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FAA Fluorescent Penetrant Laboratory Inspections

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Abstract

The Federal Aviation Administration Airworthiness Assurance NDI Validation Center currently assesses the capability of various non-destructive inspection (NDI) methods used for analyzing aircraft components. The focus of one such exercise is to evaluate the sensitivity of fluorescent liquid penetrant inspection. A baseline procedure using the water-washable fluorescent penetrant method defines a foundation for comparing the brightness of low cycle fatigue cracks in titanium test panels. The analysis of deviations in the baseline procedure will determine an acceptable range of operation for the steps in the inspection process. The data also gives insight into the depth of each crack and which step(s) of the inspection process most affect penetrant sensitivities. A set of six low cycle fatigue cracks produced in 6.35-mm thick Ti-6Al-4V specimens was used to conduct the experiments to produce sensitivity data. The results will document the consistency of the crack readings and compare previous experiments to find the best parameters for water-washable penetrant.

Introduction

The main role of the Federal Aviation Administration Airworthiness Assurance NDI Validation Center is to study and validate various nondestructive inspection techniques to support the needs of the commercial airline industry. The analysis of fluorescent-liquid penetrant inspection techniques provides a resource for industry needs in the penetrant community. Liquid penetrant inspection is used to test critical rotating engine components for small cracks that may create detrimental consequences. One such request for evaluating penetrant inspection techniques is documented in the National Transportation Safety Board Accident Report [1] of an uncontained engine failure in which detectable cracks were overlooked.

Visual inspection using fluorescent penetrant identifies an aircraft component as being problematic, requiring the replacement or repair of the part. The current baseline procedure for inspection is defined by the standards of Wright Laboratory in Dayton, Ohio. This procedure is used to qualify all commercial and military penetrants in the United States. Over the course of the summer, variations in the baseline procedure using Method A, Level 4 (water-washable penetrant) were analyzed to determine the affects on crack detection. The deviations in the procedure included changes in the dryer oven temperature, the developer dwell time, the penetrant dwell time, the rinsing water temperature and pressure, and the type of ultrasonic cleaner. The brightness of the penetrant in the cracks was recorded for each test and compared to the results of the baseline procedure to determine the best parameters for water-washable liquid penetrant inspection.

Materials and Equipment Used

The experiments were all performed at the Nondestructive Inspection Validation Center hangar on the west boundary of the Albuquerque International Airport. A liquid penetrant inspection lab, arranged in the same manner as commercial inspection labs, is located inside the hangar. The lab consists of all the necessary equipment needed for penetrant inspection. This includes a cleaning sink, a penetrant station, a rinse station with controlled water pressure and temperature, a recirculating oven drying station with variable temperature, a developer station, an inspection station with an ultraviolet light, and a postcleaning station with an ultrasonic cleaning tub.

The penetrant and dry developer used were Magnaflux Zyglo ZL-56 and ZP-4B, respectively. Methyl Ethyl Ketone was used for the ultrasonic cleaning, with one experiment using SkyKleen. The test panels were stored and rinsed in ethyl alcohol. A wire holder was used to transport the panels, and a timer capable of 60 minutes and 60 seconds controlled the station intervals. A pair of steel tongs was used to insert and remove the test panels from each of the liquids in the process. Protective equipment such as gloves and goggles was worn at all appropriate times.

A total of six titanium test panels were used for all the experiments conducted. They were selected based on their history of standard performance data. The panels were machined from a Ti-6Al-4V plate into blocks measuring 15.2 cm by 2.54 cm by 0.635 cm [2]. A single crack was initiated in the center of each panel by using a spot weld. Sine wave cyclic loading was then used to produce the low cycle fatigue cracks that were analyzed. The test panels were manufactured to create cracks with a length-to-depth ratio of 2. The six test cracks ranged from 0.778 mm to 1.12 mm in length.

Methodology

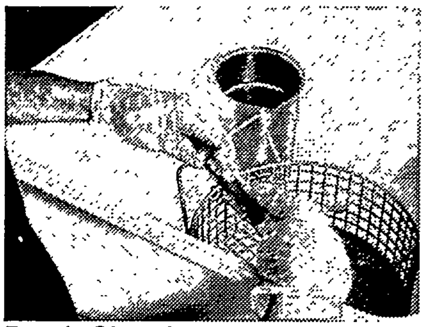
There are several different methods for performing fluorescent-liquid penetrant inspection. Each method has an associated sensitivity that determines its performance in revealing engine component cracks. The method used this summer was Method A water-washable. It was used to compare the brightness readings with previous tests utilizing Method B post-emulsifiable lipophilic. Since the water-washable method costs less to use by eliminating an extra procedural step and extra equipment, comparable results would deem this method admirable for aviation use.

The penetrant used in each of the methods is further classified into one of five levels of sensitivity. These experiments used a Level 4 penetrant, which is the most sensitive in revealing small cracks. The penetrant level of sensitivity starts with Level ½ being the lowest then increases from Level 1 to 4 by unit increments. The sensitivity of a penetrant is determined by using a TAM test panel to indicate how bright the penetrant appears in different crack sizes.

The experiments using the Method A, Level 4 process were first performed following the baseline procedure defined by Wright Laboratory [3]. The procedure is fairly straightforward after a little practice, and is outlined as follows:

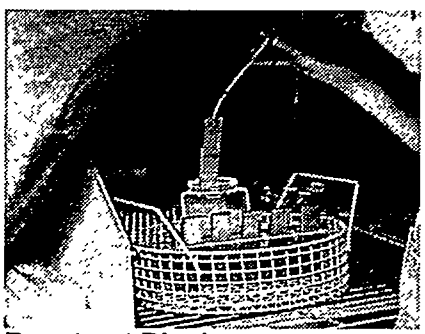
1) The first and perhaps most important step in the inspection process is to ensure that the test panels are completely clean. Any amount of dirt, grease, oil or paint on the panels can cause the cracks to be concealed from detection. In order to make sure there is no residue

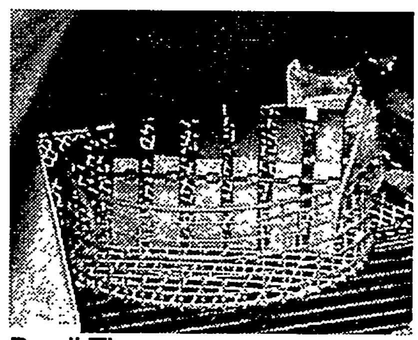
present, the panels are first cleaned with dish soap and a brush. They are then rinsed with tap water and placed in the dryer oven for 1 minute to dry. Next, the panels are placed inside a pint jar containing Methyl Ethyl Ketone (MEK) and are ultrasonically cleaned for 10 minutes. After being removed from the MEK, the panels are thoroughly rinsed with ethyl alcohol and oven dried for one minute. Now that the panels are free of any concealing particles, they are ready to be used.


Brush Cleaning


Ultrasonic Cleaning

2) The clean panels are dipped about ¾ of the way into a pint jar containing the fluorescent penetrant (in this case, Magnaflux ZL-56). They are then placed in a wire rack and allowed to drain for 5 minutes, enabling the penetrant to dwell into the cracks via capillary action.


Penetrant Dipping

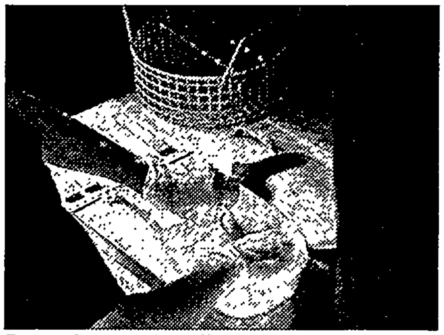

Dwell Time

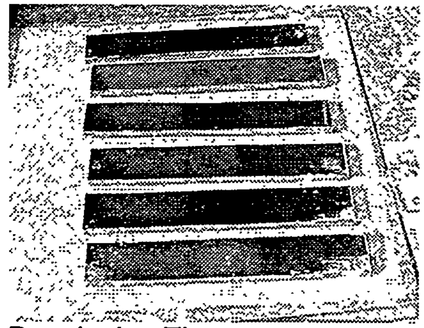
3) The panels are washed with a controllable spray nozzle. The temperature and pressure of the water should be 21.1°C (70°F±5) and 172 kPa (25 psi). In these experiments, however, cooling restrictions forced the temperature to 26.7°C (80°F±5) and the maximum pressure to 193 kPa (28 psi). The panels are sprayed front and back until all visible penetrant is driven off, for a maximum of 1 minute. This is made possible by rinsing in a sink equipped with an ultraviolet light.

4) The wire rack containing the test panels is then placed into the dryer oven. The panels are dried for 5 minutes at a temperature of 51.7°C (125°F±5).

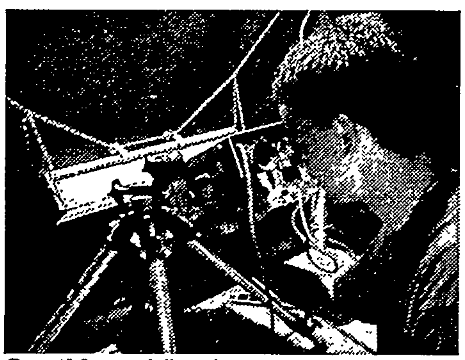
5) The panels are removed from the oven, and the developing agent is applied. The Magnaflux ZP-4B dry developer is a white powder that draws out penetrant from cracks, making them easier to detect. Each panel is swept through the developer three times to

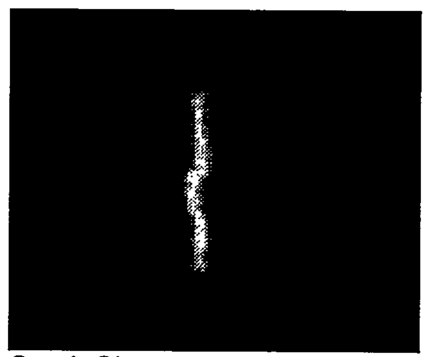
ensure complete coverage. The excess powder is gently blown off with a puff of air. The test panels are then allowed 5 minutes for the developer to extract all the penetrant from inside the cracks.


Developer Application


Developing Time

6) The Photo Research 1500 SpotMeter, which measures the brightness of the penetrant in the cracks, is calibrated while the test panels are developing. The intensity from the blacklight is measured with a digital radiometer/photometer to check if it is deteriorating. After the developing time ends, the SpotMeter is used to record the fluorescent brightness of both the panel background and the crack. These brightness readings are measured in Foot-Lamberts, a unit of luminosity. The background reading is subtracted from the crack reading to obtain the actual crack luminosity.


SpotMeter Viewing


Crack Close-up

7) The test panels are now ready to be cleaned again. The procedure listed in step 1 is again followed to prepare the panels for another test run. After the last test run of the day, the panels are all cleaned and placed in a container of ethyl alcohol for overnight storage.

The baseline procedure above is the process used by Wright Laboratory to qualify Method A, Level 4 penetrant material. The baseline tests were ran this summer to establish a comparison standard of crack luminosity readings and to document test panel consistency. Factors that influence luminosity readings were varied to examine any changes that might occur. These factors were the dryer oven temperature, the developer dwell time, the penetrant dwell time, the spray water conditions, and the ultrasonic cleaning solvent. A total of thirteen experiments were performed with four baseline experiments interspersed within to check if the cracks continued to give consistent readings. Each experiment was completed ten times to get the average and standard deviation of the crack readings for all six test panels. Table 1 shows the order in which the experiments were performed and describes the variations in the baseline operating procedure.

Table 1. Experimental Parameters

Method A, Level 4 Fluorescent Pentrant Inspection	
Experiment #	**Experimental Action**
1	Baseline (procedure listed above)
2	Dryer oven temperature changed to 40.6°C (105°F)
3	Dryer oven temperature changed to 62.8°C (145°F)
4	Dryer oven temperature changed to 73.9°C (165°F)
5	Baseline
6	Developer dwell time doubled to 10 minutes
7	Penetrant dwell time doubled to 10 minutes
8	Penetrant dwell time decreased to 2 minutes
9	Baseline
10	Water spray pressure decreased to 103 kPa (15 psi)
11	Water spray temperature increased to 32.2°C (90°F)
12	SkyKleen used for ultrasonic cleaning
13	Baseline

Results and Discussion

Each of the five deviations in the baseline procedure was tested based on the hypothesis that different experimental results would occur. The dryer oven temperature was tested at 40.6°C (105°F) and 62.8°C (145°F) to see if the penetrant viscosity was affected by heat. The developer dwell time was doubled to show whether the dry developer would draw out more penetrant given more time. The penetrant dwell time was both increased to 10 minutes and decreased to 2 minutes to analyze how long liquid penetrant needed to flow into a crack by capillary action. The spray water pressure and temperature were also varied since a water-washable penetrant, as the name indicates, must be affected by water washing conditions. The utilization of SkyKleen solvent for ultrasonic cleaning instead of MEK was considered because of its safer usability, easier disposability, and wider availability in the industry. From the results of all the experiments, test panels 13 and 37 showed continually decreasing luminosity readings. This indicates that some type of crack clogging occurred and no experimental conclusions can be based on these two panels. The results of the experimental averages and standard deviations are shown below in Table 2, with the highlighted portions indicating results near (yellow/light) or outside (orange/dark) the standard deviation of the total baseline averages. The corresponding crack lengths are shown at the bottom of the table.

Table 2. Average and Standard Deviation of Crack Luminosity Readings

Experiment	Test Panel Number 1	11	13	30	32	37
1) Baseline-Average	42.17	3.30	0.83	15.51	54.25	38.00
Standard Deviation	5.24	0.63	0.17	1.62	5.79	8.12
2) Dryer Oven at 40.6°C	38.86	2.75	0.59	13.84	60.60	32.02
(105°F)	3.74	0.70	0.06	2.70	4.77	5.42
3) Dryer Oven at 62.8°C	40.86	3.67	0.61	17.42	62.90	32.52
(145°F)	7.32	1.04	0.10	2.46	9.19	9.16
4) Dryer Oven at 73.9°C	46.21	4.82	0.42	22.62	66.57	31.02
(165°F)	5.88	0.77	0.16	4.63	5.89	5.55
5) Baseline	39.76	3.84	0.40	17.99	59.12	23.20
	3.52	0.69	0.06	3.37	5.06	2.48
6) Develop Dwell	43.60	3.97	0.30	19.58	61.24	27.86
Time of 10 minutes	5.61	0.59	0.08	4.26	4.23	11.70
7) Penetrant Dwell	48.45	3.75	0.35	21.65	63.92	28.10
Time of 10 minutes	5.77	1.31	0.06	3.31	5.04	5.52
8) Penetrant Dwell	30.23	4.19	0.09	12.76	46.17	19.24
Time of 2 minutes	4.25	1.28	0.02	3.43	10.05	10.58
9) Baseline	44.78	4.42	0.11	19.15	57.86	17.82
	4.40	0.94	0.02	5.04	3.22	12.46
10) Wash Pressure	45.06	5.39	0.09	21.21	55.62	19.48
of 103 kPa (15 psi)	3.14	0.81	0.02	3.16	9.26	5.09
11) Wash Temperature	47.13	5.31	0.08	23.35	54.51	9.90
of 32.2°C (90°F)	6.57	0.46	0.02	2.51	4.67	5.23
12) SkyKleen Cleaning	44.53	4.82	0.07	22.78	48.17	0.43
	6.83	1.05	0.02	4.71	7.31	0.14
13) Baseline	41.07	3.44	0.05	21.81	51.20	2.15
	4.89	0.69	0.02	5.45	7.92	1.97
Total Baseline Average	41.94	3.75	0.35	18.61	55.61	20.29
Standard Deviation	2.13	0.50	0.36	2.62	3.59	14.80
Crack Length:	965.9 μm	1157.1 μm	1120.0 μm	1122.1 μm	778.0 μm	1075.0 μm

The test panels numbered 1, 30 and 32 were the "standard" panels that gave consistent readings and had cracks with a length-to-depth ratio near 2 based on their luminosity [4]. Test panels 11 and 13 had longer cracks but much lower luminosity readings. This indicates that both panels have shallow cracks and have a much greater length-to-depth ratio. The structure of the cracks plays a significant part in their luminosity readings. A crack consisting of numerous microcracks allows more penetrant to seep in. Figures 1 and 2 below show Scanning Electron Micrograph photographs of test panel 32 with microcracking and test panel 13 without.

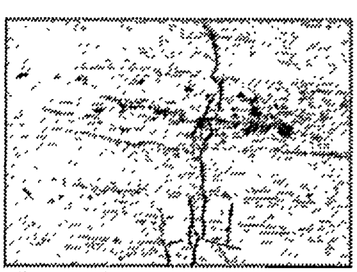


Figure 1. Panel 32, 1000X

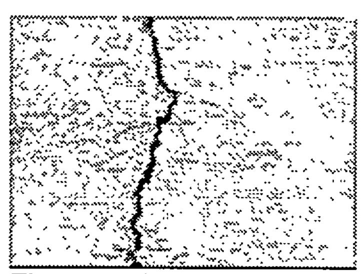


Figure 2. Panel 13, 1000X

The experimental results from the first procedural deviation show that the dryer oven temperature does indeed affect the crack luminosity readings. For the majority of the test panels, the crack luminosity increases as the oven temperature goes up. This shows that increased heat affects the penetrant viscosity, allowing it to flow easier in and out of a crack. An experiment to further support this theory was conducted at the dryer oven temperature of 165°F. The results of this experiment revealed an increase in luminosity over the baseline temperature for five of the six test panels. Panel 32 was above the range of the baseline standard deviation while panel 11 was very close to being above it, indicating that there is a statistically significant increase in crack luminosity. The highest recommended temperature setting for the dryer oven is 79.4°C (175°F) [5], so a crack will appear brighter if the baseline procedure is changed to a drying temperature at or around 73.9°C (165°F). The cost increase of running the oven at a higher temperature would need to be considered, however, since these cracks were still visible at 40.6°C (105°F). Figure 3 shows the relationship between the oven temperature and the crack luminosity.

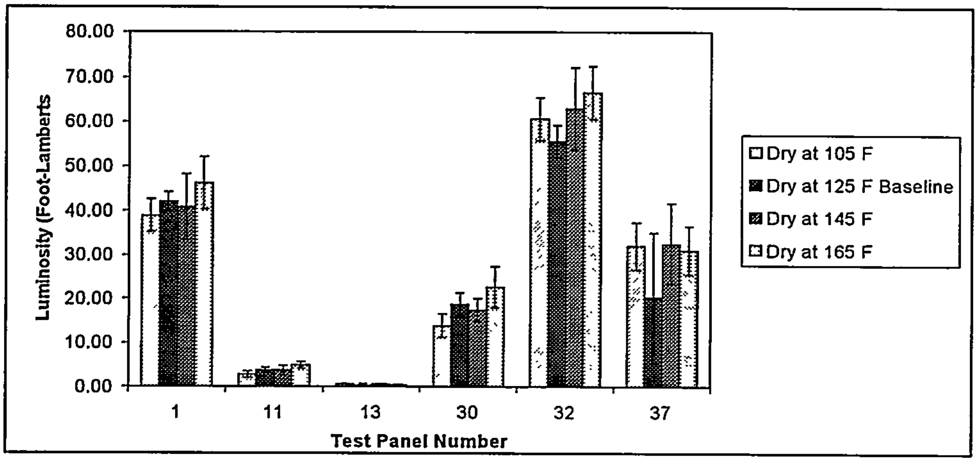


Figure 3. Variation in Dryer Oven Temperature (Experiments 2, 3, 4)

The next deviation from the baseline procedure was to double the developer dwell time to 10 minutes. The results indicate that there was no statistically significant evidence that the extra time increases crack luminosity. This means that the baseline time of 5 minutes is adequate for the dry developer to extract a detectable amount of liquid penetrant from the crack.

The penetrant dwell time was revealed to have a substantial affect on crack luminosity. Compared to the baseline time of 5 minutes, nearly all the test panels had lower readings at 2 minutes and higher readings at 10 minutes. At a 2-minute dwell time, panel 1 was well beneath the baseline standard deviation and panel 30 was close. The 10-minute dwell time yielded results for panels 1 and 32 that almost exceeded the standard deviation. The statistical evidence illustrates the importance of the penetrant dwell time. Given extra time, the penetrant is allowed to migrate completely into the crack and give a higher luminosity reading. At dwell times less than 5 minutes, the results are inconsistent and penetrant is not allowed its maximum penetrating ability. The following Figure 4 shows the relationship between the penetrant dwell times and the crack luminosity readings.

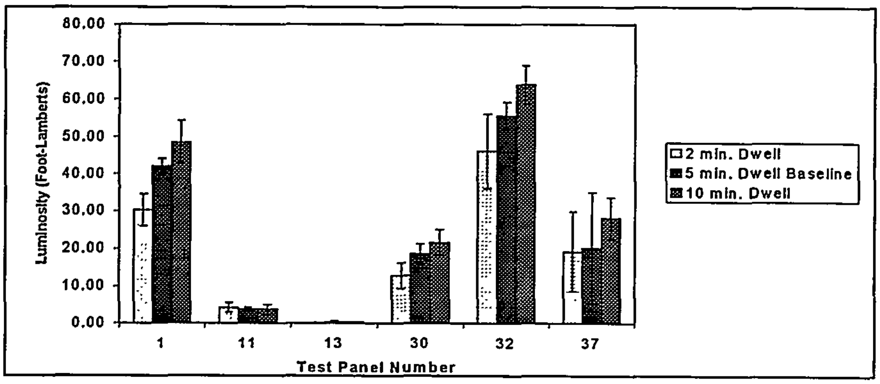


Figure 4. Variation in Penetrant Dwell Time (Experiments 7, 8)

Considering that a water-washable fluorescent penetrant was used for all the experiments, deviations in the water conditions for spraying were analyzed. Changing the water pressure from 193 kPa (28 psi) to 103 kPa (15 psi) had no significant affect on the crack luminosity except for panel 11, which was above the baseline standard deviation. Increasing the water temperature to 32.2°C (90°F) did statistically affect the luminosity readings since panels 11 and 30 were at or above the baseline deviation. Figure 5 shows the relationship between the water temperature and the luminosity readings.

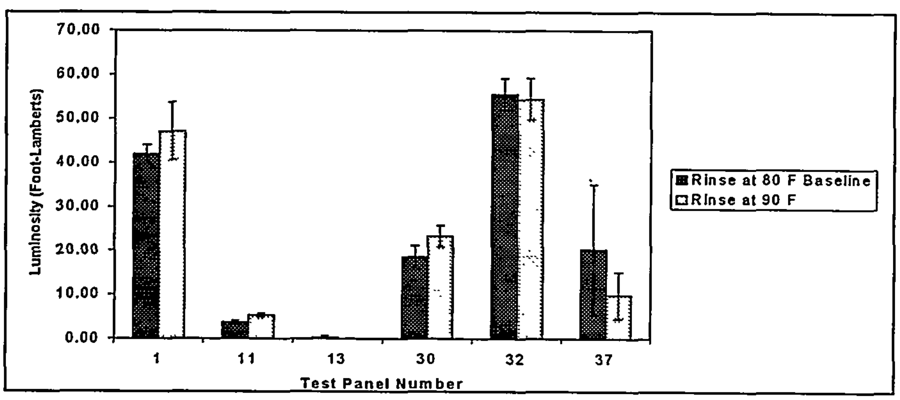


Figure 5. Variation in Rinsing Water Temperature (Experiment 11)

The final deviation from the baseline procedure tested the ultrasonic cleaning ability of SkyKleen solvent. The experimental results indicated that there was no statistically significant evidence to prove MEK cleaned the test panels any better than SkyKleen. Since SkyKleen is safer to use, easier to dispose of, and common in industry, it seems to be a very beneficial replacement for MEK in ultrasonic cleaning of the panels. Test panel 37 did show some deviation from the baseline average for the SkyKleen experiment, but it apparently needs to be re-etched based on its diminishing readings throughout the experiments.

Conclusion

Experiments were conducted to analyze the baseline procedure for Method A, Level 4 water-washable liquid penetrant inspection and the affects of various deviations in the procedure. A range of dryer oven temperatures from 40.6°C (105°F) to 73.9°C (165°F) showed that the crack luminosity readings increased with heat. The cracks were still visible at the lower temperatures, but did not appear as bright. Doubling the developer dwell time to 10 minutes caused no change in the luminosity readings. A penetrant dwell time of less than 5 minutes created lower, inconsistent readings while a dwell time up to 10 minutes increased the readings. The penetrant needed this dwell time to effectively perform its capillary action of filling the crack. Lowering the spray pressure during the rinsing process to 103 kPa (15 psi) did not appear to influence the crack luminosity readings. However, raising the temperature of the rinsing water to 32.2°C (90°F) increased the crack readings. The results of using SkyKleen solvent in place of MEK during ultrasonic cleaning showed no change in the luminosity readings. This indicates that SkyKleen cleans the titanium test panels as well as MEK and is a better alternative. The experimental results also demonstrated that wide and/or shallow cracks, like panels 11 and 13, give lower luminosity readings than tight, deep cracks.

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Recommendations

The results from these experiments indicate where further analysis should be conducted. More experiments ought to be run up to the specified dryer oven temperature limit of 79.4°C (175°F) to find out which temperature gives the greatest luminosity readings for a wide range of cracks. Also, penetrant dwell times beyond 10 minutes could be tested to reach an optimum parameter. Since the water temperature could not be decreased below 26.7°C (80°F±5) during the summer months, experiments could be run in the winter at the specified baseline temperature of 21.1°C (70°F±5) or less to evaluate the response. The cleaning effectiveness shown by SkyKleen in the final experiment illustrates its need for further testing. The four previous deviations in the baseline procedure done here could be experimentally repeated using SkyKleen throughout instead of MEK. The observation of substantially lower luminosity readings for panels 13 and 37 in the final few experiments indicates that they need to be analyzed to find out what materials are clogging the cracks.

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