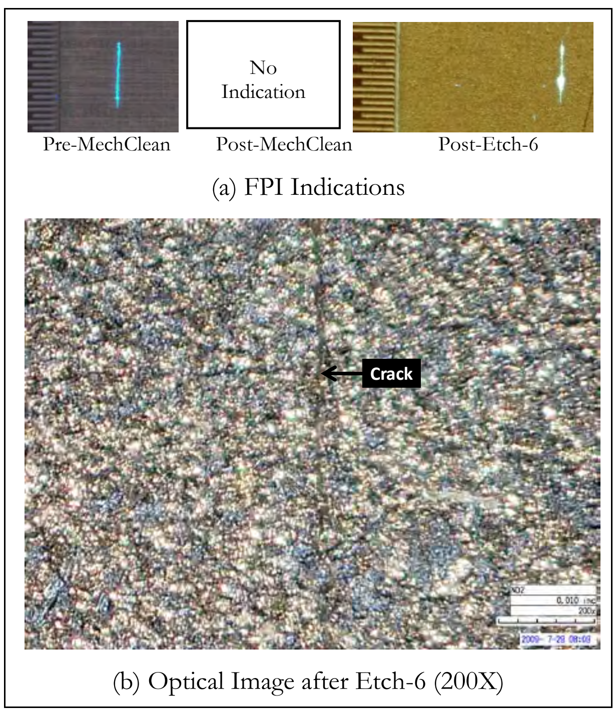


Figure A-36. Specimen 626-12 Crack Images

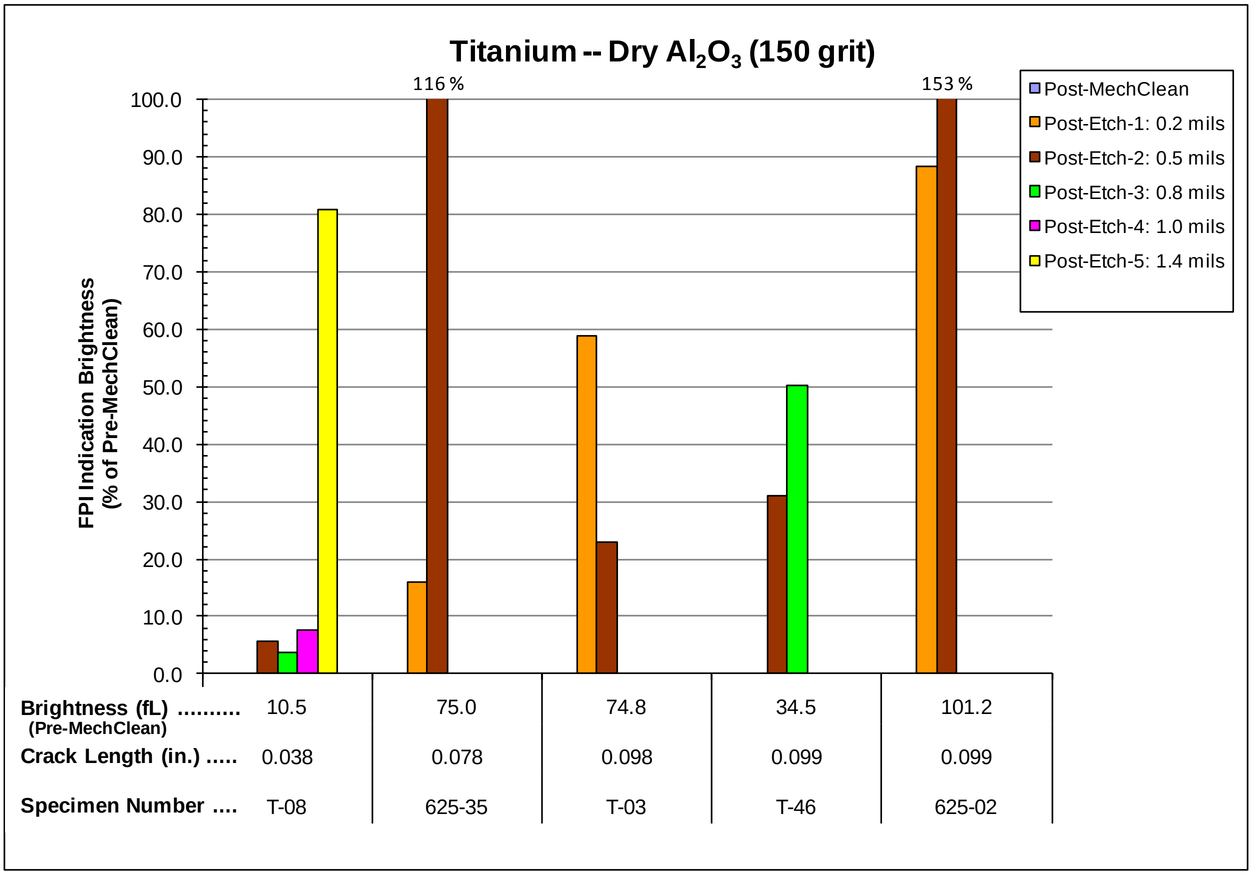
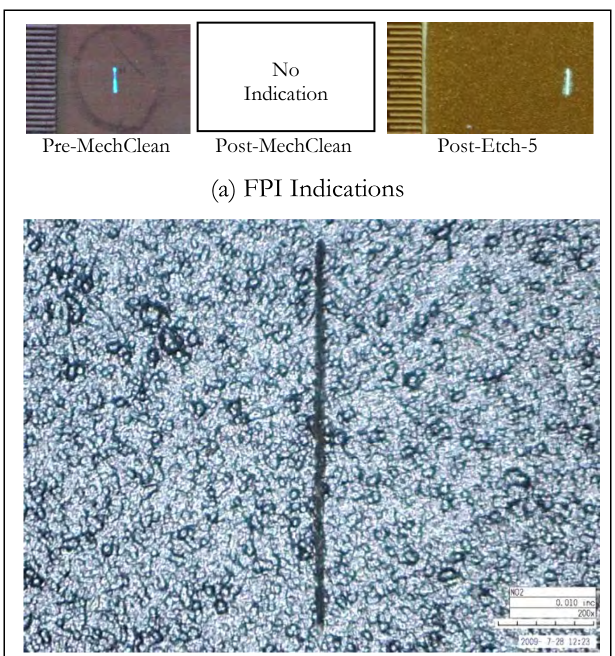
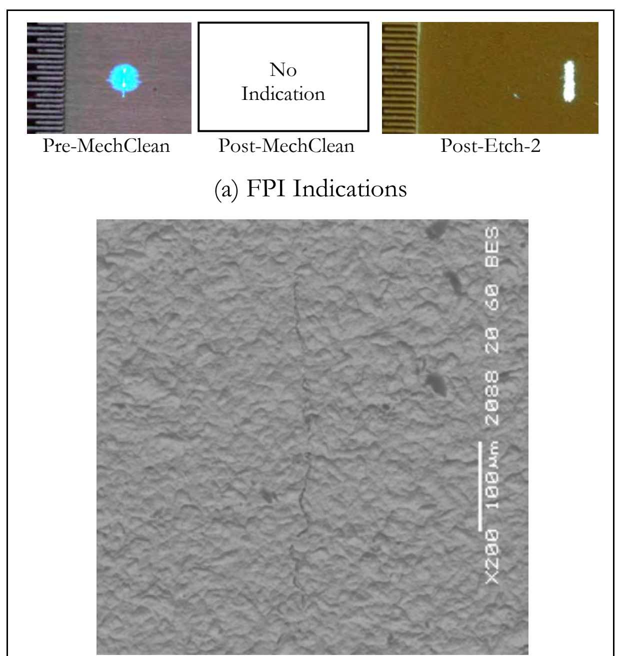


Figure A-37. FPI Data for Ti-6Al-4V Specimens Cleaned with Dry Al_2O_3 (150 grit)



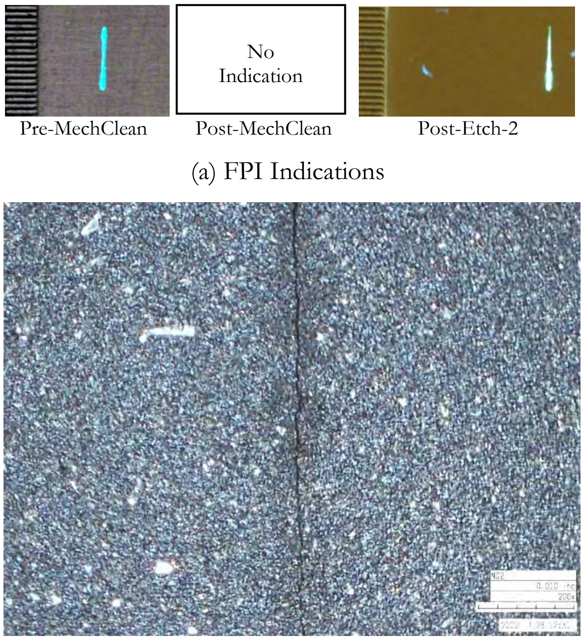
(b) Optical Image after Etch-5 (200X)

Figure A-38. Specimen T-08 Crack Images



(b) SEM Image after Etch-2 (200X)

Figure A-39. Specimen 625-35 Crack Images

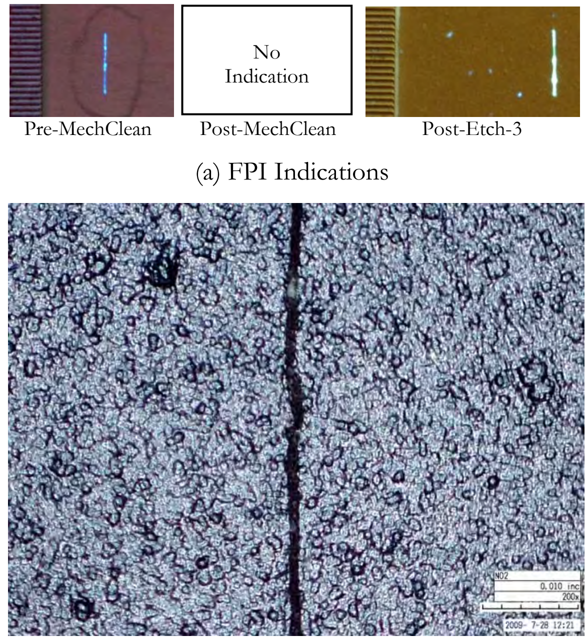


Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications

(b) Optical Image after Etch-2 (200X)

Figure A-40. Specimen T-03 Crack Images

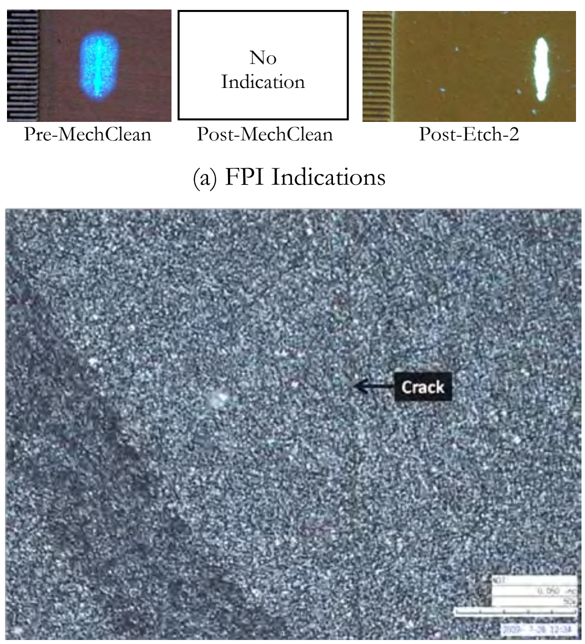


Pre-MechClean Post-MechClean Post-Etch-3

(a) FPI Indications

(b) Optical Image after Etch-3 (200X)

Figure A-41. Specimen T-46 Crack Images



Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications

(b) Optical Image after Etch-2 (200X)

Figure A-42. Specimen 625-02 Crack Images

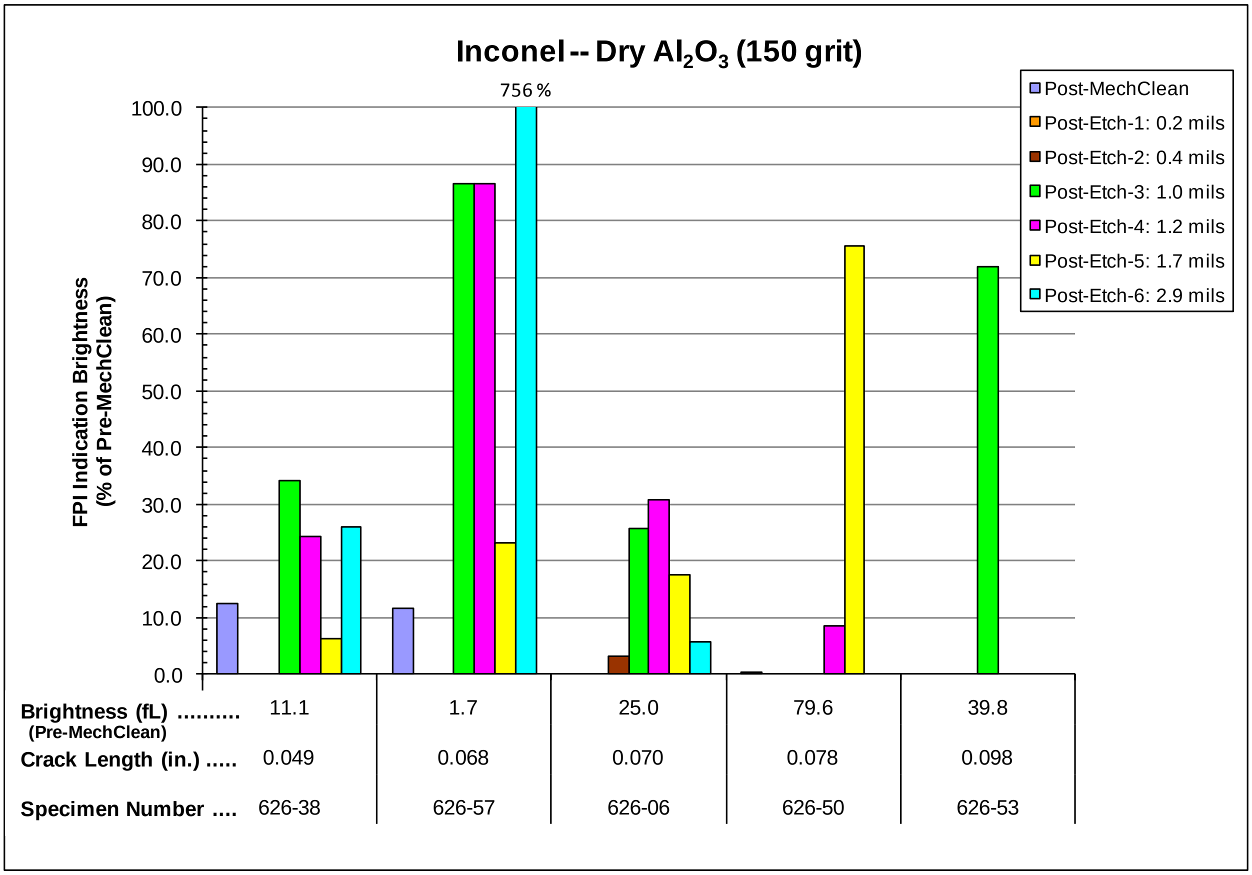


Figure A-43. FPI Data for Inconel 718 Specimens Cleaned with Dry Al_2O_3 (150 grit)

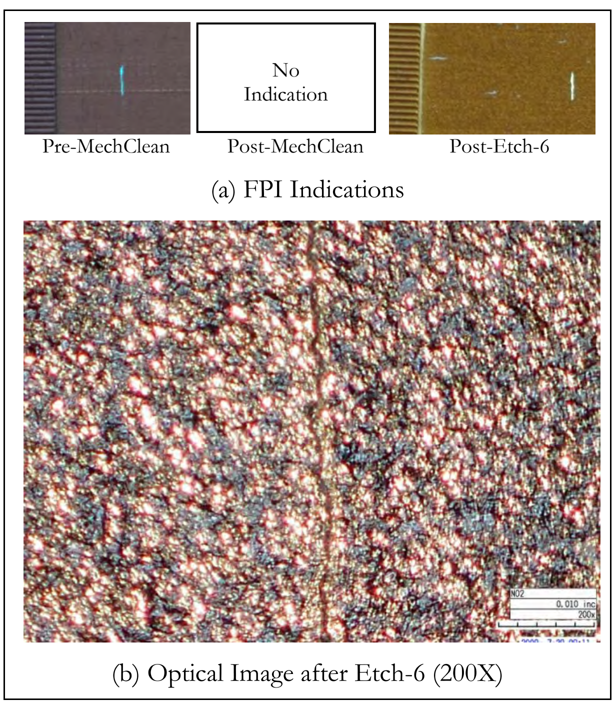


Figure A-44. Specimen 626-38 Crack Images

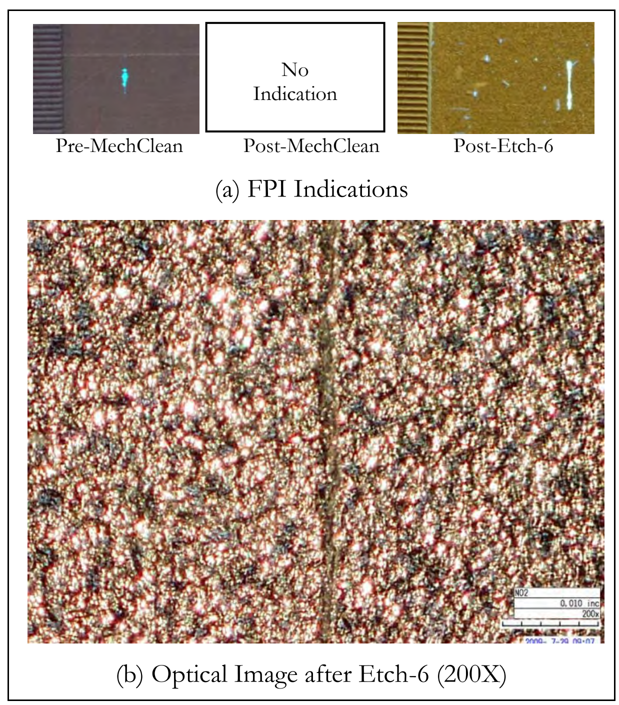
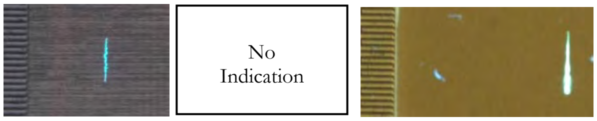
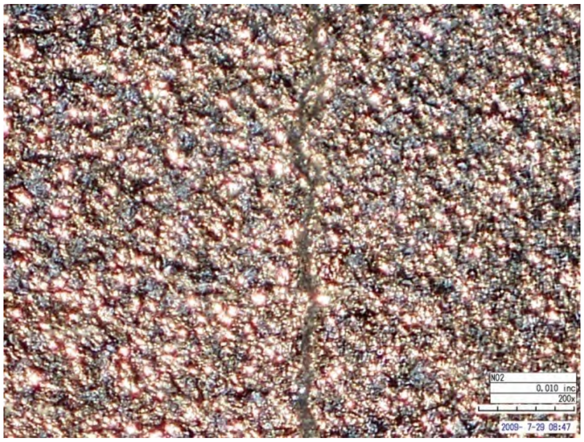


Figure A-45. Specimen 626-57 Crack Images

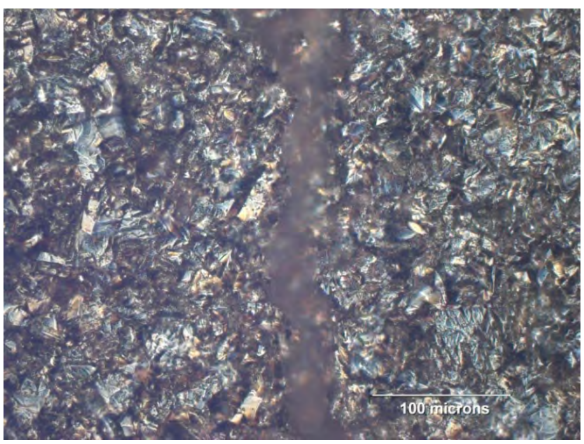


Pre-MechClean Post-MechClean Post-Etch-6

(a) FPI Indications

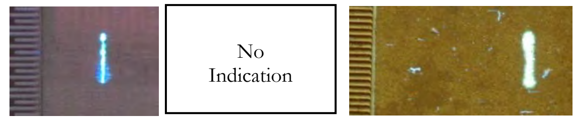


(b) Optical Image after Etch-6 (200X)



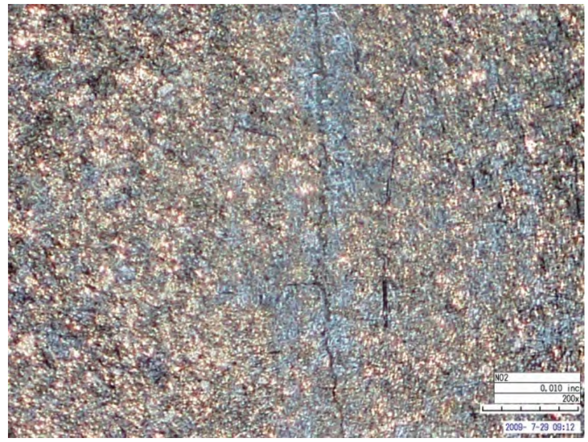
(c) Optical Image after Etch-6 (250X)

Figure A-46. Specimen 626-06 Crack Images



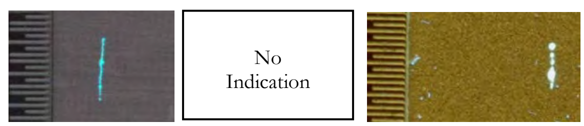
Pre-MechClean Post-MechClean Post-Etch-5

(a) FPI Indications



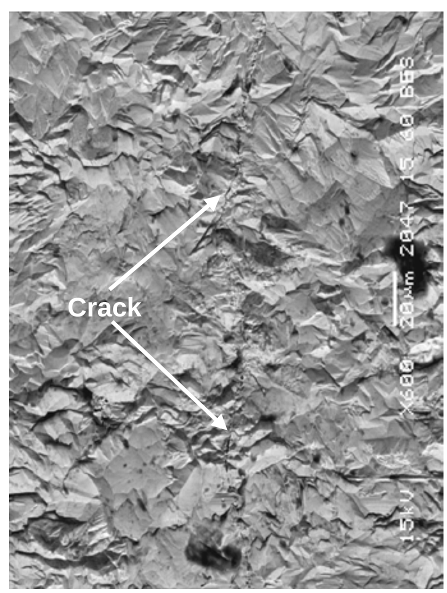
(b) Optical Image after Etch-5 (200X)

Figure A-47. Specimen 626-50 Crack Images



Pre-MechClean Post-MechClean Post-Etch-3

(a) FPI Indications



(b) Optical Image after Etch-3 (200X)

Figure A-48. Specimen 626-53 Crack Images

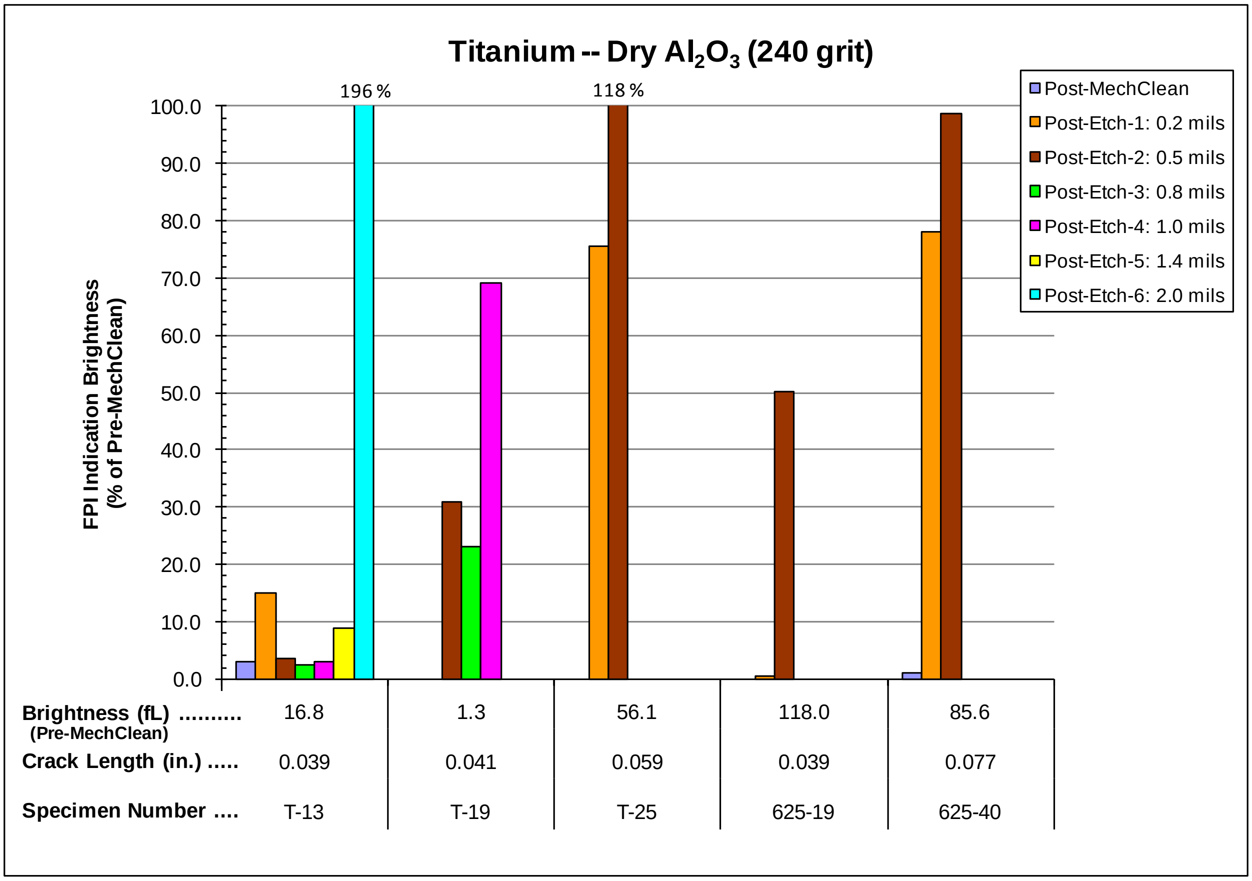
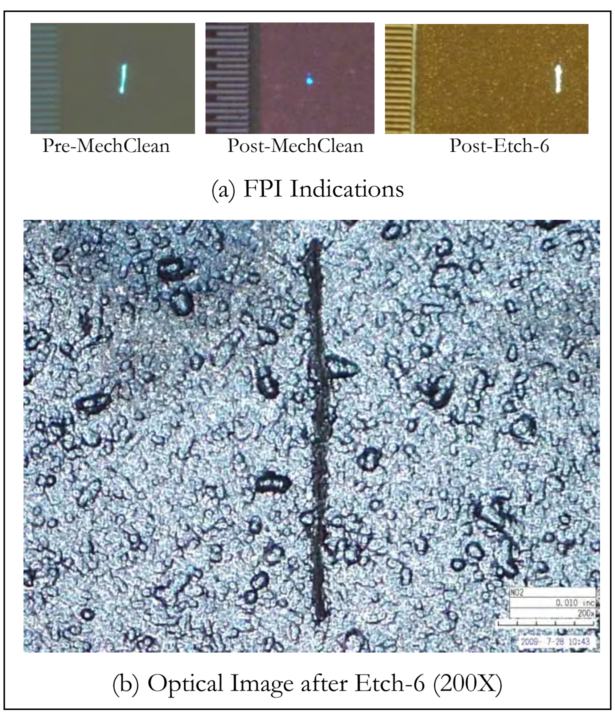


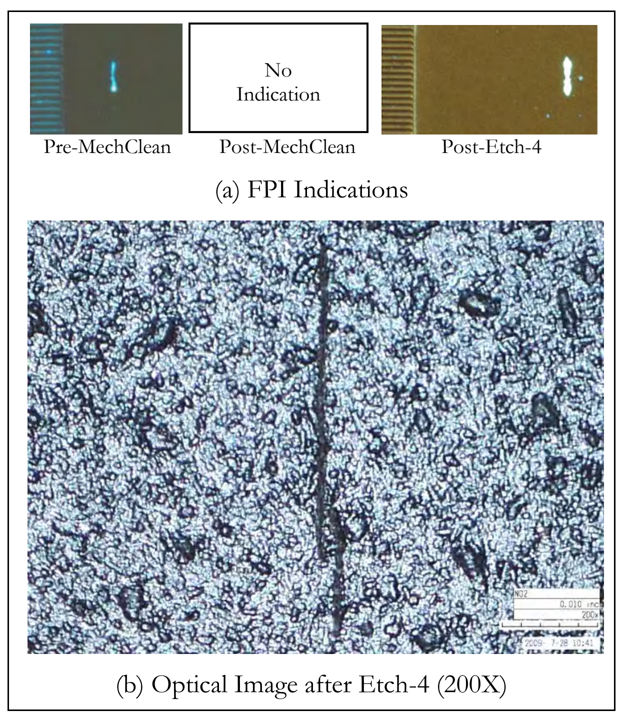
Figure A-49. FPI Data for Ti-6Al-4V Specimens Cleaned with Dry Al_2O_3 (240 grit)



(a) FPI Indications

(b) Optical Image after Etch-6 (200X)

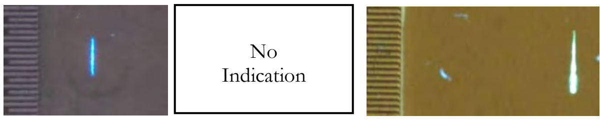
Figure A-50. Specimen T-13 Crack Images



(a) FPI Indications

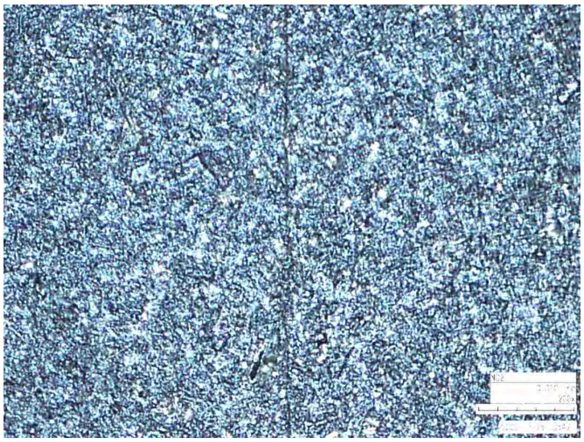
(b) Optical Image after Etch-4 (200X)

Figure A-51. Specimen T-19 Crack Images



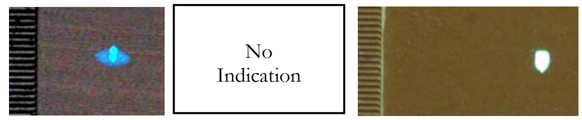
Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications



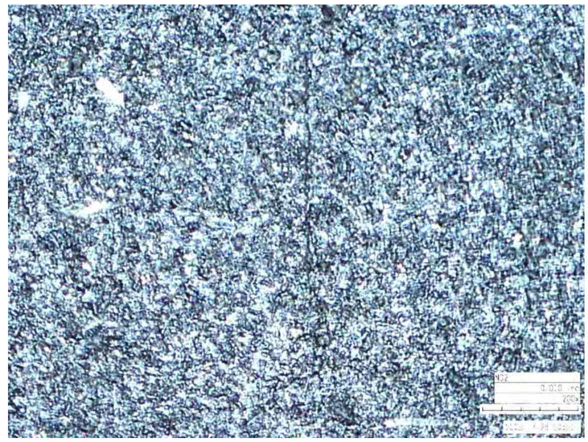
(b) Optical Image after Etch-2 (200X)

Figure A-52. Specimen T-25 Crack Images



Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications

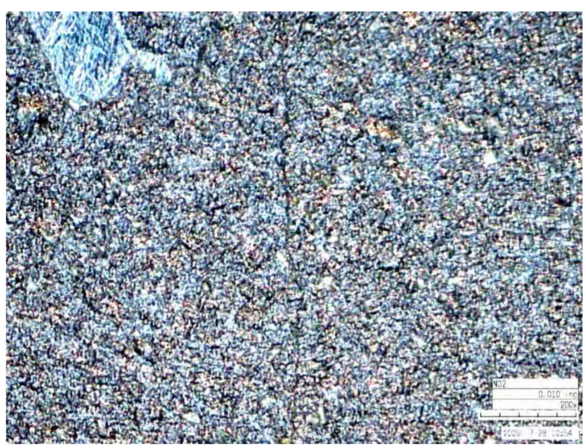


(b) Optical Image after Etch-2 (200X)

Figure A-53. Specimen 625-19 Crack Images

Pre-MechClean Post-MechClean Post-Etch-2

(a) FPI Indications



(b) Optical Image after Etch-2 (200X)

Figure A-54. Specimen 625-40 Crack Images

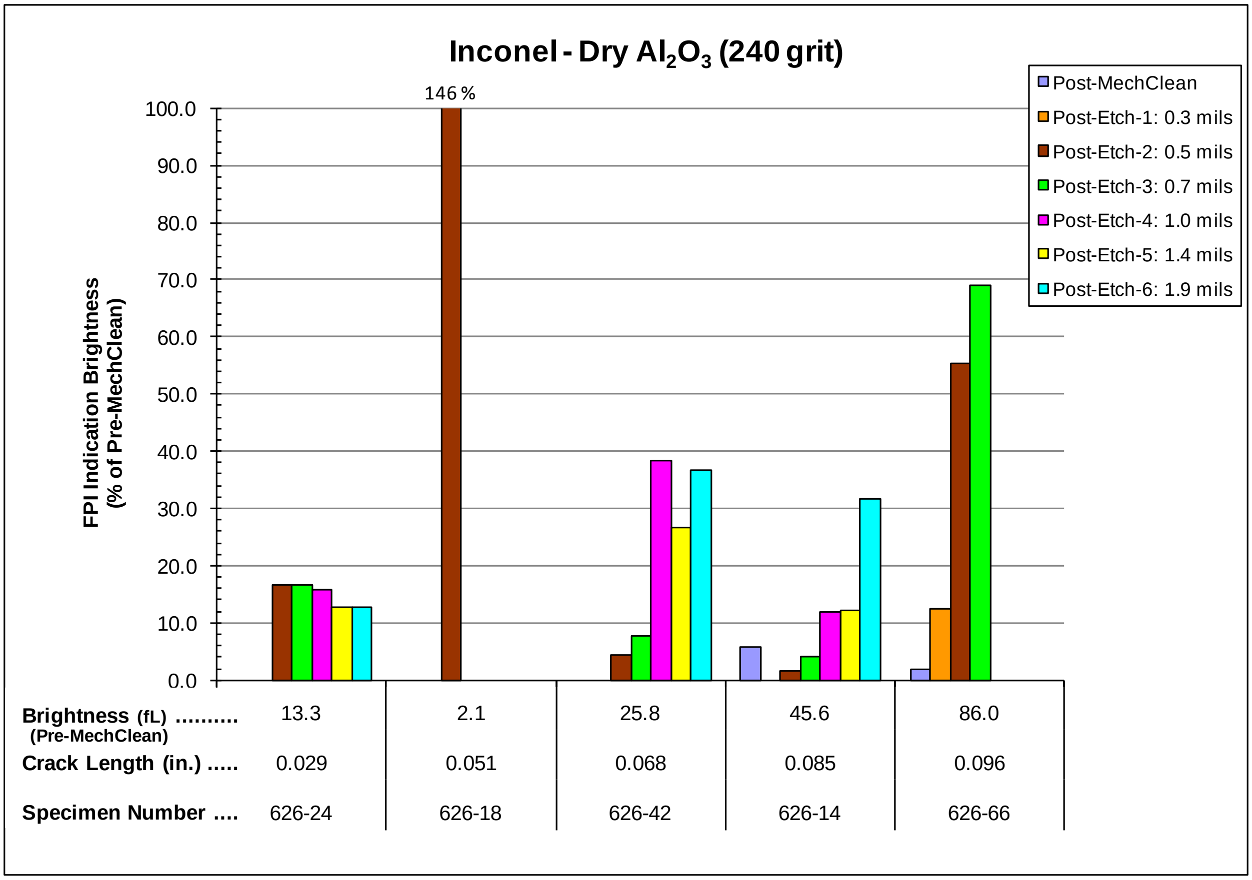


Figure A-55. FPI Data for Inconel 718 Specimens Cleaned with Dry Al_2O_3 (240 grit)

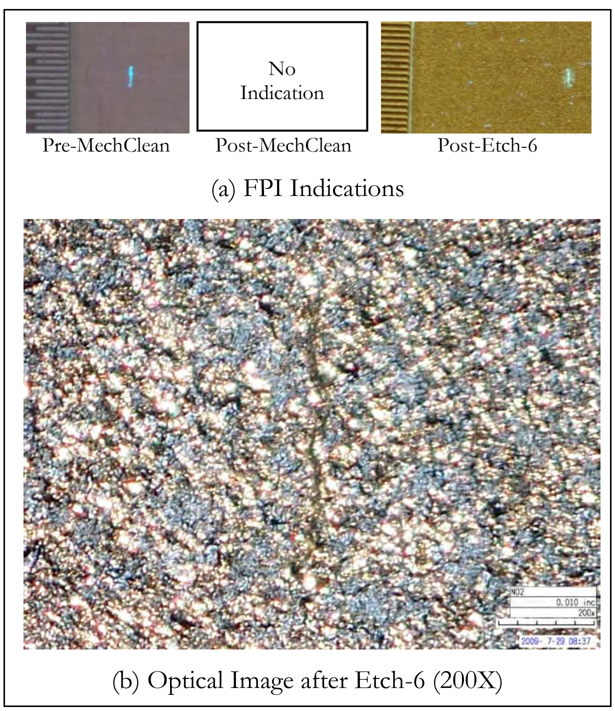


Figure A-56. Specimen 626-24 Crack Images

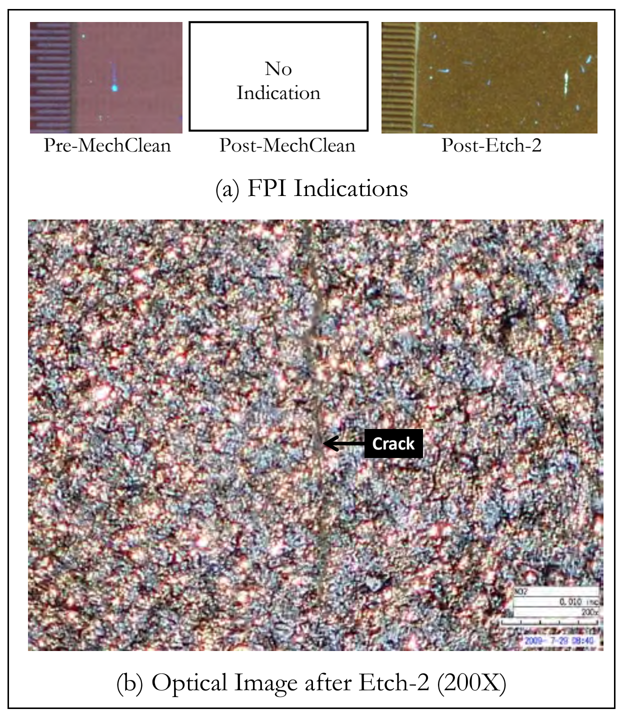


Figure A-57. Specimen 626-18 Crack Images

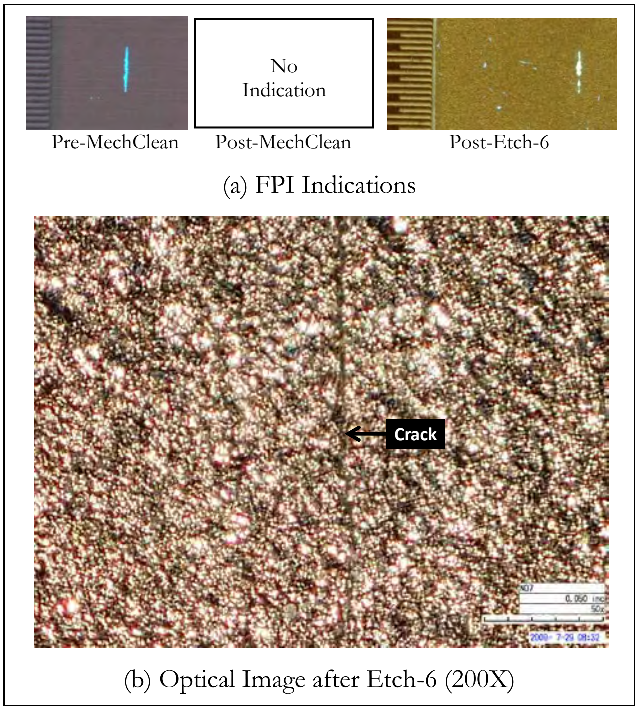


Figure A-58. Specimen 626-42 Crack Images

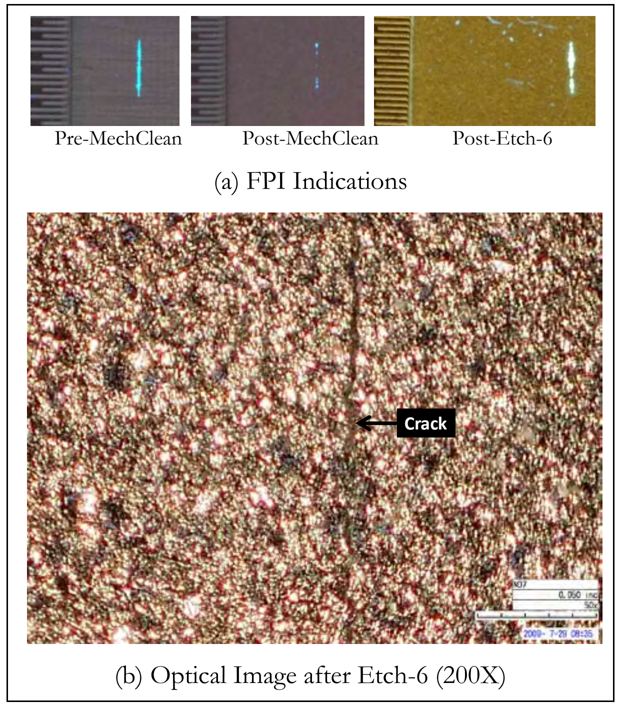


Figure A-59. Specimen 626-14 Crack Images

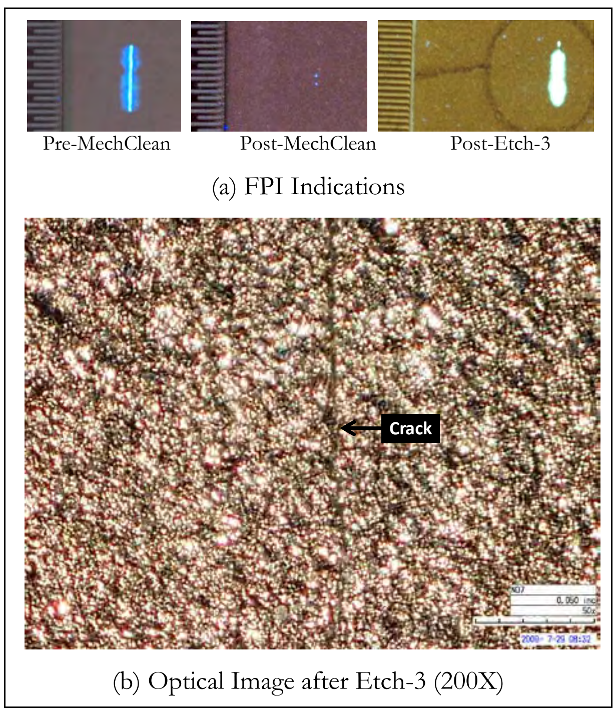


Figure A-60. Specimen 626-66 Crack Images

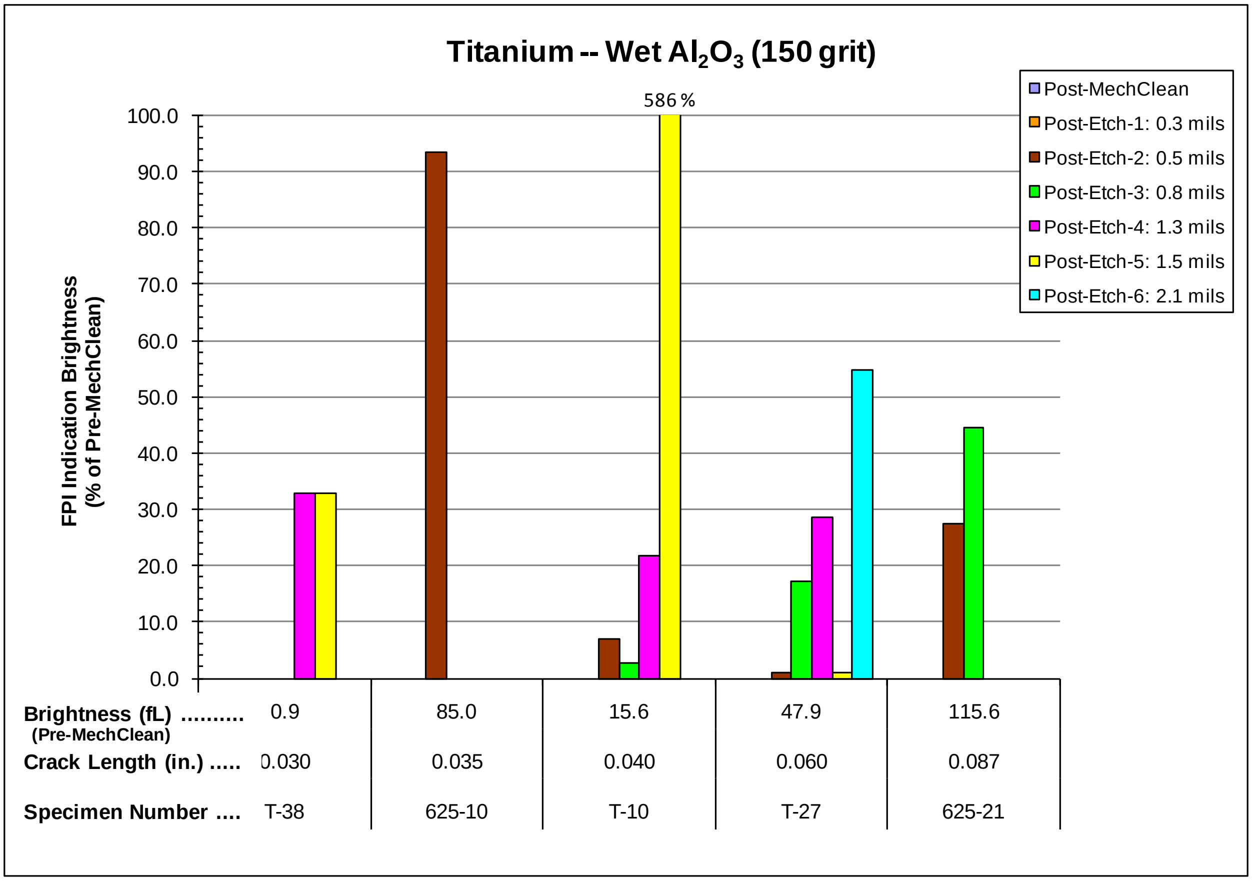


Figure A-61. FPI Data for Ti-6Al-4V Specimens Cleaned with Wet Al_2O_3 (150 grit)

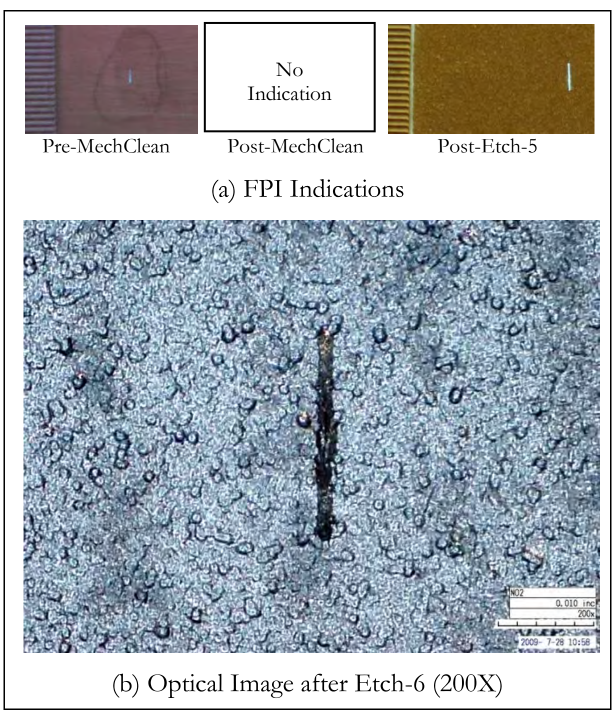


Figure A-62. Specimen T-38 Crack Images

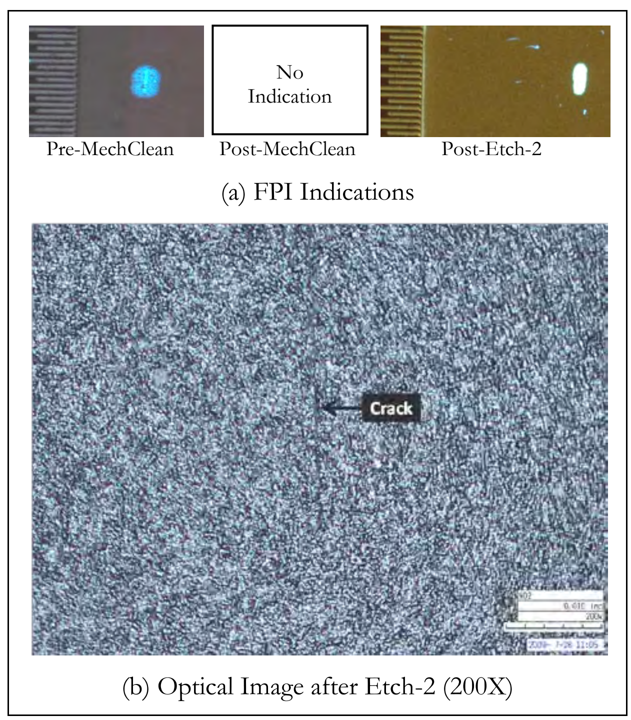
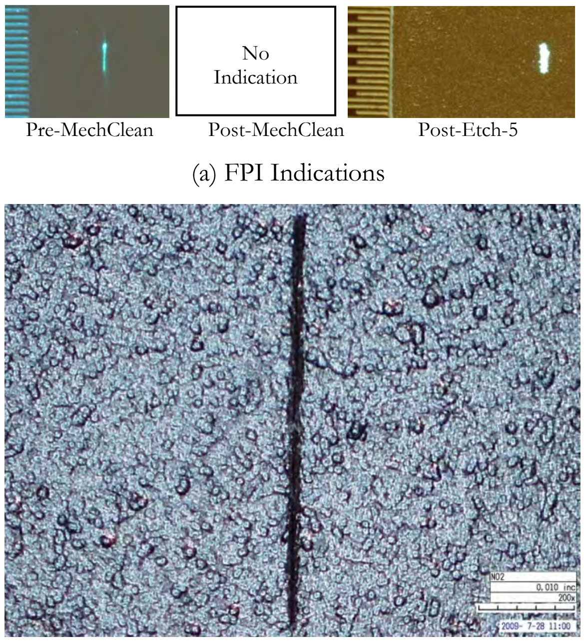


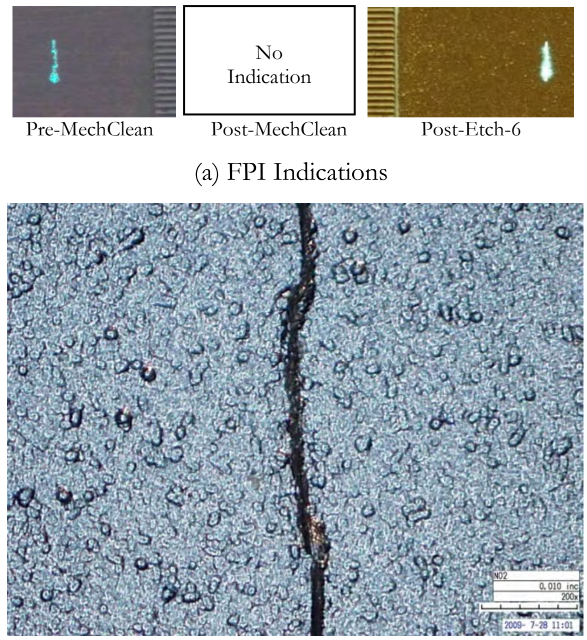
Figure A-63. Specimen 625-10 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-5 (200X)

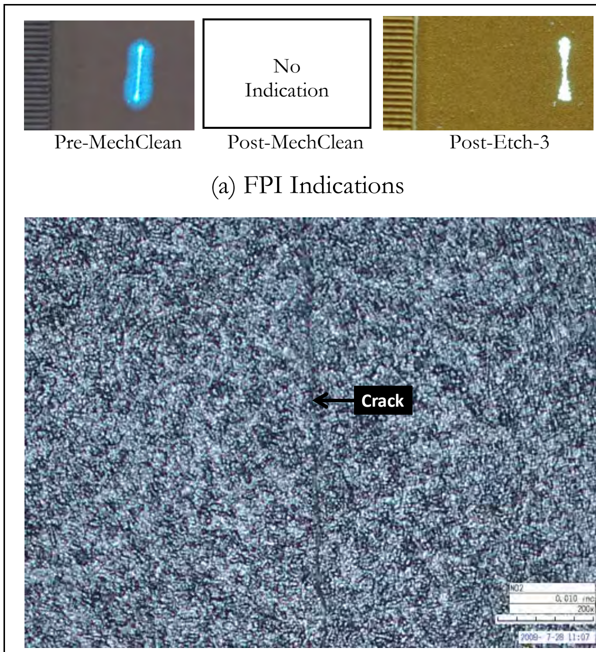
Figure A-64. Specimen T-10 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-6 (200X)

Figure A-65. Specimen T-27 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-3 (200X)

Figure A-66. Specimen 625-21 Crack Images

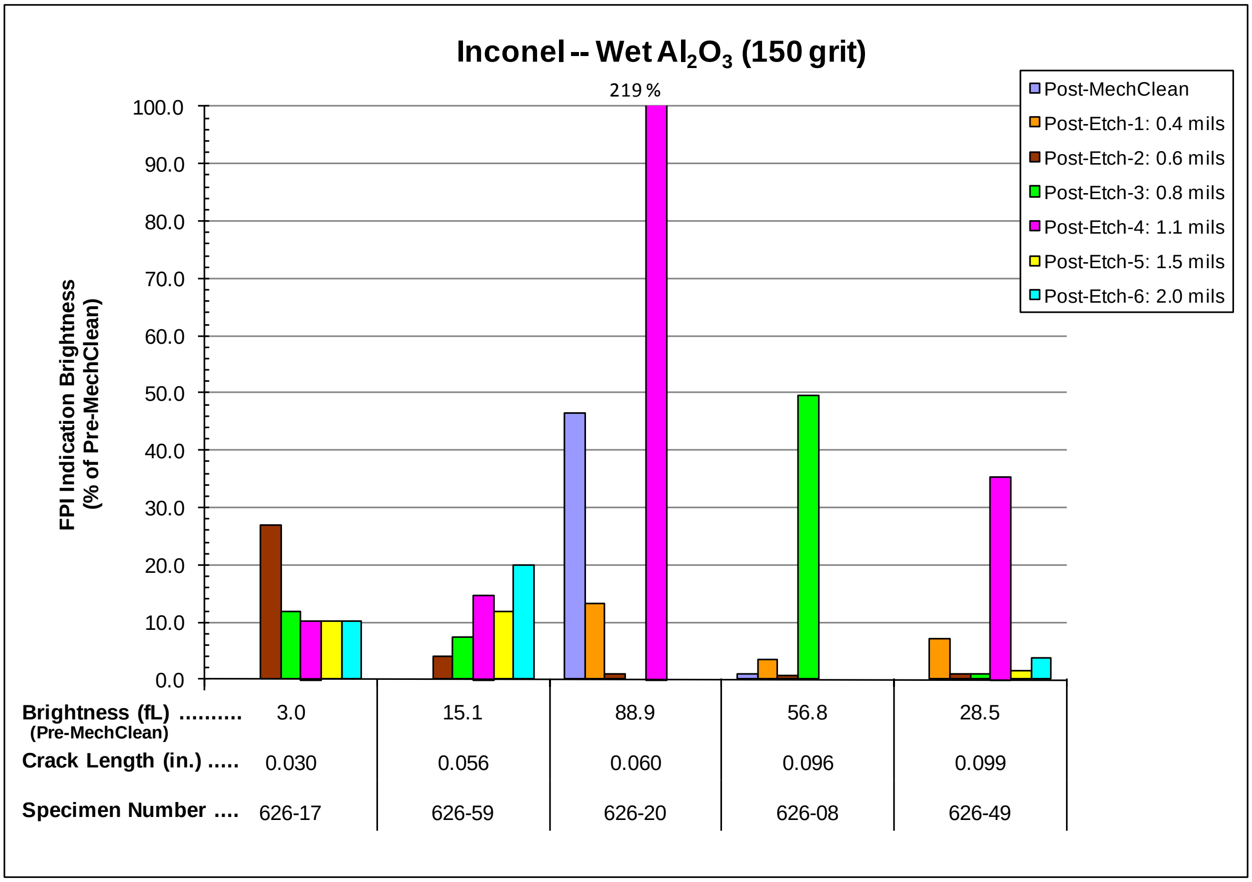


Figure A-67. FPI Data for Inconel 718 Specimens Cleaned with Wet Al_2O_3 (150 grit)

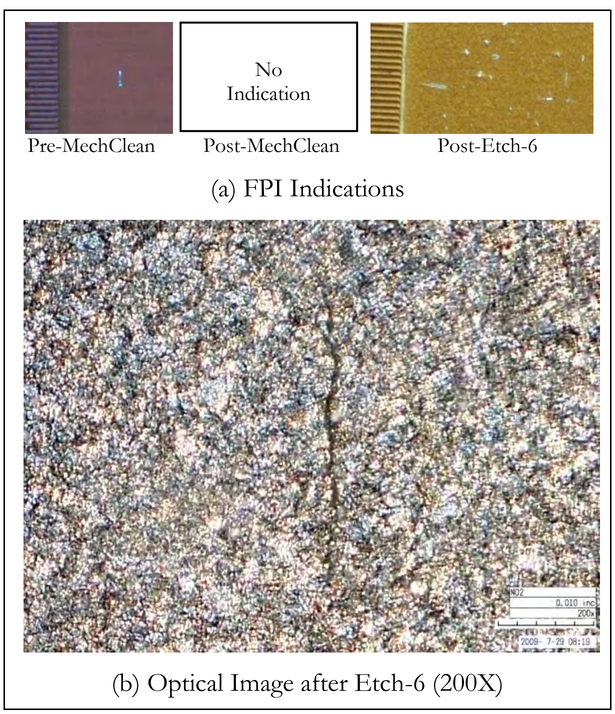


Figure A-68. Specimen 626-17 Crack Images

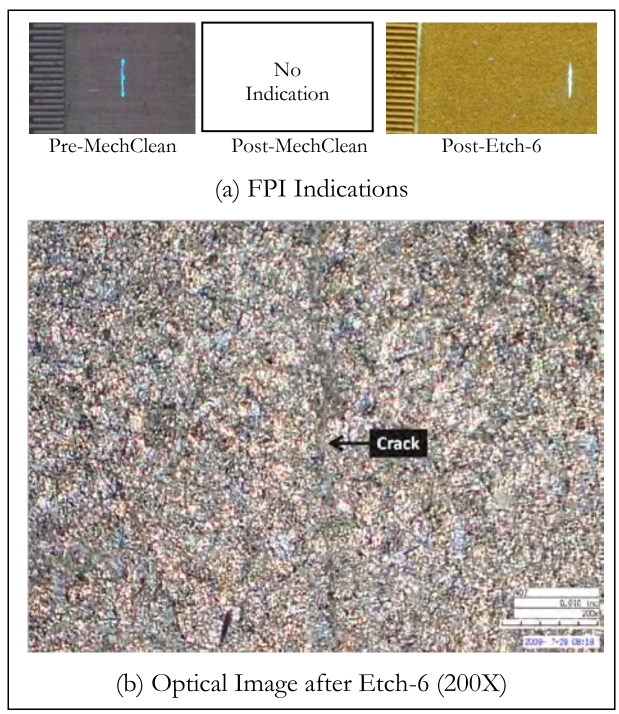


Figure A-69. Specimen 626-59 Crack Images

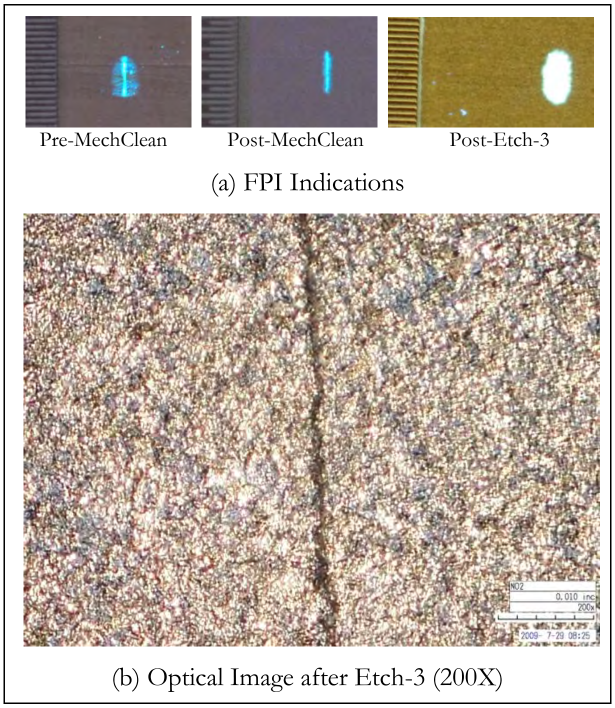


Figure A-70. Specimen 626-20 Crack Images

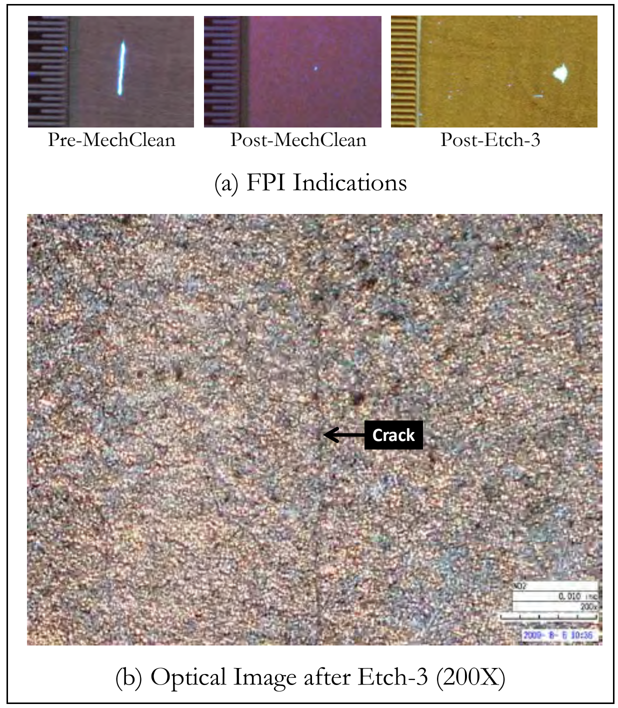


Figure A-71. Specimen 626-08 Crack Images

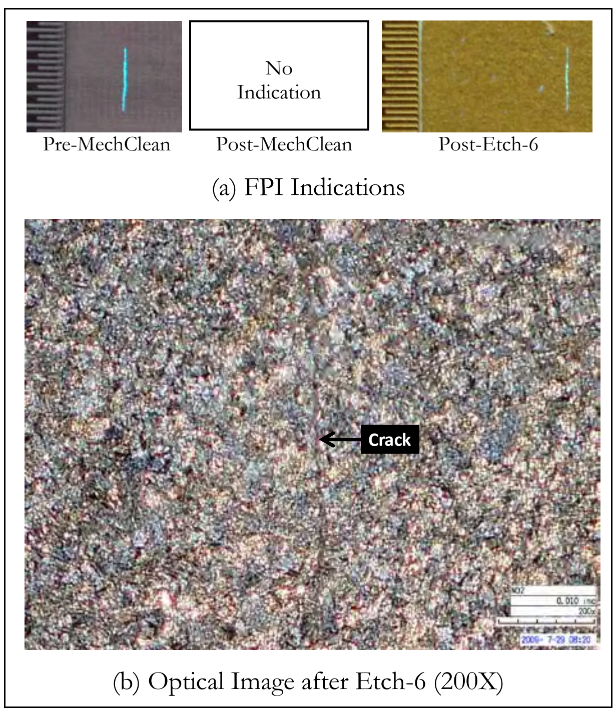


Figure A-72. Specimen 626-49 Crack Images

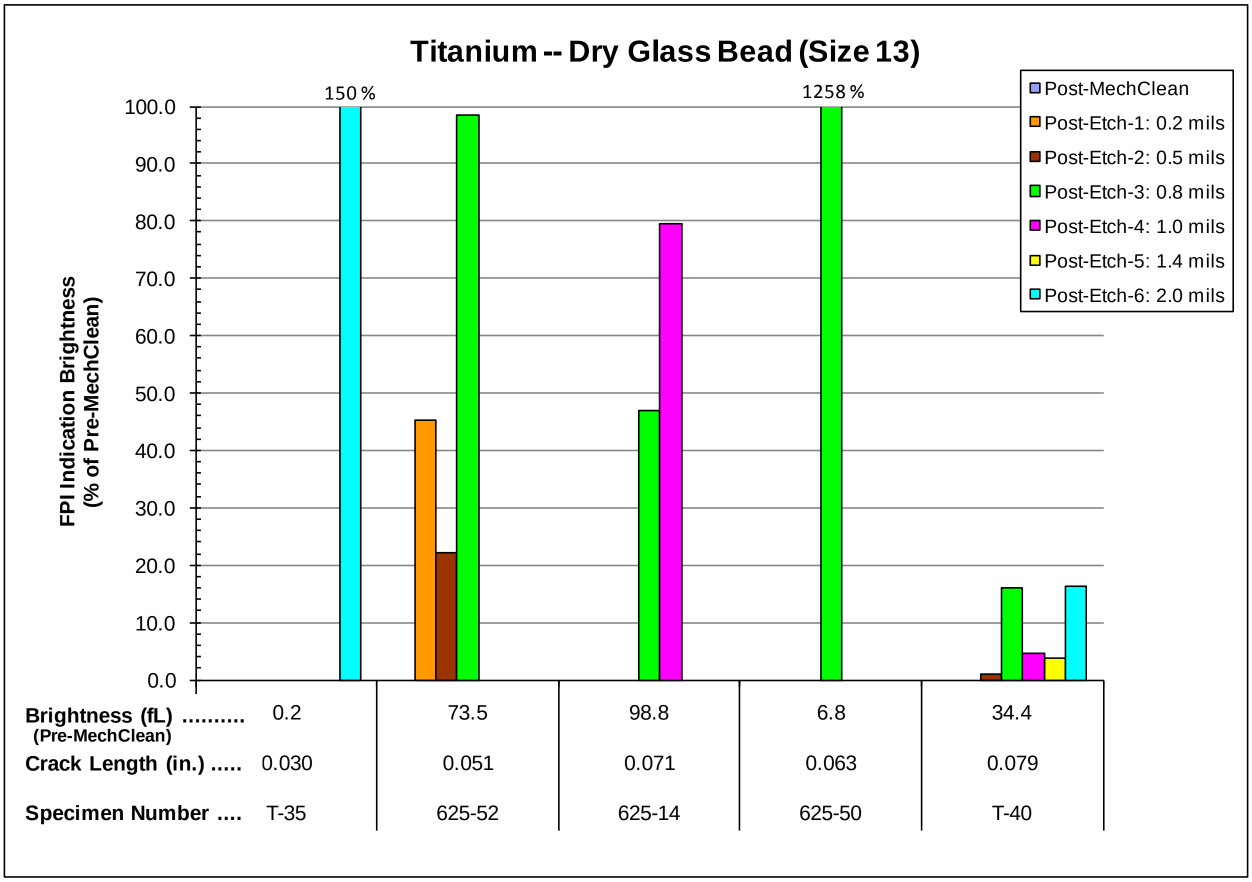


Figure A-73. FPI Data for Ti-6Al-4V Specimens Cleaned with Dry Glass Bead (Size 13)

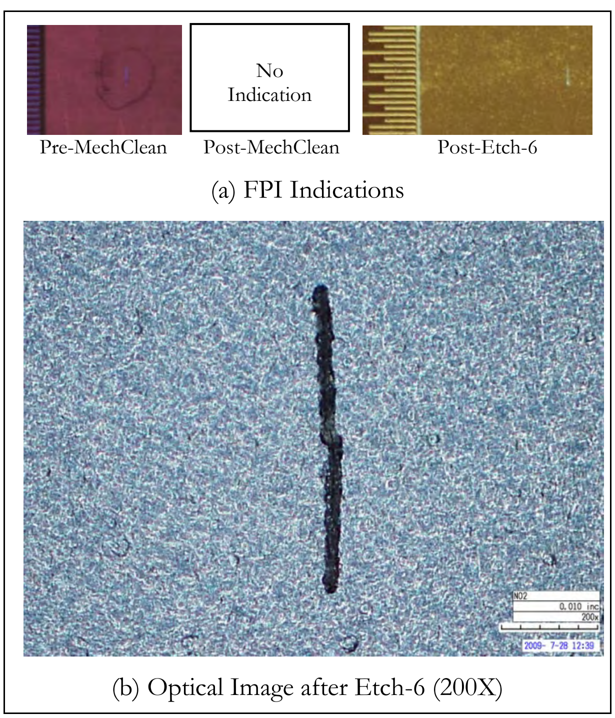


Figure A-74. Specimen T-35 Crack Images

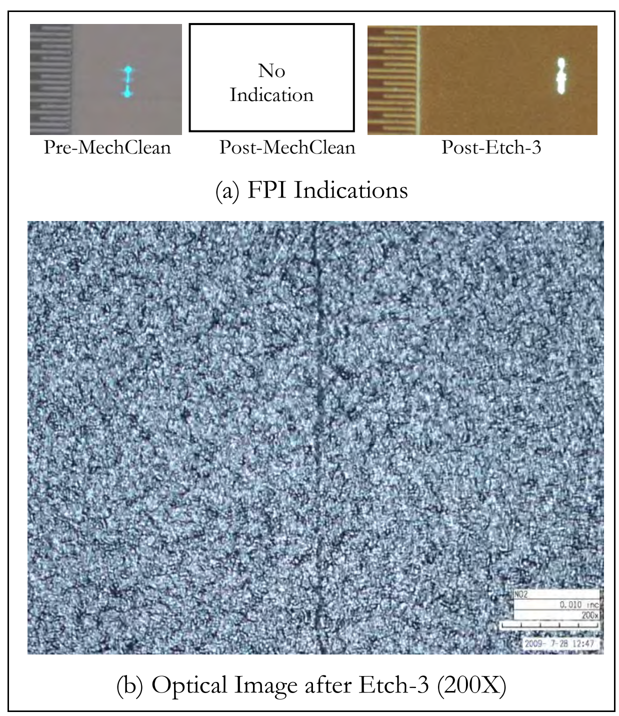
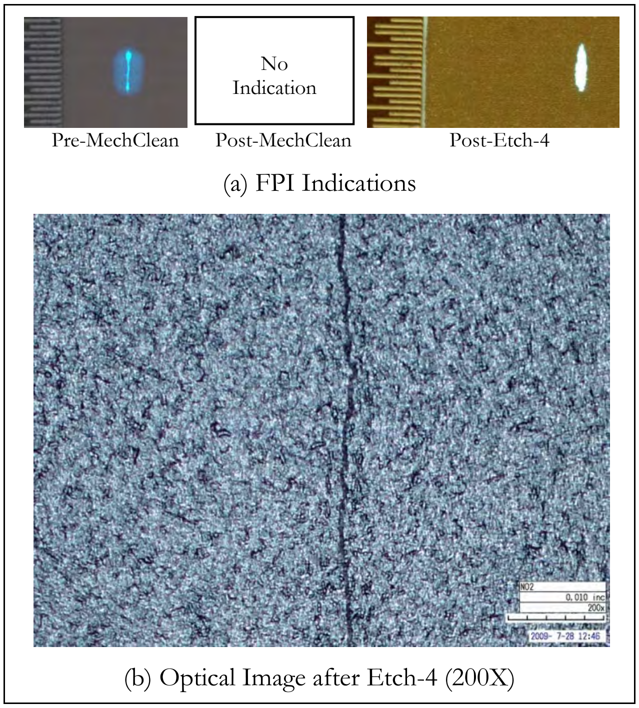


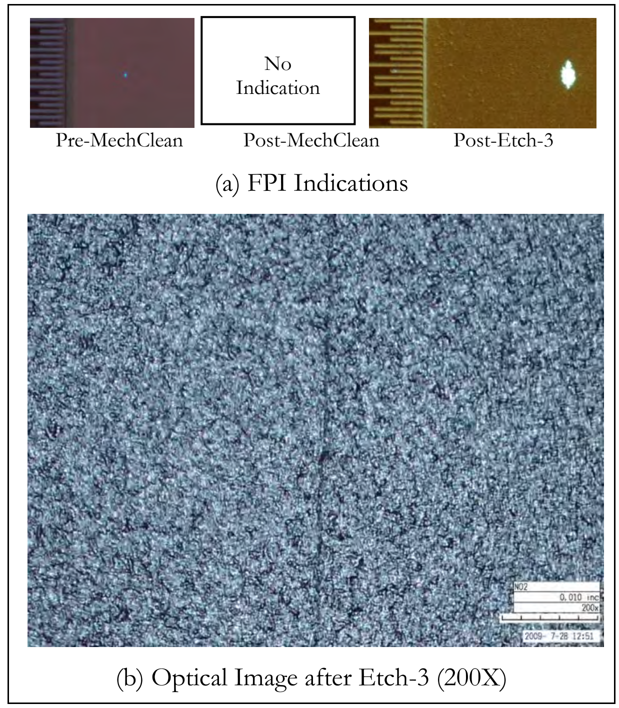
Figure A-75. Specimen 625-52 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-4 (200X)

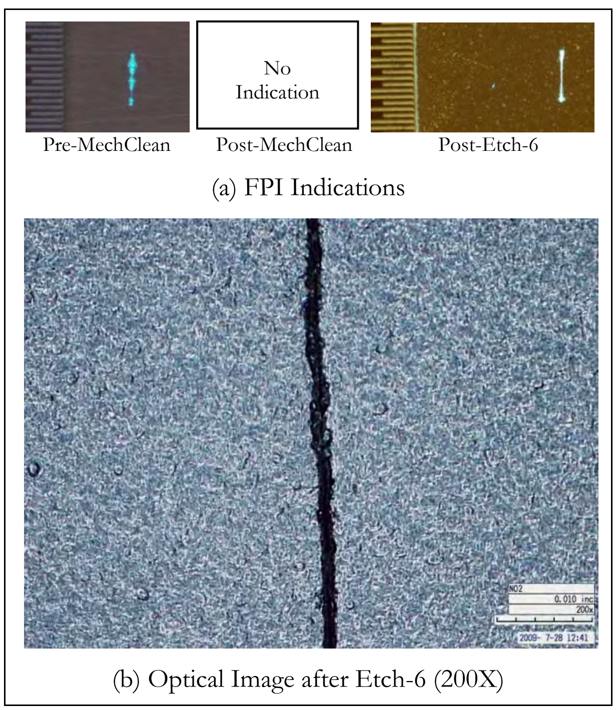
Figure A-76. Specimen 625-14 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-3 (200X)

Figure A-77. Specimen 625-50 Crack Images



(a) FPI Indications

(b) Optical Image after Etch-6 (200X)

Figure A-78. Specimen T-40 Crack Images

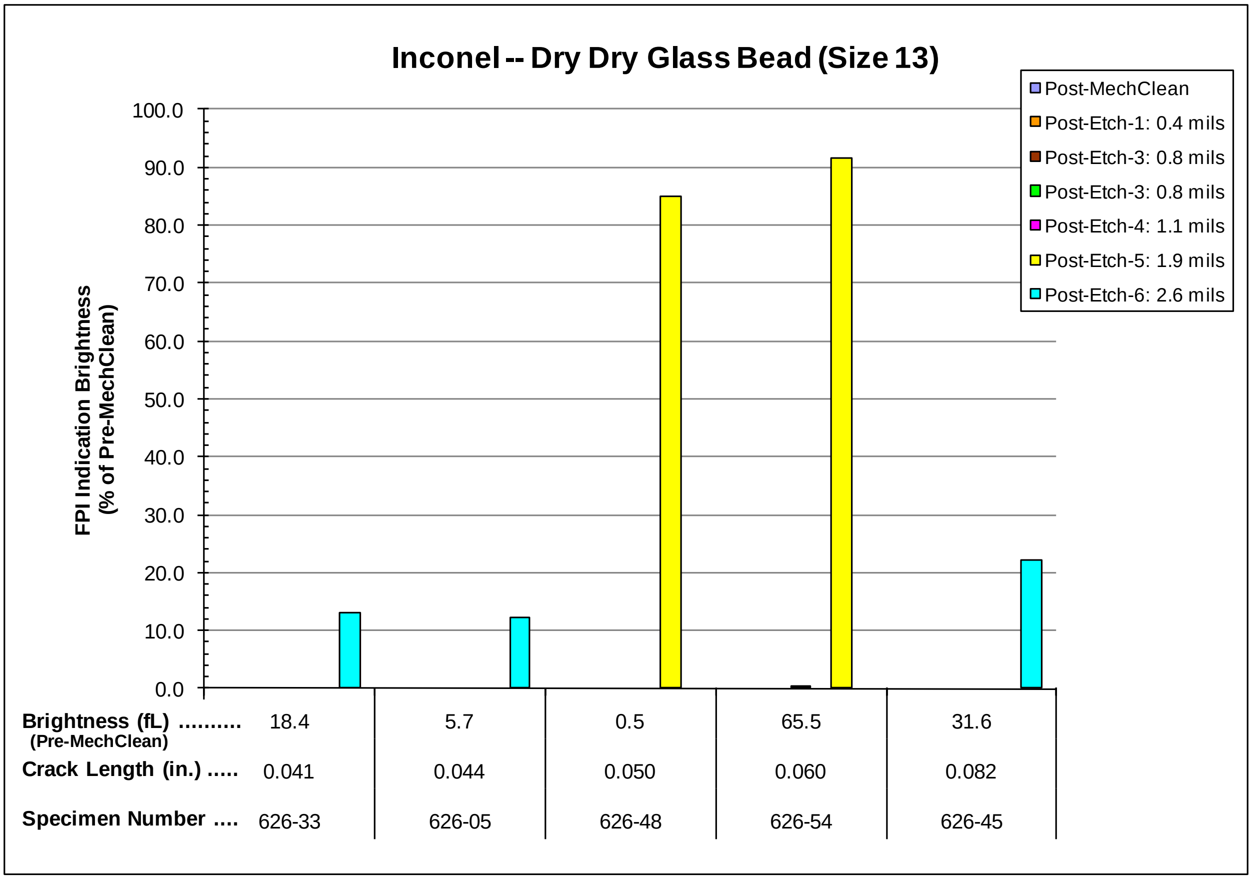
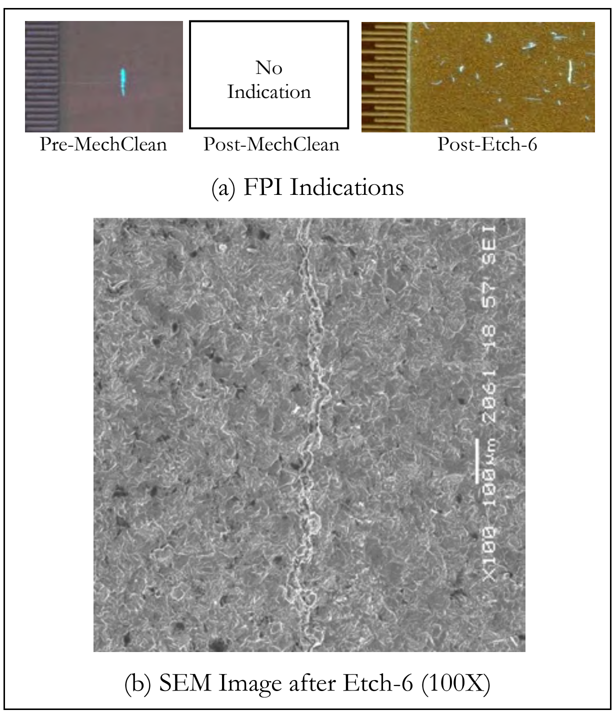


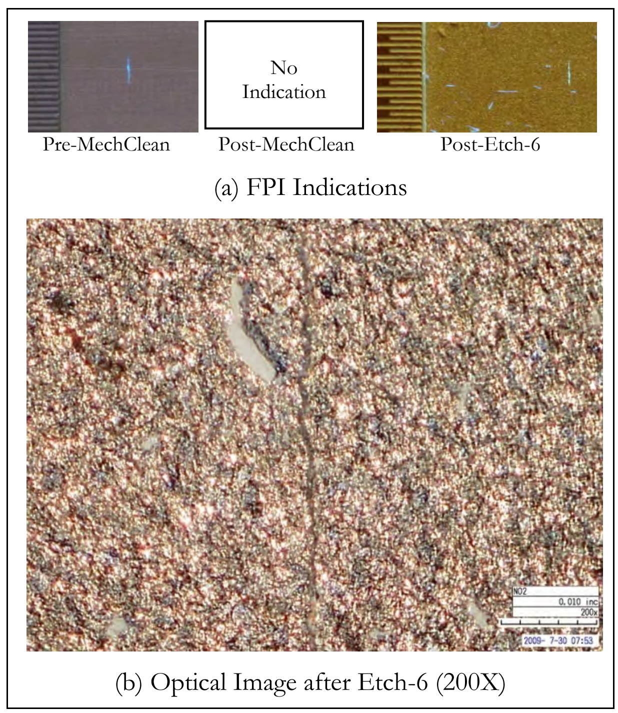
Figure A-79. FPI Data for Inconel 718 Specimens Cleaned with Dry Glass Bead (Size 13)



(a) FPI Indications

(b) SEM Image after Etch-6 (100X)

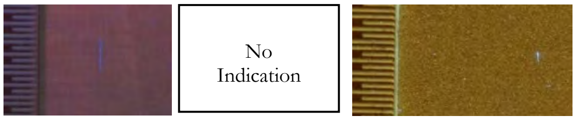
Figure A-80. Specimen 626-33 Crack Images



(a) FPI Indications

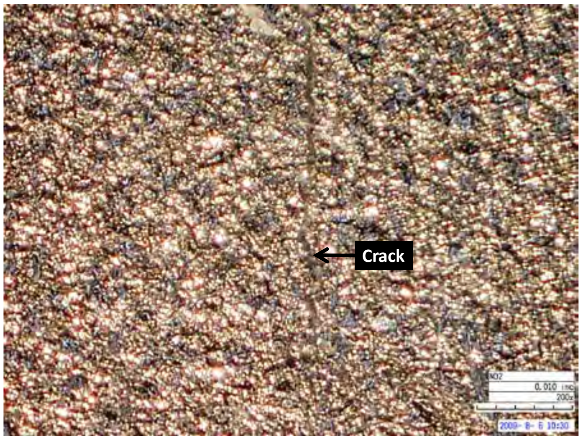
(b) Optical Image after Etch-6 (200X)

Figure A-81. Specimen 626-05 Crack Images



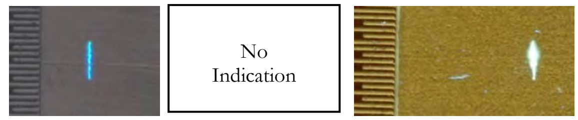
Pre-MechClean Post-MechClean Post-Etch-5

(a) FPI Indications



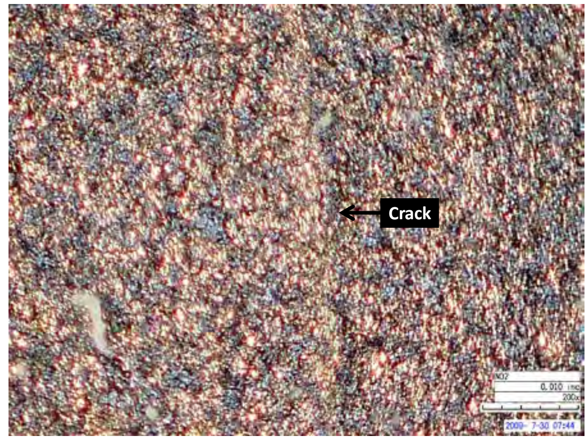
(b) Optical Image after Etch-5 (200X)

Figure A-82. Specimen 626-48 Crack Images



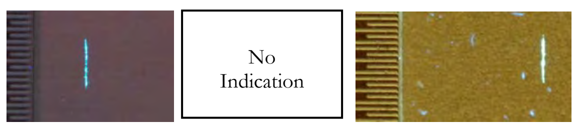
Pre-MechClean Post-MechClean Post-Etch-5

(a) FPI Indications



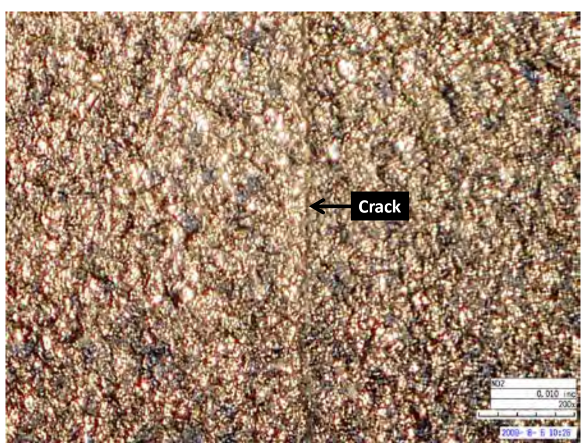
(b) Optical Image after Etch-5 (200X)

Figure A-83. Specimen 626-54 Crack Images



Pre-MechClean Post-MechClean Post-Etch-6

(a) FPI Indications



(b) Optical Image after Etch-6 (200X)

Figure A-84. Specimen 626-45 Crack Images

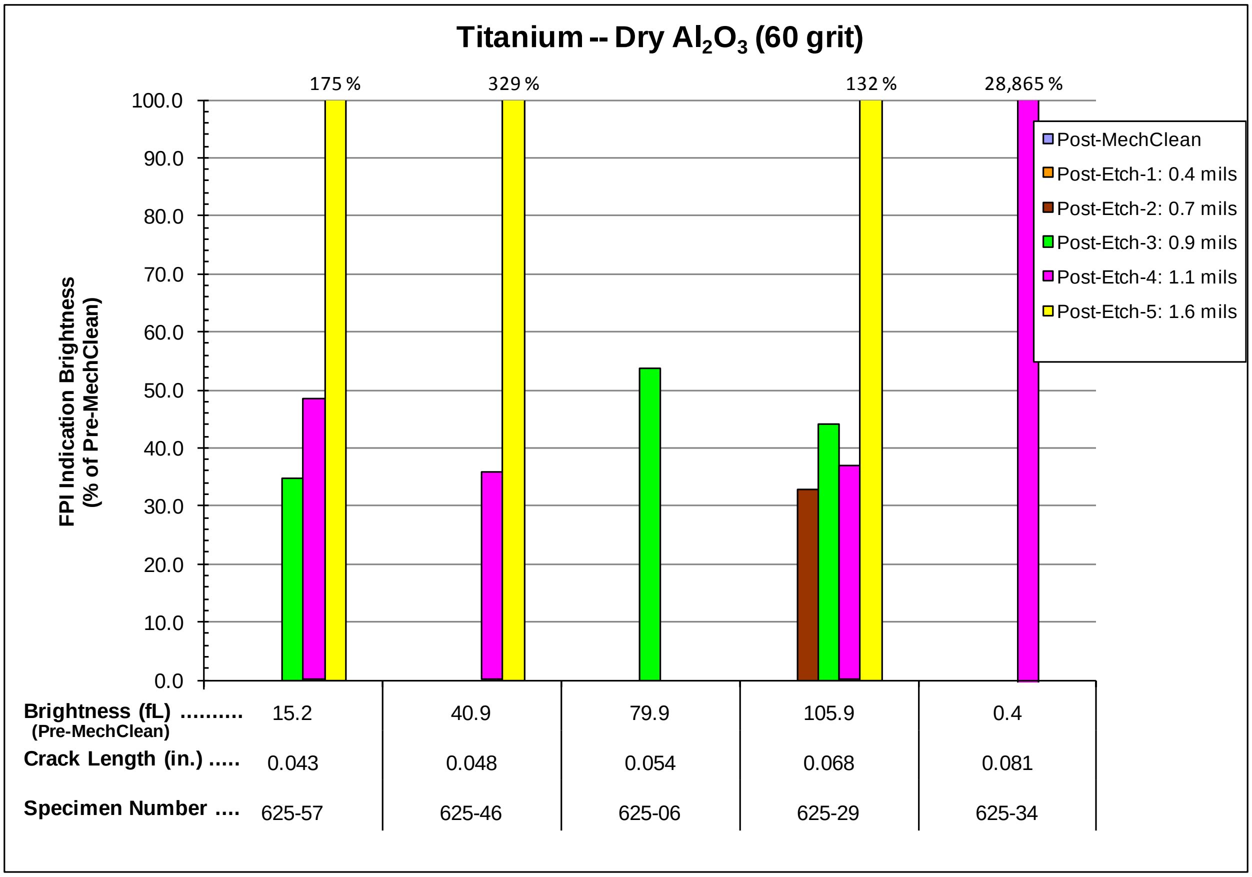
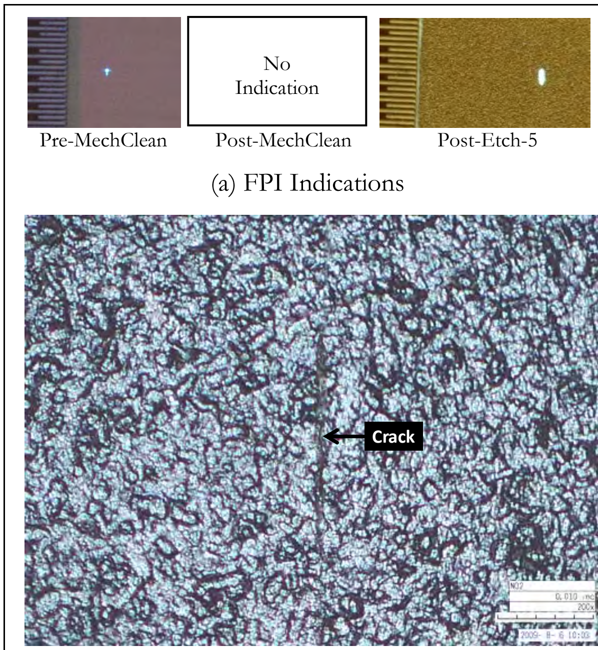


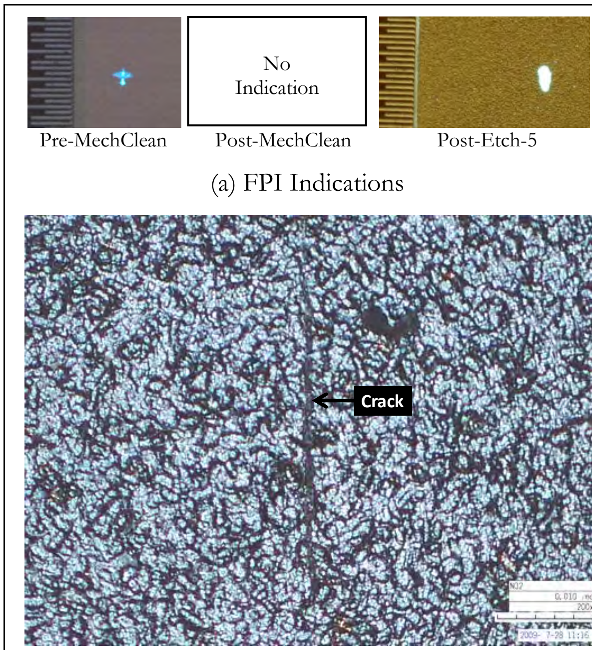
Figure A-85. FPI Data for Ti-6Al-4V Specimens Cleaned with Dry Al_2O_3 (60 grit)



(a) FPI Indications

(b) Optical Image after Etch-5 (200X)

Figure A-86. Specimen 625-57 Crack Images

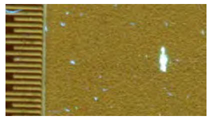


(a) FPI Indications

(b) Optical Image after Etch-5 (200X)

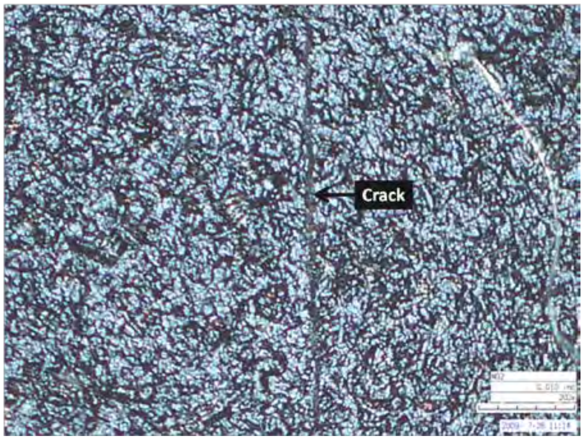
Figure A-87. Specimen 625-46 Crack Images

No Indication



Pre-MechClean Post-MechClean Post-Etch-3

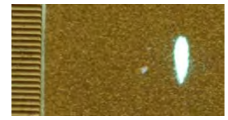
(a) FPI Indications



(b) Optical Image after Etch-3 (200X)

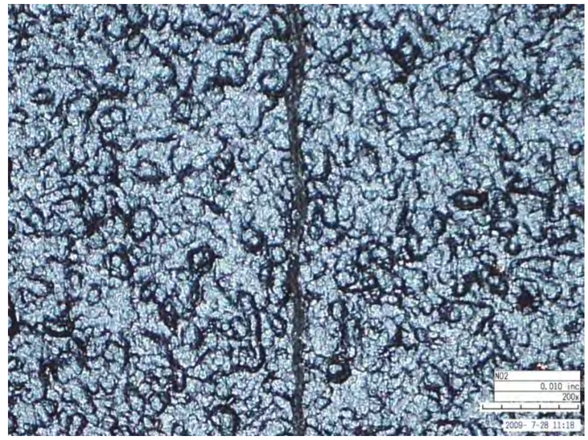
Figure A-88. Specimen 625-06 Crack Images

No Indication



Pre-MechClean Post-MechClean Post-Etch-5

(a) FPI Indications

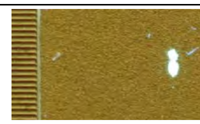


(b) Optical Image after Etch-5 (200X)

Figure A-89. Specimen 625-29 Crack Images

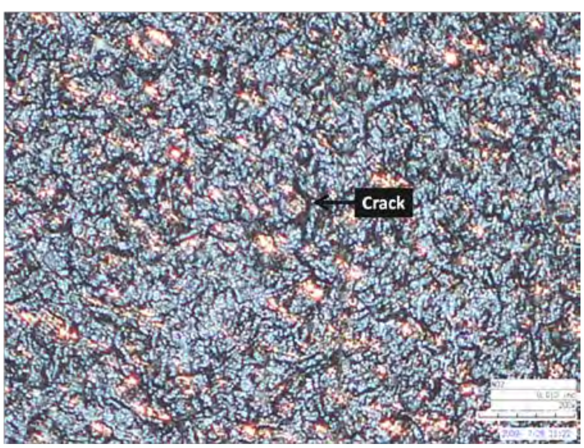
Picture Misplaced

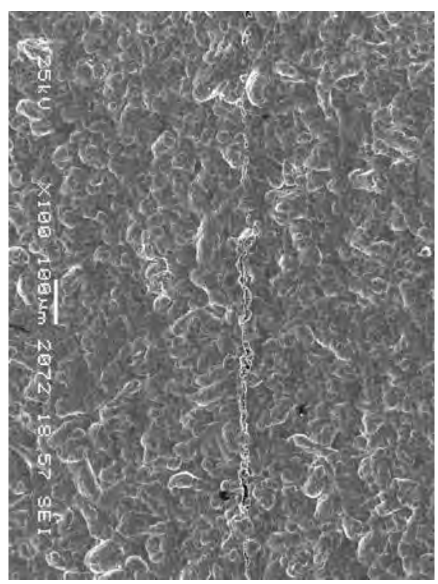
No Indication



Pre-MechClean Post-MechClean Post-Etch-4

(a) FPI Indications





(b) Optical Image after Etch-4 (200X)

(c) SEM Image after Etch-4 (100X)

Figure A-90. Specimen 625-34 Crack Images

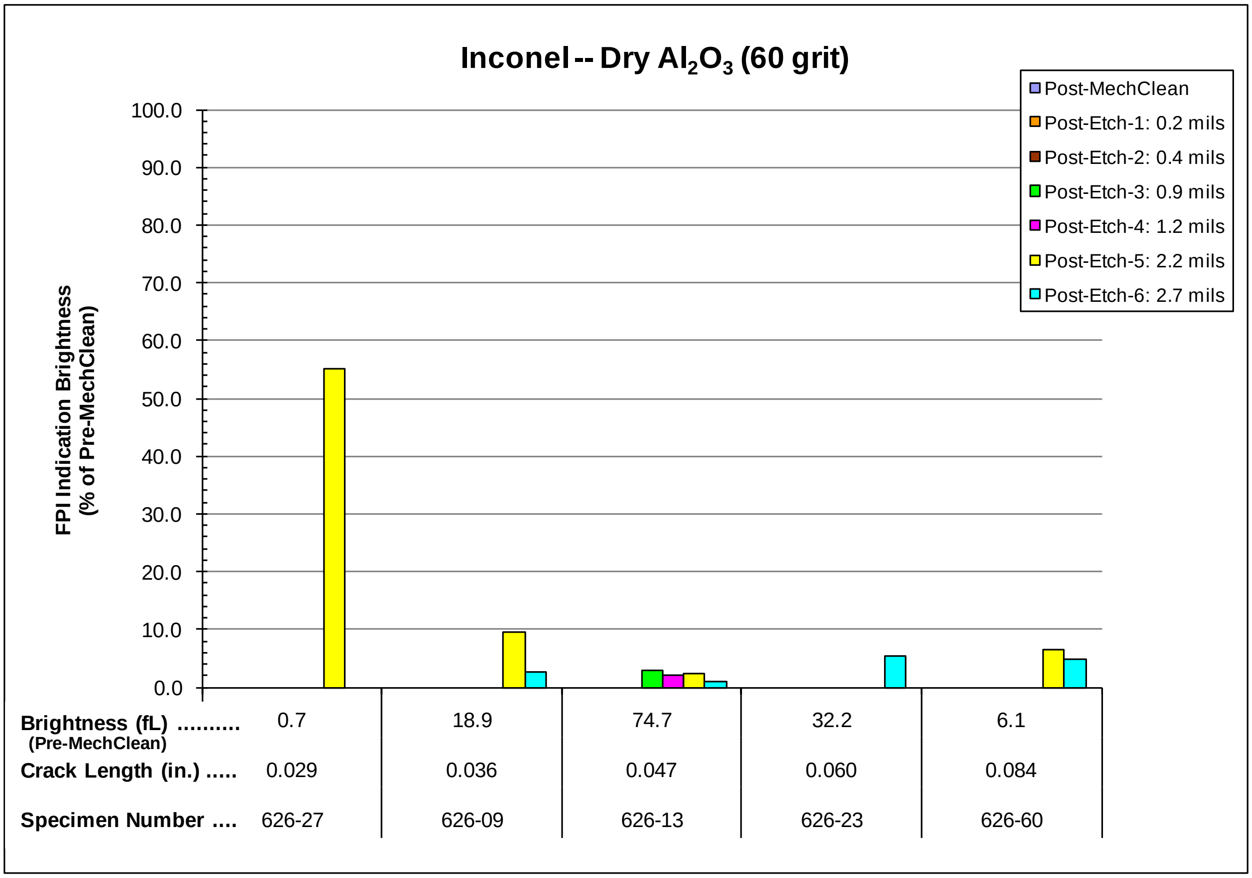
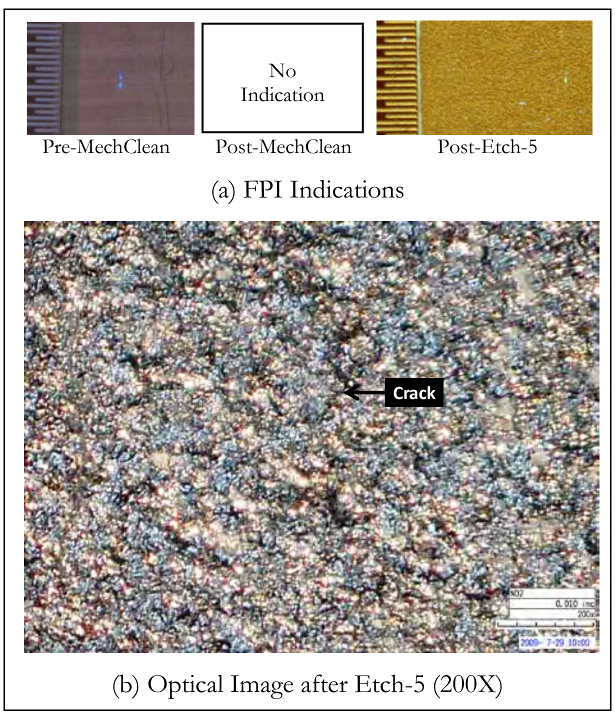


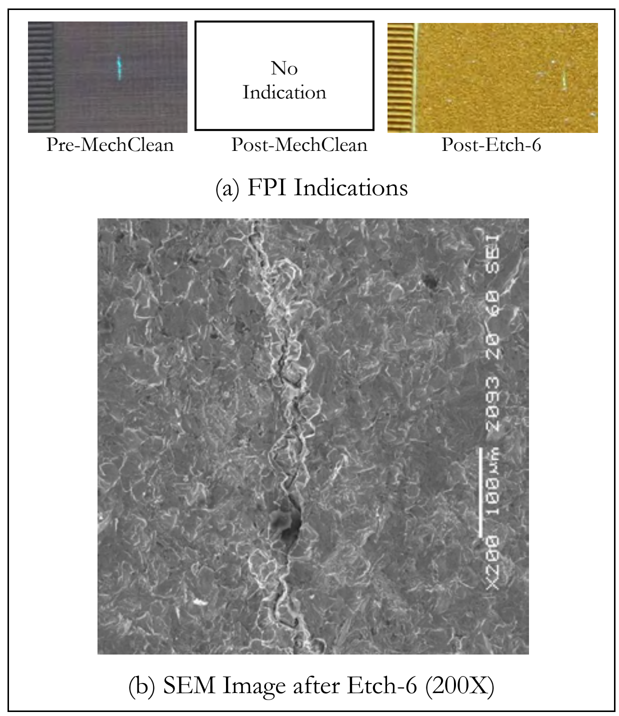
Figure A-91. FPI Data for Inconel 718 Specimens Cleaned with Dry Al_2O_3 (60 grit)



(a) FPI Indications

(b) Optical Image after Etch-5 (200X)

Figure A-92. Specimen 626-27 Crack Images



(a) FPI Indications

(b) SEM Image after Etch-6 (200X)

Figure A-93. Specimen 626-09 Crack Image

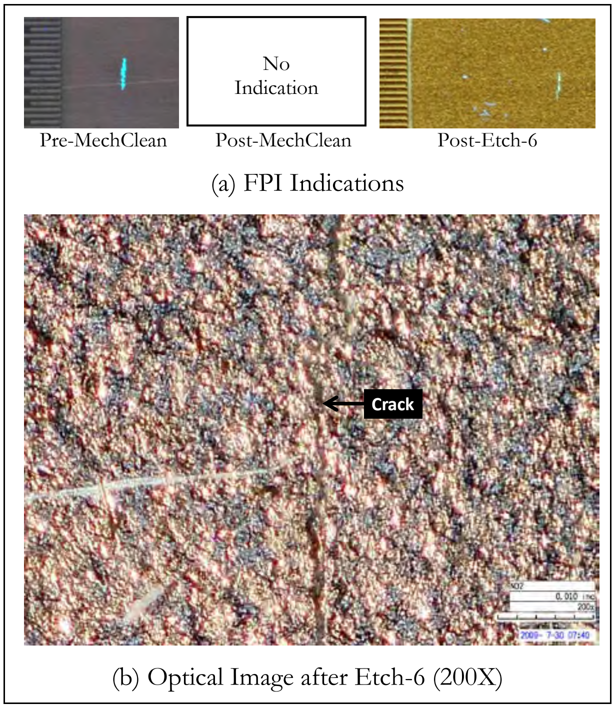


Figure A-94. Specimen 626-13 Crack Images

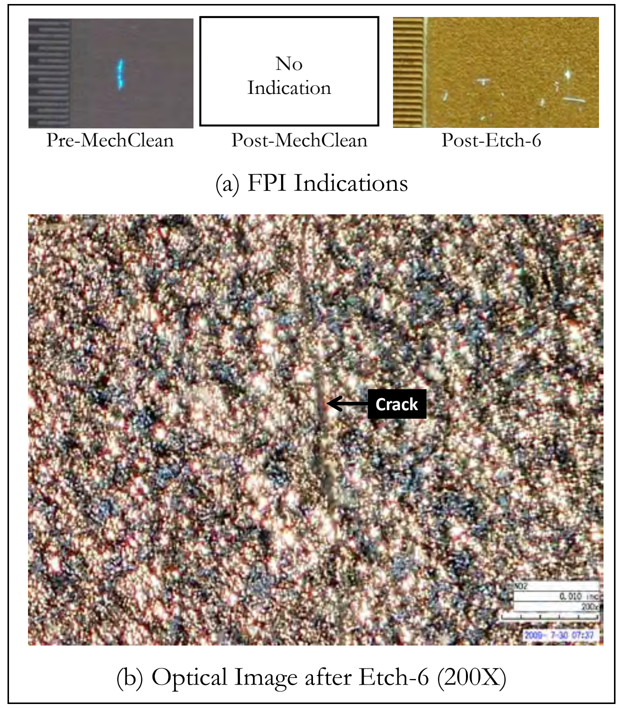


Figure A-95. Specimen 626-23 Crack Images

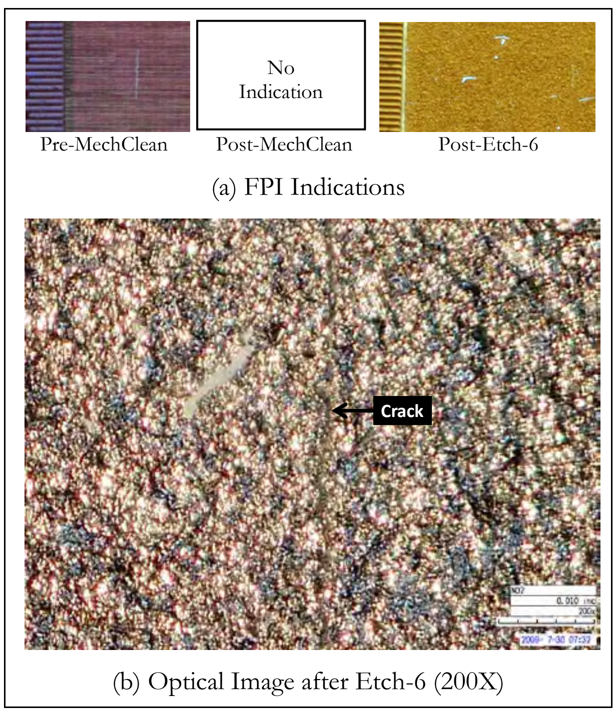


Figure A-96. Specimen 626-60 Crack Images