Fluorescent Penetrant Inspection Probability of Detection Demonstrations performed for Space Propulsion

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ABSTRACT.

Fracture critical rocket hardware requires nondestructive testing for flight quality assurance. Fracture critical hardware is defined as hardware with failure modes that may endanger space systems, missions or crew. This hardware includes major housings, disks, impellers and gas path hardware. A number of these components are evaluated with fluorescent penetrant inspection for defects open to the surface. Industry data supports the conclusion that with ultra high sensitivity penetrant, defects > 0.090 inches in length can reliably be detected with a 90/95 probability of detection (POD). To ensure the same POD on fracture critical hardware with reject lengths < 0.090 inches, POD demonstrations are conducted. These demonstrations are conducted on in-house inspectors and on approved external vendor's inspectors. Included in this paper are the results from over 50 of these demonstrations including results from different levels, methods and manufactures of penetrant. The paper describes: the specimens used, process used, specimen cleaning method, types of systems tested, analysis method, problem encountered and the lessons and conclusions that can be made.

INTRODUCTION

Fracture critical rocket hardware requires nondestructive testing for flight quality assurance. Fracture critical hardware is defined as hardware with failure modes that may endanger space systems, missions or crew. This hardware includes major housings, disks, impellers and gas path hardware. A number of these components are evaluated with fluorescent penetrant inspection (FPI) for defects open to the surface. Industry data supports the conclusion that with ultra high sensitivity penetrant, defects > 0.090 inches in length can reliably be detected with a 90/95 probability of detection (POD). To ensure the same POD on fracture critical hardware with reject lengths < 0.090 inches, POD demonstrations are conducted. These demonstrations are conducted on in-house inspectors and on approved external vendor's inspectors. Each inspector must be tested on each system they perform work on. A system is defined as a complete fluorescent penetrant process including application, washing, drying, developing and evaluation of a fluorescent penetrant. The results of the POD demonstration for each system determine the minimum flaw length an inspector is capable of detecting. Hardware inspected by Pratt & Whitney Space Propulsion (P&W SP) and the approved vendors is processed and evaluated using the same inspector. This differs from other P&W programs where separate FPI personnel are used for processing and evaluation of hardware. This paper will present the process used to perform these POD demonstrations, data collected and conclusions that can be made.

SPECIMENS AND PROCESS

The POD demonstrations are performed using a panel set manufactured by Martin Marietta. The panels were manufactured from IN718 and are ¼ inches thick, 4 inches wide and 16 inches long (Figure 1). The panels have an end milled surface finish. The panel set consists of 16 panels with 64 low cycle fatigue flaws located in random locations on both the top and bottom sides of the panels. The flaws have a length to depth ratio of approximately 2:1. The flaw lengths range from 0.008 inches to 0.417 inches with the center of the distribution near 0.060 inches.

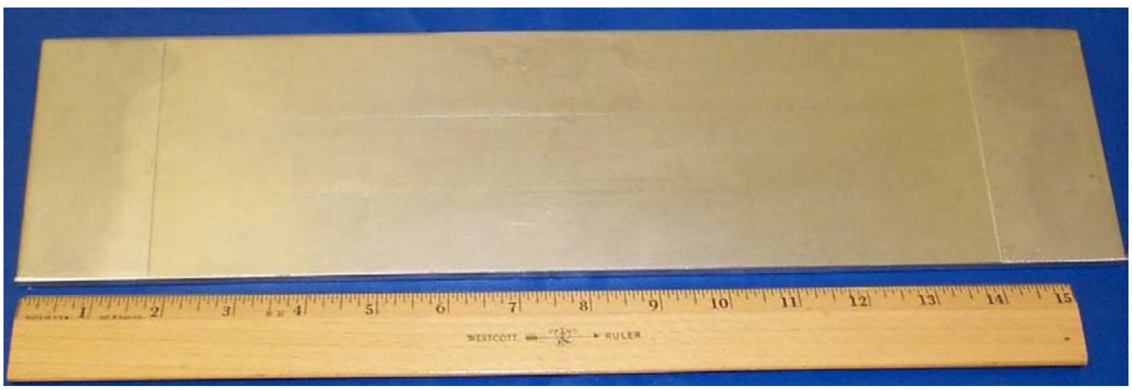

Figure 1, POD Panel

Two types of POD demonstrations are performed. The first type of demonstration is for a standard direct line of site FPI. The second type of demonstration is for an indirect line of site FPI using a borescope. Borescope inspections normally have less sensitivity due to the difficulty in viewing and evaluating indications in a cavity or other restrictive area where direct line of site is not possible. To simulate a borescope inspection the panels are placed in a closed box, which has an access hole in one end for the borescope to be inserted. The inspectors perform the demonstrations in the same manner a normal part inspection would be done. P&W SP permits indication reevaluation using solvent and a maximum magnification of 10X during inspections. A P&W SP witness observes the demonstration and records the data. All parameters of the demonstration including dwell time, wash time, wash pressure, wash method, emulsifier time, emulsifier method, oven temperature, oven time and developer time are recorded by the witness, but no comments or suggestions are made during the processing or evaluation. The witness also notes any unusual observations about the processing or the evaluation. Very often bad performance on the POD demonstrations can be explained from the observations made during the demonstration. The goal is to test the normal day to day operation of the line. A template is placed under the panel, which has a coordinate system with letters on one side and numbers on the other side. The indications are called out by the inspector and recorded by the witness using this coordinate system. The data is compared to an answer sheet and the hits, misses and false calls are recorded.

The POD curve (Figure 2) is generated according to the log normal distribution of the binary result method outlined in Mil-Hndk 1823. P&W SP has generated software based on the same algorithm to perform the hit / miss analysis of the data. This software has been verified to produce the same results as the Mil-Hndk software.

The panels are cleaned immediately after use using a three-step process. The panels are first wiped using a clean cloth dampened with Acetone to remove as much surface penetrant and developer. Next the panels are ultrasonically cleaned in Acetone for 60 minutes. The panels are then ultrasonically cleaned in reverse osmosis or distilled water heated to 160° F for 60 minutes.

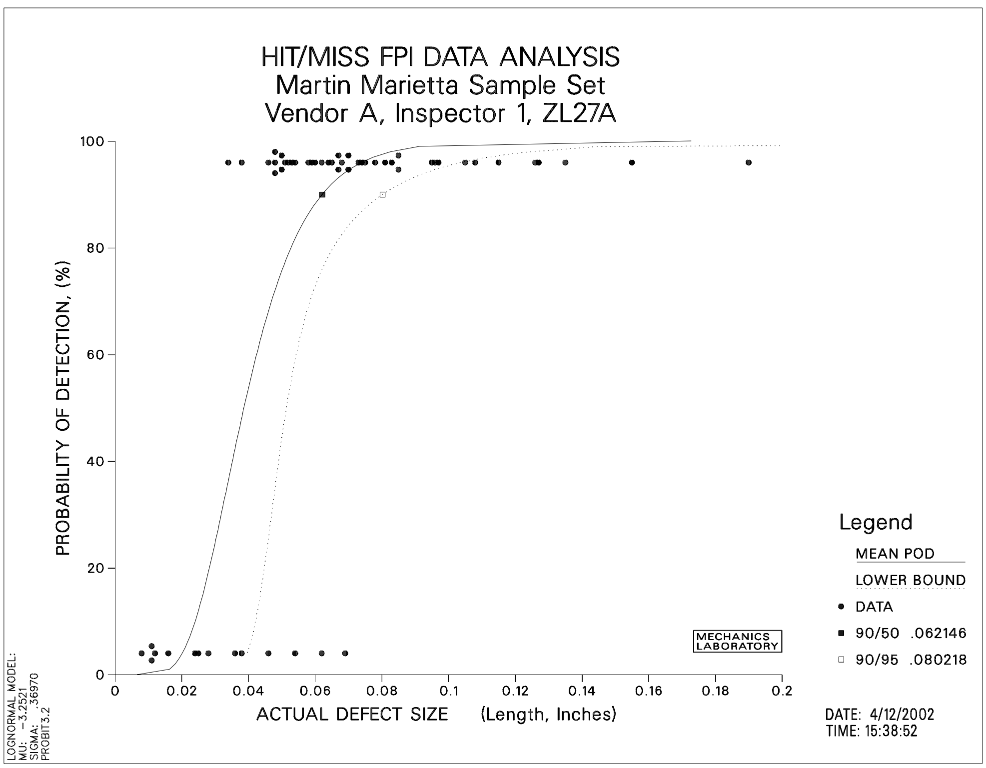

Figure 2, POD Curve

SYSTEMS

POD data has been collected on a number of different inspection lines. These lines range from large capacity commercially manufactured lines (Figure 3) to small in house manufactured lines (Figure 4). Penetrant application has been accomplished by a number of methods including electrostatically spraying, immersion, painting and spraying. Washing has been accomplished by manual spraying, automated mechanical spraying, manual immersion and automated mechanical immersion . Emulsifier has been applied by manual immersion, automated mechanical immersion and by manual spraying. Drying has been accomplished using manufactured FPI ovens, heat treat ovens and bread warming ovens. Developer has been applied by manual dusting, cloud chambers, developer wands and non-aqueous spray.

Figure 3, P&W Space Propulsion Fluorescent Penetrant Line

Figure 4, Vendor Fluorescent Penetrant Line

PENETRANTS AND LEVELS

The penetrants used by P&W SP for production inspections (Table 1) are either level IV post-emulsifiable, level III post-emulsifiable or level III water washable. The level IV penetrants are used on highly finished open surfaces. The level III penetrants are used on less finished surfaces and confined areas. The liquid oxygen compatible (LOX) penetrant is used in areas where penetrant might become entrapped. The level IV+ penetrant is used for localized high sensitivity non-production engineering evaluations within the P&W SP Nondestructive Evaluation Group (NDE).

Manufacture	Product	Sensitivity	Method
Ardrox (Chemetall)	P6F4	III	Water washable
Magnaflux	ZL27A	III	Post-emulsifiable
Magnaflux	ZL67	III	Water washable
Magnaflux	ZL37	IV	Post-emulsifiable
Met-L-Chek	FP-97A(M) S (NDE)	IV+	Post-emulsifiable
Sherwin	I345 (LOX)	III	Water washable
Sherwin	RC88	IV	Post-emulsifiable

Table 1, Penetrants and Levels

RESULTS

P&W SP requires that all inspectors be tested at three year intervals to stay qualified to perform fracture critical hardware inspections. The results presented in (Tables 2 – 6) are from internal and external inspectors tested over a 5 year period. The variations in penetrants tested and testing dates are due to workload, inspection requirements and employee changes. The results in (Table 7) provide a comparison between a production level IV penetrant used for whole field inspections and a non-production engineering evaluation level IV+ penetrant used for high sensitivity focused evaluations.

	1999	2000	2001	2002
Inspector 1				
ZL37			0.061	
ZL37 (BS)			0.062	
P6F4			0.050	
I345			0.062	
I345 (BS)				
Inspector 2				
ZL37			0.059	
ZL37 (BS)				
P6F4			0.062	
I345			0.060	
I345 (BS)				
Inspector 3				
ZL37		0.059		
ZL37 (BS)			0.060	
P6F4		0.061		
I345		0.069		
I345 (BS)				
Inspector 4				
ZL37			0.042	
ZL37 (BS)				
P6F4			0.050	
I345			0.056	
I345 (BS)				
Inspector 5				
ZL37		0.043		
ZL37 (BS)				
P6F4	0.051			0.056
I345	0.060			0.078
I345 (BS)	0.068			0.061
Inspector 6				
ZL37		0.063		
ZL37 (BS)				
P6F4		0.085		
I345				
I345 (BS)				
Inspector 7				
ZL37			0.053	
ZL37 (BS)			0.064	
P6F4				
I345	0.051			
I345 (BS)				
Inspector 8				
ZL37		0.059		
ZL37 (BS)		0.063		
P6F4		0.052		
I345		0.057		
I345 (BS)				

Table 2, P&W Space Propulsion 90/95 POD Lengths (in)

	1998	1999	2000	2001	2002
Inspector 1					
ZL37		0.052			0.086
ZL27					0.080
Inspector 2					
ZL37	0.053			0.053	
ZL27	0.081			0.069	

Table 3, Vendor A 90/95 POD Lengths (in)

	1999	2000	2001	2002
Inspector 1				
ZL37	0.051			0.056
ZL67	0.053			0.065
I345	0.055			0.070
Inspector 2				
ZL37				0.056
ZL67				0.052
I345				0.065

Table 4, Vendor B 90/95 POD Lengths (in)

	1999	2000	2001	2002
Inspector 1				
ZL37				0.065
ZL27A				0.060
I345	0.051			0.068
Inspector 2				
ZL37	0.060			0.074
ZL27A	0.053			0.073
I345	0.052			0.082

Table 5, Vendor C 90/95 POD Lengths (in)

	1998	1999	2000	2001	2002
Inspector 1					
P6F4	0.053				0.085
RC77					0.082
Inspector 2					
P6F4	0.064				0.063
RC77					

Table 6, Vendor D 90/95 POD Lengths (in)

	2001
Inspector 1	
ZL37	0.047
FP-97A(M)S	0.030
Inspector 2	
ZL37	0.059
FP-97A(M)S	0.030
Inspector 3	
ZL37	0.068
FP-97A(M)S	0.030
Inspector 4	
ZL37	0.053
FP-97A(M)S	0.030

Table 7, P&W NDE 90/95 POD Lengths (in)

FPI PROCESS ERRORS

While performing the POD demonstrations a number of FPI process deficiencies have been observed. The problem noticed most often is the over washing of the water washable penetrants. This problem is identified when flaws > 0.100" in length are missed but the normally detected < 0.100" length flaws are found. This correlates to the narrower widths and shallower depths of the longer flaws. This problem is most often noticed on penetrant lines using hydro wash spray guns. Depending on how these guns are adjusted very intense high volume sprays can be created. This problem has not been noticed with the post-emulsifiable penetrants.

One of the other problems that has occurred with various POD panel sets is not enough small flaws that are missed to allow the analysis algorithm to converge accurately. A panel set must be balanced with enough small and large flaws to allow accurate convergence. Another problem identified during these demonstrations is that POD panel sets must be calibrated to produce the same results for the same process. By selectively removing flaws from the analysis, panel sets can be calibrated to provide the same results.

The large and small flaw sizes in the panels have also caused some inspectors problems. Inspectors not accustomed to seeing very small flaws have concluded that the panels do not contain any flaws even thought there are fluorescent indications visible. Some inspectors have missed large flaws because they conclude large fluorescent indications can not possibly be flaws. Some inspectors have concentrated so much on finding the small flaws that they have over looked the large flaws.

Borescope ultraviolet light intensity while using a video camera and monitor for viewing have also caused problems. The normal practice of calibrating the borescope ultraviolet light to 1500uW/cm^2 at the focal length of the borescope may not provide the needed intensity for a camera to provide the same results as an inspectors' eyes would provide. Increasing the intensity by 10X may be required to provide the same detection capability as the human eye.

The parameters that are used to inspect the POD panels and the parameters that are used on real hardware have also caused problems. A number of inspectors and managers have wanted to use different parameters on the POD panels than they would use in normal production. This of course negates the reason for performing the demonstration in the first place as the POD numbers are used to demonstrate that engineering intent is being met. It is true that the panels do not represent real hardware which have different surface finishes and geometry but it is what we can reliably and cost effectively generate at the present.

LESSONS AND CONCLUSIONS

After performing demonstrations internally and at a number of outside vendors over a number of years a number of lessons have been learned. The dedication, integrity, experience and skill of the inspector is the largest factor in a penetrant system. The process being optimized and controlled is the second largest factor in a penetrant system. Inspectors using optimized parameters, simple containers and a stopwatch have performed equally well as inspectors using large automated systems.

If a good inspector is asked to perform the same POD demonstration a number of times the results can be very similar with variances of less than ±0.008” in length for a 90/95 POD. In a number of cases inspectors have received almost identical results when retested on three-year intervals. In almost all cases where results have changed greatly (> 0.020” for 90/95 in length) a cause has been found to explain the change. These causes have ranged from inspectors not performing evaluations over a long period of time, not using a certain penetrant method on a regular basis or the process has changed. In a number of cases it has been observed that inspectors have received better results using a lower level penetrant versus a higher level penetrant either because of more experience with the lower level penetrant or more optimization of the lower level penetrant system.

POD demonstrations provide a reliable means of verifying inspector and system capability. It must be realized that a POD demonstration is a snapshot in time. An acceptable period of time must be determined for retesting to maintain the quality of the process.

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