AD-A096 484 PRATT AND WHITNEY AIRCRAFT GROUP WEST PALM BEACH FL G--ETC F/G 7/4
METHODS IMPROVEMENT OF THE FLUORESCENT PENETRANT INSPECTION (FP--ETC(U)
OCT 80 J K MALPANI, J S CARGILL F33615-79-C-5021
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METHODS IMPROVEMENT OF THE FLUORESCENT PENETRANT INSPECTION (FPI) PROCESS

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October 1980

Technical Report AFWAL-TR-80-4161
Final Report for Period August 1979 Through July 1980

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Materials Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for publication.

James A. Holloway

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Project Engineer

FOR THE COMMANDER

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REPORT DOCUMENTATION PAGE

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1. Report Number: AFWAL-TR-80-4161 — 2. Govt Accession No.: AD-A096 484	3. Recipient's Catalog Number
4. Title (and Subtitle): METHODS IMPROVEMENT OF THE FLUORESCENT PENETRANT INSPECTION (FPI) PROCESS.	5. Type of Report & Period Covered: Final, 1 August 1979 to 31 July 1980
	6. Performing Org. Report Number: FR-13667
7. Author(s): J. K. Malpani, J. S. Cargill	8. Contract or Grant Number(s): F33615-79-C-5021
9. Performing Organization Name and Address: United Technologies Corporation, Pratt & Whitney Aircraft Group, Government Products Division, P.O. Box 2691, West Palm Beach, FL 33402	10. Program Element, Project, Task Area & Work Unit Numbers: 2418 05 05
11. Controlling Office Name and Address: Materials Laboratory (AFWAL/MLLP), Air Force Wright Aeronautical Laboratories, AFSC, Wright-Patterson AFB, Ohio 45433	12. Report Date: October 1980
	13. Number of Pages: 56
14. Monitoring Agency Name & Address *(if different from Controlling Office)*	15. Security Class. *(of this report)*: Unclassified
	15a. Declassification/Downgrading Schedule

16. Distribution Statement *(of this Report)*

Approved for public release; distribution unlimited.

17. Distribution Statement *(of the abstract entered in Block 20, if different from Report)*

18. Supplementary Notes

19. Key Words *(Continue on reverse side if necessary and identify by block number)*

Fluorescent Penetrant Inspection, Engine Overhaul Inspection, Surface Preparation Procedures, Chem-Mill Etches, Nondestructive Evaluation, Ti-6Al-4V, Inconel 718, Stress-Enhanced Fluorescent Penetrant Inspection.

20. Abstract *(Continue on reverse side if necessary and identify by block number)*

This program investigates key steps and inspection variables to identify those which significantly influence the sensitivity and reliability of Fluorescent Penetrant Inspection (FPI) in an engine maintenance/overhaul facility. The program is composed of two technical phases: (1) surface preparation procedures, and (2) FPI process variables. The program develops surface preparation procedures and optimized FPI process which can lead to improvements of FPI capability without any degradation of structural integrity of engine components.

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SUMMARY

The key steps and the variables in the Fluorescent Penetrant Inspection (FPI) process were investigated to develop improvements and enhancements of inspection capability at engine maintenance facilities. This investigation developed and optimized surface preparation procedures, and other FPI process variables. Using these procedures, improved inspection capability was demonstrated at the end of the program. The baseline was defined as FPI using state-of-the-art surface preparation and inspection procedures being currently used for typical Ti-6Al-4V and Inconel 718 rotating components in engine overhaul facilities of the USAF. Twenty AFWAL-furnished low-cycle fatigue (LCF) crack specimens of Ti-6Al-4V and Inconel 718 were used as crack standards for various tasks of the program. This program was divided into two phases. Phase I provided for the definition, evaluation, and optimization of surface preparation procedures for FPI of Ti-6Al-4V and Inconel 718. This phase included an investigation of the effects of surface preparation procedures on subsequent FPI capability as well as initial assessments of the effects of these procedures on the structural integrity of engine components, resulting in the following important observations:

1. Surface preparation procedures vary greatly between different overhaul facilities.

2. Aircraft engine operating environment causes significant reduction in capability of overhaul FPI.

3. Some current surface preparation procedures of engine components prior to FPI in an overhaul facility are inadequate and can degrade overhaul FPI capability.

4. Some current chemical cleaning procedures cause selective etching of engine components and may adversely affect structural integrity of these components.

5. Suitable chem-milling processes have been developed for Inconel 718 and Ti-6Al-4V alloys. Limited testing results indicate no degradation in mechanical properties due to the use of these etches.

6. Surface preparation procedures should be investigated in detail for their effects on mechanical properties.

Phase II provided for evaluation and optimization of FPI process variables other than surface preparation procedures. Penetrant dwell time, emulsifier (Hydrophilic) concentration, emulsification time, type of developer, etc., were chosen as significant process variables, resulting in the following important observations.

1. Penetrant dwell time of 30 min for Group VI MIL-I-25135C (Magnaflux ZL-35) provided optimum sensitivity.

2. A 33% concentration of Group VI MIL-I-25135C (Magnaflux ZR-10) emulsifier with 2 min emulsification dwell provided optimum conditions for excess penetrant removal.

3. Wet soluble developer provided much better sensitivity and reliability compared to a dry developer.

4. Stress-enhanced FPI resulted in much higher sensitivity and reliability compared to standard FPI.

Note: These observations were made for detection of small fatigue cracks initiated in smooth, flat specimens.

PREFACE

This report is submitted in accordance with the requirements of AFWAL Contract F33615-79-C-5021 and represents the final technical report covering the period of 1 August 1979 to 31 July 1980. Mr. J. A. Holloway, AFWAL/MLLP was the Air Force Project Engineer. The program was conducted under the cognizance of M. C. VanWanderham, General Supervisor of the Mechanics of Materials and Structures section of the Materials Engineering and Technology Department at the Pratt & Whitney Aircraft Group, Government Products Division (P&WA/GPD), West Palm Beach, Florida.

The Principal Investigator was J. K. Malpani and the Program Manager was J. S. Cargill, reporting to J. A. Harris.

The authors gratefully acknowledge the technical contributions of several individuals in Materials Engineering and Technology Department: B. A. Cowles, B. Manty, P. V. Young, and K. D. Smith, who contributed significantly to the program. Cooperation and assistance of R. G. Smith of Quality Assurance Department of P&WAG/GPD for demonstrations was vital to this program and is gratefully acknowledged.

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INTRODUCTION AND BACKGROUND

Improved fluorescent penetrant inspection (FPI) is of major concern to the United States Air Force, especially for advanced high-performance aeropropulsion systems which utilize materials to their ultimate capacity. Improved FPI capability will result in greater assurance of safety and improve performance of aircraft engine components. The life cycle cost of these components has been gradually escalating due to the use of advanced materials and processing techniques, design complexities, and material and energy shortages. Therefore, there is an ever-increasing need to utilize these components to the full extent of their safe life. The success of the retirement-for-cause philosophy for engine components is intimately tied to improved nondestructive inspection (NDI) techniques at the maintenance/overhaul facilities. It is generally believed that higher sensitivity and reliability of penetrant inspection in the engine overhaul environment is a must to meet the goals of retirement for cause.

The FPI is the most widely used inspection technique, and perhaps the only technique used for some critical component inspections. The apparent simplicity, low cost, and inherently high sensitivity are the main advantages of this inspection technique. But the apparent simplicity of FPI is deceptive and generates a false confidence of infallibility and tendency to overlook some of the basic technique requirements. The apparent simplicity of FPI and relatively low emphasis given to the technique in Government as well as industry has hindered serious research and development work in FPI. The result is that fundamental and applied research projects in FPI are not common. This situation is changing rapidly as the Government and industry have realized, through recent experience, that FPI is falling short of the expectations of sensitivity and reliability required to detect small surface fatigue cracks. The need for applied FPI research applicable to overhaul inspection is even greater in view of the large differences in inspection environments of overhaul FPI compared to manufacturing and laboratory type FPI.

FPI capability of engine overhaul facilities in terms of probability of detection is unknown. An AFLC SA-ALC/Martin Marietta study to quantify NDI capability is in progress (Reference 1). A recent study of the maintenance FPI capability of airframe components (Reference 2) revealed that only cracks greater than 0.70 in. (1.78 cm) will be detected with 60% probability of detection at 95% confidence level. Similar FPI capabilities for engine components in an overhaul environment may be assumed. If the assumption is valid, this presents a problem for the demonstration of continued structural integrity for in-service engine components. It should be emphasized that critical crack sizes for engine components are generally smaller than for airframe components, and engine components are subjected to very high temperatures and severe environmental conditions during engine operations, thus making it much more difficult for FPI to detect tight fatigue cracks.

This program investigated key steps and variables in the FPI process to develop improvements for inspection capability at engine maintenance facilities. The investigation evaluated surface preparation procedures, and other process variables such as, type of penetrant materials, processing times, and procedures. In Phase I of the program, optimized surface preparation procedures were developed. Demonstration of improved inspection capability using these procedures was conducted at the conclusion of the program, and compared to the baseline inspection capability. The baseline is defined as FPI using state-of-the-art surface preparation and inspection procedures currently being used for typical Ti-6Al-4V and Inconel 718 rotating components in engine overhaul facilities of the USAF. Phase II of the program consisted of investigation of FPI process variables other than surface preparation procedures. Demonstration of improvements and enhancements using optimum process variables was also conducted at the end of the program and compared to the baseline inspection capability. The flow chart of the program is shown in Figure 1. This final report covers both Phase I and Phase II of the program. An additional contract, F33615-80-C-5060, Improved Penetrant Process Evaluation Criteria, will quantify the increased performance and probability of detection (POD) of fatigue cracks as the result of improvements and modifications to the FPI process identified and evaluated in this program.

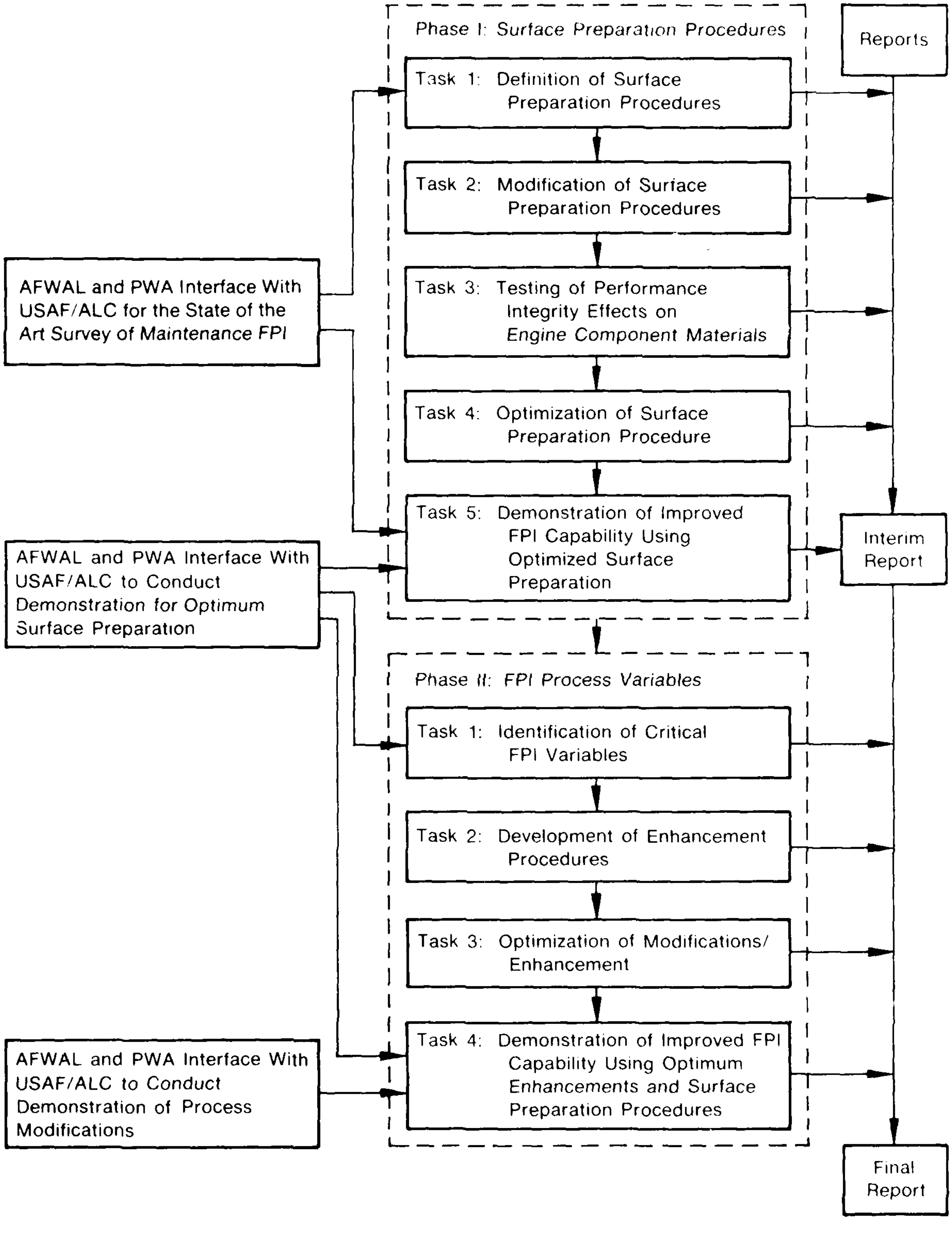


Figure 1. Flowchart of the Program

SECTION II

TECHNICAL DISCUSSION

OBJECTIVE

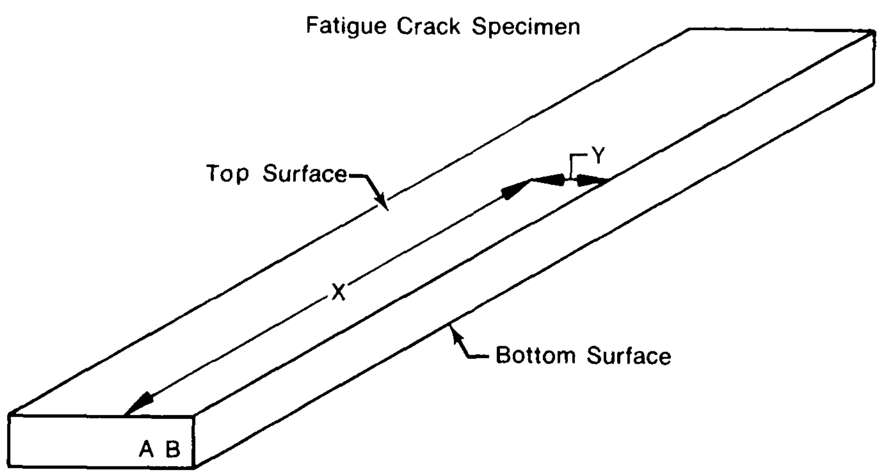
The objectives of this program were (1) to investigate key steps and variables in FPI of aircraft engine components, (2) to identify those which significantly influence the sensitivity and reliability of FPI in engine overhaul facilities, and (3) to identify or develop optimum surface preparation and inspection procedures to improve FPI capability of components.

SCOPE

Twenty 1/4 by 1 by 6 in. (0.635 by 2.54 by 15.24 cm) AFWAL-furnished low-cycle-fatigue (LCF) crack specimens were used to conduct various tasks of the program (Figure 2). The specimens include ten each Ti-6Al-4V alloy and Inconel 718 alloy. Titanium alloys are used as disk materials for fan or compressors or cold sections of gas turbine engines, while a nickel-base alloy like Inconel 718 is primarily used in turbines or hot sections of aircraft engines. The results of this program can improve the FPI capability of USAF engine overhaul, and thereby increase safety and reliability of USAF aeropropulsion systems.

Phase I of the program investigated surface preparation procedures suitable for aircraft engine overhaul. Improvements in FPI capability using the modified procedures were demonstrated at P&WA/GPD.

Phase II of the program investigated FPI process variables such as penetrant dwell time, emulsification and developers. Improvements in FPI capability using modified process variables were also demonstrated in another program conducted at P&WA/GPD.



- AB Is Specimen Identification Number
- X and Y Are Dimensions in Inches, To Define Flaw Locations

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Figure 2. Sketch of AFWAL-Furnished Fatigue Crack Specimen

SUMMARY OF WORK ACCOMPLISHED

Phase I of the program provided the definition, evaluation, and optimization of surface preparation procedures for FPI of Ti-6Al-4V and Inconel 718. Both of these alloys are used as engine component materials. The phase included an investigation of the effects of surface preparation procedures on subsequent FPI capability as well as effects of these procedures on the structural integrity of engine components.

The Air Force provided twenty 1/4 by 1 by 6 in. (0.635 by 2.54 by 15.24 cm) LCF cracked specimens. P&WA provided all other materials and equipment necessary for the program. The technical requirements and work accomplished for Phase I of the program are:

1. The surface preparation procedures typical of an overhaul engine facility were surveyed and identified. This task was accomplished through direct interface with SA/ALC and P&WA-Southington Service Center.

2. Current overhaul surface preparation procedures have been investigated for effectiveness of FPI inspection capability. Modifications to the existing surface preparation procedures are required for optimum results. These include chemical etches for Ti-6Al-4V as well as Inconel 718.

3. The following effects of chem-milling etch procedures on the structural integrity of Ti-6Al-4V and Inconel 718 were investigated:

   Structural degradation due to possible integranular attack, or selective corrosion

   Effects of chem-milling procedures on LCF and creep properties

4. Capability of FPI using current surface preparation and inspection procedures of an ALC overhaul facility were quantified in a demonstration conducted at P&WA/GPD FPI facilities. FPI materials and inspection parameters used in this demonstration were those currently being used in an ALC overhaul facility for typical Ti-6Al-4V and Inconel 718 rotating components.

5. Improvements in FPI capability using modified surface preparation procedures were quantified in a separate demonstration conducted at the P&WA/GPD assembly floor FPI facility.

Phase II of the program provided for evaluation and optimization of FPI process variables other than surface preparation procedures for Ti-6Al-4V and Inconel 718. This phase included definition and optimization of important FPI process variables. The technical requirements and work accomplished for Phase II of the program are:

1. The process variables to be investigated were defined.

2. Each of the process variables were examined independently for their effect on sensitivity and capability of FPI inspection.

3. Optimum process variables and enhancements were identified.

4. A demonstration program was conducted to quantify the effects of modified process variables on sensitivity and capability of FPI inspection of AFWAL-furnished specimens.

BASELINE INSPECTION AND CRACK DOCUMENTATION

Twenty AFWAL-furnished LCF crack specimens were received on the beginning of this program. Flaw documentation by AFWAL using Group VI (Magnaflux ZL-30) penetrant is shown in Table 1. Crack lengths were measured by replication and/or direct optical microscope photographs of the cracks. The results of crack documentation are summarized in Table 2. Typical crack photographs are shown in Figures 3 and 4.

The specimens were inspected as-received by FPI using Magnaflux ZL-55 (water-washable), and ZL-22, ZL-30, and ZL-35 (postemulsifiable) penetrants. A 33% ZR-10A (Hydrophilic Emulsifier) was used as remover for postemulsifiable penetrants. ZP-4B dry developer was also used. ZL-55 is classified as Group IV according to MIL-I-25135 specification and is a high-sensitivity, water-washable penetrant, while ZL-22, ZL-30, and ZL-35 are all classified as Group VI penetrants according to the same specification. ZL-22 has lower sensitivity compared to ZL-30 and ZL-35. ZL-35 has the highest sensitivity. The results of inspections in terms of crack lengths and brightness of indications are summarized in Tables 3 and 4. Linear regression curves of actual crack length vs FPI indicated lengths are shown in Figures 5 through 12.

TABLE 1. AFWAL SPECIMENS FLAW DOCUMENTATION USING ZL-30

Specimen No.	*Surface*	*X* in.	*X* (cm)	*Y* in.	*Y* (cm)	*Length* in.	*Length* (cm)	*Indication*
				IN 718 Specimens				
34	Bottom	2.48	(6.30)	0.28	(0.71)	0.040	(0.01)	Bright
91	Bottom	2.63	(6.68)	0.30	(0.76)	0.030	(0.08)	Bright
52	Bottom	3.62	(9.19)	0.57	(1.45)	0.030	(0.08)	Bright
15	Top	3.29	(8.36)	0.20	(0.51)	0.030	(0.08)	Medium
38	Bottom	3.15	(8.00)	0.60	(1.52)	0.050	(0.13)	Bright
43	Bottom	3.24	(8.23)	0.40	(1.02)	0.040	(0.01)	Bright
74	Bottom	2.66	(6.76)	0.45	(1.14)	0.100	(0.25)	Bright
102	Bottom	3.40	(8.64)	0.50	(1.27)	0.100	(0.25)	Bright
16	Top	2.63	(6.68)	0.35	(0.89)	0.030	(0.08)	Bright
79	Top	3.38	(8.59)	0.32	(0.81)	0.080	(0.20)	Bright
				Ti-6Al-4V Specimens				
27	Top	2.79	(7.09)	0.32	(0.813)	0.090	(0.229)	Bright
53	Bottom	2.67	(6.78)	0	(0)	0.050 × 0.060	(0.127 × 0.152)	Bright
40	Top	3.51	(8.92)	0	(0)	0.060 × 0.005	(0.152 × 0.013)	Bright
40	Top	3.58	(9.09)	0	(0)	0.005 × 0.015	(0.013 × 0.038)	Bright
40	Top	3.61	(9.17)	0	(0)	0.015	(0.038)	Bright
11	Top	2.59	(6.58)	0.70	(1.778)	0.030	(0.076)	Bright
23	Bottom	3.65	(9.27)	0.52	(1.321)	0.120	(0.305)	Bright
64	Top	2.72	(6.91)	0.38	(0.965)	0.020	(0.051)	Bright
79	Top	2.76	(7.01)	0.43	(1.092)	0.015	(0.038)	Bright
24	Top	2.80	(7.11)	0.31	(0.787)	0.030	(0.076)	Bright
33	Bottom	2.58	(6.55)	0.37	(0.940)	0.080	(0.203)	Bright
62	Top	2.60	(6.60)	0.40	(1.016)	0.080	(0.203)	Bright

X and Y are dimensions as shown in Figure 2

TABLE 2. AFWAL SPECIMENS OPTICAL MICROSCOPE CRACK LENGTHS

Specimen No.	*Surface*	*X* *in*	*X* *(cm)*	*Y* *in*	*Y* *(cm)*	*Length* *in*	*Length* *cm*
				IN 718 Specimens			
34	Bottom	2.48	(6.30)	0.28	(0.71)	0.020, 0.015	(0.051, 0.038)
91	Bottom	2.63	(6.68)	0.30	(0.76)	0.007, 0.018, 0.004	(0.017, 0.046, 0.010)
52	Bottom	3.62	(9.19)	0.57	(1.45)	0.030	(0.076)
15	Top	3.29	(8.36)	0.20	(0.508)	0.013	(0.033)
38	Bottom	3.15	(8.00)	0.60	(1.524)	0.051	(0.130)
43	Bottom	3.24	(8.23)	0.40	(1.016)	0.035	(0.089)
74	Bottom	2.66	(6.76)	0.45	(1.143)	0.086	(0.218)
102	Bottom	3.40	(8.64)	0.50	(1.270)	0.075	(0.191)
16	Top	2.63	(6.68)	0.35	(0.889)	0.103	(0.262)
79	Top	3.38	(8.59)	0.32	(0.813)	0.108	(0.274)
				Ti 6Al-4V Specimens			
27	Top	2.79	(7.09)	0.32	(0.813)	0.071, 0.027	(0.180, 0.069)
53	Bottom	2.67	(6.78)	0	(0)	0.047	(0.119)
40	Top	3.51	(8.92)		( )	0.053	(0.135)
40	Top	3.58	(9.09)	0	(0)	0.008	(0.020)
40	Top	3.61	(9.17)	0	(0)	0.020	(0.051)
11	Top	2.59	(6.58)	0.70	(1.778)	0.037	(0.094)
23	Bottom	3.65	(9.27)	0.52	(1.321)	0.104	(0.264)
64	Top	2.72	(6.91)	0.38	(0.965)	0.019	(0.048)
79	Top	2.76	(7.01)	0.43	(1.092)	0.021	(0.053)
24	Top	2.80	(7.11)	0.31	(0.787)	0.036	(0.091)
33	Bottom	2.58	(6.55)	0.37	(0.940)	0.037	(0.094)
62	Top	2.60	(6.60)	0.40	(1.016)	0.0335	(0.085)

X and Y are dimensions as shown in Figure 2

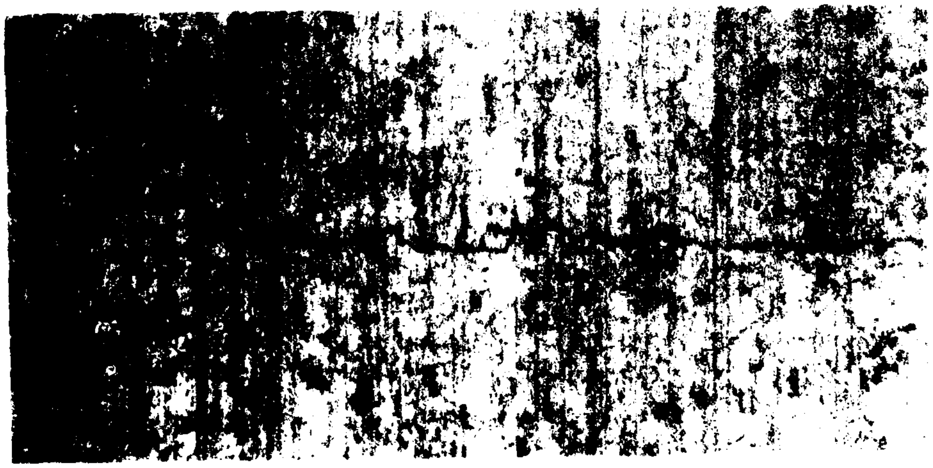

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Figure 3. Fatigue Crack in Inconel 718 Specimen No. 38 (100X)

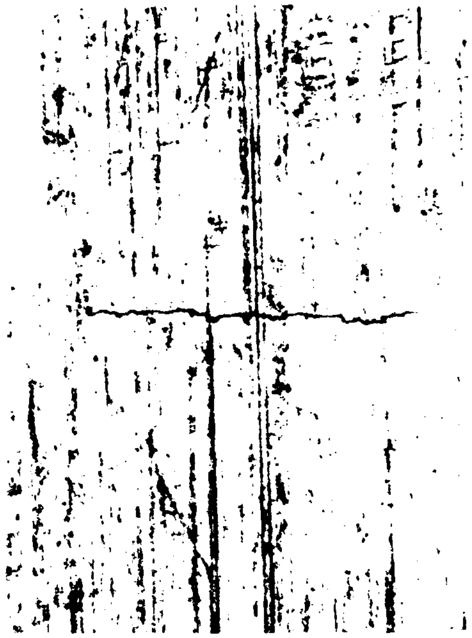

Figure 4. Fatigue Crack in Ti-6Al-4V Specimen No. 64

TABLE 3. CRACK LENGTHS FROM FPI INDICATIONS ON INCONEL 718 FATIGUE CRACK SPECIMENS (AS-RECEIVED)

Specimen Number	*Actual Length* in.	(cm)	*FPI Length — in. (cm)* *ZL-55**		*ZL-22**		*ZL-30**		*ZL-35**	
34	0.035	(0.089)	0.038B	(0.097)	0.036B	(0.091)	0.036B	(0.091)	0.039B	(0.099)
91	0.029	(0.074)	0.028M	(0.071)	0.032M	(0.081)	0.025M	(0.064)	0.037B	(0.094)
52	0.030	(0.076)	0.028M	(0.071)	0.032M	(0.081)	0.026B	(0.066)	0.033B	(0.084)
15	0.013	(0.033)	0.009M	(0.023)	**0.028M	(0.071)	0.008M	(0.020)	0.009M	(0.023)
	0.016	(0.041)	0.016B	(0.041)			0.016B	(0.041)	0.016B	(0.041)
38	0.051	(0.130)	0.049B	(0.124)	0.042B	(0.107)	0.048B	(0.122)	0.046B	(0.117)
43	0.035	(0.089)	0.041B	(0.104)	0.032B	(0.081)	0.030B	(0.076)	0.038B	(0.097)
74	0.086	(0.218)	0.099B	(0.251)	0.087L	(0.221)	0.091B	(0.231)	0.080B	(0.203)
102	0.075	(0.191)	0.084B	(0.213)	0.075B	(0.191)	0.083B	(0.211)	0.092B	(0.234)
16	0.103	(0.262)	0.117B	(0.297)	0.120B	(0.305)	0.123B	(0.312)	0.119B	(0.302)
79	0.108	(0.274)	0.114B	(0.290)	0.112B	(0.284)	0.119B	(0.302)	0.113B	(0.287)

*ZL-55 is classified as Group IV penetrant according to MIL-I-25135C whereas, ZL-22, ZL-30, and ZL-35 are classified as Group VI according to MIL-I-25135C.

**One indication for two cracks

B - Bright

M - Medium

L - Light

TABLE 4. CRACK LENGTHS FROM FPI INDICATIONS ON Ti-6Al-4V FATIGUE CRACK SPECIMENS (AS-RECEIVED)

Specimen Number	*Actual Length* in.	(cm)	*FPI Length in (cm)* *ZL-55**		*ZL-22**		*ZL-30**		*ZL-35**	
27	0.071	(0.180)	0.069B	(0.175)	0.078B	(0.198)	0.076B	(0.193)	0.078B	(0.198)
	0.027	(0.069)	0.026B	(0.066)	0.031B	(0.079)	0.034B	(0.086)	0.033B	(0.084)
53	0.048	(0.122)	0.047B	(0.119)	0.054B	(0.137)	0.071B	(0.180)	0.085B	(0.216)
40	0.053	(0.135)	0.056B	(0.142)	0.061B	(0.155)	0.059B	(0.150)	0.036B	(0.091)
	0.020	(0.051)	0.020B	(0.051)	0.021B	(0.053)	0.021B	(0.053)	0.014B	(0.036)
	0.008	(0.020)	0.012L	(0.030)	0.016L	(0.041)	0.016L	(0.041)	0.010M	(0.025)
11	0.037	(0.940)	0.043B	(0.109)	0.043M	(0.109)	0.046B	(0.117)	0.030B	(0.076)
23	0.104	(0.264)	0.097B	(0.246)	0.091M	(0.231)	0.092B	(0.234)	0.101B	(0.257)
64	0.019	(0.048)	0.011M	(0.028)	0.015L	(0.038)	0.009M	(0.023)	0.010B	(0.025)
79	0.021	(0.053)	0.024B	(0.061)	0.026M	(0.066)	0.016B	(0.041)	0.009B	(0.023)
24	0.036	(0.091)	0.047B	(0.119)	0.040B	(0.102)	0.045B	(0.114)	0.048B	(0.122)
33	0.037	(0.094)	0.044B	(0.112)	0.044B	(0.111)	0.038B	(0.097)	0.046B	(0.117)
62	0.034	(0.086)	0.025B	(0.064)	0.022M	(0.056)	0.021B	(0.053)	0.023B	(0.058)

*ZL-55 is classified as Group IV penetrant according to MIL-I-25135C whereas, ZL-22, ZL-30, and ZL-35 are classified as Group VI according to MIL-I-25135C.

B Bright
M Medium
L Light

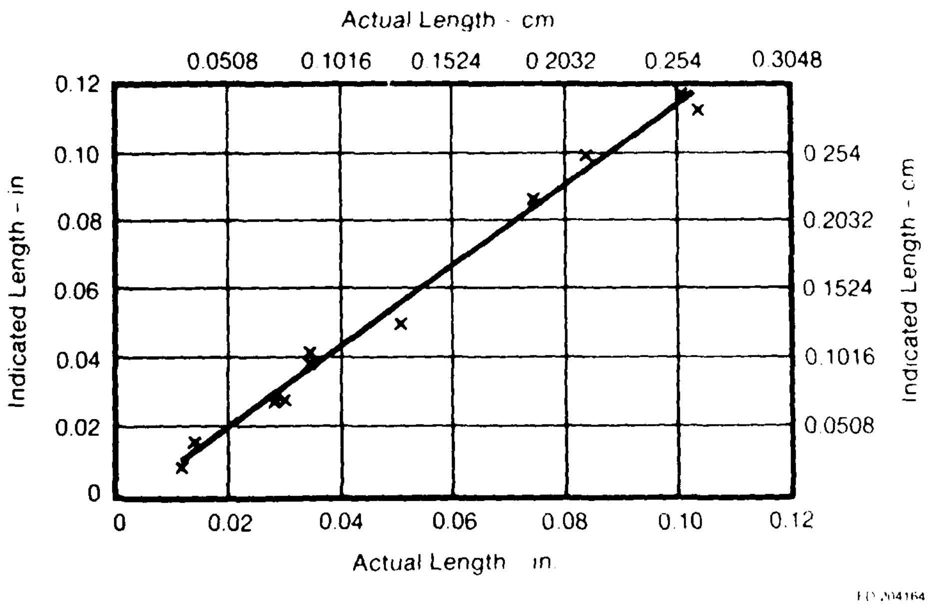

Figure 5. Actual vs Indicated Crack Length in Inconel 718 Using ZL-55

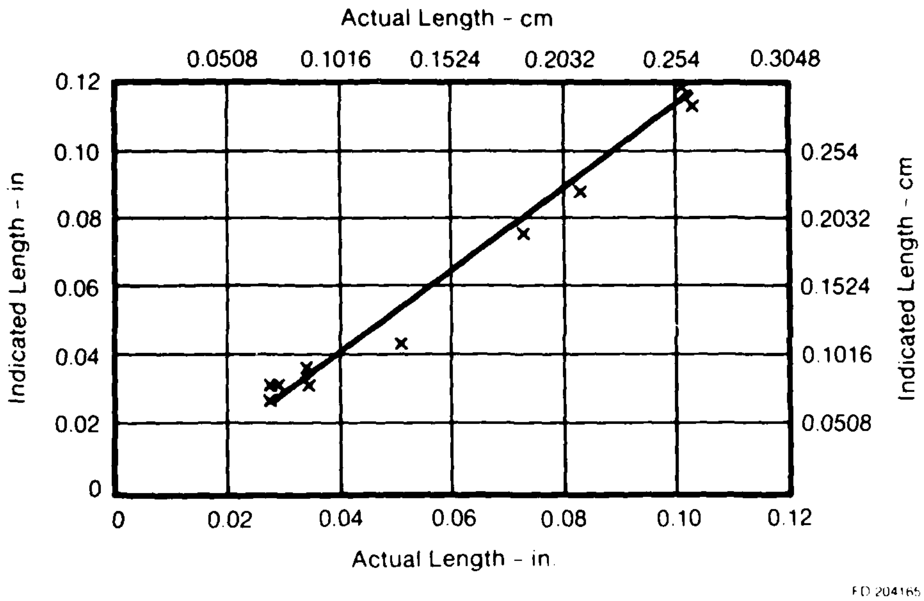

Figure 6. Actual vs Indicated Crack Length in Inconel 718 Using ZL-22

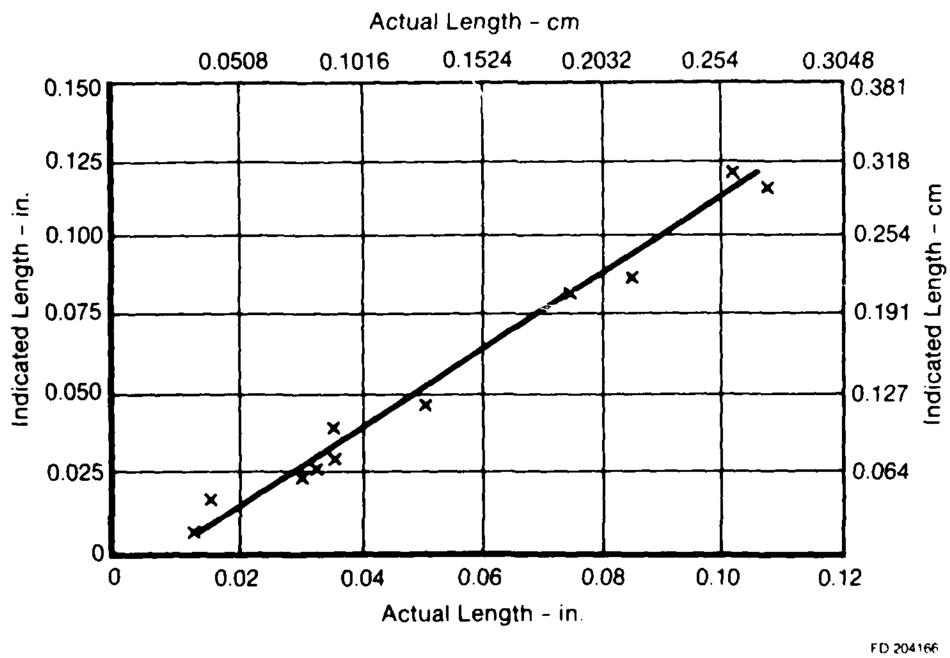

Figure 7. Actual vs Indicated Crack Length in Inconel 718 Using ZL-30

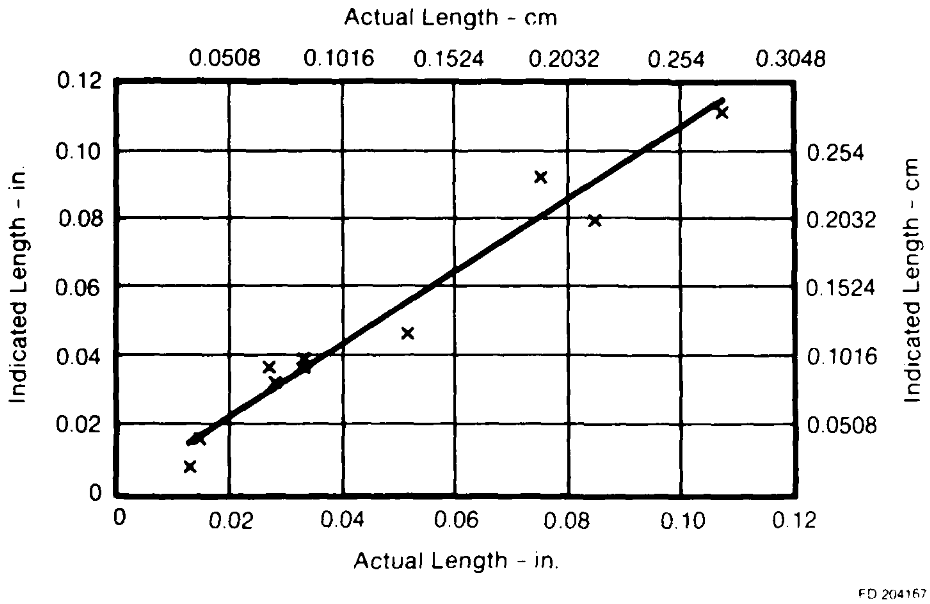

Figure 8. Actual vs Indicated Crack Length in Inconel 718 Using ZL-35

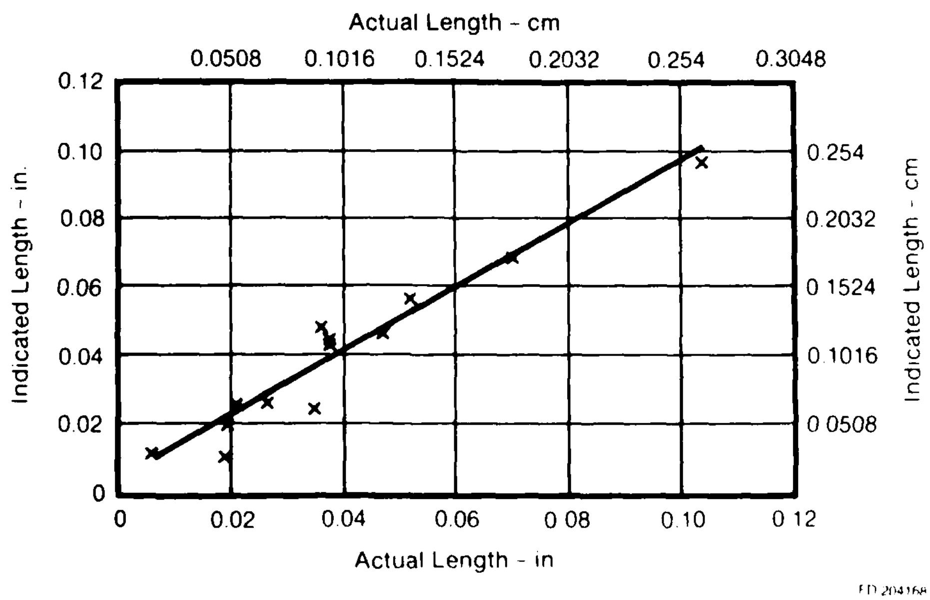

Figure 9. Actual vs Indicated Crack Length in Titanium (6Al-4V) Using ZL-55

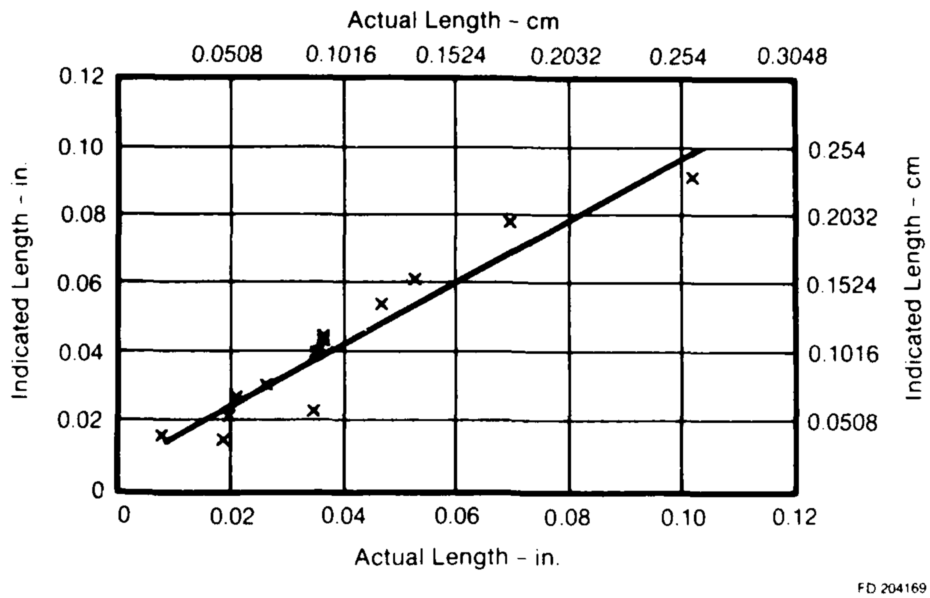

Figure 10. Actual vs Indicated Crack Length in Titanium (6Al-4V) Using ZL-22

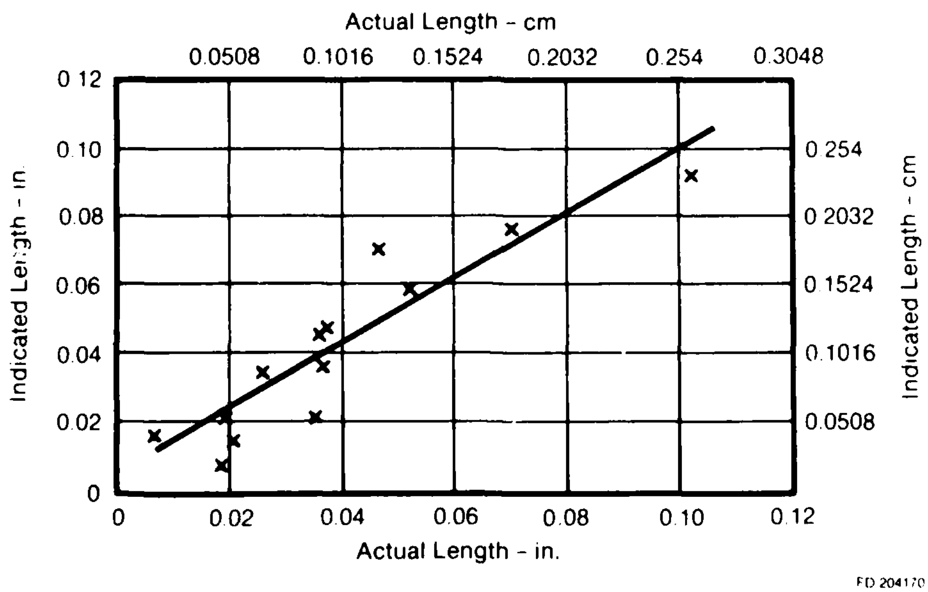

Figure 11. Actual vs Indicated Crack Length in Titanium (6Al-4V) Using ZL-30

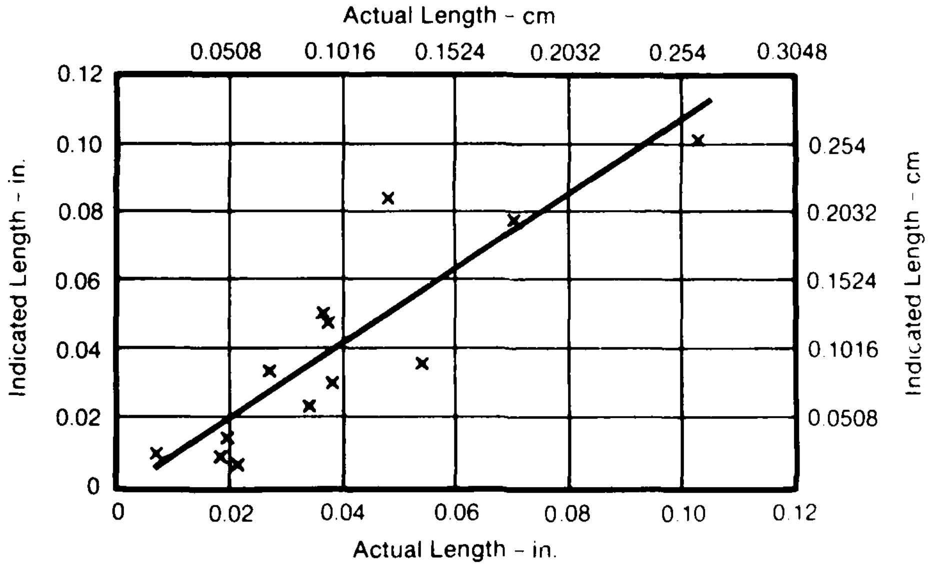

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Figure 12. Actual vs Indicated Crack Length in Titanium (6Al-4V) Using ZL-35

SECTION III

PHASE I: SURFACE PREPARATION PROCEDURES

Phase I consisted of an investigation of surface preparation procedures suitable for aircraft engine maintenance facilities. Figure 1 includes an outline of the technical approach for this phase of the program.

Liquid penetrant inspection requires not only that discontinuities occur at the inspection surface but they must also be open and free of surface contamination. Good cleaning is essential to obtain reliable penetrant indications. Great care must be taken to assure that the parts are clean and dry. Indication and detection of flaws depend upon the flow of the penetrant into what may be only a microscopic crack. It is immediately apparent that the flow cannot take place if the discontinuity is already filled with oil, dirt, water, paint, oxide, or other foreign matter. The cleaning technique being used will be determined by the type of foreign material present and may require either mechanical, solvent, etch, or special surface preparation to assure adequate cleaning.

Without adequate removal of surface contamination, relevant indications may be missed because (1) the penetrant does not enter the flaw, (2) the penetrant loses its ability to identify the flaw because it reacts with foreign matter already in the flaw, or (3) the surface immediately surrounding the flaw retains enough penetrant to mask the true appearance of the flaw. The surface preparation procedures may be classified into three categories (References 3 and 4).

1. **Mechanical Procedures:** Mechanical procedures include grit or vapor blasting, high pressure water cleaning, ultrasonic cleaning, wire brushing, and grinding. Although mechanical methods are sometimes necessary, they should not be used as the final surface preparation procedure particularly when inspecting for crack like defects. These procedures tend to smear over discontinuities, thus limiting the effectiveness of the penetrant.

2. **Chemical Procedures:** Chemical procedures can be subclassified as surface cleaning and surface etching. Surface cleaning procedures include alkaline cleaning (for removing rust, scale, oils, carbon deposits, etc.), acid cleaning (for removing light or heavy scale), molten salt bath cleaning (for heavy scale removal); and solvent methods (vapor degreasing for soil, oil, or grease — not suitable for titanium, solvent hand wiping — suitable for localized cleaning). Surface etch procedures are used to remove smeared metal and clean the surface of oxidation. The type of etchant suitable for particular inspection depends on the material and type of environment in which the component operates. Etch must be used cautiously. All the parts must be thoroughly cleaned and neutralized before applying penetrant.

3. **Combined Procedures:** These procedures use both mechanical and chemical actions for surface preparation. Examples of combined procedures are hand or power scrubbing with detergent, steam with detergent, ultrasonic cleaning with degreasers or solvents.

Special techniques may be developed to open discontinuities so that entrapment efficiency of penetrants is improved. Techniques such as stressing by differential thermal expansion, thermal shocks, spinning or mechanically loading have been effective in some cases. Vibrations (including ultrasonic vibrations) to clean surface contamination may also be used.

GENERAL SURFACE PREPARATION REQUIREMENTS

The primary purpose of cleaning gas turbine engine parts (Reference 5) is to remove the contaminants that might conceal minor cracks and defects, which if not detected could eventually lead to failure. To find the incipient defects, a thorough inspection of the surfaces is necessary, which can only be satisfactorily accomplished after the foreign contaminants are removed. Therefore, cleaning can be termed a preinspection procedure, and the quality of an engine after overhaul or repair will depend considerably on the effectiveness of the cleaning operation. To attain the degree of cleaning deemed necessary, many difficult problems are experienced as the result of the operating characteristics of the engine and the various materials employed as cleaning agents.

There is no single cleaning agent or process that will clean all of the parts. A cleaning agent that will clean one set of parts will not clean another set, or it will attack the alloys comprising the other set. Either way different cleaning agents are necessary, and the selection of these agents will sometimes have to be made individually. When this occurs, the basic factors to be considered are: will the cleaning agent attack the metal chemically and will it leave a residue that will cause corrosion? The choice of cleaning agents and the process can generally be satisfactorily made by considering the following points:

1. Composition of the part
2. Nature of the surface of the part
3. Complexity of construction
4. Type of contaminants to be removed
5. Degree of cleanliness required
6. Availability of a specific cleaning agent, equipment, and the hazards involved.

Chemical cleaning is generally specified for most parts and in most cases does a satisfactory job. However, a decision should not be made relative to any particular cleaning method unless there is a complete understanding of the metals involved and the cleaning agents to be employed.

Parts that cannot be thoroughly rinsed should not be cleaned with corrosive chemicals. Adequate removal of chemical residue from such parts is difficult, if not impossible, and will eventually promote corrosion.

Parts cleaned by soaking in a chemical solution should be removed immediately when cleaning has been accomplished. Soaking for a long time may cause discoloration or attack the metal. Immediately upon removal from the solution, parts should be rinsed. Parts that are clean should be thoroughly rinsed, air dried, and if not to be processed further, coated with rust preventive when practical or when there is danger of corrosion, prior to assembly. Any cleaning solution should be replaced when sludge interferes with cleaning results or when additions of basic materials fail to rejuvenate the solution.

Gas turbine engine components should be cleaned only as necessary to perform adequate inspections and repairs. Overcleaning in some cases can be more detrimental than beneficial to the production of quality engines. Bright surfaces are only obtained with vigorous methods and cannot be obtained without a sacrifice of some base metal. The repeated use of these methods, followed by oxidation and scale buildup in service, can be detrimental to the dimensional stability of the components. For this reason overcleaning should be avoided.

Cleaning of individual engine parts should be for functional purposes only, and should be accomplished only as necessary for the detection of defects or damage, and for elimination of contaminants such as oil, grease, flaky scale, carbon deposit, etc., which if dislodged from the surfaces might restrict oil or fuel lines or generally interfere with operation of the engine. Cleaning of parts merely for appearance is unnecessary and should not be accomplished provided the quality of the engine after overhaul will not be affected. Discoloration resulting from heat and tightly bonded films of inert oxides should not be removed.

Critical surfaces such as flanges, parting surfaces, and mounting pads should be completely free of foreign matter whereas the remaining surfaces of the same part should not require such extensive cleaning. Surface discoloration caused by heat or chemical action should be disregarded. Highly stressed parts should be cleaned only to the extent necessary to detect all flaws and imperfections.

Due to the many variables involved in the cleaning and inspection of gas turbine engine parts, it is impossible to set a standard for cleaning that would apply under all conditions. Therefore, to obtain the maximum overhaul capacity, while at the same time producing a quality product, the combined and continuous efforts of both cleaning and inspection personnel must be exerted to establish and maintain a satisfactory level of cleaning. Personnel concerned must exercise good judgment and common sense to avoid unnecessary cleaning of parts.

When cleaning requirements are found to differ from those approved, and cleaning and inspection personnel cannot agree, appropriate action should be taken. The cleaning line representatives and qualified representatives from Inspection should determine the amount of cleaning necessary to maintain the applicable quality standards.

TECHNICAL APPROACH

The objective of Phase I was to evaluate and optimize surface preparation procedures suitable for aircraft engine maintenance facilities. The first task in Phase I investigation was to define and identify the surface preparation procedures typical of aircraft engine maintenance facilities. As shown in the flow chart (Figure 1), this task was carried out with direct interface with engine maintenance facilities.

The second task was to investigate changes and modifications to the current surf preparation procedures used by engine maintenance facilities to improve FPI capability of such facilities. Consideration was given to both the surface cleaning and surface etch procedures. Etch procedures were evaluated for Ti-6Al-4V as well as Inconel 718.

The third task was to investigate the effects on structural integrity or corrosion characteristics of the materials due to the use of surface preparation procedures. The LCF and creep-rupture properties were evaluated. Strain-controlled LCF specimens (Figure 13) were tested at typical materials operating conditions. To evaluate the creep effects of surface preparation procedures, typical creep-rupture specimens (Figure 14) were tested at operating conditions. The most important concern of the surface preparation procedures was the possibility of degradation of materials. Therefore, a thorough metallurgical evaluation, including intergranular attack and chemical depletion, was done for surface preparation procedures under consideration.

In the fourth task, the results of the preceeding tasks were critically examined to suggest final modifications or changes to the surface preparation procedures.

During the fifth task, the effectiveness of optimized surface preparation procedures developed by Tasks 1 through 4 was demonstrated. The demonstration was conducted on AFWAL-furnished specimens with modified surface preparations. The inspections were performed in an overhaul facility environment at P&WA/GPD assembly floor FPI facility.

SIMULATED ENGINE ENVIRONMENT CONTAMINATION

AFWAL-furnished crack specimens were heated in aircraft engine lubricant (PWA specification 521, MIL-L-7808) fumes, and temperature cycled between room temperature and 600°F to subject the specimens to simulated engine environment, and to contaminate surfaces of the specimens and cracks. These conditions caused possibly the worst contamination to be encountered on engine components during engine overhaul cleaning and inspection (Figures 15 and 16).

Fatigue crack specimens were subjected to different state-of-the-art chemical cleaning procedures to determine the effectiveness of these procedures. Whenever FPI was performed, specimens were thoroughly cleaned after FPI using ultrasonic solvent cleaning to remove residual penetrant materials from the previous inspections.

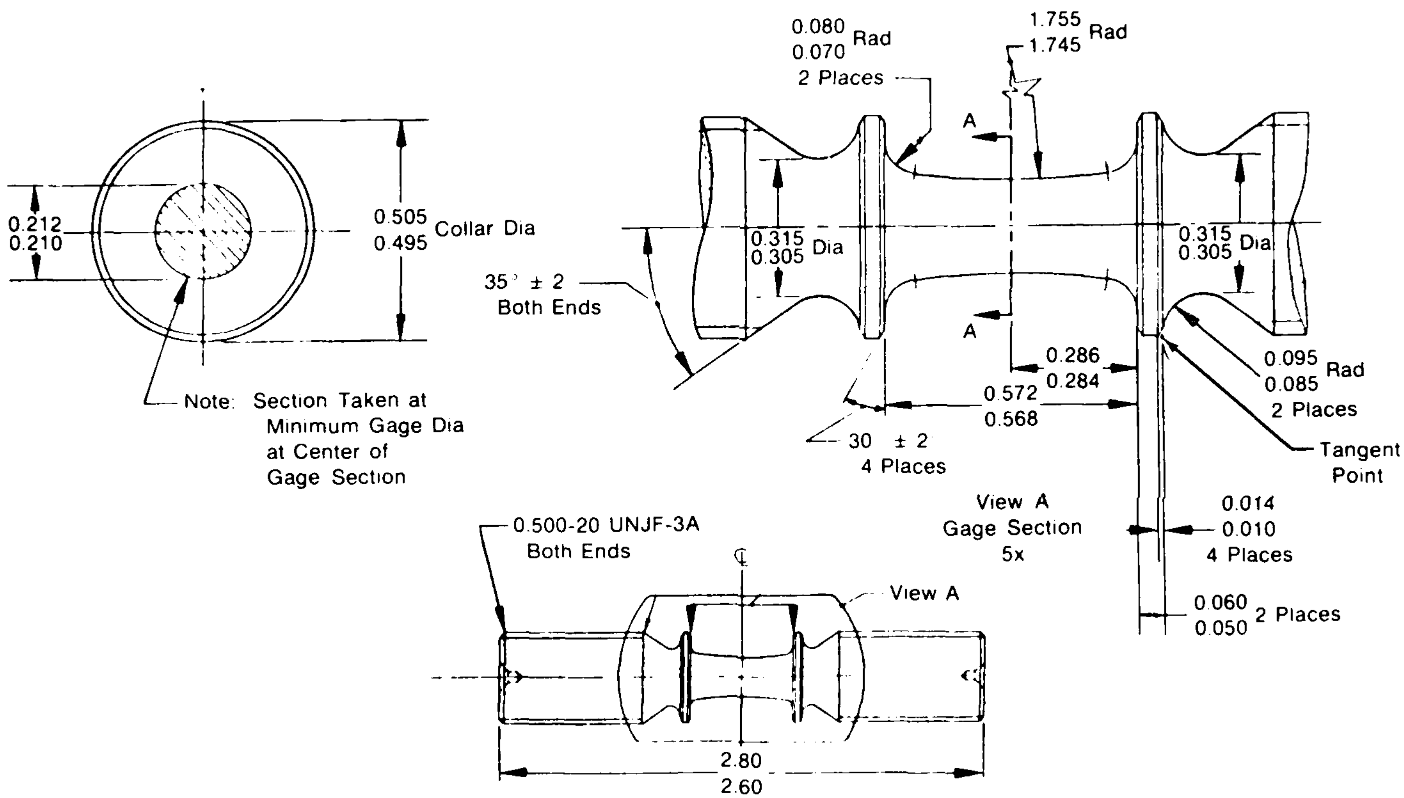
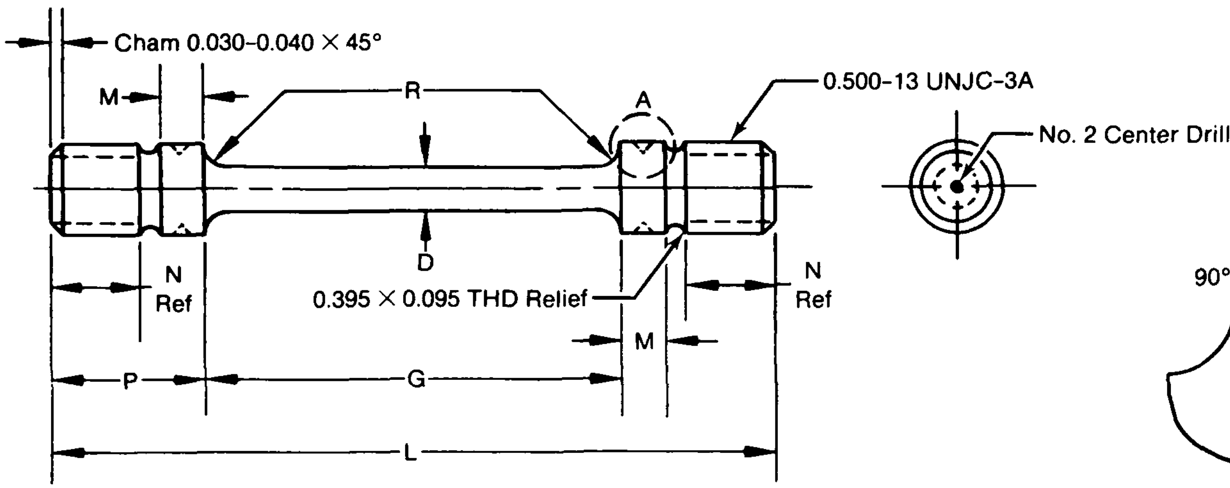
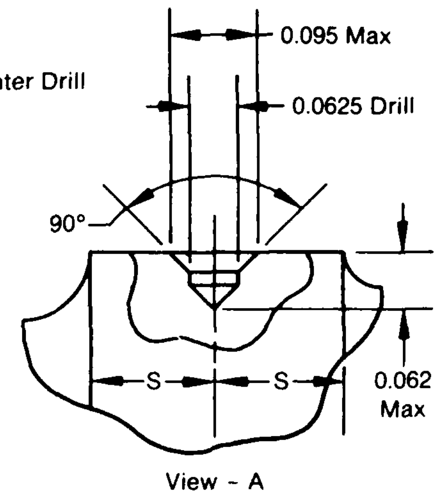


Figure 13. Strain-Controlled Low-Cycle Fatigue Specimen





Drill and C'SK 2 Holes 180° Apart Both Ends

Radial Alignment ± 00° 30′
Axial Alignment ± 0.0015

Notes

1. All Dim. in Inches
2. Tolerance ±0.010 Unless Noted
3. All Dia To Be Conc to Within 0.0005 FIR
4. Reduced Section To Be 16 ± 3 Microinch AA Grind Finish Using 320 Grit Wheel. Not To Be Polished.
5. Identification Markings Permitted Only on Specimen Ends.

Spec No.	± 0.0005 D	G	L	M	N	P	R	S
1	0.252	2.250	3.940	0.250	0.500	0.845	0.125	0.125

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Figure 14. Creep-Rupture Specimen

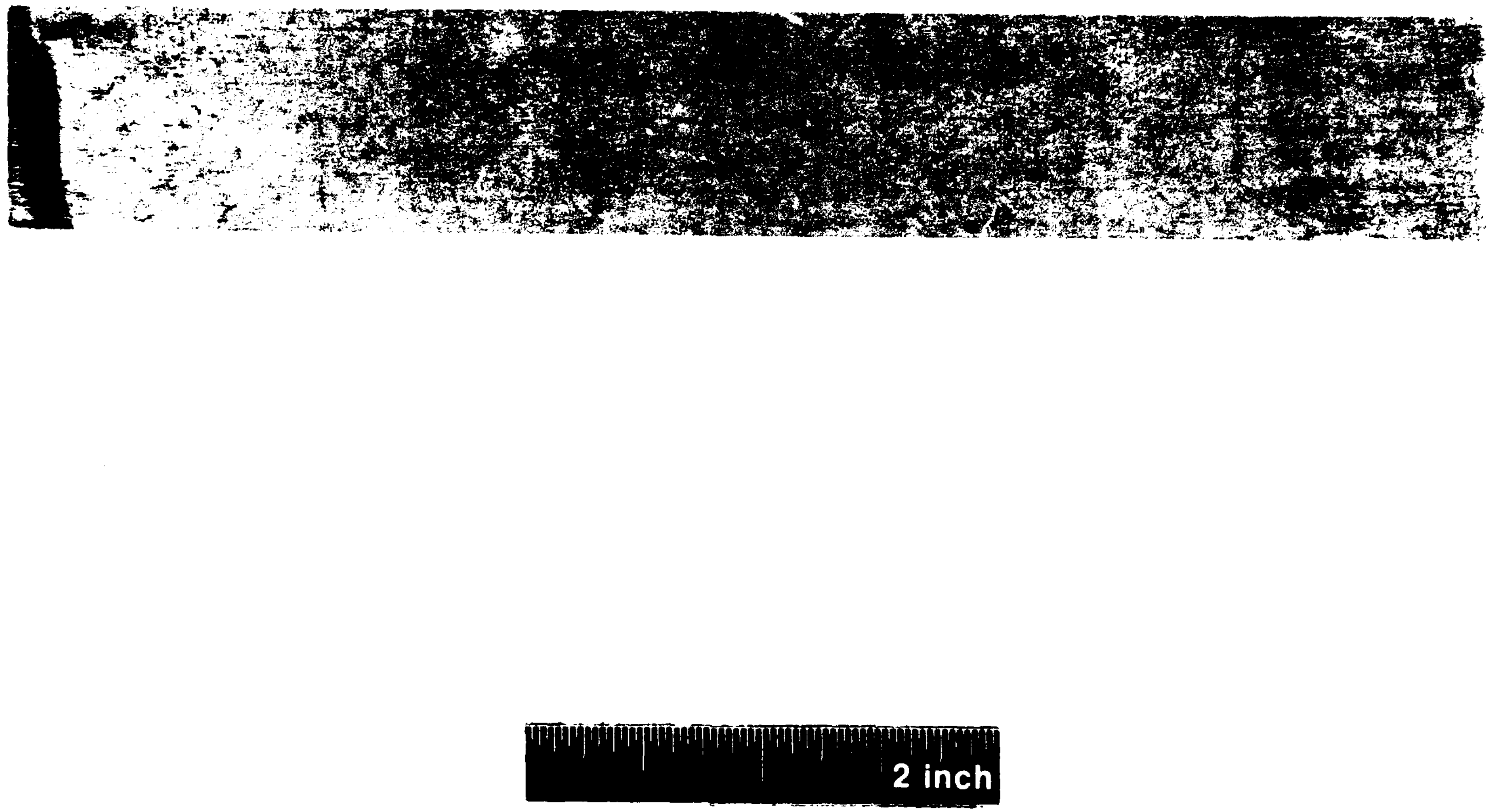
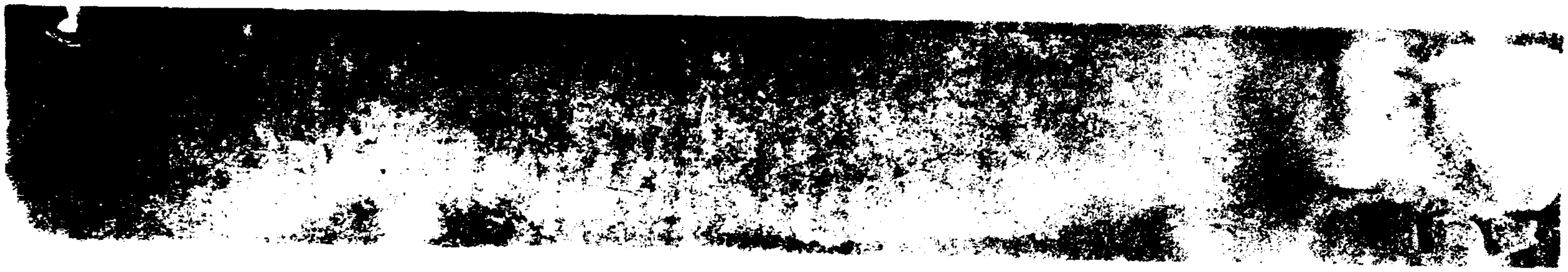


Figure 15. AFWAL Fatigue Crack Specimen No. 16 As-Received



[illegible] Simulated Engine Environment

INVESTIGATION OF SURFACE PREPARATION PROCEDURES

Current cleaning procedures used at various overhaul facilities, and modifications to these procedures, were investigated for their effectiveness as surface preparation procedures for FPI. These cleaning procedures consisted of both mechanical and chemical procedures. The mechanical procedures included mild vapor blasting and abrasive grit blasting. The mechanical procedures were evaluated on Inconel 718 and Ti-6Al-4V coupon samples as well as some Ti-6Al-2Sn-4Zr-6Mo fatigue crack bar specimens. Surface roughness and metal smear caused by grit blasting reduced FPI capability due to excessive background fluorescence and reduction in the penetrating power and subsequent bleed-out of entrapped penetrant from the cracks. Light vapor blasting, 30 sec, 40.6 to 45.7 cm (16 to 18 in.), 6.89×10^5 Pa (100 psi), did not cause any degradation in FPI capability. In fact, it seemed to enhance crack indications through reduced background fluorescence and increased definition of the cracks. Figure 17 compares the surface roughness of vapor blasted and grit blasted Ti-6Al-4V surfaces.

Chemical cleaning procedures investigated included alkaline cleaning solutions of different types and strengths, alkaline permanganate solutions, carbon solvents and carbon removers, acid descaling solutions, chromic and phosphoric acid solutions, inhibited phosphoric acid solution, vapor degreasing and cold solvents (MEK, trichloroethane). These cleaning procedures were used on coupon samples and/or contaminated fatigue-crack specimens. The chemical cleaning procedures tested were all effective to a limited extent when properly applied. However, none of these procedures completely removed all of the simulated engine contamination, but enough contamination was removed to prevent large-scale background fluorescence during most FPI. For those cases where chemical cleaning procedures were not effective enough, a light vapor blast following chemical cleaning reduced the level of background fluorescence during FPI. However, for maximum FPI effectiveness, a chem milling (nonselective) etch procedure was conducted after vapor blast. It is recommended that in any case where vapor blast may be applied heavily enough to cause metal smearing that the chem milling procedure be used before FPI.

During this investigation it was also determined that some of the cleaning procedures may be degrading the components through selective etch. For example, a chromic and phosphoric acid cleaning procedure is recommended by TO (Reference 5) for both nickel and titanium alloys. The solution was used on polished coupon samples of Ti-6Al-4V and Inconel 718. Evidence of etching of a Ti-6Al-4V sample was observed after immediate rinsing with hot water following the cleaning procedure (Figure 18). In the case of Inconel 718, a very interesting phenomenon was observed. After dip and spray rinsing with hot water following chromic-phosphoric acid cleaning, the Inconel 718 sample surface did not show any change. But after 12 to 18 hr of hold time following the cleaning and rinsing procedure, the surface exhibited selective grain boundary attack (Figure 19). Such selective etching, as a result of current chemical cleaning procedures, could possibly degrade material performance of the engine components, particularly LCF and creep properties. On further investigation it was found that it is chromic acid which causes etching of both Inconel 718 and Ti-6Al-4V. Fortunately, it was found that if the chromic and phosphoric acid cleaning procedure was followed by an alkaline cleaning procedure before rinsing with hot water, the delayed etching on Inconel 718 can be avoided. This is encouraging, since the chromic-phosphoric acid cleaning procedure is remarkably efficient in removing contamination from metal surfaces.

Surface After Vapor Blasting
(Shows Uniform Deformation of Metal Surface)

Surface After Grit Blasting
(Shows Uneven and Deeper Deformation of Metal Surface)

*Figure 17 Effects of Vapor Blasting [illegible]
Polished Surface (Cross Section [illegible])*

Polished Surface Before Cleaning

Surface Immediately After Chromic and Phosphoric Acid Cleaning and Rinsing with Hot Water

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Figure 18. Effect of Chromic-Phosphoric Acid Cleaning on Ti-6Al-4V

Surface Immediately After Cleaning and Rinsing

Surface After 18 hr of Hold Time Following Cleaning and Rinsing (Exhibits Intergranular Attack

Figure 19 Effect of Chromic Phosphoric [illegible]

CHEM-MILLING ETCH EVALUATION

Chemical cleaning procedures are generally not adequate to completely remove surface contaminants from engine components prior to FPI. Mechanical cleaning in conjunction with chemical cleaning can clean the surfaces effectively, but such procedures may close the cracks or surface discontinuities because of metal smear. Therefore, an extensive etch development and evaluation program was undertaken to suggest suitable chem-milling type etches for the enhancement of FPI capability.

A nitric and hydrofluoric acid etch was chosen for Ti-6Al-4V. Many variations of this etch are used in industry for chem-milling etch of titanium alloys. So instead of developing a new etch, a composition of nitric-hydrofluoric etch was chosen which would give a reasonable rate of metal removal without causing selective etch. The composition of this etch is given in Table 5. The effect of this etch on LCF and creep properties of Ti-6Al-4V is discussed later.

Suitable chem-milling etches were developed for Inconel 718 by detailed investigation of various combinations and concentrations of acids and salts. Metal removal and intergranular attack was used as criteria for initial evaluation. Microprobe analysis was then used to compare chemistry of the chemically etched surface to the chemistry of nonetched surface of a sample. Over 24 different solutions were investigated. Out of these, two (No. 21 and No. 9B) were chosen as most satisfactory based on metal removal, IGA, and selective metal depletion.

The compositions of these two etches are given in Table 5. Both the etches will qualify as good etches on the basis of generally accepted criteria for etch development. But in this program, additional criteria of low-cycle fatigue and creep-rupture evaluations were used to finally determine suitability of etch. According to these criteria, it had to be demonstrated that the use of the finally selected etch will not degrade LCF and creep properties at typical operating conditions. The results of these evaluations are discussed next.

Effect of Chem-Mill Etches on LCF and Creep

Test conditions used to compare strain-controlled LCF life of baseline (nonetched) and etched materials are listed in Table 6. All LCF specimens were vibratory finished (Sutton-barrel). For each material, three specimens were tested with this surface finish for a baseline, while the other three were etched before testing to compare the effect of etching. Only etched specimens were tested for creep at conditions listed in Table 7. The results of creep testing were then compared to baseline properties available in open literature and material specifications.

The results of LCF and creep testing are summarized in Tables 8 through 12. It is apparent that the initially selected etch for Inconel 718 (solution No. 21) degrades LCF life of Inconel 718 by about 50% at 1000°F (538°C) and strain-range of 1.25%. Therefore, solution No. 9B was chosen as an alternate. Solution No. 9B does not appear to degrade LCF and creep life (Tables 8 and 12). Preliminary results indicate that the adverse effect of solution No. 21 etch on LCF properties of Inconel 718 may be due to selective etching of a vibratory-finished surface by this solution. There is no degradation in LCF and creep life of Ti-6Al-4V due to nitric-hydrofluoric etch.

TABLE 5. CHEM-MILL ETCH COMPOSITIONS

Ti-6Al-4V Etch:

HNO_3	HF	H_2O	*Temperature*
35%	3.5%	61.5%	Room Temperature

Inconel 718 Chem-Mill Etch:

Solution No. 21

HCl	HNO_3	H_3PO_4	H_2O	$FeCl_3$	$CuSO_4$	$NaNO_3$	*Temperature*
35%	3%	5%	57%	20g/gal (5.28g/l)	36g/gal (9.51g/l)	10g/gal (2.64g/l)	130°F (54.4°C)

Solution No. 9B

HCl	HNO_3	H_2O	$FeCl_3$	$CuSO_4$	*Temperature*
45%	5%	50%	20g/gal (5.28g/l)	36g/gal (9.51g/l)	130°F (54.4°C)

TABLE 6. STRAIN-CONTROLLED LCF TEST CONDITIONS

Material	*Temperature*	*Strain-Range*	*Mean Strain*	*Frequency cpm*	*Heat-Treat Condition*
Ti-6Al-4V	Room Temperature	1.25	0.625	20	SP
Inconel 718	1000°F (538°C)	1.25	0.625	20	SP

SP = Solution Treated and Precipitation Hardened

TABLE 7. CREEP TEST CONDITIONS

Material	*Temperature*	*Stress*	*Heat-Treat Condition*
Ti-6Al-4V	600°F (316°C)	117 ksi (806 MPa)	SP
Inconel 718	1200°F (649°C)	100 ksi (689 MPa)	SP

SP = Solution Treated and Precipitation Hardened

TABLE 8. STRAIN-CONTROLLED LCF TEST RESULTS FOR INCONEL 718

	Specimen	*Cycles to Failure*
Baseline	398	3406
	399	3047
	400	3070
Etched with Solution No. 21 15 minutes at 130°F (54°C)	422	1883
	423	1776
	424	1577
Etched with Solution No. 9B 15 minutes at 130°F (54°C)	425	3980
	426	4016
	427	4625

TABLE 9. STRAIN-CONTROLLED LCF TEST RESULTS FOR Ti-6Al-4V

	Specimen	Cycles to Failure
	410	12,826
Baseline	385	13,555
	376	11,948
Nitric-Hydrofluoric Etch for 15 min at Room Temperature	431	8,256
	432	14,044
	433	16,291

TABLE 10. EFFECT OF CHEM-MILL (SOLUTION NO. 21) ON CREEP CAPABILITY OF INCONEL 718

Stress: 100 ksi (689 MPa) *Temp: 1200°F (649°C)*

Specimen No.	*Hours to Failure*
416	165
417	197
418	152.4

Minimum Hours to Rupture per AMS 5663 is 23 hr.

TABLE 11. EFFECT OF NITRIC HYDROFLUORIC ETCH ON CREEP CAPABILITY OF Ti-6Al-4V

Stress: 117 ksi (806 MPa) *Temp: 600°F (316°C)*

Specimen No.	*Hours*	*Creep*
419	40[illegible]*	0.[illegible]
420	40[illegible]*	[illegible]
421	40[illegible]*	[illegible]

*Tests discontinued because lives far exceeded the expected life

TABLE 12. EFFECT OF CHEM-MILL (SOLUTION NO. 9B) ON CREEP CAPABILITY OF INCONEL 718

Sress: 100 ksi (689 MPa) *Temp: 1200°F (649°C)*

Specimen No.	*Hours to Failure*
435	152.1
436	141.5
437	149.5

Minimum hours to rupture per AMS 5663 is 23 hr.

SECTION IV

PHASE II: FPI PROCESS VARIABLES

During Phase II of the program, FPI process variables other than surface preparation procedures were investigated. Figure 1 includes the technical approach for this phase.

Important FPI process variables are discussed briefly (References 3, 4, and 6).

1. Penetrant Selection -- Selection of penetrant for inspection of a component depends mainly on criticality of the part, sensitivity desired, condition of the surface to be examined, and the cost of inspection. Other factors involved in selection of penetrants are size, shape, and number of parts to be inspected, accessibility of inspection surfaces, and type of facilities and equipment available for the inspection. The following is a list of three general types of fluorescent penetrants, in order of decreasing cost and decreasing sensitivity:

1. Postemulsifiable
2. Solvent-removable
3. Water-washable.

Within each of these three types, there are different sensitivity penetrants available. Air Force Specification MIL-I-25135C classifies fluorescent penetrants in four sensitivity groups described below:

Group IV	Water-washable fluorescent penetrant and a dry, wet, or nonaqueous wet developer.
Group V	Postemulsifiable fluorescent penetrant, an emulsifier, and a dry, wet, or nonaqueous wet developer.
Group VI	High sensitivity, postemulsifiable fluorescent penetrant, an emulsifier, and a dry, wet, or nonaqueous wet developer.
Group VII	Aerosol cans of Group VI solvent removable fluorescent penetrant, cleaning remover, and a nonaqueous wet developer.

2. Method of Applying Penetrant The main methods of applying penetrant are brushing, dipping, and spraying. The method to be used depends on size and type of the part to be inspected, inspection environment, and type of inspection equipment available. Whatever method of application to be used, it is essential to thoroughly wet the area of the part to be inspected.

3. Penetrant Dwell Time The time required for optimum penetration is usually determined experimentally or by past experience. The normal dwell time is from 2 to 30 min. Longer penetration time is preferable for fatigue cracks or service-induced flaws, provided the penetrant does not dry on the surface of the inspection part.

4. Temperature of the Part/Penetrant Maximum temperature of the inspected part, according to most references and specifications, is restricted to 100 to 125°F (38 to 52°C) for FPI. Recent research, however, indicates that 100 to 125°F temperature limit on conventional fluorescent penetrants (conforming to MIL-I-23135C) is too restrictive and that temperatures as high as 200°F (93°C) may be used in many cases without any adverse effects. Temperature limits of 100 to 125°F (38 to 52°C) is justified because most of the penetrants presently in use are not stable for high temperature application (creating washability problems). Research work is continuing for development of high sensitivity, high temperature penetrants (Reference 8). Ability to use higher temperatures may enhance FPI reliability and sensitivity.

5. Excess Penetrant Removal – Penetrant removal is considered to be the most important step in the processing of parts for inspection. Tight control of the various parameters must be maintained to assure reliable results. Overwashing of parts will remove the penetrant from the discontinuities while underwashing will result in too much background fluorescence and mask real indications. Water temperature and pressures should be controlled for best results. For postemulsifiable penetrants, emulsification times depend on type of penetrant and emulsifier used, the type of surface under inspection, the level of sensitivity desired, and the type of rinse used. For solvent removable penetrants, amount and method of solvent use should be controlled.

One of the important improvements for postemulsifiable penetrants in aircraft engine inspection facilities is the use of hydrophilic emulsifiers in place of lipophilic emulsifiers. Hydrophilic emulsifiers are more efficient, more tolerant to process variables, and cost-effective. They also cause no corrosive effects as a result of residual emulsifier remaining on the components. Recent improvements in water-washable penetrants indicate their suitability for some engine components in overhaul facilities.

6. Drying – Parts must be thoroughly dried before developer is applied. Drying temperature and time should be chosen such that there is no degradation of penetrant. A clean blast of air can also be used for drying purposes.

7. Application of Developer – The developer action is considered to be a combination of solvency, adsorption, and absorption effects drawing residual penetrant to the surface from the discontinuities. Developer also provides contrast for brighter indications. Dry, wet, nonaqueous wet, and film type developers are in common use. Selection of developer plays a very important role in the sensitivity and reliability of inspection. Selection depends on the type and size of parts, surface condition, geometry of the parts, location of flaws and the type of facilities. Optimum developer parameters can be determined only by experiment and past experiences.

The method of applying developer should also be carefully selected. The developer must completely cover all areas of the parts to be inspected, yet excessive coating must be avoided to prevent masking of indications. Developer time must be adequate before inspecting the part.

8. Black Light Intensity – The black light used in fluorescent penetrant inspection peaks at 3650 Angstrom units. Recommended intensity level is 200 ft-c at 12 in. (0.3048M). Background white light should be minimized for highest sensitivity. Black light intensity levels and allowable white light can be relaxed in many inspection situations.

9. Inspector – The inspector is one of the most important factors in assuring a reliable inspection. Inspection quality is no better than the ability of the inspector to find indications and interpret them. Qualification, interest, and awareness of importance of his decision are some of the qualities of an inspector which directly influence his ability. The conditions under which an operator works also affect his ability. There has been recent effort to automate FPI, unfortunately, the human factors of FPI currently cannot be replaced by automation and one has to fully appreciate operator variability of FPI.

FPI IN OVERHAUL FACILITIES

The method of FPI in overhaul facilities is similar to a production environment. The method essentially consists of applying penetrant on the components, and after the penetrant has had time to enter the discontinuities, the excess penetrant is removed, the part goes through a drying process, and then developer is applied to the surface. The penetrant which had been entrapped in the discontinuity is drawn to the surface by the developer and produces characteristic indications which are examined by an inspector.

For over a decade semiautomated penetrant inspection systems have been in use in overhaul facilities. Usually these systems consist of several in-line stations with engine components being transported from station to station by mechanical handling systems. The stations may consist of:

1. Drying to remove any moisture away from the parts

2. Soak in a temperature controlled penetrant tank (varying dwell time is generally used depending on components)

3. Prerinse station to remove some excess penetrant

4. Controlled time dipping in an emulsifier tank

5. Rinse station, usually consisting of water spray

6. Air circulating controlled temperature drying oven

7. Developer station

8. Developer drying station if a wet developer is used

9. Black light inspection booth.

These semiautomated facilities, when properly planned and set up, should provide uniform processing for the same type of components as required in inspection procedures. These units are preferred to hand-processing units, but a small hand-processing unit is always coexistent with semiautomated units to handle small parts and specialized nonroutine inspection items.

Stress-enhanced or wink FPI is sometimes used on selected suitable components. The method was introduced for increased sensitivity and reliability for detecting tight fatigue cracks or cracks filled with contaminants to increase penetrant flaw entrapment efficiency. Unfortunately, often this method is not properly applied or is not considered for fear of the time factor involved in stress-enhanced inspection. Recent work under AFWAL sponsorship has demonstrated that significant improvements in sensitivity and reliability of FPI can be achieved by new advanced stress-enhanced FPI procedures (Reference 7). There has been no study conducted to compare the time and cost factors involved in stress-enhanced FPI vs focused eddy current inspection. In some instances stress-enhanced FPI may be more suitable and capable than other inspections. Also, as a complementary inspection to other inspections such as eddy current, stress-enhanced FPI may increase reliability of the overall inspection and decrease the time involved in evaluating false indications.

Even though the FPI procedure is basically the same for manufacturing and overhaul inspection, the capabilities may vary vastly. The main reasons for lower sensitivity and reliability of overhaul inspection are: (1) poor surface condition of components (nicks, dings, deep scratchs, etc.), (2) contaminants such as carbonized oils, oxide films, corrosion, and paint on the surface or in the discontinuities, (3) abrasive cleaning procedures used to clean the parts, (4) compressive stresses on the surface of the component, (5) poor process-variable control, and (6) human factors like variability of training, experience, and job interest.

TECHNICAL APPROACH

The objective of Phase II was to evaluate and optimize FPI process variables as they relate to aircraft engine overhaul facilities. The results of Phase I and Phase II can lead to improvements in the state-of-the-art FPI capability of these facilities.

The first task in Phase II investigation was to define and identify important FPI process variables which significantly influence sensitivity and reliability of FPI in aircraft engine maintenance facilities. As shown previously in Figure 1, this task was accomplished by direct input from and interface with such facilities.

The second task of this phase was to investigate the effects of various process variables on FPI capability of typical aircraft engine maintenance facilities. The goal of this task was to develop improvements and enhancement which may be utilized in aircraft engine maintenance facilities

The third task evaluated the results of Tasks 1 and 2. These tasks were critically examined to suggest final modifications, improvements, and enhancement techniques to the current FPI practices of typical aircraft engine maintenance facilities.

The final task of Phase II was to conduct a demonstration program using the surface preparation procedures developed in Phase I and optimum process variables developed during Phase II. The inspection of specimens was done in an engine maintenance inspection environment at the P&WA/GPD assembly floor FPI facility.

EXPERIMENTAL METHODS (PHASE II)

During investigation of process variables, only one process parameter was varied at a time, all others were held constant. Before any inspections were performed on AFWAL-furnished specimens, the specimens were ultrasonically cleaned for 2 hr to remove any foreign material and residual penetrant materials from previous inspections. The Ti-6Al-4V specimens were cleaned using methyl ethyl ketone (MEK) as solvent, but the Inconel 718 specimens were cleaned in trichloroethane. After cleaning, the specimens were allowed to dry before the penetrant was applied directly on them and allowed a 30 min dwell unless otherwise determined. During emulsification, the specimens were immersed in a beaker containing hydrophilic emulsifier solution. An automatic stirrer was used to provide good agitation of emulsifier around the specimens. The standard emulsification time of 2 min was generally used unless this time was deliberately varied to investigate this parameter. The specimens were washed with water after emulsification. The specimens were checked under black light to ensure that all the excess penetrant had been removed. Excess water was removed by 30 to 60 sec application of dry air before a wet soluble developer was applied. If dry developer was used, the drying operation was done before the application of developer. After developing for 8 to 10 minutes the inspections for cracks were done under a black light. The general experimental procedure is outlined in Figure 20. FPI process variables investigated in Phase II are summarized in Table 13.

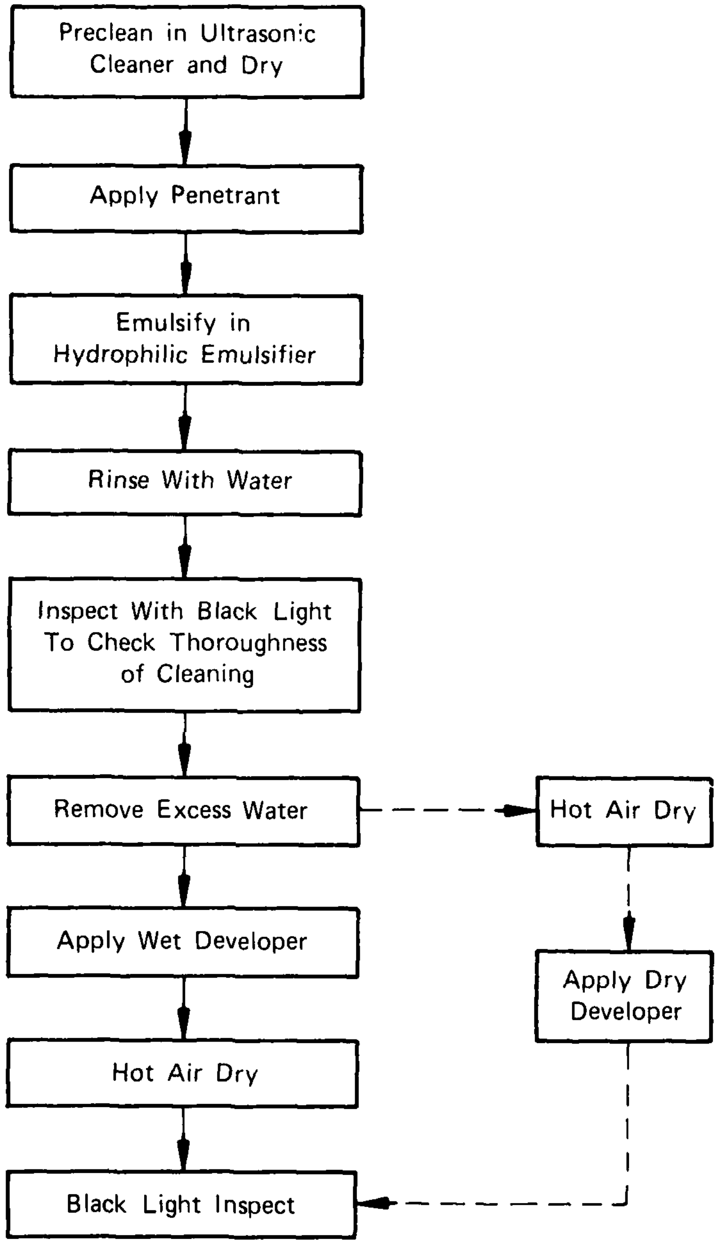


Figure 20. Fluorescent Penetrant Inspection Procedure

TABLE 13. PHASE II — FPI PROCESS VARIABLES

Process Variables	*Values*
Penetrant Dwell Time	5 min, 15 min, 30 min, 45 min
Pre-Emulsification Wash	Wash, No Wash
Emulsifier Dwell Time	½ min, 1 min, 1½ min, 2 min, 3 min
Emulsifier Concentration	15%, 25%, 33%, 45%
Developer Type	Wet, Dry
Wet Developer Concentration	4 oz/gal, 8 oz/gal, 12 oz/gal
Developer Dwell Time	5 min, 10 min, 20 min
Stress Enhancement Stress	Less than 30% of yield (Reference 7)

TEST RESULTS (PHASE II)

As discussed previously, the important FPI process variables chosen for Phase II investigation were penetrant dwell time, prewash with water before emulsification, emulsification time, emulsifier concentration, developer type, and development time. Penetrant dwell times of 5, 15, 30, and 45 min were chosen to determine optimum dwell time. The 30-min penetrant dwell time provided best sensitivity without any potential of penetrant removal problems. The results of penetrant dwell time investigation are summarized in Tables 14 and 15. Prewash or prerinse with water before emulsification did not result in any increase in sensitivity of flaw detection, but did reduce emulsification requirements. A prewash is also supposed to minimize the contamination of emulsifier by penetrant. Emulsification times of ½, 1, 1½, 2, and 3 min were used to determine optimum time of emulsification. Tables 16 and 17 summarize the effects of emulsification time on FPI of Inconel 718 and Ti-6Al-4V, respectively. Emulsification time of 1½ to 2 min gave optimum inspection results. Emulsifier (Magnaflux ZR-10) concentration was varied at 15, 25, 33, and 45% levels. The effects of emulsification concentration on FPI capability of both Inconel 718 and Ti-6Al-4V are summarized in Tables 18 and 19, respectively. A 33% concentration of ZR-10 emulsifier appeared to provide best results. Wet and dry developers were evaluated for their effectiveness on FPI capability. The results of this evaluation are summarized in Table 20. Wet soluble developer provided much higher sensitivity and less background fluorescence compared to dry developer. Wet soluble developer concentration was varied in a separate investigation. The results of this experiment are summarized in Table 21 with the 8 oz/gal concentration providing the best combination of sensitivity and background fluorescence. Stress-enhancement provided much better sensitivity and reliability compared to standard FPI. Results of stress-enhanced FPI are summarized in Table 22. Stress-enhancement fixture is shown in Figure 21.

TABLE 14. EFFECT OF PENETRANT DWELL TIME ON INCONEL 718

Dwell Time	*No. of Indications*
5 min	6 Light 1 Medium 0 Bright 3 No Indication
15 min	5 Light 3 Medium 1 Bright 1 No Indication
30 min	5 Light 2 Medium 1 Bright 2 No Indication
45 min	4 Light 3 Medium 1 Bright 2 No Indication
	Total: 10 Cracked Specimens

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)

Penetrant — ZL-35

Emulsifier — ZR-10 (Hydrophilic) 2 min Dwell — 33% concentration

Developer — ZP-13A (Wet)

Dry-Hot Air — 30 to 60 sec

TABLE 15. EFFECT OF PENETRANT DWELL TIME ON Ti-6Al-4V

Dwell Time	*No. of Indications*
5 min	4 Light 0 Medium 2 Bright 5 No Indication
15 min	3 Light 2 Medium 2 Bright 4 No Indication
30 min	5 Light 2 Medium 2 Bright 2 No Indication
45 min	5 Light 2 Medium 2 Bright 2 No Indication
	Total: 10 Cracked Specimens

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)

Penetrant — ZL-35

Emulsifier — ZR-10 (Hydrophilic) 2 min Dwell — 33% concentration

Developer — ZP-13A (Wet)

Dry-Hot Air — 30 to 60 sec

TABLE 16. EFFECT OF EMULSIFICATION TIME ON INCONEL 718

Dwell Time	*No. of Indications*
½ min	3 Light 0 Medium 0 Bright 7 No Indication
1 min	8 Light 1 Medium 0 Bright 1 No Indication
1½ min	6 Light 2 Medium 1 Bright 1 No Indication
2 min	5 Light 2 Medium 1 Bright 2 No Indication
3 min	4 Light 1 Medium 1 Bright 4 No Indication

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)
Penetrant — ZL-35 — 30 min
Emulsifier — ZR-10 (Hydrophilic) — 33%
Developer — ZP-13A (Wet)
Dry-Hot Air — 30 to 60 sec

TABLE 17. EFFECT OF EMULSIFICATION TIME ON TITANIUM 6Al-4V

Dwell Time	*No. of Indications*
½ min	3 Light 2 Medium 2 Bright 3 No Indication
1 min	4 Light 1 Medium 2 Bright 4 No Indication
1½ min	4 Light 0 Medium 4 Bright 3 No Indication
2 min	3 Light 1 Medium 2 Bright 5 No Indication
3 min	4 Light 1 Medium 2 Bright 4 No Indication
	Total: 10 Cracked Specimens

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)
Penetrant — ZL-35 — 30 min
Emulsifier — ZR-10 — 2 min
Developer — ZP-13A (Wet)
Dry-Hot Air — 30 to 60 sec

TABLE 18. EFFECT OF EMULSIFIER CONCENTRATION ON INCONEL 718

Concentration	*No. of Indications*
15%	3 Light 0 Medium 1 Bright 6 No Indication
25%	7 Light 0 Medium 1 Bright 2 No Indication
33%	5 Light 2 Medium 1 Bright 2 No Indication
45%	6 Light 0 Medium 1 Bright 3 No Indication
	Total: 10 Cracked Specimens

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)
Penetrant — ZL-35 — 30 min
Emulsifier — ZR-10 (Hydrophilic) — 2 min
Developer — ZP-13A
Dry-Hot Air — 30 to 60 sec

TABLE 19. EFFECT OF EMULSIFIER CONCENTRATION ON Ti-6Al-4V

Concentration	*No. of Indications*
15%	3 Light 1 Medium 1 Bright 6 No Indication
25%	4 Light 0 Medium 2 Bright 5 No Indication
33%	3 Light 1 Medium 2 Bright 5 No Indication
45%	3 Light 1 Medium 2 Bright 5 No Indication
	Total: 10 Cracked Specimens

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)
Penetrant — ZL-35 — 30 min
Emulsifier — ZR-10 (Hydrophilic) — 2 min
Developer — ZP-13A (Wet)

TABLE 20. EFFECT OF WET VS DRY DEVELOPER USING INCONEL 718 AND Ti-6Al-4V

Developer	*No. of Indications*	*Comments*
ZP-4B Dry Developer	3 Light	
Inconel 718	1 Medium	Too much background
	3 Bright	
	3 No Indication	
ZP-13A Wet Developer	6 Light	
Inconel 718	1 Medium	Minimal background
	2 Bright	
	1 No Indication	
Titanium (6Al-4V)		
ZP-4B Dry Developer	4 Light	
Ti-6Al-4V	0 Medium	Too much background
	3 Bright	
	4 No Indication	
ZP-13A Wet Developer	7 Light	
Ti-6Al-4V	1 Medium	*Minimal background*
	3 Bright	
	0 No Indication	
	Total: 10 Cracked Specimens	

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)
Penetrant — ZL-35 — 30 min
Emulsifier — ZR-10 (Hydrophilic) — 2 min

TABLE 21. EFFECT OF WET DEVELOPER CONCENTRATION USING INCONEL 718 AND Ti-6Al-4V

Concentration	*No. of Indications*
ZP-13A 4 oz/gal	
Inconel 718	6 Light 0 Medium 1 Bright 3 No Indication
Ti-6Al-4V	2 Light 1 Medium 2 Bright 6 No Indication
ZP-13A 8 oz/gal	
Inconel 718	5 Light 1 Medium 1 Bright 3 No Indication
Ti-6Al-4V	5 Light 1 Medium 2 Bright 3 No Indication
ZP-13A 12 oz/gal	
Inconel 718	7 Light 0 Medium 1 Bright 2 No Indication*
Ti-6Al-4V	3 Light 2 Medium 2 Bright 4 No Indication

Other Parameters: (MIL-I-25135C, Group VI Penetrant Materials)

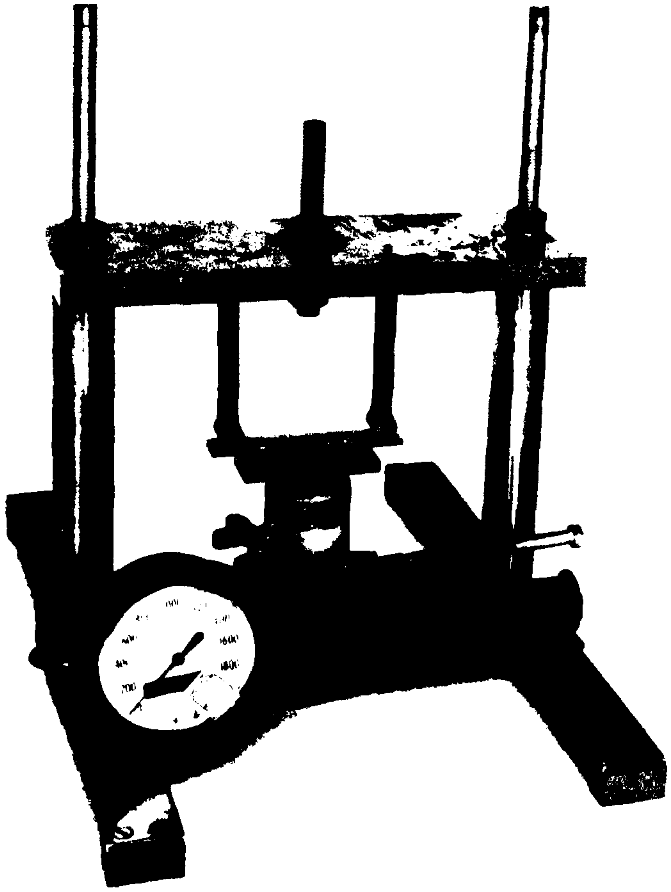
Penetrant — ZL-35 — 30 min

Emulsifier — ZR-10 (Hydrophilic)

*Excessive Background

TABLE 22. EFFECT OF STRESS-ENHANCEMENT ON FPI CAPABILITY

Material	*No. of Indications*
Inconel 718	3 Light 2 Medium 5 Bright
Ti-6Al-4V	6 Light 4 Bright



FAC 6934

Figure 21 Stress-Enhancement Fixture for AFWAL Furnished Specimens

SECTION V

DEMONSTRATION PROGRAMS

The objective of this portion of the contract was to develop implementable method improvements for overhaul fluorescent penetrant inspection of turbine engine components. Phase I of the program developed surface preparation procedures, and Phase II optimized other FPI process variables for improved FPI capability. Three demonstration programs were conducted in order to show these improvements. FPI for these demonstrations was done on AFWAL-furnished fatigue crack specimens in an inspection environment representative of engine overhaul FPI. The three demonstration programs used the P&WA/GPD assembly floor FPI facility for:

1. Baseline demonstration using current surface preparation and FPI procedures for typical Ti-6Al-4V and Inconel 718 rotating components of gas turbine engines. Test conditions are summarized in Table 23.

2. Demonstration using surface preparation procedures developed in Phase I of this program for these materials with test conditions summarized in Table 24.

3. Demonstration using FPI process variables optimized in Phase II of the program with the test conditions summarized in Table 25.

TABLE 23. BASELINE DEMONSTRATION PARAMETERS

1. *Surface Preparation Procedures* (On contaminated specimens)	
Inconel-718	Vapor degrease, carbon remover soak (PC-111) at 130 to 140°F (54 to 60°C) and hot water rinse (two times), light vapor blast, vapor degrease (Reference 8)
Ti-6Al-4V	Soak specimens in alkaline rust remover at 180 to 190°F (82 to 88°C) for 5 min, light vapor blast (Reference 9)
2. *Penetrant* Group VI* Magnaflux ZL-30	30 min dwell
3. *Emulsifier* Group VI Magnaflux ZE-4A lipophilic emulsifier	1½ min dwell
4. *Rinse* in water	
5. *Dry* in hot oven	
6. *Dry Developer* Group VI Magnaflux ZP-4B	8 to 10 min dwell

*All group classifications to MIL-I-25135C

TABLE 24. PHASE I DEMONSTRATION PARAMETERS

1.	*Surface Preparation Procedures*	
	Inconel 718	Vapor blasting and etching with No. 9B etch at 130°F for 2 min
	Ti-6Al-4V	Vapor blasting and etching with nitric-hydrofluoric etch at room temperature for 3 min
2.	*Penetrant*	30 min dwell
	Group VI*	
	Magnaflux ZL-30	
3.	*Emulsifier*	1½ min dwell
	Group VI	
	Magnaflux ZE-4A lipophilic emulsifier	
4.	*Rinse* in water	
5.	*Dry* in hot oven	
6.	*Dry Developer*	8 to 10 min dwell
	Group VI	
	Magnaflux ZP-4B	

*All group classifications to MIL-I-25135C

TABLE 25. PHASE II DEMONSTRATION PARAMETERS

1.	*Penetrant*	30 min dwell
	Group VI*	
	Magnaflux ZL-30	
2.	*Emulsifier*	2 min dwell
	Group VI	
	(33% concentration	
	Magnaflux ZR-10A	
	hydrophilic emulsifier)	
3.	*Rinse* in water	
4.	*Wet Developer*	8 to 10 min dwell
	Group VI	
	8 oz/gal (14.09 g/l)	
	Magnaflux ZP-13A	
5.	*Dry* in hot oven	

*All group classifications to MIL-I-25135C

Note: Specimens were etched for Phase I demonstration. Phase II demonstration was conducted after Phase I demonstration.

BASELINE DEMONSTRATION

All of the AFWAL specimens were subjected to engine simulated environment and then were subjected to state-of-the-art cleaning and inspection procedures currently being used in USAF/ALC (Table 23, References 8 and 9).

Baseline demonstration inspections resulted in too much background fluorescence and high incidence of false or error calls (detecting a crack where there is really no crack). The number of true indications found by assembly floor inspectors for Inconel 718 and Ti-6Al-4V specimens are summarized in Tables 26 and 27, respectively. The specimens were then inspected by ME&T/NDE at known flaw locations (Tables 28 and 29), so that the capability of the baseline demonstration could be compared with Phase I and Phase II demonstrations. This was very important since most of the flaws in the AFWAL-furnished specimens were difficult to detect after going through engine environment contamination, state-of-the-art cleaning procedures, and FPI in overhaul inspection environment.

TABLE 26. BASELINE FPI DEMONSTRATION (INCONEL 718) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Intensity*
34	No Indication
91	No Indication
52	No Indication
15	No Indication
38	No Indication
43	No Indication
74	No Indication
102	No Indication
16	No Indication
79	Light

TABLE 27. BASELINE FPI DEMONSTRATION (Ti-6Al-4V) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Intensity*
27	No Indication
53	Bright
40	Bright
11	No Indication
23	No Indication
64	No Indication
79	No Indication
24	No Indication
33	No Indication
62	No Indication

TABLE 28. BASELINE FPI DEMONSTRATION (INCONEL 718) P&WA/ME&T/NDE RESULTS

Specimen No.	*True Indication Intensity*
34	No Indication
91	No Indication
52	No Indication
15	No Indication
38	No Indication
43	No Indication
74	No Indication
102	No Indication
16	Bright
79	Bright

PHASE I (SURFACE PREPARATION) DEMONSTRATION

All the Inconel 718 specimens were etched with No. 9B etch at 130°F for 2 min while Ti-6Al-4V specimens were etched with nitric-hydrofluoric etch at room temperature for 3 min. The FPI process variables for this demonstration were those used in the baseline demonstration inspection. The Phase I demonstration had less background fluorescence and fewer false indications compared to the baseline demonstration, but assembly floor inspection results were comparable to baseline inspections regarding the number of true indications. There were no true indications found by assembly floor inspectors on Inconel 718 specimens, but laboratory inspections of actual crack locations did show improved FPI capability as a result of etch procedures. Laboratory inspections revealed six true indications for Inconel 718 compared to only two true indications seen during the baseline demonstration (Tables 28 and 32). For Ti-6Al-4V, nine true indications were found compared to only two true indications seen during the baseline demonstration (Tables 29 and 33).

TABLE 29. BASELINE FPI DEMONSTRATION (Ti-6Al-4V) P&WA/ME&T/NDE RESULTS

Specimen No.	*True Indication Intensity*
27	No Indication
53	Bright
40	Bright
11	No Indication
23	No Indication
64	No Indication
79	No Indication
24	No Indication
33	No Indication
62	No Indication

TABLE 30. PHASE I DEMONSTRATION (INCONEL 718) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Intensity*
34	No Indication
91	No Indication
52	No Indication
15	No Indication
38	No Indication
43	No Indication
74	No Indication
102	No Indication
16	No Indication
79	No Indication

*Background fluorescence less than in baseline demonstration

TABLE 31. PHASE I DEMONSTRATION (Ti-6Al-4V) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Brightness**
27	No Indication
53	Bright
40	Bright
11	No Indication
23	No Indication
64	No Indication
79	No Indication
24	No Indication
33	No Indication
62	No Indication

*Background fluorescence less than in baseline demonstration.

TABLE 32. PHASE I DEMONSTRATION (INCONEL 718) ME&T/NDE RESULTS

Specimen No.	*True Indication Brightness**
34	No Indication
91	Medium
52	No Indication
15	Light
38	Light
43	No Indication
74	No Indication
102	Light
16	Bright
79	Bright

TABLE 33. PHASE I DEMONSTRATION (Ti-6Al-4V) ME&T/NDE RESULTS

Specimen No.	*True Indication Brightness*
27	Medium
53	Bright
40	Bright
11	Light
23	Light
64	Light
79	Light
24	Light
33	No Indication
62	Medium

PHASE II (FPI PROCESS VARIABLES) DEMONSTRATION

All fatigue crack specimens (already etched in Phase I) were inspected using the modified FPI procedures outlined in Table 25. Phase II demonstration had the least background fluorescence and highest sensitivity and resolution. More true indications were found using assembly floor inspection when (two for Inconel 718 and three for Ti-6Al-4V) compared to those of the baseline and Phase I demonstration (Tables 34 and 35). ME&T/NDI laboratory investigations revealed more true indications for Inconel 718 compared to the baseline and Phase I demonstration (Table 36), but for Ti-6Al-4V the number of true indications found by laboratory evaluation (Table 37) was less than the number found during the Phase I demonstration. This may be due to possibility of over-washing during the Phase II demonstration on Ti-6Al-4V specimens.

TABLE 34. PHASE II FPI DEMONSTRATION (INCONEL 718) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Intensity*
34	No Indication
91	No Indication
52	Light
15	No Indication
38	No Indication
43	No Indication
74	No Indication
102	No Indication
16	No Indication
79	Medium

TABLE 35. PHASE II FPI DEMONSTRATION (Ti-6Al-4V) P&WA/ASSEMBLY FLOOR INSPECTION RESULTS

Specimen No.	*True Indication Intensity*
27	Bright
53	Bright
40	Bright, Light
11	No Indication
23	No Indication
64	No Indication
79	No Indication
24	No Indication
33	No Indication
62	No Indication

TABLE 36. PHASE II FPI DEMONSTRATION (INCONEL 718) P&WA/ME&T/NDE RESULTS

Specimen No.	*True Indication Intensity*
34	No Indication
91	Medium
52	Light
15	Light
38	Light
43	Light
74	No Indication
102	No Indication
16	Light
79	Bright

TABLE 37. PHASE II FPI DEMONSTRATION (Ti-6Al-4V) P&WA/ME&T/NDE RESULTS

Specimen No.	*True Indication Intensity*
27	Bright
53	Bright
40	Bright, Light
11	No Indication
23	Light
64	No Indication
79	No Indication
24	No Indication
33	No Indication
62	Light

FPI capability of the three demonstrations has been summarized in Tables 38 and 39. Background fluorescence and number of false indications decreased, going from baseline to Phase I to Phase II demonstrations. Similar results were obtained on AFWAL specimens, some P&WA-supplied titanium fatigue crack specimens and Inconel 718 coupon samples in the laboratory before actual demonstrations were conducted using the P&WA/GPD assembly floor FPI facility.

TABLE 38. FPI DEMONSTRATION RESULTS ON INCONEL 718

	True Indications Found				
Demonstration	*Bright*	*Medium*	*Light*	*Total Number of True Indications*	*No Indication*
Baseline (PL*)	0	0	1	1	9
Baseline (LAB**)	2	0	0	2	8
Phase I (PL)	0	0	0	0	10
Phase I (LAB)	2	1	3	6	4
Phase II (PL)	0	1	1	2	8
Phase II (LAB)	1	1	5	7	3

*PL: Assembly Floor *Production Line* Inspection
**LAB: ME&T Laboratory Verification

TABLE 39. FPI RESULTS FOR Ti-6Al-4V

Demonstration	True Indications Found				No Indication
	Bright	Medium	Light	Total Number of True Indications	
Baseline (PL*)	2	0	0	2	8
Baseline (LAB**)	2	0	0	2	8
Phase I (PL)	2	0	0	2	8
Phase I (LAB)	2	2	5	9	1
Phase II (PL)	3	0	0	3	7
Phase II (LAB)	3	0	2	5	5

*PL: Assembly Floor Production Line Inspection
**LAB: ME&T Laboratory Verification

SECTION VI

CONCLUSIONS

Phase I of the program provided for the definition, evaluation, and optimization of surface preparation procedures for FPI of Ti-6Al-4V and Inconel 718 in an engine overhaul inspection environment. This phase included an investigation of the effects of surface preparation procedures on subsequent FPI capability as well as initial assessments of the effects of these procedures on the structural integrity of engine components, resulting in the following important observations:

1. Surface preparation procedures vary greatly between different overhaul facilities.

2. Aircraft engine operating environment causes significant reduction in capability of overhaul Fluorescent Penetrant Inspection (FPI).

3. Some current surface preparation procedures of engine components prior to FPI in an overhaul facility are inadequate and can degrade overhaul FPI capability.

4. Some current chemical cleaning procedures cause selective etching of engine components and may adversely affect structural integrity of these components.

5. Suitable chem-milling processes have been developed for Inconel 718 and Ti-6Al-4V alloys. Limited testing results indicate no degradation in mechanical properties due to the use of these etches.

6. Surface preparation procedures should be investigated in detail for their effects on mechanical properties.

7. Chem-mill etches increase FPI capability on surfaces subjected to abrasive mechanical processes such as grit blasting.

Phase II provided for evaluation and optimization of FPI process variables other than surface preparation procedures. Penetrant dwell time, emulsifier (hydrophilic) concentration, emulsification time, type of developer, etc., were chosen as significant process variables, resulting in the following important observations.

1. Penetrant dwell time of 30 min for Group VI MIL-I-25135C (Magnaflux ZL-35) provided optimum sensitivity.

2. A 33% concentration of Group VI MIL-I-25135C (Magnaflux ZR-10) emulsifier with 2-min emulsification dwell provided optimum conditions for excess penetrant removal.

3. Wet soluble developer provided much better sensitivity and reliability compared to a dry developer.

4. Stress-enhanced FPI resulted in much higher sensitivity and reliability compared to standard FPI.

Note: These observations were made for detection of small fatigue cracks initiated in smooth, flat specimens.

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