Study Title: Spotmeter Spot Size versus Measured Brightness

Background Information

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Key words: photometer, spotmeter, fluorescent penetrant, brightness, spot size, inconel, titanium, fatigue crack

Abstract (less than 100 words):

An experiment was performed to determine the best photometer spot size setting for measuring the brightness of fluorescent penetrant indications (FPI) of low-cycle fatigue (LCF) cracks. Six cracked samples were borrowed from a previous ETC-funded project. Two samples were chosen, based on optically-measured crack length, to represent each of the target lengths of 0.020”, 0.060”, and 0.120”. Three FPI runs were performed to evaluate the effect of spot size on brightness readings, demonstrate the inherent variability of the measurement, and determine which setting provided the highest inter-sample discrimination. The spotmeter has five different spot sizes, which vary the angle of the aperture, and each was used in the comparison.

Technical Summary

Purpose of Study:

This experiment was performed using a Photo Research PR-880 photometer to measure the brightness of fluorescent penetrant indications formed by small fatigue cracks. The photometer has many settings that may be varied, such as the spot size. A photometer’s spot size refers to the angle of the aperture opening, which directly affects the size of the area of interest on the sample to be measured. A smaller degree opening will result in a smaller area of the sample being interrogated. In prior ETC and CASR FPI studies, the ½° setting has been used. Use of the smaller aperture opening may result in readings being taken over only a portion of longer fatigue cracks, with some part of the indication lying outside the measurement region. This study gathered data on the effects of spot size versus measured brightness and variability for a variety of crack lengths.

Background:

Six samples were chosen for this experiment based on optically-measured crack length. These samples had been fabricated and used in a previous study[1], and have been exposed to a combination of chemical and mechanical cleanings. Two samples from each target length of 0.020”, 0.060”, and 0.120” were sought. These samples were then processed using a standard procedure as specified by AMS 2647 rev. B[2].

FPI Chemistry[3]:

Magnaflux ZL-37 Penetrant (level 4, ultra-high sensitivity, post-emulsifiable)
Magnaflux ZR-10B Hydrophilic Emulsifier at 19% concentration
Magnaflux ZP-4B Developer (dry powder)

Experimental Procedure:

The group of six samples was cleaned in ultrasonically-agitated acetone for 30 minutes, dried for 30 minutes at 155°F, then allowed to cool to approximately 100°F prior to penetrant application. The level 4 ultra-high sensitivity penetrant was applied, then allowed to dwell for 20 minutes prior to a one-minute prerinse. The samples were then immersed in emulsifier with slight agitation for a total contact time of 2 minutes prior to a 1-minute postrinse. The samples were then dried for 8 minutes at 155°F, dragged through dry powder developer, and allowed to develop for 10 minutes. The photometer was used immediately after completion of the development time, and each visible indication was photographed under ultraviolet (UVA) illumination at 40X magnification. FPI indications were measured by capturing an image with a Moritex MS-400 video microscope, using approximately 15,000 µWatts/cm^2 of ultraviolet illumination from an Olympus ALS-UV 2000U light source, in the Image Pro® package by Media Cybernetics. A small hand-held reticle was used at times to verify the length of visible indications.

The FPI indication brightness was measured by the spotmeter using all available aperture openings: ⅛°, ¼°, ½°, 1°, and 3° with the standard equipment setup[1]. Changing the spot size using the PR-880 is done by simply choosing the desired setting from a selection menu on the device[4]. Of the six total samples used, five were fabricated from inconel-718, and one sample (00-078) was made from titanium 6-4. Samples 01-035 and 01-031 had crack lengths near 0.020”, 00-105 and 00-124 were close to 0.060”, and samples 00-078 and 00-120 were approximately 0.120” long. All brightness results provided in this report are the actual readings obtained by the spotmeter, i.e., no background subtraction was performed.

For all tests the spotmeter was set up to view cracked samples from approximately 24° off horizontal[1]. Note that the angle is controlled by rigid fixturing which has been optimized for measurement of crack samples. Selection of other configurations, i.e. different angle, distances, etc., may produce different results. This fact motivated the design and use of a rigid, repeatable fixture. The configuration projects an elliptical area of interest (AOI) with dimensions governed by the distance between photometer and sample and aperture angle as shown in Figure 1. The standard setup used in the ISU studies results in x and y dimensions for the AOI listed in Table 1. For example, the 1° aperture will completely cover crack indications with lengths up to 0.232”.

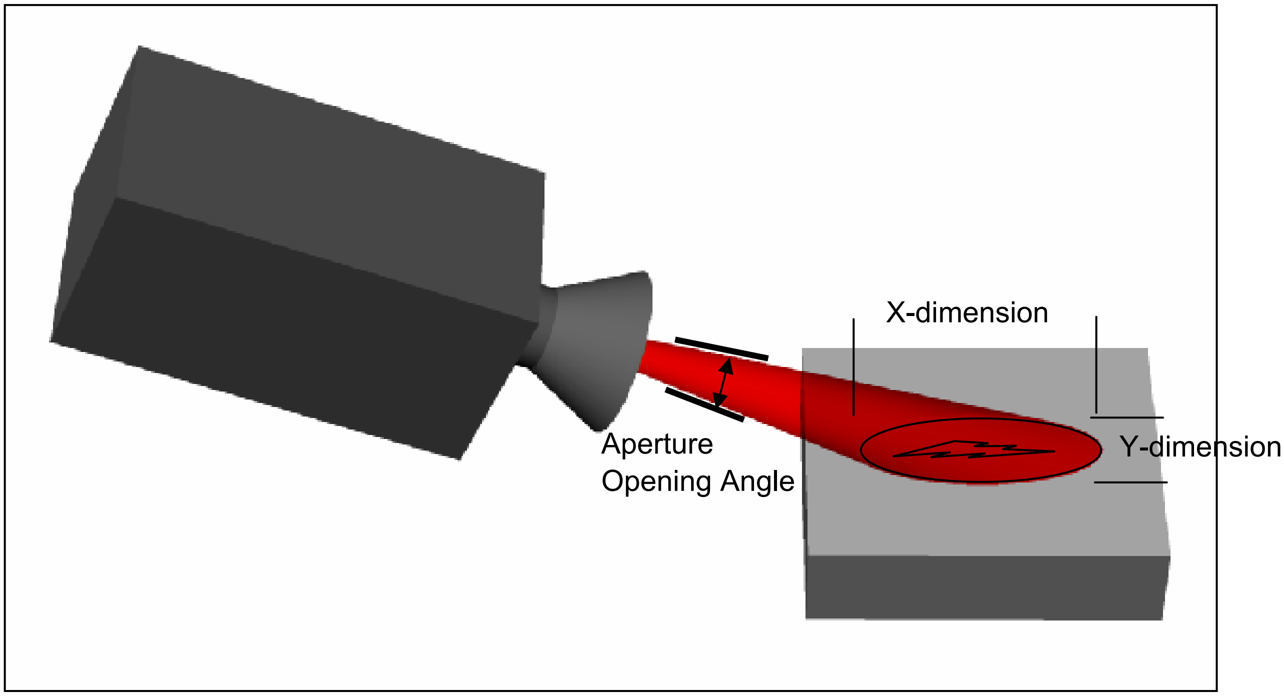


Figure 1: Spotmeter's elliptical area of interest with dimensions x and y based on aperture angle shown covering an entire crack indication

Table 1: Elliptical AOI approximate size versus aperture angle

Aperture Angle Setting	Y-dimension	X-dimension (crack length direction)
$^1/_8$°	0.019"	0.036"
¼°	0.033"	0.062"
½°	0.060"	0.113"
1°	0.123"	0.232"
3°	0.357"	0.673"

Each sample remained in a fixed position for the initial data collection run to avoid measurement error due to sample placement variation. Indication brightness versus spot size was evaluated after two separate FPI runs (Run 1 and Run 2) to demonstrate each sample's inherent variability. A second round of data collection (Run 3) was obtained using only three samples, one from each target crack size. During Run 3, the samples were removed from under the photometer, and then replaced for each photometer measurement in order to determine the reproducibility of the brightness values at each spot size setting.

Results:

The combined effects of each sample's history, crack morphology and width, and surface finish make a direct correlation between optically-measured crack length and FPI indication length difficult. Some cleaning methods, such as blasting techniques, can smear portions of the crack, which can make FPI indications appear shorter than the optical crack length. Dim FPI indications, when viewed using the video microscope, may not show the full extent of its length because of limitations of the image capture sensitivity.

A 5X magnification reticle was used in conjunction with UVA illumination to provide a slightly more sensitive length reading. In all cases (with the exception of sample 00-078) the smallest aperture provided the highest brightness readings, and the largest aperture gave the smallest brightness readings. Software measurements on sample 00-120, for example, appeared to show a 0.065" indication while reticle measurements showed that 0.110" was actually visible. Another sample (00-078) formed such a dim FPI indication that the spotmeter reported readings that were nearly the same as brightness readings taken on the background away from the crack, and the video microscope was unable to capture the indication.

Each sample provided FPI indications that varied in brightness slightly between runs 1 and 2. The results are presented graphically in Figure 2, where the indications seem to have a logarithmic outcome with an R^2 trend line value of approximately 0.97. In all cases the background reading taken away from the crack indication did not vary appreciably with spot size. Brightness readings on the FPI indications approached the background readings as the spot size increased. This occurs because the FPI indication represented less of the measurement area with larger aperture settings.

A second study where the samples were moved and replaced for each reading at each spot size was performed. This run involved only three samples, one from each size range. This method provided data regarding the reproducibility of measurements with respect to spot size as provided in Table 3. Figures 3(a) and (b) show graphically how the smallest spot size gave the highest readings, but also resulted in the worst repeatability. The repeatability improved for increasing spot size until the ½° aperture setting. A balance between sample discrimination, as provided by small spot sizes, and test repeatability, as provided by the larger spot sizes must be sought as part of the experiment's design.

The spotmeter's ability to distinguish between two indications is an important aspect of FPI research. As shown in Figure 2 the spotmeter returned very large values for bright indications, and very small values for dim indications when using the smallest spot sizes. The ability to distinguish between a bright and dim indication decreases when using the larger spot sizes, to a point where there is very little difference in readings at the 3° setting. The length of the indication will not govern the brightness, as demonstrated by sample 00-078's 0.050" indication being much dimmer than those one-half its length. The area of the fluorescent indication is more relevant since the photometer integrates over the entire spot. For example, a 0.025" deep and wide crack may form an indication that is brighter than one from a 0.025" shallow and tight crack.

Table 2: FPI indication brightness and length results for each sample sorted by the optical crack length as measured under white light at 500X magnification

Run 1	Brightness Readings with Spotmeter					UVA Indication Length	Indication Length w/Comparator	Optical Crack Length	Background Readings with Spotmeter				
Part #	1/8 deg	1/4 deg	1/2 deg	1 deg	3 deg				1/8 deg	1/4 deg	1/2 deg	1 deg	3 deg
01-035	44.6	12.1	3.47	1.53	0.95	0.025		0.025	0.92				0.89
01-031	18.5	4.89	1.78	1.1	0.91	0.022		0.026		0.89	0.9	0.89	0.88
00-124	576.3	364.1	128.5	33	4.41	0.083		0.064	0.963	0.941	0.943	0.937	0.97
00-105	571.2	425.1	150.4	38	4.95	0.075		0.067	0.93		0.93		0.89
00-120	324.9	182.5	57.2	14.6	2.24	0.063		0.112	0.75	0.74	0.75	0.75	0.77
00-078	0.82	0.79	0.74	0.72	0.71		0.050	0.120			0.07		
Run 2	**Brightness Readings with Spotmeter**					**UVA Indication Length**	**Indication Length w/Comparator**	**Optical Crack Length**	**Background Readings with Spotmeter**				
Part #	1/8 deg	1/4 deg	1/2 deg	1 deg	3 deg				1/8 deg	1/4 deg	1/2 deg	1 deg	3 deg
01-035	17.07	8.45	2.88	1.34	0.92	0.025	0.025	0.025					0.87
01-031	3.32	2.22	1.23	0.98	0.89	0.021	0.025	0.026	0.93				0.87
00-124	552.6	402.8	167.3	43.64	5.78	0.085	0.085	0.064					0.96
00-105	599.1	357.9	131.5	33.27	4.48	0.073	0.075	0.067					0.93
00-120	352.8	150.3	58.45	14.95	2.28	0.065	0.110	0.112					0.75
00-078	0.75	0.72	0.71	0.71	0.73		0.055	0.120	0.71		0.71		0.71

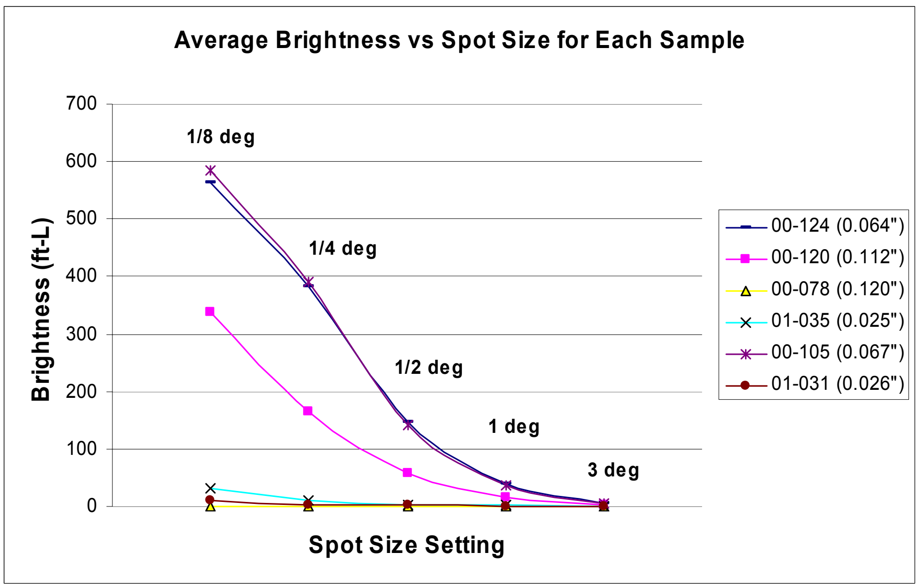
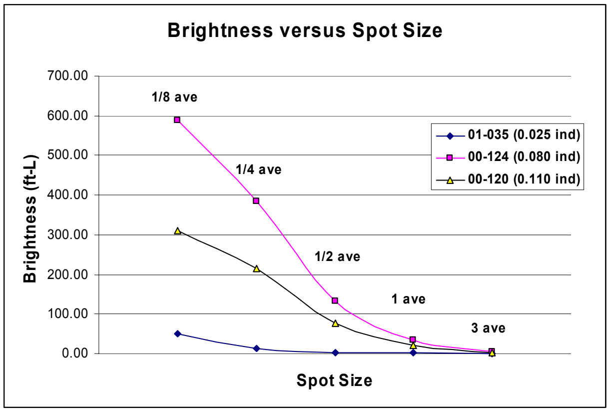


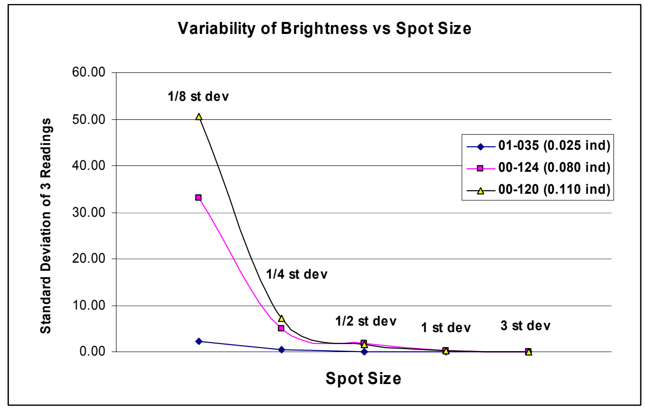
Figure 2: Average brightness readings for each sample at each spot size setting with optical crack lengths provided in parenthesis

Table 3: Reproducibility data collected by moving the sample between each reading for each spot size using only bright-indication samples 01-035 (0.025”), 00-124 (0.064”), and 00-120 (0.112”)

Aperture Setting	1/8 deg			1/4 deg			1/2 deg			1 deg			3 deg		
Reading #	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Specimen ID															
01-035	52.38	48.70	48.16	13.66	13.11	12.85	3.65	3.63	3.58	1.55	1.54	1.53	0.95	0.94	0.94
00-124	620.10	591.00	554.10	388.60	382.20	378.80	135.20	133.00	131.70	33.51	33.25	33.04	4.50	4.50	4.43
00-120	362.30	261.60	305.90	222.60	209.80	210.90	77.69	75.52	74.64	21.06	20.70	20.49	3.12	3.09	3.04



(a)



(b)

Figure 3: Reproducibility of brightness measurements versus spot size obtained by moving the samples between measurements showing the average reading (a) and the standard deviation of 3 readings (b) for each UVA indication length

The background readings provided in Table 2 signify how well the sample surface was cleaned after FPI processing, and give an indication of the contrast noted by the photometer. These readings ranged from 0.71 to 0.97 ft-L, and were generally around 0.88 ft-Lamberts. Post-FPI analysis using the video microscope showed that the UVA-illuminated indication length was not always fully visible to the camera. Sample 00-078, for example, provided indications so dim that they were not visible under the microscope, and sample 00-120 had faint extensions that were missed by the microscope but picked up under the reticle during run 2.

Figure 3(b) shows the standard deviation of three measurements for each of 3 FPI indication lengths. As one would expect, the measurement becomes more repeatable when a spot size that completely covers the FPI indication is used. During the third run the ¼° aperture completely covered sample 01-035's indication, while the ½° was required to cover 00-124, and the 1° was necessary for 00-120. The variability was not appreciably higher for the ½° aperture when compared to the 1° setting for any sample, however.

Although the true indication length, as measured with the reticle, did not relate closely to the measured indication brightness, the software measurements of indication length did show a correlation. For all spot sizes the length of the indication visible to the video microscope correlated nicely with photometer brightness as shown in Figure 4. Trend lines displayed for each spot size had R^2 values that were between 0.86 and 0.96.

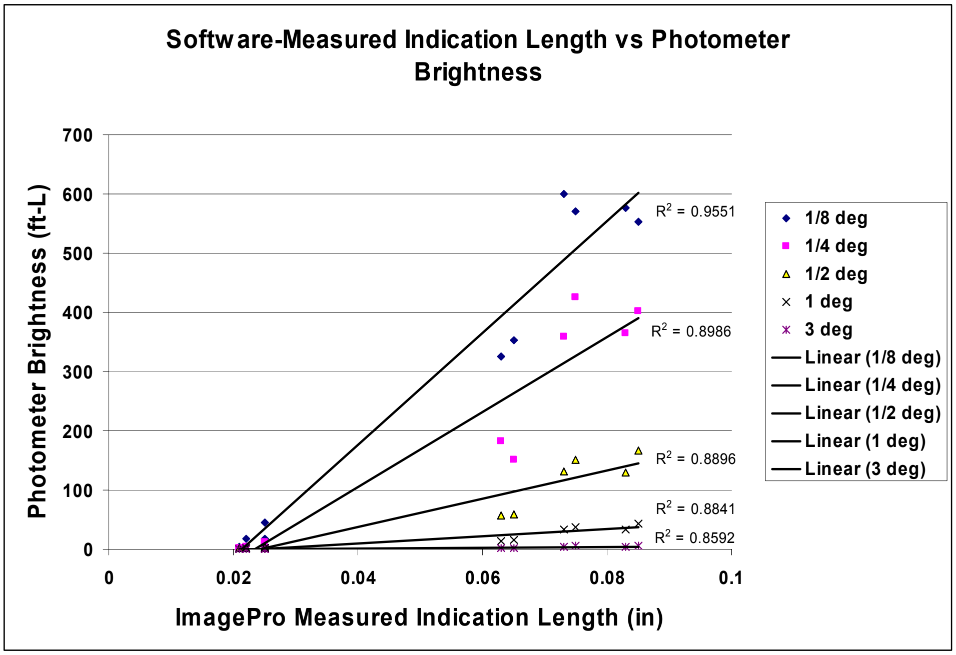


Figure 4: Photometer brightness readings compared to length measurements as taken with image analysis software for each spot size setting

Conclusions:

- When attempting to measure the difference between two samples, a small spot size is necessary. However, to optimize measurement reproducibility a larger spot size is required. Obviously, equilibrium between these two needs is critical in quantitative FPI research efforts. In arriving at a balanced approach, the ½° setting has adequate measurement reproducibility and brightness contrast for the crack sizes and morphologies. Although this setting will not completely cover all fatigue cracks in the small crack studies performed to date[1], data gathered in this study leads to the conclusion that the ½° setting is optimal. If future studies involve the use of larger cracks, another study similar to the one outlined in this document is warranted to select optimal settings.

- Video microscope images, as obtained by the Moritex unit, did not always capture the full extent, or for some samples, any of the FPI indications that were present. These indications were detectable using the photometer, and by the operator. The hand-held reticle provided an affordable verification of indication length. Length measurements taken by the image analysis software, which were less sensitive to very dim indications, correlated very well with the measured photometer brightness.

- Correlations between the optical crack length, or FPI indication lengths measured with the reticle, and measured photometer brightness were poor. One of the longest indications, as measured with the reticle, was too dim to be visible under the video microscope. The sensitivity of the video microscope more closely emulated the photometer capability, and a relationship between software-measured indication length and spotmeter brightness could be established. Because the spotmeter integrates over an area, correlation between the photometer brightness and total indication area is expected to be even stronger. Future efforts are justifiable to improve the capability of the video microscope, and use other tools available through image analysis that determine indication area.

Footnotes

[1] Engineering Studies of Cleaning and Drying Processes in Preparation for Fluorescent Penetrant Inspection (FPI). Engine Titanium Consortium Phase II Task 2.2.3, final report not yet published. Contact Lisa Brasche (515) 294-5227.

[2] AMS 2647 Rev. B: Fluorescent Penetrant Inspection Aircraft and Engine Component Maintenance. SAE International, October 1999

[3] This FPI product was selected as a typical material and its use does not imply endorsement.

[4] The spotmeter was approximately 20 days overdue for recalibration at the time of this experiment; however no changes in performance had been noticed.