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Engineering Studies of Cleaning and Drying Processes in Preparation for Fluorescent Penetrant Inspection

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16. Abstract Fluorescent penetrant inspection (FPI) plays a crucial role in the overall inspection strategy for commercial jet engines. While over 90% of the metallic components that are used in jet engines will receive at least one fluorescent penetrant inspection as part of production qualification, FPI also plays a critical role in in-service maintenance and overhaul for the commercial aircraft industry. In-service inspection brings with it unique challenges brought about by service-induced conditions and materials used as part of the maintenance process. For FPI to provide effective crack detection, the defect must be clean, dry, and open to the surface. There are several methods approved for part cleaning and drying in preparation for FPI. The purpose of this program was to compare approved drying methods and to evaluate the effectiveness of a variety of cleaning methods on a range of typical contaminants. Quantitative methods to assess the changes in FPI indication response were developed and used to characterize low-cycle fatigue cracks grown in titanium and nickel samples. The samples were characterized in a laboratory environment by means of optical micrographs, measurements of crack brightness, and ultraviolet-A photographs of the FPI indication. Three separate 1-week studies were held at the Delta Air Lines facility, using typical cleaning methods and realistic inspection setups. The first study provided baseline data for the samples and compared two drying techniques: flash dry and oven dry. The second study compared cleaning methods used to remove service coatings (antigallant, room temperature vulcanizing, and high-temperature sealant) and oil contamination. Between the second and final study, the samples were exposed to various conditions to generate oxidation and scale, soot, or coke and varnish conditions. The third study evaluated the removal of these baked-on contaminants. During the course of the two cleaning studies, six mechanical blasting techniques and thirteen chemical cleaning processes were evaluated. In addition to the cleaning and drying studies, local etching practices were assessed. Results and recommendations, which include changes to industrial practice, are provided.					
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LIST OF ACRONYMS

AANC	Airworthiness Assurance NDI Validation Center
Al	Aluminum
CASR	Center for Aviation Systems Reliability
Cu	Copper
EDM	Electrodischarge machined
EDS	Energy dispersive spectroscopy
ETC	Engine Titanium Consortium
FAA	Federal Aviation Administration
FOD	Foreign object damage
FPI	Fluorescent penetrant inspection
GEAE	General Electric Aircraft Engines
HAZ	Heat-affected zone
HTA	Hierarchical Task Analysis
ISU	Iowa State University
LCF	Low-cycle fatigue
Mg	Magnesium
NDI	Nondestructive inspection
NDT	Nondestructive testing
Ni	Nickel
NTSB	National Transportation Safety Board
OEM	Original equipment manufacturer
P&W	Pratt & Whitney
PMB	Plastic media blast
PoD	Probability of detection
QPL	Qualified products list
Ra	Average roughness
RR	Rolls-Royce plc
RTV	Room temperature vulcanizing
SAE	Society of Automotive Engineers
SEM	Scanning Electronic Microscope
TAM	Testing and monitoring
Ti	Titanium
USAF	United States Air Force
UT	Ultrasonic
UV	Ultraviolet
UVA	Ultraviolet-A
WPAFB	Wright-Patterson Air Force Base

EXECUTIVE SUMMARY

Fluorescent penetrant inspection (FPI) plays a crucial role in the overall inspection strategy for commercial jet engines. While over 90% of the metallic components that are used in jet engines will receive at least one fluorescent penetrant inspection as part of production qualification, FPI also plays a critical role in in-service maintenance and overhaul for the commercial aircraft industry. In-service inspection brings with it unique challenges brought about by service-induced conditions and materials used as part of the maintenance process. For FPI to provide effective crack detection, the defect must be clean, dry, and open to the surface. There are several methods approved for part cleaning and drying in preparation for FPI. The purpose of this program was to compare approved drying methods and to evaluate the effectiveness of a variety of cleaning methods on a range of typical contaminants. Quantitative methods to assess the changes in FPI indication response were developed and used to characterize low-cycle fatigue cracks grown in titanium and nickel samples. The samples were characterized in a laboratory environment by means of optical micrographs, measurements of crack brightness, and ultraviolet-A (UVA) photographs of the FPI indication. Three separate 1-week studies were then held at an airline overhaul facility, using typical cleaning methods and realistic inspection setups. The first study provided baseline data for the samples and compared two drying techniques: flash dry and oven dry. The second study compared cleaning methods used for removal of service coatings (antigallant, room temperature vulcanizing, and high-temperature sealant) and oil contamination. Between the second and final study, the samples were exposed to various conditions to generate oxidation and scale, soot, or coke and varnish conditions. The third study evaluated the removal of these baked-on contaminants. During the course of the two cleaning studies, six mechanical blasting techniques and thirteen chemical cleaning processes were evaluated. In addition to the cleaning and drying studies, local etching practices were assessed.

All observations are based on a set of assumptions, a number of factors, and on changes in brightness values from relatively small cracks most of which were less than 0.100" long.

Statistical analysis of brightness and UVA lengths did not reveal significant differences between the two drying methods at the temperatures used in this study, i.e., minimum flash-drying temperature at 150°F (65°C) and maximum oven-drying temperature at 225°F (107°C).

Adequate cleaning methods exist for nickel components but additional study is needed for titanium alloy.

Wet glass bead, plastic media at 80 psi, and larger grit (240 and 320) Al₂O₃ led to surface damage and loss of FPI indications.

1. INTRODUCTION.

1.1 PURPOSE.

Fluorescent penetrant inspection, a widely used nondestructive inspection (NDI) method for surface crack detection, is commonly employed for both production and in-service inspection of engine and airframe components. It is often the only nondestructive testing (NDT) method used for ensuring flight safety of critical rotating components. It is therefore recognized by the Engine Titanium Consortium (ETC), other original equipment manufacturers (OEMs), the airlines, and the Federal Aviation Administration (FAA) that significant efforts should occur to improve the overall reliability of the penetrant process.

1.2 BACKGROUND.

Fluorescent penetrant inspection (FPI) is used for a range of aviation applications, with many production and overhaul facilities having multiple inspection lines to accommodate the various requirements. FPI is used to detect surface-breaking defects in a wide range of parts, including aircraft, landing gear, and engine components. FPI involves multiple steps that must be controlled and monitored to ensure acceptable performance. FPI requires a clean, dry part [1] be made available for the application of penetrant. The penetrant solution is a liquid capable of entering discontinuities or defects open to the surface and, for most aerospace applications, will contain fluorescent dyes that enhance the detectability. Several different penetrant types are available. Typical aviation applications will use Sensitivity Level 3 penetrants on airframe hardware and components and Sensitivity Level 4 penetrants for rotating engine hardware and components, as recommended in AMS 2647B [1], "Fluorescent Penetrant Inspection Aircraft and Engine Component Maintenance," a commonly used industry specification. After application of the penetrant and an appropriate dwell time, excess penetrant is removed from the surface and the part is dried for developer application. After appropriate developer dwell time, the part is inspected under ultraviolet light, commonly referred to as black light, at an acceptable intensity. Recommended parameters for each of these steps are provided in AMS 2647B [1] as well as other industry standards and OEM documents. It is recognized that proper surface preparation of parts is critical to the successful detection of defects. Part preparation is performed prior to penetrant application to ensure that the discontinuity is clean, dry, and open to the surface and that minimal fluorescent background occurs on the part surface during inspection.

The successful use of FPI plays an important role in the overall safety of commercial aviation. At least 90% of engine parts will undergo FPI as part of the inspection qualification process during manufacture. A typical U.S. air carrier will have over 30,000 parts in its inventory that require FPI at some point in their lifetime. In reviewing approximately 1500 airworthiness directives issued between 1996 and 2000, nearly 200 called for fluorescent penetrant inspection. Failure of the FPI process has contributed to the occurrence of catastrophic events [2 and 3] and led to several National Transportation Safety Board (NTSB) recommendations related to FPI, including the following [3]:

- Establish and require adherence to a uniform set of standards for materials and procedures used in the cleaning, drying, processing, and handling of parts in the fluorescent penetrant inspection process. In establishing those standards, the FAA should do the following:
 - Review the efficacy of drying procedures for aqueously cleaned rotating engine parts being prepared for fluorescent penetrant inspections (A-98-11 in reference 3).
 - Determine whether flash drying alone is a sufficiently reliable method (A-98-12 in reference 3).
 - Address the need to ensure the fullest possible coverage of dry developer powder, particularly along hole walls (A-98-13 in reference 3).
 - Address the need for a formal system to track and control development times (A-98-14 in reference 3).
 - Address the need for fixtures that minimize manual handling of the part without visually masking large surfaces of the part (A-98-15 in reference 3).

The FAA [4 and 5] has also expressed concern over the current processes used in the maintenance and overhaul of critical rotating components. One of the most critical steps in the prepenetrant process is the prepenetrant surface preparation. Numerous studies and work experience have demonstrated that the condition of the component surface at the time of inspection has a significant impact on the final penetrant inspection results [6, 7, and 8]. Preservation fluids, rust inhibitors, cutting or lubricating oils, carbon deposits, water, chemical residues, oxides, and surface conditions such as shot peening or abusive machining can impair the effectiveness of the process. Proper surface preparation aids in the ability of the penetrant to wet the component surface, enter into discontinuities and, later, bleed out for detection. The selected surface preparation method must be capable of removing the potential sources of inspection interference without damage to the component. Undesirable surface conditions that could interfere with the inspection may be categorized into two broad groups:

- Surface contaminants or conditions within discontinuities that impair proper penetrant wetting and capillary action or suppress dye performance.
- Surface contaminants or conditions that actually cover up or block the penetrant from entering discontinuities.

The Clean Air Act, established in December 1995, has greatly affected the manner in which industry handles prepenetrant cleaning. Until that time, 1,1,1-trichloroethane was the most common and effective vapor-degreasing solvent for nontitanium-based alloys with other aqueous and alkaline chemical cleaners being used for titanium-based alloys. Although the use of 1,1,1-trichloroethane was not banned, existing supplies are being exhausted and stricter air pollution regulations are forcing an end to its use. With the advent of new cleaning methods in response to these changes, the issue of effective cleanliness has arisen. Aqueous cleaners have

met with limited success as a replacement for 1,1,1-trichloroethane and in turn have introduced new issues, namely rinsing and drying. A clean, dry part [1] is necessary prior to applying a penetrant to the component under evaluation. Without proper drying, cleaning fluids may remain in the crack either blocking or diluting the penetrant solution necessary for detectability.

There have been limited programs funded by the U.S. Air Force Industrial Modernization Incentives Program to provide necessary data on the effect of removal and replacement of chlorinated solvents used in vapor degreasers [9]. Until the efforts of the program reported in this document, an industrywide cooperative effort had not been undertaken to establish the impact that the numerous cleaning and drying processing parameters have on the inspectability of titanium and nickel alloys typical of critical rotating hardware. The use of local etching practices to remove smeared metal resulting from local blending of foreign object damage (FOD) or other surface anomalies has also not received industrywide attention. Some variation between titanium and nickel alloys response to chemical and mechanical processes is expected due to the differences in reactivity and ductility. For that reason, samples were fabricated using Ti-6Al-4V and IN-718.

The work reported in this document was completed by the ETC members in partnership with Rolls-Royce (RR) plc and Delta Air Lines. The ETC members, which include three U.S. engine manufacturers, realized that the results of the program would benefit from broader industry participation. RR has worked with the ETC throughout the program's duration and has made valuable contributions to the work. For the data to have relevance and reflect the effect of typical cleaning practices, it was necessary to perform the studies in an airline or overhaul shop environment. Delta Air Lines hosted the ETC team on three separate 1-week visits, making available access to a variety of cleaning methods, oven- and flash-drying facilities, and a full FPI line and inspection booth. In some cases, the ability to vary the cleaning parameters to assess the impact on crack detectability was made available even though the processes were not part of standard practice at Delta. Not all cleaning methods included in the study were available at Delta's Atlanta facility. In those cases, Northwest Airlines-Atlanta provided access to their cleaning lines enabling the team to complete the desired experimental matrix.

To ensure proper component processing, it is essential to follow strict cleaning, drying, and inspecting practices. Studies to establish the effect of cleaning and drying processes on the detectability of cracks in nickel and titanium alloys and to provide guidance for local etching procedures were completed in this program. The results of the engineering studies will be used to update appropriate guidance documents and specifications and to provide recommendations for further improvements and additional study.

1.3 PROGRAM OBJECTIVES.

- To determine the effect of chemical cleaning, mechanical cleaning, and drying processes on the detectability of low-cycle fatigue (LCF) cracks in titanium and nickel alloys that would be typical in field-run engine hardware.
- To establish the effect of local etching on detectability and provide guidance on the best practices for removal of local surface damage from FOD and other surface anomalies.

- To provide recommendations for improved processes and identify areas of further study.

1.4 RELATED ACTIVITIES AND DOCUMENTS.

The ETC was established in 1993 and includes Iowa State University (ISU), General Electric Aircraft Engines (GEAE), Honeywell Engine Systems and Services, and Pratt & Whitney (P&W) in a partnership to perform research that contributes to improvements in flight safety. The Phase I program, which was completed in 1998, led to improvements in production inspection of titanium billet [10], improved physics models for ultrasonics [11 and 12], and a feasibility study for phased array for ultrasonic inspection of billets [13]. In-service inspection efforts led to a commercially available portable scanner [14] and eddy-current probes [15], as well as improved probe designs [16] and eddy-current probe design tools [17]. Considerable progress was also made in the development of a new approach [18] to quantifying inspection performance, as reported in an FAA report “A Methodology for the Assessment of the Capability of Inspection Systems for Detection of Subsurface Flaws in Engine Components”[19]. The ETC program continued with a Phase II effort in June 1999, including the task that is the subject of this report. Efforts are also under way in production inspection of titanium billets, nickel billets, and titanium forgings and in-service inspection of bolt holes using high-speed eddy-current scanners.

In addition to the comprehensive inspection development activities of the ETC, the FAA has also funded inspection development activities at the Center for Aviation Systems Reliability (CASR) at ISU. Among the CASR tasks was a comprehensive review of the factors that affect the sensitivity of penetrant. The review was published as an FAA report “Study of the Factors Affecting the Sensitivity of Liquid Penetrant Inspections: Review of Literature Published from 1970 to 1998”[20]. Over 40 factors were identified that can affect the performance of penetrant inspection. These factors include variables affected by (1) the formulation of the materials, (2) the inspection methods and techniques, (3) the process control procedures, (4) human factors, and (5) the sample and flaw characteristics.

In January 2002, additional activities were also initiated as part of the CASR program, in a new program entitled “Engineering Assessment of Fluorescent Penetrant Inspection.” The program has identified 12 key areas in which engineering data is insufficient. Data is being generated to address the insufficiencies and will be used in updates to industry specifications and inspection protocols. Details of the program, including interim technical reports, are available at <http://www.cnede.iastate.edu/faa-casr/fpi/index.html>.

In response to a recommendation from the NTSB [3], the FAA also initiated a research study of human factors associated with the performance of FPI of critical rotating engine components. The primary objective of the effort was to derive a set of recommendations for human factors good practices in the performance of FPI. This project was designed to apply human factors engineering techniques to enhance the reliability of inspection of rotating engine parts. Human factors considerations are not new in NDI, but this project provided a more systematic view of the human/system interaction, using data on factors affecting human inspection performance from a number of sources beyond aviation and even beyond NDI. Site visits to a number of engine overhaul facilities that have FPI facilities revealed a generally high standard of

operations. They also showed many areas where improvements could be made by applying the principles of human factors engineering. Three sets of recommendations were made in a final FAA report [21]. The first is a set of 86 specific good practices arising from the detailed Hierarchical Task Analysis (HTA) of engine FPI. This list can be used as a checklist for actions by inspectors and managers in FPI. A second list of five more general areas of improvement came from both the HTA and the detailed notes of the site visits. Finally, a set of five research and development needs was generated to provide solutions to currently unsolved issues.

The FAA has also funded work at the Airworthiness Assurance NDI Validation Center (AANC) at Sandia National Laboratories to establish an on-site capability that evaluates liquid penetrant inspection capabilities [22]. AANC conducted a knowledge preservation project of the present penetrant evaluation and qualification process used at the U.S. Air Force (USAF) Materials Laboratory at Wright Patterson Air Force Base (WPAFB) in Dayton, Ohio. During this time, six sample calibration panels underwent brightness evaluation testing, as defined by AMS 2644 [23].

FPI is also a widely used technique for military applications and, as such, has also benefited from efforts within Department of Defense. The U.S. Army Research Laboratory published the results of a recent study on penetrant precleaning [24]. Although this study does not make any direct measurements of the effect of cleaning on sensitivity, it does report on the performance of various cleaning chemicals in comparison to the 1,1,1-trichloroethane. As indicated earlier, the use of 1,1,1-trichloroethane is rapidly being phased out because it is an ozone-depleting substance. This study used a grease hydraulic fluid mix to contaminate the surface of titanium and Inconel specimens that contained LCF cracks ranging from 0.51 to 1.5 mm (0.020 to 0.060 inch) in length. One large crack, 9.5 mm (0.372 inch), was also included in the study to better evaluate the potential of a cleaner to wash the penetrant out of the defect. A variety of chemical cleaners were used to clean the specimens prior to penetrant inspection. Both solvent removal (Method C) and hydrophilic postemulsifiable (Method D) penetrant inspection methods [1] were included in the study. A photometer was used to measure the brightness of the indications produced and compared them to the brightness readings obtained when cleaned with 1,1,1-trichloroethane. The cleaners were determined to be acceptable or unacceptable as replacements for 1,1,1-trichloroethane and ranked by cleaning performance.

The USAF has traditionally served as the custodian for the qualified products list (QPL) for fluorescent penetrants, including their classification into the various levels and types. The Systems Support Division at WPAFB maintains the QPL for military procurement of penetrant materials. Prior to 1996, this was governed by a military specification, MIL-I-25135 and the associated qualified products list, QPL-25135-16 [25]. More recently, Society of Automotive Engineers (SAE) Committee K-Aerospace NDE has worked with the USAF to develop an industry specification, AMS 2644 [23] and the associated QPL-AMS-2644-1. This specification is applicable to penetrant materials used for production and in-service applications. In addition to QPL custodial responsibility, the Systems Support Division has also looked at the relationship between compressive stress and penetrant response [26]. Conditions of concern are those generated either from shot-peening operations or from residual compressive stresses from plastic deformation that occurs from loading in service. Compressive stresses were shown to affect the penetrant volume and, therefore, the response on a limited number of samples.

In a cooperative effort between the USAF and the FAA, AANC personnel were responsible for documenting the procedures used by the USAF in evaluation of penetrants for inclusion in the qualified products list. Included as part of the USAF evaluation is a quantitative measurement of brightness using a photometer, a process also used by AANC in their quantitative studies. A similar approach was adopted by the ETC team as described in the approach section following.

2. APPROACH.

The approach for this research effort included the following, with details provided below.

- Survey of current practices used by airlines and OEMs.
- Establish matrix of contaminants and cleaning methods and determine drying study parameters.
- Fabricate samples from titanium (Ti) and nickel (Ni) samples including characterization using optical micrographs to record the original crack condition.
- Develop quantitative characterization measurements using a photometer and digital recording of ultraviolet-A (UVA) indications.
- Characterize samples at ISU.
- Perform comparison studies at industry inspection facility that allows use of typical industrial cleaning methods and access to industrial drying facilities.
- Analyze results, prepare final report, and share findings with industry groups for consideration in specification changes.

2.1 INDUSTRY SURVEY AND MATRIX GENERATION.

The effects of the drying and cleaning methods on penetrant inspectability were evaluated as part of the program. Input from the airlines and overhaul facilities was solicited to help make this an effective study. The information was collected through a telephone survey conducted by ISU personnel. The feedback was used to determine the extent that various cleaning and drying practices are being used and to identify concerns and questions overhaul facilities had about current practices. Responses indicated consistency among the prevalent chemical cleaning methods, while a wider range of mechanical cleaning processes were mentioned. Flash dry was more prevalent than oven-dry processes. The results of the survey are provided in appendix A. Based on this input and review by the OEM partners, a cleaning versus contaminants matrix was generated and is shown in figure 1. Table 1 provides a summary of the cleaning methods, typical components for which they are used, as well as typical soils, uses, and practices.

	CLEANING METHODS												
Ti 6-4	Chemical	Chemical	Mechanical/Chem.	Chemical	Chemical	Mech./Chem.	Chemical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
CONTAMINANTS	Alkaline De-Rust Solution A (P&W 2-3 lb./gal)	Alkaline De-Rust Solution B (GE 12 oz./gal)	Ultrasonic w/Alkaline Derust Solution B	Aqueous Degreaser	Alkaline Gel Cleaner (Turco 5805)	Steam w/Aqueous Degreaser	Rubber Stripper	Plastic Media (Type 2) *	Wet Glass Bead	Al Oxide 240 Grit	Al Oxide 320 Grit	Al Oxide 500 Grit	Walnut Shell Blast*
	C2a	C2b	C7b	C1	C5	C6	C8	B1	B2	B3	B4	B5	B6
Anti-Galling Comp.	(YES)	(YES)	(YES)	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Oxidation & Scale	YES	YES	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	NO
Soot	YES	YES	NO	(YES)	(YES)	(YES)	NO	YES	NO	NO	NO	NO	YES
RTV Compound	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	YES
Penetrating Oil	YES	YES	NO	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO
High Temp Sealant (Nickel base)	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES	YES

	CLEANING METHODS												
Inconel 718	Chemical	Chemical	Mechanical/Chem.	Chemical	Chemical	Mech./Chem.	Chemical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
CONTAMINANTS	Alkaline De-Rust Solution A (P&W 2-3 lb./gal)	Four Step Process	Ultrasonic w/Alkaline De-Rust Solution A	Aqueous Degreaser	Alkaline Gel Cleaner (Turco 5805)	Steam w/Aqueous Degreaser	Rubber Stripper	Plastic Media (Type 2) *	Wet Glass Bead	Al Oxide 240 Grit	Al Oxide 320 Grit	Al Oxide 500 Grit	Walnut Shell Blast*
	C3	C4	C7a	C1	C5	C6	C8	B1	B2	B3	B4	B5	B6
Anti-Galling Comp.	(YES)	NO	(YES)	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Oxidation	YES	YES	YES	NO	NO	NO	NO	NO	YES	YES	YES	YES	NO
Soot	YES	YES	YES	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Penetrating Oil	YES	NO	YES	(YES)	NO	(YES)	NO	NO	NO	NO	NO	NO	NO
Coke/Varnish	YES	YES	YES	NO	(YES)	NO	NO	YES	NO	NO	NO	NO	YES
High Temp Sealant (Nickel base)	YES	NO	YES	NO	NO	NO	NO	YES	NO	YES	YES	YES	YES

() Not a primary cleaning process for this contaminant

* Plastic media and shell blast grit size - 12 - 20

Note: Cleaning methods evaluated in the study correlated with the contaminants for which they are typically used. The C1 through C8 designations were used to identify the various chemical cleaning methods, and B1 through B6 were used to designate mechanical blasting methods.

FIGURE 1. CLEANING VERSUS CONTAMINANTS MATRIX

TABLE 1. SUMMARY OF CLEANER METHODS

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
C1	Aqueous degreaser (20% aqueous degreaser followed by ambient- and hot-water rinses)	Ti and Ni fan hubs and disks, compressor disks, turbines disks, drum rotors, shafts, fan blades, compressor blades, turbine blades and vanes, seals, fan cases, compressor cases, and turbine cases	Fingerprints Shop soils (dirt) Oils and greases Soot Coolants Dust	Primarily used as a precleaner step for other cleaning methods on all engine components, to remove oily and greasy soils, which can quickly degrade alkaline tanks or contaminate grit blast cabinets. Not used for bearings or carbon seals. Used as primary replacement for vapor degreasing. Used as primary cleaner for aluminum (Al) and parts.
C2a	Alkaline derust short soak (50%-75% alkaline cleaner for 3 minutes followed by ambient- and hot-water rinses)	Ti fan hubs and disks, compressor disks, drum rotors, shafts, fan blades, compressor blades, compressor cases, and housings	Oxide and scale Coke and varnish Soot Oils and greases if not removed by precleaner	For overhaul cleaning prior to FPI. Typically used as a follow-on treatment on Ti parts if aqueous degreaser is ineffective. Surface is visually examined for cleanliness, and if blue/gold oxide still exists, additional cleaning cycles will be run. Breaks down antigallant and antiseize materials before plastic media blasting. Not for Al or copper (Cu) alloys. Tank is restricted to Ti parts only.
C2b	Alkaline derust long soak (20% alkaline cleaner for 20 minutes followed by ambient- and hot-water rinses)	Ti fan hubs and disks, compressor disks, drum rotors, shafts, fan blades, compressor blades, compressor cases, and housings	Oxide and scale Coke and varnish Soot Oils and greases if not removed by precleaner	Alternate process to C2a. For overhaul cleaning prior to FPI. Typically used as a follow-on treatment on Ti parts if aqueous degrease is ineffective. Surface is visually examined for cleanliness, and if blue/gold oxide still exists, an additional cleaning cycles will be run. Breaks down antigallant and antiseize materials before plastic media blasting. Not for Al or Cu alloys. Tank is restricted to Ti parts only.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

TABLE 1. SUMMARY OF CLEANER METHODS (Continued)

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
C3	One-step alkaline (66%-70% alkaline cleaner followed by ambient- and hot-water rinses)	Iron- and Ni-based compressor disks/spools, turbines, drum rotors, shafts, compressor blades, compressor cases, turbine cases, and hot section frames	Oxide and scale Coke and varnish Soot Oils Service coatings such as room temperature vulcanizing (RTV), high-temperature sealant Antigallant compound	Typically used, as a follow-on treatment on Ni parts if aqueous degrease is ineffective. Surface is visually examined for cleanliness, and if oxide or visual contamination still exists, an additional cleaning cycle will be run. Used as a single step and in multistep processes prior to FPI, depending on the hardware.
C4	Four-step alkaline (50%-75% alkaline cleaner, acid descaler, permanganate, 50%-75% alkaline cleaner followed by ambient- and hot-water rinses)	Ni-based compressor disks and spools, turbines, drum rotors, shafts, compressor blades, compressor cases, turbine cases, and hot section frames	Oxide and scale Coke and varnish Soot	Recommended multistep pre-FPI cleaning process for Ni-based critical rotating hardware. Last alkaline step may be replaced by phosphoric acid for additional final brightener.
C5	Alkaline gel cleaner (100% alkaline gel followed by hot-water pressure rinse)	Hot section frames, struts, sumps, HPT/LPT spline ends of shafts, and coked oil tubes	Coke and varnish Soot Oils	Originally intended for local removal of coked or varnished oil on frames, struts, sumps, and spline ends of shafts where complete disassembly is not performed. Usually in a module level for FPI or eddy-current inspection. Occasionally used locally on other hardware where immersion cleaning did not remove soils.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

TABLE 1. SUMMARY OF CLEANER METHODS (Continued)

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
C6	Degreaser (steam application of aqueous degreaser followed by ambient- and hot-water rinses)	Fan hubs and disks, compressor disks, turbines, drum rotors, shafts, fan blades, compressor blades, turbine blades vanes, seals, fan cases, compressor cases, and turbine cases	Fingerprints Shop soils (dirt) Oils and greases Soot	Primarily used as a precleaner step for other cleaning methods to remove oily/greasy soils, which can quickly degrade alkaline tanks prior to FPI or visual inspection. Used as one of the replacements for vapor degreasing.
C7a	Ultrasonic alkaline cleaning – Ni (50%-75% alkaline with ultrasonic agitation, followed by ambient- and hot-water rinses)	Ni-based compressor disks/spools, turbines, drum rotors, shafts, compressor blades, compressor cases, turbine cases, and hot section frames	Oxide and scale Coke and varnish Soot Oils	Same as the C3 process except with ultrasonic agitation to determine if the ultrasonic agitation would significantly enhance the cleaning process. Typically used for cleaning air-cooled turbine blades. Not commonly used in engine hardware cleaning lines in most shops.
C7b	Ultrasonic alkaline cleaning – Ti (20% alkaline with ultrasonic agitation followed by ambient- and hot-water rinses)	Ti fan hubs and disks, compressor disks, drum rotors, shafts, fan blades, and compressor blades	Oxide and scale Coke and varnish Soot Oils and greases if not removed by precleaner	Same as the Ti C2b except with ultrasonic agitation to determine if there is an enhanced cleaning effect. Not commonly used in engine hardware cleaning lines in most shops.
C8	RTV rubber stripper followed by ambient- and hot-water rinses	Approved for Ti and Al parts only (GEAE). Broader use by other OEM's for RTV removal	Service coatings such as RTV	Used to digest RTV silicone rubber after the bulk of the materials has been peeled/scraped away. Light blasting with plastic media is often used to remove the remaining RTV after this cleaning step.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

TABLE 1. SUMMARY OF CLEANER METHODS (Continued)

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
B1	Plastic media blast, 60-120 mil	Fan hubs and disks, compressor disks, turbines, drum rotors, shafts, fan blades, compressor blades, turbine blades and vanes, seals, fan cases, compressor cases, and turbine cases	Antigallant compound Varnish Soot Service coatings such as RTV, high-temperature sealant Epoxy, paint	Care must be taken when using this process on Al and Mg parts, as erosion may occur. Otherwise, this process is safe on all other metallic engine parts and is often used after chemical cleaning to remove conditioned soil from complex geometry areas. Maximum allowable pressures should not be exceeded, as evidence of metal smearing and embedding of particles was found.
B2	Wet glass bead blast, 0.0021" to 0.0029" diameter beads	Fan hubs and disks, compressor disks, turbines, drum rotors, shafts, fan blades, compressor blades, turbine blades and vanes, seals, fan cases, compressor cases, and turbine cases	Oxide and scale Varnish Soot Service coatings such as RTV, high-temperature sealant Plasma coatings	This process is not recommended as a cleaning process prior to FPI. It tends to smear metal and change surface conditions, including degradation of the FPI detection. Often used as a final surface finishing operation after inspection and repair on airfoils and for compaction of sacrificial aluminum coatings (paints).
B3	Dry Al ₂ O ₃ 240 grit blast	Fir tree areas of turbine disks, turbine air seals, turbine blades, turbine vanes, turbine cases, and compressor cases	Oxide and scale Varnish Soot Service coatings such as RTV, high-temperature sealant Plasma spray coatings	This process is not recommended as a cleaning process prior to FPI for critical rotating parts. It tends to smear metal and change surface conditions including degradation of the FPI detection. It can be used on nonpressure vessel frames and cases where cracks are wider and less prone to smearing or peening closed.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

TABLE 1. SUMMARY OF CLEANER METHODS (Continued)

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
B4	Dry Al ₂ O ₃ 320 grit blast	Fir tree areas of turbine disks, turbine air seals, turbine blades, turbine vanes, turbine cases, and compressor cases	Oxide and scale Varnish Soot Service coatings such as RTV, high-temperature sealant Plasma coatings Thermal barrier coatings	This process is not recommended as a cleaning process prior to FPI for critical rotating parts. It tends to smear metal and change surface conditions, including degradation of the FPI detection. It can be used on nonpressure vessel frames and cases where cracks are wider and less prone to smearing or peening closed.
B5	Dry Al ₂ O ₃ 500 grit blast	Fir tree areas of turbine disks, turbine air seals, turbine blades, turbine vanes, turbine cases, and compressor cases	Oxide and scale Varnish Soot High-temperature sealant	This process is recommended as a cleaning process after chemical cleaning and prior to FPI. An option to plastic media for removing high-temperature sealant.
B6	Walnut shell media blast, 60-120 mils	Fan hubs and disks, compressor disks, drum rotors, shafts, fan blades, and compressor blades	Varnish Soot Service coatings such as RTV, high-temperature sealant	Similar to plastic media blast. Care must be taken when using this process on Al and Mg parts, as erosion may occur. Otherwise, this process is safe on all other metallic engine parts and is often used after chemical cleaning to remove conditioned soil from complex geometry areas. However, this process is not as effective as plastic media blast and most shops do not use it. It is more common in European shops, whereas plastic media is more common in U.S. shops.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

TABLE 1. SUMMARY OF CLEANER METHODS (Continued)

Designation	Cleaner Type	Typical Components	Typical Soils	Typical Uses and Practices
VDG	Vapor degreasing use 1,1,1-trichlorethylene	Nontitanium compressor disks, turbines, drum rotors, shafts, compressor blades, turbine blades, turbine vanes, seals, fan cases, compressor cases, and turbine cases	Oils Some greases	This process has mainly been replaced by aqueous-based cleaning due to the chemical being rated as a suspect carcinogen. Prior use was as preferred preclean step just prior to FPI process for all metallic parts except Ti. No longer used in most shops.
Alkaline Permanganate	Alkaline Permanganate	Ni-based compressor disks, turbines, drum rotors, shafts, compressor blades, turbine blades vanes, seals, compressor cases, and turbine cases	Oxide and scale Varnish Soot Oils Service coatings such as RTV, high-temperature sealant Plasma coatings	One of the chemicals added to the multistep process for cleaning of iron- and Ni-based parts prior to FPI. Can be used in descaling of Ti parts after heat treatment to remove alpha case.
Acid descaler	Acid descaler	Ni-based compressor disks, turbines, drum rotors, shafts, compressor blades, turbine blades vanes, seals, compressor cases, and turbine cases	Oxide and scale Varnish Soot Oils Service coatings such as RTV, high-temperature sealant	This chemical is one of the additional chemicals added to the multistep process for cleaning of Ni-based parts prior to FPI. Not for use on low alloy steels. Not normally used on Ti-based parts.

Note: Column 1 provides a designation used by program members to track sample treatments and is not related to any industry standards. Included in the other columns are typical components and soils removed with a given cleaner type. The last column describes typical uses and practices and in some cases, reflects results of the work of this program.

2.2 SAMPLE FABRICATION AND CHARACTERIZATION METHODS.

The decision was made to include both Ti and Ni alloys in the study with sample fabrication details described in section 3.1. Over 80 LCF cracks were generated for use in the quantitative comparison. Optical microscopy was used to characterize each of the samples with digital images originally recorded at 100X magnification. Note that images may have been modified from their original magnification for inclusion in this document. A review of the brightness measurement techniques used by AANC and the USAF was completed and similar equipment purchased. To promote repeatable measurements, rigid-fixtured sample stands were fabricated to control the distances between the measurement surface, the black light source, and the spotmeter. Digital images of the UVA indications were also captured using a commercial off-the-shelf software package, ImagePRO™. Upon completion of the quantitative characterization methods, initial measurements were completed at ISU, including both a brightness measurement of the sample and a digital image capture of the UVA indication. The characterization runs helped determine consistency of results from each sample. Details of each of the characterization methods and representative examples are included in section 3.2.

2.3 ASSESSMENT OF THE DRYING METHOD ON INSPECTABILITY.

Once a part is appropriately cleaned, it is essential that all fluids be removed from any defects so that the penetrant solution can easily enter the flaw. Definition of and adherence to appropriate drying times and temperatures is critical to the overall effectiveness of the FPI process. An engineering study was performed in June 2001 to compare two drying methods:

- Oven Dry—This typically involves the use of a forced-air furnace capable of handling the size and complexity of the parts to be inspected. Furnace controls that monitor and control temperature and time are used to ensure that the recommended parameters are met and that moisture is removed from the surface and possible defects.
- Flash Dry—This is accomplished by submerging the part in 150° to 200°F water for a sufficient length of time to allow the part to reach the water temperature. Proper flash drying is indicated by seeing the water on the surface of a part start to flash or whisk off as the part is being removed from the hot-water tank.

2.4 ASSESSMENT OF THE EFFECT OF CLEANING METHOD ON INSPECTABILITY.

Upon completion of the drying study, an engineering study, which was conducted to determine the effect of cleaning methods on detectability, was completed using the same LCF blocks. The study was comprised of both mechanical and chemical cleaning methods and was accomplished on two separate 1-week periods at the Delta Air Lines maintenance facility in Atlanta, GA. The first part of the cleaning study occurred in October 2001 and focused on typical items that may be used in the routine operation and overhaul of engine components but could also lead to clogging of surface cracks if not effectively cleaned from the part prior to FPI. The surface contaminants considered included penetrating oil, antigallant compound, RTV, and high-temperature sealants. Penetrating oils are often used to assist with engine teardown. Antigallant compound is applied to pressure surfaces of rotating components to prevent galling and metal-to-

metal transfer from normal service use. Galling is a condition of surface roughening and cracking of material by mating part contact, usually caused by thermal or mechanical breakdown of the material under heavy loading. RTV compound is typically a silicone-based material used to prevent air flow between mating surfaces at lower gas temperatures. High-temperature sealants are used to prevent fluid flow between mating surfaces and is made of a material capable of withstanding the high gas temperatures experienced in the hot sections of jet engine operation.

The second part of the cleaning study focused on removal of surface conditions that result from engine operation. The sample set was shipped to Honeywell Engine Systems and Services in Phoenix, AZ, and several methods were used to generate oxidation and scale, soot, and coke and varnish on the sample surface, for details see table 2. The Ti oxidation temperature was selected to develop a relatively thick, dense oxide in a short amount of time (and at reasonable cost). The ETC team members identified some instances where Ti parts operate at or near these temperatures in the rim area, which motivated the temperature selection. While this occurrence is rare, it was felt by the team that this was a conservative approach given that successful removal of these oxides would imply effective cleaning of lower-temperature oxides as well. Upon successful contamination, samples were then returned to the Delta facility for the final cleaning study to be completed by the ETC team. Details of the cleaning methods are provided in section 3.2.

TABLE 2. CONTAMINATION PARAMETERS FOR EACH MATERIAL

Contaminant	Equipment	Temperature/Time	Environment	Notes
Ti 6-4 oxidation and scale	Crest furnace	1290°F/120 minutes	Forced air	
Ti 6-4 soot	Crest furnace	900°F/12 minutes	Air	Supported face down over a pan of Exxon 2380 oil. Process repeated twice for some samples.
IN-718 oxidation and scale	Crest furnace	1290°F/120 minutes	Forced air	
IN-718 soot	Crest furnace	900°F/12 minutes	Air	Supported face down over a pan of Exxon 2380 oil.
IN-718 coke and varnish	Despatch Oven	3 runs of 482°F for 120 minutes	Air	Coated every run with Exxon 2380 oil

2.5 LOCAL ETCHING STUDY.

In some cases, blending is allowed on engine components to remove minimal surface damage or anomalous conditions such as from FOD or other local anomalies. Upon completion of the blending operation, local etching to remove smeared metal and improve crack detectability is a

common practice. An evaluation of local etching practices was performed as a separate activity during the program with results provided in sections 3.9 and 3.10.

2.6 INFORMATION DISSEMINATION.

Information about the program has been shared with various industry groups including the Air Transport Association NDT Forum and Working Group, the American Society for Nondestructive Testing Aerospace and Penetrant Testing committees, and the SAE-Committee K-Aerospace NDE. The SAE Committee K has custodial responsibility for aerospace specifications and standards and is comprised primarily of airline and OEM representatives. This includes responsibility for the SAE Aerospace Materials Specification 2647B [1], which is considered the predominant standard for the practice of FPI in commercial aviation. The ETC team members, through the auspices of their home organizations, will continue to work with SAE Committee K in updating the specification or to generate additional specifications to reflect the results of this program.

3. DISCUSSION OF RESULTS.

3.1 SAMPLE PREPARATION.

The Ti 6-4 and IN-718 fatigue crack specimens were 1 inch wide by approximately 6 inches long. All samples were machined from a large piece of plate so that the rolling direction was parallel to the width of the specimen. The thickness of the sample varied between 0.25 and 0.5 inch, depending on the original plate thickness, although some specimens were machined thinner to remove an unsuccessful crack and conserve material. Each sample was excised from the plate using a bimetallic band saw blade, and rough edges were sanded or milled smooth so that the band saw scratches would not trap the penetrant material.

One of the 1-inch wide areas was chosen for the fatigue crack, and a belt sander with 50-grit aluminum oxide sandpaper was used to remove the rough mill finish. Each sample was then sanded by hand using silicon dioxide abrasive paper to obtain a surface finish that made visually finding small fatigue cracks easier. A stress riser was introduced near the center of the sanded surface on each specimen so that a crack would initiate in a desired location. The stress risers were either small spot welds or electrodischarge-machined (EDM) notches with typical examples shown in figures 2(a) and 2(b) respectively. The spot weld diameters were approximately 0.125", and the EDM notches were approximately 0.050 inch long, 0.005 inch wide, and 0.002 inch deep. The sample with the stress riser was then placed into a three-point bending fixture on ISU's MTS machine, shown in figure 3, and cycled at approximately 80% of its yield strength. A load ratio of 0.1 was used during the LCF process, and yield strengths of 104 ksi for Ti and 120 ksi for Inconel were assumed. Sample width and thickness and the span between the bottom bending supports were used to determine the exact load settings required.

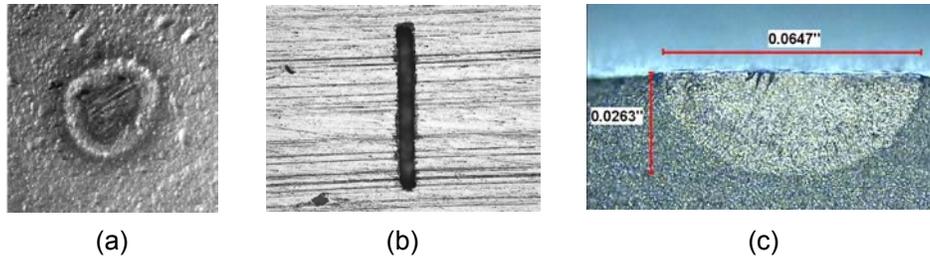


FIGURE 2. (a) TYPICAL SPOT WELD, (b) EDM NOTCH USED AS STRESS RISERS TO INITIATE CRACKING IN LCF SAMPLES, AND (c) TYPICAL CRACK ASPECT RATIO

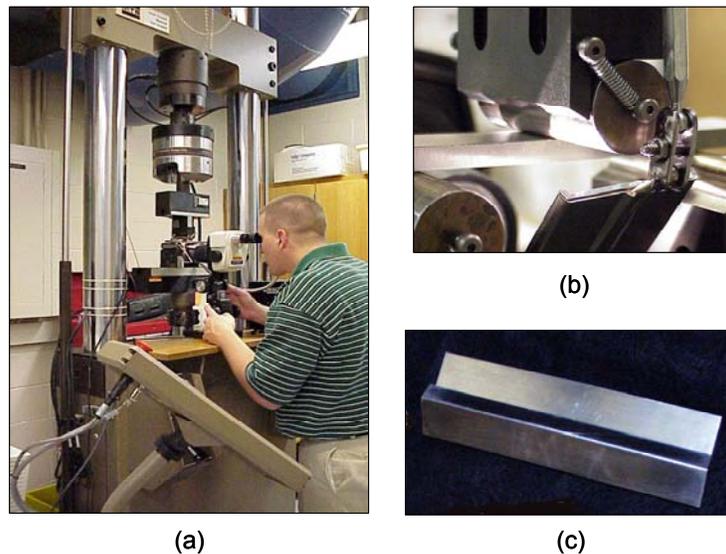


FIGURE 3. (a) FATIGUE TESTING MACHINE THAT INCLUDES THE ABILITY TO MAKE OPTICAL CHECKS ON CRACK GROWTH WITHOUT SAMPLE REMOVAL, (b) CLOSE-UP OF THE SAMPLE IN THE THREE-POINT BEND FIXTURE, AND (c) SAMPLE GEOMETRY

Samples were fatigued until a small crack was noted at the stress riser, typically within 20,000 cycles. The starter defect was then sanded away using silicon dioxide sanding paper so that no remnant of the stress riser was visible. Finish sanding grit varied among the group of samples, but the final surface finish, measured as average roughness (Ra), ranged between 5 and 18 Ra for Inconel samples and between 10 and 35 Ra for Ti samples. A bleedout effect that was noted when the Ti sample surface was rougher than approximately 30 Ra was not determined until after all specimens were fabricated and testing initiated at the engine overhaul facility. Surface scratches from sanding channeled the penetrant material in a direction normal to the crack length, which caused a much larger indication than normal on some samples. It is recommended that a surface finish smoother than 30 Ra be used for future studies.

Each sample was then fatigued and measured periodically until the crack propagated to the required size. Crack length measurements were taken at 500X magnification on a metallurgical microscope. A small quantity of samples was fractured to determine the crack aspect ratio,

which was in the range of 1:2 through 2:5 in depth versus length. A typical crack morphology is shown in figure 2(c).

For the more traditional probability of detection (PoD) studies, a broad crack size range is typically used, i.e., a crack size distribution with larger crack sizes. While a distribution of cracks that include larger cracks are needed for PoD studies, the focus of a quantitative process study necessitates the use of smaller crack sizes. Development of LCF blocks by the industry partners for their use in prior internal studies to monitor the performance of an FPI line used for critical rotating parts indicated that smaller cracks (≤ 10 mils) were needed to be sensitive enough to detect small variations in the process. The larger cracks did not reveal the level of sensitivity required for process parameter studies. Based on this guidance, cracks contained in the sample set used in this study were in the range of 0.021-0.146 inch in length. Note that this crack size distribution was used to determine the effect of various cleaning and drying parameters on quantitative FPI response. Table 3 shows how the range of lengths was divided into five bins and the number of cracks in a particular length bin. Ti samples were centered about the second and third bin, while Inconel samples fell mainly into the first and second bins. Fatigue cracks typically initiated by the completion of 20,000 cycles and were fully grown by 150,000 cycles for both materials.

TABLE 3. CRACK SIZE DISTRIBUTION IN Ti AND INCONEL SAMPLES

Crack Size Bin Range (in.)	Ti Samples in Bin	Inconel Samples in Bin
0.020-0.049	8	19
0.050-0.073	12	12
0.074-0.098	11	7
0.099-0.122	7	0
0.123-0.146	4	1

Digital optical photographs were recorded for each of the samples prior to the cleaning studies. Typical examples are shown in figure 4 for both Ti and Ni. Note that remnant surface sanding marks are also visible on some samples.

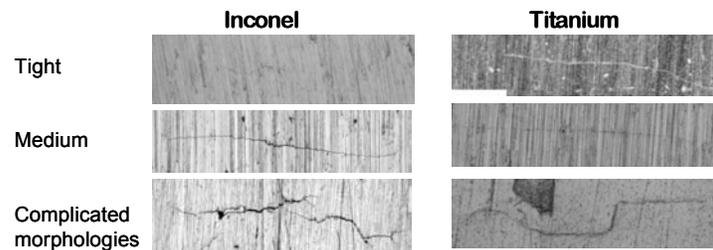


FIGURE 4. TYPICAL CRACK MORPHOLOGIES FOR IN-718 (LEFT) AND Ti-6Al-4V (RIGHT) SAMPLES (Crack morphologies could be categorized as tightly closed (shown at top), medium or somewhat open (shown in the middle), or of complicated morphology with visible surface branching and twisting.)

3.2 QUANTITATIVE ASSESSMENT OF FPI INDICATIONS—CHARACTERIZATION MEASUREMENTS.

In preparation for the engineering studies to be performed in an airline shop environment, the samples were fully characterized at ISU. In addition to the optical micrographs described above, each sample was inspected at least three times in most cases. Samples were cleaned in an acetone bath with ultrasonic agitation for 30 minutes prior to FPI. Samples were viewed under black light prior to processing to ensure no contamination. Samples were dried at 160°F for 30 minutes prior to FPI. Because ISU does not have a large FPI line, samples were run in batches of five to eight samples. The processing steps were completed using 32-oz. jars, as shown in figure 5. The FPI process consisted of a 20-minute penetrant dwell, 90-second prerinse, 120-second emulsification, 90-second postwash, 8-minute dry at 140°F, and a 10-minute development time. The FPI products included Magnaflux ZL-37 Penetrant (level 4, postemulsifiable penetrant), Magnaflux ZR-10B Emulsifier at 19% concentration, and Magnaflux ZP-4B Developer. The penetrant was applied in a dip and drain fashion. A refractometer curve was developed using two operators who made measurements in 5% emulsifier concentration increments. The results of the two measurements were averaged to create the graph shown in figure 5. The developer was applied by dragging the samples through the dry developer and allowing them to dwell by standing on their side for the full 10 minutes.

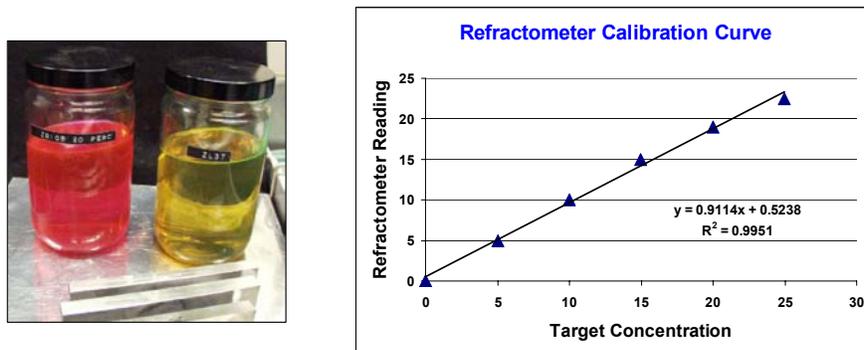


FIGURE 5. JARS USED TO PROCESS THE SAMPLES FOR CHARACTERIZATION AT ISU (Jars containing the emulsifier (left) and penetrant (right) solutions. Two of the samples are also shown in the foreground. The refractometer calibration curve used in determining the emulsifier concentration is also shown.)

After FPI, each sample was examined under a Photo Research (PR-880) photometer (see figure 6(a)) to determine the brightness of the FPI indications. Maintaining consistent spacing and a common angle is important to the overall repeatability of the spotmeter measurements. A rigid-fixtured stand was fabricated of components typically used for optical labs. Figure 6(b) shows the focal spot size over which the brightness reading will be taken. The focal spot is being shown on a fluorescent intensity card that is used as part of the setup verification. The schematic layout is shown in figure 7. Fluorescent tubes were used for more even ultraviolet (UV) illumination because hot spots would affect consistency of readings. The center of the focal spot of the PR-880 was placed over each crack indication to reduce variation in the brightness reading. The brightness reading was made with the focal spot over the crack and a

background reading was made with the focal spot just to the side of the crack in a representative area. The corrected brightness was arrived at by subtracting the background from the brightness reading. All values of brightness used in the evaluation and in the plots shown in this report are of the corrected brightness and are reported in foot-Lamberts.



FIGURE 6. PHOTOMETER SETUP AND FLUORESCENT INTENSITY CARD
 (a) PHOTOMETER SETUP. PHOTOMETER IS SHOWN ON THE RIGHT WITH SAMPLE POSITIONING FIXTURE AND HIGH-INTENSITY BLACK LIGHT SHOWN ON THE LEFT. (b) FLUORESCENT INTENSITY CARD USED AS PART OF SETUP VERIFICATION. THE BLACK SPOT SHOWN IN THE IMAGE INDICATES THE FOCAL SPOT OVER WHICH THE BRIGHTNESS READING IS AVERAGED. NOTE COMPARISON TO THE 3/64" SPOT

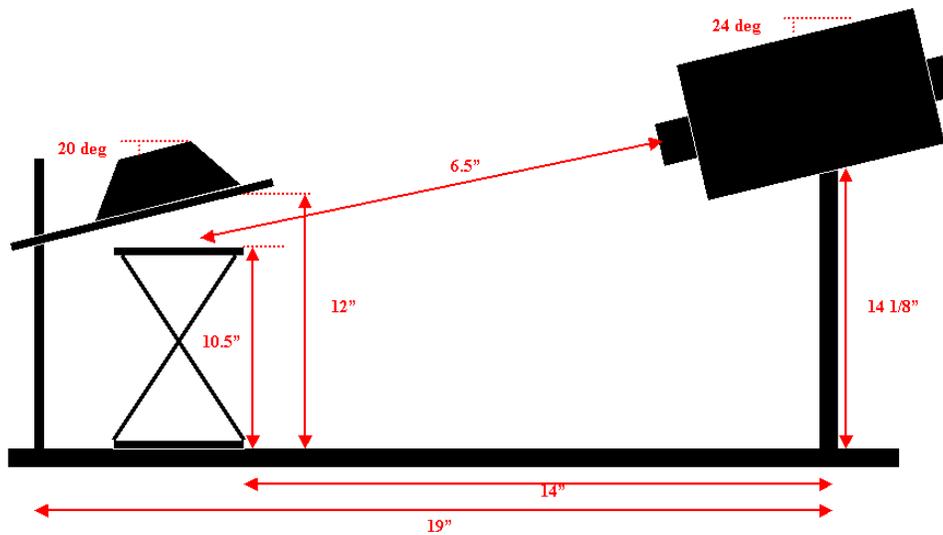


FIGURE 7. SCHEMATIC OF THE SPOTMETER AND SAMPLE POSITIONING SETUP
 (Diagram not to scale)

After completion of the brightness measurements, indications were captured at 40X magnification using a Moritex video microscope with an Olympus high-intensity UV light source. Equipment parameters are given in table 4. Typical UVA indication and corresponding optical image of the crack is shown in figure 8 for one of the characterization runs made at ISU.

The same setup was used for the field inspections at Delta. The setup was designed for both easy portability and repeatable performance. Note that while UVA images were captured for most of the indications, in some instances during the field studies and after the baked-on contamination processes, the indications were so dim that an image capture was not possible.

TABLE 4. EQUIPMENT PARAMETERS USED

Equipment	Settings
Photo Research PR-880 photometer/UVP XX-BLB 17" fluorescent UVA source	1/2" aperture, auto gain/4960-5020 $\mu\text{Watts}/\text{cm}^2$
Moritex video microscope/Olympus high-intensity UVA Source with saline light guide, ImagePro™ image capture software	40X magnification, maximum sensitivity/15,000 $\mu\text{Watts}/\text{cm}^2$

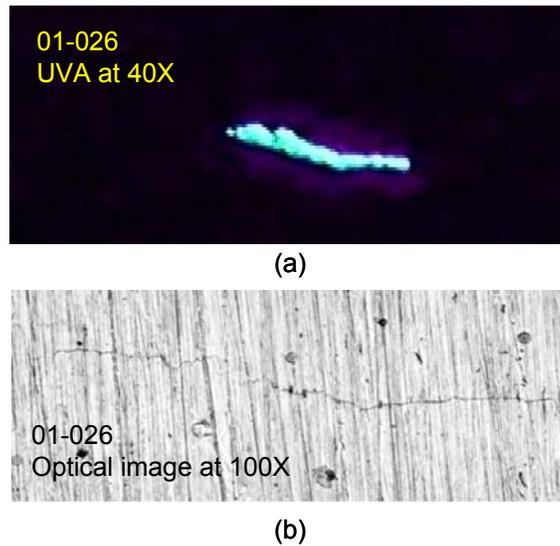
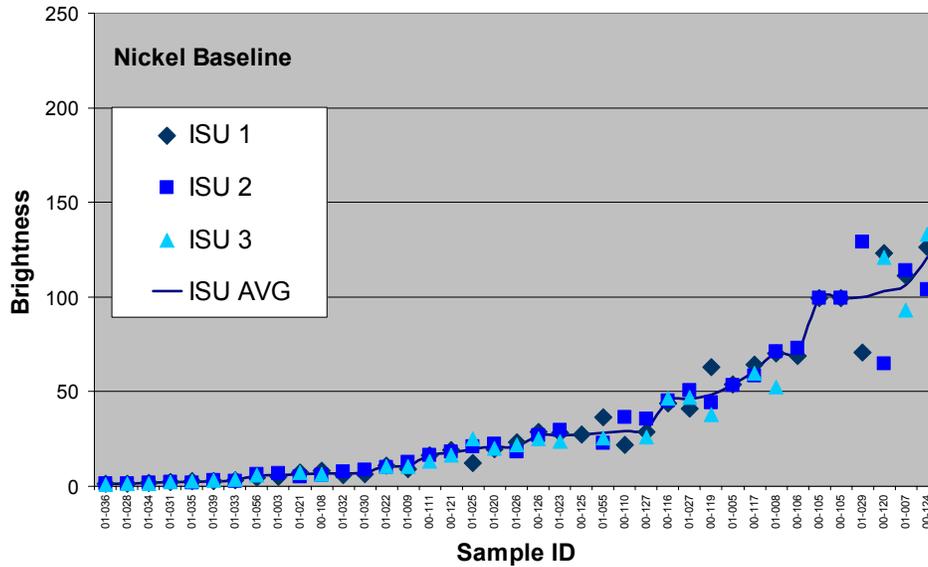


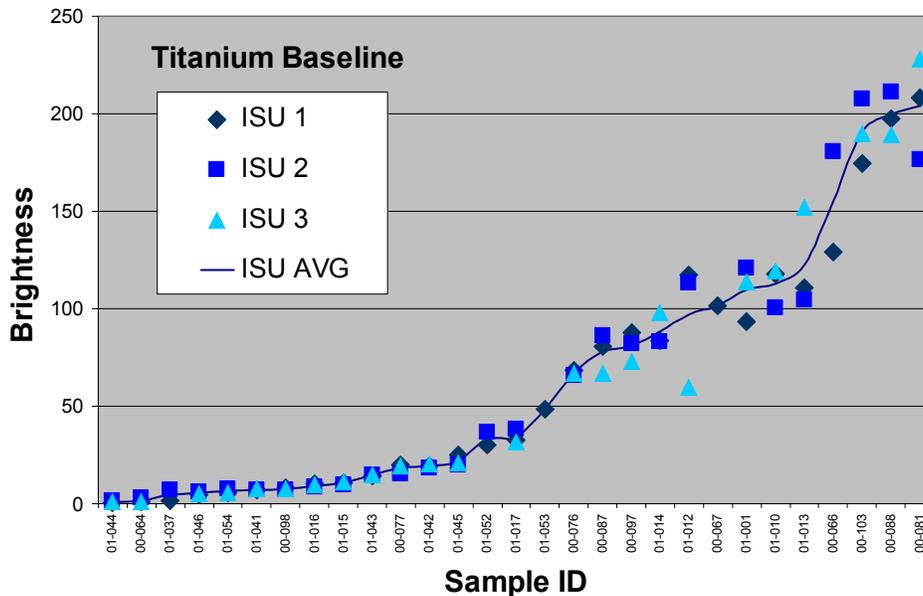
FIGURE 8. ULTRAVIOLET-A IMAGE OF CHARACTERIZATION FOR 0.055" LCF CRACK SAMPLE (a) UVA IMAGE OF CHARACTERIZATION RUN FOR SAMPLE 01-026 WHICH IS A 0.055" LCF CRACK IN Ni AND (b) OPTICAL IMAGE OF SAME CRACK TAKEN PRIOR TO ANY CLEANING STUDIES THAT WOULD IMPACT THE SURFACE OR CRACK CONDITION. THE ORIGINAL OPTICAL IMAGE WAS TAKEN AT 100X. BOTH UVA AND OPTICAL RESULTS ARE TYPICAL OF THE SAMPLE SET USED FOR THIS STUDY

Brightness measurements were repeated at least three times for each sample as part of the characterization process. This enabled optimization of the sample characterization procedures and allowed removal of samples that did not give repeatable performance. In some cases, further cycling was used to improve performance prior to the field studies. Brightness measurements are provided in figure 9(a) for Ni and in 9(b) for Ti samples, which provided repeatable performance prior to the field studies. The samples are shown in order of increasing brightness

with the actual values shown by points with an average indicated by the line. Tables 5 and 6 provide the data in tabular form for the Ni and Ti samples respectively. There was somewhat more variation in the Ti samples than the Ni, which was attributed to occurrence of bleedout in the Ti samples that resulted from polishing artifacts in some samples.



(a)



(b)

FIGURE 9. BRIGHTNESS RESULTS FOR (a) Ni AND (b) Ti USED TO CHARACTERIZE THE SAMPLES PRIOR TO FIELD STUDIES

TABLE 5. BRIGHTNESS MEASUREMENTS FOR Ni SAMPLES CHARACTERIZED PRIOR TO FIELD STUDIES

Ni Sample ID	Crack Length (inch)	Brightness ISU Run 1	Brightness ISU Run 2	Brightness ISU Run 3
01-036	0.026	1.32	1.27	1.05
01-028	0.034	1.53	1.18	1.24
01-034	0.024	1.69	1.88	1.57
01-031	0.026	2.25	2.16	2.11
01-035	0.025	2.62	1.88	2.66
01-039	0.021	2.65	3.00	3.01
01-033	0.021	3.07	2.92	3.50
01-056	0.067	4.46	6.24	5.72
01-003	0.030	5.04	6.73	NA
01-021	0.063	7.10	4.80	7.50
00-108	0.033	8.20	5.93	6.30
01-032	0.021	6.00	7.70	NA
01-030	0.026	6.44	8.45	NA
01-022	0.023	10.82	10.17	10.46
01-009	0.028	9.04	12.57	10.60
00-111	0.038	16.56	16.27	13.36
00-121	0.063	18.96	18.43	16.26
01-025	0.053	12.50	20.99	24.90
01-020	0.025	19.77	22.50	20.10
01-026	0.055	23.30	18.30	21.78
00-126	0.061	28.54	26.70	25.30
01-023	0.049	28.13	29.55	23.57
00-125	0.084	27.23	NA	NA
01-055	0.058	36.30	23.00	25.45
00-110	0.054	22.06	36.50	NA
00-127	0.083	28.90	35.60	26.13
00-116	0.056	43.60	45.00	46.43
01-027	0.061	40.92	50.57	47.18
00-119	0.080	63.12	44.25	37.92
01-005	0.064	54.00	53.50	NA
00-117	0.081	64.15	58.60	59.81
01-008	0.078	70.40	71.24	52.26
00-106	0.070	68.75	73.10	NA
00-105	0.067	99.34	99.29	NA
01-029	0.083	70.60	129.00	NA
00-120	0.122	123.00	65.00	120.90
01-007	0.078	111.40	114.10	93.28
00-124	0.064	126.30	103.90	133.00

TABLE 6. BRIGHTNESS MEASUREMENTS FOR Ti SAMPLES CHARACTERIZED PRIOR TO FIELD STUDIES

Ti Sample ID	Crack Length (inch)	Brightness ISU Run 1	Brightness ISU Run 2	Brightness ISU Run 3
01-044	0.031	0.26	0.34	0.33
00-064	0.128	0.79	3.17	1.18
01-037	0.093	1.7	7.35	NA
01-046	0.028	4.82	6.3	5.3
01-054	0.035	5.61	7.78	5.8
01-041	0.031	6.96	7.14	7.7
00-098	0.020	7.98	7.34	7.6
01-016	0.050	10.05	8.43	9.6
01-015	0.033	10.82	9.64	11.26
01-043	0.054	14.24	14.95	14.95
00-077	0.039	20.13	15.32	19.48
01-042	0.058	19.43	18.48	20.34
01-045	0.052	25.12	19.9	20.7
01-052	0.049	30	36.8	NA
01-017	0.054	32.5	38.48	31.86
01-053	NA	48.7	NA	NA
00-076	0.063	68.46	65.76	66.75
00-087	0.068	80.6	86.07	66.92
00-097	0.062	87.8	82.23	73.19
01-014	0.061	83.46	83.25	98.13
01-012	0.093	117.3	113.5	59.9
00-067	0.065	101.5	NA	NA
01-001	0.063	93.39	121	114
01-010	0.112	118	100.4	119.5
01-013	0.081	110.7	104.6	152.1
00-066	0.108	129.3	180.6	NA
00-103	0.104	174.5	207.8	189.6
00-088	0.114	197.6	211	189.5
00-081	0.12	208	176.7	228

3.3 ESTABLISHMENT OF FIELD MEASUREMENT PROCEDURES.

The most meaningful comparison of drying and cleaning methods required access to typical industry facilities. Through on-going interactions between the FAA-funded research programs at ISU and Delta Air Lines, arrangements were made to use the Delta facilities in Atlanta, Georgia. Three separate 1-week visits were required to complete the full experimental matrix planned for the program. Delta made available an auxiliary penetrant line for the week-long testing sessions. Brightness measurements and UV images of crack indications were processed in the nearby penetrant viewing area. This proved ideal, as there was no interference with their production inspection and the experimental studies were not interrupted by the processing of nontest items.

The chemistry used was approved prior to the experiment and matches that currently used by Delta. It was considered a typical penetrant and its use in this study should not be construed as a preferential endorsement of a particular brand. The same penetrant chemistry was used in the characterization studies at ISU and the field studies at Delta.

Penetrant processing used Type I, Method D, Sensitivity Level 4 penetrant, i.e., a fluorescent, postemulsifiable, hydrophilic, ultra-high-sensitivity penetrant typically specified for critical rotating engine hardware. Fluorescent penetrant processing was consistent within the limits of AMS 2647B [1] and ASTM E 1417 [27], for all the various studies, including the baselining of fatigue crack specimens to establish individual crack brightness and crack length under black light conditions as well as the drying, cleaning, and etching studies.

Process control steps were conducted prior to penetrant inspection of any specimens. A written procedure developed by the ETC team was used to ensure that all steps were followed and appropriate parameters recorded. A copy is provided in appendix B. Section A of appendix B provides assurance that the penetrant line was ready to process parts. These checks included emulsifier contamination and concentration, wash water pressure and temperature, drying oven temperature, dry developer contamination, booth and equipment cleanliness, inspection area white light, setup and calibration of PR-880 spotmeter, UV light intensity for spot meter measurements and in the wash booth. In addition, a testing and monitoring (TAM) panel was processed as a system performance check. Process control requirements and any actual measured ranges are summarized in table 7.

Part of the PR-880 spotmeter setup is a dimension check of distances and angles, as shown in figure 7. There is also a manufacturer's calibration that is performed at the start of each day and periodically throughout the day. Additionally, a 40% spot on a UTE-3 card (sometimes used as an inspector's dark adaptation check, as shown in figure 6(b)) was measured for fluorescent brightness and kept in the range of 2.5 to 3.0 foot-Lamberts. This measurement was repeated before and after each inspection run to ensure that parameters had not drifted or been inadvertently changed. The UV light intensity was also measured before and after each of the inspection runs using a Spectroline DSE-100X and the value recorded with the datasets.

The penetrant used was Magnaflux ZL-37, batch 99M052. This is a Method D, postemulsifiable penetrant rated at level 4 sensitivity in QPL-AMS-2644 [23]. Specimens were processed in stainless steel baskets that held approximately 20 specimens. Specimens were arranged on two sides of the basket with each specimen standing on one end and inclined at approximately a 70 degree angle leaning against the long side of the basket, as shown in figure 10(a). The fatigue cracks always faced up or towards the center of the baskets. Following a brief immersion in the penetrant solution, specimens were lifted out and allowed to drain or dwell for 20 minutes. Process timing was closely monitored by a process monitor/timer. The process monitoring and parameter recording was completed by the same individual throughout the three studies. A second person was used to process all the sample batches throughout the three studies at Delta.

TABLE 7. PROCESS CONTROLS FOR FPI AND SPOTMETER MEASUREMENTS

Parameter	Requirement	Results
Emulsifier contamination	No penetrant floating on surface or adhering to sides of tank	Passed
Emulsifier concentration	Approximately 20% per manufacturer requirement	Passed with the following values: 19.6% (July) 20.7% (Oct) 20.1% (Feb)
Wash water pressure (prerinse and postrinse)	Not to exceed 40 psi (275 kPa)	23 psi (July); 26 to 40 psi (Oct.)
Wash water temperature	50° to 100°F (10° to 38°C)	81°-82°F (July); 72°-72°F (Oct.)
Dryer oven temperature	Not to exceed 160°F (71°C)	Passed, very consistent 150°F
Dry developer condition	Fluffy, not caked, less than 10 fluorescent specks in 4" circle	Passed, replaced when greater than ten specks
Inspection area/equipment cleanliness	No penetrant contamination and no excess clutter	Passed
Visible light in inspection area	Less than 2 foot-candles	Passed
UV light in wash booth	1000 microwatts/cm ² at 15 inches	Passed
System performance check	5 stars on TAM Panel	Passed
UV light in inspection area (UV photo area)	1200 microwatts/cm ² at 15 inches	Passed
UV light in inspection area (at spotmeter target)	5050 to 5200 microwatts/cm ²	Passed
Spotmeter setup and brightness check	40% spot on UTE-3 card, 2.5 to 3.0 foot-Lamberts	Passed

Following 30 minutes of dwell time, the basket of specimens was prerinse for 90 seconds to removed excess penetrant from the specimens as well as from the basket. A seasonal wash water temperature change of 10 degrees between July and October was observed for both pre- and postrinse. Wash times were held constant, as the baseline brightness results did not appear to be affected by the slight temperature difference. Pre- and postrinse water pressures were held between 23 to 25 psi during July, as it was the highest pressure available. Pressure was higher in

October with a 36-psi prerinse and a 32-psi postrinse. These all fall within the 40 psi maximum pressure requirement per AMS 2647B [1].

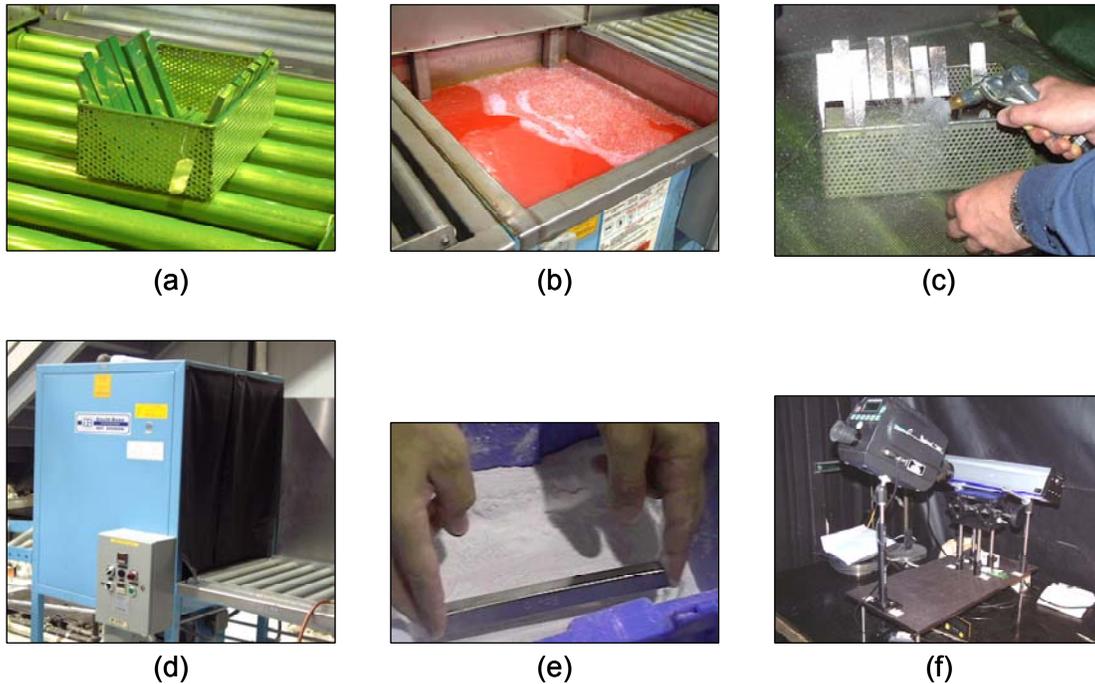


FIGURE 10. FLUORESCENT PENETRANT INSPECTION PROCESS (a) SAMPLE BATCH CONSISTING OF 20 SAMPLES IN A SINGLE BASKET FOR PROCESSING, (b) EMULSIFIER TANK USED FOR THE STUDY, (c) SAMPLES BEING RINSED AFTER EMULSIFICATION, (d) DRYER OVEN USED PRIOR TO DEVELOPER APPLICATION, (e) DRY DEVELOPER APPLIED TO SAMPLES INDIVIDUALLY, AND (f) SPOTMETER MEASUREMENT SETUP IN THE INSPECTION AREA

Emulsification was performed with a nominal 20% solution of Magnaflux ZR-10B, batch 01B065, which is compatible with the Magnaflux ZL-37 penetrant. A lowervator was used to cycle the baskets up and down in the emulsifier solution shown in figure 10(b) for three cycles, giving a total of 2 minutes of emulsification followed by a 10-second drain. Concentration was checked daily with either a Misco model 10430 (0-30° Brix) s/n S5952 or a Reichart model 10440 s/n 937237 refractometer. Both gave readings that were graphically converted to concentration values. Concentrations held steady throughout each week of testing and ranged from 19.6% during the first week (July 2001), 20.7% the second week (October 2001), and 20.1% during the third week of testing (February 2002).

Postrinsing, as with the prerinsing (figure 10(c)), was also for 2 minutes. The spraying was at 12-18 inches from the surfaces with 90 seconds of that time concentrated on the crack surfaces. The 90 seconds was divided between all specimens in the basket, which does not mean that every sample was rinsed for 90 seconds. A 150°F 10-minute dry in a circulating-air oven dryer (figure 10(d)) was determined to be an adequate time to remove water from the specimens. Time and temperature were held constant throughout the studies.

Type A or dry developer was next applied by holding the specimen ends and dragging it through the Magnaflux ZP-4B, as shown in figure 10(e). A plastic container was used to hold an appropriate amount of the developer to ensure adequate sample coverage. The samples were laid in a tray by order of development, and a timer was started. The tray of specimens was then transported to the inspection booth where brightness measurements and UV photographs were taken in the same order as the parts were developed. A two-person team completed the spotmeter operation and data recording for all samples with one person making all the spotmeter measurements and the other person recording the development times along with each brightness and background brightness measurements. The decision to use the same individual to make all spotmeter measurements in all three field studies was made to minimize operator variability. The spotmeter setup is shown in figure 10(f). After each brightness measurement was completed and recorded, the sample was provided to another two-person team for digital recording of the UVA image. The equipment and software used for these steps is the same as used for the characterization measurements at ISU and as listed in table 4.

The posttest cleaning process started with a water rinse and a soft-bristled brush, which was used on each individual specimen. After the specimens dried at 150°F for 10 minutes, they were placed in an ultrasonic (UT) cleaner containing acetone and cleaned using a 30-minute cycle. A check was made for bleed back after the first 30-minute acetone cycle. If the penetrant was visible under black light, additional acetone/UT cleaning was performed until bleed back no longer occurred. A ministudy of the cleaning process was performed to evaluate the postcleaning parameters using the UT cleaner available at ISU. The study showed that after a 30-minute UT cleaning in acetone and application of nonaqueous wet developer, there was no residual penetrant bleed, even under an applied vacuum. As a check of processing at Delta, it was discovered in July that the largest cracks were showing some bleed back after the 30-minute acetone/UT clean. A longer cleaning cycle was then used for the balance of that week, seemed to take care of the problem. It was thought that the UT cleaner available at Delta was not as powerful as the ISU UT cleaner. This new UT cleaner, which has better cleaning action, was shipped to Delta and that eliminated the bleed back problem in subsequent studies.

Following the acetone/UT cycle, the specimens were dried at 225°F (107°C) in a large circulating, air dryer for 30 minutes. Following cool down, the specimens were ready for baselining or testing. The field measurement process described in this section was used for all experiments during the three 1-week visits to Delta. Any variations will be noted in the subsequent sections.

3.4 COMPARISON OF DRYING METHODS IN OVERHAUL SHOP ENVIRONMENT.

3.4.1 Description of Drying Methods.

During the preparation of revision B for SAE Aerospace Material Specification AMS 2647 [1], there was a discussion regarding the necessity of specialized oven drying of components after aqueous-based cleaning and prior to FPI. Data was presented [28] that showed that there could be significant losses in detection capability if components were not oven-dried after aqueous cleaning and prior to FPI. This phenomenon could not be consistently verified in other NDT facilities [29]. Therefore, it was determined that a comparative study of the two drying methods

currently allowed in AMS 2647B [1] be included as part of this study. The two drying methods under consideration are flash dry and oven dry:

- Flash Dry—The flash-dry process requires that the components that have been through the cleaning process receive a final immersion rinse in a clean water bath at 150° to 200°F (66°C) for a sufficient length of time to allow the component to reach the temperature of the water. The component is then removed and allowed to flash dry as evidenced visually by the rapid evaporation of the water from the part.
- Oven Dry—The use of forced-air ovens to dry the part after cleaning and prior to application of the penetrant solution. AMS 2647B [1] recommends that the oven temperature not exceed 225°F (107°C). There are some Standard Practice Manual requirements that require critical components be dried for a minimum of 1 hour at a temperature of 248°F (120°C). Note that if the surface temperature of the component can be measured (e.g., load thermocouple), the time in the oven can be reduced to 10 minutes from the time the surface has reached that temperature.

The ETC team decided to use parameters from AMS 2647B [1]. The minimum flash-dry temperature of 150°F (65.5°C) and an oven-dry temperature of 225°F (107°C) were selected for this study. The lowest flash-dry temperature and the highest oven-dry temperature were selected, providing the largest parameter difference in the hope of revealing differences between the two methods. The Delta Air Lines facility was selected for these studies because they have part-drying ovens in the FPI area and flash-dry capabilities as part of their cleaning line. Figure 11(a) shows the hot-water rinse tank that is used for flash-drying parts at the Delta facility. For the duration of the flash-dry study, the flash-dry tank temperature was lowered to 150°F (65.5°C) from Delta's normal operating temperature of 185°F (85°C). Figure 11(b) shows the oven-drying facility, which includes three independently controlled ovens. One of the ovens was made available for the study and was set at 225°F (107°C) throughout the three studies. Samples are placed at the entry point of the oven and automatically pulled into the furnace through a conveyor belt. They are cycled through the full length of the furnace over a 30-minute duration and exit the furnace at the point shown in figure 11(b).



FIGURE 11. (a) HOT-WATER RINSE TANK USED TO FLASH-DRY PARTS AND (b) OVEN-DRY FACILITY, SHOWING THREE SEPARATE, INDEPENDENTLY CONTROLLED, AUTOMATED OVENS

The parts were flash-dried in one of the Delta rinse stations set to operate at 150°F (65.5°C). This was verified using a digital thermocouple, as shown in figure 12(a). Figure 12(b) shows the samples after removal from the hot-water bath and while in the flashing process.

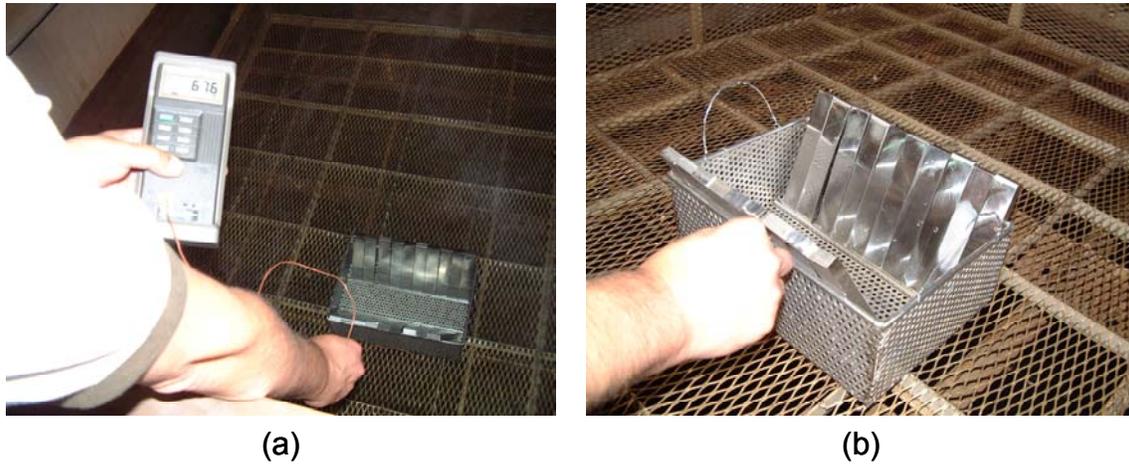


FIGURE 12. (a) SAMPLES SHOWN IN FLASH-DRY TANK OPERATING AT 150°F AND (b) SAMPLES HAVE BEEN RAISED OUT OF THE HOT-WATER TANK AND ARE SHOWN FLASHING

3.4.2 Establishment of Baseline.

The first step in the drying study was to compare the ISU characterization results to the baseline runs at the Delta facility for the samples that would be used for the drying study. The two graphs in figure 13 show that comparison for the brightness values. The points show the actual brightness values for the various runs with the average of those points indicated by the solid lines. While some scatter was observed for individual samples, the general trends were similar, and the decision was made to continue with the drying studies. Differences between the ISU and Delta results could be attributed to the variation in processing between the two locations, i.e., batches of 6 samples that were processed by hand at ISU compared to batches of 20 samples processed using the industrial facilities at Delta.

Based on the brightness values, the 40 Ti and 40 Ni samples were both subdivided into two separate sets of 20 samples each and results are plotted in figure 13 for each of the sets. This was done to accommodate the processing constraints, i.e., not exceeding recommended developer dwell time before analysis, limited an individual run to 20 samples. The data shown in figure 13 has been sorted to show the two separate sample sets for each material. Note that there was somewhat more variability with the Ti samples than the Ni. This has been attributed to the surface finish differences that led to some bleedout on the Ti samples, which was not observed with the Ni samples.

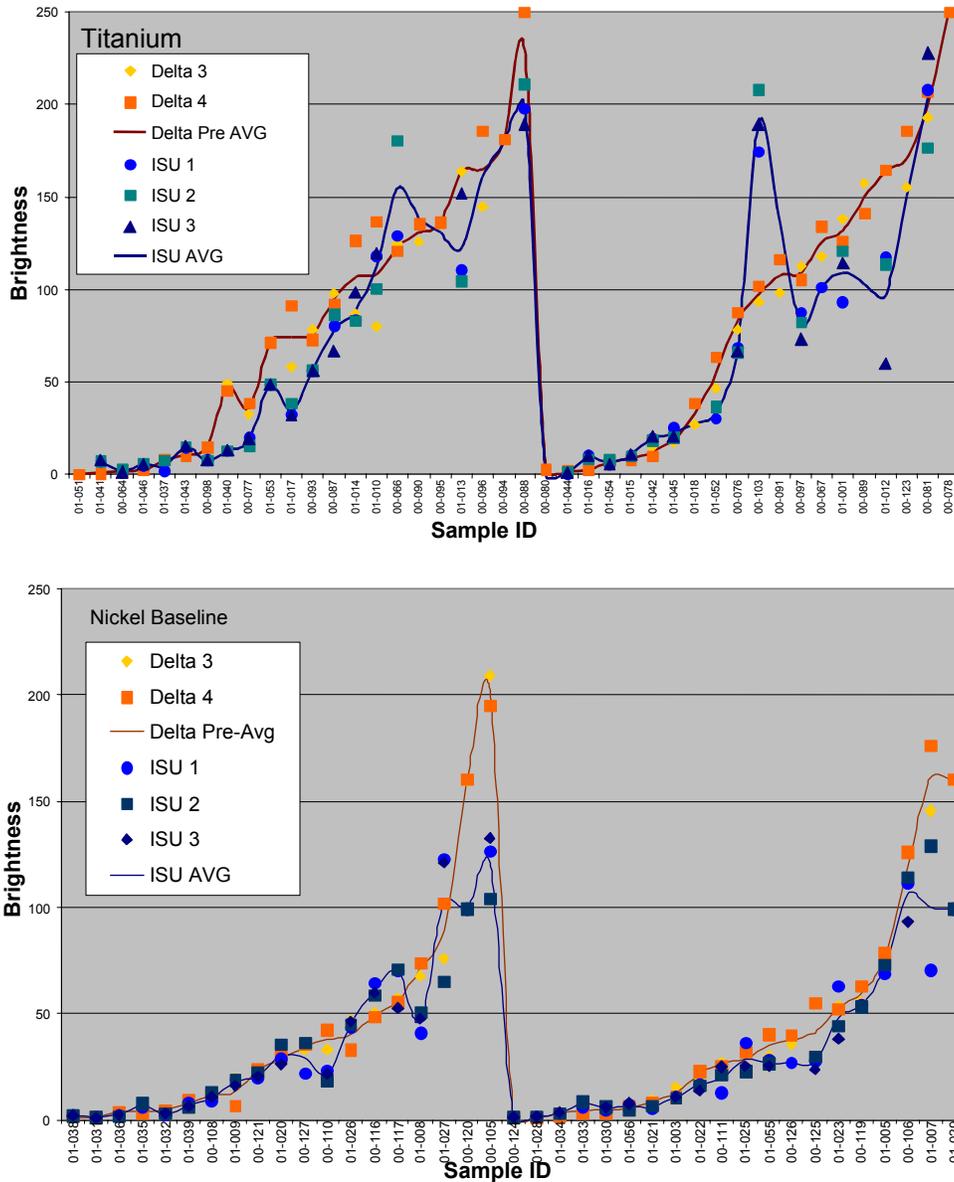


FIGURE 13. COMPARISON OF ISU CHARACTERIZATION DATA SHOWN IN BLUE AND DELTA BASELINE SHOWN IN ORANGE (The points represent brightness values for the individual runs and the lines are the average at each of the locations. Data is shown for Ti (above) and Ni (below).)

3.4.3 Experimental Steps for the Drying Study.

The flow chart in figure 14 shows the experimental steps for the drying study. Comparison of the baseline brightness measurements made at the Delta facility was consistent with the brightness measurements made at ISU, leading to the decision by the ETC team to proceed with the drying study. After sorting the samples into two sets of 20 Ti cracks and two sets of 20 Ni cracks, the samples were either flash-dried or oven-dried. After the first study, a repeat run was

made so that two data points were generated for every sample for both drying methods. The final step was to repeat the baseline run twice for comparison to the original baseline.

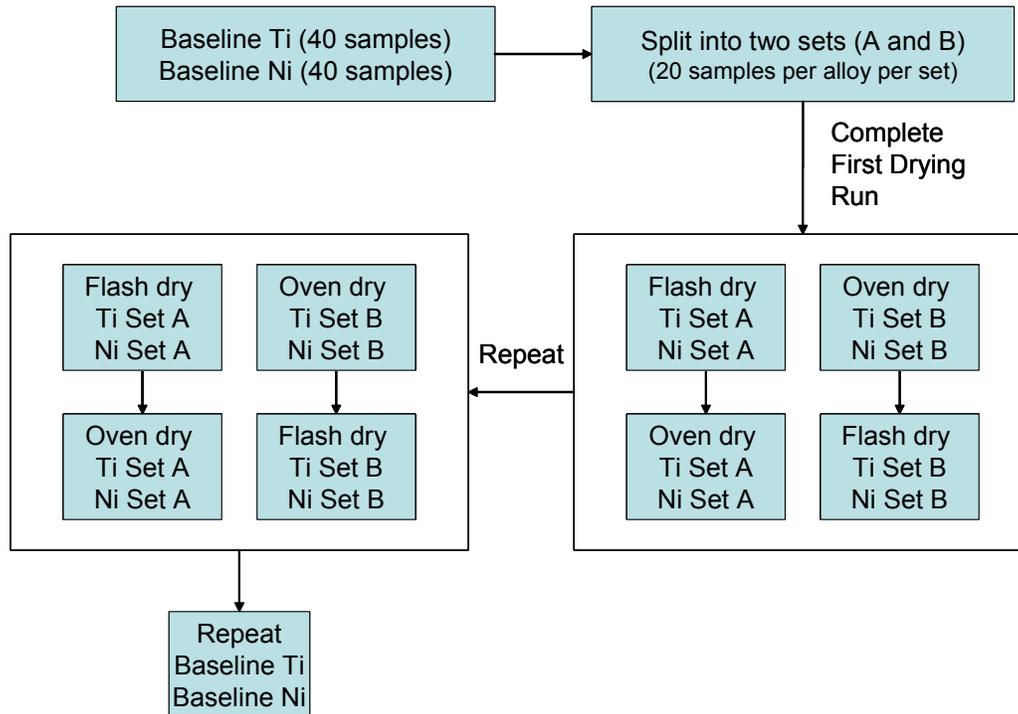


FIGURE 14. FLOWCHART OF THE EXPERIMENTAL STEPS USED IN THE DRYING STUDY

3.4.4 Results of the Drying Study.

The results of the drying study are shown in figures 15 through 18 with data tabulated in tables 8 and 9. The results for brightness are shown in figure 15 and for UVA length in figure 16 for both the Ti and Ni sample sets. The values are shown as points in green for flash drying and orange for oven drying. The average of the drying methods is shown as solid lines. The solid red line indicates the average for the four baseline runs (two pre- and two postruns). Note that the UVA lengths show less variability than the brightness. In general, the Ti samples show more variability than the Ni samples which is attributed to the occurrence of bleedout in the Ti samples. A linear regression analysis was performed for brightness and UVA length measurements with plots for each alloy and drying method combination provided in figure 17. Statistical analysis revealed no significant differences between the two drying methods for the samples and temperatures used in this study, as shown in figure 18.

A separate analysis to estimate the relationship between UVA crack length and optical crack length for each drying method was also completed with results shown in figure 18. Comparison of the amount of variability for the different drying methods is of importance because a method that has higher variability would generally have a higher probability of providing misleading conclusions. For Ni, the oven-drying method had a little more variability when compared with the flash method. For Ti, the flash method had a little more variability. Formal tests indicate,

however, in spite of the large number of specimens, there is not a statistically important difference between the drying methods, in either case. The graphical results of the analysis are shown in figure 18. One noted difference is substantially more variability (measured as standard deviation from the fitted regression lines) in the UVA crack length measurements from the Ti specimens, relative to the Ni specimens.

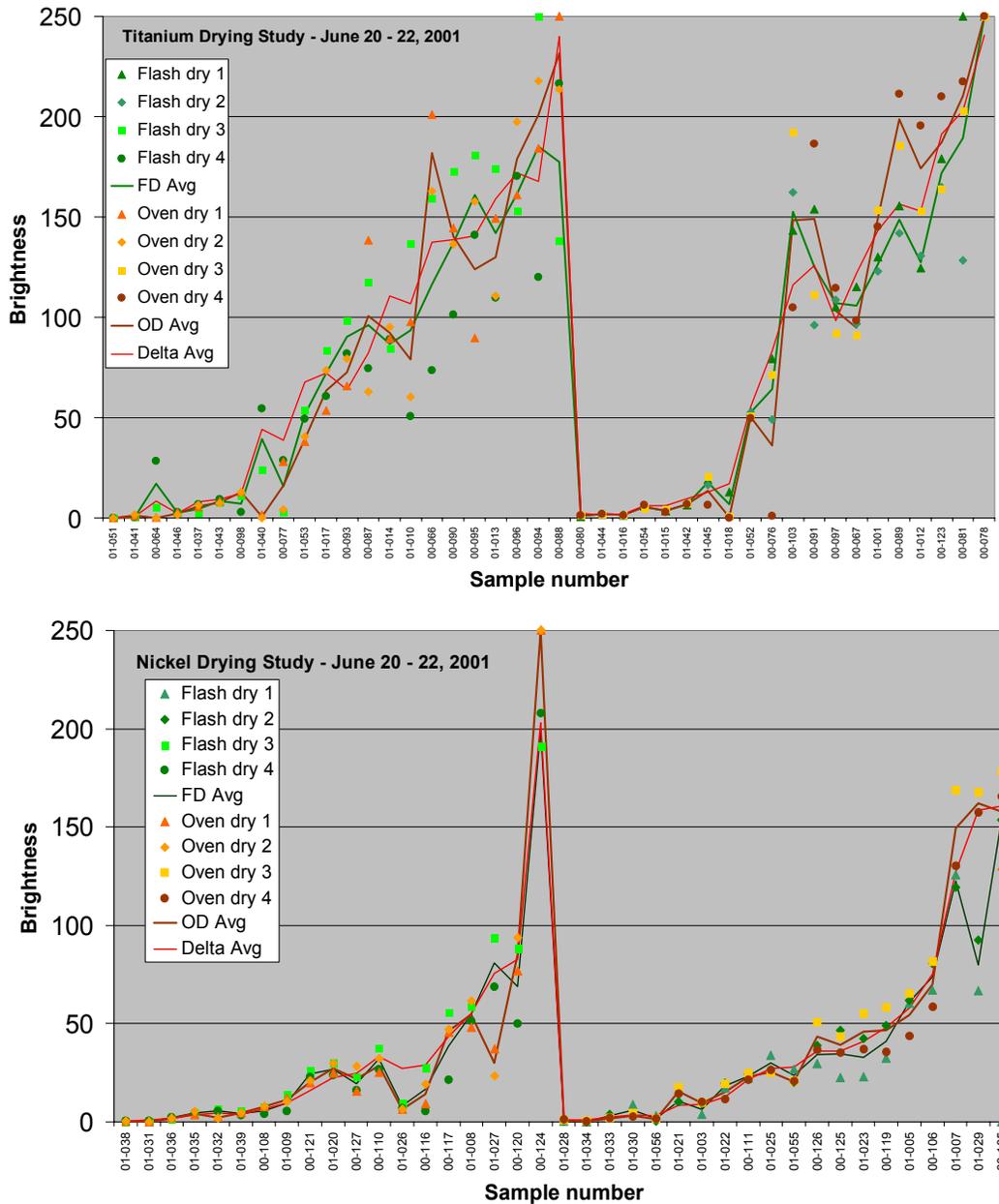


FIGURE 15. BRIGHTNESS RESULTS FOR Ti AND Ni
 (Flash dry points shown in green and oven-dry points shown in orange. Note that two flash-dry runs and two oven-dry runs were completed for each sample.)

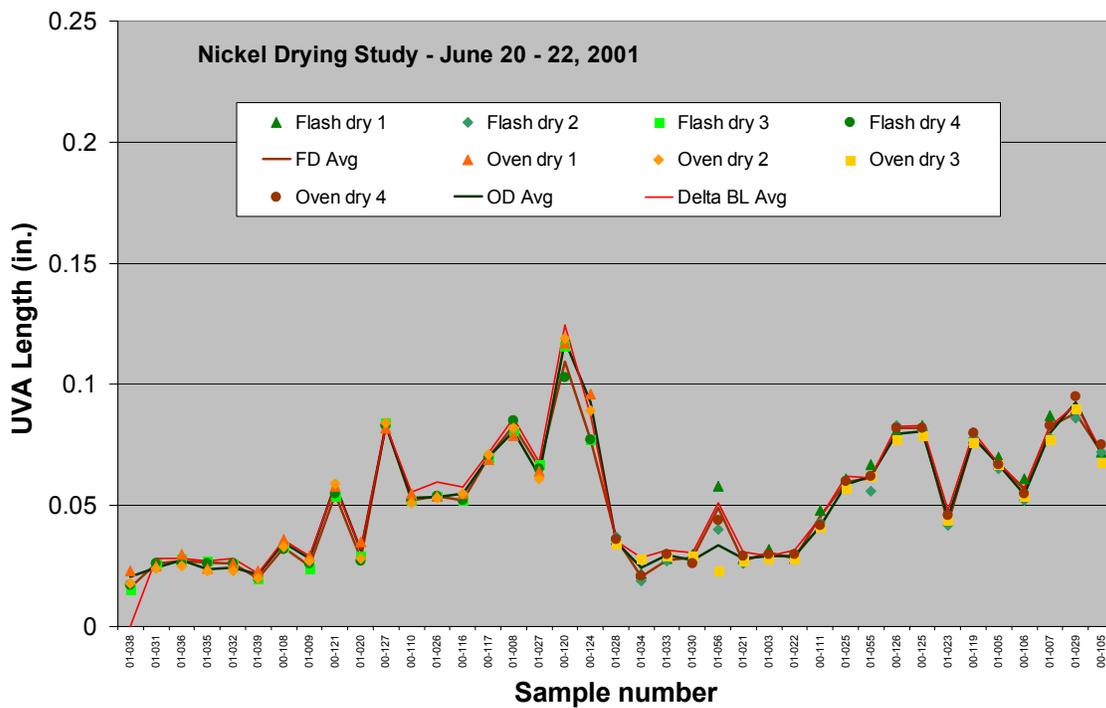
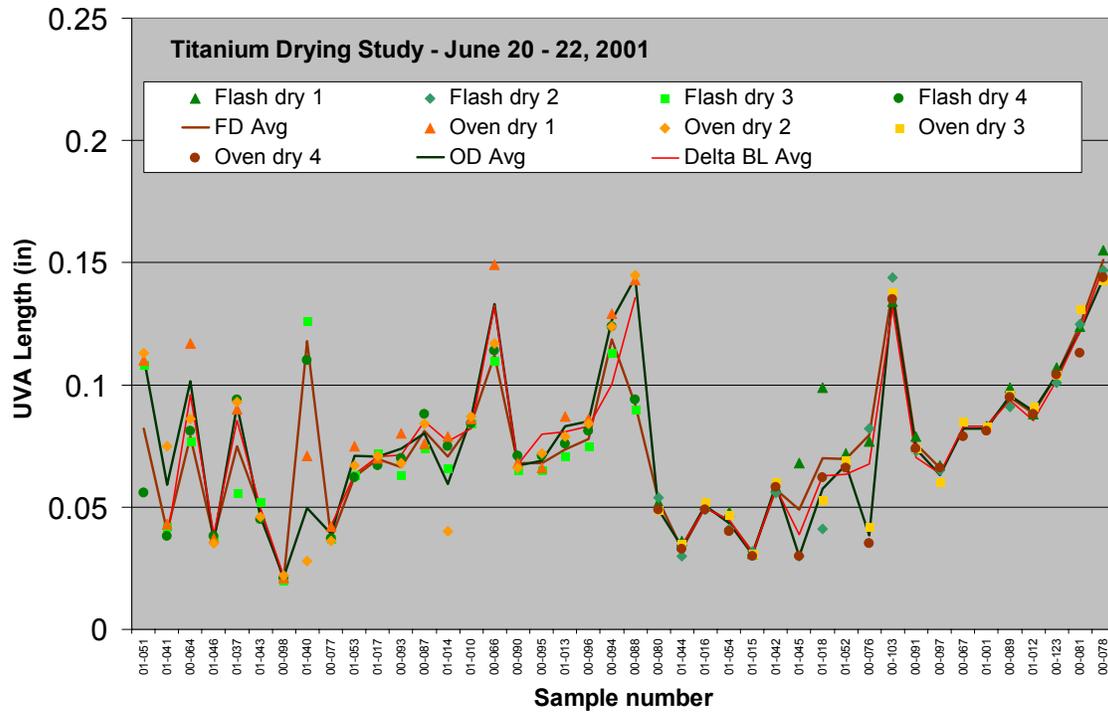


FIGURE 16. ULTRAVIOLET-A LENGTH RESULTS FOR Ti AND Ni (Flash-dry points are shown in green and oven-dry points are shown in orange. Note that two flash-dry runs and two oven-dry runs were completed for each sample. The average of the baseline results are shown by the solid red line.)

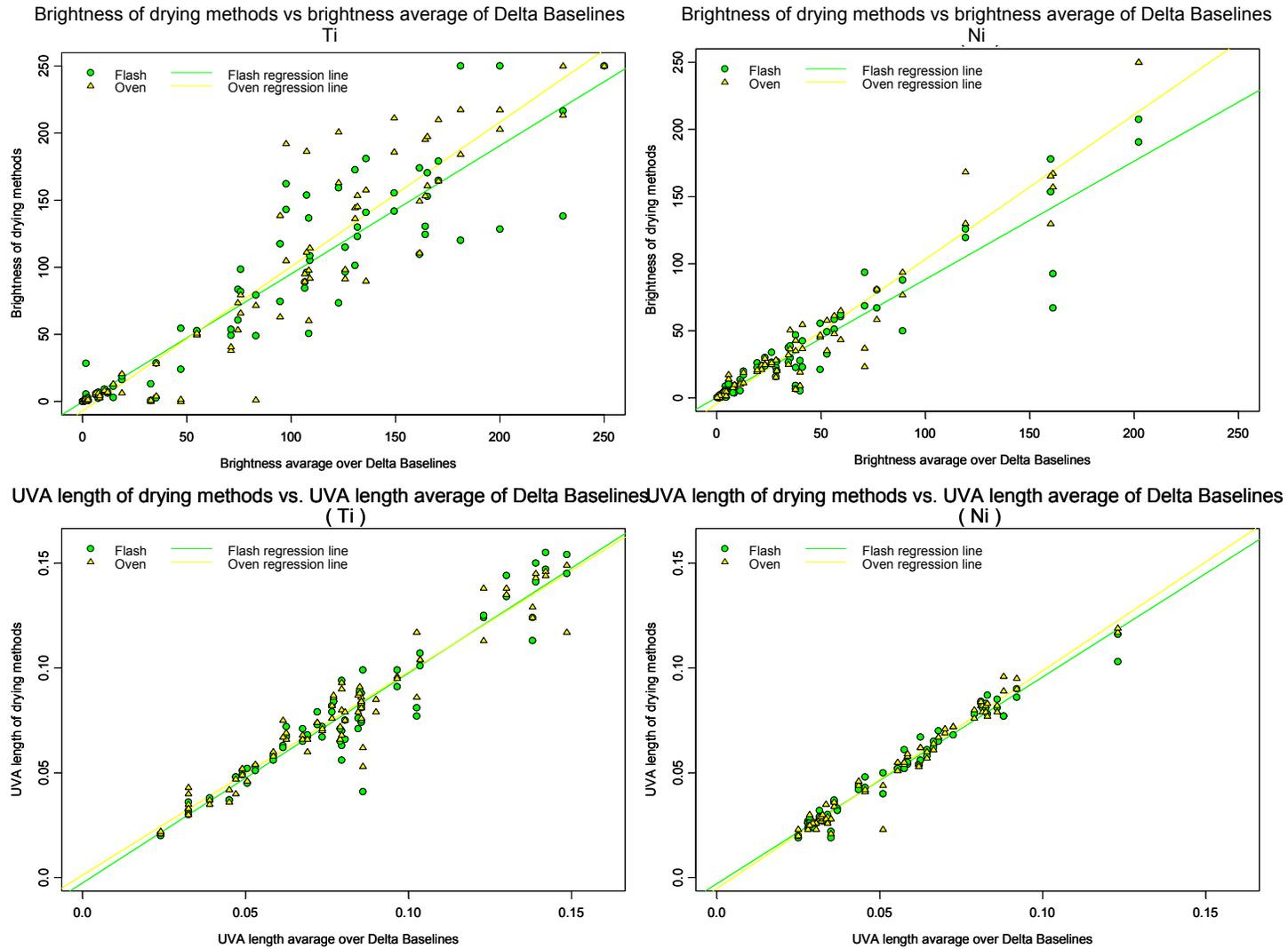


FIGURE 17. BRIGHTNESS (TOP) AND UVA LENGTH (BOTTOM) PLOTTED AGAINST AVERAGE VALUES FOR Ti (LEFT) AND Ni (RIGHT) ALLOYS USING FLASH- AND OVEN-DRY METHODS

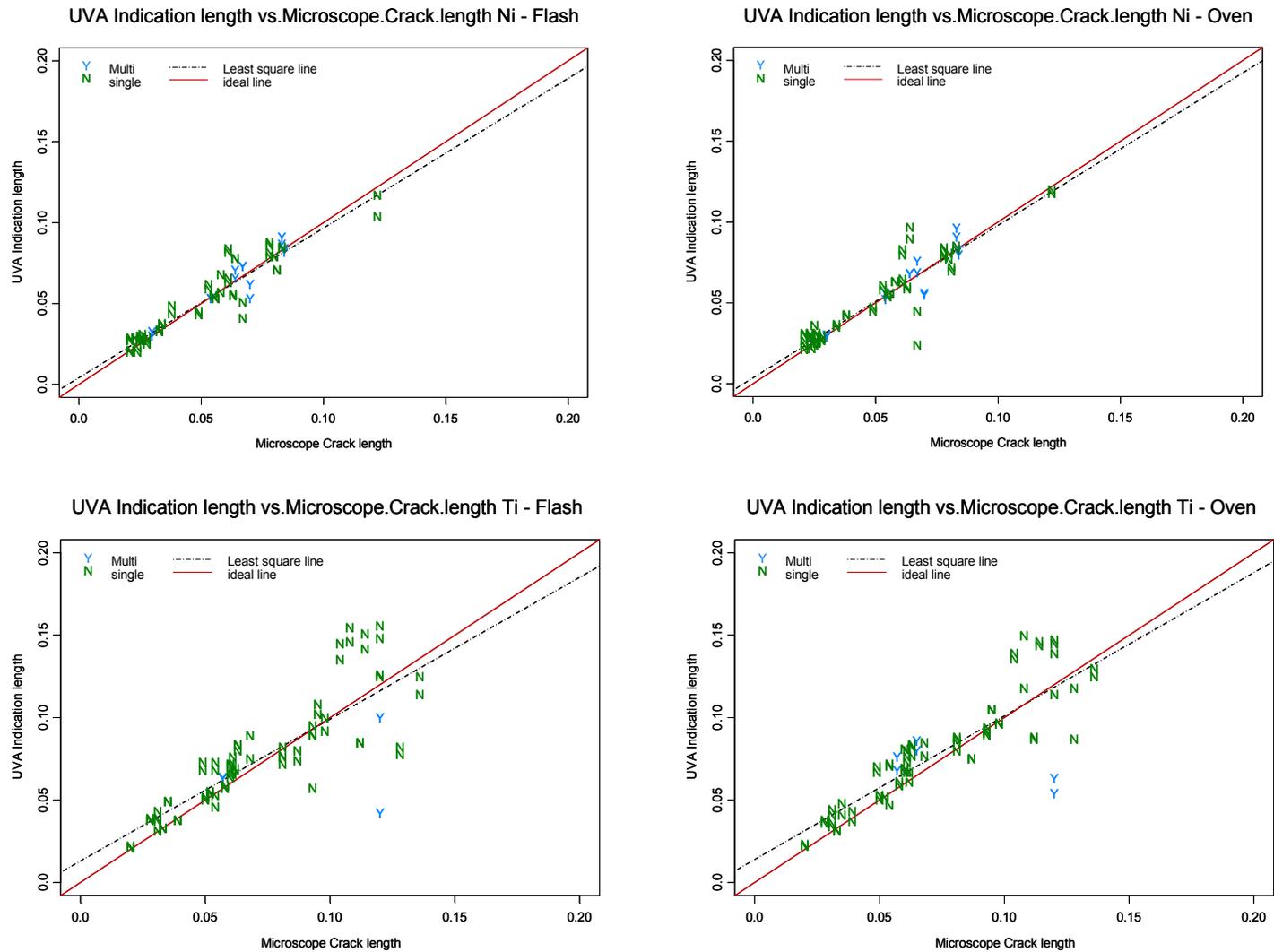


FIGURE 18. RESULTS OF STATISTICAL ANALYSIS (UVA lengths were compared to the optical lengths for each sample type and drying method.)

TABLE 8. BRIGHTNESS MEASUREMENTS FOR THE Ni SAMPLES AT THE FIELD LOCATION

Nickel Sample ID	Delta BL 3	Delta BL 4	Flash Dry 1	Flash Dry 2	Flash Dry 3	Flash Dry 4	Oven Dry 1	Oven Dry 2	Oven Dry 3	Oven Dry 4	Delta BL 5	Delta BL 6
00-080	NA	2.636	0.65	1.116	NA	NA	NA	NA	1.345	1.351	1.355	2.752
01-044	0.726	1.871	1.913	1.948	NA	NA	NA	NA	1.94	1.846	2.04	2.148
01-016	2.78	2.1	1.32	1.765	NA	NA	NA	NA	1.646	1.338	1.443	1.646
01-054	6.06	6.74	5.705	5.09	NA	NA	NA	NA	4.93	6.31	5.74	5.4
01-015	8.238	8.18	3.53	3.833	NA	NA	NA	NA	4.246	2.848	3.332	4.744
01-042	14.426	9.61	6.34	7.338	NA	NA	NA	NA	7.036	6.834	7.537	6.538
01-045	17.425	20.32	18.91	16.328	NA	NA	NA	NA	20.62	6.426	5.7	8.529
01-018	26.904	38.603	13.049	0.813	NA	NA	NA	NA	0.895	0.07	1.95	0.325
01-052	46.4	63.17	52.837	52.436	NA	NA	NA	NA	50.843	49.638	51.047	60.937
00-076	78.326	87.814	79.327	48.939	NA	NA	NA	NA	71.534	1.045	73.44	93.228
00-103	93.29	101.83	143.11	162.227	NA	NA	NA	NA	192.1	104.935	100.94	168.926
00-091	98.415	116.33	153.82	96.226	NA	NA	NA	NA	111.335	186.515	125.528	163.018
00-097	112.533	105.315	105.23	108.738	NA	NA	NA	NA	91.84	114.436	74.737	100.732
00-067	117.819	133.89	115.01	96.627	NA	NA	NA	NA	91.336	98.33	98.72	136.731
01-001	138.032	125.45	129.93	123.027	NA	NA	NA	NA	153.533	145.235	165.919	143.229
00-089	157.408	141.312	155.42	141.829	NA	NA	NA	NA	185.927	211.327	153.122	174.6
01-012	163.8	164.615	124.53	130.523	NA	NA	NA	NA	153.232	195.333	124.125	158.515
00-123	155.13	186.029	179.12	164.825	NA	NA	NA	NA	164.313	210.033	196.93	227.315
00-081	193.09	206.88	250	128.431	NA	NA	NA	NA	202.932	217.432	161.926	250
00-078	250	250	250	250	NA	NA	NA	NA	250	250	212.035	250

Note: Delta 3 and Delta 4 were baseline runs used to separate the samples into two sets. Samples were then processed through flash- or oven-dry runs with two repeats, followed by postbaseline runs known as Delta BL 5 and Delta BL 6. NA – not applicable.

TABLE 9. BRIGHTNESS MEASUREMENTS FOR THE Ti SAMPLES AT THE FIELD LOCATION

Titanium Sample ID	Delta BL 3	Delta BL 4	Flash Dry 1	Flash Dry 2	Flash Dry 3	Flash Dry 4	Oven Dry 1	Oven Dry 2	Oven Dry 3	Oven Dry 4	Delta BL 5	Delta BL 6
01-051	NA	0.02	NA	NA	0.033	0.022	0.034	0.015	NA	NA	0.022	0.039
01-041	1.223	0.51	NA	NA	0.263	0.217	1.027	1.518	NA	NA	0.09	0.453
00-064	2.028	1.216	NA	NA	5.538	28.435	0.174	0.018	NA	NA	13.225	16.934
01-046	2.38	2.56	NA	NA	2.345	2.834	2.928	1.64	NA	NA	1.539	2.046
01-037	7.231	7.815	NA	NA	2.367	6.849	5.35	6.451	NA	NA	9.647	7.553
01-043	10.829	10.18	NA	NA	7.746	9.242	8.243	7.543	NA	NA	8.446	7.935
00-098	15.022	14.447	NA	NA	11.322	3.04	13.047	13.047	NA	NA	12.14	7.44
01-040	48.93	45.34	NA	NA	24.032	54.438	1.516	0.02	NA	NA	44.44	38.635
00-077	32.11	38.47	NA	NA	2.831	28.715	28.14	4.04	NA	NA	46.27	37.722
01-053	71.09	71.15	NA	NA	53.74	49.343	37.95	40.55	NA	NA	82.34	46.93
01-017	57.97	90.96	NA	NA	83.638	60.636	53.424	73.538	NA	NA	72.428	68.231
00-093	78.414	73.04	NA	NA	98.541	81.943	65.844	79.442	NA	NA	77.543	26.424
00-087	97.613	91.825	NA	NA	117.535	74.531	138.49	62.932	NA	NA	68.132	71.928
01-014	86.514	126.52	NA	NA	84.46	89.037	89.34	95.14	NA	NA	123.24	105.819
01-010	79.907	136.93	NA	NA	136.7	50.635	97.84	60.223	NA	NA	115.339	95.132
00-066	124.622	120.87	NA	NA	159.304	73.39	200.816	163.017	NA	NA	191.823	112.608
00-090	125.514	135.609	NA	NA	172.636	101.333	144.425	136.421	NA	NA	156.434	136.81
00-095	135.214	136.434	NA	NA	180.926	140.938	89.825	157.627	NA	NA	151.138	140.423
01-013	163.93	NA	NA	NA	174.125	109.72	149.237	110.74	NA	NA	161.916	151.018
00-096	144.702	185.828	NA	NA	152.84	170.427	160.833	197.436	NA	NA	172.532	185.012
00-094	181.02	181.23	NA	NA	250	120.1	184.124	217.62	NA	NA	139.119	169.714
00-088	210.519	250	NA	NA	138.136	216.529	250	213.429	NA	NA	250	250

Note: Delta 3 and Delta 4 were baseline runs used to separate the samples into two sets. Samples were then processed through flash- or oven-dry runs with two repeats, followed by postbaseline runs known as Delta BL 5 and Delta BL 6. NA – not applicable

The final step of the drying study in June 2001 was to repeat the original baseline measurements. This was done to ensure that the samples had not changed over the course of the week-long study, i.e., the cracks did not become contaminated through their use in evaluating the drying parameters. In general, the brightness values were consistent, with the Ti samples showing somewhat more variability than the Ni. The results are shown in figure 19. After completion of the study, the samples were shipped back to ISU for thorough UT cleaning in acetone prior to continuation of the program.

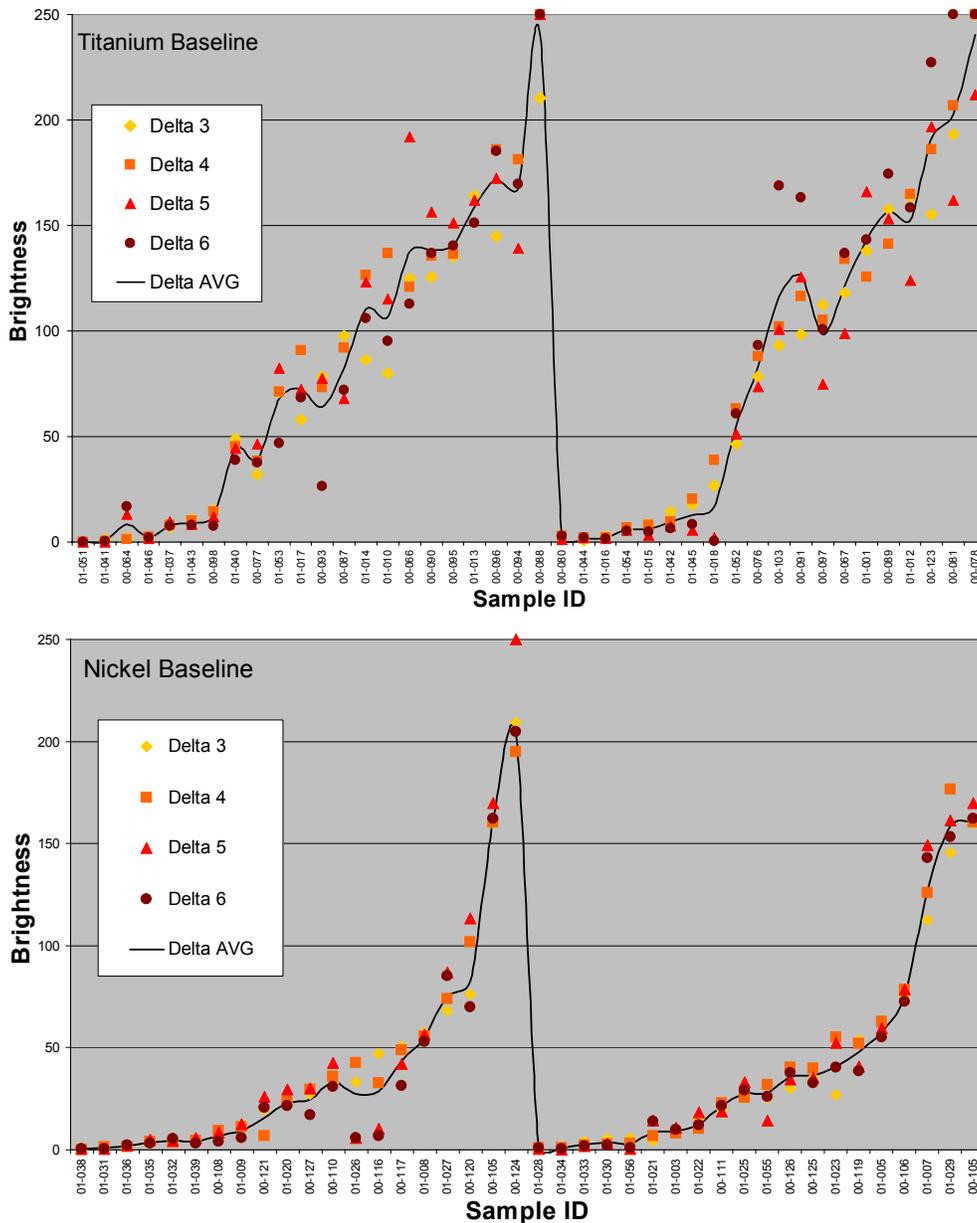


FIGURE 19. PREBASELINE (RUNS 3 AND 4) AND POSTBASELINE (RUNS 5 AND 6) COMPARISON OF BRIGHTNESS RESULTS FOR Ti AND Ni

3.5 DRYING STUDY OBSERVATIONS AND RECOMMENDATIONS.

- Statistical analysis of brightness and UVA lengths did not reveal significant differences between the two drying methods at the temperatures used in this study, i.e., flash drying at 150°F and oven drying at 225°F.
- Potential factors that were not considered in this study were the effect of thermal mass, potential differences in penetrant level, crack sizes greater than 0.150", and a range of drying temperatures. Additional studies that explore these factors are recommended.
- While significant differences were not found between the two methods, the importance of process monitoring and control for either method should be emphasized in specifications, standard practice documents, and training and guidance materials. Without careful adherence to the recommended practices, reductions in detectability can occur with either method.

3.6 COMPARISON OF CLEANING METHODS IN OVERHAUL SHOP ENVIRONMENT.

The importance of the cleaning process in the overall successful implementation of FPI is well recognized by the aviation community. In the past 10 to 15 years, requirements to protect the environment have changed dramatically [30]. There have been several regulatory changes, including the following:

- Resource Conservation and Recovery Act (RCRA)
- Clean Water Act (CWA)
- Hazardous and Solid Waste Amendments (HSWA)
- National Emission Standards for Hazardous Air Pollutants (NESHAPS)
- Sara-Title III Emergency Planning and Community Right-To-Know Act
- Water Quality Act

These regulatory changes have impacted the penetrant process in several ways. The Clean Air Act, which outlawed the use of methyl chloroform, has led to the demise of vapor degreasing and instigated the more prevalent use of alkaline cleaners in preparation for FPI. The use of solvents has been restricted in most shops, including removal of chlorinated solvents. New developers and cleaners with slower evaporation rates were introduced. Given these changes, a review of the effectiveness of the current cleaning processes on typical contaminants was warranted and is the focus of this portion of the program.

3.6.1 Description of Contaminants.

The study included mechanical and chemical cleaning methods, which were on the approved list of at least one of the OEMs participating in the program. The first part of the cleaning study occurred in October 2001 and focused on typical items that may be used in the routine operation and overhaul of engine components but could also lead to clogged surface cracks if not effectively cleaned from the part prior to FPI. The surface contaminants included penetrating oil, antigallant compound, RTV, and high-temperature sealants. The penetrating oil was placed

directly over the cracks as shown in figure 20(a), while the compounds were placed off to the side of the crack, as shown in figure 20(b). Cleaning parameters were evaluated for effective removal of the compounds from the surface and for any impact on FPI detectability. Application of the compounds over the cracks was not considered as part of the current program because it would have complicated the analysis of the effects of the cleaning processes.

The second part of the cleaning study focused on the removal of surface conditions that result from engine operation. The sample set was shipped to Honeywell in Phoenix, AZ, and several methods were used to generate oxidation and scale, soot, and coke and varnish on the sample surface. Details of the sample preparation are shown in table 2. Figure 21 shows each of the baked-on contaminants prior to any cleaning steps. A detailed description of all the contaminants is provided in table 10.

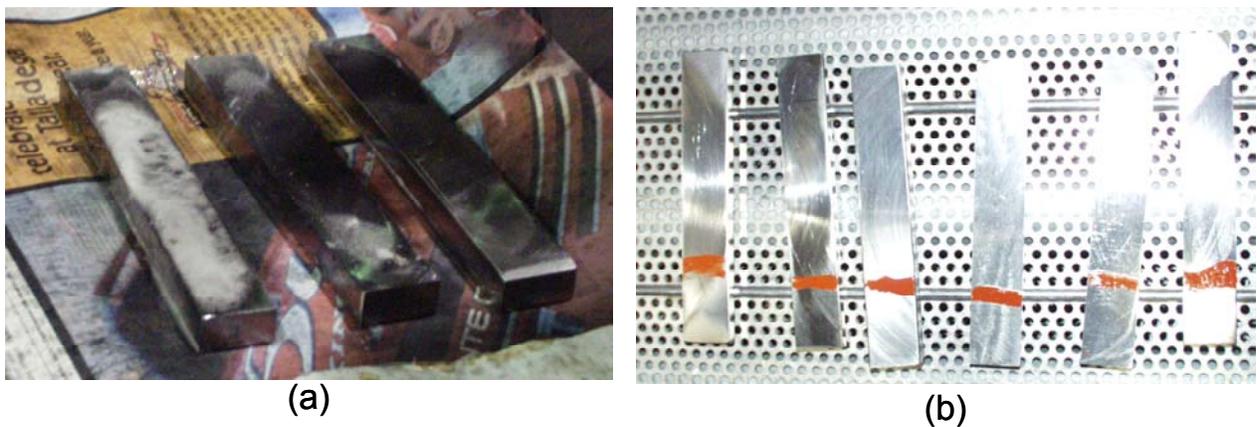


FIGURE 20. (a) PENETRATING OIL APPLIED DIRECTLY OVER CRACKS AND (b) RTV APPLIED TO ONE SIDE OF THE CRACKS

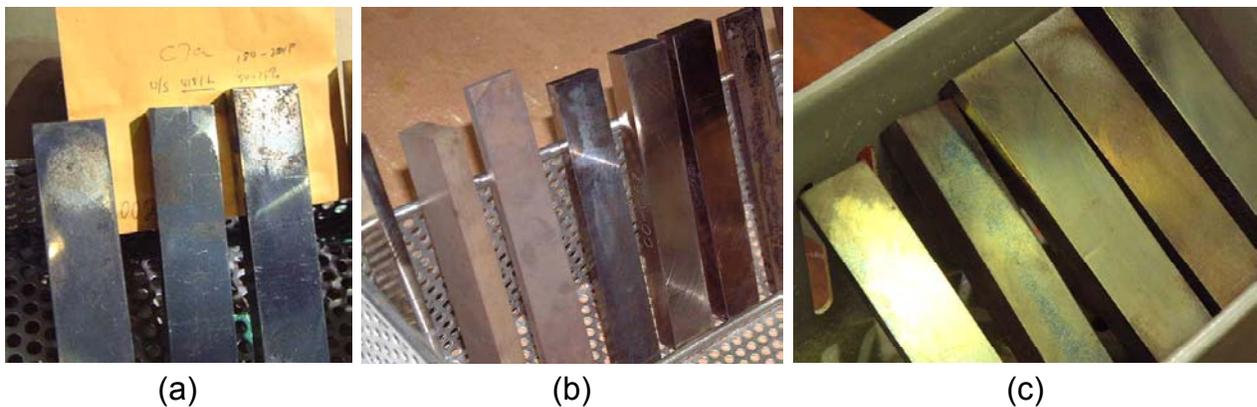


FIGURE 21. (a) OXIDATION AND SCALE, (b) SOOT, AND (c) VARNISH

TABLE 10. LIST OF CONTAMINANTS USED FOR THE CLEANING STUDY

Contaminant	Description	Application
Penetrating Oil	Thinned mineral oil with corrosion inhibitors (limited number of approved products for Ti alloys).	Applied over the crack and allowed to sit over night (approximately 15 hours).
Antigallant - Ti alloys	A molybdenum disulphide/inorganic binder-based compound applied by spraying or brushing and baked.	Applied to the side of the sample away from the crack.
Antigallant - Ni alloys	A graphite/organic binder-based compound applied by spraying or brushing and baked.	Applied to the side of the sample away from the crack.
RTV Compound	Silicone rubber compound used for insulation or bonding and sealing of engine components. Can be air-cured or a two-part mix.	Applied to the side of the sample away from the crack.
High-Temperature Sealant	Nickel powder and binder used for thread lubricant and sealant for some high-compressor components.	Applied to the side of the sample away from the crack.
Scale	Heavy heat-induced oxidation produced during high-temperature engine operation or heat treatment in an air furnace, often time-at-temperature dependent.	Full coverage of sample surface.
Oxidation	Thin oxide film produced during lower-temperature engine operation or short-duration heat treatments.	Full coverage of sample surface.
Soot	Loosely adherent carbonaceous particles resulting from incomplete combustion of fuel or oil. Could also include airborne particles deposited onto the components.	Full coverage of sample surface.
Coke and Varnish	Heavy carbonaceous deposits and polymerized oil residues caused by oxidation and local high temperatures in the engine environment.	Full coverage of sample surface.

3.6.2 Description of Cleaning Methods.

Two broad classes of cleaning processes were considered in the program: chemical methods and mechanical or blasting methods. To facilitate tracking of parts, the chemical methods were designated by a C and the mechanical methods by a B, followed by numbers as indicated in table 11. The processes contain chemical solutions and blasting media approved by various engine manufacturers and should not be considered an endorsement for any particular product line or vendor. Although there are other equivalent materials that are approved by engine OEMs, it was felt that the materials used in this study were representative. Table 11 provides a summary of the cleaning parameters, including the designations used during this program. Detailed steps used to process the samples are provided in appendix C. Figure 22(a) shows as-received and used for the plastic media and walnut shells. Figure 22(b) shows the glass beads

used in the wet glass bead process and two grit sizes of Al_2O_3 . With the exception of the wet glass bead process, all mechanical blasting processes were performed in the cleaning shop at Delta Air Lines in Atlanta. Wet glass bead processes were not available at Delta so arrangements were made with Northwest Airlines to use their facilities, also located in Atlanta. Figure 23(a) shows the pressure cabinet used for plastic media blasting. In the study performed at the Delta facility, adjustments to the pressure were made using the dial gauges on the cabinet. Two different pressures were evaluated: 40 psi, which is the recommended pressure in OEM standard practices manuals for pressure-type cabinets, and 80 psi. Figure 23(b) shows the interior of the pressure cabinet used for walnut shell blasting, and figures 23(c) and 23(d) provide a closer view of the sample before and during the cleaning process. The sample is held in one hand and the media gun is held in the other. The media is applied with a sweeping motion for the time durations shown in table 11 for each of the media types. A distance of 3 to 4 inches (76 to 102 mm) was used for the nozzle-to-part distance and a 45 to 60 degree angle was maintained to the work surface. The sweeping motion was perpendicular to the crack direction.

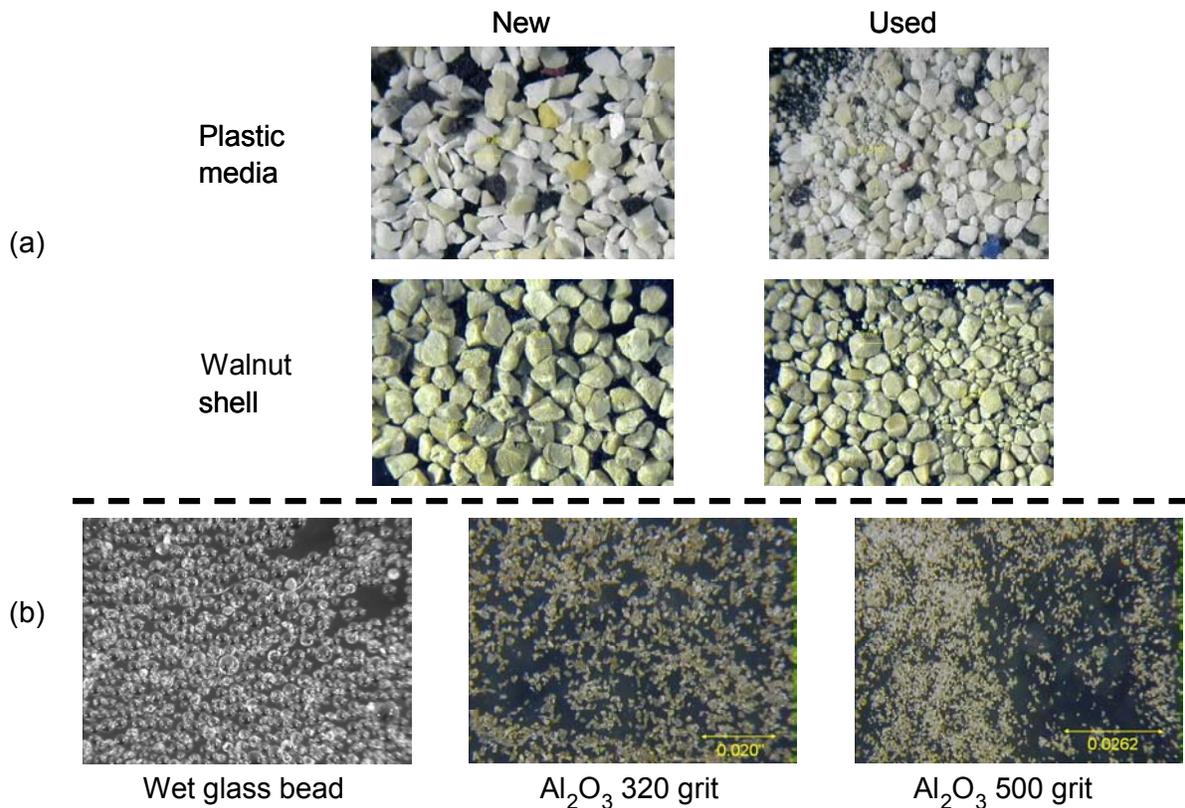


FIGURE 22. VARIOUS MEDIA USED DURING THE STUDY (a) AS-RECEIVED AND USED MEDIA FOR PLASTIC MEDIA AND WALNUT SHELLS AND (b) AS-RECEIVED MEDIA FOR WET GLASS BEAD AND TWO Al_2O_3 GRIT SIZES



(a)



(b)



(c)



(d)

FIGURE 23. (a) PRESSURE CABINET USED FOR PLASTIC MEDIA BLASTING, (b) INTERIOR VIEW OF THE PRESSURE CABINET USED FOR WALNUT SHELL BLASTING, (c) SAMPLE AND MEDIA GUN SHOWN PRIOR TO MEDIA BLASTING, AND (d) VIEW OF THE CLEANING PROCESS WITH MEDIA SHOWN BEING APPLIED TO THE SAMPLE

TABLE 11. CLEANING STUDY PARAMETERS

Designation	Cleaning Method	Cleaning Chemical or Materials	Temperature/Pressure/Time
B1	Plastic media blast	Plasti-Grit (60-120 mil)	NA/40 psi/30 seconds. Some tests were also run at 80 psi to evaluate the effect of media blast pressure on detectability.
B2	Wet glass bead blast	0.0021"-0.0029" diameter beads (SPS 235)	NA/50 psi/10 seconds
B3	Dry Al ₂ O ₃ grit blast	240-grit aluminum oxide	NA/25-30 psi/5-10 seconds
B4	Dry Al ₂ O ₃ grit blast	320-grit aluminum oxide	NA/25-30 psi/5-10 seconds
B5	Dry Al ₂ O ₃ grit blast	500-grit aluminum oxide	NA/25-30 psi/5-10 seconds
B6	Walnut shell media blast	Walnut shells (60-120 mil)	NA/40 psi/30 seconds
C1	Aqueous degreaser	Turco 5948R at 20% concentration	150°F (65.5°C)/NA/15 minutes
C2a	Alkaline derust short soak	Degrease in Turco 5948R (20%/150°F (65.5°C)/15 minutes), Turco 4181L (50%-75%/180°-200°F (82.2°-93.3°C)/3 minutes), 1-minute, cold-water agitated rinse	Details given on left
C2b	Alkaline derust long soak	Degrease in Turco 5948R (20%/150°F (65.5°C)/15 minutes), Turco 4181L (20%/180°-190°F (82.2°-87.77°C)/20 minutes), 1-minute, cold-water agitated rinse	Details given on left
C3	One-step alkaline	Turco 4181L at 66%-70% concentration	180°-200°F (82.2°-93.3°C)/ NA/ 30 minutes
C4	Four-step alkaline	Turco 4181L (50%-75%/ 180°-200°F (82.2°-93.3°C)/ 15 minutes), water spray rinse, Turco ScaleGon 5 (20%/ 175°-195°F (79.4°-90.55°C)/15 minutes), spray rinse, Turco 4338L (20%/180°-200°F (82.2°-93.3°C)/15 minutes), spray rinse, Turco 4181L (50%-75%/180°-200°F (82.2°-93.3°C)/ 5 minutes), cold-water dip and spray rinse	Details given on left

TABLE 11. CLEANING STUDY PARAMETERS (Continued)

Designation	Cleaning Method	Cleaning Chemical or Material	Temperature/Pressure/Time
C5	Alkaline gel cleaner	Turco 5805 (100%) followed by hot-water pressure spray wash	Ambient/NA/30 minutes
C6	Degreaser	Spray, steam, or foam solution of Turco 5948R followed by hot-water spray wash.	Ambient/NA/1 minute
C7a	Ultrasonic alkaline cleaning – Ni	Alkaline rust remover solution Turco 4181L at 50%-75% by volume with water, at 180°-200°F (82.2°-93.3°C)	180°-200°F (82.2°-93.3°C)/ NA/15 minutes
C7b	Ultrasonic alkaline cleaning – Ti	Turco 4181L at 20% by volume with water, at 180°-190°F (82.2°-87.77°C)	180°-200°F (82.2°-93.3°C)/ NA/15 minutes
C8	Rubber stripper	Turco T6045 for 4 hours	Ambient/NA/4 hours
ACT	Acetone	Acetone soak with no agitation	Ambient/NA/15 hours
UT ACT	Acetone	Ultrasonically agitated acetone cleaning	NA/NA/30 minutes
VDG	Vapor degreaser*	Vapor degreasing using trichlorethylene (ASTM D 4080)	NA/NA/3-5 minutes
Permanganate	Permanganate*	Turco 2-part 20% 4338L (sodium hydroxide and sodium permanganate = parts 1 and 2)	190°F (87.77°C)/NA/ 30 minutes
Acid descaler	Acid descaler*	Turco ScaleGon 5 (20% concentration)	190°F (87.77°C)/NA/ 30 minutes
UT H ₂ O	Agitated water soak**	Ultrasonically agitated water	NA/NA/10 minutes
H ₂ O	Water soak**	Water soak with no agitation	70°F/NA/10 minutes

*Cleaning methods were not planned as part of the original study. They were added to evaluate the cleaning of baked-on contaminants.

**Two water treatment steps were added to evaluate the potential effect of water entrapment on detectability. These were not expected to serve as cleaning steps.

In addition to the mechanical cleaning methods described above, eight chemical cleaning methods were selected for evaluation. Methods C1, C2a, C2b, C3, and C4 are incorporated in the primary cleaning lines at the Delta facility, as shown in figure 24(a). Samples were placed in metal baskets and processed along with production parts following the appropriate steps as listed in appendix B. Ultrasonic cleaning of parts (C7a and C7b) was accomplished using a separate cleaning line shown in figure 24(b). The alkaline gel (C5) removal step is shown in figure 24(c). Oven drying, chosen to be the standard drying procedure for use in the cleaning study, followed all the chemical cleaning procedures. The oven temperature and time used in the drying study was also used in the cleaning study, i.e., 225°F (107°C) for 30 minutes.

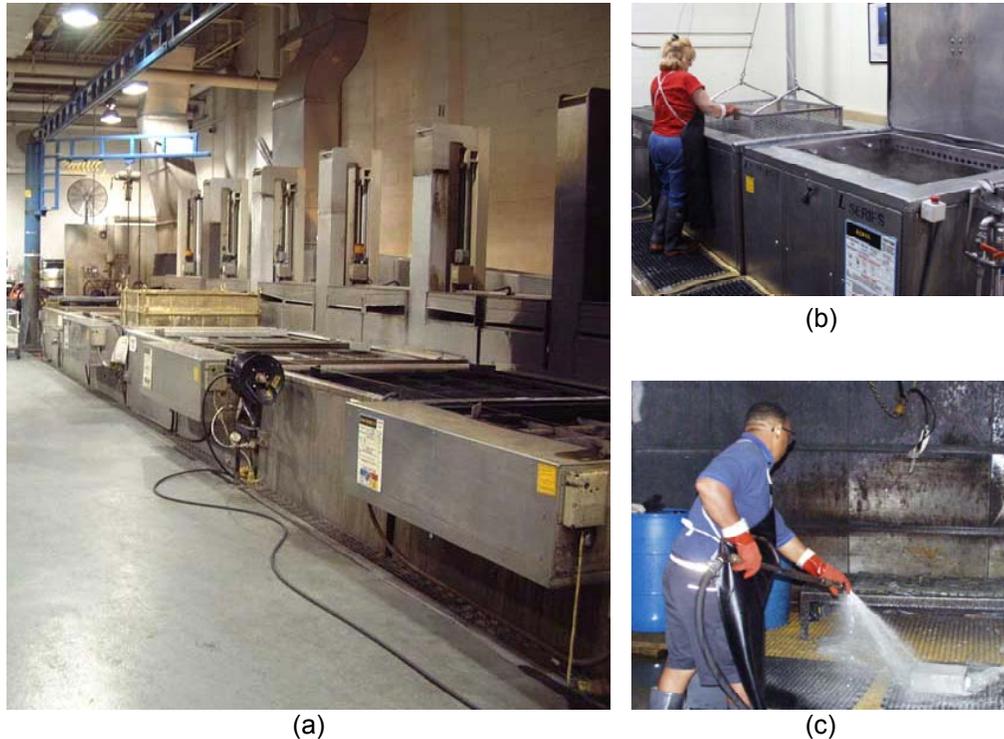


FIGURE 24. (a) CLEANING LINE, (b) ULTRASONIC-ASSISTED CLEANING PROCESSES, AND (c) SPRAY CLEANING REMOVAL OF ALKALINE GEL

3.6.3 Experimental Steps for the Cleaning Study.

The cleaning study was accomplished in two separate 1-week studies performed at the Delta facility in Atlanta. Based on the optical crack length measurements and the brightness response of the samples, the samples were subdivided into groups of three samples with a small, medium, and large crack in each group. The samples were contaminated as indicated in table 10. Table 12 indicates the cleaning methods used in the two-part study. The samples were exposed to high-temperature processes between the two studies to simulate contamination that can occur from engine operation. Note that the temperatures for the oxidation process were chosen to produce surface contamination in a reasonable, accelerated time and are not representative of typical engine operation. After contamination and cleaning, the samples were inspected with FPI and characterized by brightness measurements and UVA images.

TABLE 12. CONTAMINANTS AND CORRESPONDING CLEANING METHODS

Contaminants	Cleaning Methods*
Cleaning Studies – Part 1	
Penetrating oils	C1 – Aqueous degreaser C2a – Alkaline derust solution A used for Ni C2b – Alkaline derust solution B used for Ti C3 – One-step alkaline cleaner C6 – Steam with aqueous degreaser C7a – Ultrasonic with alkaline derust solution B used for Ni
Antigallant compound	C2b – Alkaline derust solution B used for Ti C7a – Ultrasonic agitation in alkaline derust solution B used for Ni C7b – Ultrasonic agitation in alkaline derust solution A used for Ti B1 – Plastic media blast (at 80 and 40 psi) for 30 sec. using pressure cabinet B6 – Walnut shell blast (at 50 psi) for 1 minute using pressure cabinet
RTV compound and high-temperature sealant	B1 – Plastic media blast (at 80 and 40 psi) for 30 sec. using pressure cabinet B5 – Al ₂ O ₃ 500 grit B6 – Walnut shell blast (at 50 psi) for 1 minute using pressure cabinet
Cleaning Studies – Part 2	
Oxidation and scale	C2a – Alkaline derust solution A used for Ni C2b – Alkaline derust solution B used for Ti C3 – One-step alkaline cleaner C4 – Four-step alkaline cleaner C7a – Ultrasonic with alkaline derust solution B used for Ni B2 – Wet glass bead blast B3 – Al oxide at 240 grit B4 – Al oxide at 320 grit B5 – Al oxide at 500 grit
Soot	C1 – Aqueous cleaner C2a – Alkaline derust solution A used for Ni C2b – Alkaline derust solution B used for Ti C3 – One-step alkaline cleaner C4 – Four-step alkaline cleaner C5 – Alkaline gel cleaner C7a – Ultrasonic with alkaline derust solution B used for Ni B1 – Plastic media blast (40 psi) for 30 sec. using pressure cabinet B3 – Al oxide at 240 grit B4 – Al oxide at 320 grit
Coke and varnish	C3 – One-step alkaline cleaner C4 – Four-step alkaline cleaner C5 – Alkaline gel cleaner C7a – Ultrasonic with alkaline derust solution B used for Ni B1 – Plastic media blast (40 psi) for 30 sec. using pressure cabinet

*These cleaning methods are used throughout this report. Please refer to this table for complete definition of the cleaning methods.

To understand the effect of the various cleaning methods on detectability, brightness measurements were made on the samples after cleaning. A comparison of the brightness and UVA image after contamination and cleaning was made to the prior baseline measurements. In an effort to facilitate comparisons, a color scale was established, as shown in figure 25. Samples which exhibited reductions in brightness of more than 40% (indicated by orange) or no brightness measurement (indicated by red) were cause for concern. The results for each of the cleaning methods are provided in the following sections.

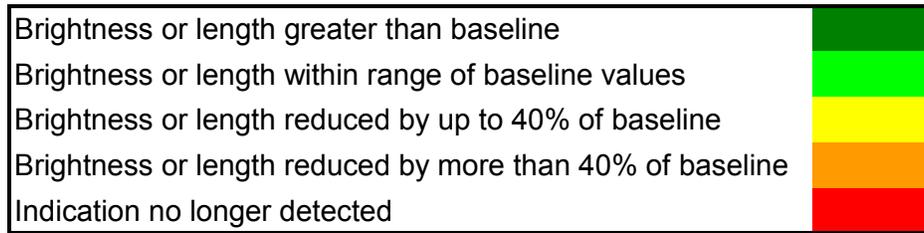


FIGURE 25. COLOR SCALE

3.6.4 Results of the Cleaning Study.

To facilitate comparisons of results, data was tabulated for each of the cleaning methods, as shown in table 13. The results for both Ti and Ni are shown with Ti shaded in yellow and Ni in green and indicated in the third column of the table. The first column indicates the contamination type. In some cases, such as the last set of three Ni samples, once a sample was restored to baseline brightness, it was often used for additional studies. The second column indicates the cleaning method. The specimen ID number and optical lengths are included in the fourth and fifth columns respectively. The baseline brightness values are listed in two sets of three columns. The remaining columns list brightness values after the contamination and cleaning process. For these columns, the color scale described in figure 25 was used. In addition to the brightness values, UVA lengths were also evaluated and comparisons of the images was completed, as shown in figures 26 and 27.

TABLE 13. RESULTS FOR C1 USED TO REMOVE OIL CONTAMINATION AND SOOT

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct C1	Feb C7a	Feb C4	Feb ace	Feb C1	Feb C1 (after oil)
Soot	C1	Ti	00-077	0.039				46.2	44.8						21.6	
Soot	C1	Ti	01-042	0.058				8.4	8						lost	
Soot	C1	Ti	01-013	0.081				173.9	166.3						13.3	
Oil C	C1	Ti	00-093	0.06	68.28	73.53	81.3				71.65					
Oil C	C1	Ti	01-012	0.093	96.76	110.8	128.9				103.5					
Oil C	C1	Ti	01-015	0.033	3.88	5.2	7.8				2					
Oil C	C1	Ni	00-116	0.056	2.5	2.1	18.1				22.2					
Oil C	C1	Ni	01-029	0.083	107.4	129.3	129.3				92.5					
Oil C	C1	Ni	01-031	0.026	0.52	6.5	1.2				0.5					
Soot+C7a+C4+ace	C1+oil	Ni	01-031	0.026				0.04	0.9	0.9		lost		2.1	2.5	2.4
Coke & Varnish+C7a+C4+ace	C1+oil	Ni	00-124	0.064				174.3	250			169.3	sat	sat		sat
Oxidation & Scale+C7a+C4+ace	C1+oil	Ni	00-120	0.122				53.4	73.7	81.6		46.6	76.4	79.9		82.4

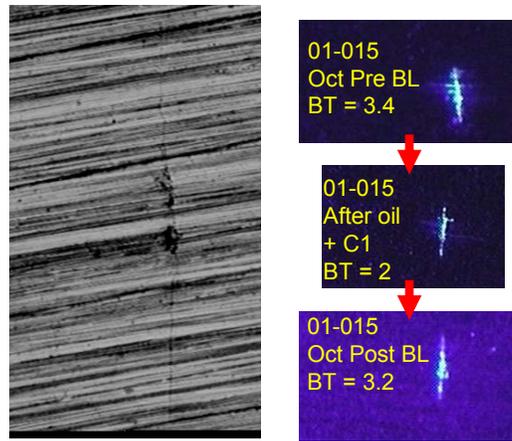


FIGURE 26. RESULTS FOR THE 01-015 Ti SAMPLE AFTER OIL CONTAMINATION AND CLEANING WITH C1

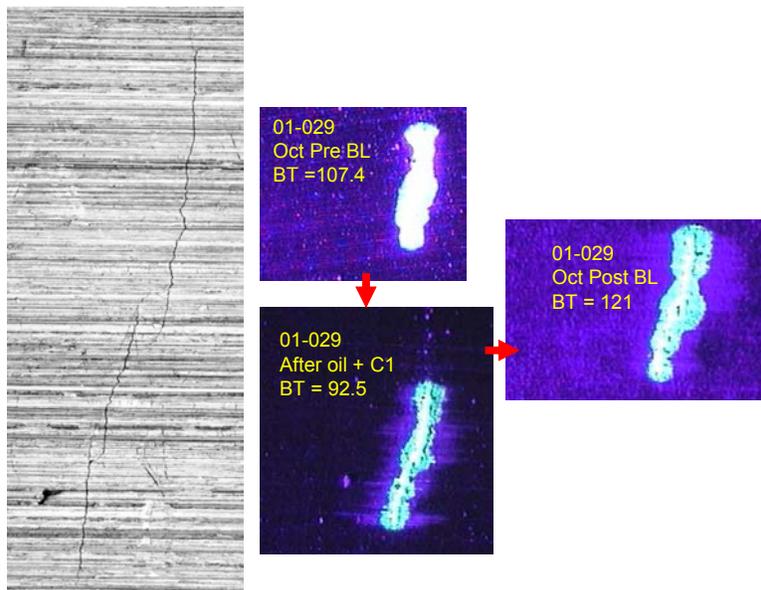


FIGURE 27. RESULTS FOR THE 01-029 Ni SAMPLE AFTER OIL CONTAMINATION AND SUBSEQUENT CLEANING WITH C1

3.6.4.1 Aqueous Degreaser.

Aqueous degreaser (C1) (Turco 5948R at 20% concentration) at 150°F (65.5°C) for 15 minutes followed by a cold-water rinse. Samples were oven-dried at 225°F (107°C) prior to FPI processing. C1 was used to clean sooted and oil-contaminated samples, both Ti and Ni. Table 13 shows the brightness results after contamination and cleaning with C1.

All three cracks showed degradation in brightness after C1 was applied to the clean sooted samples of Ti, as shown in table 13, with one of the three improving after using C2b.

Given these results, aqueous degreasers may not be an effective method for soot removal.

Eight of the nine (three Ti and six Ni) samples showed acceptable brightness after cleaning to remove oil contamination with C1. Three Ti and three Ni samples were evaluated in October and three Ni samples were evaluated in February. Note that one sample, 01-015, which had a 0.033" crack, showed a significant reduction in brightness as evidenced by the orange shade in the Oct C1 column in table 13. UVA results for this sample are shown in figure 26, which shows that the indication was still visible. The results for a larger crack (0.083"), sample 01-029, are provided in figure 27 for comparison.

Given these results, C1 is believed to be effective for removal of oil contamination from both Ti and Ni samples.

3.6.4.2 Alkaline Derust Short Soak, High Concentration.

Alkaline derust short soak, high concentration (C2a) (degrease in Turco 5948R (20%/150°F (65.5°C)/15 minutes), Turco 4181L (50%-75%/180°-200°F (82.2°-93.3°C)/3 minutes), and a 1-minute, cold-water-agitated rinse) is used for Ti alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C2a was used to clean oxidation and scale, soot, and oil-contaminated Ti samples. Table 14 shows the brightness results after contamination and cleaning with C2a.

TABLE 14. RESULTS FOR C2a USED TO REMOVE OIL CONTAMINATION, OXIDATION AND SCALE, AND SOOT

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct C2a	Feb C2a
Oxidation & Scale	C2a	Ti	00-067	0.065				121.2	97.1	119.8		lost
Oxidation & Scale	C2a	Ti	00-080	0.057				2.3	2.4			lost
Oxidation & Scale	C2a	Ti	00-090	0.060				104.9	111.1			lost
Soot	C2a	Ti	01-014	0.061				114.7	102.2			lost
Soot	C2a	Ti	01-016	0.050				3.7	4.3			lost
Soot	C2a	Ti	00-091	0.087				113.5	92.6			35.5
Oil A	C2a	Ti	00-080	0.057	2.49	3.49	3.9				1.4	
Oil A	C2a	Ti	00-088	0.114	250	250	250				44.8	
Oil A	C2a	Ti	01-013	0.081	61.85	82.4	101.7				90.6	

The results for the three oxidation and scale samples are shown in the first three lines of table 14, which show that C2a was not an effective cleaning method for oxidation and scale. None of the three indications were detected after oxidation and scale and cleaning with C2a. Subsequent use of C2b led to improvement for one of the three samples but was not effective for the remaining two. Using acetone on the remaining two samples led to a return of one of the indications, 00-090, as shown in figure 28. The optical micrographs for the crack before (left) and after (right) oxidation and scale are shown. The UVA baseline image is shown in the upper middle with the UVA image after using acetone shown in the lower middle. It was postulated that residue from the alkaline cleaner may also be contributing to the loss of penetrant brightness.

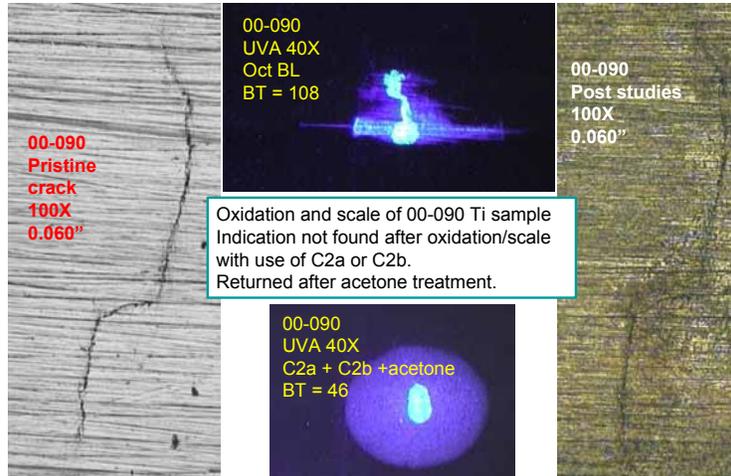


FIGURE 28. RESULTS FOR THE 00-090 Ti SAMPLE AFTER OXIDATION AND SCALE

The brightness comparison results for the three soot samples are shown in table 14 and indicate that two of the three cracks were not found after cleaning with C2a alone, and the third indication saw significant reduction in brightness going from a reading of 92.6 in October to 35.4 in February. Additional cleaning methods were tried with some success. The results for sample 01-014 are shown in figure 29. The optical micrographs for the crack before (left) and after (right) soot are shown. The UVA baseline image is shown in the upper middle. No indication was found after using C2a, a minimal indication was found after using C2b. Using a permanganate step and a subsequent acetone cleaning restored the brightness as shown in the lower middle of figure 29. Given the present results, C2a is not an effective cleaning method for oxidation and scale or soot for Ti.

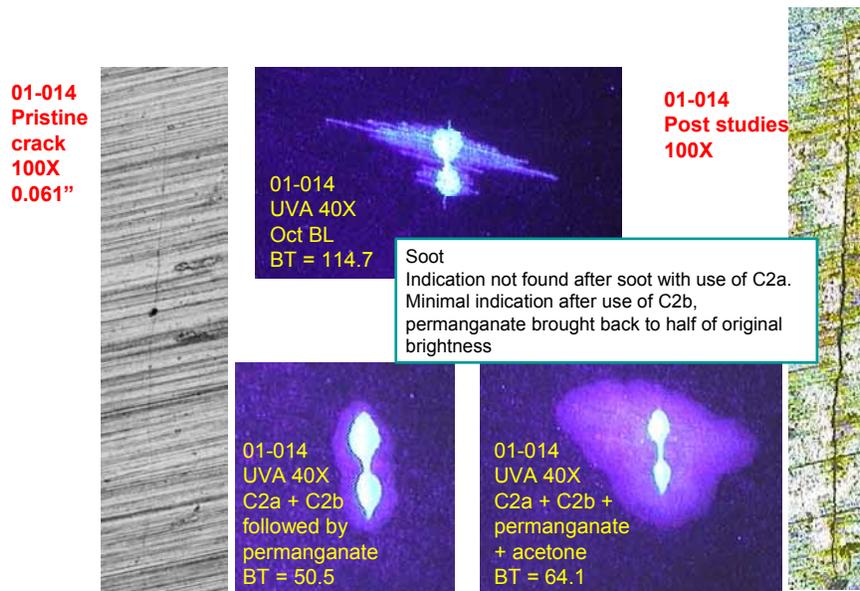


FIGURE 29. RESULTS OF 01-014 Ti SAMPLE AFTER SOOT AND SUBSEQUENT CLEANING WITH ALKALINE DERUST CLEANING PROCESSES

Reductions were found in two of the three oil-contaminated samples, even after using C2a as the cleaning method. Note the results shown for the last three rows in table 14.

Given these results, C2a is not a robust method for cleaning oil residue or baked-on contaminants. Consideration of additional cleaning methods is recommended, including the evaluation of multiple-step processes currently used for nonrotating Ti parts.

3.6.4.3 Alkaline Derust Long Soak, Low Concentration.

Alkaline derust long soak, low concentration (C2b) (degrease in Turco 5948R (20%/150°F/15 minutes), Turco 4181L (20%/180°-190°F/20 minutes), and a 1-minute cold-water-agitated rinse) is used for Ti alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C2b was used to clean oil contamination and antigallant compound from Ti samples in October. Table 15 shows the brightness results after contamination and cleaning with C2b. C2b was also used to remove oxidation and scale and soot in February, with data provided in table 15. In some cases, C2b was a follow-up process. Results for the baked-on contaminants follow those for the oil and antigallant studies.

TABLE 15. RESULTS FOR C2b USED TO REMOVE OIL CONTAMINATION AND ANTIGALLANT

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct C2b
Oil B	C2b	Ti	00-066	0.108	100.1	111.33	161.1				173.3
Oil B	C2b	Ti	01-042	0.058	6.34	6.7	12.3				3.6
Oil B	C2b	Ti	01-044	0.031	1.36	1.5	2.9				0.35
No oil	C2b cold	Ti	00-090	0.06	68.2	116.9	162.9				121.3
No oil	C2b cold	Ti	01-012	0.093	96.76	110.8	128.9				92.1
No oil	C2b hot	Ti	00-093	0.06	68.28	73.53	81.3				55.2
No oil	C2b hot	Ti	00-123	0.095	149.25	156.6	186.9				157.1
Oil Repeat	C2b cold	Ti	00-077	0.039	37.6	40.94	47.1				4.2
Oil Repeat	C2b cold	Ti	01-040	0.121	37.03	46	54.8				0.5
Oil Repeat	C2b hot	Ti	00-097	0.062	54.45	85.11	107.3				0.6
Oil Repeat	C2b hot	Ti	00-098	0.02	10.34	12.84	15.4				9.9
AG B	C2b	Ti	01-037	0.093	5.25	7.18	10.67				0.04
AG B	C2b	Ti	01-041	0.031	0.16	0.8	0.7				lost
AG B	C2b	Ti	01-053	0.057	30.19	37.27	6.75				69

Significant reductions were found in two of the three oil-contaminated samples after using C2b as the cleaning method, as shown by the first three samples listed in table 15. In an effort to determine if the reductions were because of oil contamination or because of residue from the alkaline cleaner and to determine if the temperature of the cleaner had an effect, a repeat study was performed using two samples for each condition (no oil – hot or cold C2b and with oil – hot or cold C2b). Significant reductions occurred in brightness of the oiled samples, as shown by the orange shading. The no oil samples performed in an acceptable fashion, indicating that the reductions were because of inadequate oil removal.

Three samples were also processed with antigallant applied off to the side of the crack as discussed in table 10. The compound was successfully removed, but note that one of the three cracks was not found after cleaning with C2b and another showed significant reductions. These

results, in combination with the oil results, led to a repeat C2b study with no oil contamination. The repeat study was performed to assess the potential contamination from the alkaline cleaner, which led to brightness reductions and potential fading of the indications. The results showed reduction in two of the four samples, as evidenced by the yellow shading for the no oil samples in table 15. The potential for alkaline or other effects from the cleaner residue to effect brightness and detectability of small, tight cracks, such as the 0.031" crack in sample 01-041, is a concern.

Given these results, C2b is not an acceptable cleaning method for oil contamination.

Reductions in brightness were found in samples that were only exposed to the cleaning solution. Therefore, further steps to improve the resistance of penetrant solutions to degradation from alkaline cleaners would be valuable.

Three samples (00-076, 00-098, and 00-095) were processed with C2b as the first cleaning step after oxidation and scale treatments shown in table 10. Two of the three samples showed significant reductions in brightness, as shown in table 16. The highest brightness was found for 00-095 and results are shown in figure 30. A second C2b treatment to the same three samples showed further reductions in brightness. Note that while the results for sample 00-095 do show a brightness reduction, it is much better than for the remaining two samples. C2b was also applied to three other oxidation and scale samples (00-067, 00-080, and 00-090) for which cracks were not detectable after using the C2a method. Only one of the three, 00-067, showed marginal improvement with C2b, as shown in figure 31.

TABLE 16. RESULTS FOR C2b USED TO REMOVE BAKED-ON CONTAMINANTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct C2b	Feb B1	Feb C1	Feb C5	Feb C2a	Feb C2b	FebC2b
Oxidation and Scale	C2a	Ti	00-067	0.065	121.2	97.1	119.8					lost		13
Oxidation and Scale	C2a	Ti	00-080	0.057	2.3	2.4						lost		lost
Oxidation and Scale	C2a	Ti	00-090	0.060	104.9	111.1						lost		lost
Oxidation and Scale	C2b	Ti	00-076	0.063	101.4	89.5								3.1
Oxidation and Scale	C2b	Ti	00-098	0.020	10.2	9.5								0.2
Oxidation and Scale	C2b	Ti	00-095	0.061	109.3	119.2								117.6
Oxidation and Scale + C2b	C2b	Ti	00-076	0.063	101.4	89.5							3.1	0.3
Oxidation and Scale + C2b	C2b	Ti	00-098	0.020	10.2	9.5							0.2	lost
Oxidation and Scale + C2b	C2b	Ti	00-095	0.061	109.3	119.2							117.6	64.8
Soot	C2b	Ti	01-040	0.121	44	49.4								lost
Soot	C2b	Ti	01-037	0.093	6.1	9								lost
Soot	C2b	Ti	00-081	0.120	120.6	115.3								sat
Soot + C2b	C2b	Ti	01-040	0.121	44	49.4							lost	lost
Soot + C2b	C2b	Ti	01-037	0.093	6.1	9							lost	lost
Soot + C2b	C2b	Ti	00-081	0.120	120.6	115.3							sat	sat
Soot + C5	C2b	Ti	01-017	0.054	34.8	69.8					20.3			21.3
Soot + C5	C2b	Ti	01-041	0.031	1.1	2.8					lost			lost
Soot + C5	C2b	Ti	00-087	0.068	60.1	92.5					38.3			69.1
Soot + C1	C2b	Ti	00-077	0.039	46.2	44.8					21.6			46.2
Soot + C1	C2b	Ti	01-042	0.058	8.4	8					lost			lost
Soot + C1	C2b	Ti	01-013	0.081	173.9	166.3					13.3			12.6
Soot + B1	C2b	Ti	01-052	0.049	44.9	44.8			68.3					71.5
Soot + B1	C2b	Ti	01-045	0.052	1.9	1.5			0.95					lost
Soot + B1	C2b	Ti	01-001	0.063	67.3	106.6			29.7					15.6

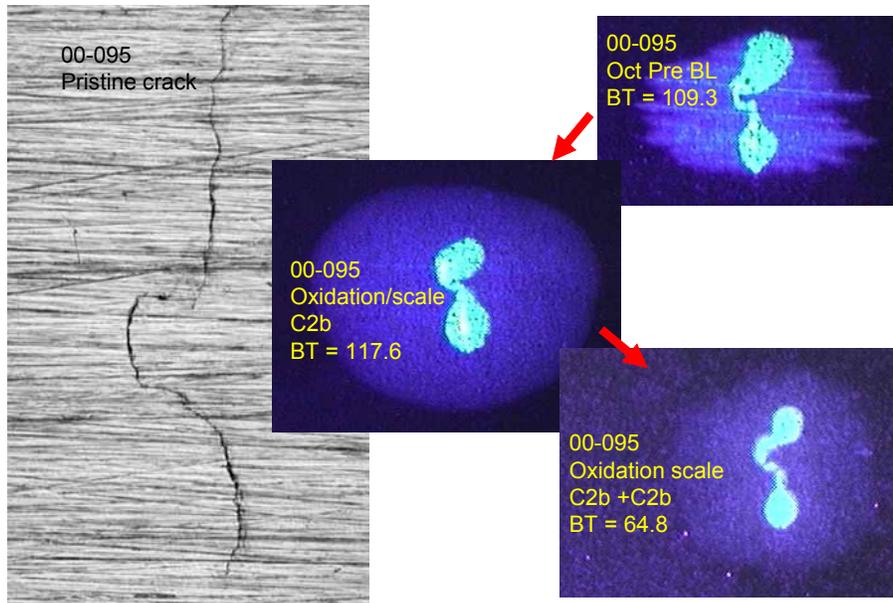


FIGURE 30. RESULTS FOR THE 00-095 Ti SAMPLE AFTER OXIDATION AND SCALE AND SUBSEQUENT CLEANING WITH THE C2b METHOD

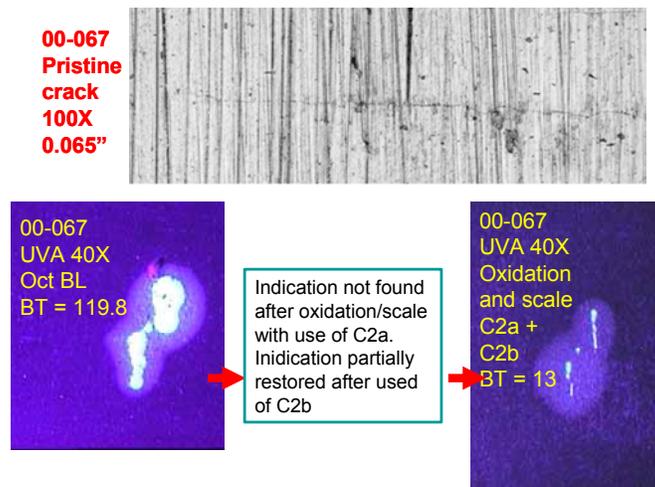


FIGURE 31. RESULTS FOR 00-067 Ti SAMPLE AFTER OXIDATION AND SCALE AND SUBSEQUENT CLEANING WITH ALKALINE DERUST METHODS

Given these results, C2b does not provide acceptable performance for removal of oxidation and scale from Ti. As indicated in the C2a results, consideration of additional cleaning methods is recommended, including the evaluation of multiple-step processes currently used for nonrotating Ti parts.

A total of 12-sooted samples were cleaned with the C2b process. Four of twelve cracks had acceptable brightness, as indicated by the green shading in table 16. Only one of the original cracks, 00-081, was found after sooting. There were no improvements after a second application

of C2b. C2b was also selected as a follow-on treatment to C1, C5, and plastic media blast (B1), which did show some improvement for one of the three samples in each of the cleaning methods but also showed a reduction in some samples.

Neither alkaline derust method proved to be an effective cleaning method for removal of oxidation and scale or soot. Additional studies to understand and document the impact of alkaline on fluorescence and the buildup of residue from alkaline cleaners in fatigue cracks would be valuable.

3.6.4.4 One-Step Alkaline.

One-step alkaline (C3) (Turco 4181L at 66%-70% concentration) is used for Ni alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. Alkaline cleaner was used to clean oil contamination from Ni samples in October. Table 17 shows the brightness results after contamination and cleaning with C3. C3 was also used to remove oxidation and scale and soot in February. The results for the baked-on contaminants follow the discussion of those for the oil studies. Table 17 shows the brightness results after oil contamination and cleaning with the one-step alkaline cleaner method.

TABLE 17. RESULTS FOR C3 USED TO REMOVE OIL CONTAMINATION

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Oct C3
Oil A	C3	Ni	00-110	0.054	23.94	29.3	32.7				14.6
Oil A	C3	Ni	00-119	0.08	29.4	31.3	39.3				17.2
Oil A	C3	Ni	01-039	0.021	2.89	3.6	4.4				5.2
No oil	C3 cold	Ni	01-005	0.064	36	38.3	61.2				37
No oil	C3 cold	Ni	01-021	0.028	4.74	6.3	3.9				9.9
No oil	C3 cold	Ni	01-035	0.025	3.42	4	4				4
No oil	C3 hot	Ni	01-009	0.028	8.6	8.9	12.7				13.2
No oil	C3 hot	Ni	01-030	0.026	2.66	4.47	3.35				6.5
No oil	C3 hot	Ni	01-027	0.061	57.13	67.9	68.6				78.7
Oil Repeat	C3 cold	Ni	00-105	0.067	136.24	108.4	74.4				192
Oil Repeat	C3 cold	Ni	01-022	0.023	16.09	16.8	9.5				10.9
Oil Repeat	C3 cold	Ni	01-055	0.058	27.48	37.5	31.6				37.2
Oil Repeat	C3 hot	Ni	00-124	0.064	186.8	172.1	250				126.8
Oil Repeat	C3 hot	Ni	01-020	0.025	16.25	20	18				26.4
Oil Repeat	C3 hot	Ni	01-025	0.053	17.31	25.3	25.3				28.8

Reductions were found in two of the three oil-contaminated samples after using C3 as the cleaning method, as shown by the first three samples in table 17. In an effort to determine if the reductions were because of oil contamination or because of residue from the alkaline cleaner and to determine if the temperature of the rinse water had an effect, a repeat study was performed using three samples for each condition (no oil—followed by C3 with either a hot- or cold-water rinse, and with oil—followed by C3 with either a hot- or cold-water rinse). Similar performance was found for the no oil and oil samples, as shown by the prevalence of green shading in 11 of the 12 samples. The only sample that showed a reduction, 00-124, still had an acceptable indication for detection, as shown in the upper row of figure 32. Figures 32 and 33 show the results for the oil-contaminated samples that were subsequently cleaned with C3 followed by a hot- or cold-water rinse. As with the other postbaseline treatments, all samples were returned to an acetone bath and ultrasonically agitated for 30 minutes prior to a 30-minute oven dry at 225°F

and subsequent FPI processing. The last column of figures 32 and 33 shows the UVA image for the postbaseline results, all of which returned to original or better brightness.

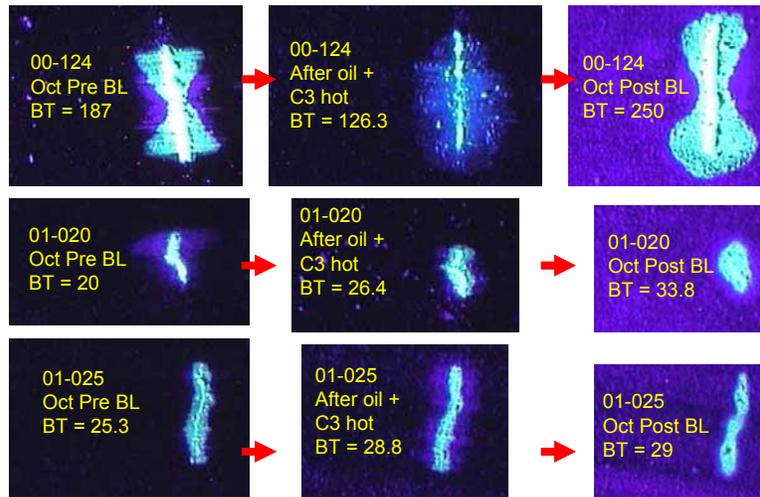


FIGURE 32. COMPARISON OF UVA IMAGES OF OIL-CONTAMINATED Ni SAMPLES CLEANED WITH C3 FOLLOWED BY A HOT-WATER RINSE (Images for three samples are shown, including a prebaseline image in the left column, an image of the cleaned sample in the center, and a postbaseline image in the right column.)

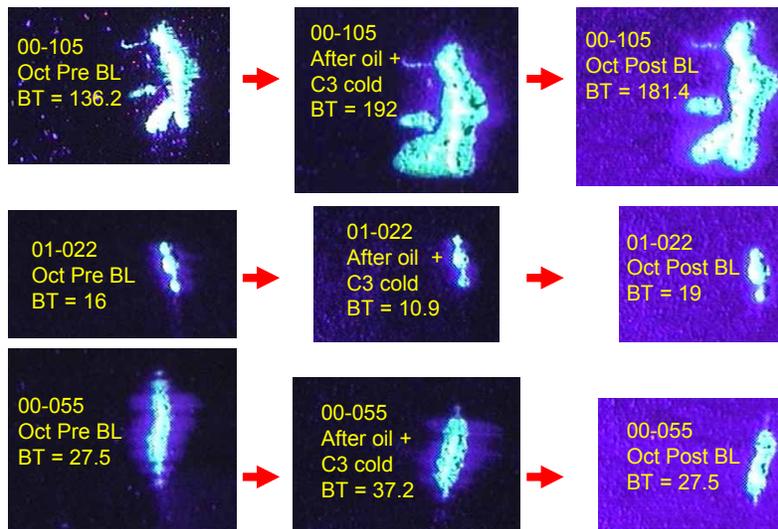


FIGURE 33. COMPARISON OF UVA IMAGES OF OIL-CONTAMINATED Ni SAMPLES CLEANED WITH C3 FOLLOWED BY A COLD-WATER RINSE (Images for three samples are shown, including a prebaseline image in the left column, an image of the cleaned sample in the center, and a postbaseline image in the right column.)

C3 was an effective method for oil removal on six of the nine Ni samples. The water rinse temperature was not found to have an effect and no detrimental effects were found for those samples that were exposed only to the cleaning process, i.e., no oil results. The C2a process

used for Ti uses similar chemistries and concentrations as the C3 process for Ni. However, the Ti process includes a shorter duration in the alkaline solution. Given the better performance for C3 on Ni than the C2a results reported for Ti, additional work is needed to understand if this comes from an alloy effect or a cleaning time effect. Because these effects could not be considered in the current program, future work to compare pristine crack fracture surfaces with those after repeat alkaline treatments would be valuable. Possible effects could include a reaction of the alkaline with Ti, which would clog the cracks with corrosion products. To understand the differences, future work could compare Ni and Ti cracks contaminated with and without oil to be cleaned with the C2a and C3 processes.

Three samples (00-106, 00-108, and 01-055) were cleaned with C3 after the oxidation and scale treatment described previously. As indicated by the orange shading, the C3 method was not effective in removing the oxidation and scale from the crack. The results for one of the samples, 01-055, are shown in figure 34. The baseline image from October shows the result prior to oxidation. After cleaning with C3, the crack image is smaller and dimmer. Given the poor performance of the C3 process, the samples were subsequently cleaned with the four-step alkaline process, designated as C4, and acceptable performance was found. Evidence of the improved performance is provided in the final UVA image of figure 34.

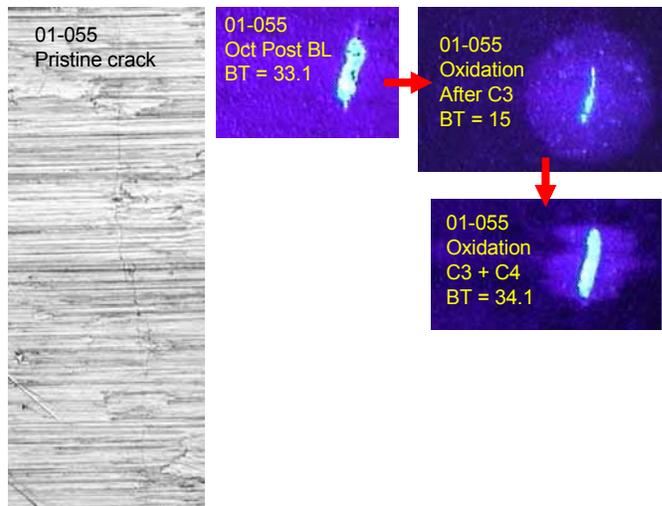


FIGURE 34. RESULTS FOR THE 01-055 Ni SAMPLE AFTER OXIDATION AND SCALE AND SUBSEQUENT CLEANING WITH THE C3 CLEANING PROCESS

Three sooted samples were also selected for cleaning using the C3 method. As indicated by the red shading in table 18, the indication in sample 00-126 was not found after the C3 method. Given the poor performance of the C3 process, the samples were subsequently cleaned with the C4 process and acceptable performance was found.

Table 18 also includes results for three coke and varnish samples that were cleaned with the C3 method. As indicated by the orange shading, one of the samples did not provide an acceptable indication. Subsequent use of C4 following the C3 process did improve the FPI response for sample 01-032.

TABLE 18. RESULTS FOR C3 USED TO REMOVE BAKED-ON CONTAMINANTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb B1	Feb C3
Oxidation and Scale	C3	Ni	00-106	0.07	47.8	24			0.7
Oxidation and Scale	C3	Ni	00-108	0.033	13.9				4.7
Oxidation and Scale	C3	Ni	01-055	0.058	27.5	33.1			15
Soot	C3	Ni	00-126	0.061	37.9	34.4		lost	
Soot	C3	Ni	01-021	0.028	11.3	7.3			12.3
Soot	C3	Ni	01-029	0.083	121.4	148			98.6
Coke and Varnish	C3	Ni	01-008	0.078	2.6	31.4			14.7
Coke and Varnish	C3	Ni	01-032	0.021	7	6.6			0
Coke and Varnish	C3	Ni	00-105	0.067	250	181.4			143.4
Soot + B1	C3	Ni	01-005	0.064	30.1	40.3		8	lost
Soot + B1	C3	Ni	01-030	0.026	4	3.9		1.3	2.3
Soot + B1	C3	Ni	01-038	0.023	0.1			0.56	0.1
Coke and Varnish + B1	C3	Ni	01-027	0.061	79.8	93.2		lost	65.9
Coke and Varnish +B1	C3	Ni	01-035	0.025	4.7	4.7		3.2	2.6
Coke and Varnish + B1	C3	Ni	01-056	0.067	2.6	2.76		0.1	lost

Note: For the sample 01-032, an indication was detectable but the brightness measurement for the indication was the same as the brightness measurement for the surrounding background that leads to a 0 brightness measurement.

Given these results, using the C3 method did not consistently recover samples that had oxidation and scale, soot, or coke and varnish contamination. For this reason, the decision was made to clean all the Ni samples with C4, which is described in the following section.

3.6.4.5 Four-Step Alkaline.

Four-step alkaline (C4) (Turco 4181L (50%-75%/180°-200°F (82.2°-87.77°C)/15 minutes), followed by a water spray rinse, Turco ScaleGon 5 (20%/175°-195°F (79.4°-90.55°C)/15 minutes), followed by a spray rinse, Turco 4338L (20%/180°-200°F (82.2°-87.77°C)/15 minutes), followed by a spray rinse, Turco 4181L (50%-75%/ 180°-200°F (82.2°-87.77°C)/5 minutes), and a cold-water dip and spray rinse is used for Ni alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing.

The C4 process was not originally planned as part of the cleaning program. However, after initial processing of the Ni samples through the planned methods (B1, B2, B5, C3, C5, and C7a), it was decided that potential advantages of the C4 method should be explored. As shown by the results in table 19, brightness values increased for 30 of the 33 samples, including the revelation of eight cracks which were not visible after the prior cleaning steps, i.e., red shading went to green in four of the eight cases, to yellow in two cases, and to orange in the remaining two cases.

Given these results, the C4 process is an effective method for cleaning of all baked-on contaminants for Ni samples. Note that many of the results in table 19 are for C4 following a mechanical blasting step designated by plastic media blasting (B1), wet glass bead blasting (B2), and Al₂O₃ 500-grit (B5). Using of the C4 method followed by the mechanical blasting processes also led to improvements with the implications discussed in the mechanical cleaning methods section later in this section.

TABLE 19. RESULTS FOR C4 USED TO REMOVE BAKED-ON CONTAMINANTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb B1	Feb B2	Feb B5	Feb C3	Feb C5	Feb C7a	Feb C4
Oxidation and Scale + C3	C4	Ni	00-106	0.07	47.8	24					0.7			61.6
Oxidation and Scale + C3	C4	Ni	00-108	0.033	13.9						4.7			7
Oxidation and Scale + C3	C4	Ni	01-055	0.058	27.5	33.1					15			34.1
Oxidation and Scale + C7a	C4	Ni	00-110	0.054	29.4	7							3.4	10.5
Oxidation and Scale +C7a	C4	Ni	01-003	0.03	8.7	8.8							2.5	3
Oxidation and Scale +C7a	C4	Ni	00-120	0.122	53.4	73.7	81.6						46.6	76.4
Oxidation and Scale + B2	C4	Ni	00-111	0.038	31.8	31.2			15.6					38.5
Oxidation and Scale + B2	C4	Ni	01-009	0.028	7.5	15.6		lost						4.4
Oxidation and Scale + B2	C4	Ni	01-036	0.026	2.2			lost						0.9
Oxidation and Scale +B5	C4	Ni	00-119	0.08	45.9	44.1				0.6				20
Oxidation and Scale +B5	C4	Ni	01-020	0.025	16	33.8				11.7				5.6
Oxidation and Scale +B5	C4	Ni	01-007	0.078	162.3	130.8				53.2				97.4
Soot + C3	C4	Ni	00-126	0.061	37.9	34.4					lost			45.9
Soot + C3	C4	Ni	01-021	0.028	11.3	7.3					12.3			8.2
Soot + C3	C4	Ni	01-029	0.083	121.4	148					98.6			63.1
Soot +C7a	C4	Ni	00-127	0.083	79.8	93.2							lost	34.1
Soot +C7a	C4	Ni	01-034	0.024	1.4	1.6							1	1.8
Soot +C7a	C4	Ni	01-031	0.026	0.04	0.9	0.9						lost	2.1
Soot +B1+C3	C4	Ni	01-005	0.064	30.1	40.3		8			lost			28.5
Soot +B1+C3	C4	Ni	01-030	0.026	4	3.9		1.3			2.3			6.6
Soot +B1+C3	C4	Ni	01-038	0.023	0.1			0.56			0.1			0.5
Coke and Varnish + C3	C4	Ni	01-008	0.078	2.6	31.4					14.7			26.8
Coke and Varnish + C3	C4	Ni	01-032	0.021	7	6.6					0			6.5
Coke and Varnish + C3	C4	Ni	00-105	0.067	250	181.4					143.4			199.1
Coke and Varnish +C7a	C4	Ni	01-025	0.053	6.7	29							lost	16.8
Coke and Varnish +C7a	C4	Ni	01-033	0.021	5.2								5	8.2
Coke and Varnish +C7a	C4	Ni	00-124	0.064	174.3	250							169.3	sat
Coke and Varnish+C5	C4	Ni	01-026	0.055	40.1	49.9						4.1		48.2
Coke and Varnish+C5	C4	Ni	01-022	0.023	19	20.1						4.4		18.8
Coke and Varnish+C5	C4	Ni	01-039	0.021	6.2	5.5						lost		8.1
Coke and Varnish +B1+C3	C4	Ni	01-027	0.061	79.8	93.2		lost			65.9			99.3
Coke and Varnish +B1+C3	C4	Ni	01-035	0.025	4.7	4.7		3.2			2.6			5.4
Coke and Varnish +B1+C3	C4	Ni	01-056	0.067	2.6	2.76		0.1			lost			3.2

Note the significant improvement after use of the C4 method over the prior cleaning processes.

3.6.4.6 Alkaline Gel Cleaner.

Alkaline gel cleaner (C5) (Turco 5805 (100%)) followed by a hot-water pressure spray wash). After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C5 was used for soot on Ti samples and coke and varnish on Ni samples. Table 20 shows the brightness results after contamination and subsequent cleaning with C5.

TABLE 20. RESULTS FOR C5 USED TO REMOVE BAKED-ON CONTAMINANTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Oct	Feb C5
Soot	C5	Ti	01-017	0.054				34.8	69.8			20.3
Soot	C5	Ti	01-041	0.031				1.1	2.8			lost
Soot	C5	Ti	00-087	0.068				60.1	92.5			38.3
Coke and Varnish	C5	Ni	01-026	0.055				40.1	49.9			4.1
Coke and Varnish	C5	Ni	01-022	0.023				19	20.1			4.4
Coke and Varnish	C5	Ni	01-039	0.021				6.2	5.5			lost

Six of six samples showed significant reductions in brightness with two samples not showing an indication after the using C5 on the baked-on contaminants, as indicated by the red shading. C5 did not lead to effective cleaning of either Ti or Ni samples with baked-on contamination. However, C5 would typically be followed by another cleaning process, i.e., C4 for Ni and C2 for Ti. C4 did restore the three Ni samples to original or better brightness, as shown in figure 35.

Subsequent cleaning with C2b led to improvements in two of the three Ti cracks, as shown in figure 36.

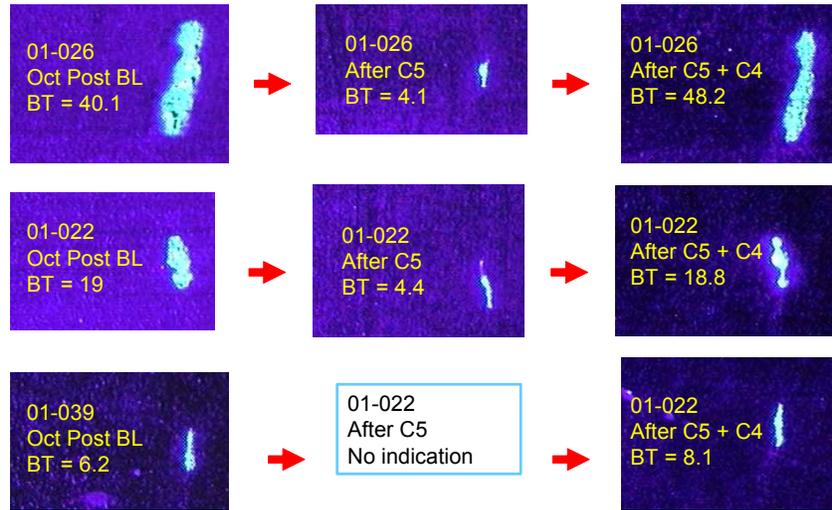


FIGURE 35. ULTRAVIOLET-A IMAGES OF COKE AND VARNISH Ni SAMPLES (The left column shows baseline images for three samples prior to the coke and varnish process. Results for the C5 process are shown in the center. Note the marked improvement after using the C4 process shown in the images on the right.)

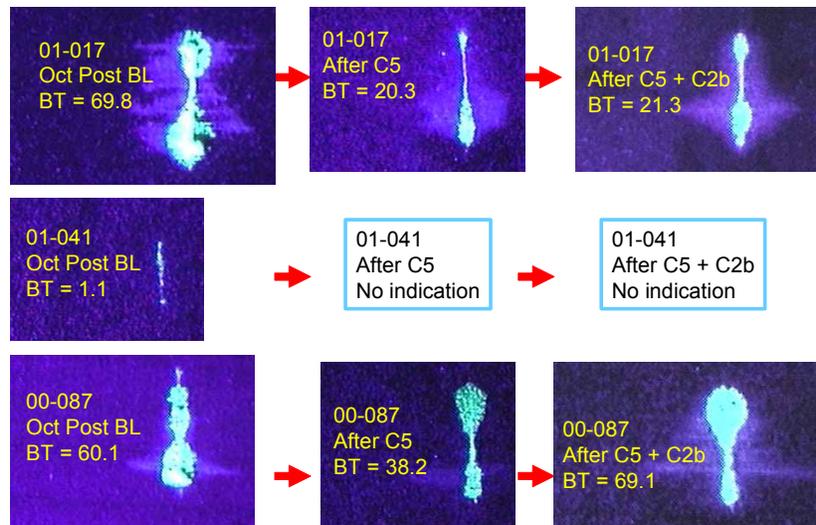


FIGURE 36. ULTRAVIOLET-A IMAGES OF SOOTED Ti SAMPLES (The left column shows baseline images for three samples prior to the sooting process. Results for the C5 process are shown in the center. Subsequent cleaning with C2b led to improvement in two of the three samples.)

As indicated in table 1, the C5 method is typically used to clean heavy soot or coked oil from struts and other structural components prior to disassembly to module level for a visual

inspection. It is occasionally used for spot cleaning and would typically be followed by a full C2 (for Ti) or C4 (for Ni) process prior to FPI. In these tests, C5 was not effective in cleaning samples contaminated with soot or coke and varnish either because of ineffective cleaning or because of cleaning residue effect on the penetrant. Insufficient data are available from this study to determine the cause since the study did not include C5 on samples prior to the baked-on contamination processes. Improvements were found after the C2 and C4 processing.

3.6.4.7 Degreaser.

Degreaser (C6) (Spray, steam, or foam solution of Turco 5948R followed by a hot-water spray wash). After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C6 was used to clean oil-contaminated Ti and Ni samples. Table 21 shows the brightness results after contamination and cleaning with C6.

TABLE 21. RESULTS FOR C6 USED TO REMOVE OIL

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Oct C6
Oil D	C6	Ti	00-077	0.039	37.6	40.94	47.1				30.7
Oil D	C6	Ti	00-097	0.062	54.45	85.11	107.3				122.7
Oil D	C6	Ti	00-098	0.020	10.34	12.84	15.4				8.6
Oil D	C6	Ni	01-120	0.025	16.25	20	18				37.1
Oil D	C6	Ni	01-030	0.026	2.66	4.47	3.35				3.1
Oil D	C6	Ni	01-055	0.058	27.48	37.5	31.6				35.6
Etch SC/A	C6	Ti	00-090	0.06	68.2	116.9	162.9				145.1
Etch SC/A	C6	Ti	00-123	0.095	149.25	156.6	186.9				186.6
Etch SC/A	C6	Ti	01-040	0.121	37.03	46	54.8				21.6
SC A	C6	Ni	01-035	0.025	3.42	4	4				4.9
SC A	C6	Ni	01-025	0.053	17.31	25.3	25.3				22.9
SC A	C6	Ni	01-008	0.078	50	39.2	54.05				40.2

Using C6 led to some reduction in brightness in three of the six Ti samples, while all six Ni samples had same or better brightness. As indicated in table 1, degreasers are used as a precleaning step prior to other cleaning methods. Parts would be further processed in alkaline cleaners prior to FPI.

Given these results, C6 was found to be a robust precleaning process for oil removal and does not appear to have a negative effect on the FPI process.

3.6.4.8 Ultrasonic Alkaline Cleaning.

Ultrasonic alkaline cleaning (C7a) (alkaline derust remover solution Turco 4181L at 50%-75% by volume with water, at 180°-200°F (82°-93C)) is used for Ni alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C7a was used to clean oil contamination and antigallant compound from Ni samples in October. Table 22 shows the brightness results after contamination and subsequent cleaning with C7a. C7a was also used to remove oxidation and scale, coke and varnish, and soot in February. In some cases, C7a was a follow-up process as discussed below. Results for the baked-on contaminants follow those for the oil and antigallant studies.

TABLE 22. RESULTS FOR C7a USED TO REMOVE OIL CONTAMINANTS AND ANTIGALLANT COMPOUND

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Oct C7a
Oil B	C7a	Ni	00-127	0.083	57.13	67.9	68.6	79.8	93.2		3.9
Oil B	C7a	Ni	01-026	0.055	8.78	13.8	20.8	40.1	49.9		20
Oil B	C7a	Ni	01-034	0.024	0.52	0.9	0.9	1.4	1.6	1.6	1.5
AG C	C7a	Ni	01-003	0.03	7.5	8	5.43	8.7	8.8		5.5
AG C	C7a	Ni	00-126	0.061	28.2	33.1	64.2	37.9	34.4		16.4
AG C	C7a	Ni	01-007	0.078	95.5	97.9	121.5	162.3	130.8		76.7

One of the three Ni samples contaminated with oil showed a reduction in brightness when compared to the prebaseline after using C7a. However, as shown in figure 37, the indication is still visible. The primary difference between C3 and C7a was the use of ultrasonic agitation of the cleaning solution in the C7a process. Significant advantages were not seen between the two processes evaluated in this study. The use of ultrasonic agitation may show improvement at lower bath temperatures. Further quantification of bath temperature effects on the effectiveness of ultrasonic agitation would be useful.

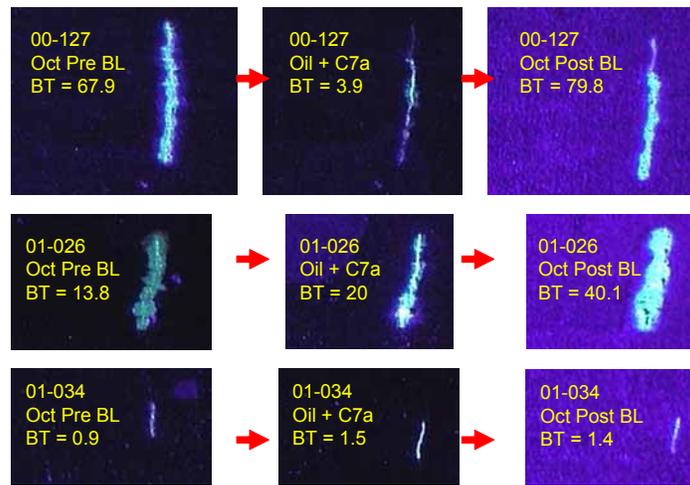


FIGURE 37. ULTRAVIOLET-A IMAGES OF SAMPLES CONTAMINATED WITH PENETRATING OIL (The outer columns show the pre- and postbaseline results respectively. The center column shows the results after applying the penetrating oil and subsequent removal with C7a.)

Using C7a to remove antigallant compound led to a reduction in brightness in two of the three samples in October. Given that the antigallant compound was placed off to the side of the crack, the reduction in brightness likely comes from the alkaline cleaning solution. Note that the postbaseline brightness numbers returned to the prebaseline numbers, further supporting this hypothesis. As indicated previously, additional efforts to prevent alkaline cleaner residue or make penetrants more tolerant of the presence of alkalines are needed.

C7a showed reductions in all three oxidation and scale samples with two of the three being significant, which is similar to the results with C3 (without ultrasonic agitation). Using C4,

subsequent to C7a, did improve the brightness with two of the three returning to original or better values.

Indications were not visible in two of the three sooted samples, as indicated by the red shading in table 23. Using C4 also improved brightness for this set of three samples, including sufficient cleaning action to restore the two lost indications.

TABLE 23. RESULTS FOR C7a USED TO REMOVE BAKED-ON CONTAMINANTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb C7a
Oxidation and Scale	C7a	Ni	00-110	0.054	29.4	7		3.4
Oxidation and Scale	C7a	Ni	01-003	0.03	8.7	8.8		2.5
Oxidation and Scale	C7a	Ni	00-120	0.122	53.4	73.7	81.6	46.6
Soot	C7a	Ni	00-127	0.083	79.8	93.2		lost
Soot	C7a	Ni	01-034	0.024	1.4	1.6		1
Soot	C7a	Ni	01-031	0.026	0.04	0.9	0.9	lost
Coke and Varnish	C7a	Ni	01-025	0.053	6.7	29		lost
Coke and Varnish	C7a	Ni	01-033	0.021	5.2			5
Coke and Varnish	C7a	Ni	00-124	0.064	174.3	250		169.3

One of the three coke and varnish samples did not contain a detectable indication after cleaning with C7a. All three samples returned to original or better brightness with subsequent use of C4.

Comparison of the C3 (no ultrasonic agitation) and C7a (with ultrasonic agitation) process did not show significant differences. The ultrasonic agitation may show improvement at lower bath temperatures. Further quantification of bath temperature effects on the effectiveness of ultrasonic agitation would be useful. Reductions in brightness could be related to alkaline cleaner residue effects. Efforts to reduce the effect of alkaline cleaner residue on fluorescence are recommended.

Given the above results, C7a did not prove to be a robust cleaner for baked-on contaminants. However, subsequent use of C4, was effective for all three types of baked-on contamination. Consideration should be given to more frequent use of the C4 method on parts that will undergo subsequent FPI.

3.6.4.9 One-Step Alkaline With Ultrasonic Agitation.

One-step alkaline with ultrasonic agitation (C7b) (Turco 4181L at 20% by volume with water, at 180°-190°F (82.2°-87.77°C) is used for Ti alloys. After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C7b was evaluated for removal of antigallant compound from three Ti samples in October. Table 24 shows the brightness results after contamination and cleaning with C7b. Significant reductions in brightness occurred in all three samples, as indicated by the orange shading. The results of the UVA image capture for these three samples are shown in figure 38.

TABLE 24. RESULTS FOR C7a USED TO REMOVE ANTIGALLANT COMPOUND FROM Ti

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Oct C7b
AG C	C7b	Ti	00-087	0.068	45.2	97.7	134.6	60.1	92.5		35.3
AG C	C7b	Ti	01-001	0.063	102	117.4	134.32	67.3	106.6		27.3
AG C	C7b	Ti	01-054	0.035	5.26	5.86	5.94	0	0	0	0.05

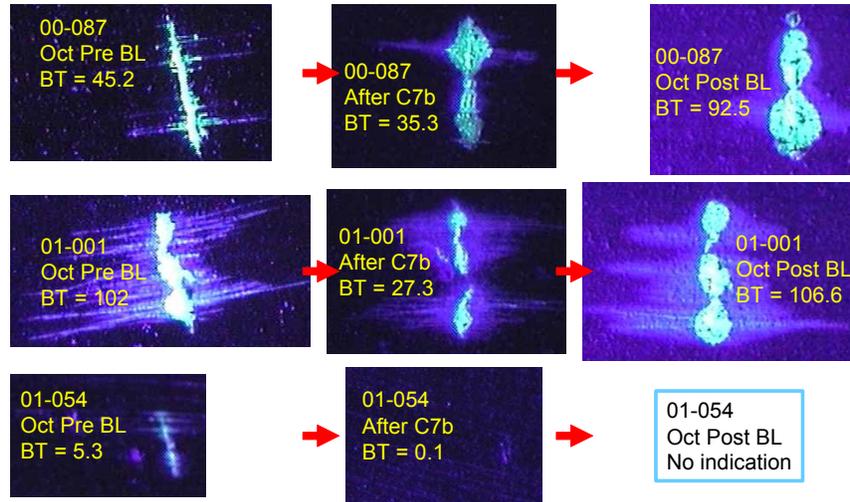


FIGURE 38. ULTRAVIOLET-A IMAGES OF SAMPLES WITH AN APPLICATION OF ANTIGALLANT COMPOUND TO Ti SAMPLES (The outer columns show the pre- and postbaseline results respectively. The center column shows the results after application of antigallant compound and subsequent removal with C7b.)

C7b was effective in removing the antigallant compound from Ti samples. Since the compound was placed to the side of the cracks, reductions in brightness can be attributed to the cleaning process and are likely the result of alkaline cleaner residue.

As with the C7a results for Ni samples, reductions in brightness occurred with C7b for the Ti samples. Additional steps to reduce the impact of alkaline cleaning residue on penetrant inspection are needed.

3.6.4.10 Rubber Stripper.

Rubber stripper (C8) (Turco T6045 for 4 hours). After the cleaning steps, samples were oven-dried at 225°F (107°C) prior to FPI processing. C8 was used to remove RTV from Ti samples in October. Table 25 shows the brightness results after application of the RTV and cleaning with C8. Note that reductions were found in two of the three samples. Because the next step for these samples involved the mechanical blasting processes, no further analysis was possible. An additional study of this cleaning method is warranted to determine if the reductions in brightness were the result of the cleaning process.

TABLE 25. RESULTS FOR RUBBER STRIPPER USED TO REMOVE RTV FROM Ti SAMPLES

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct C8
RTV B	C8	Ti	00-076	0.063	87.5	83.9	99.9	50
RTV B	C8	Ti	00-081	0.12	153	187.62	63.4	129.2
RTV B	C8	Ti	01-014	0.061	84.12	116.3	112.83	43.8

3.6.4.11 Plastic Media Blast.

Plastic media blast (PMB (B1)) (Plasti-Grit (60-120 mil)) is used to remove detrimental surface conditions or coatings that could affect the sensitivity of FPI. The media is applied using the equipment shown in figure 23. For this study, a pressure cabinet was used. A comparison was made of the recommended pressures of 40 psi, as read at the cabinet gage, and at 80 psi. The angle, which is also an important variable, was held constant in all PMB studies performed as part of this program. The results are shown in tables 26 and 27 respectively. As indicated earlier, several types of coatings, including RTV, were applied to the side of the crack. Media application time was established on one sample and maintained as a constant throughout the study. For plastic media, that time was standardized at 30 sec. for removing coatings and baked-on contaminants.

TABLE 26. RESULTS FOR PMB AT 40 psi

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct B1-40	Feb B1-40
RTV -B C8	B1-40	Ti	00-076	0.063	87.5	83.9	99.9				61.7	
RTV -B C8	B1-40	Ti	00-081	0.12	153	187.62	63.4				79.9	
RTV -B C8	B1-40	Ti	01-014	0.061	84.12	116.3	112.83				94.5	
Soot	B1-40	Ti	01-052	0.049				44.9	44.8			68.3
Soot	B1-40	Ti	01-045	0.052				1.9	1.5			0.95
Soot	B1-40	Ti	01-001	0.063				67.3	106.6			29.7
Soot	B1-40	Ni	01-005	0.064				30.1	40.3			8
Soot	B1-40	Ni	01-030	0.026				4	3.9			1.3
Soot	B1-40	Ni	01-038	0.023				0.1				0.56
Coke & Varnish	B1-40	Ni	01-027	0.061				79.8	93.2			lost
Coke & Varnish	B1-40	Ni	01-035	0.025				4.7	4.7			3.2
Coke & Varnish	B1-40	Ni	01-056	0.067				2.6	2.76			0.1

TABLE 27. RESULTS FOR PMB AT 80 psi

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct B1-80
AGA+C2a	B1-80	Ti	00-091	0.087	53.39	69.61	18.7	113.5	92.6	101.3	62.5
AGA+C2a	B1-80	Ti	01-017	0.054	60.86	82.29	79.3	34.8	69.8		54.8
AGA+C2a	B1-80	Ti	01-046	0.028	2.18	1.27	1.9	0.15	0.13		lost
AG D	B1-80	Ti	00-103	0.104	64.7	78.87	157.4	133.7	149		150.2
AG D	B1-80	Ti	01-051	0.118	0.06	0.039	0.02	0.02	0.04		0.03
AG D	B1-80	Ti	01-052	0.049	35.53	43.77	39.7	44.9	44.8		50.9
RTV C/HTS A - C2a	B1-80	Ti	00-095	0.061	81	99.82	126.1	109.3	119.2		125.1
RTV C/HTS A - C2a	B1-80	Ti	01-018	0.12	22.65	30.93	31	7.7	10.1		0.02
RTV C/HTS A - C2a	B1-80	Ti	00-064	0.128	2.64	1.2	1	39.6	57.1	47.8	lost
AGA + C3	B1-80	Ni	01-032	0.021	5.74	0.5	4.5	7	6.6		2.2
AGA + C3	B1-80	Ni	01-023	0.04	32.39	32.5	39.9	6.9	2.3		7.2
AGA + C3	B1-80	Ni	00-106	0.07	50.9	45.4	78.4	47.8	24		8.7
AG D	B1-80	Ni	01-028	0.034	0.84	0.7	1	0.1	0.1		0
AG D	B1-80	Ni	00-121	0.063	4.74	6.3	3.9	0.63	0.33		0.3
AG D	B1-80	Ni	00-117	0.081	24.1	23.9	50.3	2.6	1.9		5.2

PMB was used to remove RTV and antigallant compound from Ti and Ni samples as shown in tables 25-27. The results for Ti show brightness reduction in two of six samples at 40 psi and four of nine Ti samples at 80 psi. Exposure to 80 psi led to loss of indications in two of the nine Ti samples. The results for sample 01-076 are shown in figure 39. Note the change in surface condition before and after the B1-40 treatment, which shows evidence of polishing. After the B1-40 treatment, FPI results were recorded, the sample was spray rinsed in water, cleaned in ultrasonic acetone for 30 minutes and oven-dried at 225°F (107°C) prior to the postbaseline FPI measurements. The cleaning steps, which involved fluids, may have carried away plastic media residue that led to the improved brightness in the postbaseline UVA image in figure 39. Comparison of pre- to postbaseline brightness for the other B1-40 samples showed similar results, indicating that following the PMB with a wet process may prove beneficial. Because a baseline run, which includes acetone, was made after the B1-40 treatment, comparisons of before and after rinsing with water were not completed but could be the subject of future studies.

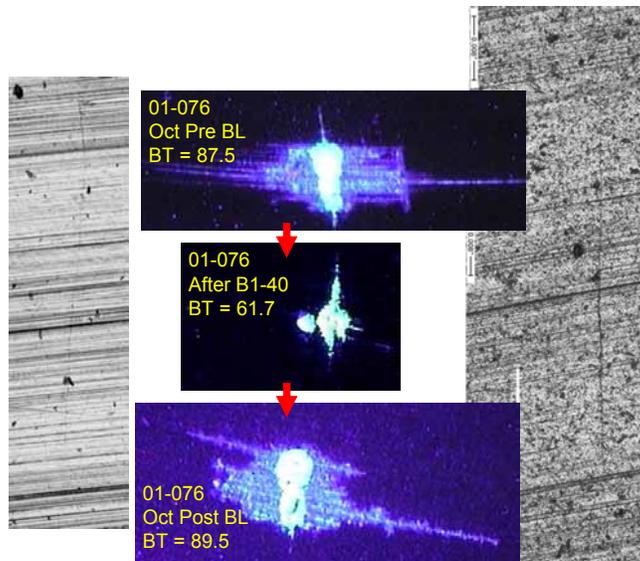


FIGURE 39. RESULTS FOR THE 01-076 Ti SAMPLE (The optical image for the pristine crack is shown at the left and the final surface condition after PMB is shown to the right. UVA images for prebaseline, after PMB and postbaseline are also shown.)

As shown in table 27, nine Ti samples with either RTV or antigallant compound were exposed to PMB at 80 psi (B1-80). This enabled a comparison of potential pressure effects. B1-80 caused a loss of two indications and a significant reduction in a third sample, 01-018. The results for 01-018 are shown in figure 40. The optical image at the top shows the crack prior to FPI, while the lower optical image shows the crack after application of B1-80. UVA images are shown for two prebaseline runs and one postbaseline run. While a measurable brightness of 0.02 was recorded for the B1-80 sample between the pre- and postbaseline results, the indication was too faint to capture with the digital camera. Note the polishing of the surface and potential crack closure in the postoptical image.

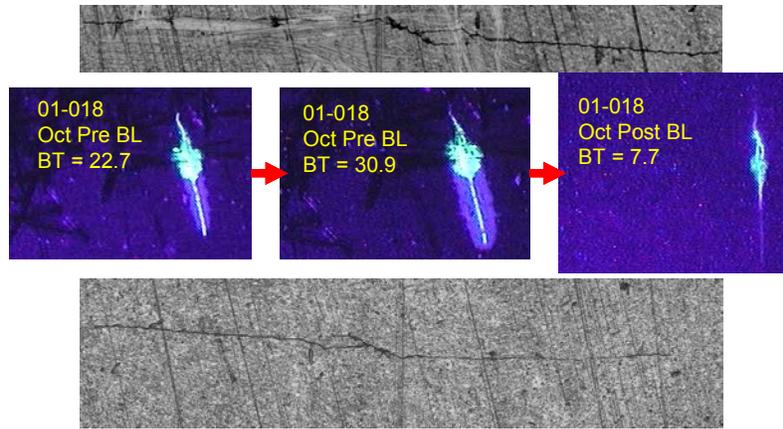


FIGURE 40. RESULTS FOR THE 01-018 Ti SAMPLE (Note that UVA indication was not available for the B1-80 treatment until after subsequent processing with acetone, as shown in the October postbaseline image.)

Figure 41 shows the results for sample 01-052. Note that for this sample, the B1-80 treatment did not lead to a reduction in brightness but surface polishing is evident when comparing the pre- and postoptical images. Several of the Ti samples showed this improvement, as indicated by the green shading in table 27. However, the loss of some indications and the changes in surface finish indicate that using pressures higher than 40 psi is not advisable for Ti.

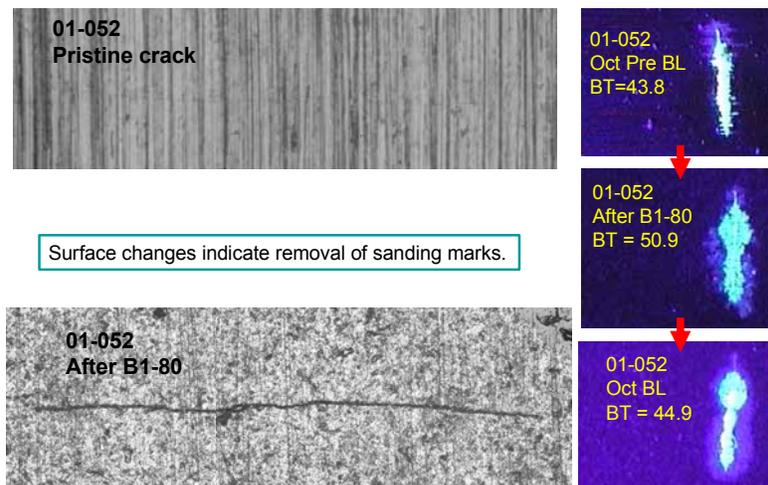


FIGURE 41. RESULTS FOR THE 01-052 Ti SAMPLE AFTER PMB AT 80 psi

The approach used for removing surface coatings on Ni samples was limited to the B1-80 treatment, as shown in table 27. Note that all six Ni samples showed reductions in brightness with four of the six being significant and with one indication not found after the B1-80 treatment. The results for two of the samples, 00-106 and 00-117, are shown in figures 42 and 43 respectively. Sample 00-106 results include optical images before and after exposure to B1-80. Note that while the crack is visible in the post-PMB image, the sanding marks from the pristine crack have been polished. The UVA images are also shown for the pre- and

postbaseline FPI process. Note the reduction in brightness between the prebaseline image and the B1-80 image. Also note that the UVA indication is somewhat discontinuous when contrasted to the prebaseline image. This sample was also examined using scanning electronic microscope (SEM) with a 500X image, as shown in figure 42. The plastic media particles can be seen embedded in the crack. The chemical analysis revealed peaks characteristic of plastic media.

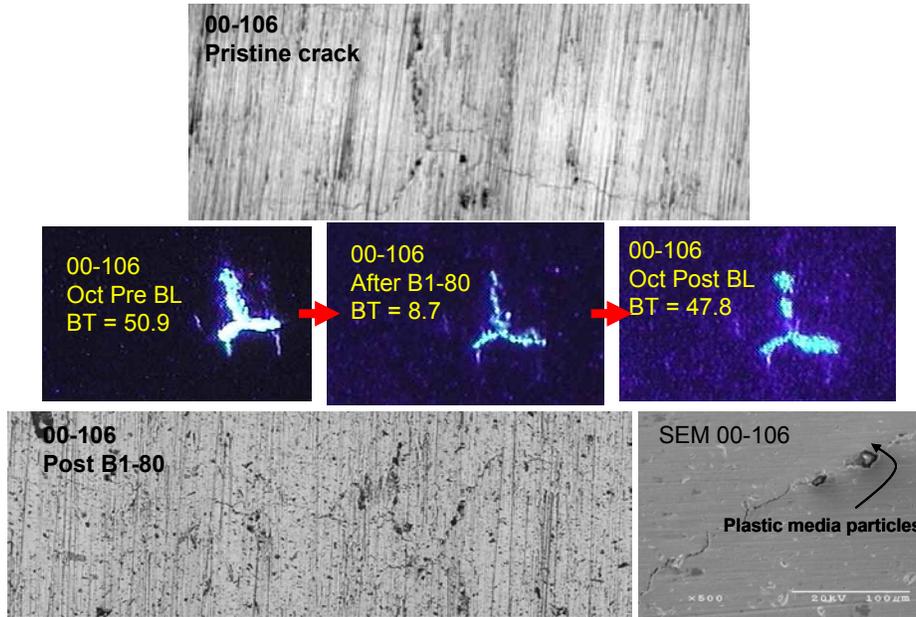


FIGURE 42. RESULTS FOR THE 00-106 Ni SAMPLE, PROCESSED WITH PMB AT 80 psi (Note the plastic media particles visible with SEM.)

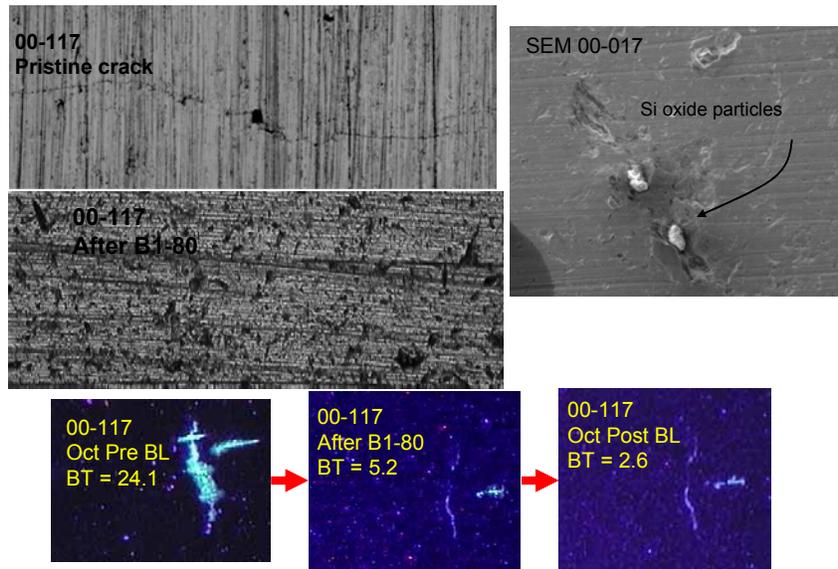


FIGURE 43. RESULTS FOR THE 00-117 Ni SAMPLE AFTER PROCESSING WITH PMB AT 80 psi

Sample 00-117 was also exposed to 80-psi PMB. Figure 43 shows the optical images of the pristine crack and the final surface condition, UVA pre- and postbaseline images, and the UVA image after the B1-80 process. Note the significant reductions in brightness and the intermittent nature of the indication after the B1-80 process. The crack was not detectable with optical or SEM microscopy after the B1-80 process. Note the surface damage in the after B1-80 image. SEM results did reveal the presence of silicon oxide particles of an unknown origin. These could be the result of initial sample preparation or contamination introduced during the study.

Given the combined results for Ti and Ni, exceeding the recommended pressure of 40 psi for PMB is not advisable.

Using B1-40 PMB for removing baked-on contaminants was evaluated in February using three Ti and six Ni samples, as shown in table 26. The results for one of the Ti samples exposed to 40 psi after the soot treatment are shown in figure 44. The figure includes optical images of the crack before (top) and after exposure to the 40-psi PMB (bottom). Note that the PMB treatment did polish the surface, removing some surface sanding marks. The UVA image shows evidence of masking portions of the indication after the B1-40 treatment because of the discontinuous nature of the UVA indication. The bottom image in figure 44 shows the final surface condition. The last UVA image, with a brightness of 29.7, was taken after the February B1-40 treatment to remove soot. After additional cleaning steps in February, which included C2b and a vapor degrease, the indication did not return to the baseline conditions.

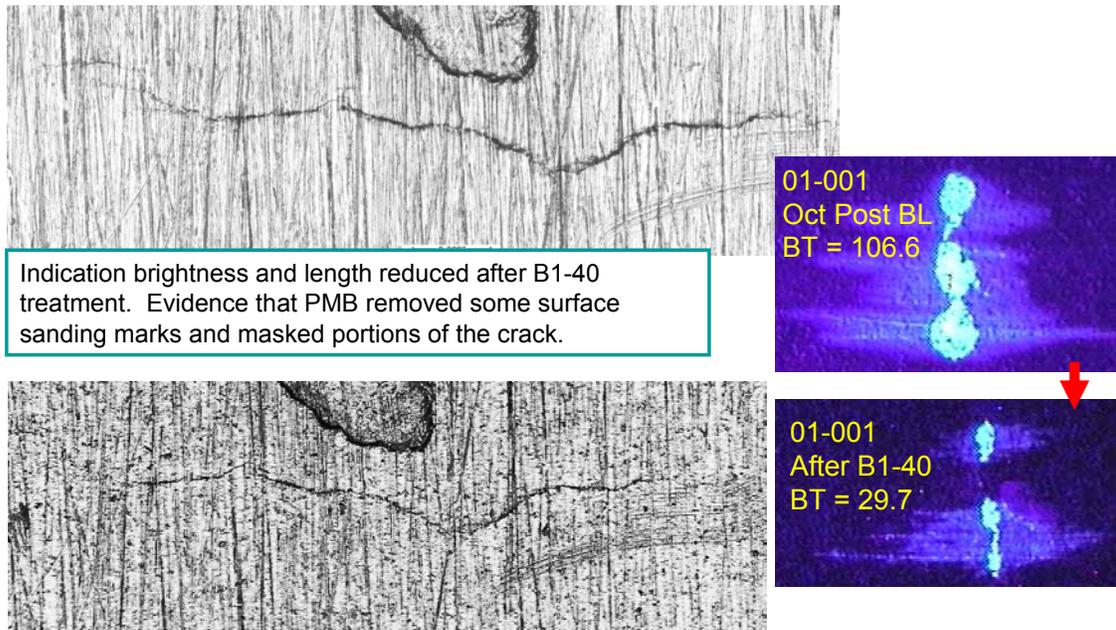


FIGURE 44. RESULTS FOR THE 01-001 Ti SAMPLE (The top image shows the surface condition prior to PMB and the lower image shows the surface condition after soot and PMB. The UVA images are also provided. Note the discontinuous nature of the UVA indication after the PMB treatment.)

The results for 01-052 (a Ti sample that was processed with B1-80 in October, went through the heating process to produce soot, and then underwent a B1-40 treatment in February) are shown in figure 45. Results are shown for the October and February studies. Note that there were surface changes, resulting from the B1-80 process, to the pristine crack evidenced by removal or polishing of the sanding marks that were generated as part of the sample fabrication process. Additional changes are not visibly evident in the subsequent B1-40 process. Profilometry measurements were not performed between the various processes but would be a useful characterization tool in future studies.

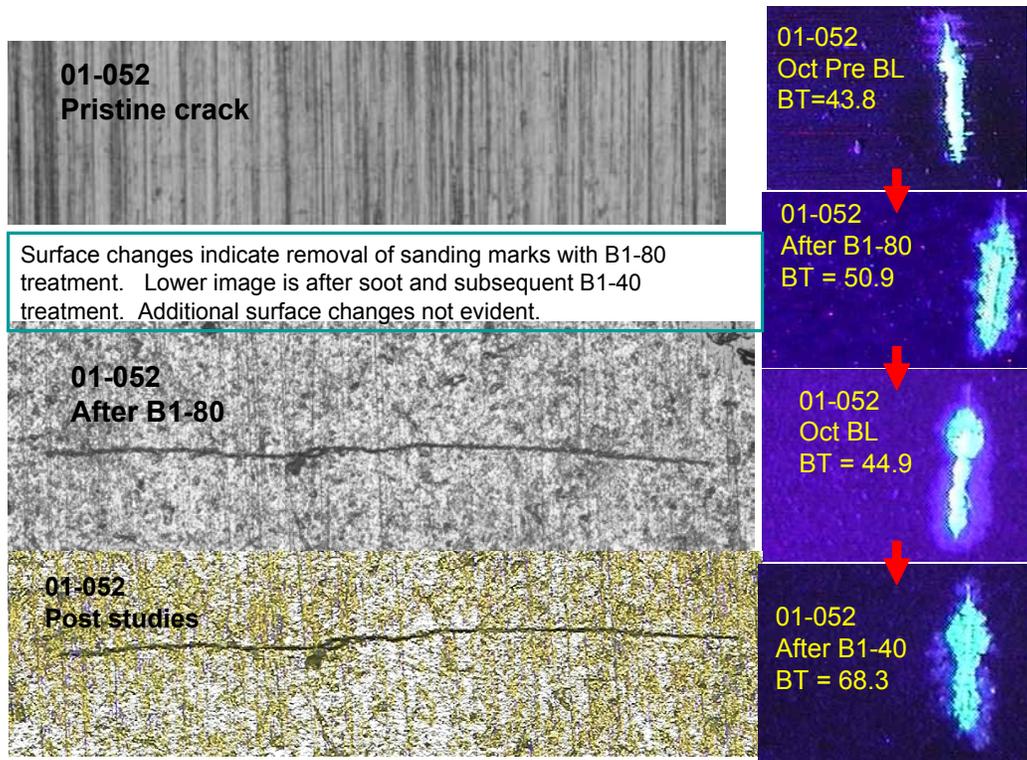


FIGURE 45. RESULTS FOR THE 01-052 Ti SAMPLE

Five of six Ni samples, which were treated with B1-40 to remove soot or coke and varnish conditions, saw reductions in brightness, as shown in table 26, with one of the indications not found after the B1-40 process. Following the PMB process and FPI evaluation, the samples were cleaned with C3 and then with C4. The results for the three samples that were processed to produce a soot condition are shown in figure 46, and the three samples that were processed to produce a coke and varnish condition are shown in figure 47.

As evidenced by the change in UVA images from the October baseline (left column) to the results after B1-40, changes did occur in the sample after processing to generate baked-on contaminants and subsequent cleaning with B1-40. Following the PMB process with a wet cleaning process, namely C4, returned the samples back to acceptable brightness readings. Reductions in UVA lengths were noted for three of the six samples, including sample 01-005. Optical and SEM results for 01-005 are shown in figure 48.

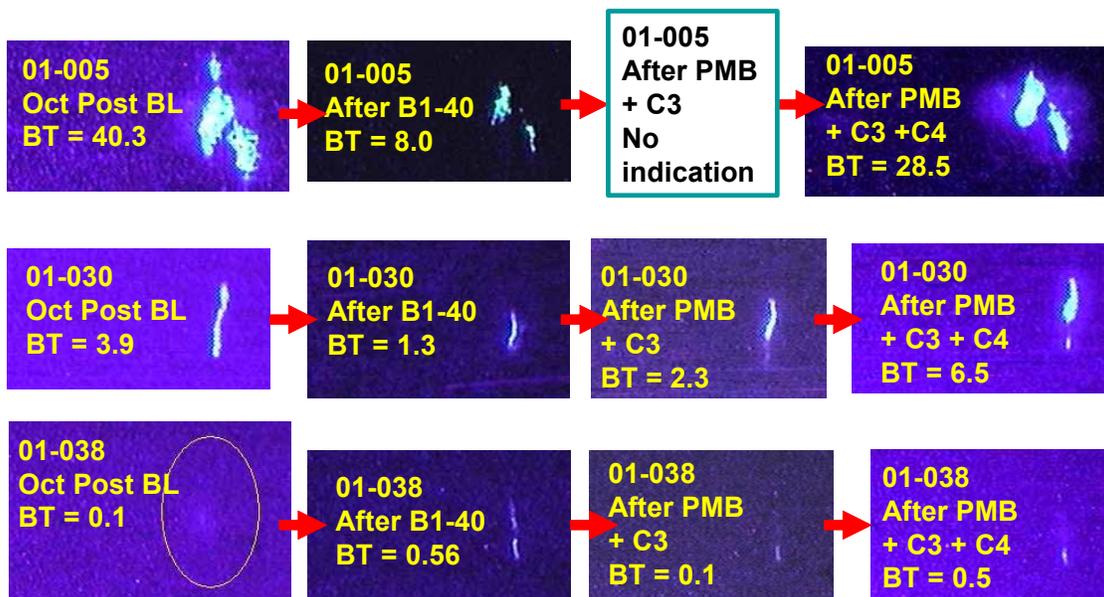


FIGURE 46. RESULTS FOR SOOTED Ni SAMPLES, WHICH WERE SUBSEQUENTLY CLEANED WITH PMB AT 40 psi FOLLOWED BY A C3 CLEAN AND A C4 CLEAN

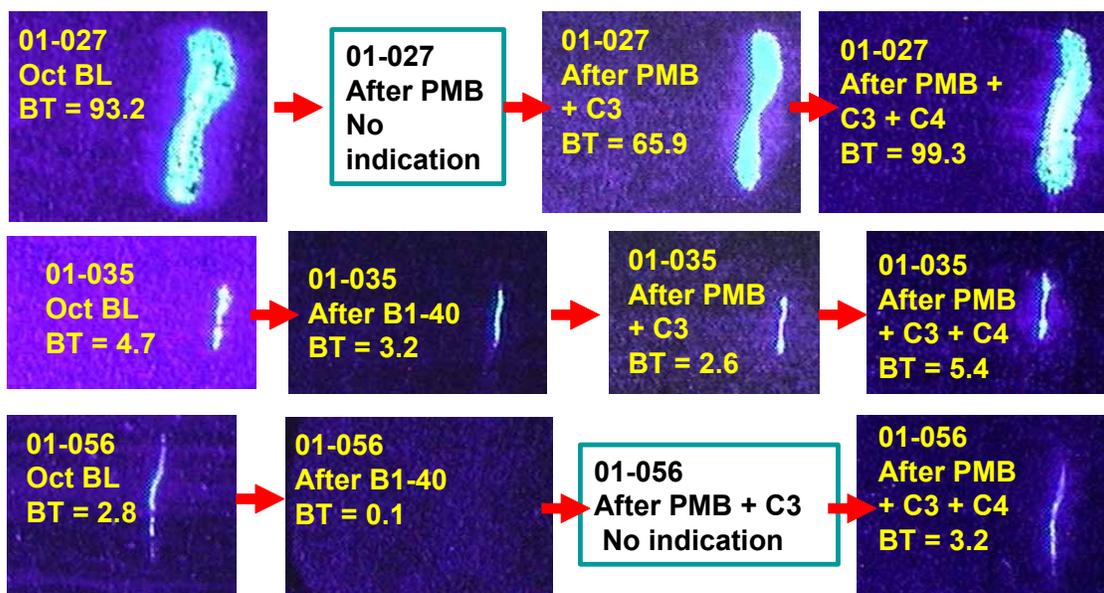


FIGURE 47. RESULTS FOR COKE AND VARNISH Ni SAMPLES, WHICH WERE SUBSEQUENTLY CLEANED WITH PMB AT 40 psi FOLLOWED BY A C3 CLEAN AND A C4 CLEAN

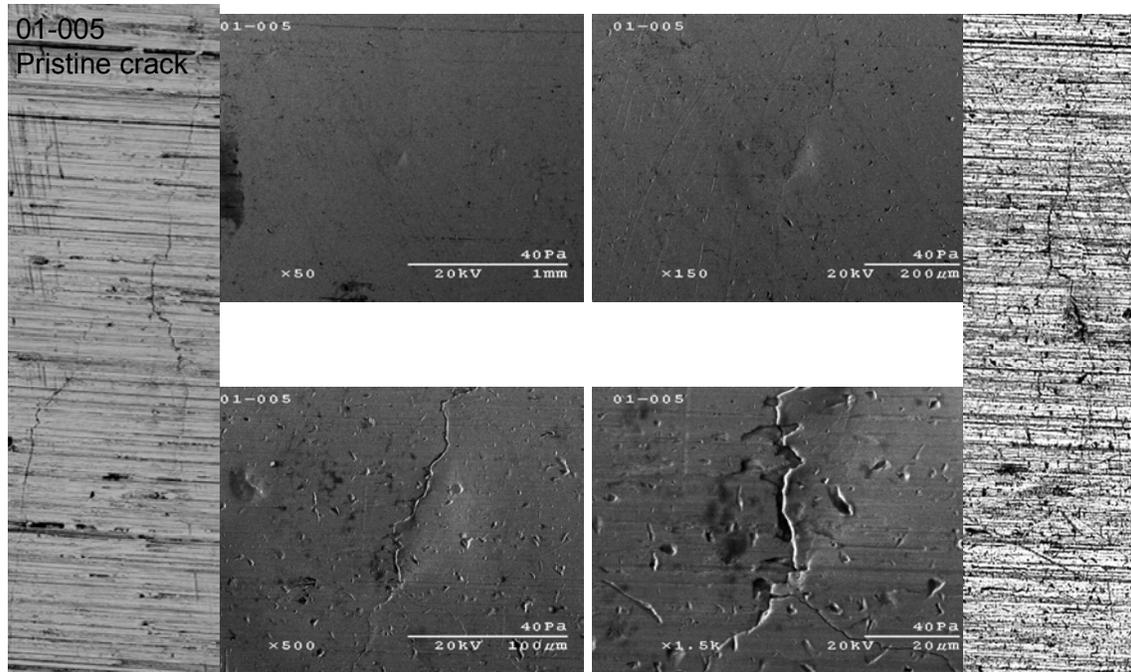


FIGURE 48. OPTICAL AND SEM RESULTS FOR SAMPLE 01-005

Given the results from coating and baked-on contaminant samples, following the PMB with a chemical cleaning process may lead to improved detectability in Ni. While this observation was made based on the brightness and UVA image data, additional effort is needed to understand the reason. Possible scenarios include a simple washing action from the chemical cleaning solutions or a chemical attack action on the plastic media either from the cleaning solutions or from the penetrant solution.

3.6.4.12 Wet Glass Bead Blast.

Wet glass bead blast (B2) (0.0021"-0.0029" diameter beads (SPS 235)). Three Ni and Ti samples were cleaned with B2. After the B2 process, the samples were oven-dried at 225°F (107°C) for 30 minutes to ensure no water carried over from the cleaning process. The B2 process led to significant reductions in six of six samples with loss of four of the six cracks, as shown by the orange and red shading in table 28.

TABLE 28. RESULTS FOR B2

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL1	Oct Post BL2	Feb B2
Oxidation and Scale	B2	Ni	00-111	0.038	31.8	31.2	15.6
Oxidation and Scale	B2	Ni	01-009	0.028	7.5	15.6	lost
Oxidation and Scale	B2	Ni	01-036	0.026	2.2		lost
Oxidation and Scale	B2	Ti	01-053	0.057	77.1	77.6	36.8
Oxidation and Scale	B2	Ti	01-015	0.033	3.2	9.3	lost
Oxidation and Scale	B2	Ti	00-097	0.062	42.9	64.7	lost

Following B2, the Ni samples were cleaned using C4, which improved the brightness on all three cracks. This may indicate that oxides inside the cracks were not removed by the mechanical process that contributed to the original reductions or loss of brightness. After C4, oxides were potentially removed and crack brightness improved. The results for two of the Ni samples, 00-111 and 01-009, are shown in figures 49 and 50. The results for sample 00-111, shown in figure 49, include the original optical image of the crack on the left and the optical image after B2. SEM results at 50X, 150X, 500X, and 1500X are also shown. The baseline UVA image from October, prior to oxidation and scale, is shown followed by the image after B2 and subsequent C4 processes. Comparison of the optical images shows crack closure resulting from the B2 process. The results for sample 01-009 also show significant surface damage and reduction in sensitivity of the UVA indication, as shown in figure 50.

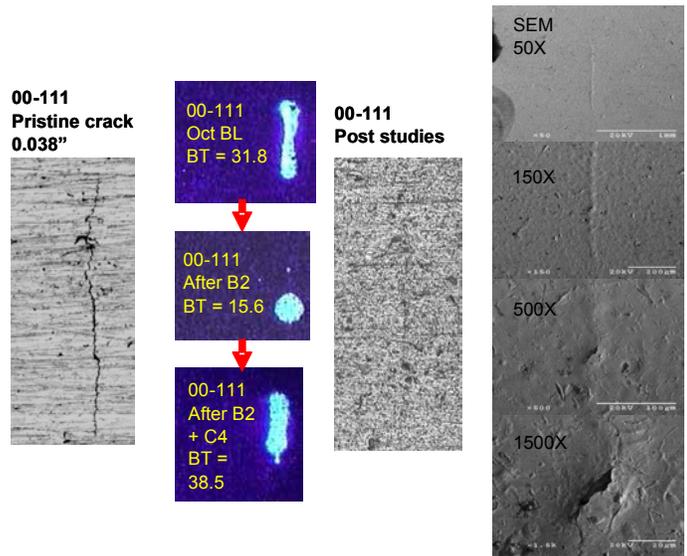


FIGURE 49. RESULTS FOR THE 00-111 Ni SAMPLE AFTER B2 PROCESSING

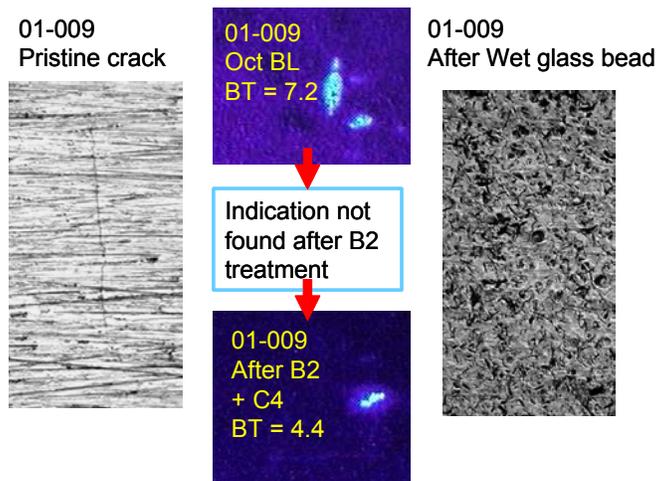


FIGURE 50. RESULTS FOR THE 01-009 Ni SAMPLE AFTER B2 PROCESSING

Similar to the C4 processing on Ni samples, C2b was applied to the Ti cracks, which led to improved brightness in only one of the three samples (01-053), as shown in figure 51. Two of the three cracks have yet to be restored, indicating that effective cleaning (descaling) of the oxides did not occur with the approved Ti methods. Loss of indications could result from either remaining oxide in the cracks or compressive stresses or metal smearing induced by the B2 processing.

Given the results for Ni and Ti, using B2 prior to FPI is not recommended.

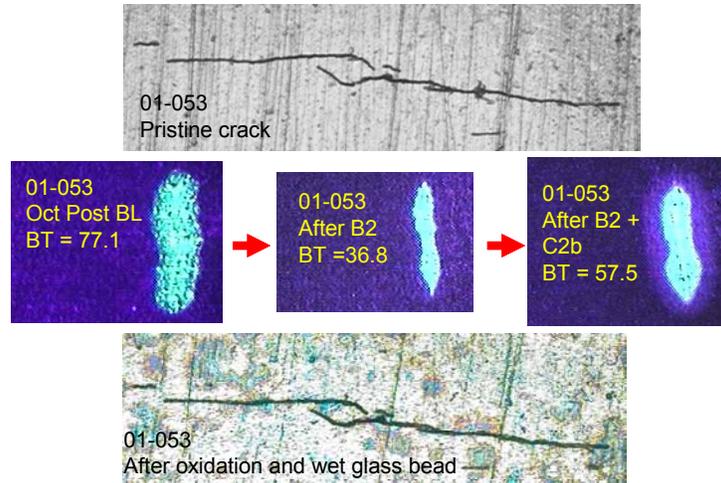


FIGURE 51. RESULTS FOR THE 01-053 Ti SAMPLE AFTER B2 PROCESSING

3.6.4.13 Aluminum Oxide Blasting.

Three different grit sizes were evaluated, which include

- B3—240-grit Al_2O_3 (240-grit dry aluminum oxide).
- B4—320-grit Al_2O_3 (320-grit dry aluminum oxide).
- B5—500-grit Al_2O_3 (500-grit dry aluminum oxide).

The results for each of the studies are shown in table 29. Initial work was completed in October as shown in the lower set of data and using only the 500-grit (B5) process. All three processes were evaluated in February. In an effort to maximize sample use, many samples were cleaned using various methods prior to the aluminum oxide blasting process, as shown in the multiple columns in the first two sets of data.

3.6.4.13.1 240 Grit.

As shown in table 29, two Ti and three Ni samples were processed using the 240-grit (B3) treatment with three of the five indications not found. Typical examples for the two alloys are shown in figures 52 and 53. The optical image of the original crack is shown for both samples along with UVA images, a postoptical image, and a series of SEM images of increasing magnification. Surface-induced damage is evident in both alloy types with the B3 process.

Because the samples used for the B3 study previously showed FPI results, the loss of indications can only be due to the mechanical damage induced from the blasting process.

Given these results, using B3 processing prior to FPI is not recommended.

TABLE 29. RESULTS FOR THE ALUMINUM OXIDE BLASTING TREATMENTS

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL1	Oct Post BL2	Feb C1	Feb C3	Feb C4	Feb C5	Feb C2b	Feb VDG	Feb ace	Feb UT H2O	Feb H2O	Feb B3
Soot+C5+C2b+VDG+ace+H2O	B3	Ti	00-087	0.068	60.1	92.5				38.3	69.1	74.2	76.1	11.1		3.4
Soot+C1+C2b+VDG+ace+H2O	B3	Ti	00-077	0.039	46.2	44.8	21.6				46.2	54.4	54.6	22.9	69.1	lost
Oxidation & Scale+C3+C4+acetone	B3	Ni	00-106	0.07	47.8	24		61.6					56			0
Oxidation & Scale+C3+C4+acetone	B3	Ni	00-108	0.033	13.9			7					6			lost
Oxidation & Scale+C3+C4+acetone	B3	Ni	01-055	0.058	27.5	33.1		34.1					25.2			lost

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL1	Oct Post BL2	Feb B5	Feb C2b	Feb C2b	Feb VDG	Feb C3	Feb C4	Feb ace	Feb UTH2O	Feb H2O	Feb B4	Feb acetone
Oxidation & Scale +B5+C2b	B4	Ti	01-012	0.093	113	110.8	105.7	105.6								71.2	73.3
Soot+C2b+C2b+VDG+ace+H2O	B4	Ti	00-081	0.120	120.6	115.3	sat	sat	sat				161.7	33.8	175.3	sat	sat
Soot+C3+C4+ace	B4	Ni	00-126	0.061	37.9	34.4				lost	45.9	41.9				lost	lost
Soot+C3+C4+ace	B4	Ni	01-021	0.028	11.3	7.3				12.3	8.2	9.1				lost	lost
Soot+C3+C4+ace	B4	Ni	01-029	0.083	121.4	148				98.6	63.1	65.7				lost	lost

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct Post BL3	Oct B6 +C2a	Oct B5	Feb B5	Feb B5	
Oxidation & Scale	B5	Ti	00-093	0.060				66.7	51.9					0.1	
Oxidation & Scale	B5	Ti	01-018	0.120				7.7	10.1					0.1	
Oxidation & Scale	B5	Ti	01-012	0.093				113	110.8					105.7	
Oxidation & Scale + B5	B5	Ti	01-018	0.120				7.7	10.1					0.1	0.2
RTV A + HTS B + (C2a + B6)	B5	Ti	00-067	0.065	114.33	131.1	151.8	121.2	97.1	119.8	116.3	108.5			
RTV A + HTS B + (C2a + B6)	B5	Ti	01-010	0.112	37.94	111.9	125.83	250	250		101.5	99.3			
RTV A + HTS B + (C2a + B6)	B5	Ti	01-045	0.052	13.72	16.39	5.2	1.9	1.5		10.2	1.2			

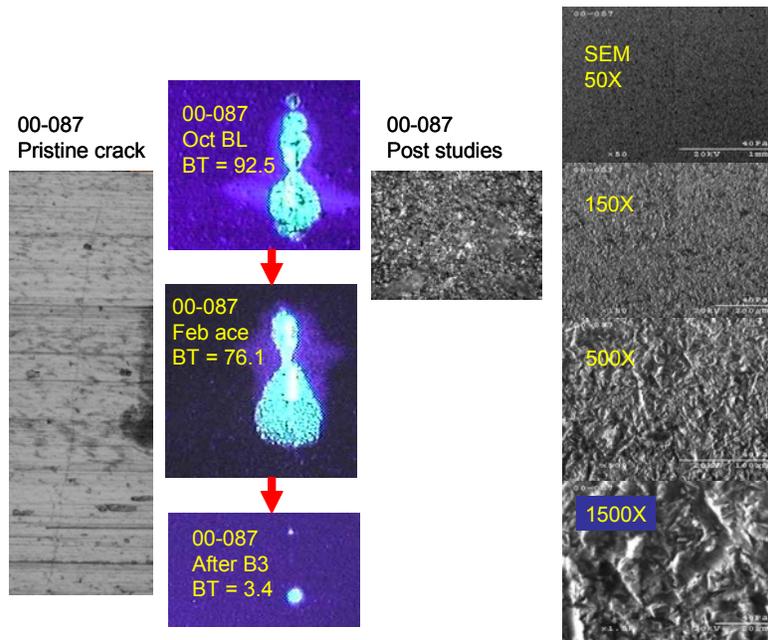


FIGURE 52. RESULTS FOR THE 00-087 Ti SAMPLE AFTER B3 PROCESSING

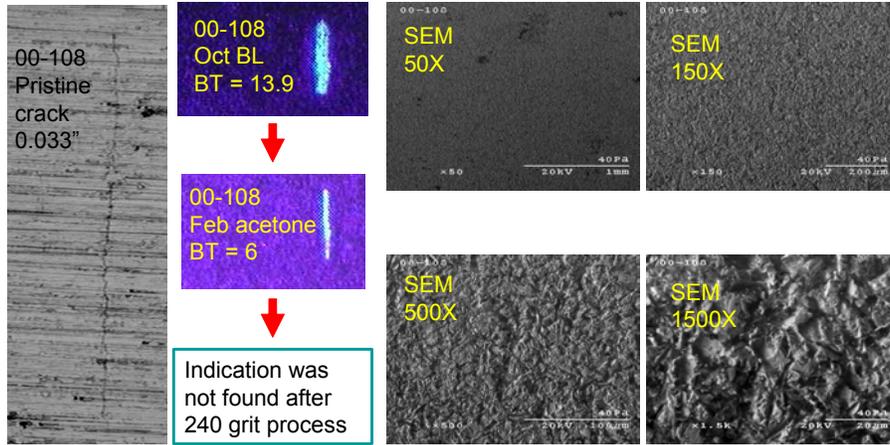


FIGURE 53. RESULTS FOR THE 00-108 Ni SAMPLE AFTER B3 PROCESSING

3.6.4.13.2 320 Grit.

The results for two of the five samples used in the 320-grit (B4) studies are shown in figures 54 and 55. As evidenced by the saturated signals after the B4 process and the optical image shown at the bottom of figures 55, it appears that a portion of the crack broke away, most likely as a result of the grit blast process. Results are also shown for a typical Ni sample. Note that after the B4 process, FPI indications were not found in any of the three Ni samples. As with the B3 study, all samples had shown FPI indications just prior to the B4 process. Therefore, the loss of the indication is the result of mechanical changes that occurred from the grit blast process.

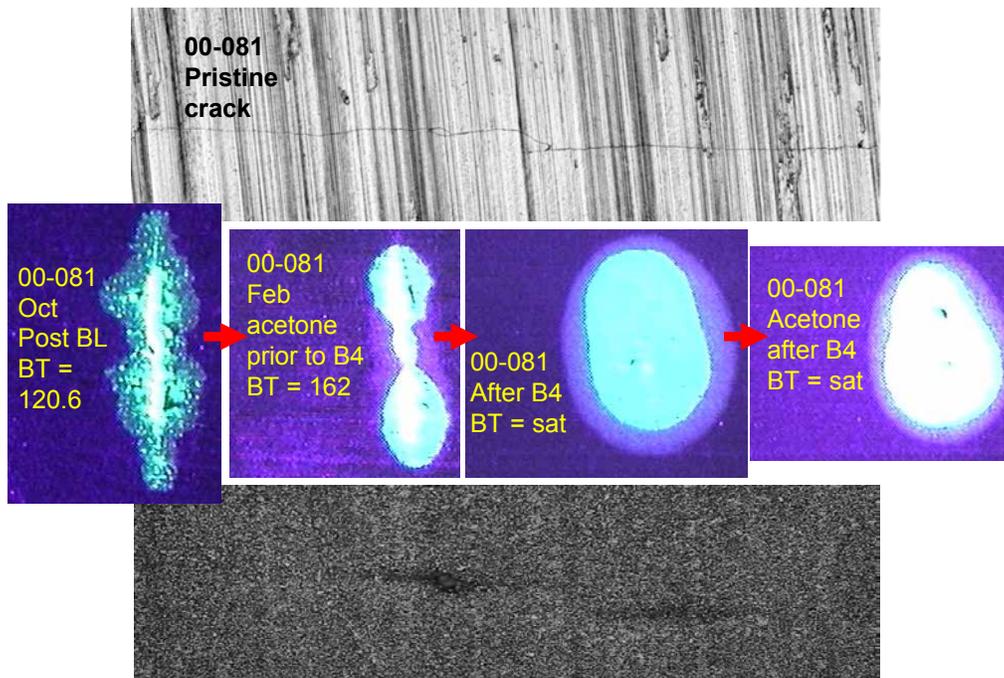


FIGURE 54. RESULTS FOR THE 00-081 Ti SAMPLE AFTER B4 PROCESSING

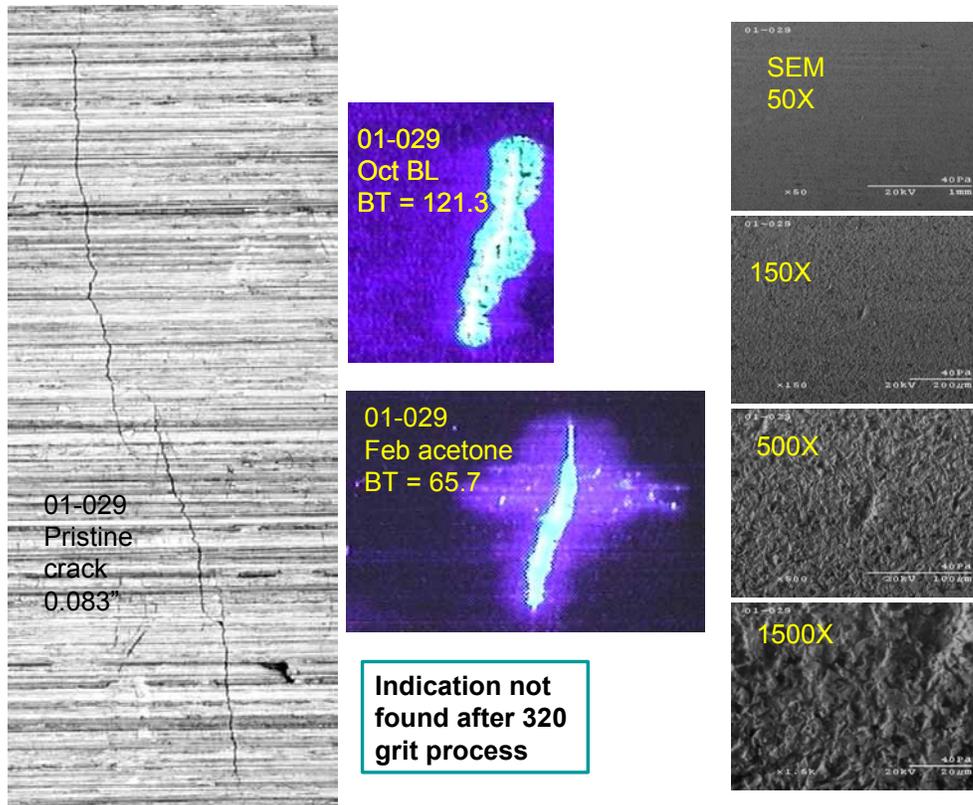


FIGURE 55. RESULTS FOR THE 01-029 Ni SAMPLE AFTER B4 PROCESSING

Given the current results, the data suggests that B4 is not a robust process for processing critical rotating hardware. In this study, the blast materials were new, unused grit without conditioning. Studies of the effect of grit usage time on cutting efficiency versus peening effect would provide useful data.

3.6.4.13.3 500-Grit Aluminum Oxide.

The smallest Al_2O_3 grit considered in this program was 500 grit (B5). The B5 samples show some smoothing and removing of surface sanding marks without the overall surface damage observed in B3 and B4 processes. Brightness reductions were observed in four of the six samples with significant reduction in three of the six samples for this grit size. UVA length reductions were found in all four samples evaluated in February, while UVA indication lengths without oxidation (October data) showed no change. The samples processed in October had RTV applied in prior steps. Comparing the results from October (prior to baked-on contamination) to February, the reductions in brightness could result from oxidation effects and not the effect of mechanical damage. Figure 56 shows typical results for a sample processed in October prior to the baked-on contamination process, while the results shown in figure 57 are for a sample that was processed to generate oxidation and scale contamination. Note that the optical image shows an obvious crack very similar to the prior optical image.

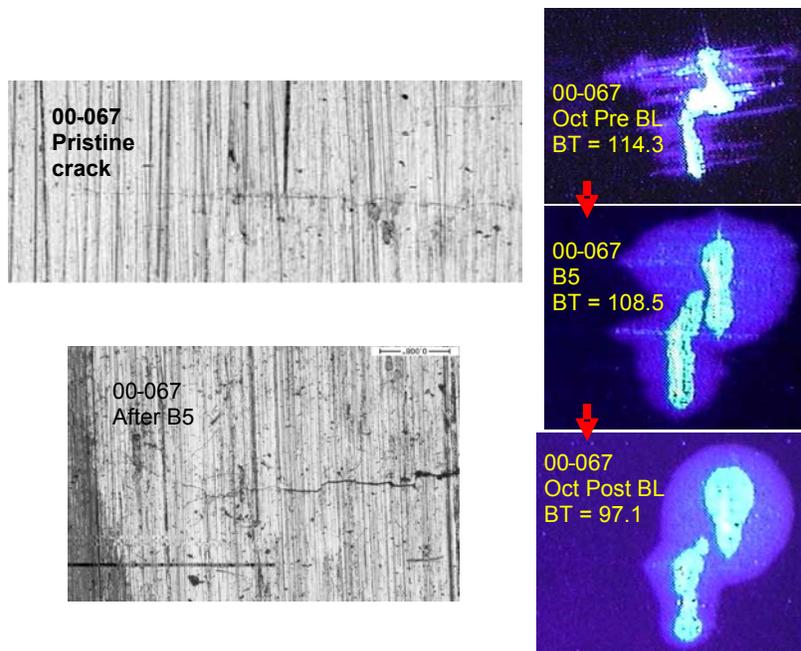


FIGURE 56. RESULTS FOR THE 00-067 Ti SAMPLE AFTER B5 PROCESSING

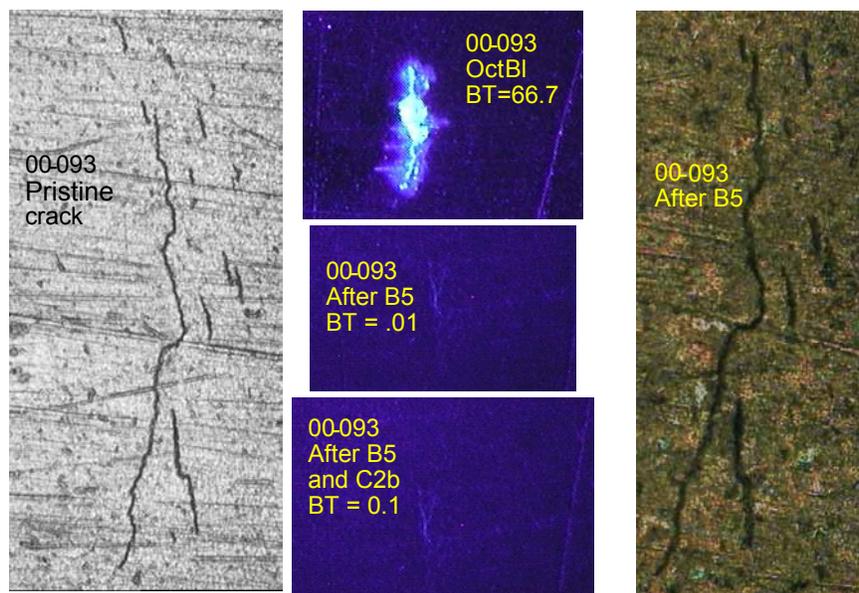


FIGURE 57. RESULTS FOR THE 00-093 Ti SAMPLE AFTER B5 PROCESSING

Comparison of the three grit sizes, 240, 320, and 500, indicates that the large grit (240 and 320) should not be used prior to FPI. The 500-grit processes can lead to some reduction in sensitivity, therefore, it should be used sparingly. It should also be noted that grit blasting only removes surface contaminants. It will not effectively remove contaminants from within the crack. If the contamination of concern is in the interior of the crack, such as oxidation and scale, chemical processes must be used in conjunction with the grit-blasting technique.

3.6.4.14 Walnut Shell Blast (B6) (Walnut Shells (60-120 mil)).

The B6 studies were performed in October and were applied to coating removal processes for both Ti and Ni, as shown in table 30. Of the nine Ti samples, two showed brightness reductions. Of the six Ni samples, three showed reductions in brightness. One sample showed a reduction in the UVA indication length. No obvious surface deformation or smearing was evident after reviewing the optical images. Typical results for the Ti and Ni samples are provided in figures 58, 59, and 60. The baseline process (acetone UT followed by 225°F (107°C) oven dry) returned samples to original brightness.

TABLE 30. RESULTS FOR WALNUT SHELL BLAST

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Pre BL1	Oct Pre BL2	Oct Pre BL3	Oct Post BL1	Oct Post BL2	Oct C2b	Oct C7a	Oct B6
RTV a/HTS b - C2a	B6	Ti	00-067	0.065	114.33	131.1	151.8	121.2	97.1			116.3
RTV a/HTS b - C2a	B6	Ti	01-010	0.112	37.94	111.9	125.83	250	250			101.5
RTV a/HTS b - C2a	B6	Ti	01-045	0.052	13.72	16.39	5.2	1.9	1.5			10.2
AG B + C2b	B6	Ti	01-037	0.093	5.25	7.18	10.67	6.1	9	0.04		2.4
AG B + C2b	B6	Ti	01-041	0.031	0.16	0.8	0.7	1.1	2.8	lost		0.6
AG B + C2b	B6	Ti	01-053	0.057	30.19	37.27	6.75	77.1	77.6	69		47.6
AG E	B6	Ti	00-078	0.12	125.99	139.25	170.85	250	250			110.4
AG E	B6	Ti	01-016	0.05	1.45	1.6	2	3.7	4.3			2
AG E	B6	Ti	01-043	0.054	6.4	7.6	1.7	1.8	0.3			1.8
AG C + C7a	B6	Ni	01-007	0.078	95.5	97.9	121.5	162.3	130.8		76.7	56.3
AG C + C7a	B6	Ni	01-003	0.03	7.5	8	5.43	8.7	8.8		5.5	5.5
AG C + C7a	B6	Ni	00-126	0.061	28.2	33.1	64.2	37.9	34.4		16.4	30.4
AG E	B6	Ni	00-111	0.038	22	10.6	18.7	31.8	31.2			23
AG E	B6	Ni	01-056	0.067	1.23	2.12	3.6	2.6	2.76			1.1
AG E	B6	Ni	00-125	0.084	21.6	35.2	46.9	6.7	29			12.9

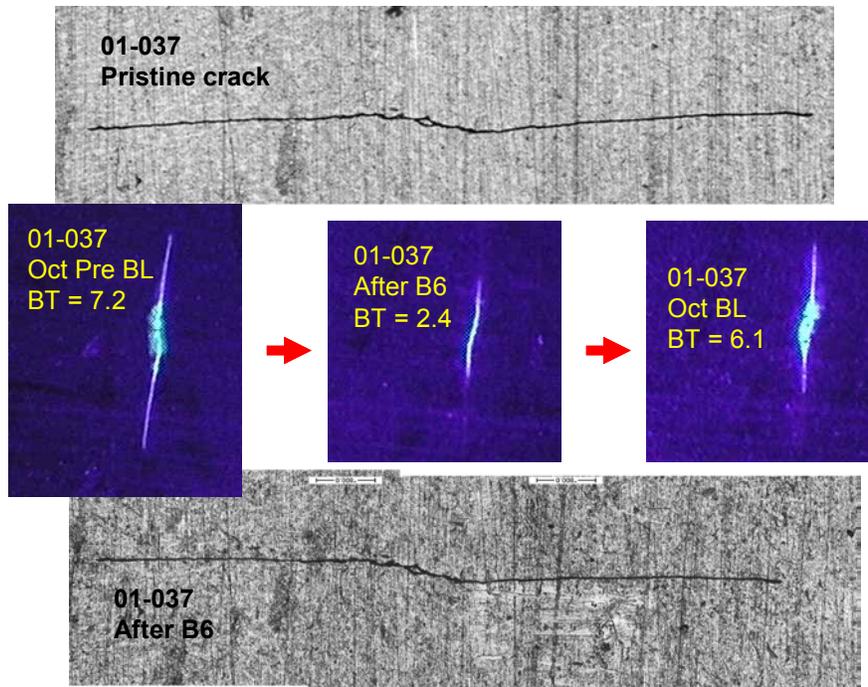


FIGURE 58. RESULTS FOR THE 01-037 Ti SAMPLE AFTER B6 TREATMENT

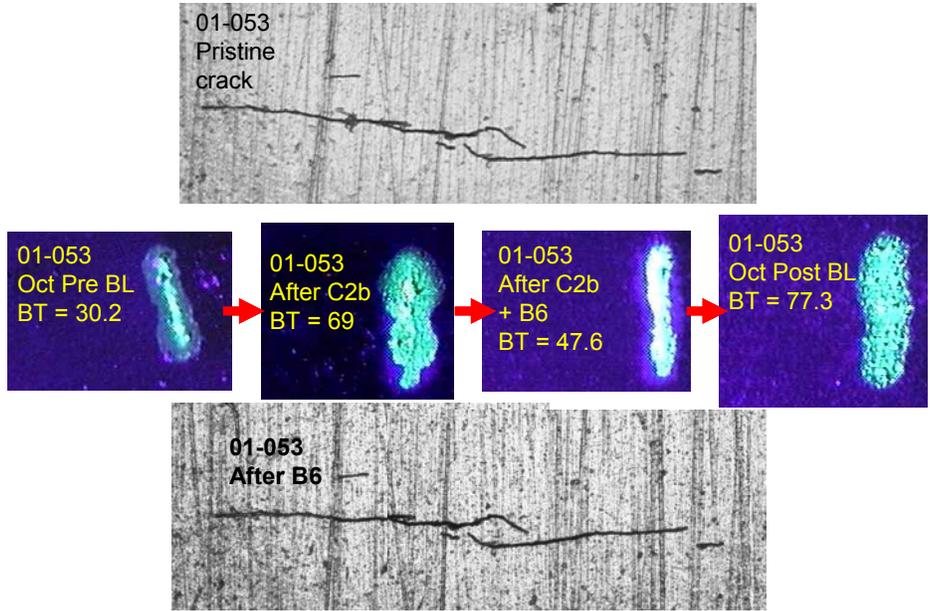


FIGURE 59. RESULTS FOR THE 01-053 Ti SAMPLE AFTER B6 TREATMENT

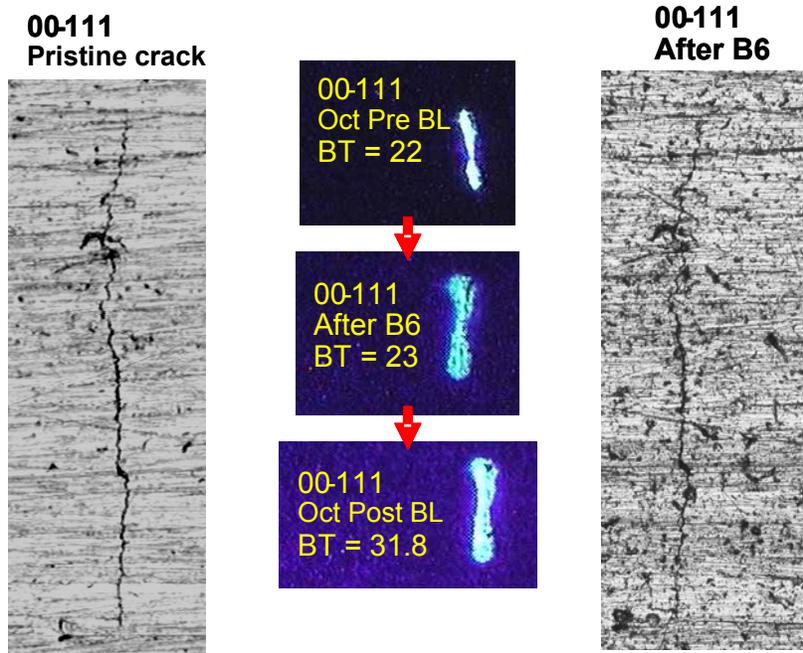


FIGURE 60. RESULTS FOR THE 00-111 Ni SAMPLE AFTER B6 TREATMENT

Given these results, as with the other blasting methods, a rinse step after B6 would improve sensitivity. An analysis of samples immediately after the B6 and prior to acetone, to determine presence of residue (oil from the media), shell particles, etc., would also provide relevant engineering data. A study that compares water rinse/dry to acetone UT/dry would be helpful in sorting out whether there is oil residue from walnut shells, which the liquid washes out, or if UT agitation is required to unclog the media.

3.7 INVESTIGATIVE STUDIES RELATED TO CLEANING METHOD COMPARISONS.

The original ETC program plan included an evaluation of eight chemical cleaning methods (C1-C8) and six mechanical cleaning methods (B1-B6), as described in table 11. A composite of the results from each of the cleaning studies that occurred in February is provided in table 31 for Ni and in table 32 for Ti. The color scale shown in figure 25 was also used in the composite results, where the green shading indicates that the brightness was the same or better than the baseline results. The results through run 8 were part of the original program plan. For those samples that have color shading in later runs (runs 9 through 22), additional processes were applied. A numerical tabulation of the brightness values is provided in tables 33 and 34.

Note that, overall, the results for the Ni samples were better than the Ti samples. A primary contributor was the four-step alkaline clean for the Ni samples, shown in table 31, in the C4 column. After reviewing the C3 results, which revealed numerous orange and red shading, the decision was made to clean all the Ni samples using C4. The improvement after using C4 is evident by the changes in shading. Also note that for the Ni samples, only those that were treated with B3 and B4 remained undetectable at the conclusion of the cleaning studies.

The results for the Ti samples shown in table 32 indicate less effective cleaning of the baked-on contaminants, given the more prevalent occurrence of red and orange shading. In an effort to recover additional samples, several other cleaning methods were tried. A summary of results is provided in sections 3.7.1 through 3.7.3.

- Vapor degreasing
- Permanganate
- Acid descaler

In addition to the cleaning processes, a ministudy of the effect of water on penetrant brightness was conducted at the Delta facility. This was not intended to serve as a cleaning process but rather to provide data concerning the impact of water on FPI sensitivity. Several other ministudies were also performed on a subset of the samples to provide additional data interpretation. These included the following, with details provided in sections 3.7.4 through 3.7.6.

- Hot-water soak
- Additional fatigue study
- Crack characterization

TABLE 31. BRIGHTNESS COMPARISON FOR Ni SAMPLES (FEBRUARY)

Contamination	Specimen	Optical Length	FPI run 2	FPI run 2	FPI run 4	FPI run 5	FPI run 6	FPI run 8	FPI run 8	FPI run 12	FPI run 15	FPI run 17	FPI run 18	FPI run 19	FPI run 19	FPI run 19	FPI run 20	FPI run 20	FPI run 20	FPI run 20	FPI run 21	FPI run 22
Indicates soot process repeated			C3	C7a	B1 40	C5	B5	B2	C3	C4	acetone	UT H ₂ O	H ₂ O	B3	B4	oil repeat	B3	B4	oil repeat	acetone	acetone	acetone
Oxidation and Scale	00-106	0.07																				
Oxidation and Scale	00-108	0.033																				
Oxidation and Scale	01-055	0.058																				
Oxidation and Scale	00-110	0.054																				
Oxidation and Scale	01-003	0.03																				
Oxidation and Scale	00-120	0.122																				
Oxidation and Scale	00-111	0.038																				
Oxidation and Scale	01-009	0.028																				
Oxidation and Scale	01-036	0.026																				
Oxidation and Scale	00-119	0.08																				
Oxidation and Scale	01-020	0.025																				
Oxidation and Scale	01-007	0.078																				
Soot	00-126	0.061																				
Soot	01-021	0.028																				
Soot	01-029	0.083																				
Soot	00-127	0.083																				
Soot	01-034	0.024																				
Soot	01-031	0.026																				
Soot	01-005	0.064																				
Soot	01-030	0.026																				
Soot	01-038	0.023																				
Coke & Varnish	01-008	0.078																				
Coke & Varnish	01-032	0.021																				
Coke & Varnish	00-105	0.067																				
Coke & Varnish	01-025	0.053																				
Coke & Varnish	01-033	0.021																				
Coke & Varnish	00-124	0.064																				
Coke & Varnish	01-026	0.055																				
Coke & Varnish	01-022	0.023																				
Coke & Varnish	01-039	0.021																				
Coke & Varnish	01-027	0.061																				
Coke & Varnish	01-035	0.025																				
Coke & Varnish	01-056	0.067																				

TABLE 32. BRIGHTNESS COMPARISON FOR Ti SAMPLES (FEBRUARY)

Contamination	Specimen	Optical Length	FPI run 4	FPI run 5	FPI run 5	FPI run 5	FPI run 6	FPI run 6	FPI run 7	FPI run 7	FPI run 7	FPI run 7	FPI run 8	FPI run 9	FPI run 10	FPI run 14	FPI run 16	FPI run 17	FPI run 18	FPI run 18	FPI run 19	FPI run 20	FPI run 20	FPI run 20
			B1	C1	C2b	C5	C2a	B5	C1	C2b	C5	B5	B2	VDG	C2b	ACE	scalagone	UT H ₂ O	H ₂ O	permanganate	B4	acetone	B3	B4
Oxidation and Scale	00-067	0.065																						
Oxidation and Scale	00-080	0.057																						
Oxidation and Scale	00-090	0.060																						
Oxidation and Scale	00-076	0.063																						
Oxidation and Scale	00-098	0.020																						
Oxidation and Scale	00-095	0.061																						
Oxidation and Scale	01-053	0.057																						
Oxidation and Scale	01-015	0.033																						
Oxidation and Scale	00-097	0.062																						
Oxidation and Scale	00-093	0.060																						
Oxidation and Scale	01-018	0.120																						
Oxidation and Scale	01-012	0.093																						
Soot	01-014	0.061																						
Soot	01-016	0.050																						
Soot	00-091	0.087																						
Soot	01-040	0.121																						
Soot	01-037	0.093																						
Soot	00-081	0.120																						
Soot	01-017	0.054																						
Soot	01-041	0.031																						
Soot	00-087	0.068																						
Soot	00-077	0.039																						
Soot	01-042	0.058																						
Soot	01-013	0.081																						
Soot	01-052	0.049																						
Soot	01-045	0.052																						
Soot	01-001	0.063																						

TABLE 33. NUMERICAL TABULATION OF BRIGHTNESS VALUES FOR Ni SAMPLES (FEBRUARY)

Contamination	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	FPI run 2	FPI run 2	FPI run 4	FPI run 5	FPI run 6	FPI run 8	FPI run 8	FPI run 12	FPI run 15	FPI run 17	FPI run 18	FPI run 19	FPI run 20	FPI run 21	FPI run 22				
						C3	C7a	B1 40	C5	B5	B2	C3	C4	acetone	UT H ₂ O	H ₂ O	VDG	C1	C3	B3	B4	acetone	acetone	acetone
Oxidation and Scale	00-106	0.07	47.8	24		0.7							61.6	56						0				
Oxidation and Scale	00-108	0.033	13.9			4.7							7	6						lost				
Oxidation and Scale	01-055	0.058	27.5	33.1		15							34.1	25.2						lost				
Oxidation and Scale	00-110	0.054	29.4	7			3.4						10.5	10.7			8.4						12.3	
Oxidation and Scale	01-003	0.03	8.7	8.8			2.5						3	4.9					5.8				7.1	
Oxidation and Scale	00-120	0.122	53.4	73.7	81.6		46.6						76.4	79.9				92.4					109.1	
Oxidation and Scale	00-111	0.038	31.8	31.2							15.6		38.5											
Oxidation and Scale	01-009	0.028	7.5	15.6							lost		4.4											
Oxidation and Scale	01-036	0.026	2.2								lost		0.9											
Oxidation and Scale	00-119	0.08	45.9	44.1						0.6			20											
Oxidation and Scale	01-020	0.025	16	33.8						11.7			5.6	79.9										
Oxidation and Scale	01-007	0.078	162.3	130.8						53.2			97.4											
Soot	00-126	0.061	37.9	34.4		lost							45.9	41.9							lost		lost	
Soot	01-021	0.028	11.3	7.3		12.3							8.2	9.1							lost		lost	
Soot	01-029	0.083	121.4	148		98.6							63.1	65.7							lost		lost	
Soot	00-127	0.083	79.8	93.2			lost						34.1	20.5			27.4						40.8	
Soot	01-034	0.024	1.4	1.6			1						1.8	2					2				2.4	
Soot	01-031	0.026	0.04	0.9	0.9		lost						2.1	2.5				2.4					2.3	

TABLE 33. NUMERICAL TABULATION OF BRIGHTNESS VALUES FOR Ni SAMPLES (FEBRUARY) (Continued)

Contamination	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	FPI run 2	FPI run 2	FPI run 4	FPI run 5	FPI run 6	FPI run 8	FPI run 8	FPI run 12	FPI run 15	FPI run 17	FPI run 18	FPI run 19	FPI run 20	FPI run 21	FPI run 22				
						C3	C7a	B1 40	C5	B5	B2	C3	C4	acetone	UT H ₂ O	H ₂ O	VDG	C1	C3	B3	B4	acetone	acetone	acetone
Soot	01-005	0.064	30.1	40.3				8				Lost	28.5											
Soot	01-030	0.026	4	3.9				1.3				2.3	6.6											
Soot	01-038	0.023	0.1					0.56				0.1	0.5											
Coke and Varnish	01-008	0.078	2.6	31.4		14.7							26.8	32.2	33.7	11.8						36.4		45.9
Coke and Varnish	01-032	0.021	7	6.6		0							6.5	8	0.1	1.8						4		5.1
Coke and Varnish	00-105	0.067	250	181.4		143.4							199	sat	160	199						212.6		207.1
Coke and Varnish	01-025	0.053	6.7	29			lost						16.8	18			19.2						24.6	
Coke and Varnish	01-033	0.021	5.2				5						8.2	7.4					7.6				9	
Coke and Varnish	00-124	0.064	174.3	250				169.3					sat	sat				sat					sat	
Coke and Varnish	01-026	0.055	40.1	49.9					4.1				48.2	30	36.8	21.9						24.6		41
Coke and Varnish	01-022	0.023	19	20.1					4.4				18.8	27	16.7	13.8						31.2		19.1
Coke and Varnish	01-039	0.021	6.2	5.5					lost				8.1	7.7	7.4	7.9						8.6		9.6
Coke and Varnish	01-027	0.061	79.8	93.2				lost				65.9	99.3											
Coke and Varnish	01-035	0.025	4.7	4.7				3.2				2.6	5.4											
Coke and Varnish	01-056	0.067	2.6	2.76				0.1				Lost	3.2											

TABLE 34. NUMERICAL TABULATION OF BRIGHTNESS VALUES FOR Ti SAMPLES (FEBRUARY)

Contamination	Specimen	Optical Length	Oct PostBL1	Oct PostBL2	FPI run 4	FPI run 5	FPI run 5	FPI run 5	FPI run 6	FPI run 6	FPI run 7	FPI run 8	FPI run 9	FPI run 10	FPI run 14	FPI run 16	FPI run 17	FPI run 18	FPI run 18	FPI run 19	FPI run 20	FPI run 20	FPI run 21	FPI run 22
					B1	C1	C2b	C5	C2a	B5	C2b	B2	VDG	C2b	acetone	scalagone	UT H ₂ O	H ₂ O	permanganate	B4	B3	acetone	acetone	acetone
Oxidation and Scale	00-067	0.065	121.2	97.1					lost					13										
Oxidation and Scale	00-080	0.057	2.3	2.4					lost					lost	lost		lost	lost				lost		lost
Oxidation and Scale	00-090	0.060	104.9	111.1					lost					lost	46		11.5	0.6				0.1		0.05
Oxidation and Scale	00-076	0.063	101.4	89.5			3.1				0.3		lost						2.5			lost		0.07
Oxidation and Scale	00-098	0.020	10.2	9.5			0.2				lost		lost						lost			lost		lost
Oxidation and Scale	00-095	0.061	109.3	119.2			118				64.8		92.8			70.3								
Oxidation and Scale	01-053	0.057	77.1	77.6								36.8		57.5										
Oxidation and Scale	01-015	0.033	3.2	9.3								lost		lost										
Oxidation and Scale	00-097	0.062	42.9	64.7								lost		lost										
Oxidation and Scale	00-093	0.060	66.7	51.9						0.1				0.1										
Oxidation and Scale	01-018	0.120	7.7	10.1						0.1	0.2			lost										
Oxidation and Scale	01-012	0.093	113	110.8						106				105.6						71.2			73.3	
Soot	01-014	0.061	114.7	102.2				lost						0.1					50.5			64.1		56.1
Soot	01-016	0.050	3.7	4.3				lost						lost		lost								
Soot	00-091	0.087	113.5	92.6				35.5						0.1		50.4								
Soot	01-040	0.121	44	49.4			lost				lost		lost											
Soot	01-037	0.093	6.1	9			lost				lost		lost											
Soot	00-081	0.120	120.6	115.3			sat				sat		sat		162		33.8	175.3		sat			sat	

TABLE 34. NUMERICAL TABULATION OF BRIGHTNESS VALUES FOR Ti SAMPLES (FEBRUARY) (Continued)

Contamination	Specimen	Optical Length	Oct PostBL1	Oct PostBL2	FPI run 4	FPI run 5	FPI run 5	FPI run 5	FPI run 6	FPI run 6	FPI run 7	FPI run 8	FPI run 9	FPI run 10	FPI run 14	FPI run 16	FPI run 17	FPI run 18	FPI run 18	FPI run 19	FPI run 20	FPI run 20	FPI run 21	FPI run 22
					B1	C1	C2b	C5	C2a	B5	C2b	B2	VDG	C2b	acetone	scalagone	UT H ₂ O	H ₂ O	permanganate	B4	B3	acetone	acetone	acetone
Soot	01-017	0.054	34.8	69.8				20.3			21.3		4											
Soot	01-041	0.031	1.1	2.8				lost			lost		lost											
Soot	00-087	0.068	60.1	92.5				38.3			69.1		74.2		76		11.1					3.4		
Soot	00-077	0.039	46.2	44.8		21.6					46.2		54.4		55		22.9	69.1				lost		
Soot	01-042	0.058	8.4	8		lost					lost		lost		lost		lost	lost				lost		lost
Soot	01-013	0.081	173.9	166.3		13.3					12.6		1.4		19		9.3	5.1					15.2	16.6
Soot	01-052	0.049	44.9	44.8	68.3						71.5		85.3		58		63.6	69.8					66.2	100.3
Soot	01-045	0.052	1.9	1.5	0.95						lost		lost											
Soot	01-001	0.063	67.3	106.6	29.7						15.6		22.6											

3.7.1 Vapor Degreasing.

To determine if vapor degreasing would be an effective cleaning method for baked-on contaminants, 15 Ti samples were processed after processing with other methods (B1, C1, C5, and C2b), as shown in table 35. Of the fifteen Ti samples processed, five showed improvement and three decreased in brightness. While vapor degreasing may contribute to the cleaning of Ti parts, it was not sufficient to remove all baked-on contamination.

TABLE 35. RESULTS FOR VAPOR DEGREASER FOR Ti SAMPLES

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Feb B1	Feb C1	Feb C5	Feb C2b	Feb C2b	Feb VDG
Oxidation and Scale +C2b+C2b	VDG	Ti	00-076	0.063	101.4	89.5				3.1	0.3	lost
Oxidation and Scale +C2b+C2b	VDG	Ti	00-098	0.020	10.2	9.5				0.2	lost	lost
Oxidation and Scale +C2b+C2b	VDG	Ti	00-095	0.061	109.3	119.2				117.6	64.8	92.8
Soot +C2b +C2b	VDG	Ti	01-040	0.121	44	49.4				lost	lost	lost
Soot +C2b +C2b	VDG	Ti	01-037	0.093	6.1	9				lost	lost	lost
Soot +C2b +C2b	VDG	Ti	00-081	0.120	120.6	115.3				sat	sat	sat
Soot +C5 +C2b	VDG	Ti	01-017	0.054	34.8	69.8			20.3	21.3		4
Soot +C5 +C2b	VDG	Ti	01-041	0.031	1.1	2.8			lost	lost		lost
Soot +C5 +C2b	VDG	Ti	00-087	0.068	60.1	92.5			38.3	69.1		74.2
Soot +C1 +C2b	VDG	Ti	00-077	0.039	46.2	44.8		21.6		46.2		54.4
Soot +C1 +C2b	VDG	Ti	01-042	0.058	8.4	8		lost		lost		lost
Soot +C1 +C2b	VDG	Ti	01-013	0.081	173.9	166.3		13.3		12.6		1.4
Soot +B1 +C2b	VDG	Ti	01-052	0.049	44.9	44.8	68.3			71.5		85.3
Soot +B1 +C2b	VDG	Ti	01-045	0.052	1.9	1.5	0.95			lost		lost
Soot +B1 +C2b	VDG	Ti	01-001	0.063	67.3	106.6	29.7			15.6		22.6

In addition, three Ni samples, which had reasonable brightness levels after using C4 and a baseline process using acetone, were used in an oil contamination ministudy. The results are shown in table 36. Three samples were selected for the study. Penetrating oil was applied over the crack and allowed to sit for several hours. The samples were then cleaned in a vapor-degreasing tank at the Delta facility. Note that all three samples showed improvement. Given the results, VDG is an effective cleaning method for oil contamination.

TABLE 36. RESULTS FOR VAPOR DEGREASER TRIAL FOR OIL REMOVAL ON Ni SAMPLES

Contamination	Cleaning Method	Alloy	Specimen	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb C7a	Feb C4	Feb acetone	Feb VDG (after oil)	Feb acetone
Soot+C7a+C4+ace	VDG+oil	Ni	00-127	79.8	93.2		lost	34.1	20.5	27.4	40.8
Coke and Varnish+C7a+C4+ace	VDG+oil	Ni	01-025	6.7	29		lost	16.8	18	19.2	24.6
Oxidation and Scale+C7a+C4+ace	VDG-oil	Ni	00-110	29.4	7		3.4	10.5	10.7	8.4	12.3

3.7.2 Permanganate.

Given the less than satisfactory results for the Ti samples, the decision was made to clean three samples using a permanganate treatment. While not currently used for Ti rotating components, it was felt that permanganate may be effective in removing baked-on contaminants. Note that of the three samples shown in table 37, two showed improvements in brightness after using

permanganate, although not back to the baseline levels. Figure 61 shows the UVA images for the three samples. Permanganate is used for cleaning heat-treated Ti parts for alpha case removal, but not typically used for critical rotating parts. Given the overall results of this study, evaluation of new cleaning methods for Ti would be beneficial. It is recommended that the development of a hot-line process similar to that used for Ni components and for nonrotating Ti components be considered for Ti rotating parts. Given its use for Ni and nonrotating Ti parts, permanganate could become part of the four-step hot-line process for Ti.

TABLE 37. RESULTS FOR PERMANGANATE TREATMENT

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb C2a	Feb C2b	Feb C2b	Feb VDG	Feb Permanganate	Feb acetone	Feb acetone
Oxidation & Scale +C2b+C2b+VDG	Permanganate	Ti	00-076	0.063	101.4	89.5			3.1	0.3	lost	2.5	lost	0.07
Oxidation & Scale +C2b+C2b+VDG	Permanganate	Ti	00-098	0.020	10.2	9.5			0.2	lost	lost	lost	lost	lost
Soot +C2a+C2b	Permanganate	Ti	01-014	0.061	114.7	102.2		lost	0.1			50.5	64.1	56.1

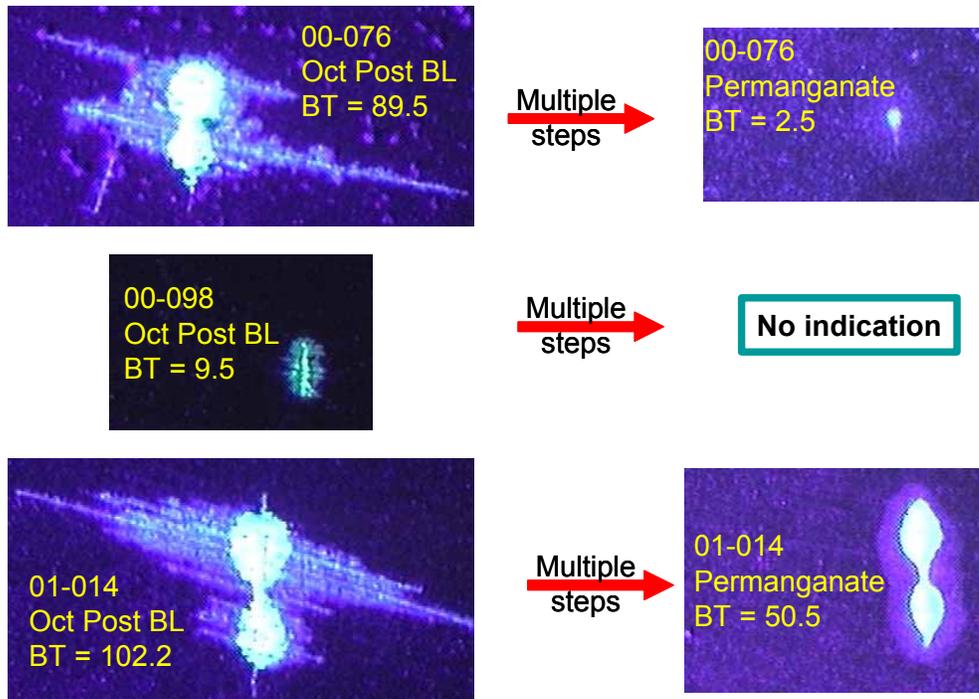


FIGURE 61. RESULTS FOR Ti SAMPLES AFTER PERMANGANATE TREATMENTS

3.7.3 Acid Descaler.

Acid descalers are typically used to condition high-temperature oxides on hot-section parts as part of a multistep process. Using an acid descaler as a single-step process is not a recommended practice. Usually it is combined with permanganate to provide a robust cleaning process. This study evaluated each step individually to determine the effectiveness in removing baked-on contaminants. The results for the three samples cleaned with acid descaler (ScalGon 5) are shown in table 38, with UVA images provided in figure 62. Of the three samples, one showed improvement over prior C2a and C2b; one showed similar performance; and a third

sample, for which the indication had not been found since the sooting process, remained undetectable. Given the results of the permanganate and acid descaler processes, it is recommended that a hot-line, multistep process be developed for Ti.

TABLE 38. RESULTS FOR THE ACID DESCALER TREATMENT

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Feb C2a	Feb C2b	Feb C2b	VDG	Acid descaler
Oxidation & Scale +C2b+C2b+VDG	Acid descaler	Ti	00-095	0.061	109.3	119.2		117.6	64.8	92.8	70.3
Soot +C2a+C2b	Acid descaler	Ti	01-016	0.050	3.7	4.3	lost	lost			lost
Soot +C2a+C2b	Acid descaler	Ti	00-091	0.087	113.5	92.6	35.5	0.1			50.4

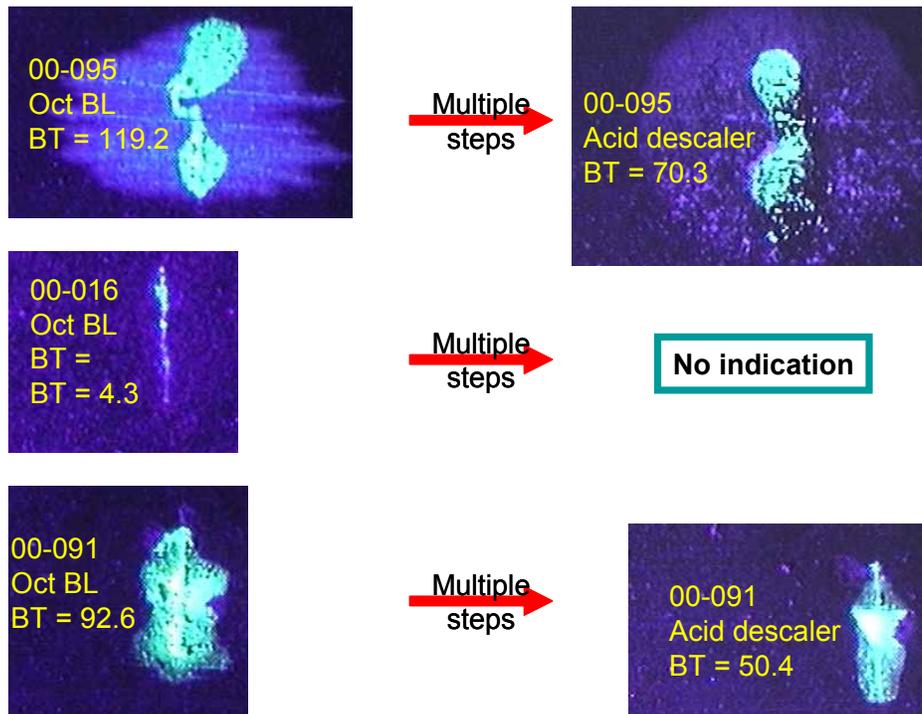


FIGURE 62. RESULTS FOR THREE Ti SAMPLES CLEANED USING ACID DESCALER

Effective FPI requires a clean, dry, open surface crack that allows the penetrant solution to enter the defect for later blotting action by the developer. In an effort to quantify the effect of water contamination, a subset of the samples was selected for use in a two-part study. In the first experiment, samples that had been dried at 225°F (107°C) and allowed to cool to ambient temperature were placed in a bucket of 70°F water and ultrasonically agitated for 10 minutes, as shown in figure 63(a) and 63(b). The posttemperature of the water was 102°F. The samples were taken from the UT water bath, blotted with a paper towel to remove excess surface moisture, as shown in figure 63(c), and immediately taken through the FPI process (figure 63(d)) without a drying step prior to the application of penetrant. In the second study, the dry samples were immersed in 70°F water for 10 minutes, blotted with a paper towel, and processed with FPI without a drying step. As shown in table 39, six Ni samples and eight Ti samples were used in the study. All 14 samples had been used for the baked-on contaminants study and undergone

chemical cleaning processes, as indicated in column one of table 39. (The results are not shown for the prior cleaning steps.) However, all 14 samples underwent a baseline process (30-minute acetone soak with ultrasonic agitation, followed by a 225°F (107°C) oven dry). The results are shown in the first Feb acetone column in table 39. Two additional baseline runs were made after the water contamination study, as shown in the last two columns of table 39 labeled Feb acetone. Note that reductions in brightness were found with both water contamination treatments, with the results more severe for the ultrasonic agitation. UT H₂O led to lower brightness in all but one case with less impact on length values. Because some cracks showed reduced brightness in plain H₂O and others showed increased brightness, a review of correlation to crack size was performed, see figure 64. The brightness after water contamination was normalized with the brightness after the acetone/oven dry process. Values of 1 indicated no change, values greater than 1 indicated brightness improvement, and values less than 1 indicated brightness degradation. From the results, no correlation with indication length was found. If a conservative approach is taken, reductions in brightness are of concern. Therefore, water should be considered a contaminant that degrades the penetrant process, indicating that drying is an important step in preparation for FPI. Typical results for several samples are shown in figure 65.

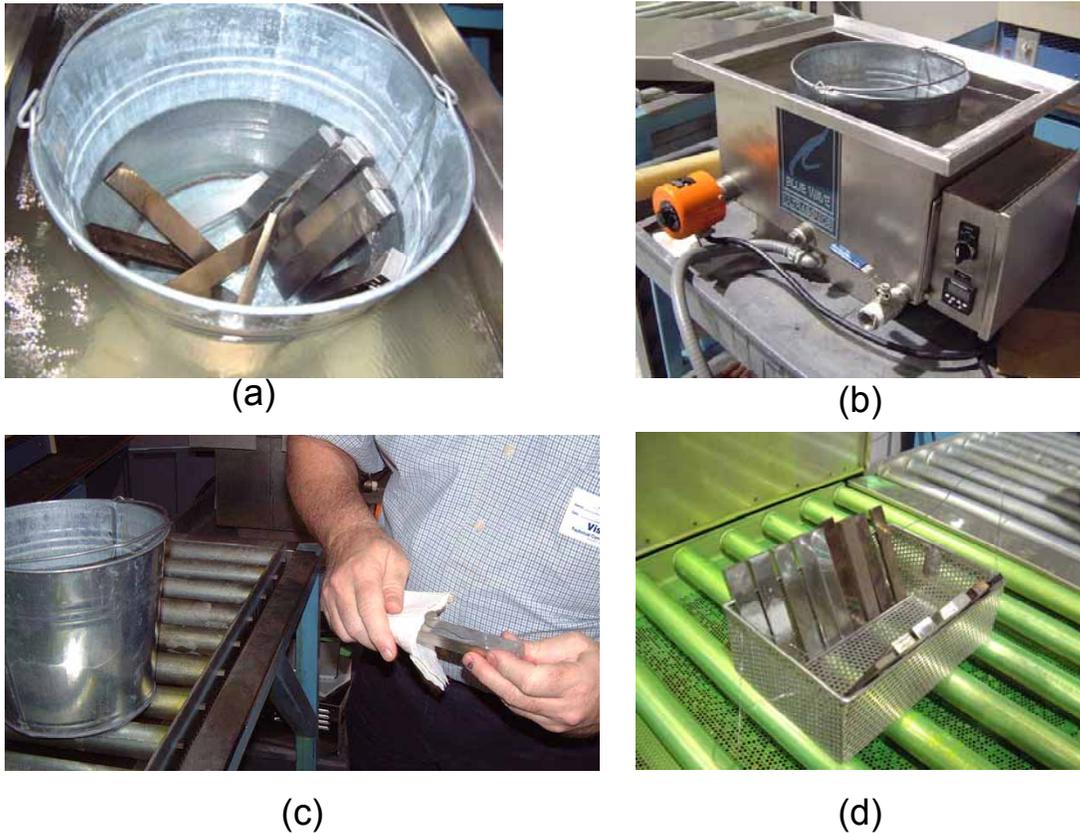


FIGURE 63. PROCEDURE FOR WATER CONTAMINATION TEST (a) SAMPLES IN 70° WATER, (b) SAMPLES IN ULTRASONIC CLEANER, (c) EXCESS WATER IS BLOTTED FROM THE SURFACE, AND (d) SAMPLES READY FOR FPI

TABLE 39. RESULTS OF WATER CONTAMINATION STUDY

Contamination	Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Oct Post BL 3	Feb acetone	Feb UT H ₂ O	Feb H ₂ O	Feb acetone	Feb acetone
Coke and Varnish +C3+C4+ACE	UT H ₂ O	Ni	01-008	0.078	2.6	31.4		32.2	33.7	11.8	36.4	45.9
Coke and Varnish +C3+C4+ACE	UT H ₂ O	Ni	01-032	0.021	7	6.6		8	0.1	1.8	4	5.1
Coke and Varnish +C3+C4+ACE	UT H ₂ O	Ni	00-105	0.067	250	181.4		sat	159.6	198.6	212.6	207.1
Coke and Varnish+C5+C4	UT H ₂ O	Ni	01-026	0.055	40.1	49.9		30	36.8	21.9	24.6	41
Coke and Varnish+C5+C4	UT H ₂ O	Ni	01-022	0.023	19	20.1		27	16.7	13.8	31.2	19.1
Coke and Varnish+C5+C4	UT H ₂ O	Ni	01-039	0.021	6.2	5.5		7.7	7.4	7.9	8.6	9.6
Oxidation and Scale+C2a+C2b+ace	UT H ₂ O	Ti	00-080	0.057	77.1	77.6		lost	lost	lost	lost	lost
Oxidation and Scale+C2a+C2b+ace	UT H ₂ O	Ti	00-090	0.060	3.2	9.3		45.5	11.5	0.6	0.1	0.05
Soot +C2b+C2b+VDG+ace	UT H ₂ O	Ti	00-081	0.120	42.9	64.7		161.7	33.8	175.3	sat	
Soot +C5+C2b+VDG+ace	UT H ₂ O	Ti	00-087	0.068	66.7	51.9		76.1	11.1			
Soot+C1+C2b+VDG+ace	UT H ₂ O	Ti	00-077	0.039	7.7	10.1		54.6	22.9	69.1		
Soot+C1+C2b+VDG+ace	UT H ₂ O	Ti	01-042	0.058	113	110.8		lost	lost	lost	lost	lost
Soot+C1+C2b+VDG+ace	UT H ₂ O	Ti	01-013	0.081	114.7	102.2		19.1	9.3	5.1	15.2	16.6
Soot+B1+C2b+VDG+ace	UT H ₂ O	Ti	01-052	0.049	3.7	4.3		58.4	63.6	69.8	66.2	100.3

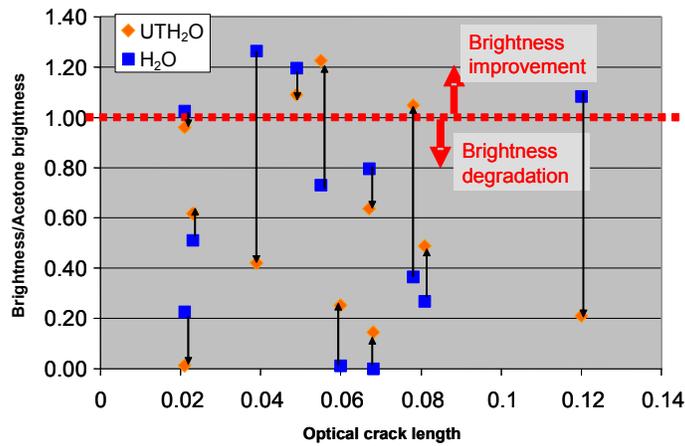


FIGURE 64. COMPARISON OF BRIGHTNESS AFTER WATER CONTAMINATION TO BASELINE AS A FUNCTION OF THE OPTICAL CRACK LENGTH

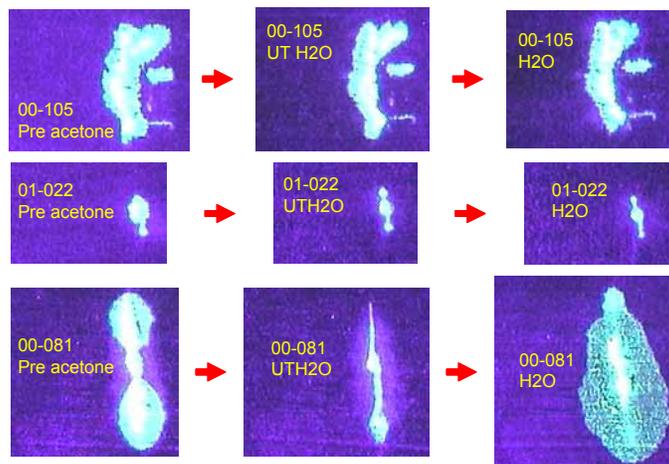


FIGURE 65. TYPICAL RESULTS FROM WATER CONTAMINATION STUDY

3.7.4 Hot-Water Soak Study.

During analysis of the various chemical cleaning methods, it was suggested that residual byproducts of the cleaning processes could be interfering with the penetrant performance. A ministudy was performed to determine if the chemical cleaning methods used to remove high-temperature contaminants from Ni and Ti samples left residual byproducts that interfered with subsequent FPI. The residues left by some alkaline cleaners, especially those that contain sodium metasilicate (Na_2SiO_3), have a known tendency to greatly degrade the brightness of the yellow dye contained in fluorescent penetrant [20]. After returning the samples to ISU, a subset consisting of 14 samples was selected, see table 40. All samples remained in the as-received condition from the cleaning operations performed at the Delta facility. Each sample received a surface wipe with an acetone-damp cloth to remove any handling contamination. The samples were divided into two groups to facilitate processing at ISU, i.e., processing in jars as described in section 3.2. Group 1 consisted of samples 00-080, 00-098, 01-015, 01-018, 01-037, 01-039, and 01-041, and group 2 was comprised of samples 00-091, 01-005, 01-014, 01-016, 01-042, 01-045, and 01-052.

Each group was immersed in 150°F (65.6°C) distilled water for 5 minutes in an effort to rinse away any possible cleaning residues. The water was heated on a hot plate to 152°F prior to sample immersion. The water temperature dropped to 148°F before rising back to 150°F at the end of the 5 minutes. The samples were then oven-dried with a target temperature of 225°F (107°C). Because of a mechanical thermostat failure, the oven temperature actually reached 260°F (127°C). The samples were dried for a total of 30 minutes (the samples were over the target temperature for approximately 15 of the 30 minutes). The FPI process consisted of a 20-minute penetrant dwell, 90-second prerinse, 120-second emulsification, 90-second postwash, 8-minute dry at 140°F, and a 10-minute development time, followed by evaluation and measurement of brightness. After the hot-water study, an acetone soak was also done to determine its effectiveness in returning the brightness of FPI indications. The samples were stored in acetone overnight (15 hours) and dried at 140°F for 30 minutes. FPI was performed using the same procedure outlined in section 3.2.

Eight of the fourteen samples gave an FPI indication after the 5-minute, 150°F water soak. Three of the eight samples (01-015, 01-018, and 01-042) that gave an FPI indication had not provided a visible indication during the last cleaning run at the Delta facility. Two cracked samples that gave an FPI indication after the hot-water soak (01-015 and 01-042) had not formed an indication after any of the previous cleaning methods, although neither of those formed an indication after the acetone soak. The results of the brightness comparisons are provided in table 41.

In an effort to determine if contaminants were present, samples used in the hot-water soak study were also evaluated using optical microscopy. Figure 66 shows magnified areas of samples that gave poor FPI results, possibly due to a residual contaminant in the crack that was not removed by cleaning. Figure 66(a) shows possible residual contaminant, as viewed optically in crack 01-015 after the alkaline cleaning, grit blasting, hot-water soak, and acetone soak (500X). Figure 66(b) shows a high-temperature contaminant, viewed in the crack and adjacent pockets of

sample 01-018 after grit blasting, alkaline cleaning, hot-water soak, and acetone (200X). The fatigue crack shown in figure 66(c) (sample 01-042) was very tight with no residual contaminant visible at 500X. Although the crack was not located in sample 01-016 some possible high-temperature contaminant was visible in a surface scratch after all cleaning attempts (500X), as shown in figure 66(d). No FPI runs were attempted at the Delta facility prior to the first cleaning method listed. It was not determined if all samples, such as the soot-contaminated samples, were degraded to an extent that an FPI indication would be produced by the crack prior to cleaning. Therefore, it could not be determined if the loss of indications was the result of residual contamination from the baked-on contaminants or potential contamination from the cleaning processes.

TABLE 40. SAMPLES USED IN THE HOT-WATER SOAK STUDY

ID Number (material)	Crack Length (in/mm)	Contamination	Notes
00-080 (Ti 6-4)	0.057/1.45	Oxidation and scale	
00-091 (Ti 6-4)	0.087/2.21	Soot	Medium width crack
00-098 (Ti 6-4)	0.020/0.51	Oxidation and scale	
01-005 (IN-718)	0.064/1.63	Soot	Tight crack
01-014 (Ti 6-4)	0.061/1.55	Soot	Medium width crack
01-015 (Ti 6-4)	0.033/0.84	Oxidation and scale	
01-016 (Ti 6-4)	0.050/1.27	Soot	Crack not found optically
01-018 (Ti 6-4)	0.120/3.05	Oxidation and scale	Tight to medium width crack
01-037 (Ti 6-4)	0.093/2.36	Soot	Soot applied twice due to problems on first run.
01-039 (IN-718)	0.021/0.53	Coke and varnish	Tight to medium width crack. This sample was included as a control specimen due to previously consistent length readings and low brightness.
01-041 (Ti 6-4)	0.031/0.79	Soot	Soot applied twice due to problems on first run.
01-042 (Ti 6-4)	0.058/1.47	Soot	Tight crack, with soot applied twice due to problems on first run.
01-045 (Ti 6-4)	0.052/1.32	Soot	Soot applied twice due to problems on first run. Heavily deformed surface, crack not found optically.
01-052 (Ti 6-4)	0.049/1.25	Soot	Wide crack. This sample was included as a control specimen due to previously consistent brightness and length readings.

TABLE 41. RESULTS OF HOT-WATER SOAK AND ACETONE STUDY

Contamination/Cleaning Method	Alloy	Specimen	Optical Length	Oct Post BL 1	Oct Post BL 2	Feb B1	Feb B2	Feb B5	Feb C2a	Feb C5	Feb C2b	Feb C2b	Feb C3	Feb C4	Feb VDG	Feb acetone	Feb Permanganate	Scalegone	Feb UT H ₂ O	Feb H ₂ O	Feb Acetone	Feb Acetone	May Hot-Water Soak	May Acetone
Oxidation and Scale+C2a+C2b+ace +UT H ₂ O	Ti	00-080	0.057	77.1	77.6				0.7	lost					lost			lost	lost	lost	lost	lost	lost	lost
Soot +C2a+C2b+Scalegone	Ti	00-091	0.087	113.5	92.6				35.5	0.1								50.4					18.9	43.8
Oxidation and Scale +C2b+C2b+VDG+permanganate	Ti	00-098	0.020	10.2	9.5					0.2	lost			lost			lost				lost	lost	lost	lost
Soot +C2a+C2b+permanganate	Ti	01-014	0.061	114.7	102.2				lost	0.1								50.5			64.1	56.1	29.1	53.7
Oxidation and Scale + B2 + C2b	Ti	01-015	0.033	3.2	9.3		lost			lost													0.1	lost
Soot +C2a+C2b+Scalegone	Ti	01-016	0.050	3.7	4.3				lost		lost							lost					lost	lost
Soot +B1+C3+C4	Ni	01-005	0.064	30.1	40.3	8							lost	28.5									11.7	13
Oxidation and Scale + B5+C2b+C2b	Ti	01-018	0.120	3.7	4.3			0.1			0.2	lost											0.04	0.01
Soot +C2b +C2b+VDG	Ti	01-037	0.093	6.1	9					lost	lost	lost			lost								lost	lost
Soot +C5 +C2b+VDG	Ti	01-041	0.031	1.1	2.8					lost	lost	lost		1.1	lost								lost	lost
Soot+C1+C2b+VDG+ace+UT H ₂ O	Ti	01-042	0.058	113	110.8				lost		lost	lost			lost				lost	lost	lost	lost	0.02	lost
Soot +B1 +C2b+VDG	Ti	01-045	0.052	1.9	1.5	0.95					lost	lost			lost								lost	lost
Soot+B1+C2b+VDG+ace+UT H ₂ O	Ti	01-052	0.049	3.7	4.3	68.3					71.8				85.3	58.4			63.6	69.8	66.2	100.3	55.3	58.8
Coke & Varnish+C5+C4	Ni	01-039	0.021	6.2	5.5					lost				8.1		7.7			7.4	7.9	8.6	9.6	2.5	0.01

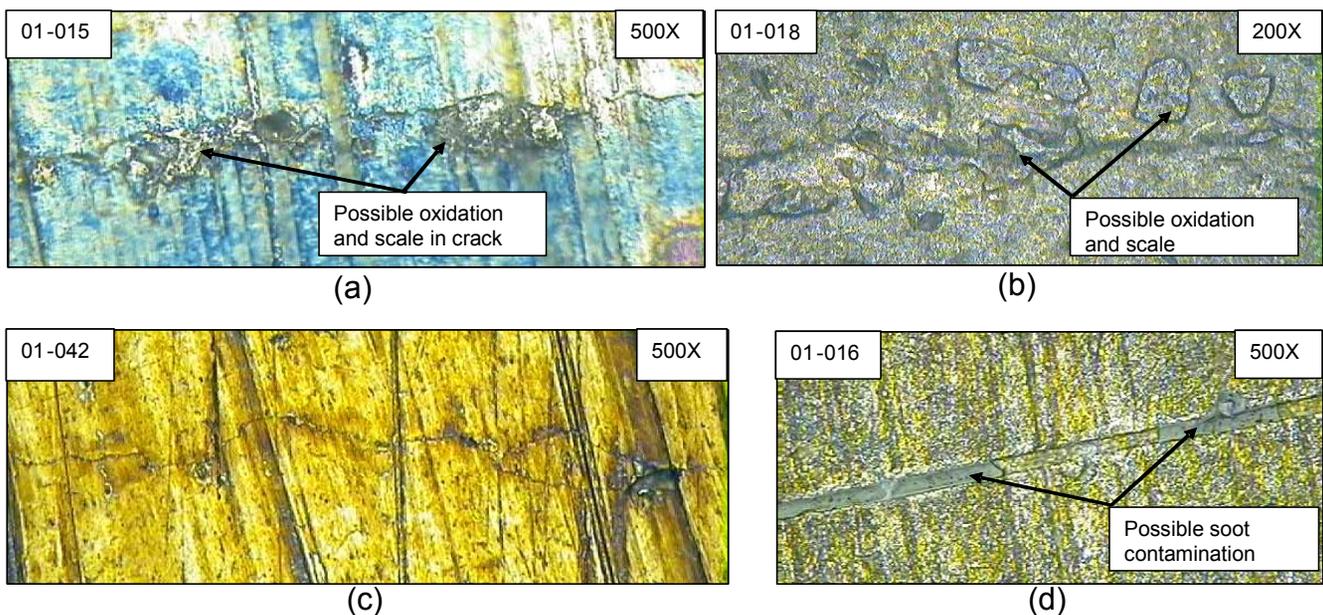


FIGURE 66. MICROGRAPHS OF SAMPLES USED IN THE HOT-WATER STUDY

3.7.5 Fatigue Study.

It was observed by the program team that cracks in engine run hardware would see stress cycling that could lead to crack growth while at temperature. This implies that while oxides, scale, soot, and varnish may form in cracks, the crack faces may also be in contact with the oxides, scale, soot, and varnish such that rubbing occurs, breaking up the baked-on contaminants and rendering more detectable indications. As indicated earlier, a number of specimens with known fatigue cracks were not producing FPI indications that resembled those obtained prior to contamination and cleaning. Two possible reasons for lack of inspection success could be that the mechanical cleaning methods may have caused metal smearing and crack closure or that crack-clogging contaminants remained despite cleaning. In an effort to assess the relationship between fatigue and FPI response, ten samples were selected for this ministudy and subjected to a small number of fatigue cycles to open the crack for successful FPI. Ten samples, six Ti and four Ni, were used, see table 42 for a description of the samples.

TABLE 42. SAMPLES USED IN FATIGUE STUDY

ID Number (material)	Crack Length (in/mm)	Contamination	Notes
00-087 (Ti 6-4)	0.068/1.73	Soot	Soot applied twice due to problems on first run.
00-093 (Ti 6-4)	0.060/1.52	Oxidation and scale	
00-098 (Ti 6-4)	0.020/0.51	Oxidation and scale	Heavy FPI background noise.
00-108 (IN-718)	0.033/0.83	Oxidation and scale	Heavy surface deformation, cannot see crack optically.
00-119 (IN-718)	0.080/2.03	Oxidation and scale	Heavy surface deformation, cannot see crack optically.
01-009 (IN-718)	0.028/0.71	Oxidation and scale	
01-029 (IN-718)	0.083/2.11	Soot	Heavy surface deformation. Cannot see crack optically, but slightly visible to SEM at low magnification.
01-037 (Ti 6-4)	0.093/2.36	Soot	Soot applied twice due to problems on first run.
01-042 (Ti 6-4)	0.058/1.47	Soot	Soot applied twice due to problems on first run.
01-045 (Ti 6-4)	0.052/1.32	Soot	Soot applied twice due to problems on first run. Only very small crack sections are visible optically.

Each sample received 15 fatigue cycles with a maximum load that resulted in a surface stress equivalent to 80% of the material's yield strength with a 0.1 R ratio. After fatigue cycling, the samples were acetone cleaned with ultrasonic agitation for 30 minutes, then soaked in acetone for 15 hours. Following a 2-hour dry at 160°F, the samples were inspected using FPI. The FPI process consisted of a 20-minute penetrant dwell, 90-second prerinse, 120-second emulsification, 90-second postwash, 8-minute dry at 140°F, and a 10-minute development time as used in all other FPI processes in the program.

Nine of the ten samples produced an FPI indication. The test results for baseline readings taken prior to high-temperature contamination, previous FPI runs during the cleaning attempts at the Delta facility, a previous hot-water soak study described above, and this fatigue cycle ministudy are provided in table 43. Figures 67 and 68 compare the optical image (a) to the UVA images (b) for a Ti and Ni sample respectively. Figures 67 and 68(c) show the transition of an optical image to a UVA image, using a UVA-equipped optical microscope. For sample 01-037, shown in figure 67(c), it is clear that only a portion of the defect is fluorescing. For sample 00-119, shown in figure 68(c), note that while the UVA image is visible, the crack cannot be found optically under white light at up to 1000X magnification.

As indicated in table 43, nine of the samples produced indications after fatigue. Five of the samples had not produced visible FPI indications on the prior cleaning run at the Delta facility. Three samples (00-108, 00-119, and 01-029), producing FPI indications, had a heavily deformed surface finish such that the fatigue cracks were not found during optical microscopy. Sample 00-098 had heavy background noise and scratches that may have masked an FPI indication if present. A combination UVA and white light illumination technique, like that shown in figures 67 and 68, did not assist in locating cracks in these samples. Four indications showed a large brightness improvement (00-093, 00-119, 01-042, and 01-045), while five samples showed no marked improvement over previous baseline results (00-087, 00-108, 01-009, 01-037, 01-029). Figures 69 and 70 compares the UVA changes for soot and oxidation and scale samples respectively. Given these results, adding fatigue cycles with loading, such that the surface stress was 80% of the material yield strength, was successful in improving the brightness and length of FPI indications in seven of the ten samples over the previous FPI inspection results. Further efforts to determine the number of fatigue cycles to return the samples to original brightness could prove useful in understanding the relationship between high-temperature contamination and crack rubbing.

TABLE 43. RESULTS FROM THE FATIGUE STUDY

00-087 (Ti-Soot)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C5	C2b	VDG	Acetone	UT H2O	B3					Fatigue
Brightness	76.3	38.3	69.1	74.2	76.1	11.1	3.4					6.7
Indication Length	0.074	0.067	0.067	0.069	0.076	0.057	0.04					0.047
00-093 (Ti-Ox+Scale)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	B5	C2b									Fatigue
Brightness	59.3	0.1	0.1									106.3
Indication Length	0.067	0.03	0.021									0.07
00-098 (Ti-Ox+Scale)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C2b	C2b	VDG	Perm	Acetone	Acetone			Hot H2O	Acetone	Fatigue
Brightness	9.85	0.2	0	0	0	0	0			0	0	0
Indication Length	0.025	0.012	0	0	0	0	0			0	0	0
00-108 (Ni-Ox+Scale)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C3	C4	Acetone	B3							Fatigue
Brightness	12.7	4.7	7	6	0							0.001
Indication Length	0.037	0.02	0.035	0.035	0							0.006
00-119 (Ni-Ox+Scale)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	B5	C4									Fatigue
Brightness	45	0.6	20									42.5
Indication Length	0.066	0.005	0.045									0.085
01-009 (Ni-Ox+Scale)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	B2	C4									Fatigue
Brightness	11.55	0	4.4									1.95
Indication Length	0.027	0	0.007									0.01
01-029 (Ni-Soot)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C3	C4	Acetone	B4	Acetone						Fatigue
Brightness	134.7	98.6	63.1	65.7	0	0						1.31
Indication Length	0.092	0.042	0.082	0.08	0	0						0.028
01-037 (Ti-Soot)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C2b	C2b	VDG						Hot H2O	Acetone	Fatigue
Brightness	7.55	0	0	0						0	0	0.27
Indication Length	0.056	0	0	0						0	0	0.016
01-042 (Ti-Soot)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	C1	C2b	VDG	Acetone	UT H2O	H2O	Acetone	Acetone	Hot H2O	Acetone	Fatigue
Brightness	8.2	0	0	0	0	0	0	0	0	0.02	0	15.38
Indication Length	0.041	0	0	0	0	0	0	0	0	0.015	0	0.072
01-045 (Ti-Soot)		-----Previous Cleaning Attempts at Overhaul Facility-----								ISU Recovery Attempts		
	Average Baseline	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	ISU1	ISU2	ISU3
Method	UT Acet	B1	C2b	VDG						Hot H2O	Acetone	Fatigue
Brightness	1.7	0.095	0	0						0	0	11.85
Indication Length	0.023	0.031	0	0						0	0	0.082

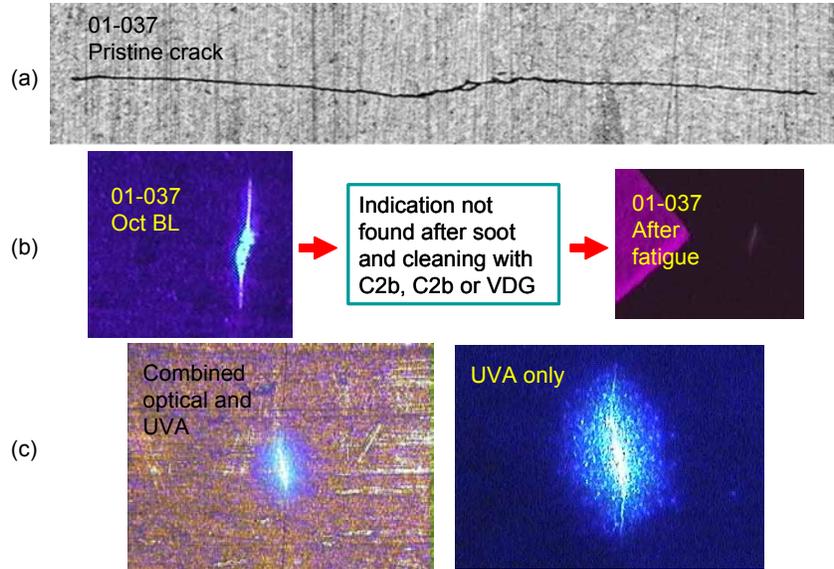


FIGURE 67. TRANSITION OF AN OPTICAL IMAGE TO A UVA IMAGE FOR THE 01-037 Ti SAMPLE (a) OPTICAL IMAGE OF A CRACK PRIOR TO STUDIES, (b) COMPARISON OF UVA IMAGE FROM OCTOBER BASELINE AND AFTER FATIGUE. NOTE THAT NO INDICATION WAS VISIBLE AFTER SOOT AND CLEANING, AND (c) COMBINED OPTICAL AND UVA IMAGE AND UVA-ONLY IMAGE

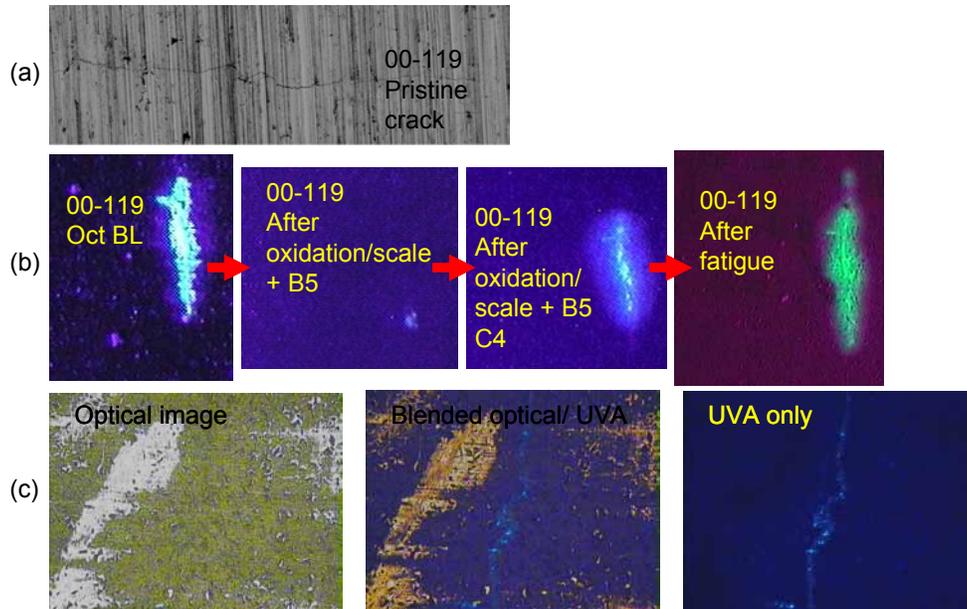


FIGURE 68. TRANSITION OF AN OPTICAL IMAGE TO A UVA IMAGE FOR THE 00-119 Ni SAMPLE (a) OPTICAL IMAGE OF A CRACK PRIOR TO STUDIES; (b) COMPARISON OF UVA IMAGE FROM OCTOBER BASELINE, FEBRUARY CLEANING STEPS, AND AFTER FATIGUE; AND (c) COMBINED OPTICAL AND UVA IMAGE AND UVA-ONLY IMAGE

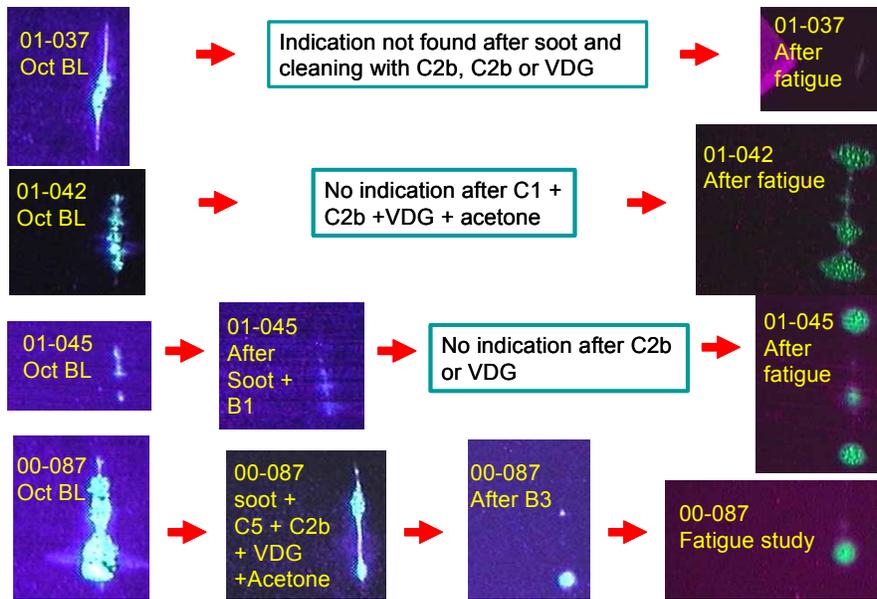


FIGURE 69. COMPARISON OF UVA IMAGES BEFORE AND AFTER FATIGUE FOR Ti SOOT SAMPLES

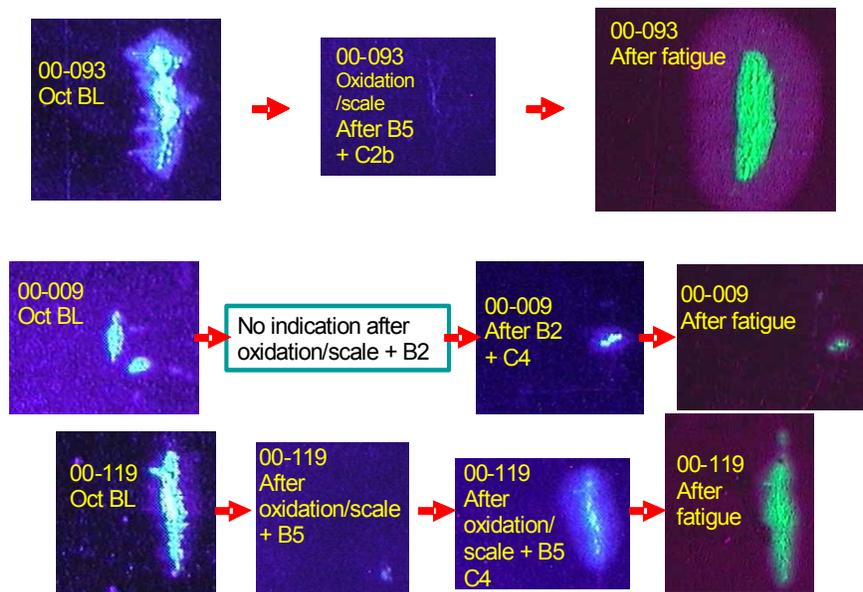


FIGURE 70. COMPARISON OF UVA IMAGES BEFORE AND AFTER Ti AND Ni OXIDATION AND SCALE SAMPLES

3.7.6 Crack Characterization.

The final step in the program included a destructive analysis of several samples. The purpose of the characterization effort was to determine if the cracks used in this study were typical of surface-breaking cracks found in engine hardware. Three samples from each alloy were selected for transverse sectioning with a sample from each contamination type, as shown in table 44.

Results for the transverse sectioning are shown in figures 71 through 76. The samples were sectioned transverse to the crack length, as shown in the diagram in figure 71. The samples were mounted and then ground to reach the crack start. The crack was polished to approximately 25%, 50%, and 75% through the length. However, the actual positions were documented as shown in the micrographs in figures 73 through 76. Kroll's etchant was used for Ti samples and Kalling's etchant was used for Ni samples.

TABLE 44. SAMPLES USED FOR TRANSVERSE SECTIONING

Sample Number/Optical Length (in)	Starter Feature	Average Brightness/Average UVA Length	Contamination Type	February Cleaning Methods
00-110 (Ni)/0.054	Spot weld	35.6/0.056	Oxidation and scale	C7a + C4 + acetone + VDG + acetone
01-025 (Ni)/0.053	EDM	28.8/0.062	Coke and varnish	C7a + C4 + acetone + VDG + acetone
00-127 (Ni)/0.083	Spot weld	26.0/0.083	Soot	C7a + C4 + acetone + VDG + acetone
01-015 (Ti)/0.033	Spot weld	6.1/0.031	Oxidation and scale	B2 + C2b
00-097 (Ti)/0.062	Spot weld	98.3/0.064	Oxidation and scale	B2 + C2b
01-040 (Ti)/0.121	EDM	44.3/NA	Soot	C2b + C2b + VDG

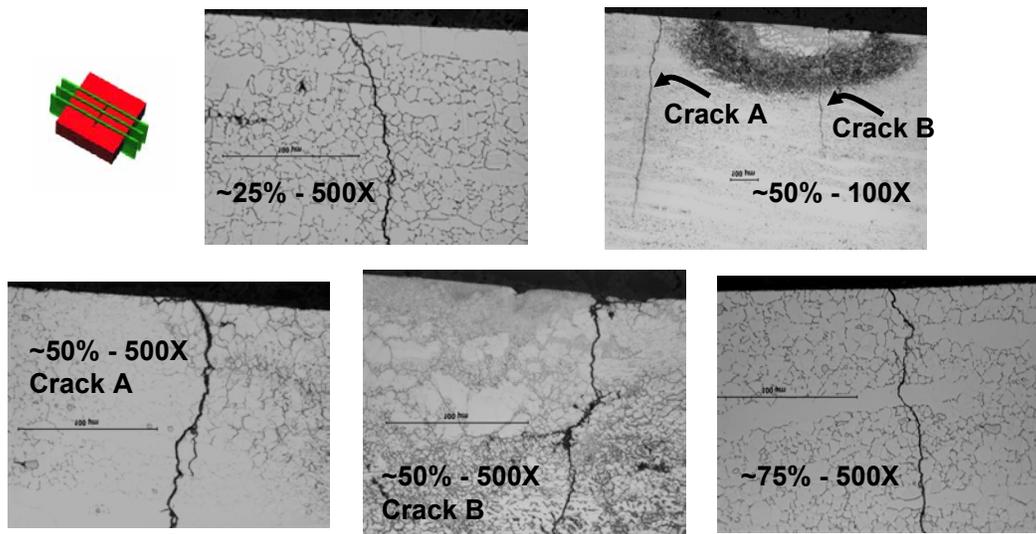


FIGURE 71. TRANSVERSE SECTIONING RESULTS FOR THE 01-110 Ni SAMPLE (Note that the crack showed branching at the 50% section. Higher magnification is shown of the two branches.)

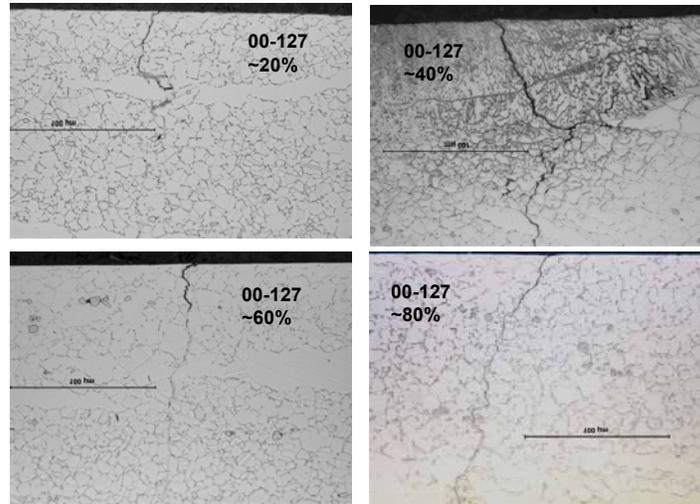


FIGURE 72. TRANSVERSE SECTIONING RESULTS FOR THE 00-127 Ni SAMPLE

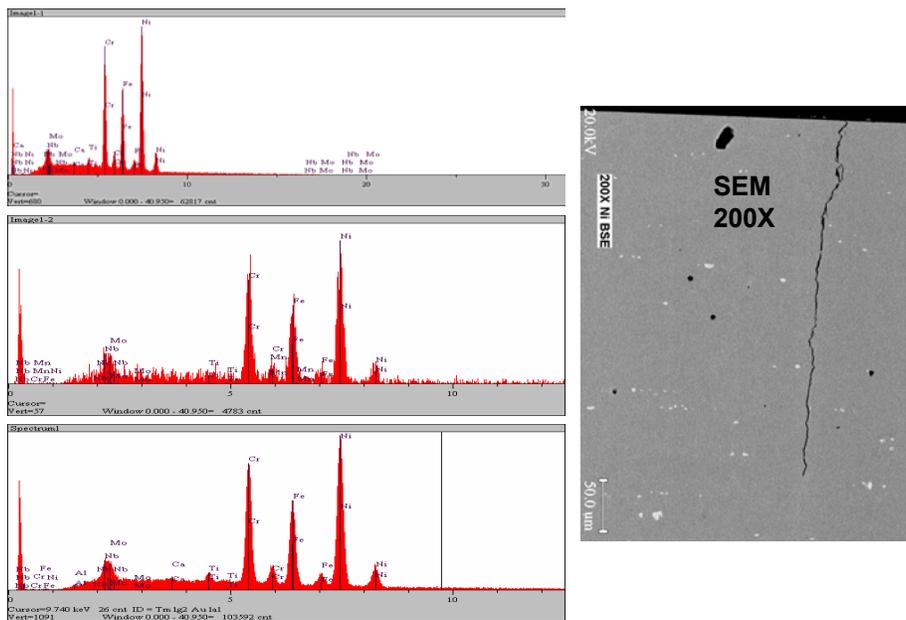
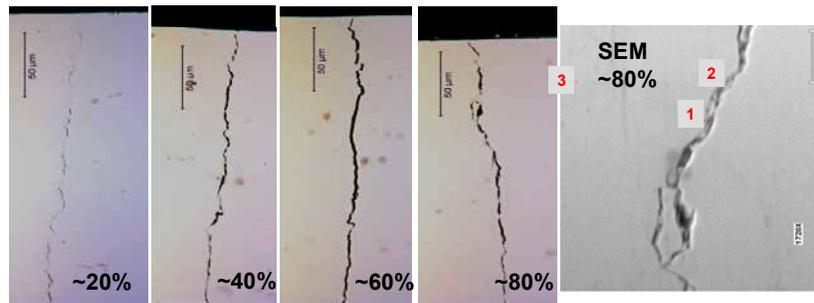


FIGURE 73. TRANSVERSE SECTIONING RESULTS FOR THE 01-025 Ni SAMPLE AND THE ENERGY DISPERSIVE SPECTROSCOPY RESULTS FROM THREE POSITIONS

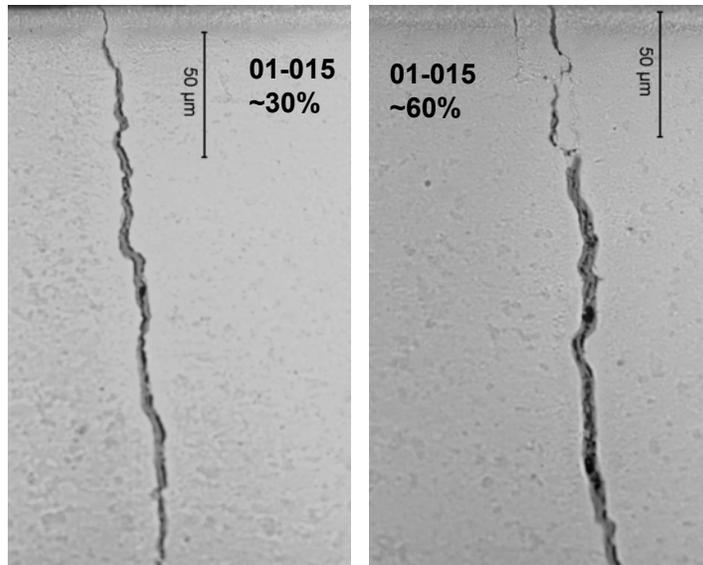


FIGURE 74. TRANSVERSE SECTIONING RESULTS FOR THE 01-015 Ti SAMPLE

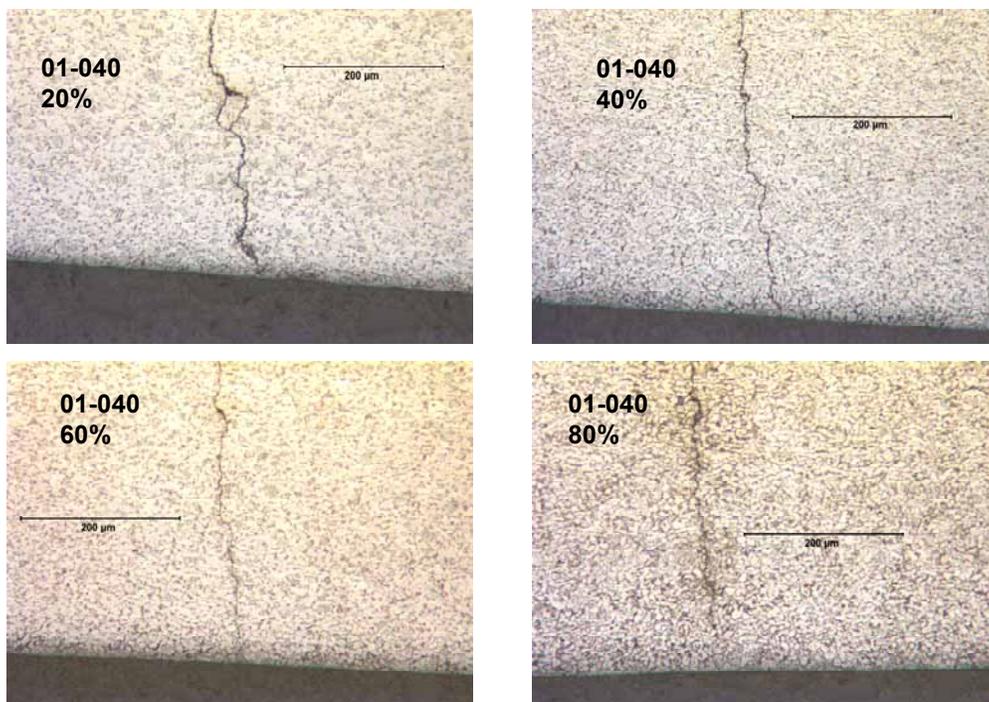


FIGURE 75. TRANSVERSE SECTIONING RESULTS FOR THE 01-040 Ti SAMPLE

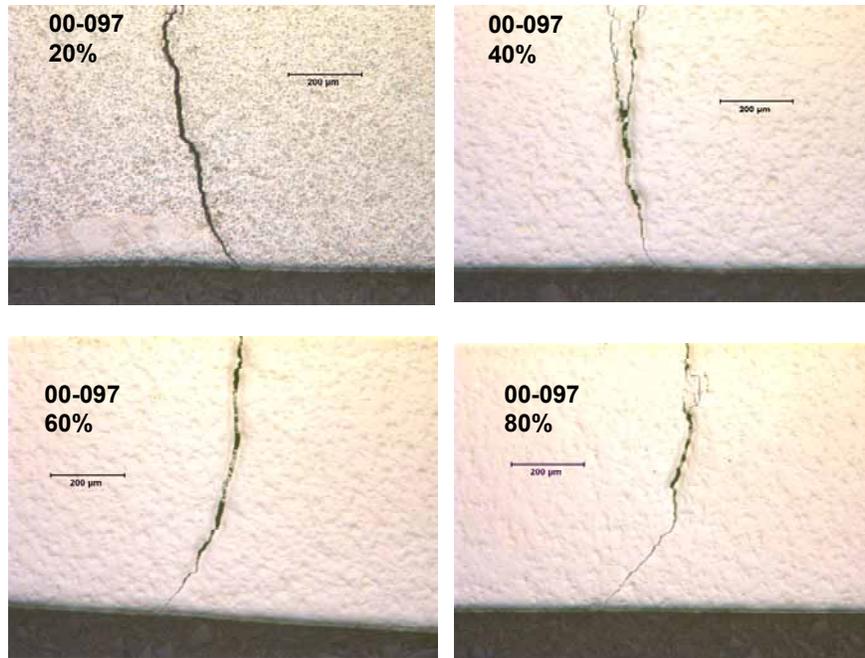


FIGURE 76. TRANSVERSE SECTIONING RESULTS FOR THE 00-097 Ti SAMPLE

The results for sample 01-110 included the sectioning at the 25%, 50%, and 75% positions at 500X. Also included is a 100X micrograph at the 50% position, which was etched to bring out microstructural features. The darker microstructural region is the result of the heat-affected zone (HAZ) from the original tack weld used for crack initiation. This sample showed crack branching as seen in the 50% section, as shown in figure 71. No evidence of foreign materials was found in the crack. The results for the other two Ni samples, 00-127 and 01-025, are also shown in figures 72 and 73 respectively. The SEM results, originally taken at 1720X and 200X magnification, are included for sample 01-025. Three locations were selected for energy dispersive spectroscopy (EDS) measurement, two near the crack and one away from the crack. The EDS analysis appears similar for all three locations. Note that calcium was found in locations 1 and 3, and manganese was found in location 2.

The first sample to be sectioned was 01-015, the Ti sample shown in figure 74. It was noticed with the initial sample that the crack was tighter near the surface than subsurface, which indicated potential surface stresses leading to crack closure. The results are shown for the remaining two Ti samples (01-140 and 00-097) in figures 75 and 76. The transverse sectioning results were judged to be similar to low-cycle fatigue cracks typical for these alloys, validating the data.

3.8 CLEANING STUDY OBSERVATIONS AND RECOMMENDATIONS.

Contaminants evaluated in this study included oil contamination, several coating types (antigallant compound, RTV and high-temperature sealant), and baked-on contaminants (oxidation and scale, soot, and coke and varnish).

3.8.1 Oil Contamination.

Methods used for cleaning oil-contaminated samples included C1, C2a, C2b, C7a, C3, and C6. With the exception of C2a and C2b, all methods were effective in oil removal without detrimental impact to the FPI process. Because C2a and C2b are alkaline cleaning processes, it is not clear whether the reduction in indication response results from ineffective cleaning or from residue left after the cleaning process. Vapor degreaser was also evaluated for oil removal. The results led to the following recommendations.

- The C2a process used for Ti uses similar chemistries and concentrations as the C3 process for Ni. However, the Ti sample is in alkaline for a shorter time. Given the better performance for C3 on Ni than the C2a results reported for Ti, additional work is needed to understand if this is an alloy effect or a cleaning time effect. It is recommended that future work include using Ni cracks contaminated with and without oil to be cleaned with the C2a process. Possible effects could include a reaction of the alkaline with Ti, which would clog the cracks with corrosion products. Because these effects could not be considered in the current study, future work to compare pristine crack fracture surfaces with those after repeat alkaline treatments would be valuable for both Ti and Ni.
- Further steps to improve the resistance of penetrant solutions to residue from alkaline cleaners would be valuable to the aviation community.
- Consideration of additional cleaning methods is recommended for Ti components, including the evaluation of multistep processes currently used for nonrotating Ti parts.

3.8.2 Coating Types.

All cleaning methods used to remove service coatings (antigallant compound, RTV and high-temperature sealant) were effective in removing the coatings. However, reductions in FPI indication response did occur in some cases.

- Using C8 to remove high-temperature sealant led to reductions in FPI indication response. Using the samples for further study prevented analysis of the cause. An additional study of this cleaning method is warranted.
- Three methods, B1 at 40 and 80 psi, B5, and B6, were effective in removing surface coatings with the following conclusions.
 - The B1 40-psi PMB treatment led to effective removal of the coatings. Following the B1-40 process with a subsequent chemical clean (wet process) restored the indication to the same or better FPI response than the baseline. It is recommended that the reason for the improvement be evaluated and appropriate changes be made to industry practices to follow the PMB process with a wet process. Factors to be considered include whether water alone is sufficient or some other chemical step is necessary and at what temperature (hot or cold processes).

- The 80-psi PMB treatment, which was twice the recommended pressure, led to surface damage and loss of indications. Exceeding the recommended pressure of 40 psi for PMB is not advisable, given the surface deformation and loss of FPI response.
- Similar to the results for PMB, the FPI response for B6 was also improved by a wet process. Given these results, it is recommended, as with the other blasting methods, a rinse step after B6 would improve sensitivity. An analysis of samples immediately after B6 and prior to acetone to determine presence of residue (oil from the media), shell particles, etc., would also provide relevant engineering data. A study that compares water rinse and dry to acetone UT and dry would be helpful in sorting out whether there is oil residue from walnut shells, which the liquid washes out, or if UT agitation is required to unclog the media.

3.8.3 Baked-On Contaminants.

After the baked-on contamination processes to generate oxidation and scale, soot, and coke and varnish, sample sets of three were exposed to various initial cleaning methods that included both chemical (C1, C2a, C2b, C3, C5, and C7a) and mechanical (B1, B2, and B5) processes. After the initial cleaning step, a visual assessment was made as to whether the surface contamination had been effectively removed. Samples were classified as clean, marginal, or not clean. Results of the assessment are provided in table 45. Follow-on cleaning steps included C2b, C3, C4, VDG, permanganate, and acid descaler. Additional studies included B3 and B4.

With one exception, the samples judged to be marginal or not clean also showed reductions in FPI indication response, implying that while a visibly clean surface is not a sufficient condition for effective FPI, it is a necessary condition.

As previously shown in tables 31 and 32, the results indicate that the penetrant is not entering the cracks effectively for many of the methods used to clean baked-on contaminants. This poor performance could result from several causes as discussed below.

- The contamination process was a worst-case condition and a different performance might result if lower temperatures (shallower oxide layer) were used to generate the oxides and soot conditions. Future studies to characterize the baked-on contamination and the relationship to detectability and whether actual service conditions are warranted.
- Cleaning process residue could be causing reductions in brightness. In other words, the defects may be fully open to penetrant but contamination from the cleaning process is rendering the penetrant ineffective.

TABLE 45. VISUAL ASSESSMENT OF SAMPLE CLEANLINESS AFTER BAKED-ON CONTAMINATION AND CLEANING

Alloy and Contaminant	Cleaning Method	Visual Assessment of Effectiveness
Titanium		
Oxidation and scale	C2a – alkaline derust short soak	3/3 clean
	C2b – alkaline derust long soak	3/3 clean
	B2 – wet glass bead blast	3/3 clean
	B5 – 500-grit Al ₂ O ₃	3/3 clean
Soot	C1 – aqueous degreaser	2/3 clean, 1/3 not clean
	C2a – alkaline derust short soak	3/3 clean
	C2b – alkaline derust long soak	2/3 clean, 1/3 marginal
	C5 – alkaline gel cleaner	2/3 clean, 1/3 not clean
	B1 – plastic media blast	3/3 clean
Nickel		
Oxidation and scale	C3 – one-step alkaline	2/3 clean, 1/3 marginal
	C7a – ultrasonic alkaline	2/3 clean, 1/3 marginal
	B2 – wet glass bead blast	3/3 clean
	B5 – 500-grit Al ₂ O ₃	3/3 clean
Soot	C3 – one-step alkaline	3/3 clean
	C7a – ultrasonic alkaline	3/3 clean
	B1 – plastic media blast	2/3 clean, 1/3 marginal
Coke and varnish	C3 – one-step alkaline	3/3 clean
	C5 – alkaline gel cleaner	2/3 clean, 1/3 not clean
	C7a – ultrasonic alkaline	3/3 clean
	B1 – plastic media blast	2/3 clean, 1/3 not clean

Discussion of each of the major cleaning types follows.

- Alkaline cleaners used in the study included C2a and C2b, which differ in concentration and exposure time; C7a and C7b, which are similar to C2a and C2b but with ultrasonic agitation; C5, and the Ni processes C3 and C4.
 - Of these methods, the alkaline cleaners used for Ti, C2a, C2b, and C7b, were not found to be effective for baked-on contaminants with little difference between the performances of C2 and C7, indicating that the ultrasonic agitation is not aiding in the cleaning process for the temperatures and concentrations used in this study. C7a was also not effective for Ni. Using ultrasonic agitation may show improvement at lower bath temperatures. Further quantification of bath temperature effects on the effectiveness of ultrasonic agitation would be useful.

- Reductions in brightness could be related to alkaline effects. Efforts to reduce the effect of alkaline on fluorescence are recommended.
- Further studies are needed to understand and document the impact of alkaline on fluorescence and the potential buildup of alkaline in fatigue cracks as part of a cleaning process or after multiple cleaning steps. Consideration of additional cleaning methods is recommended, including the evaluation of multistep processes currently used for nonrotating Ti parts.
- C3 also did not consistently recover Ni samples that had oxidation and scale, soot, or coke and varnish contamination. For this reason, the decision was made to clean all the Ni samples with C4.
- C4 was found to be an effective method for cleaning all baked-on contaminants for Ni samples, including as a follow-up to mechanical processes, i.e., B1, B2, and B5. More frequent use is recommended.
- C5 was not effective in restoring FPI indications contaminated with soot or coke and varnish either because of ineffective cleaning or because of the effect of the alkaline cleaner on penetrant response. There was insufficient data available from this study to determine the cause since the study did not include using C5 on noncontaminated cracks. C5 was also not evaluated for its effectiveness in cleaning oil contamination. Further studies to understand effectiveness on oils and potential penetrant-dimming effects would be of value not only to the engine community but for airframe components since this process is also used on airframe parts.
- Mechanical media blasting used in the baked-on contaminants study included B1, B2, and B5 were evaluated on as-received samples, and B3 and B4 were evaluated on samples that had demonstrated repeatable performance after using other cleaning methods. B6 was not used in this portion of the study. The following conclusions were reached based on the data presented above.
 - B1 at 40 psi was effective for surface cleaning without damage to the surface. However, performance was enhanced by following the PMB process with a chemical cleaning process. While this observation was made based on the brightness and UVA image data, additional effort is needed to understand the reason. Possible scenarios include a simple washing action from the chemical cleaning solutions or a chemical attack action on the PMB, either from the cleaning solutions or from the penetrant solution. Further studies are warranted.
 - Because of surface damage and loss of indications, using B2 prior to FPI is not recommended. Future study of the relationship between residual stress and FPI is warranted. Factors to be considered include residual stress imparted by the B2 process with and without the presence of an oxide.

- Comparison of three grit sizes, 240-, 320-, and 500-grit Al₂O₃, indicates that the larger grits (240 and 320) should not be used prior to FPI. The 500-grit processes can lead to some reduction in sensitivity and should be used sparingly. It should also be noted that grit blasting only removes surface contaminants. It will not effectively remove contaminants from within the crack. If the contamination of concern is in the interior of the crack, such as oxidation and scale, chemical processes must be used in conjunction with the grit-blasting technique.
- In this study, the blast materials were new, unused grit without conditioning. Studies of the effect of grit usage time on cutting efficiency versus peening effect would provide useful data.
- Degreasers—Two degreasers, C1 and a vapor degreaser, were evaluated during the study. As indicated above, C1 was effective for removing oil contamination. However, it was ineffective in soot removal. Using a vapor degreaser (trichlorethylene), which had traditionally been used for cleaning, was also evaluated for oil removal with successful results. However, it was not effective in restoring crack response to the samples with baked-on contamination.
- Chemical cleaning methods beyond those currently used for Ti critical rotating components are needed. C4 used to clean the Ni samples after baked-on contamination was quite effective in restoring FPI response for oxidation and scale, soot, and coke and varnish. Results for the Ti samples indicate less effective cleaning of the baked-on contaminants, given the more prevalent occurrence of red and orange shading shown in table 32. Given the results of this study, evaluation of new cleaning methods for Ti is needed. In an effort to recover additional samples, permanganate and acid descaler were evaluated as separate steps. Permanganate is used for cleaning of heat-treated parts for alpha case removal, but not typically used for critical rotating parts. Both methods showed some improvements to some samples but not full restoration. It is recommended that the development of a hot-line process, similar to that used for Ni components, be considered. Remaining samples from this study could be used for that development.

A summary of the cleaning methods, as applied to each contaminant type, is provided in table 46.

3.9 EVALUATION OF LOCAL ETCHING PRACTICES.

Occasionally surface damage from inadvertent contact or foreign object damage that results from use can occur. If the damage is minimal and within allowable limits, local blending can be used to remove surface conditions as long as dimensional requirements are still acceptable. In some cases, local blending is followed by a light chemical etch in the area where the blending occurred. As part of the program, an etch study was included to determine the effect of local etching on crack detectability after removing local surface damage and other surface anomalies. The goal of this study was to gather data on the effect of local etching on detectability and provide guidance on the best practices for removing local surface damage while maintaining FPI sensitivity.

TABLE 46. MATRIX OF EFFECTIVENESS OF CLEANING METHODS FOR VARIOUS CONTAMINANTS

Cleaning Method	Oil	Antigallant	RTV	High-Temperature Sealant	Oxidation and Scale	Soot	Coke and Varnish
B1 at 40 psi	NA, NS	NS	Effective removal but follow-on rinse recommended to prevent degradation of indication response.	NS	NA, NS	Effective removal but follow-on rinse recommended to prevent degradation of indication response.	Effective removal but follow-on rinse recommended to prevent degradation of indication response.
B1 at 80 psi	NA, NS	Pressure exceeds recommended value. Led to surface damage and loss of indications.	Pressure exceeds recommended value. Led to surface damage and loss of indications.	NS	NA, NS	NA, NS	NA, NS
B2	NA, NS	NA, NS	NA, NS	NA, NS	Not recommended. Led to surface damage and loss of indications.	NA, NS	NA, NS
B3	NA, NS	NA, NS	NA, NS	NA, NS	Not recommended. Led to surface damage and loss of indications.	NA, NS	NA, NS
B4	NA, NS	NA, NS	NA, NS	NA, NS	Not recommended. Led to surface damage and loss of indications.	NA, NS	NA, NS

NA indicates that the cleaning method is not recommended for a given contaminant. NS indicates that the cleaning method was not considered during this study.

TABLE 46. MATRIX OF EFFECTIVENESS OF CLEANING METHODS FOR VARIOUS CONTAMINANTS (Continued)

Cleaning Method	Oil	Antigallant	RTV	High-Temperature Sealant	Oxidation and Scale	Soot	Coke and Varnish
B5	NA, NS	NA, NS	NA, NS	NS	Effective surface cleaning without damage. Not effective for cleaning contaminants from crack interior without follow-up rinse.	NA, NS	NA, NS
B6 at 50 psi		Effective removal. Recommend follow with rinse step.					
C1	Effective cleaning for oil contamination	NA, NS	NA, NS	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	NA, NS
C2a	Not effective for oil removal	NS	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.	NA, NS
C2b	Not effective for oil removal	Effective antigallant removal. Concern with alkaline contamination.	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.	NA, NS

NA indicates that the cleaning method is not recommended for a given contaminant. NS indicates that the cleaning method was not considered during this study.

TABLE 46. MATRIX OF EFFECTIVENESS OF CLEANING METHODS FOR VARIOUS CONTAMINANTS (Continued)

Cleaning Method	Oil	Antigallant	RTV	High-Temperature Sealant	Oxidation and Scale	Soot	Coke and Varnish
C3	Effective for oil removal	NA, NS	Not used with Ni	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.
C4	NA, NS	NA, NS	Not used with Nickel	NA, NS	Effective cleaning method.	Effective cleaning method.	Effective cleaning method.
C5	NA, NS	NA, NS	NA, NS	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response in Ti samples.	Removed visual evidence of surface condition. Not effective in restoring crack response in Ni samples.
C6	Effective for oil removal	NA, NS	NA, NS	NA, NS	NA, NS	NA, NS	NA, NS
C7a	Not effective for oil removal	Effective antigallant removal. Concern with alkaline contamination.	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.

NA indicates that the cleaning method is not recommended for a given contaminant. NS indicates that the cleaning method was not considered during this study.

TABLE 46. MATRIX OF EFFECTIVENESS OF CLEANING METHODS FOR VARIOUS CONTAMINANTS (Continued)

Cleaning Method	Oil	Antigallant	RTV	High-Temperature Sealant	Oxidation and Scale	Soot	Coke and Varnish
C7b	NS	NA, NS	NA, NS	NA, NS	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.	Removed visual evidence of surface condition. Not effective in restoring crack response.
C8	NA, NS	NA, NS	Effective removal of RTV but accompanied by reductions in indication response.	NA, NS	NA, NS	NA, NS	NA, NS
Vapor degreaser (VDG)	Effective oil removal.	NA, NS	NA, NS	NA, NS	Not effective in restoring crack response.	Not effective in restoring crack response.	Not effective in restoring crack response.
Permanganate	NA, NS	NA, NS	NA, NS	NA, NS	Showed improvement. Further study warranted.	NA, NS	NA, NS
Acid descaler	NA, NS	NA, NS	NA, NS	NA, NS	Showed improvement. Further study warranted.	NA, NS	NA, NS

NA indicates that the cleaning method is not recommended for a given contaminant. NS indicates that the cleaning method was not considered during this study.

3.9.1 Specimen Fabrication and Selection.

Twelve samples were fabricated in the same manner as those used for the drying and cleaning portions of the program with six Ti and six Inconel samples selected for use in the local etching study. Samples were dry sanded on one side using 50-grit Al_2O_3 on a belt sander to remove the rough mill surface of the plate material. Water-cooled silicon carbide papers were then used to obtain a surface finish finer than 64 Ra. A study to compare manual sanding techniques to a rotary sanding platen was completed. Surface roughness was measured using a profilometer. Ra values, which compare surface peaks and valleys to a mathematical centerline, were collected. Figure 77 presents the surface roughness data comparing the manual and machine sanding methods for 120-, 180-, and 240-grit sand paper.

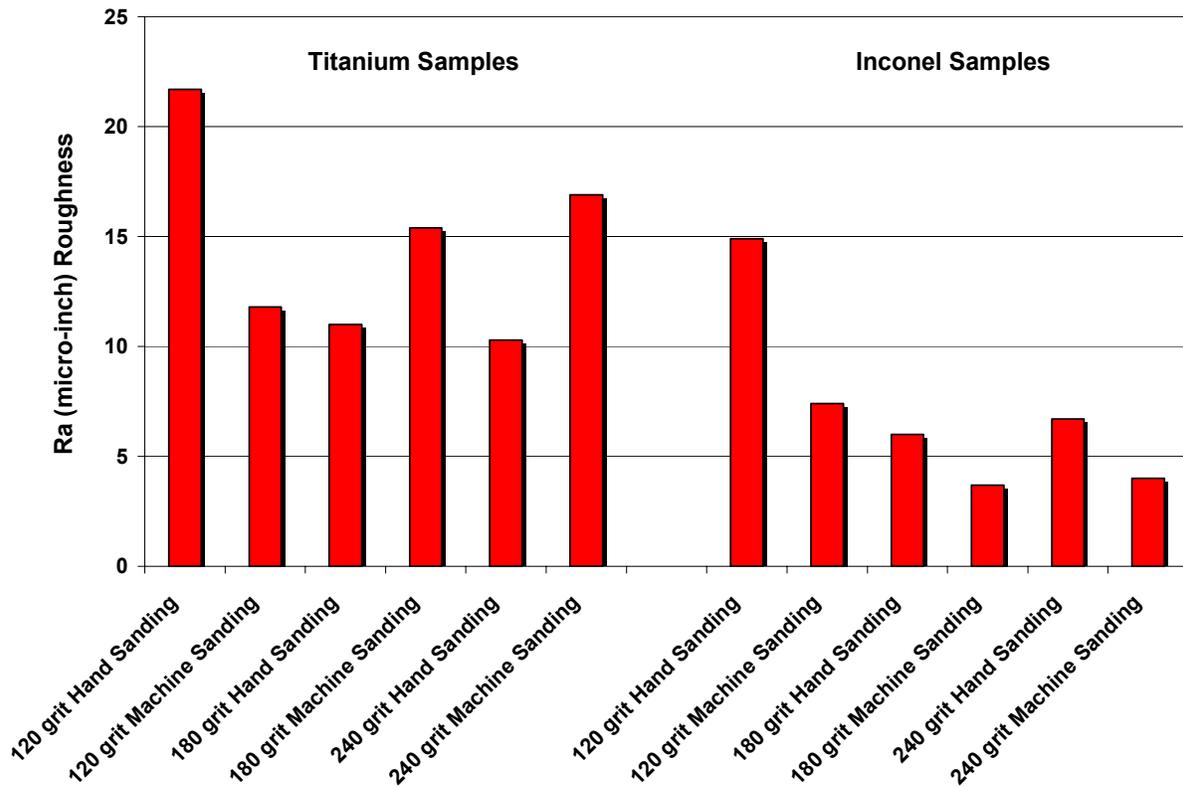


FIGURE 77. SURFACE ROUGHNESS DATA SHOWING THE EFFECT OF SANDING METHODS

All sanding methods and grits produced a surface finish better than 64 Ra; therefore, 180- or 240-grit SiC paper for use on the sanding platen was selected as the final sanding method used during sample fabrication.

Optical images of the cracks used in this study were captured using an inverted metallurgical microscope at 100X magnification, and crack lengths were measured using 500X magnification. Crack lengths for the 12 samples are provided in table 47. Figures 78 and 79 show the optical micrographs of the original crack morphologies for the Ti and Ni samples, respectively.

TABLE 47. SAMPLE DESCRIPTION FOR ETCH STUDY SAMPLES

Sample	ID Number	Crack Length (inches)
Titanium samples		
1	00-089	0.073
2	00-090	0.047
3	00-094	0.109
4	00-096	0.061
5	00-123	0.078
6	01-040	0.097
Nickel samples		
1	00-092	0.075
2	00-104	0.073
3	00-107	0.060
4	00-112	0.058
5	00-113	0.068
6	01-020	0.060

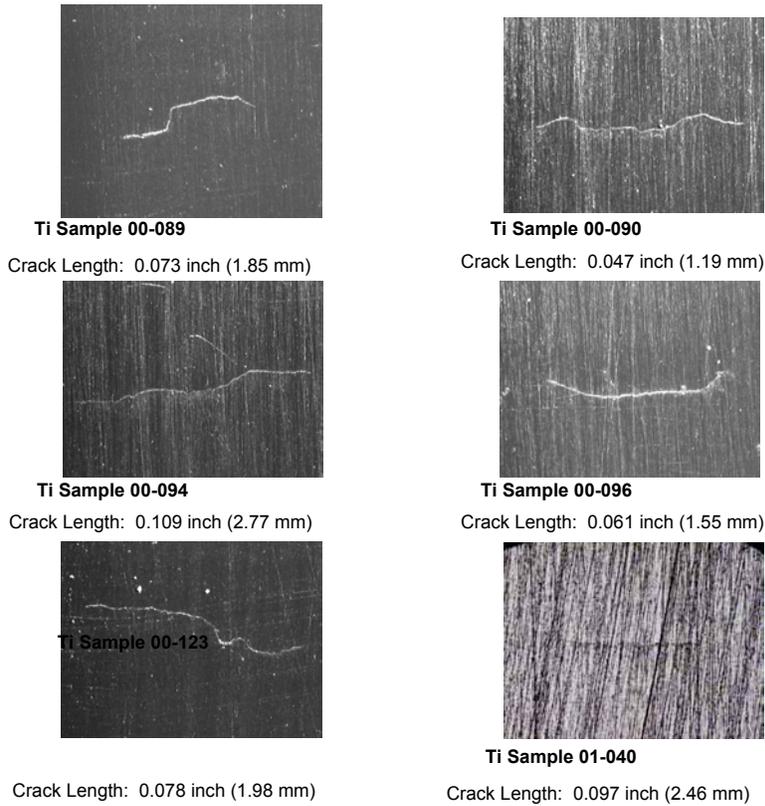


FIGURE 78. CRACK MORPHOLOGIES FOR Ti SAMPLES

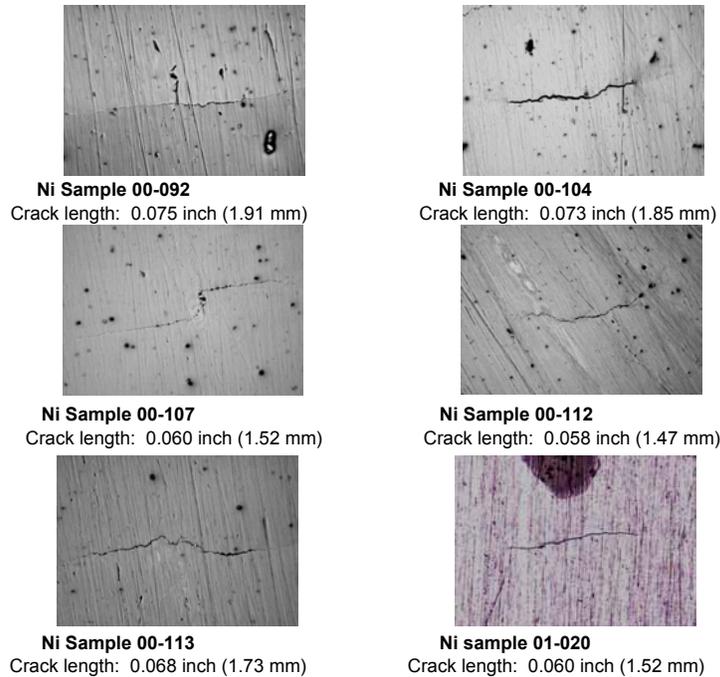


FIGURE 79. CRACK MORPHOLOGIES FOR Ni SAMPLES

Eight level 4 sensitivity postemulsifiable FPI (Method D) were performed to determine the baseline variability and brightness information for each crack. This baseline data was used to evaluate detectability after the blending and etching trials.

Table 48 provides the baseline FPI run information. Variability is given as low, medium, and high and is based on 0%-20%, 21%-30%, and >30% when the standard deviation was divided by the average brightness, respectively. Brightness classification is based on a 0-83, 84-166, and 167-250 foot-Lambert average brightness.

3.9.2 Etchant Selection.

GEAE and Honeywell have standard practices for blending of FOD and subsequent etching of the blended area prior to FPI for both Ti-6Al-4V and IN-718. RR and P&W have internal standard practices for blending, which include etchants that are applicable to Ti-6Al-4V and IN-718. RR and P&W have not released these documents due to past experience, indicating that smearing is not a problem when proper blending procedures are followed, and general concerns regarding potential improper application of etchants to critical rotating engine components. Procedures have only been released on a limited basis for specific applications, e.g., to determine the presence of welds. Table 49 summarizes the etchants defined by the OEM's for Ti-6Al-4V and IN-718. The formulations of the etchants are provided in appendix D.

TABLE 48. SUMMARY OF BRIGHTNESS DATA

Sample	ID Number	Length inch (mm)	Variability (Standard Deviation)	Brightness (Average ft-L)
Titanium samples				
1	00-089	0.073 (1.85)	M (31.0)	M (134)
2	00-090	0.047 (1.19)	M (32.6)	M (111)
3	00-094	0.109 (2.77)	H (72.9)	H (235)
4	00-096	0.061 (1.55)	M (42.6)	H (171)
5	00-123	0.078 (1.98)	L (28.5)	M (150)
6	01-040	0.097 (2.46)	L (9.3)	L (62)
Nickel samples				
1	00-092	0.075 (1.91)	L (16.2)	M (95)
2	00-104	0.073 (1.85)	H (9.2)	L (18.4)
3	00-107	0.060 (1.52)	L (9.4)	L (65.7)
4	00-112	0.058 (1.47)	L (5.6)	L (36.6)
5	00-113	0.068 (1.73)	M (14.1)	L (67.6)
6	01-020	0.060 (1.52)	L (6.7)	L (63.3)

TABLE 49. ETCHANTS USED BY OEMS FOR INCONEL AND Ti ALLOYS

Base Metal and Etchant Name	Chemical Ingredients and Variations	Etchant Used By:			
		GE	HE&S	RR	P&W
Ti-6Al-4V					
	H ₂ O - HNO ₃ - HF				
GE Class B		X	X		X
RR-1	Less HF; More HNO ₃			X	
RR-2	Desmut solution			X	
IN-718					
	FeCl ₃ - HCl - H ₂ O				
GE Class G	More FeCl ₃ and HCl	X	X		
RR-3	HF and HNO ₃ added			X	
General Ni-based					
	FeCl ₃ - HCl - H ₂ O				
GE Class D	H ₂ SO ₄ , HNO ₃ and C ₂ H ₄ O ₂ added	X	X		
RR-4				X	

Review of the etchant chemistries indicated typical components with the following differences:

- Base compositions of the Ti-6Al-4V etchants were similar with the exception of a slightly higher volume of HNO₃ and HF in the RR etchants.
- The GE IN-718 etchant uses a hexahydrate (yellow-orange lump) form of FeCl₃, while an anhydrous (green-black powder) form is used in the RR version; and less HCl is used in the RR etchant with HF and HNO₃ added in its place.
- For the General Nickel Alloy etchant, sulfuric (H₂SO₄), nitric (HNO₃), and acetic acid (C₂H₄O₂) are added to the GE etchant; and more hydrochloric (HCl) is used in the RR etchant.

The experimental team decided on the GE Class B etchant for the Ti-6Al-4V samples, and the GE Class G etchant for the IN-718 samples.

3.9.3 Description of Surface Blending Techniques.

Current OEM standard practices define the approved tooling and blending operations used to remove stress concentrations caused by nicks, dents, and scratches to provide a surface favorable to FPI. These operations used manual or power tool techniques using media ranging from coarse-grade abrasives and files to fine-grade abrasives and crocus cloths to obtain a surface finish as similar to the original finish as possible. For this study, the blending of samples would be conducted using a power tool (electric or air) with abrasive-impregnated wheels, stones, or pads, which are commonly used in the aviation industry. Available blending media included Cratex abrasive-impregnated rubber points, Norton Al₂O₃, SiC wheels available in a typical Dremel tool kit, to a wide variety of media currently used at the Delta facility. The coarsest available abrasive media was 80 grit. Figure 80 shows a variety of blending media used to smear metal over the fatigue crack samples.



FIGURE 80. A VARIETY OF BLENDING MEDIA USED TO REMOVE STRESS CONCENTRATION

3.9.4 Etching Trials.

Several separate experimental trials were conducted at various times during the program. A timeline of the work is presented in table 50.

TABLE 50. ETCH STUDY TIMELINE AND ACTIONS TAKEN

Date	Location	Actions
March 2001	AANC of Sandia National Laboratories	Smearing attempts on Ti and Inconel. Ti etched but unable to remove Inconel-smear metal.
September 2001	GE	Smear Inconel sample with successful etch and FPI recovery.
October 2001	Delta Air Lines	Difficult smearing of Inconel with no successful etch.
February 2002	Delta Air Lines	Smearing and etching of Ti and Inconel samples.

An initial trial to determine the best method for smearing the cracks was conducted in March 2001 at Sandia National Laboratories using two spare Ti-6Al-4V and IN-718 samples. The Ti-6Al-4V sample was blended using an electric Dremel™ tool with Cratex abrasive-impregnated rubber points. FPI confirmed the lack of an indication after the blending operation on the surface in the area of the known crack. A dimensional measurement of the samples indicated less than 0.002 inch of material was removed from the Ti sample and less than 0.003 inch of material was removed from the Inconel sample during the blending process. The smeared Ti sample was subsequently etched using the Class B etchant, which successfully produced a crack indication after subsequent cleaning and FPI. The IN-718 sample was blended with a technique similar to the Ti sample. After a visual inspection, the crack was located, indicating that smearing had not occurred. Additional blending, starting with a coarse media and finishing with the abrasive-impregnated rubber points, was performed. Visual inspection and FPI did not locate the defect, indicating successful smearing. Subsequent etching using the Class G etchant did not remove the smeared metal during the initial trial at Sandia National Laboratories. An additional Inconel trial involving surface grinding with a progression of grit sizes, from coarse to fine, prior to re-etching was also performed as part of this initial study. The etchant was not successful in returning an indication during the Sandia National Laboratories trial. A lack of smutting, which is a result of surface attack by the chemicals and indicates successful chemical action, was noted during the etching of the Inconel sample. A review of the etchant preparation indicated that a diluted concentration of the Class G etchant was prepared and may have resulted in a very weak chemical action. Figure 81 shows SEM images of the etched Inconel and Ti samples.

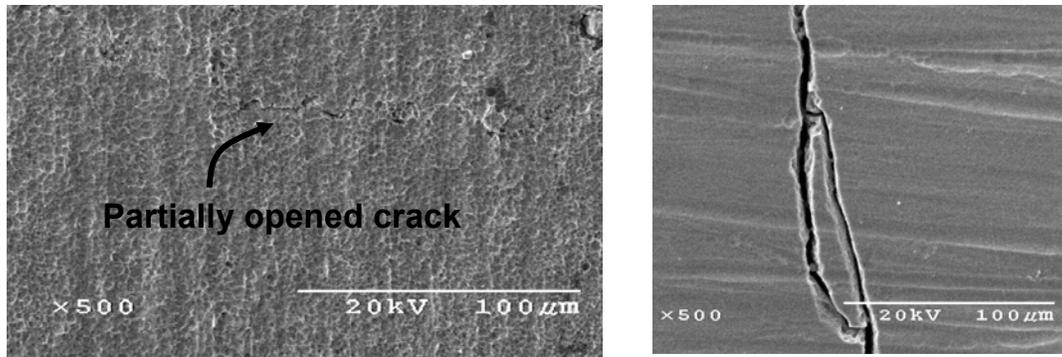


FIGURE 81. SURFACES OF INCONEL (LEFT) AND Ti (RIGHT) SAMPLES AFTER BLENDING AND SUBSEQUENT ACID ETCH (500X MAGNIFICATION). (The Inconel fatigue crack was not reopened by etching, while the Ti crack was recovered.)

In an effort to ensure the Inconel etchant would perform as expected, a trial was conducted at GE on another spare sample. The Class G etchant was prepared according to the available guidance, and applied to the mechanically smeared fatigue crack sample. Smutting, typical of successful chemical action, was observed. After the etching process, FPI detected the indication, but a penetrant was not used to ensure obliteration of the crack indication prior to etching. During October 2001, an etching trial was conducted using two additional IN-718 samples, 00-114 and 01-006, to determine the optimum grinding method to be used in February 2002. It took several blending iterations before the FPI indication of one of the samples was rendered undetectable. After successful smearing, this Inconel sample was etched by using the GE Class G mixture, which is commonly used on the shop floor. After etching, FPI did not lead to a crack indication. Additional evaluation occurred in February 2002.

The primary etching study was conducted in February 2002 and consisted of five primary steps:

- FPI per Method D (level 4 sensitivity postemulsifiable) to document the presmeared indication length and brightness
- Blend samples to impart metal smear over the crack
- FPI per Method D to ensure the area was smeared and the crack undetectable
- Etch the sample using the corresponding etchant (Class B etchant for Ti-6Al-4V and Class G etchant for IN-718) to remove the smeared metal
- FPI per Method D to determine the effect of the etching process

Three baseline FPI runs were conducted on each Ti-6Al-4V and IN-718 sample at the Delta facility. The Delta chemistry laboratory prepared fresh solutions of Class B and Class G etchants for this study. Blending attempts on the Ti-6Al-4V samples were unsuccessful as evidenced by either visual inspection or FPI detection of a crack indication. Several attempts to smear the surface were made by ETC participants. The participants took turns using a variety of blending media, dwell times, and imparted force. Figure 82 shows a typical surface finish

obtained after blending of Ti samples. Although all three samples showed some evidence of smearing during visual inspection, only sample 00-089 had smeared to the extent that it did not produce an FPI indication. The postblend indication from sample 00-090 had a brightness similar to the baseline measurements, and sample 00-096 showed only a slight decrease in measured brightness. Etching of the smeared Ti sample 00-089 was conducted by swabbing it with the Class B etchant for 60 seconds. A subsequent FPI inspection detected a crack indication that measured 0.094", which is very similar to the baseline length of 0.098". After etching, the brightness measurement of sample 00-089 was only a fraction of the baseline measurement. The results from all Ti samples are presented in table 51.

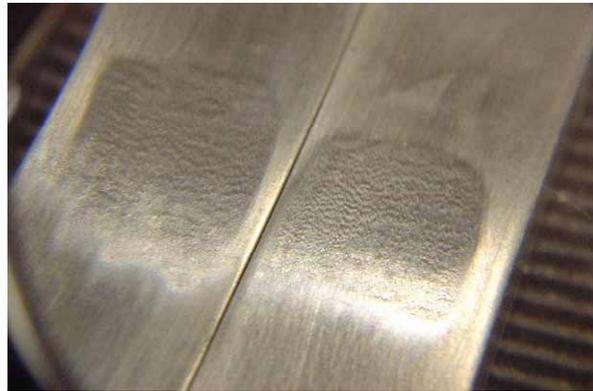


FIGURE 82. SURFACE APPEARANCE OF Ti-6Al-4V SAMPLES AFTER BLENDING

TABLE 51. RESULTS FOR Ti-6Al-4V SAMPLES IN FEBRUARY 2002

ID	Spot Photometer Measurements						
	Baseline 1	Baseline 2	Baseline 3	Blend 1	Blend 2	Etch	Final
00-089	198.4	191.1	162.7	145.9	0.0	23.3	57.8
00-090	223.8	250.0	197.4	250.0	250.0		35.9
00-094	214.7	215.7	73.3				12.6
00-096	190.0	250.0	163.5		72.2		10.8
00-123	250.0	250.0	250.0				15.0
01-040	181.5	250.0	194.0				

Blending the IN-718 samples to induce metal smearing continued to be a challenge. Again, several ETC members took turns using a variety of blending media and techniques. Numerous blending attempts on samples 00-092 and 00-104 did not hinder FPI from locating these cracks. Figure 83 shows typical surfaces of IN-718 samples after blending. After several attempts, samples 00-107 and 00-113 became smeared, as verified by FPI, and were etched by swabbing for a minimum of 3 minutes. After the etching process, liquid penetrant results showed that the chemical attack removed only a portion of the metal smearing.

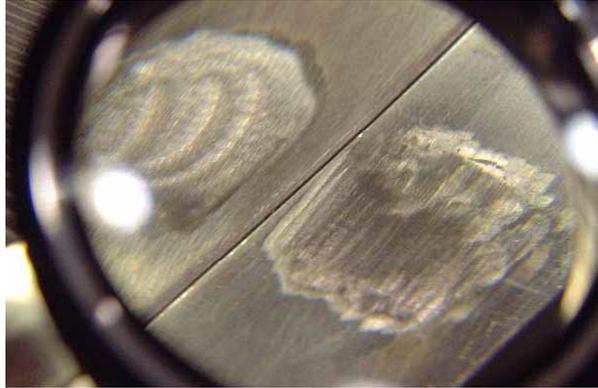


FIGURE 83. SURFACE APPEARANCE OF IN-718 SAMPLES AFTER BLENDING PROCESS

Four samples, 00-092, 00-104, 00-107, and 00-113, were reprocessed through FPI without applying the etchant. All samples exhibited a decrease in brightness. Additional etching for 6 minutes produced a much brighter indication from sample 00-107 and no improvement for sample 00-113. A final additional etch was performed on both samples with a dramatic loss of brightness on sample 00-107 and no change for sample 00-113. On the last run, no attempt was made to remove the acid from the surface of the sample, other than a swipe with a cloth, which may have affected the subsequent FPI brightness. The brightness measurement results for the IN-718 samples are presented in table 52.

TABLE 52. RESULTS FOR INCONEL SAMPLES

ID	Baseline 1	Baseline 2	Baseline 3	Blend 1	Blend 2	Etch 1 3 min.	FPI	Etch 2 6 min.	Etch 3 1 min.
00-092	136.7	166.9	138.2	64.9			46.0		
00-104	53.0	58.3	50.2	71.5			22.1		
00-107	94.0	115.1	104.2			0.1	0.0	22.5	1.5
00-112	58.3	62.0	54.5						
00-113	117.2	142.9	108.8			0.8	0.0	0.5	0.5
01-020	130.1	153.5	115.0						

4. LOCAL ETCHANT STUDY OBSERVATIONS AND RECOMMENDATIONS.

- Smearing of cracks due to blending was not easily accomplished in this study. Factors may include material hardness, abrasive style and coarseness, blending force and dwell time, and crack opening width. Because the samples were fabricated from plate stock, correlation between the ability to blend these samples and forged materials, typical of engine disks, may not be warranted.

- Several factors or a combination of factors may lead to an observed decrease in crack detectability by FPI after blending, including metal smearing, imbedded blending media, or retained acid etchant within the crack. Sectioning samples to characterize the crack at the blended surface may provide improved understanding.
- Because of the difficulties in arriving at a controlled surface condition in the field environment, additional efforts to understand the effect of etching practices on FPI detectability is warranted.

5. OBSERVATIONS AND RECOMMENDATIONS.

Drying study observations and recommendations:

- Statistical analysis of brightness and UVA lengths did not reveal significant differences between the two drying methods at the temperatures used in this study, i.e., flash drying at 150°F and oven drying at 225°F.
- Potential factors that were not considered in the current study are the effects of thermal mass, geometrical complexities of engine components, potential differences in penetrant level, and a range of drying temperatures. The study was also limited to crack sizes less than 0.146" with the majority less than 0.080". Additional studies that explore these factors and include larger crack sizes are recommended.
- While significant differences were not found in this study between the two methods, the importance of process monitoring and control for either method should be emphasized in specifications, standard practice documents, and training and guidance materials. Without careful adherence to the recommended practices, reductions in detectability can occur with either method.

Cleaning study observations and recommendations:

- Effective cleaning methods exist for removing oil contamination for both Ti and Ni alloys without being detrimental to the FPI process.
- Development of additional cleaning methods for Ti is needed. For Ti parts that experience high temperature exposure, the evaluation of a multistep process including an acid descaler is recommended for consideration.
- Use of some alkaline cleaners lead to reduction in FPI indication response. Further studies are recommended to determine if the cause is ineffective cleaning or alkaline cleaner residues, which negatively affect the fluorescence. Differences were found between cleaning processes used for Ti and Ni, which would benefit from further study.
- Further steps to improve the resistance of penetrant solutions to the effect of alkaline cleaners would be of value.

- Use of wet glass bead, plastic media at 80 psi, and larger grit (240 and 320) Al₂O₃ led to surface damage and loss of FPI indications which were not recoverable with subsequent chemical cleaners or baseline processing. Steps to prevent their use for components that will undergo FPI are recommended.
- Use of plastic media at 40 psi, Al₂O₃ 500 grit, and walnut shell led to acceptable performance, i.e., the samples were clean with no observable surface damage and demonstrated acceptable FPI response. However, the FPI response improved when the media blasting process was followed by a wet process. Additional data is needed to determine if a wet chemical process is needed to arrive at the improved performance or a water wash step would lead to sufficient improvement. Changes to industry specifications and practices that recommend media blasting processes to be followed by a wet process may be required.
- Surface cleanliness is not a sufficient condition to ensure effectiveness of the FPI process but data supports that it is a necessary condition. The crack also has to be clean and open to the surface. Components should appear visibly free of surface conditions such as scale, soot, and coke and varnish, prior to fluorescent penetrant inspection.
- The four-step process for cleaning of Ni was effective in removing baked-on contaminants, including improving the FPI response after media blasting processes. More frequent use of this process for Ni components may be warranted. A similar process would be useful for contamination of Ti components, possibly using remaining samples from this program available for the development. Preliminary data generated in this program indicates that permanganate and acid descaler may be useful steps in such a process. Consideration of a hot line process for Ti is recommended.
- Further characterization of ultrasonic agitation used with alkaline cleaners would be of value including evaluation of the contribution of bath temperature and concentration on cleaning effectiveness.
- Additional data on alkaline gel cleaners is needed for both engine and airframe materials. Factors to be addressed include both effectiveness of the cleaning method as well as the occurrence of potential residue from the cleaning process.
- Potential factors not considered in the present study include fatigue cycling and contamination while at temperature as is the case in actual engine operation. This could lead to different crack morphologies and contamination products than the serial processing (fatigue followed by temperature-generated contamination) of this program.

Hot water study observations and recommendations:

- Exposure of samples to water and ultrasonic agitation in water led to reductions in brightness with the results more severe with ultrasonic agitation. UT H₂O led to lower brightness in all but one case with less impact on length values. Water should be

considered a contaminant that degrades the penetrant process, indicating the importance of drying in preparation for FPI.

Local etchant study observations and recommendations:

- Smearing of cracks due to blending was not easily accomplished in this study. Factors may include material hardness, abrasive style and coarseness, blending force and dwell time, and crack opening width. Because the samples were fabricated from plate stock, correlation between ability to blend these samples and forged materials typical of engine disks may not be warranted.
- Several factors or a combination of factors may lead to an observed decrease in crack detectability by FPI after blending including metal smearing, imbedded blending media, or retained acid etchant within the crack.
- Because of difficulties in arriving at a controlled surface condition in the field environment, additional efforts to understand the effecting of etching practices on FPI detectability is warranted.

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APPENDIX A—SUMMARY OF A SURVEY OF OVERHAUL FACILITIES

Cleaning and Drying Practices Used on Critical Rotating Components Prior to FPI

Introduction:

General Electric, Honeywell, Pratt & Whitney, Rolls Royce/Allison, and Iowa State University are collaborating on a study of the effects of cleaning and drying practices on FPI crack detectability. The FAA is funding the effort as part of the Engine Titanium Consortium. Prior research has contributed to the establishment of the current practices but there are some shortcomings in the data and a few areas of disagreement. This collaboration is focused on conducting engineering studies to provide needed data. The goal is to produce a report with industrywide acceptance that documents performance of current practices.

Input from the airlines and overhaul facilities was solicited to help make this an effective study. The feedback will help to determine the extent that various cleaning and drying practices are being used, and to identify concerns and questions overhaul facilities have about current practices. The information will help to further define the studies being planned. The information was collected through a telephone survey conducted by personnel at Iowa State University.

Feedback was provided by:

- American Airlines, Tulsa, OK
- GE Aircraft Engine Services, South Wales, UK
- Delta Air Lines, Atlanta, GA
- Northwest Airlines, St. Paul, MN
- United Airlines, San Francisco, CA
- Honeywell Engine Systems and Services, Phoenix, AZ

Questions:

1. What cleaning processes and equipment are currently being used in your facility?

Titanium Parts

Alkaline rust remover:	6 of 6
• High conc./short dwell (5 min)	
• Lower conc./longer dwell (15-30 minutes):	6 of 6
Aqueous degreaser:	6 of 6

Grit blasting (Al oxide):	3 of 6
• Grit sizes:	
220	1 of 6
240	1 of 6
325	1 of 6
500	Data not available
Wet	1 of 6
Dry	3 of 6
Vapor or steam	4 of 6
Plastic media blast	4 of 6
Ultrasonic cleaner	0 of 6
Others: Shell blast, vapor degreasing, hand scrub	

Nickel Parts

One to four-step descaling:	6 of 6
Grit blasting (Al Oxide):	4 of 6
• Grit Sizes:	
220	1 of 6
240	1 of 6
325	1 of 6
500	1 of 6
Wet	0 of 6
Dry	2 of 6
Plastic media blast	3 of 6
Ultrasonic cleaner	3 of 6
Others: Shell blast, vapor degreasing, hand scrub	

2. What drying processes and equipment are currently being used?

Flash dry:	6 of 6
Oven dry:	
• Part of UT cleaning line	2 of 6
• All critical rotating parts	1 of 6
• On parts with internal cavities	1 of 6

3. Are your current cleaning practices effective on all parts? If not, please comment on any particularly difficult to clean situations and what you did to accomplish the cleaning task. (What is the procedure for removing contaminants that are not removed using the standard cleaning practices?)

- Yes. Vapor degrease for some hard to clean parts. Will repeat cleaning process two or three times to get some parts clean. Chromic acid based cleaner per Pratt SPOP 252.
- Yes. Difficult to clean parts are cleaned in an UT cleaning using an acid descaler (1873 solution).

- Yes. The turbine sections of some engines are difficult to clean due to carbon build-up from leaky seals. Hand cleaning with a soft bristled brush is sometimes used.
 - Yes. Vapor degrease for some hard to clean parts.
 - Yes. Close control of chemicals eliminates many problems. If background glow is too high, parts are recleaned and reinspected
 - Yes. Some parts require hand scrubbing to remove baked on carbon. Aluminum deposits that occasionally occur from a rub condition usually require a second treatment with rust stripper.
4. Please identify any cleaning processes that you are currently prohibited from using that you would like evaluated for possible use?
- Have a passing interest in laser cleaning.
 - Highly evaporative chemicals such as skyclean.
 - A soy extract cleaner as a replacement for Oakite Rust Stripper.
 - Permanganate cleaning (four-step process)
5. Are there cleaning or drying requirements that are not fully understood or that more information on the rationale for the requirements is needed?
- Have made a special effort to make cleaning personnel understand that flash drying times need to be closely followed. Would like better guidance on “how clean is clean?”
 - Have added special training to reinforce time and temp requirements for flash dry.
 - What is a clean part? Currently rely on water break test and finger wipe for dust. Have worked to make sure cleaning personnel understand why temperatures need to be maintained at required levels. (A varnish can form on the surface of parts if alkaline solution is not warm enough.) Also must explain need to regulate pressure of blasting processes.
 - Does 320 and 500 grit move metal?
 - Need to constantly remind cleaning personnel to keep parts separated to prevent damage.
6. To what extent would you be willing to contribute to this study?
- Provide input 6 of 6
 - Contribute crack samples 2 of 6
 - Process a limited number of test parts in your facility 4 of 6

APPENDIX B—FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE

The level 4 method D fluorescent penetrant inspection experiment procedural checklist used in field studies performed at the Delta Air Lines facility, Atlanta, Georgia, is shown in table B-1.

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section A: Start-Up and Daily QC Checklist					
Instructions: At the start of each day or following any changes in the system, perform the following system and material checks and record the information in the boxes to the right. (Ref AMS 2647B)	Date and Time				
1. Turn on the following: DRYER OVEN, BLACK LIGHTS in WASH SINK BOOTH and in INSPECTION BOOTH, and the SPOTMETER. (Allow a half hour warm-up time before daily calibration check.)					
2. Check the emulsifier for penetrant contamination. Discard the emulsifier if the bath has penetrant floating on the surface or adhering to the sides of the tank.					
3. Check the emulsifier concentration using a refractometer. The concentration should be 20%, and note the actual refractometer reading.					
4. Check and adjust the wash water pressure. The water pressure shall be in the range of 35 to 40 psi.					
5. Check the wash water temperature. The water temperature should be in the range of 50°-100°F.	Water temp:___				
6. Check the dry developer to ensure that it is fluffy and not caked. Spread out a thin layer of dry powder into a 4-inch (approximate) circle on a piece of Whatman filter paper. Inspect under black light. If more than ten fluorescent specks are present, discard and replace the developer with new powder.	Oven Temp:___				
7. Examine the inspection booth and measurement equipment for penetrant contamination. Clean using solvent if necessary.					
8. Check the visible light intensity in the darkened inspection booth using the Spectroline DSE-100X DIGITAL RADIOMETER. The reading should be less than 2 foot-candles. (White light from fluorescent UVA source measures 2.3 fc.)					

B-2

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section A: Start-Up and Daily QC Checklist					
Instructions: At the start of each day or following any changes in the system, perform the following system and material checks and record the information in the boxes to the right. (Ref AMS 2647B)	Date and Time				
9. Check the physical location (setup) of the PR-880 spotmeter's angle, the lab jack stand, and black light, and make sure they are in the proper positions. See page B-7 for an illustration of the equipment setup.					
10. Check the luminous intensity of the black light in the inspection booth. Place the sensing element of the radiometer directly under the spotmeter sensing element. The meter should read between 5050 to 5200 microwatts/cm ² .					
11. Check and record the black light intensity in the wash booth. The intensity should be at least 1000 microwatts/cm ² at a distance of 15 inches from the filter.					
12. The PR-880 spotmeter automatically calibrates itself every 20 minutes. Manually calibrate the machine by pressing the ALT key, and then press the CAL key.					
13. Place the UNIVERSAL TEST EQUIPMENT UTE-3 INSPECTABILITY SCALE on the lab jack stand and align the 40% spot under the aperture.					
14. Record the meter reading. This is the luminance of the subject, i.e., the 40% spot on the UTE-3 card. The value should be approximately 2.5-3.0 foot-Lamberts.	Multiplier Factor: _____ Meter Reading:				

B-3

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section B: Testing Procedure Zyglo ZL-37 Zyglo ZR-10B Zyglo ZP-4B	Run #: ___									
	Date: ___		Date: ___		Date: ___		Date: ___		Date: ___	
	By: _____									
Instructions: Use step 4A if running oven-dry procedure. Use steps 4B.1 and 4B.2 if running the flash-dry procedure.	√	Time								
1. Ultrasonically clean the samples in acetone for 30 minutes.										
2. When the timer at the UT cleaner sounds, remove the panels from the acetone and allow to drain. Place the panels in order from the left in the divided basket. View the samples for fluorescent contamination.										
3. Immerse the samples in clean, room temperature water for 5 minutes.										
4A. Oven dry the samples for 30 minutes at 225°F (107°C).										
4B.1 Flash dry the samples for 10 minutes in clean 150°F (66°C) water.										
4B.2 Drain excess water by tipping the basket until water drops run.										
5. Allow the samples to cool until they can comfortably be held in hand (104°F).										
7. Set the timer for 20 minutes. Dip the basket of samples into the ZL-37 Penetrant. Immediately after placing the basket into the penetrant to dwell, start the timer. Remove the basket from the penetrant and allow the samples to dwell for the full 20 minutes. Near the end of the dwell time place the basket into the wash sink to prepare for the next step.										

B-4

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section B: Testing Procedure Zygro ZL-37 Zygro ZR-10B Zygro ZP-4B	Run #: __									
	Date: __		Date: __		Date: __		Date: __		Date: __	
	By: _____		By: _____		By: _____		By: _____		By: _____	
Instructions: Use step 4A if running oven-dry procedure. Use steps 4B.1 and 4B.2 if running the flash-dry procedure.	√	Time								
8. Prerinse the specimens with a water spray that concentrates on the crack surfaces for 90 seconds at a distance of 12-18 inches. Concentrate the spray on each sample for 3 seconds and alternate samples for 60 seconds on the cracked face, flip the samples over to rinse the back and sides adequately, then flip and rinse the samples for an additional 30 seconds.										
9. Set the timer for 2 minutes and start the timer as the samples are immersed into the 20% ZR-10B Emulsifier Solution.										
10. Gently agitate the basket of samples. During the last 35 seconds of the emulsification time remove the samples from the emulsifier and allow them to briefly drain and move them to the wash station.										
11. Postrinse the specimens with a water spray that concentrates on the crack surfaces for 90 seconds at a distance of 12-18 inches. Concentrate the spray on each sample for 3 seconds and alternate samples for 60 seconds on the cracked face, flip the samples over to rinse the back and sides adequately, then flip and rinse the samples for an additional 30 seconds.										
12. Let the samples drain for a few seconds, and then place the basket containing the panels in the 125 F drying oven for 8 minutes. Record the temperature of the oven.		Dryer Temp: __								

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section B: Testing Procedure Zyglo ZL-37 Zyglo ZR-10B Zyglo ZP-4B	Run #: ____ Date: ____ By:	Run #: ____ Date: ____			
Instructions: Use step 4A if running oven-dry procedure. Use steps 4B.1 and 4B.2 if running the flash-dry procedure.	√ Time	√ Time	√ Time	√ Time	√ Time
13. When the drying time elapses, remove the specimens from the oven. Reset the timer for 10 minutes.					
14. Develop the left panel by scooping through the ZYGLO ZP-4B dry developer powder in a horizontal position, with the indication surface up. With a quantity of developer on the cracked face move the sample side-to-side for 3 seconds, then dump off the excess powder. Do not tap or blow on the sample. Place the sample with the indication surface up. Proceed to develop the remainder of the panels in numerical order.					
15. Immediately after developing the last specimen, start the timer and allow the specimens to develop for 10 minutes. Make sure the samples are not exposed to high-intensity ultraviolet light during the development time.					
18. When the dwell time is over, measure the indication brightness with the Spotmeter by covering the entire crack with the spot. Measure the samples in the same order they were developed.					
19. If no indication is visible, apply a light coating of nonaqueous wet developer (NAWD) to the sample directly over the dry powder developer coating. Allow an additional 5-minute development time. If now present, perform the normal brightness measurement. Note if NAWD was used.	NAWD?	NAWD?	NAWD?	NAWD?	NAWD?
20. Measure the indication length using an FPI comparator or 7X magnified pocket comparator					

TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section B: Testing Procedure Zyglo ZL-37 Zyglo ZR-10B Zyglo ZP-4B	Run #: ____ Date: ____ By:	Run #: ____ Date: ____			
Instructions: Use step 4A if running oven-dry procedure. Use steps 4B.1 and 4B.2 if running the flash-dry procedure.	<input checked="" type="checkbox"/> Time				
21. Photograph the indication under black light.	<input type="checkbox"/>				
22. Clean the panels with Ivory™ Liquid Soap. Brush using approximately 50 strokes with a soft bristle brush in direction of indication, and brush all remaining sides. Tap water rinse.	<input type="checkbox"/>				
23. Blot the tops of the samples dry.	<input type="checkbox"/>				
24. Return to step 1 and repeat 3 times for each method (4A and 4B).	<input type="checkbox"/>				

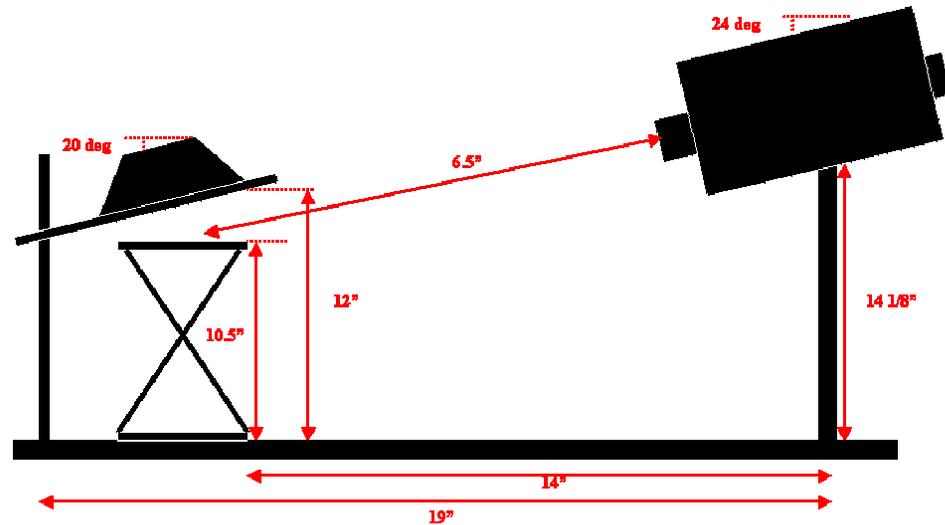
TABLE B-1. FLUORESCENT PENETRANT INSPECTION DRYING AND CLEANING STUDY PROCEDURE (Continued)

Level 4 Method D Fluorescent Dye Penetrant Inspection Experiment Procedural Checklist
Baseline Experiment

Section C: Shutdown Procedure	Run #: __									
	Date: __		Date: __		Date: __		Date: __		Date: __	
	√	Time								
1. Return all chemicals to flammables cabinet or other chemical storage location.										
2. Replace the lens cap. Turn the PR-880 spotmeter off.										
3. Turn off the black lights, video microscope, and other equipment.										
4. Cover the penetrant, emulsifier, and developer.										
5. Store the samples in a protected place.										

B-8

Spotmeter and Sample Setup



APPENDIX C—DETAILED CLEANING STUDY PARAMETERS

The detailed steps used during the cleaning study are provided below. Note that C1 through C8 were used to designate the chemical cleaning methods and B1 through B6 were used to designate the mechanical cleaning methods. These designations have no relevance to industry practices but were primarily a convenience to assist with data tracking.

C.1 CHEMICAL CLEANING PROCESSES.

- C1—Degreasing of Parts by Aqueous Cleaning
 1. Soak the part in Turco T5948R, 20% by volume with water, at 150°F (65.6°C) for 15 minutes.
 2. Flush fully over aqueous cleaner tank with air-assisted pressure cold-water spray.
 3. Put part fully in cold water for 5 minutes.
 4. Use an air-assisted pressure spray gun to flush part with cold water.
 5. Oven dry at 225°F (107°C) for 30 minutes.

- C2—Cleaning Titanium by Heavy Duty Alkaline Cleaning (short and long soak methods)

Caution: alkaline rust remover cleaning tanks used for titanium must be restricted to titanium parts only.

 1. Degrease in Turco 5948R, 20% by volume with water, at 150°F (65.6°C) for 15 minutes.
 2. Soak in one of the alkaline rust remover solutions that follow; use either method 1 or 2.
 - a. Method 1/Solution A (short soak, high concentration)—Turco 4181L, 70% by volume with water, at 180°-200°F (82°-93°C) for 3 minutes (agitated).
 - b. Method 2/Solution B (long soak, low concentration)—Turco 4181L, 20% by volume with water, at 180°-190°F (82°-87°C) for 20 minutes.
 3. Pressure spray rinse with water over the alkaline solution. Dip in agitated cold-water tank for 1 minute followed by pressure spray rinse in cold water.
 4. Oven dry at 225°F (107°C) for 30 minutes.

- C3—Cleaning Inconel by Heavy Duty Alkaline Cleaning (one-step long soak)
 1. Soak in alkaline rust remover solution (Turco 4181L at 70% by volume with water) at 180°-200°F (82°-87°C) for 30 minutes and Turco 4181L at 66% by volume with water at 180°-200°F for 30 minutes.
 2. Pressure spray rinse with cold water over the alkaline solution tank. Dip in a cold-water tank then pressure spray rinse.
 3. Oven dry at 225°F (107°C) for 30 minutes.

- C4—Four-Step Alkaline Rust Remover, Acidic Scale Conditioner and Alkaline Permanganate Cleaning of Steel and Nickel Parts

(Note: This process is used only if the one-step process (C3) is unsuccessful in cleaning the samples. This was necessary for the nickel samples after the baked-on contamination.)

1. Soak in alkaline rust remover solution (Turco 4181L at 70% by volume with water) at 180°-200°F (82°-93°C) for 15 minutes.
2. Pressure spray rinse with cold water over the alkaline solution tank. Dip in cold-water tank then pressure spray rinse.
3. Soak in acidic scale conditioner solution (Turco ScalGon 5 at 20% by volume with water) at 175°-195°F (80°-90°C) for 15 minutes.
4. Pressure spray rinse with cold water over acidic solution tank. Dip in cold-water tank then pressure spray rinse.
5. Soak in alkaline permanganate solution (Turco 4338L at 20% by volume) at 180°-200°F (82°-93°C) for 15 minutes.
6. Pressure spray rinse with cold water over alkaline solution tank. Dip in a cold-water tank then pressure spray rinse.
7. Soak in alkaline rust remover solution (Turco 4181L at 70% by volume with water) at 180°-200°F (82°-93°C) for 5 minutes.
8. Pressure spray rinse with cold water. Dip in cold-water tank then pressure spray rinse.
9. Oven dry at 225°F (107°C) for 30 minutes.

- C5—Local Removal of Carbon by Alkaline Gel
 1. Apply Turco 5805 alkaline gel carbon remover (as-received, 100% by volume, at ambient temperature) to the part. Soak for 10 minutes.
 2. Flush fully with cold-water pressure spray.
 3. Pressure spray rinse with cold water. Dip in cold water then pressure spray rinse.
 4. Oven dry at 225°F (107°C) for 30 minutes.
- C6—Degreaser (typically used for exterior of the engine)
 1. Steam solution of Turco 5948R onto sample and let solution dwell for 1 minute.
 2. Flush fully with ambient rinse for 5 minutes.
 3. Oven dry at 225°F (107°C) for 30 minutes.
- C7—Ultrasonic Cleaning of Parts

Cautions: Do not permit parts or rack to touch the bottom or sides of the tank. Do not permit parts to hang from the side of the tank. Be sure to support parts in the tank. Use a rack with a large opening toward the transducers for the most effective cleaning. All parts in the rack must be fully submerged under the surface of the cleaning solution by 1 inch (25.4 mm) minimum. Do not stack parts on top of one another. Do not overload the tank with too many parts because they absorb ultrasonic energy, which decreases the effect of the cleaning action and increases the cleaning time.

1. Fill the tank with one of the following alkaline cleaning solutions:
 - a. Inconel specimens use alkaline rust remover solution Turco 4181L, 70% by volume with water, at 176°F (80°C).
 - b. Titanium specimens use Turco 4181L, 20% by volume with water, at 180°-190°F (82°-87°C).
2. Start the ultrasonic generator without the parts in the tank and operate the generator until the gas in the cleaning solution is fully removed (or degassed). NOTE: Degassing is only necessary when a new cleaning solution is added to the tank. Once degassed, the solution will stay degassed. Initial degassing will occur in a few seconds to a few minutes. The temperature of the solution and the depth of the tank will have an effect on the amount of time that will be necessary to degas the solution. The colder the solution and the deeper the tank, the longer the degas time. It can take 30 to 60 minutes to fully degas the solution, but you can decrease this amount of time if you heat the solution to the recommended range specified.

3. Slowly put the rack into the ultrasonic cleaning solution and ultrasonically clean the parts for a 15-minute cycle. NOTE: Ultrasonic agitation will increase the temperature of the C7 cleaning solution. Operate the solutions at the temperature range specified in C7-1 above.
 4. After 15 minutes, raise the rack from the solution and examine the samples for cleanliness. An additional 15-minute cycle can be run if required to clean the part. The maximum ultrasonic time is 60 minutes total for each FPI process run. This study was limited to a single 15-minute process.
 5. Immerse in ambient temperature water for 2 minutes and spray rinse.
 6. Oven dry at 225°F (107°C) for 30 minutes.
- C8—Rubber Stripper
 1. Immerse in Turco T6045 for 4 hours.
 2. Rinse with pressure wash at ambient temperature.

C.2 BLASTING PROCESSES.

- B1—Dry Plastic Blast (Pressure-Type Machine)
 1. (Plasti-Grit (12—2-grit), Composition Materials Co., Inc., Milford, CT, www.compomat.com).
 2. An evaluation of pressure effects was performed as part of the program. Set machine air pressure at either 40 or 80 psi. Note that 40 psi is the recommended maximum pressure for cleaning critical rotating components.
 3. Blast with plastic blast media type 2 media Mil-P-85891 with sweeping motion for 30 seconds. There must be a 3- to 4-inch (76- to 102-mm) nozzle-to-part distance at a 45 to 60 degree angle to the work surface.
 4. Blow clean with air at 30 psi (206.8 kPa) maximum to remove any remaining media.
 5. Visually check that the part has been evenly cleaned and that there is no remaining blasting media or masking.
 6. No drying step was used.

- B2—WET Glass Bead (0.0021-0.0029 inch diameter) Blast Cleaning

Caution: Do not dwell in any one area for more than two seconds; use continuous motion.

1. Set machine air pressure at 40 psi (275.8 kPa).
2. Blast with glass bead abrasive solution (SPS 235), with sweeping motion for 10 seconds as necessary, to remove scale. There must always be a 3- to 4-inch (76- to 102-mm) nozzle-to-part distance at a 45 to 60 degree angle to the work distance.
3. Pressure spray rinse with cold or hot water.
4. Oven dry at 225°F (107°C) for 30 minutes.

- B3—Dry Abrasive Grit Blast (240-Grit Aluminum Oxide) (Pressure-Type Machine)

Caution: Do not dwell in one area for more than two seconds; use continuous motion.

1. Set machine air pressure at 25-30 psi (172.4-206.8 kPa) for pressure-type machine
2. Blast with aluminum oxide grit (240), with sweeping motion for 10 seconds as necessary, to remove scale. There must be a 3- to 4-inch (76- to 102-mm) nozzle-to-part distance at a 45 to 60 degree angle to the work surface.
3. Blow clean with air at 30 psi (206.8 kPa) maximum to remove any remaining media.
4. No drying step was used.

- B4—Dry Abrasive Grit Blast (320-Grit Aluminum Oxide) (Pressure-Type Machine)

Caution: Do not dwell in one area for more than two seconds; use continuous motion.

1. Set machine air pressure to 25-30 psi (172.4-206.8 kPa) for a pressure-type machine.
2. Blast with aluminum oxide grit (320), with sweeping motion for 10 seconds as necessary, to remove scale. There must be a 3- to 4-inch (76- to 102-mm) nozzle-to-part distance at a 45 to 60 degree angle to the work surface.
3. Blow clean with air at 30 psi (206.8 kPa) maximum to remove any remaining media.
4. No drying step was used.

- B5—Dry Abrasive Grit Blast (500 aluminum oxide grit) (pressure-type or suction-type machine)

Caution: Do not dwell in one area for more than two seconds; use continuous motion.

1. Set machine air pressure at 25-30 psi (172.4-206.8 kPa) for pressure-type machine.
 2. Blast with aluminum oxide 500 grit, with sweeping motion for 10 seconds as necessary, to remove oxides. The nozzle-to-part distance shall be held to 3-4 inches (76-102 mm) and the angle to work surface shall be held at a 45 to 60 degree angle.
 3. Blow clean with air at 30 psi (206.8 kPa) maximum to remove any remaining media.
 4. No drying step was used.
- B6—Walnut Shell Blast
1. Set machine air pressure at 25-30 psi (172.4-206.8 kPa) for pressure-type machine.
 2. Blast with walnut shell (12-20 grit), with sweeping motion for 10 seconds as necessary, to remove contamination. The nozzle-to-part distance shall be held to 3-4 inches (76-102 mm) and the angle to work surface shall be held at a 45 to 60 degree angle.
 3. Blow clean with air at 30 psi (206.8 kPa) maximum to remove any remaining media.
 4. No drying step was used.

APPENDIX D—ETCH SOLUTION COMPARISONS

Titanium Etchant (Components required to make 100 ml solution)

- Swab etch for 60 to 90m seconds

<u>GEAE, HON E&S, P&W (Class B)</u>	<u>Rolls-Royce plc (RR-1)</u>
62 ml distilled H ₂ O	67 ml distilled or demineralized H ₂ O
35 ml 69%-71% w/w HNO ₃	20 ml 70% w/w HNO ₃
3 ml 48% w/w HF	13 ml 48% w/w HF (11 ml 40% w/w HF + adj. water)
	<u>Rolls Royce plc Desmut Solution (RR-2)</u>
	75 ml Demineralized H ₂ O
	20 ml 70% w/w HNO ₃
	5 ml 48% w/w HF (6 ml 40% w/w HF)

IN-718 Etchant

- Swab etch for 4 to 5 minutes with intermediate reswab to remove smut during etch

<u>GEAE, HON E&S (Class G)</u>	<u>Rolls-Royce plc (RR-3)</u>
38 grams FeCl ₃ solid	40 grams FeCl ₃ Anhydrous
28 ml 36.5-38% HCl	17 ml 36% w/w HCl
76 ml Tap H ₂ O	6 ml 40% w/w HF
	12 ml 70% w/w HNO ₃
	*Demineralized H ₂ O (balance to make 100 ml)

General Ni-Based Etchant

- Swab etch for 4 to 5 minutes with intermediate reswab to remove smut during etch

<u>GEAE, HON E&S (Superalloy Class D)*</u>	<u>Rolls-Royce plc (RR-4 – General Ni-Based etchant)</u>
45.4 grams FeCl ₃ solid (1/10 lb.)	150 grams FeCl ₃ solid
18 ml HCl	600 ml HCl
15 ml H ₂ SO ₄	H ₂ O (Balance to make 1 liter)
50 ml HNO ₃	
75 ml C ₂ H ₄ O ₂ (acetic acid)	
75 ml H ₂ O	
*Add equal amounts of the Schantz Reagent, listed above, and HCl.	