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A Comparison of the Capability of Sensitivity Level 3 and Sensitivity Level 4 Fluorescent Penetrants to Detect Fatigue Cracks in Various Metals

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January 2011

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Introduction

Under the auspices of the NASA Nondestructive Evaluation (NDE) Program, the Goddard Space Flight Center (GSFC) Materials Engineering Branch initiated a task in October 2008 to investigate the effect of liquid penetrant sensitivity level on probability of crack detection. The purpose of the task was to address the requirement in NASA-STD-5009[1], "Nondestructive Evaluation Requirements for Fracture Critical Metallic Components," which was released in April 2008, that states only sensitivity level 4 penetrants could be used for NASA Standard Level liquid penetrant inspections.

During the development of NASA-STD-5009, there was considerable debate within the NASA NDE community about this requirement, as it was a change from the Agency's previous policy of allowing the use either sensitivity level 3 or level 4 liquid penetrants for NASA Standard Level liquid penetrant inspections. The rationale for the requirement change was the fact that the data used to establish the reliably detectable crack sizes for liquid penetrant inspection was from studies performed in the 1970s using penetrants deemed to be equivalent only to modern day sensitivity level 4 penetrants. Hence, it was argued that there was a lack of data to support allowing the use of sensitivity level 3 liquid penetrants.

In this study, NDE inspectors performed probability of detection (POD) demonstration tests on aluminum (6061-Al), a high temperature cobalt based alloy (Haynes 188) and titanium (Ti-6Al-4V) crack panels sets using various sensitivity level 3 and level 4 penetrants. In order to quantify the POD, the hit-miss data from the individual demonstration tests were analyzed using both the point estimate method and the curve fitting method of data analysis. In addition, combinations of hit-miss data sets were analyzed using the curve fitting technique in order to further compare the data not only by penetrant sensitivity level, but also by inspection method, inspector and metal. The end goal was to determine if there is a significant difference in the crack detection capability of sensitivity level 3 and level 4 penetrants.

Penetrant Inspection Materials

The penetrants selected for the study were Method A, Water Washable and Method D, Post Emulsifiable, Hydrophilic, as these are the most common penetrant inspection methods used in the aerospace industry. Sensitivity level 3 and level 4 penetrants from two manufactures, Sherwin and Magnaflux, were selected. Table 1 shows the matrix of eight penetrant inspection materials (four sensitivity level 3 and four sensitivity level 4) used in the study. The same nonaqueous developer (Sherwin D-100, which is applied by spray can) was used for all the Method A inspections and likewise a consistent dry powder developer (Magnaflux ZP-4B) was used for the Method D inspections.

Table 1: Summary of the penetrant materials used in this study.

Method	Sensitivity Level	Penetrant	Remover	Developer
A	3	Magnaflux ZL-67	N/A	Sherwin D-100
A	4	Magnaflux ZL-56	N/A	Sherwin D-100
A	3	Sherwin HM-607	N/A	Sherwin D-100
A	4	Sherwin HM-704	N/A	Sherwin D-100
D	3	Magnaflux ZL-27A	Magnaflux ZR-10B	Magnaflux ZP-4B
D	4	Magnaflux ZL-37	Magnaflux ZR-10B	Magnaflux ZP-4B
D	3	Sherwin RC-65	Sherwin ER-83A	Magnaflux ZP-4B
D	4	Sherwin RC-77	Sherwin ER-83A	Magnaflux ZP-4B

Crack Panels

As mentioned previously, three different sets of crack panels were used in the study. Table 2 summarizes the attributes of each panel set. In the table, the crack aspect ratio is defined as the crack depth divided by the crack length. In all three sets, the cracks were produced in low cycle bending fatigue. The 6061-Al panels are owned by GSFC and their production is described in NASA Technical Memorandum 2009-215850[2]. The Haynes 188 set was borrowed from NASA Marshall Space Flight Center (MSFC) and their production is described in NASA-CR-170879[3]. The Ti-6Al-4V panel set was borrowed from NASA Johnson Space Center (JSC). The production of the Ti-6Al-4V panels is described in Appendix B.

Table 2: Attributes of the three crack panel sets used in the study.

Metal	Number of Panels	Panel Dimensions (inches)	Total Number of Cracks	Crack Length Ranges (inches)	Nominal Crack Aspect Ratio
6061-Al	30	8 x 3.5 x 0.25	82	0.023-0.215	0.3
Haynes 188	30	16 x 4 x 0.25	107	0.010-0.350	0.2
Ti-6Al-4V	29	6 x 3.9 x 0.125	54	0.032-0.094	0.4

Figure 1 shows statistical box plots of the crack length distributions for each panel set. There is a sharp contrast between the distribution in the Ti-6Al-4V set and the other two metals. The Ti-6Al-4V set was designed for point estimate POD demonstration testing at a crack length of 0.050 inches. Hence, 45 of the 54 cracks in the set have lengths between 0.045 and 0.055 inches. For the Haynes 188 and 6061-Al sets there is broader distribution of crack lengths and these two sets are better suited for the curve fitting POD data analysis technique.

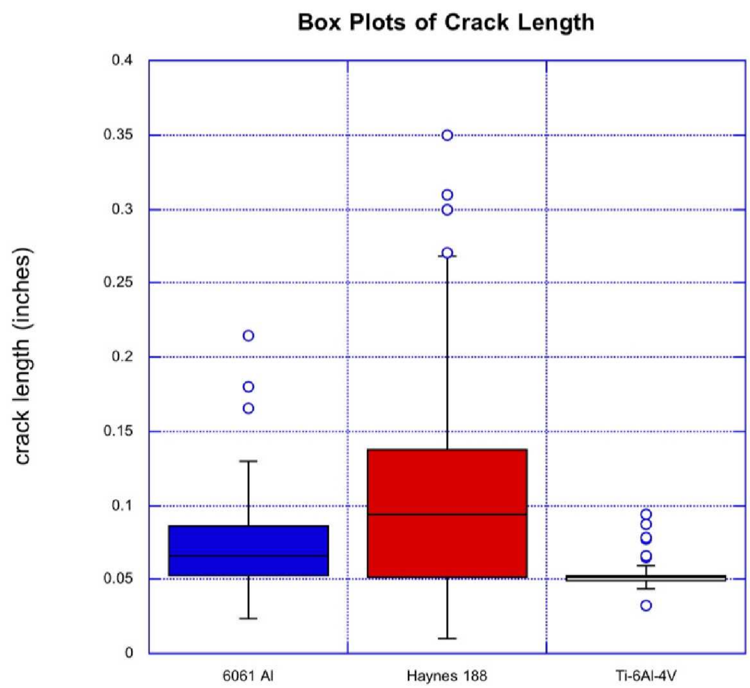

Figure 1: Box plots of crack length distribution for each of the crack panel sets.

Procedures

General Procedures

Seven of the nine inspectors that participated in the study were at a vendor local to NASA GSFC. The remaining two inspectors were members of the GSFC Materials Engineering Branch. Because of inspector turn over at the NDE vendor and the availability of the crack panel sets (the Haynes 188 and the Ti-6Al-4V sets were borrowed from other NASA Centers), not all nine inspectors performed POD demonstration tests on all three metals using the complete matrix of Method A and Method D penetrants. Table 3 summarizes the POD demonstration testing performed in the study. The table shows that a total of 92 penetrant POD demonstration tests were performed. Forty-six of the demonstrations were with sensitivity level 3 penetrants and 46 were performed with sensitivity level 4 penetrants.

As a consequence of having to borrow two of the crack panels sets, the demonstration tests were performed in three phases. First, all the Method A and Method D demonstration tests were performed on the 6061-Al panel set. Once the 6061-Al testing was complete, the request was placed to borrow the Haynes 188 panels from MSFC. The testing with the Haynes 188 panels was then completed prior to receipt of the Ti-6Al-4V panel set from JSC.

Metal	Method	Inspectors	Total Number of Trials	
			Sensitivity Level 3	Sensitivity Level 4
6061-Al	A	Vendor 1 Vendor 2 Vendor 3 Vendor 4 GSFC 1	10	10
6061-Al	D	Vendor 3 Vendor 4 Vendor 5 Vendor 6 Vendor 7 GSFC 1	12	12
Haynes 188	A	Vendor 3 Vendor 5 GSFC 1	6	6
Haynes 188	D	Vendor 3 Vendor 5 GSFC 1	6	6
Ti-6Al-4V	A	Vendor 1 Vendor 3 Vendor 7	6	6
Ti-6Al-4V	D	Vendor 1 GSFC 1 GSFC 2	6	6

Table 3: Summary of the POD demonstration tests performed in the study.

In order to help avoid memorization of the crack panel identification numbers that were either etched or stamped on the panels (many inspectors inspected the same panel set eight times), the panels were given random and new numbers for each inspection. The new numbers were placed on the panel using a "permanent" marker. The inspectors were instructed to use this temporary number when identifying the panel during a demonstration test. After each inspection, the numbers were removed during the panel cleaning process and then new numbers were assigned after cleaning.

For all three panels sets, a grid was used for identification of crack locations. Figure 2 is an optical photograph of a 6061-Al panel with the corresponding inspection grid. Similar grids were used for the Haynes 188 and Ti-6Al-4V panel inspections. All inspections were of the hit-miss type. In addition to hits and misses, the number of false calls was also recorded.

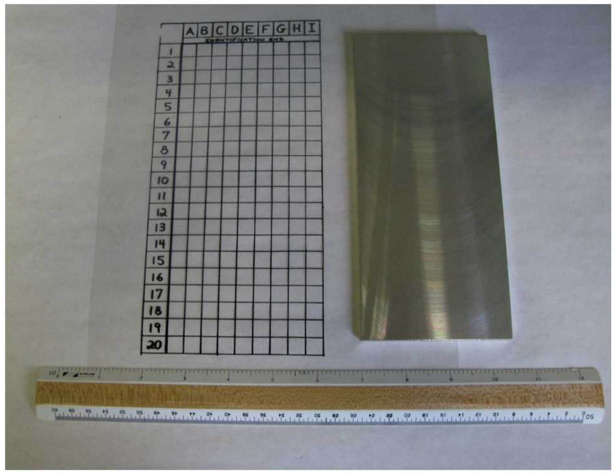

Figure 2: Optical photograph of an aluminum crack panel and the grid used to identify the detected crack locations.

Method A Procedure

For the Method A inspections, the vendor's procedure was utilized by all the inspectors including the GSFC inspector. The minimum penetrant dwell time was 20 minutes and the developer time was 10 minutes. All the other parameters, i.e., wash pressure, wash temperature and drying oven temperature were within established limits. Quality assurance checks for black lights, background lighting, etc. were in place and maintained. As important, all these parameters were constant throughout the test matrix.

Each inspector progressed through the matrix of four Method A penetrants with no knowledge of the actual penetrant being used. The order in which a particular inspector progressed through the penetrants was varied. In addition, the inspectors were given no feedback about their performance until the study was complete. Inspectors were typically tested once a week and due to scheduling there were often several week delays between a specific inspector taking the test.

Method D Procedure

The vendor did not address Method D in their penetrant procedure. As a consequence, GSFC introduced a procedure for this process. The minimum penetrant dwell time was 30 minutes, the emulsifier concentration for both the Magnaflux ZR-10B and the Sherwin ER-83A was 16.7 percent by volume (one gallon of emulsifier mixed with five gallons of water) and the emulsification time was 2 minutes. Specimens were prewashed prior to emulsification, however there was no established limit on the prewash or post wash times. After oven drying, the dry powder developer was applied by a manual dip and drag technique and there was no minimum developer time. All other parameters (wash pressure, oven temperature, etc.) were the same as those used in the vendor procedure for Method A. Again, the sequence that an inspector progressed through the matrix of penetrants was varied and no performance feedback was supplied.

Data Analysis

The hit-miss data from each demonstration test was analyzed using two different approaches to yield crack lengths that have a 90 percent probability of detection with 95 percent confidence (a90/95). The first technique was a point estimate technique, which is based on binominal distribution statistics. The second method is a curve fitting method based on the Logit model.

Point Estimate Method

Usually, the point estimate method is applied to a set of cracks with a narrow range of sizes. For example, NASA uses this technique to qualify inspectors for the NASA Special Level penetrant inspection crack length of 0.050 inches. During such a demonstration test, the inspector is given a set of crack panels that ideally contains 29 cracks of exactly 0.050 inches length. Because of the difficulty in controlling the crack length during panel production, the 29 cracks typically have a range of 0.045 to 0.055 inches (plus or minus 10 percent). Based on the binomial statistics, if the inspector finds all 29 cracks, then an a90/95 at 0.050 inches has been demonstrated. Volume 11 of the Metals Handbook 8th Edition[4] gives an excellent explanation of the statistics used by the point estimate method. As previously noted the Ti-6Al-4V panel set from JSC is ideally suited for the point estimate method of analysis.

Another outcome of the panel production process, is that in order to get 29 cracks within the desired length range, one usually ends up with a significant number of cracks both smaller and larger than the desired range. This is a consequence of the fact that many panels in a set contain more than one crack. If a panel ends up with any crack within the desired range it will probably be included in the set even if it has both cracks larger and smaller than the desired range. This is the reason the Ti-6Al-4V panel set has some crack lengths outside the 0.045 to 0.055 inch range.

During a NASA Special Level demonstration test with a panel set containing 29 cracks in the target range of 0.050 inches and with both some larger and smaller cracks, the inspector successfully demonstrates an a90/95 of 0.050 inches if they find all 29 cracks in the target range as well as all the larger cracks. There is no penalty for missing cracks smaller than the target range.

In the case of the demonstration tests in this study, there is not a requirement that an inspector demonstrates an a90/95 of 0.050 inches. On the contrary, we are interested in seeing at what length a90/95 is successfully demonstrated and then comparing this demonstrated length for the different sensitivity Level penetrants. For this reason, the point estimate data analysis method was also applied to the Haynes 188 and the 6061-Al sets, even though these sets were not specifically design for this analysis technique. The implementation of the point estimate in this context requires finding a group of 29 cracks that are found where all the cracks with lengths above the range of these 29 cracks are also found. The demonstrated size is then considered to be the largest crack length in the set of 29 flaws (not the average).

The hit-miss data set is also evaluated to look for sequences of flaws that meet the other a90/95 hit-miss combinations identified in the Metals Handbook article[4], i.e., 45 hits for 46 cracks, 59 hits for 61 cracks and 72 hits for 75 cracks. Again there is the consideration that all of the cracks larger than the identified set must also be correctly hit or found. The combination that yields the lowest a90/95 is the reported number.

Curve Fit Technique

In this study, the curve fit technique is used only to compare the results between different penetrant sensitivity levels, inspection methods, inspectors or metals and is not used to quantify or demonstrate NASA Special Level capability.

Statisticians have proposed numerous models such as the log normal distribution function, log-logistics (also referred to as the log odds) functions and Probit and Logit models to fit hit-miss inspection data. The statisticians recognized that most nondestructive inspection techniques produce a situation where below a certain crack length almost all of the cracks are missed and above a slightly larger crack length almost all of the cracks are hit. In this case, a plot of the probability of detection (POD) as a function of the crack length (or the log of the crack length) yields a characteristic "S" shape curve. This "S" shaped curve can be well fit by the various models mentioned above to yield an a90/95 crack size. This approach is explained in detail in Volume 17 of the Metals Handbook 9th Edition[5] for the log normal distribution and the log-logistics function. The statistics book by J.A. Cramer[6] gives a full explanation and history of the Probit and Logit models.

The hit-miss inspection results generated in this study for the 6061-Al and Haynes 188 panel sets generally produce "S" shaped curves and hence using a curve fit technique to analyze the data is appropriate. There were eight trials out of 68 with the 6061-Al and Haynes 188 panels where the data did not conform to the curve fit technique. In seven trials with the 6061-Al panels, there were no missed flaws and as a consequence no curve fit. In one additional trial with the 6061-Al panels, the inspector missed only one crack out of 82, however the crack length was 0.070 inches and hence was near the center of the distribution of lengths. In this situation the curve fit also failed. As will be seen in the results section, applying the curve fitting technique to the individual hit-miss data sets from the Ti-6Al-4V panels was much less successful, which is not surprising given the narrow distribution of flaw sizes in the set.

The curve fit technique adds value to this study because it allows for the evaluation of combination hit-miss data sets, i.e., all Haynes 188 Method A sensitivity Level 3 hit-miss results versus all Haynes 188 Method A sensitivity Level 4 results. The use of the point estimate method to evaluate such data sets can produce misleading results. For example, if one of the inspectors performing the Method A inspections during a particular inspection missed a very large crack when using one of the sensitivity Level 3 penetrants, and if we were to combine the hit-miss data from all inspectors into a single data set, the overall point estimate a90/95 would be determined by this one inspector's result (a consequence of the point estimate method is that the a90/95 will never be smaller than the largest missed crack length). On the other hand, the overall data set would have the characteristic "S" shape and evaluation of the data set using the curve fit technique would not produce a result dominated by a single inspection, yet still would include the results from all inspectors.

In support of an effort to update MIL-HDBK-1823[7], Charles Annis developed a R (an open source mathematics software program for statistical computing and analysis) package titled "mh1823 POD." The menu driven package uses R commands for all data manipulation , statistical analysis and graphics. For hit-miss data, the package offers the user eight different curve fit options all of which are appropriate models for studies were the response or outcome is binary, i.e., a crack is hit (1) or missed (0). Four of the models are based on the log of the crack length and four are not. Each is based on a link to an existing R function, e.g., logit, probit, loglog or cloglog. For each of the eight models, the package provides a deviance value which is a measure of the goodness of fit. For this study, the Logit link using the log of the crack length was selected for all the data set analyses, as the deviance for this choice was generally the lowest. Note that for the data sets in this study all the model options produced similar a90/95 results. For example, a Method A inspection of the 6061-Al panel set with 77 hits and 4 misses was fitted using the eight possible links and the a90/95 values ranged from 0.052 to 0.055 inches (the deviance values ranged from 13 to 15).

Note again that in this study we are not using the curve fit technique to qualify penetrant inspectors and we are not attempting to determine which model is the best. Here, a single curve fit technique (Logit) is universally applied to compare results from the two different sensitivity levels, and the different inspectors. We state this because the point estimate method is a more conservative technique for quantifying a90/95 and is the approach preferred by NASA for demonstrating capability at a single crack length.

False Calls

False calls were not included in the analysis of the data. The tables in Appendix A do include the number of false calls for each inspection. The grid provided for locating crack indications had 180, 160 and 96 cells for the 6061-Al, Haynes 188 and Ti-6Al-4V panel sets, respectively. Hence, for a demonstration test with 30 6061-Al panels and a one-sided inspection, there are 5400 possible crack locations. For the Haynes 188 and Ti-6AL-4V panels sets the total number of grid locations was 4800 and 2784, respectively. The inspectors were instructed to identify only "crack like" indications, however they were given no feedback about their false call rates between inspections. Based on the available number of grid locations, the average false call rates were 0.17, 0.14 and 0.04 percent for the 6061-Al, Haynes 188 and Ti-6Al-4V demonstration tests, respectively.

Results

The results from all the individual inspection trials for each metal and for each penetrant inspection method are provided in Appendix A tables. These tables include the number of cracks hit and missed and the number of false calls for each trial. The tables also include point estimate and curve fitting data analysis results for each individual trial. The tables included in the various results sections below provide a summary of all the individual trials found in the Appendix A tables as a function of penetrant sensitivity level. These tables include the total number of cracks hit and missed, the overall percentage of cracks hit and curve fit analysis results for combined hit/miss data sets. In addition to the summary tables, the sections below contain graphical representations of the a90/95 Logit curve fits for various combined hit/miss sets.

6061-Al Method A

Table1-A in Appendix A contains all of the individual 6061-Al Method A inspection results. The first vendor inspector (Vendor 1) to go through the matrix of tests was given 23 to 26 crack panels with 59 to 66 cracks. With this number of cracks, there was not a point estimate method solution for two of the four trials. As a consequence, additional crack panels were added to the set to increase the number of larger cracks for all subsequent inspectors.

Point estimate analysis for the remaining four inspectors with 81 to 82 total cracks produced a solution in all cases. As mentioned in the Data Analysis section, there was one trial where the Logit curve fit technique did not produce a solution. This is the case for the Vendor 3 inspector using Sherwin HM-704 where the one crack missed was 0.070 inches long.

Table 4 provides a comparison of the sensitivity level 3 versus the level 4 penetrants. The table shows that the total percentage of cracks found for the 10 trials with each sensitivity level of penetrant is essentially identical (92.7 versus 93.0 percent). The values in the final column of the table were obtained by combining all the sensitivity level 3 hit-miss data (774 cracks) into a single record and all the level 4 hit-miss data (775 cracks) in to a single record and then performing Logit curve fits to obtain a90/95 values. With this approach, the a90/95 values for the two sensitivity level penetrants differ by only 0.001 inches.

Table 4: Summary of sensitivity level 3 versus level 4 penetrant performance for 6061-Al Method A demonstration tests.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)

3	10	774	718	56	92.7	0.052
4	10	775	721	54	93.0	0.051

In order to compare the individual inspectors and the individual penetrants, hit-miss results from individual trials were combined and analyzed using the Logit curve fit technique. Figure 3 shows the a90/95 curve fits for the four different Method A penetrants. Each curve fit was performed on the combined hit-miss data from the five

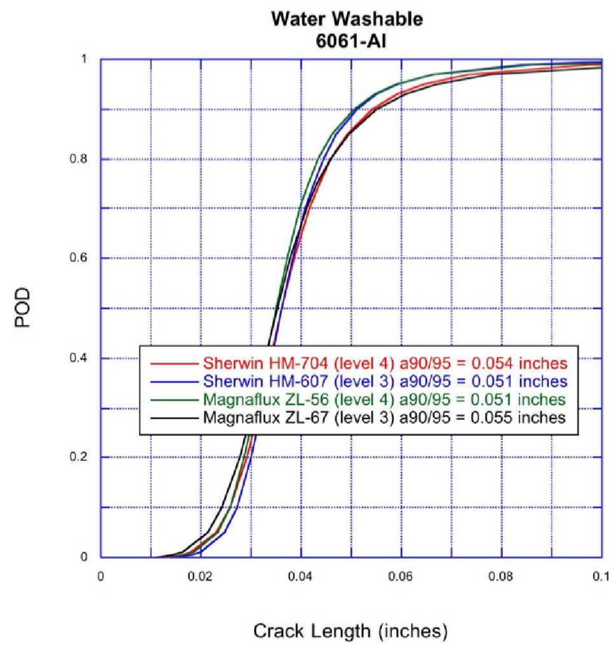

Figure 3: Logit curve fit a90/95 results as a function of Method A penetrant for 6061-Al POD demonstration tests.

trials (one trial for each of the five inspectors) performed using the penetrant. The a90/95 values for the penetrants range from 0.051 to 0.055 inches.

In a similar fashion, all of the hit-miss results for each inspector (four trials, two with sensitivity level 3 and two with sensitivity level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 4, show that the demonstrated a90/95 is a stronger function of the inspector than of the penetrant. Here, the a90/95 values varied between 0.041 and 0.058 inches.

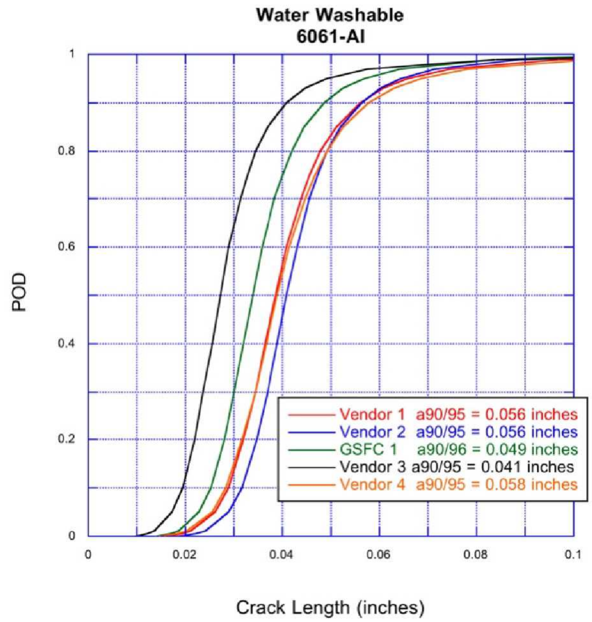

Figure 4: Logit curve fit a90/95 results as a function of Method A inspector for the 6060-Al demonstration tests.

For the Method A inspections, the largest variable in the process was the application of the nonaqueous Sherwin D-100 developer. One inspector (Vendor 1) applied a heavy coating of the developer (there was no evidence of the aluminum beneath the developer), whereas the remaining inspectors applied lighter coatings. One inspector (Vendor 3) inspected the panels completely before developing and then inspected the panels again during the development process, i.e., the developer was applied to one crack panel and the panel was immediately observed under the black light. After recording all crack locations, the inspector proceeded to the next panel. This inspector had the lowest number of misses. The remaining inspectors developed batches of panels and waited at least 10 minutes before beginning the crack identification process.

6061-Al Method D

Table 2-A in Appendix A contains all of the inspection results for the Method D demonstration tests on 6061-Al. Point estimate method solutions were obtained for all 24 cases. There were seven cases where no cracks were missed. The Logit curve technique for data sets with all hits and no misses does not yield an a90/95 solution. Switching the smallest crack in the set (0.023 inches) from a hit to a miss yielded an a90/95 solution of 0.026 inches and this is the value reported for the seven cases with no misses.

Table 5 is a summary of the sensitivity level 3 versus level 4 Method D penetrants. The overall percentage of the cracks found is slightly higher for the level 3 penetrants (97.4) versus the level 4 penetrants (96.1). The values in the final column of the table were obtained by combining all the sensitivity level 3 hit-miss data into a single record and all the level 4 hit-miss data in to a single record and then performing Logit curve fits to obtain a90/95 values. With this approach, the a90/95 values for the two sensitivity level penetrants differ by only 0.005 inches. In all these modes of comparison, the level 3 penetrants performed better than the level 4 penetrants.

Table 5: Comparison of sensitivity level 3 versus level 4 penetrants for Method D demonstration tests performed on 6061-Al.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	12	960	935	25	97.4	0.040
4	12	967	929	38	96.1	0.045

In order to compare the different penetrants and inspectors, hit-miss results from individual trials were combined and analyzed using the Logit curve fit technique. Figure 7 shows the a90/95 curve fits for the four different Method D penetrants. Each curve fit was performed on the combined hit-miss data from the six trials (one trial for each of the six inspectors) performed using the penetrant. The plots show that one penetrant, Magnaflux ZL-27A, performed better than the remaining three penetrants. Interestingly, this penetrant is sensitivity level 3. This result is not unprecedented. In a report by John Lively,[8] four of six inspectors who performed penetrant deomonstrations tests on Inconel 718 panels using Magnaflux ZL-37 (sensitivity level 4) and Magnaflux ZL-27A (sensitivity level 3) performed better with ZL-27A.

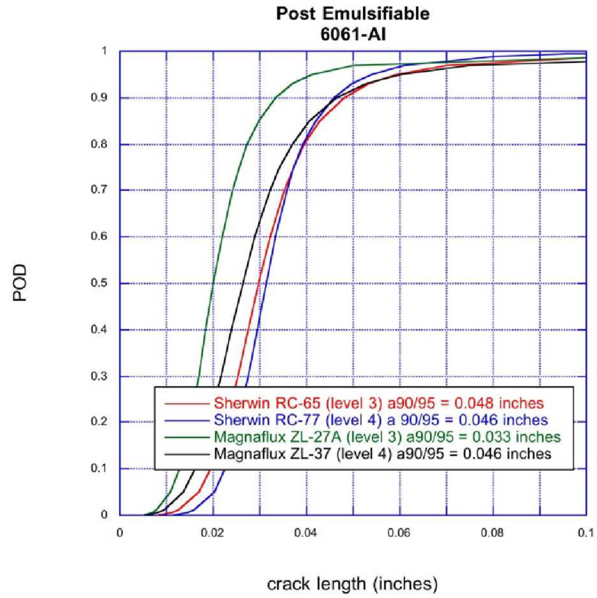

Figure 7: Logit curve fit a90/95 results as a function of Method D penetrant for 6061-Al demonstration tests.

Table 6 provides summary results for all four Method D penetrants. This data again shows that the inspectors performed better with ZL-27A and that the remaining three penetrants performed similarly. There was no characteristic of ZL-27A that surfaced during the inspections that would lead one to believe that this penetrant would perform better.

Again, all of the hit-miss results for each inspector (four trials, two with sensitivity level 3 and two with sensitivity level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 8, show that the demonstrated a90/95 is again a stronger function of the inspector than of the penetrant. Here, the a90/95 values varied between 0.031 and 0.057 inches, which is similar to the range for the Method A inspectors (0.041 to 0.058 inches). It should also be noted, that the inspector with the largest overall demonstrated a90/95 for Method A, also had the largest a90/95 for Method D.

Table 6: Comparison of the four Method D penetrants used in the 6061-Al demonstration tests.

Penetrant and (Sensitivity Level)	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Average Point Estimate a90/95 (inches)	Average Logit Curve Fit a90/95 (inches)	Logit Curve Fit on Combined Hit/Miss Data (inches)
Magnaflux ZL-27A (3)	6	480	475	5	99.0	0.064	0.035	0.033
Sherwin RC-65 (3)	6	480	460	20	95.8	0.084	0.053	0.048
Magnaflux ZL-37 (4)	6	484	465	19	96.1	0.090	0.053	0.046
Sherwin RC-77 (4)	6	483	464	19	96.1	0.068	0.049	0.046

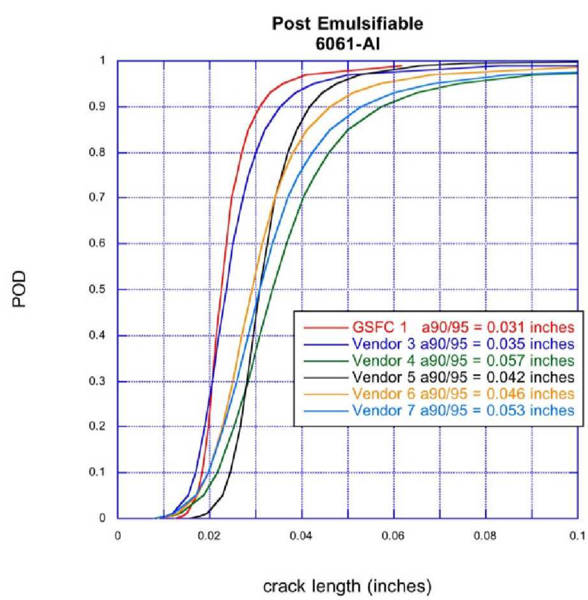

Figure 8: Logit curve fit a90/95 results as a function of Method D inspector for 6061-Al demonstration tests.

Haynes 188 Method A

Table 3-A in Appendix A contains the results from all the Method A inspections performed on the Haynes 188 panel set. Point estimate solutions were found in 11 of the 12 trials and curve fit solutions were found for all 12 trials. Table 7 summarizes the sensitivity level 3 results versus level 4 results for all the trials. The table shows essentially identical percentages of cracks detected for the two sensitivity levels (94.7 and 94.5 percent).

Table 7: Comparison of sensitivity level 3 versus level 4 penetrants for Method A demonstration tests performed on Haynes 188.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	6	642	608	34	94.7	0.046
4	6	638	603	35	94.5	0.049

The values in the final column of Table 7, which were obtained by performing Logit curve fits on the combination of all 6 sensitivity level 3 hit-miss data sets and all six of the level 4 sets, show the a90/95 values for the two levels of penetrants differ by 0.003 inches. These results are shown graphically in Figure 9.

All of the hit-miss results for each inspector (four trials, two with sensitivity Level 3 and two with sensitivity Level 4 penetrants) were also combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 10, show that the demonstrated a90/95 is again a stronger function of the inspector than of the penetrant. Here, the a90/95 values varied between 0.026 and 0.075 inches. Note that the range of a90/95 values as a function of inspector is much broader for the Haynes 188 compared to the 6061-Al using the same inspection method and materials. This larger range of values was attributed to variations in the application of the D-100 developer.

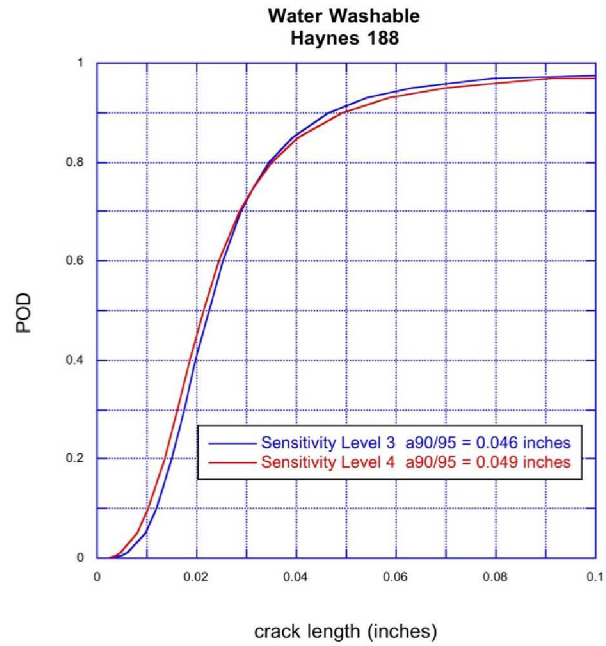

Figure 9: Logit curve fit a90/95 results as a function of Method A penetrant sensitivity level for Haynes 188 demonstration tests.

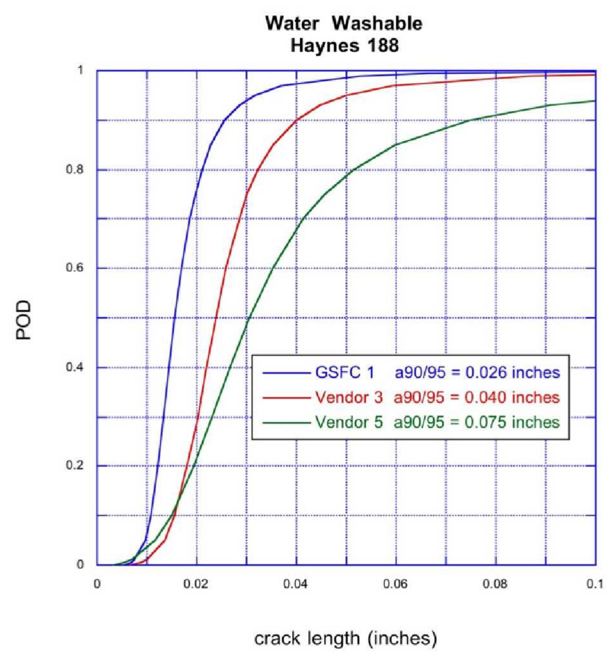

Figure 10: Logit curve fit a90/95 results as a function of Method A inspector for Haynes 188 demonstration tests.

During his first trial, the GSFC inspector noticed that for some of the longer cracks, the indications were intermittent, almost as if the crack was partially clogged with debris. Upon low magnification (10 to 20 times) microscopic examination, he observed that the intermittent indications were a result of the non-uniform and sparse nature of his developer application. As a consequence, this inspector applied an unusually heavy coating of the developer and the indications became stronger and continuous. This technique was then adopted for all his inspections. The Vendor 3 inspector to some extent discovered the same thing. In his case, the discovery occurred during the checking of some flaw indications. The inspector was witnessed wiping potential flaw indications with a alcohol dampened swab and then re-developing the area with a concentrated developer application, i.e., a much heavier application than was initially applied to the entire panel. The Vendor 5 inspector consistently gave the panels a light dusting of developer and never discovered the strong influence of the development process on the crack detection in Haynes 188. The strong influence of developer application for detection of cracks in Haynes 188 was previously noted by Ward Rummel in his 1998 paper[9]. In this paper, the POD for Haynes 188 panels before and after developing was compared. Rummel gives the example of an inspector detecting only 86 of 284 cracks without developer with no a90/95 achieved. With developer, the same inspector found 277 of 311 cracks with an a90/95 of 0.077 inches.

As previously noted, for the Method A 6061-Al demonstration tests, inspectors also displayed extreme variations in the amount of D-100 developer applied, but the resultant variation in POD was much less. Observations in this study showed that the increase in indication brightness after developer application was much greater for the Haynes 188 panels as compared to the 6061-Al and Ti-6Al-4V panels. It was also noted that the majority of the cracks in the 6061-Al and Ti-6Al-4V panels could be detected prior to developer application, but this was not the case for the Haynes 188 panels.

Haynes 188 Method D

Table 4-A in Appendix A contains the results from all the Method D inspections performed on the Haynes 188 panel set. Point estimate and curve fit solutions were found for all 12 trials. Table 8 summarizes the sensitivity level 3 results versus level 4 results for all the trials. This table shows that the Method D sensitivity level 4 penetrants performed better on the Hayes 188 panels. The overall percentages of cracks detected were 95.6 and 96.7 percent for the sensitivity level 3 and level 4 penetrants, respectively. The final column of Table 8, which was obtained by performing Logit curve fits on the combination of all 6 sensitivity level 3 hit-miss data sets and all six of the level 4 sets, show the a90/95 values for the two levels of penetrants differ by 0.004 inches. These results are shown graphically in Figure 11.

Table 8: Comparison of sensitivity level 3 versus level 4 penetrants for Method D demonstration tests performed on Haynes 188.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	6	637	609	28	95.6	0.043
4	6	641	618	23	96.7	0.039

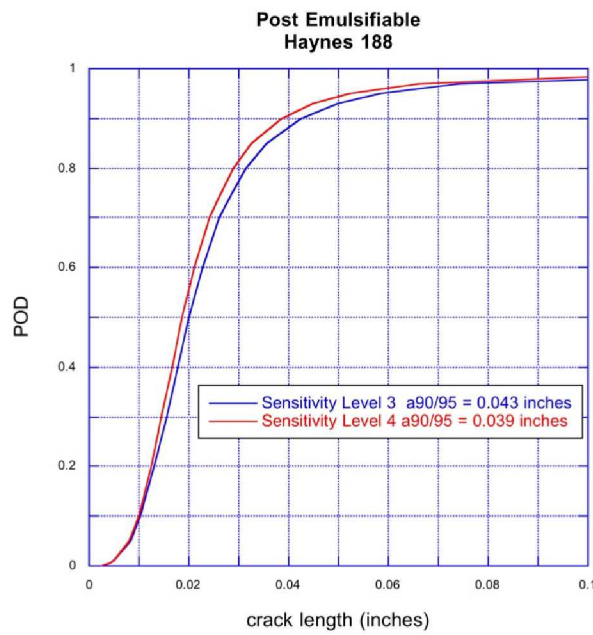

Figure 11: Logit curve fit a90/95 results as a function of Method D penetrant sensitivity level for Haynes 188 demonstration tests.

Again, all of the hit-miss results for each inspector (four trials, two with sensitivity level 3 and two with sensitivity level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 12, show that the demonstrated a90/95 is again a stronger function of the inspector than of the penetrant. The range of variation for the three inspectors, which were the same three that performed the Method A inspections on this panels set, is smaller (0.026 to 0.075 inches for Method A and 0.023 to 0.059 inches for Method D). The biggest change was with Vendor 5 inspector. This may be due to the fact that the dry powder developer, by its nature of application (dip and drag), will completely coat the surface, whereas this may not be the case for a light dusting with the D-100 developer. This appears more critical for the Haynes 188, where crack detection is strongly influenced by the development process.

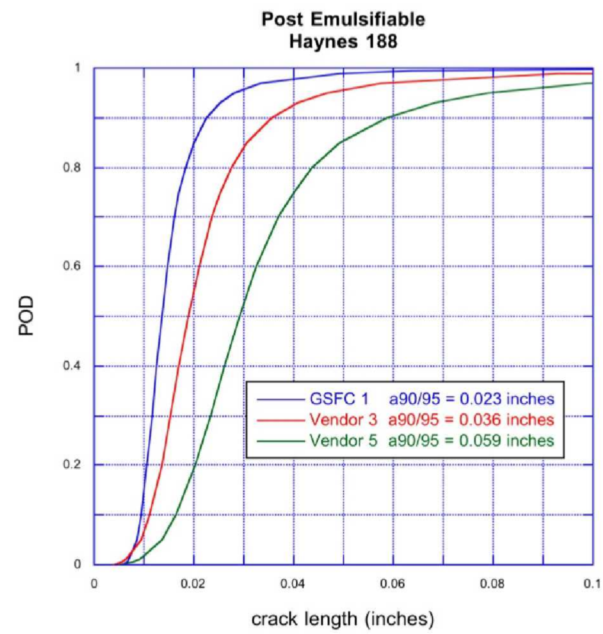

Figure 12: Logit curve fit a90/95 results as a function of Method D inspector for Haynes 188 demonstration tests.

Ti-6Al-4V Method A

All of the individual inspector demonstration test results for the inspections of the Ti-6Al-4V panels set using the Method A penetrants is shown in Table 5-A in Appendix A. The table shows that in 5 of the 12 trials there was no point estimate solution. This is a consequence of the small number of cracks in this panel set; as few as two missed cracks can result in no point estimate solution. In addition, there were two trials with no Logit curve fit solution. Table 9 shows that the overall average number of cracks detected for the sensitivity level 3 trials (97.8 percent) was higher than for the level 4 trials (96.2 percent). The Logit curve fit a90/95 values obtained by combining all six level 3 trials (0.043 inches) is with in 0.001 inches of the a90/95 obtained by combining the six level 4 trials (0.044 inches). These results are shown graphically in Figure 13.

Table 9: Comparison of sensitivity level 3 versus level 4 penetrants for Method A demonstration tests performed on Ti-6Al-4V.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	6	324	317	7	97.8	0.043
4	6	315	303	12	96.2	0.044

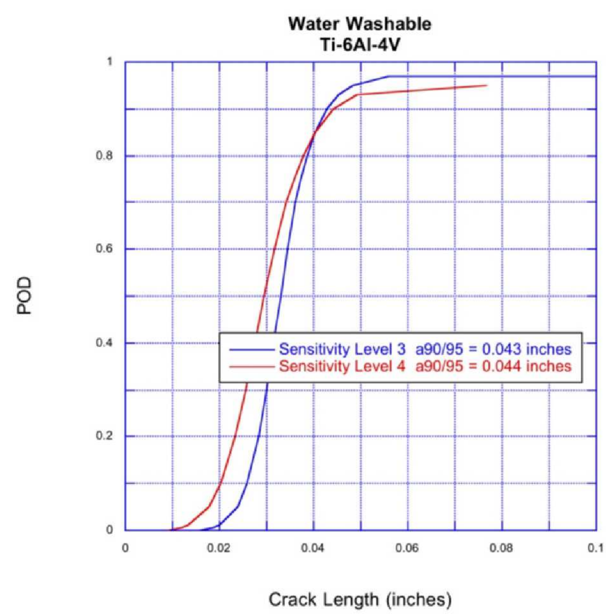

Figure 13: Logit curve fit a90/95 results as a function of Method A penetrant sensitivity level for Ti-6Al-4V demonstration tests.

Again, all of the hit-miss results for each inspector (four trials, two with sensitivity level 3 and two with sensitivity level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 14, show that the demonstrated a90/95 varies little between the three inspectors (0.041-0.048 inches). Having observed all the inspections for the three panel sets, this may be attributed to the very low background found on the Ti-6Al-4V panels. In addition, the cracks in the Ti-6Al-

4V set produced relatively bright indications before developing, which minimizes the variability created by variations in development technique.

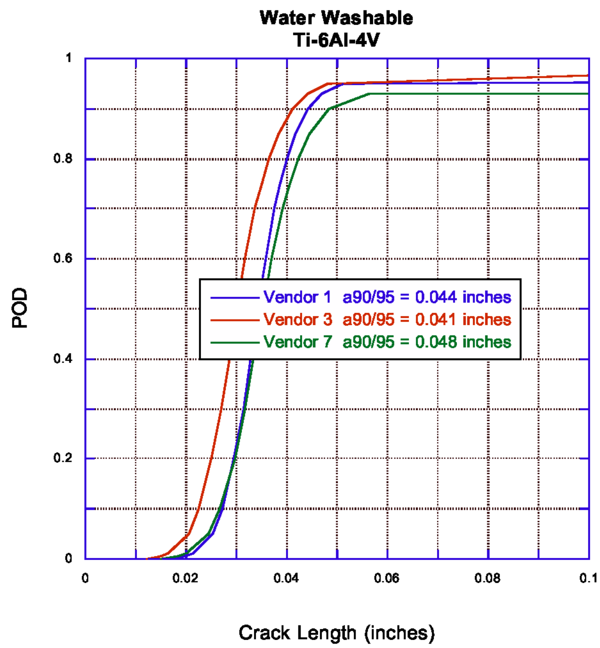

Figure 14: Logit curve fit a90/95 results as a function of Method A inspector for Ti-6Al-4V demonstration tests.

Ti-6Al-4V Method D

All of the individual inspector demonstration test results for the inspections of the Ti-6Al-4V panels set using the Method D penetrants is shown in Table 6-A in Appendix A. The table shows that there was no point estimate solution in eight of the 12 trials. This is again a consequence of the small number of cracks in this panel set. In addition, there were four trials with no Logit curve fit solution. Table 10 shows that the overall average number of cracks detected for the sensitivity level 4 trials (97.2 percent) was higher than for the level 3 trials (96.4 percent). The Logit curve fit a90/95 values obtained by combining all six level 3 trials (0.041 inches) is with in 0.001 inches of the a90/95 obtained by combining the six level 4 trials (0.042 inches). These results are shown graphically in Figure 15.

Table 10: Comparison of sensitivity level 3 versus level 4 penetrants for Method D demonstration tests performed on Ti-6Al-4V.

Sensitivity Level	Number of Trials	Total Number of Flaws	Total Number of Hits	Total Number of Misses	Percent of Flaws Hit	Logit Curve Fit on Combined Hit/Miss Data (inches)
3	6	306	295	11	96.4	0.041
4	6	319	310	9	97.2	0.042

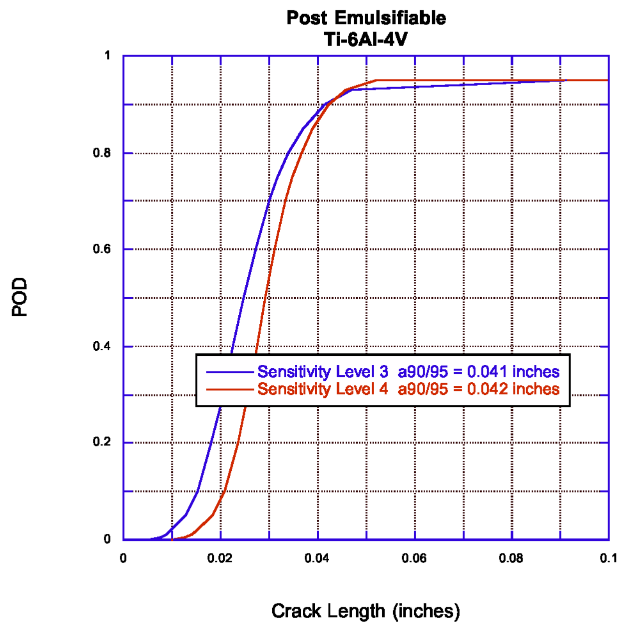

Figure 15: Logit curve fit a90/95 results as a function of Method D penetrant sensitivity level for Ti-6Al-4V demonstration tests.

Again, all of the hit-miss results for each inspector (four trials, two with sensitivity level 3 and two with sensitivity level 4 penetrants) were combined and analyzed using the Logit curve fit technique. These results, which are plotted in Figure 16, show that the demonstrated a90/95 varies little between the three inspectors (0.043-0.047 inches).

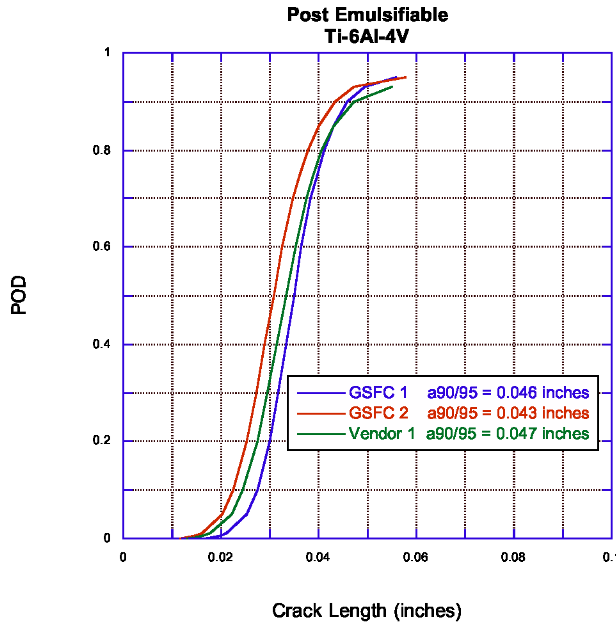

Figure 16: Logit curve fit a90/95 results as a function of Method D inspector for Ti-6Al-4V demonstration tests.

Conclusions

Table 11 provides a summary for all 92 demonstration tests performed in this study. The table presents the overall percentage of cracks found and the Logit curve fit a90/95 value for the combined hit/miss data sets as a function of metal, penetrant inspection method and penetrant sensitivity level. These results show that for all three metals and both inspection methods, the crack detection capability of the sensitivity level 3 penetrants is essentially identical to the sensitivity level 4 penetrants.

Metal	Method	Number of Trials	Sensitivity Level	Percent of Cracks Hit	Logit Curve Fit a90/95 on Combined Data Set (inches)
6061 Al	A	10	3	92.7	0.052
6061 Al	A	10	4	93.0	0.051
Haynes 188	A	6	3	94.7	0.046
Haynes 188	A	6	4	94.5	0.049
Ti-6Al-4V	A	6	3	97.8	0.043
Ti-6Al-4V	A	6	4	96.2	0.044
6061 Al	D	12	3	97.4	0.040
6061 Al	D	12	4	96.1	0.045
Haynes 188	D	6	3	95.6	0.043
Haynes 188	D	6	4	96.7	0.039
Ti-6Al-4V	D	6	3	96.4	0.041
Ti-6Al-4V	D	6	4	97.2	0.042

Table 11: Summary of all demonstration tests performed in the study.

The largest difference in the overall percentage of cracks detected was 1.6 percent for the Ti-6Al-4V Method A case. In this case the sensitivity level 3 penetrants performed better (97.8 percent) than the sensitivity level 4 penetrants (96.2 percent). There were two additional cases (Haynes 188 Method A and 6061-Al Method D) where based on the overall percentage of cracks hit, the sensitivity level 3 penetrants performed slightly better than the level 4 penetrants. For the other three cases (6061-Al Method A, Haynes 188 Method D and Ti-6Al-4V Method D) the sensitivity level 4 penetrants performed slightly better.

The table also shows that the Logit curve fit a90/95 values for the combined hit/miss data sets for the two penetrant sensitivity levels vary no more than 0.005 inches. Also the results show that in four of the six cases, the a90/95 is lower for the sensitivity level 3 penetrants.

The results from this study show that there is no significant difference in crack detection capability between sensitivity level 3 and sensitivity level 4 penetrants. As a consequence, sensitivity level 3 penetrants should be acceptable for NASA Standard Level penetrant inspections.

References:

[1]NASA-STD-5009, "Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components," Baseline Release, April, 2008.

[2]NASA/TM-2009-215850, "A Comparison of the Capability of Sensitivity Level 3 and Sensitivity Level 4 Fluorescent Penetrants to Detect Fatigue Cracks in Aluminum,"

[3]NASA-CR-170879, "NDE Detectability of Fatigue Type Cracks in High-Strength Alloys," Martin Marietta Corporation, July 1983.

[4]P.F. Packman et al., "Reliability of Flaw Detection by Nondestructive Inspection," Metals Handbook, 8th Edition, Volume 11, 1976.

[5]A.P. Berens, "NDE Reliability Data Analysis," Metals Handbook, 9th Edition, Volume 17, 1989.

[6]J.S. Cramer, Logit Models from Economics and Other Fields, Cambridge University Press, 2003.

[7]MIL-HDBK-1823A, "Nondestructive Evaluation System Reliability Assessment," April 2009.

[8]J.A. Lively and T.L. Aljundi, "Fluorescent Penetrant Inspection Probability of Detection Demonstration Performed for Space Propulsion," AIP Conf. Proc., Vol. 657, Issue 1, 2003.

[9]W. D. Rummel, "Probability of Detection as a Quantitative Measure of Nondestructive Testing End-To-End Process Capabilities", Materials Evaluation, January 1998.

Appendix A

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
12/10/08	Vendor 1	ZL-67	3	66	59	7	1	0.073	N/A
11/12/08	Vendor 1	ZL-56	4	61	56	5	1	0.052	0.063
11/5/08	Vendor 1	HM607	3	59	51	8	0	0.081	N/A
12/3/08	Vendor 1	HM704	4	63	57	6	0	0.056	0.085
1/28/09	Vendor 2	ZL-67	3	81	70	11	15	0.071	0.130
1/21/09	Vendor 2	ZL-56	4	82	75	7	22	0.061	0.085
2/11/09	Vendor 2	HM607	3	81	75	6	21	0.057	0.080
2/4/09	Vendor 2	HM704	4	81	74	7	19	0.059	0.076
1/28/09	GSFC 1	ZL-67	3	81	78	3	5	0.050	0.062
1/21/09	GSFC 1	ZL-56	4	82	79	3	3	0.056	0.082
1/14/09	GSFC 1	HM607	3	82	77	5	5	0.056	0.070
1/7/09	GSFC 1	HM704	4	82	77	5	8	0.055	0.065
3/4/09	Vendor 3	ZL-67	3	81	80	1	9	0.042	0.059
3/11/09	Vendor 3	ZL-56	4	81	80	1	7	0.042	0.059
2/25/09	Vendor 3	HM607	3	81	77	4	5	0.054	0.065
2/18/09	Vendor 3	HM704	4	81	80	1	7	N/A	0.070
4/15/09	Vendor 4	ZL-67	3	81	73	8	2	0.071	0.090
4/22/09	Vendor 4	ZL-56	4	81	73	8	5	0.061	0.080
4/1/09	Vendor 4	HM607	3	81	78	3	9	0.048	0.062
4/29/09	Vendor 4	HM704	4	81	70	11	1	0.077	0.130

Table 1-A: Individual results for each inspector performing Method A demonstration tests on the 6061-Al panel set.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
5/8/09	GSFC 1	ZL-27A	3	81	81	0	5	0.026	0.058
5/6/09	GSFC 1	ZL-37	4	81	80	1	8	0.044	0.059
7/9/09	GSFC 1	RC65	3	81	81	0	2	0.026	0.058
7/10/09	GSFC 1	RC77	4	81	81	0	3	0.026	0.058
5/20/09	Vendor 4	ZL-27A	3	81	79	2	6	0.05	0.065
5/13/09	Vendor 4	ZL-37	4	81	75	6	1	0.083	0.165
8/6/09	Vendor 4	RC65	3	80	72	8	3	0.078	0.165
8/14/09	Vendor 4	RC77	4	80	73	7	11	0.061	0.07
6/2/09	Vendor 3	ZL-27A	3	81	81	0	1	0.026	0.058
6/10/09	Vendor 3	ZL-37	4	80	80	0	0	0.026	0.058
8/25/09	Vendor 3	RC65	3	79	77	2	2	0.052	0.065
9/1/09	Vendor 3	RC77	4	80	79	1	3	0.043	0.059
6/17/09	Vendor 5	ZL-27A	3	79	79	0	16	0.026	0.058
6/30/09	Vendor 5	ZL-37	4	81	75	6	47	0.062	0.09
8/18/09	Vendor 5	RC65	3	80	77	3	3	0.056	0.076
8/20/09	Vendor 5	RC77	4	80	78	2	1	0.05	0.075
6/24/09	Vendor 6	ZL-27A	3	78	78	0	8	0.026	0.058
7/8/09	Vendor 6	ZL-37	4	81	80	1	6	0.026	0.058
7/20/09	Vendor 6	RC65	3	80	77	3	2	0.048	0.062
7/22/09	Vendor 6	RC77	4	81	77	4	2	0.052	0.075
8/13/09	Vendor 7	ZL-27A	3	80	77	3	16	0.058	0.09
8/11/09	Vendor 7	ZL-37	4	80	75	5	30	0.077	0.112
7/25/09	Vendor 7	RC65	3	80	76	4	45	0.059	0.076
7/27/09	Vendor 7	RC77	4	81	76	5	35	0.059	0.07

Table 2-A: Individual results for each inspector performing Method D demonstration tests on the 6061-Al panel set.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
1/5/10	GSFC 1	ZL-67	3	107	106	1	7	0.030	0.055
11/30/09	GSFC 1	ZL-56	4	103	101	2	12	0.012	0.055
12/14/09	GSFC 1	HM-607	3	107	106	1	6	0.030	0.055
12/7/09	GSFC 1	HM-704	4	107	105	2	7	0.037	0.055
12/21/09	Vendor 3	ZL-67	3	107	102	5	7	0.048	0.085
1/12/10	Vendor 3	ZL-56	4	107	103	4	13	0.048	0.087
12/16/09	Vendor 3	HM-607	3	107	104	3	14	0.020	0.055
12/2/09	Vendor 3	HM-704	4	107	102	5	10	0.055	0.105
1/19/10	Vendor 5	ZL-67	3	107	96	11	6	0.087	0.229
3/2/10	Vendor 5	ZL-56	4	107	91	16	2	0.189	n/a
3/9/10	Vendor 5	HM-607	3	107	94	13	1	0.085	0.136
1/26/10	Vendor 5	HM-704	4	107	101	6	2	0.051	0.087

Table 3-A: Individual results for each inspector performing Method A demonstration tests on the Haynes 188 panel set.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
5/4/10	GSFC 1	ZL-27A	3	102	101	1	8	0.031	0.055
5/6/10	GSFC 1	ZL-37	4	107	106	1	10	0.030	0.055
5/3/10	GSFC 1	RC-65	3	107	106	1	15	0.030	0.055
5/5/10	GSFC 1	RC-77	4	107	106	1	9	0.030	0.055
3/31/10	Vendor 3	ZL-27A	3	107	104	3	6	0.047	0.095
4/6/10	Vendor 3	ZL-37	4	106	102	4	6	0.048	0.085
2/18/10	Vendor 3	RC-65	3	107	104	3	7	0.020	0.055
2/24/10	Vendor 3	RC-77	4	107	105	2	9	0.040	0.082
4/27/10	Vendor 5	ZL-27A	3	107	96	11	1	0.087	0.232
4/20/10	Vendor 5	ZL-37	4	107	95	12	1	0.087	0.137
3/23/10	Vendor 5	RC-65	3	107	98	9	1	0.066	0.133
3/17/10	Vendor 5	RC-77	4	107	104	3	4	0.020	0.055

Table 4-A: Individual results for each inspector performing Method D demonstration tests on the Haynes 188 panel set.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
8/26/10	Vendor 1	ZL-67	3	54	53	1	0	0.047	0.058
8/31/10	Vendor 1	ZL-56	4	54	54	0	0	0.032	0.052
8/18/10	Vendor 1	HM-607	3	54	53	1	1	0.048	0.058
8/24/10	Vendor 1	HM-704	4	54	52	2	2	0.063	n/a
7/27/10	Vendor 3	ZL-67	3	54	51	3	0	0.051	0.059
7/29/10	Vendor 3	ZL-56	4	54	54	0	0	0.032	0.052
8/20/10	Vendor 3	HM-607	3	54	54	0	1	0.032	0.052
8/13/10	Vendor 3	HM-704	4	52	50	2	0	n/a	n/a
8/2/10	Vendor 7	ZL-67	3	54	52	2	2	0.059	n/a
7/15/10	Vendor 7	ZL-56	4	47	43	4	7	0.055	n/a
8/9/10	Vendor 7	HM-607	3	54	54	0	2	0.032	0.052
8/11/10	Vendor 7	HM-704	4	54	48	4	2	n/a	n/a

Table 5-A: Individual results for each inspector performing Method A demonstration tests on the Ti-6Al-4V panel set.

Date	Inspector	Penetrant	Sensitivity	Flaws	Hits	Misses	False Calls	a90/95 Logit Curve Fit	a90/95 Point Estimate
10/6/10	GSFC 1	ZL-27A	3	50	50	0	0	0.032	0.052
9/27/10	GSFC 1	ZL-37	4	54	52	2	4	n/a	n/a
10/4/10	GSFC 1	RC-65	3	48	45	3	2	n/a	n/a
10/5/10	GSFC 1	RC-77	4	54	54	0	2	0.032	0.052
9/13/10	GSFC 2	ZL-27A	3	54	53	1	0	0.047	0.058
9/21/10	GSFC 2	ZL-37	4	54	51	3	0	n/a	n/a
9/7/10	GSFC 2	RC-65	3	54	52	2	0	0.063	n/a
9/16/10	GSFC 2	RC-77	4	53	53	0	1	0.032	0.059
11/16/10	Vendor 1	ZL-27A	3	50	47	3	1	n/a	n/a
11/8/10	Vendor 1	ZL-37	4	50	48	2	0	0.196	n/a
11/18/10	Vendor 1	RC-65	3	50	48	2	0	0.196	n/a
11/22/10	Vendor 1	RC-77	4	54	52	2	0	0.056	n/a

Table 6-A: Individual results for each inspector performing Method D demonstration tests on the Ti-6Al-4V panel set.

Appendix B

Production of Ti-6Al-4V Crack Panels

The JSC set of specimens was made from the solution treated and aged titanium alloy, 6 aluminum, 4 vanadium (Ti-6Al-4V STA). The intent was to produce 29 primary fatigue cracks with surface lengths of 0.050 +/- 0.005 inches and with aspect ratios of 0.5. A number of secondary cracks were also produced, some with longer and shorter lengths than the primary set of cracks. Two such sets of specimens were produced.

The cracks were introduced into panels that were initially 18 inches long by 3.9 inches wide by 0.250 inches thick. Seven electric-discharge machine (EDM) fatigue crack starter notches were randomly introduced along the 18-inch length on one side of the panel. The intended crack sites were first prepared with a pair of slotting cutters that were used to scoop metal out at each site. The scooped out area was approximately one inch square and was cut to a depth of 0.050 inches. The closely spaced slotting cutters, shown in Figure B-1, left a thin (0.010 inches) upstanding, lengthwise rib centered in the cut. The rib was subsequently EDM-notched to a depth of 0.020 inches. This scoop-rib method of initiating cracking was performed to facilitate producing short fatigue cracks with aspect ratios near 0.5.

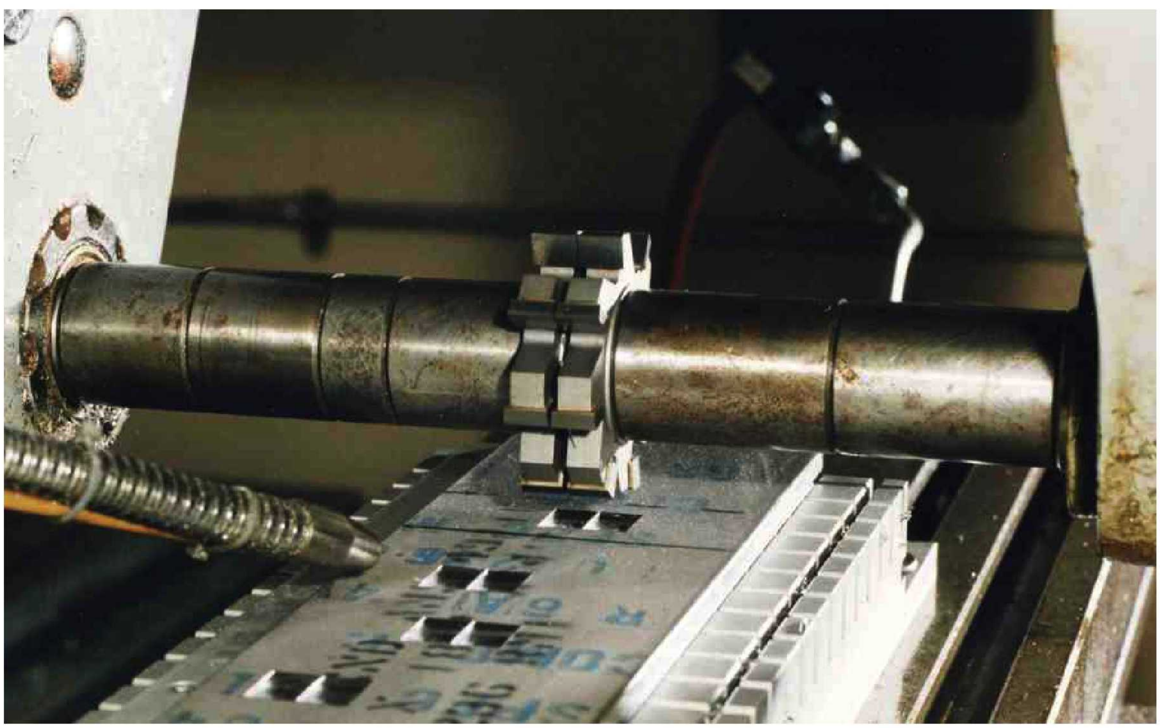

Figure B-1. Slotting Cutters and resulting Scoop-Rib Areas on a Test Panel

Fatigue cracking was accomplished in cantilever bending using a Vishay fatigue machine. Growing fatigue cracks in bending with conventional EDM notches tended toward low aspect ratio cracks. The scoop-rib method allowed short, 0.5 aspect ratio cracks to be produced relatively easily where the crack initiated in the notched rib and grew into the base metal at a high aspect ratio. Each crack was grown separately by clamping the scooped out site such that the notch in the rib was at the point of maximum stress in bending (i.e., just beyond the end of the clamp). A moment arm of four inches was used during cycling and the displacement was controlled so as not to exceed 50 percent of the material's yield strength. A typical test set up is shown in Figure B-2. As each crack was grown to the desired length, the panel was re-clamped at the next scoop-rib site and the completed crack was moved under the clamps so that no additional crack growth occurred. This process of fatigue cycling a scoop-rib site to the desired crack length and moving the finished crack under the clamps was continued until all seven cracks were completed.

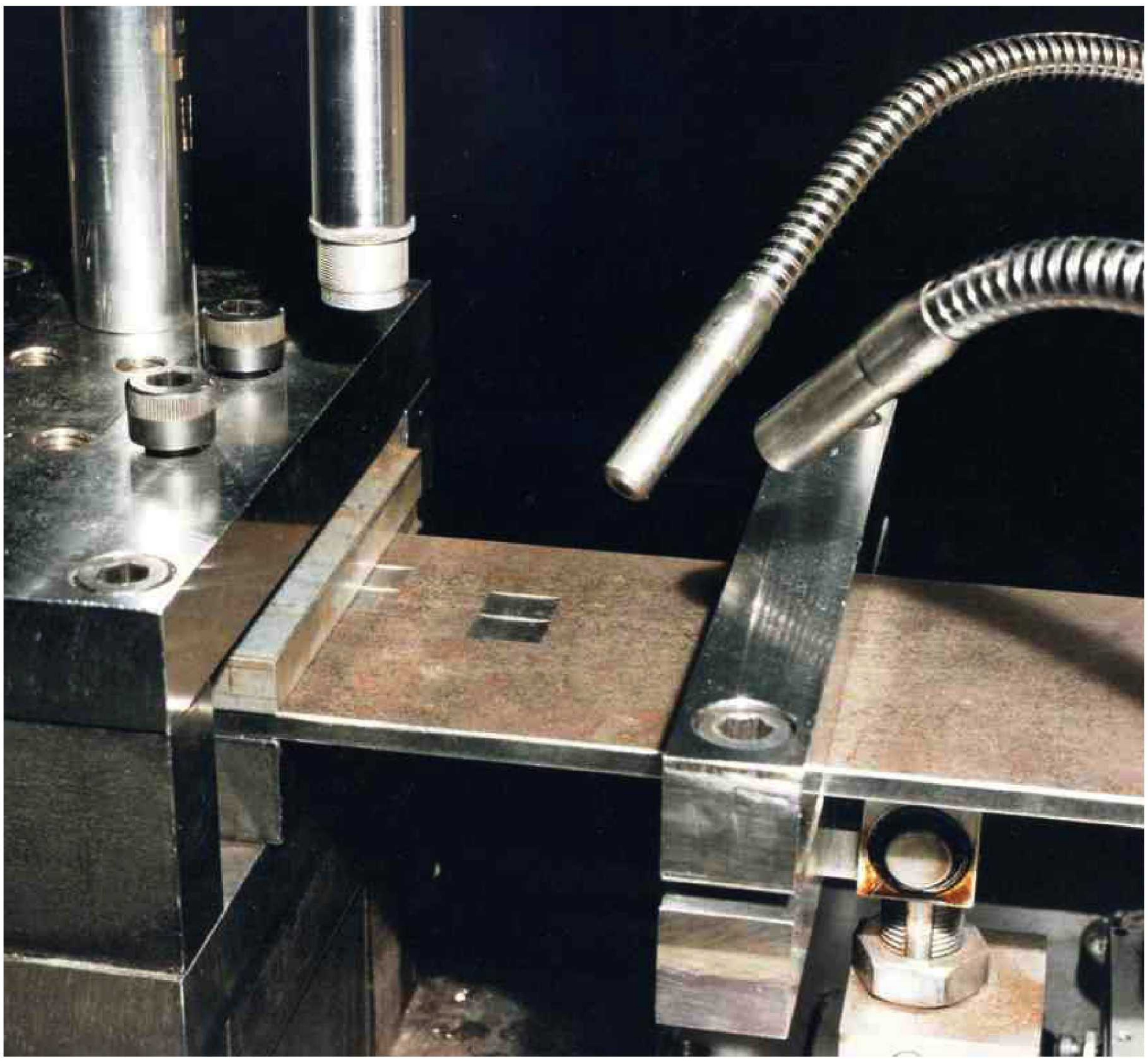

Figure B-2. Typical Fatigue Test Set Up Showing Loading Arrangement

Crack growth was monitored with a long focal length traveling microscope at a magnification of 50x. As the crack grew in depth and length, the surface length was measured with the traveling microscope. By interrupting the fatigue cycling, applying the maximum stress to the panel, and reading the crosshair locations of the crack tips, the crack length was determined to the nearest 0.001 inches. At 50x with a static maximum stress applied, the crack tips were readily visible.

After the cracking was completed, the individual panels were surface milled on both surfaces to near final thickness and then surface ground on both surfaces to the final thickness of 0.125 inches. The final surface grinding of the crack was performed to remove any trace of the scoop machined surfaces at the crack sites. After final grinding to the finished thickness, the 18 inch panels were cut into three panels 6 inches long. The final surface preparation was completed by chemically-etching to remove smeared metal from the milling and grinding operations. The etchant used was a 20 percent muriatic acid that removed approximately 0.0003 to 0.0004 inches of metal per side. After etching, the final recorded crack length measurement was made on an optical comparator to the nearest 0.0001 inches. The detectability of each crack was verified with a spot solvent removable penetrant test.

To validate the cracking process, a number of the cracks were broken open. Breaking open the cracks allowed the crack depths to be measured and the crack aspect ratios to be determined. Four cracks were broken open before any machining occurred and six cracks were opened after the machining and etching were completed. The pre-machined cracks did have high aspect ratios and ranged from 0.48 to 0.57. The post-machined and etched cracks had aspect ratios ranging from 0.36 to 0.46. The lower than intended aspect ratios of the finished cracks was due to the shallowness of the crack depths and the need to insure the complete removal of any evidence of the scoop machined surfaces by removing a few ten-thousandths of an inch past the scooped surface. The end result was that the cracks in the final specimen set had aspect ratios closer to 0.4 than to 0.5. Several broken open crack surfaces from a similarly manufactured set of 0.025 inch long cracks are shown in Figures B-3 and B-4.

As a result of the etching process, the surface crack opening for the cracks in the set is on the order of 0.0003 to 0.0004 inches. The crack opening gets significantly tighter just below the surface where the etching process had little effect. This fact became evident when one of the cracks in the set was sacrificed for a metallurgical examination of crack tightness as a function of depth. The metallurgical cross section of the sacrificed crack, which is also from the set of 0.025 inch long cracks, is shown in Figure B-5. The crack opening at the surface measures about 0.0004 inches and is V-shaped to a depth of about 0.002 inches after which the opening is very tight and measures less than 0.0001 inches. The V-shape is due to the removal of metal from the crack faces by the etchant.

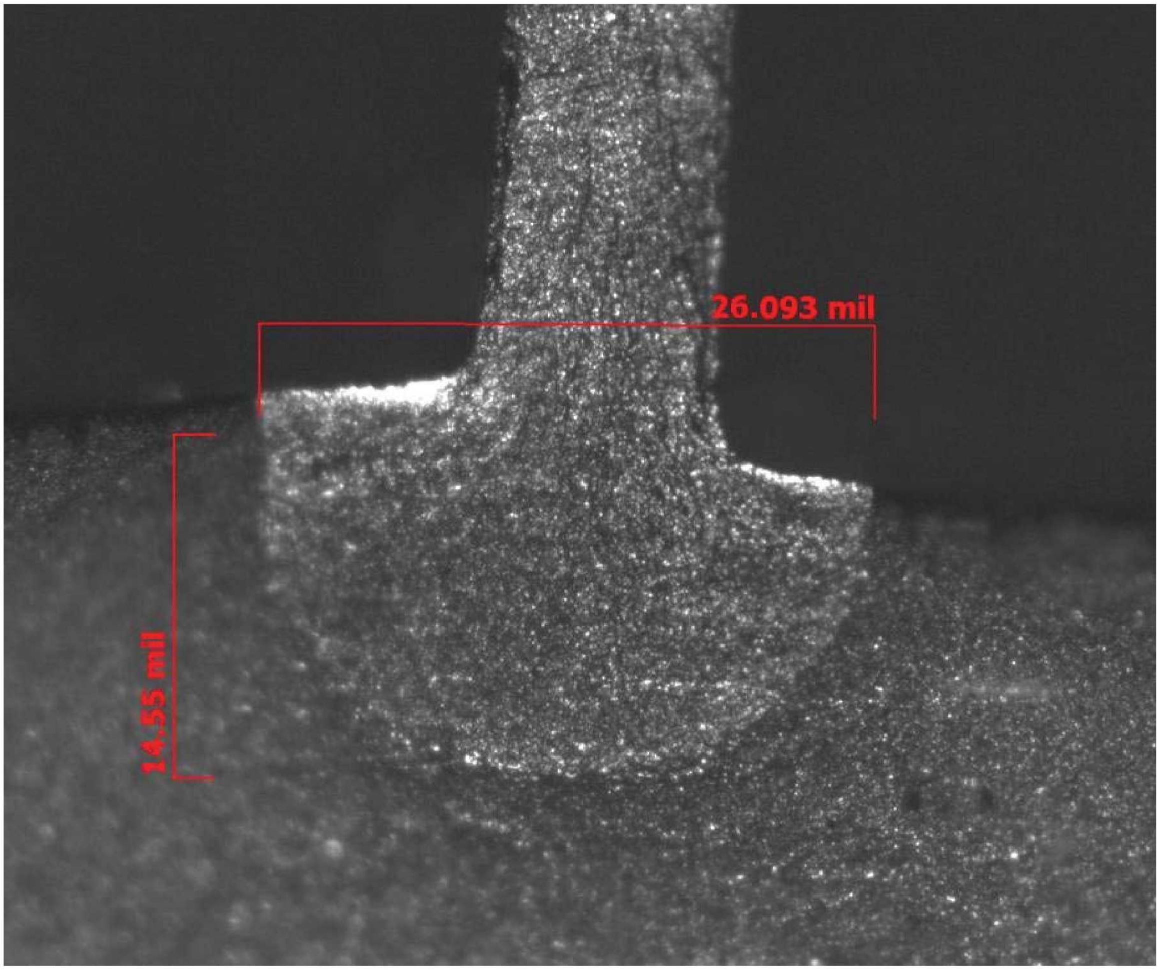

Figure B-3. Pre-machined Crack Surface with Rib. Mag: 70x

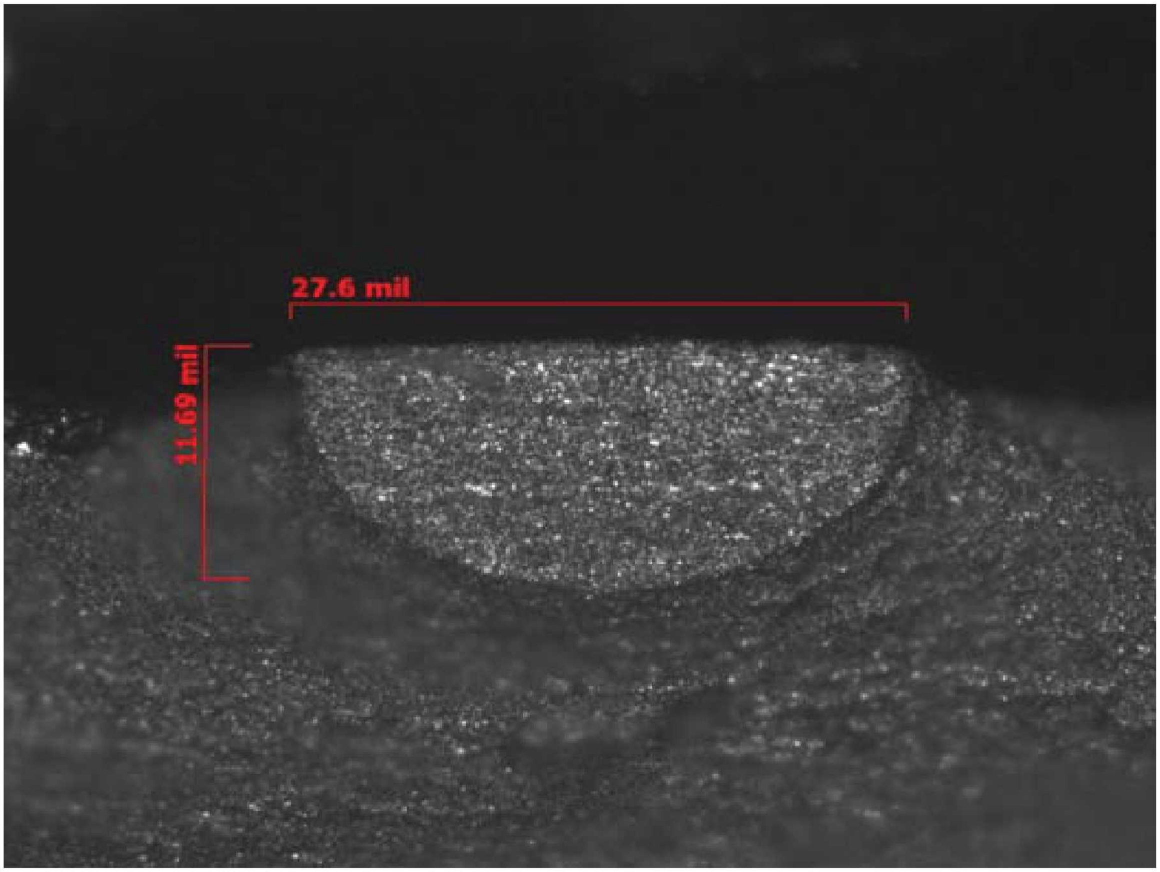

Figure B-4. Post-machined and Etched Crack Surface. Mag: 70x

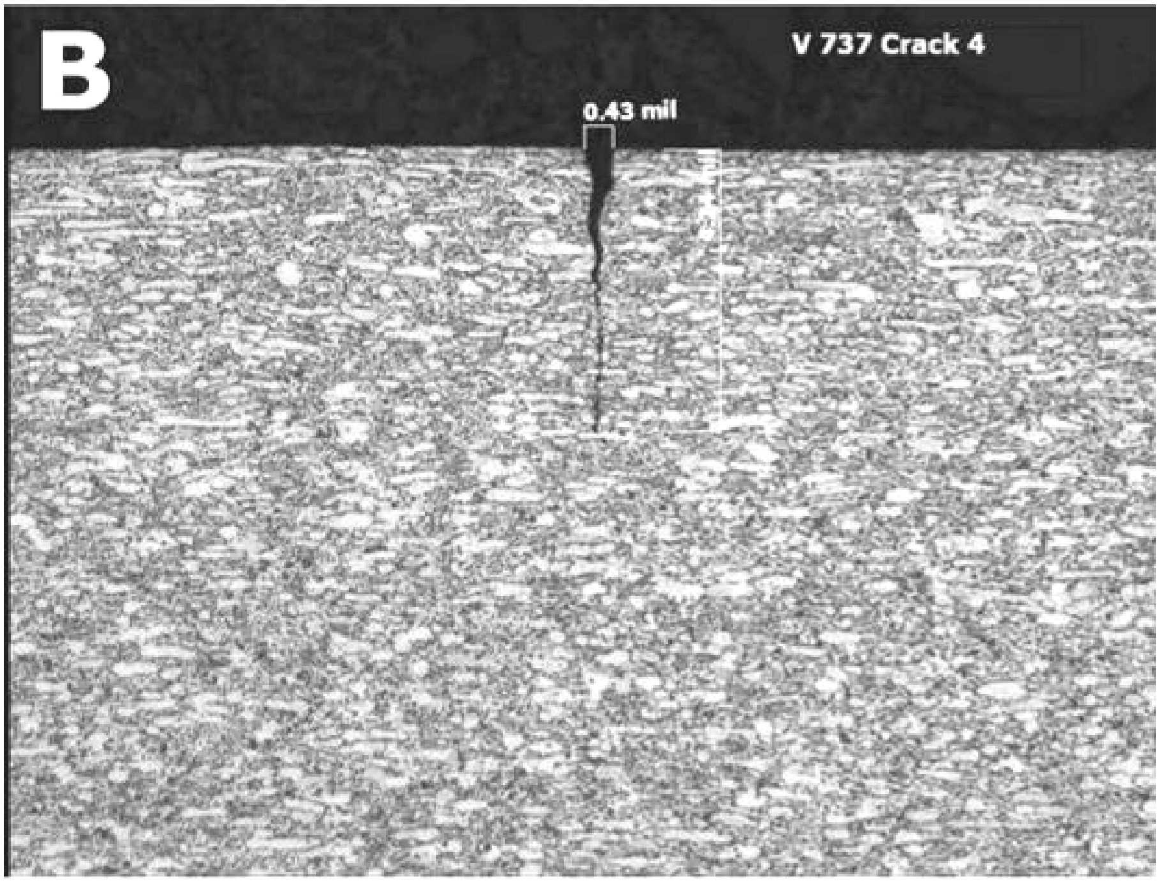

Figure B-5. Metallographic Cross Section of a Crack. Mag: 200x

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14. ABSTRACT
In April 2008, NASA-STD-5009 established a requirement that only sensitivity level 4 penetrants are acceptable for NASA Standard Level liquid penetrant inspections. Having NASA contractors change existing processes or perform demonstration tests to certify sensitivity level 3 penetrants posed a potentially huge cost to the Agency. This study was conducted to directly compare the probability of detection (POD) of sensitivity level 3 and level 4 penetrants using both Method A and Method D inspection processes. POD demonstration tests were performed on 6061-Al, Haynes 188 and Ti-6Al-4V crack panel sets. The study results strongly support the conclusion that sensitivity level 3 penetrants are acceptable for NASA Standard Level inspections.

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