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Engineering studies for fluorescent penetrant inspection with a focus on developer application methods

L Brasche, R Lopez, D Eisenmann and K Griffiths

Fluorescent penetrant inspection (FPI) is the most widely used global inspection method, playing a particularly important role in aviation. Given the contribution that reliable implementation of the FPI process can make to flight safety, the US Federal Aviation Administration (FAA) has funded a programme to assess the FPI parameters and their role in effective detection of typical flaws. Iowa State University's Center for NDE (CNDE) has led a team that includes many industry partners from the aviation industry during this six-year programme. The industry partners have provided guidance and prioritisation input, and in many cases access to internal data, samples or use of facilities to support the programme. The focus of the programme has been on quantitative assessment of FPI performance using a combination of data gathering methods, which includes indication luminance as measured using a photometer, UV-A indication appearance using a fluorescence stereomicroscope, and in some cases the more traditional probability of detection (POD) study. Numerous studies have been completed, although results of developer studies will be the focus of this paper. Choice of indication development parameters starts with the selection of the developer form. All four forms have been evaluated during this programme: dry powder, water-soluble, water-suspendible, and non-aqueous wet developers. The results of the developer studies are presented below along with key 'lessons learned'.

1. Introduction

Fluorescent penetrant inspection (FPI) is the most widely used global inspection method, with over 90% of aviation components being inspected with FPI at some point during their engineering life. FPI requires the cleaning and drying of surfaces to be inspected, followed by application of the penetrant, removal of the excess penetrant, drying of the surface (when necessary), and application of the developer. Recommended parameters, such as time, temperature, pressure, concentration etc, exist for each of the steps and are dependent on the penetrant/developer selection. For most aircraft engine applications, Level 4 sensitivity post-emulsifiable penetrant and dry powder (Form A) developer are used. Typically, the penetrant is applied for 20 to 30 min, followed by a water rinse (90 s or less), emulsification (two min or less) and post rinse (less than one min), drying (10 min), developer application and indication development (10 min to 2 h), and inspection.

Because of the complexity and size of many aviation components, the usual approach to FPI is the use of inspection lines where individual stations are used for each step in the process. The inspection lines typically include part handling equipment and automated controls for all or some aspects of the inspection.

Application of the dry powder developer is typically accomplished using a ‘dust storm/cloud chamber’ or a spray wand. The option to use electrostatic application of dry powder developer is also available, although not currently utilised routinely by US airline maintenance facilities. Other developer options regularly used on processing lines include the aqueous soluble (Form B) and aqueous suspendible (Form C). Given the many choices associated with developer application, engineering data comparing the approaches was deemed a high priority by the FAA and industry partners.

2. Technical approach

2.1 Measurement process

A goal of the overall programme is to provide quantitative data upon which engineering decisions could be made regarding the most effective implementation of FPI. To that end, the measurement process used by the US Air Force in generating the liquid penetrant Qualified Products List (QPL) was mimicked, including the use of a photometer for measuring luminance of indications. Several steps in the penetrant material qualification process utilise the measurement of indication luminance as a metric for acceptable performance. A Photo Research PR-880 photometer coupled with a Macro-Spectar MS-55 lens and photopic filter set was used to measure indication luminance. The photopic filter set in the photometer closely matches the relative spectral efficiency of the human eye, and approximates the mesopic response that an inspector’s eye would be adjusted to in a dim inspection booth.

For each sample and set of inspection parameters, a luminance measurement is made using the photometer, as shown in the left of Figure 1. The sample fixture and UV-A source are shown in position with the photometer. On the right is the view as seen when looking through the photometer. The black dot shows the measurement area which is placed over the area of interest and the brightness measurement is recorded. Fluorescence images are also captured of each processed indication. Figure 2 shows typical responses for a series of baseline runs on a given sample.

![Figure 1. Photometer and measurement fixture (left) and view of measurement area as seen through viewing port of the photometer. Dark circle shows the measurement region which is placed over the region of interest (right) (2.2 Baseline assessment)](image)

2.2 Baseline assessment

The basic approach of the programme has been to compare the ‘baseline brightness’ to the brightness of the sample processed using the parameter(s) of interest. The baseline conditions are as listed in Figure 3. Of particular note is the developer application process

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used during the baseline runs. A dip/drag application method which mimics the QPL process was utilised, as shown in the middle right photograph. The samples contained low-cycle fatigue (lcf) cracks grown in three-point bending with typical sizes of 20 to 120 mm. The sample was dragged through dry powder developer to ensure contact between the developer powder and the lcf crack.

In most studies, 6 to 20 samples containing a range of crack sizes and brightness characteristics were selected. The samples were processed as a set for three runs to establish the baseline measurements, such as shown in Figure 2. Following the baseline runs, the samples are processed keeping parameters constant with the exception of the factor of concern. For example, in the studies reported here the process parameters listed in Figure 3 were used with the exception of the method of developer application.

3. Results

3.1 Form A developer application – dust cloud chambers and spray wands

The typical developer application method used for commercial aviation is dry powder developer applied in a dust cloud chamber or with a spray wand. During the course of the programme four different chambers were evaluated, each of which introduced the developer in different ways. Figure 4 shows the four chambers (a – d) along with a fixture used to hold the samples at different locations within the chamber (e) and a close-up of the samples (f).

Chamber a introduced the developer powder through linear diffusers that ran along the top and bottom of the chamber which contained exit holes at about 1.5” spacing. Chambers b and c utilised circular diffusers located at the top of the chamber. Chamber d introduced developer using two pressurised jets located at the ¼ and ¾ position beneath the rollers upon which the parts will sit. The fixture shown in Figure 4(d) allowed placement of samples at three elevations within the chamber (bottom, middle, top), left and right, and at various positions between the entry and exit points of the chamber. The fixture also allowed control of the crack orientation with respect to the fixture, ie crack facing up, down or to the side.

Figure 5 shows results for Chamber d which was typical for the chambers. Samples were evaluated using the dip/drag baseline parameters in groups of 20 to establish their baseline performance (Figure 3). A linear regression analysis was completed to compare other runs using the same sample set to the average baseline response. As seen in Figure 5, the runs completed with samples placed in the up, down, and side positions showed considerably lower luminance than the baseline performance in which developer was applied using the dip/drag method. Similar reductions in brightness were found in use of the spray wand systems.

3.2 Form B aqueous soluble developer and Form C aqueous suspendible developer study

Given the lower than expected luminance results for the Form A dry developer, a comparison of Form B and Form C developers was undertaken. The study compared two concentrations,
the manufacturer’s recommended concentration and a lower concentration. In some cases, a lower concentration is utilised in production settings because of concerns with masking indications. No evidence of indication masking was found with the concentrations used in this study. Figure 6 compares the indication luminance for Form C to Form B for a set of roughly 30 samples. The lower concentration led to reduction in brightness for both Form B and C. Form C was on average 30% brighter than the Form B results. Form B and Form C indications were more diffuse in nature, particularly when compared to the linear indications generated by the Form A developer. It is important that inspectors be aware of these differences and the implications for detectability. Variation in indication appearance with choice of developer could also be considered during inspector training.

3.3 Electrostatic application of Form A developer application

The option exists to utilise electrostatic attraction of the developer powder to enhance adherence of the developer to the part. For electrostatic systems, the part is electrically grounded. Electrostatic spray machines impart a negative charge to the developer particles. Particles ejected from the gun are attracted by this charge, which increases transfer efficiency over standard spray applications. As with any process, there are many variables which must be controlled. The study utilised an electrostatic spray unit originally designed for use in powder-coat paint applications. Variables include the fluidising air, powder output, air volume, spray current, spray voltage, spray time, gun-to-specimen distance, gun-to-specimen angle, gun motion, grounding method, ambient humidity, ambient temperature, airflow rate, and compressed air quality to name a few. In the studies performed to date, the recommended parameter settings for use with flat surfaces were selected as listed in Figure 7 (left). A typical set-up is shown to the right. The specimen-to-gun angle was kept at zero. Studies were completed to establish the optimal spray time using luminance of lcf indications as a guide. Other factors considered included the distance (comparing 12" and 24"), airflow (both with and without an exhaust hood), orientation of the flaw with respect to direction of the impinging spray (front, top, back, bottom), and grounding state (with and without grounding). Using the available system and parameters listed in Figure 7, initial runs indicated that a spray time of 3 to 4 s at 12" distance yielded optimal indication luminance when compared to the baseline response achieved for the same sample set. This corresponded to a coating thickness of approximately 0.0012 to 0.0017" on the sample facing forward. Coating thickness was greatest on the front and top surfaces, compared to the bottom and backside. When increasing the spray distance from 12 to 24", as expected, a decrease in indication brightness was found. Humidity (which could not be controlled but was measured) did have an impact on coating thickness. It is recommended that users of electrostatic systems complete a system performance characterisation.

4. Conclusions

Several developer options exist for use in fluorescent penetrant inspection systems. A series of studies evaluating developer forms and applications methods was completed. Key recommendations are as follows:

Variation within chambers evaluated in this study are expected to be representative, indicating widespread variation across the industry as well. It is recommended that measurements be made of operational chambers to ensure inspectors are aware of any deficient regions. Known defect standards such as TAM panels, low-cycle fatigue cracks, twin crack panels, or parts with known cracks can be processed and placed at different locations and orientations in a systematic manner. Comparison between defect responses as a function of position should provide an indication of deficient regions.

Allowing the inspectors to arbitrarily reduce powder volume within a dust storm cabinet, whether to avoid a mess in the inspection booth, or reduce powder usage, is not likely a good choice when seeking the most sensitive inspection possible.

Obstacles impeding developer motion to the sample’s surface, such as stacking of baskets, fixtures, rollers, and slings should be noted and avoided when feasible. Additional developer should be applied to these areas using a dusting bulb, spray wand, or non-aqueous wet developer to ensure adequate and complete coverage of all surfaces.

In most cases, the location of a crack, ie top vs bottom, is unknown prior to inspection. This may warrant either processing of parts twice, inverting the part on the second run so that the other surface has the opportunity to be in the most sensitive 'up position' during developer application. Alternatively, a secondary development method could be used to add supplemental developer to the lower surface and other critical areas of the component. Research has shown that self-development of indications does not occur and use of developer is required to produce optimal indication luminance.

In most training programmes, the inspector is taught to use a light coat of developer because of concerns with masking indications. While this can be an issue, it is important to ensure that adequate developer is applied. When using manual spray wands the inspector should make an effort to apply powder to all surfaces rather than holding the wand near a single location and expecting developer to reach all surfaces.

Use of evacuation systems too early in the development process can reduce the developer contact with the surface and potentially lead to missing indications.
In the use of Form B and/or Form C developers, it is important to use the manufacturer’s recommended concentration. In the use of immersion systems, care should be taken to ensure pooling of the developer around geometrical features (in crevices and cavities) does not occur. In spray applications, it is important that developer be applied to all surfaces.

For electrostatic application of developer, a performance characterisation study of the system prior to routine use and at periodic intervals is recommended. The time necessary to arrive at an optimal coating thickness for the typical part-to-gun distance should be established. Given that thickness variation (and resulting indication luminance variations) can occur with respect to the impinging direction of the spray, care should be taken to encircle the part with the spray gun when feasible.

Acknowledgements

This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order 0016 and performed at Iowa State University’s Center for NDE as part of the Center for Aviation Systems Reliability programme. Industrial partners include Boeing Commercial Airplane Company, Boeing Phantom Works, General Electric Aviation, Honeywell Engines and Systems, Pratt & Whitney, Rolls-Royce (US and UK), Delta Air Lines, United Airlines, Sherwin Inc, Magnalux, Met-L-Chek, and D & W Enterprises Ltd. Experimental efforts have included contributions from numerous students at ISU as well as inspectors at industrial locations.

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