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Effect of application process and physical properties of penetrant material to the sensitivity of liquid penetrant inspection

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Abstract

Liquid Penetrant Testing is one of the most popular and widely used NDT method in a wide range of industries such as oil & gas, power generation, aerospace, marine and automotive. It can be used to detect open to surface defects on all non-porous materials. Solvent removable visible dye penetrant testing is employed in this project. Reliability of using dye penetrants that have elapsed their manufacturer-recommended usable time for liquid penetrant testing, is presented in this paper. There are two main parts in this study; comparing the sensitivity of dye penetrants by varying inspection techniques, and comparing the physical properties of penetrant materials. Four color contrast dye penetrant samples, with different chemical aging, were selected to perform the tests. For the first part, penetrant testing was performed on two selected welding discontinuities by varying dwell time and the number of developer layers with the aid of selected dye penetrant samples. For the second part, the density and viscosity of each dye penetrants were measured. According to the results, sensitivity and detectability of solvent removable visible dye penetrant decreases with the chemical aging. However, with increased dwell time and a minimal number of developer layers, it can be used to detect volumetric defects. With chemical aging, density does not change significantly but viscosity can be changed with different thermal and environmental influences.

Keywords

Color contrast dye penetrant, Liquid penetrant testing, Non-destructive testing, Penetrant dwell time, Sensitivity

Introduction

Some phenomena like a fine surface crack on a flight of an airplane wing, landing gears or engine fan blades could lead to catastrophic failures, even to the loss of human lives. In order to prevent such undesirable circumstances, regular quality assurance inspections and maintenance procedures have been established in many industries. To carry out this task, Non-Destructive Testing (NDT) is a leading technique that has been used over the last few decades.

NDT is a physical inspection and analysis technique which used to evaluate the properties of a material, component, or system without causing any damage to the tested object.

Liquid Penetrant Testing (PT) is one of the most popular and widely used NDT method in the industry, since it is a relatively low cost and effective method with high accuracy. It requires minimal training compared to other NDT methods. PT can be used to detect cracks, fractures, porosity, and any other surface opening defects and applicable to all non-porous materials. Welding inspection is one of the most common applications of PT in the local industry.

PT mechanism is based on the physical principle of capillary action. First, dye penetrant is applied on the surface of the specimen. Then this fluid penetrates into surface-breaking discontinuities with the aid of capillary action. After adequate penetration time (this time is known as "Dwell Time") excess penetrant is removed from the surface and a developer is applied. It draws back the penetrant trapped in discontinuities and provides visible indications of discontinuities which are invisible to the naked eye.

Although PT is widely used in the local industry, there are no local penetrant material manufacturers. Hence, these penetrant materials are imported from the international market and stored for some time in local warehouses before distributing among users. Also, these chemicals are not freely available in the local market so, the procurement process will also take another short time. These issues cause to elapse of the date, that the manufacturer stated as "Best Before" after a short period received by the end-users. Then, such penetrant materials are discarded without use. This is a huge material and economical waste. In addition to that, discarding these materials could have an adverse impact on the environment due to their high penetrability and toxicity. These materials can penetrate into the water through the soil and results in serious threats to the ecosystem.

In this paper, the reliability of using color contrast dye penetrants that have elapsed their manufacturer-recommended usable time is presented. This consists two main parts,

- Comparing sensitivity of dye penetrants by varying inspection technique (dwell time, number of developer layers)
- Comparing physical properties of dye penetrants (viscosity, density)

Methodology

In this study, penetrant testing was performed according to the international standard of American Society of Mechanical Engineers (ASME) boiler and pressure vessel code, section V, article 6. As given in the below table, four color contrast dye penetrant samples from the same product, the same manufacturer and the same country of origin but with different chemical aging were used in this study. In addition to that, for the first part of the study intact developers and cleaner/solvent removers were used from the same penetrant family.

Table 1. *Details of used penetrant materials*

Penetrant Material	Product Specification	Batch Number	Manufacture Date	Use Best Before
Dye Penetrant Sample 1	Type II-Visible Penetrant	120106	19th Jan 2012	Jan 2015
Dye Penetrant Sample 2	Type II-Visible Penetrant	151103	05th Nov 2015	Nov 2018
Dye Penetrant Sample 3	Type II-Visible Penetrant	160803	10th Aug 2016	Aug 2019
Dye Penetrant Sample 4	Type II-Visible Penetrant	180701	03rd Jul 2018	Jul 2021
Cleaner	Solvent Remover	191108	23rd Oct 2019	Oct 2022
Developer	Non-aqueous Type II	190E03	14th Jun 2019	Jun 2022

Part I*:* In this part, two surface breakings of welded joints are investigated by performing PT. For this, two test blocks with artificially made flaws given in below table were used.

Table 2. *Details of artificially made flaws*

Flow Number	Test Block	Discontinuity Description	Start of flaw to Reference Edge	Total flaw Length	Flaw Type
1	Flawtech RT-2839	Toe Crack in Butt weld	64mm	13mm	Surface Breaking
2	Flawtech MT-7719	Lack of Fusion in Fillet weld	33mm	8mm	Surface Breaking

First, the surfaces of the two test blocks were cleaned using a wire brush to remove rust. Then the test blocks were dipped in a hydrophilic emulsifier for 5 min and then cleaned with water for 2 min. This is an extra step to clean inside the flaws additionally to general cleaning using solvent remover in the pre-clean step. Then, the test blocks were completely dried by keeping them under sunlight for 10 min. In the pre-cleaning step, the test blocks were cleaned using solvent remover/cleaner. It was applied to the surface by spraying and then wiped using a lint-free cloth. After completion of pre-cleaning, a thin uniform layer of sample 1 visible dye penetrant was applied to the test blocks by spraying, such that the dye layer covers the inspection area. To achieve the objective of the study, PT was performed by varying dwell times. As per the standard methodology given in the ASME Code, minimum dwell time is 5 min. As a rule of thumb, applicable range of the dwell time is considered 5min to 20 min. Therefore, in this study, dwell time was chosen to be 5 min, 10 min, 15 min, and 20 min. After the dwell time, excess penetrant was removed by wiped using a lint free cloth and then wiped using a lint free cloth dampened with solvent remover. Once the part is dried by normal evaporation, as soon as possible a non-aqueous Type II developer was applied by spraying. For each chosen dwell time, the developer was applied by varying the number of developer layers. As per the standard methodology given in the ASME code, it has to apply minimum no of thin transparent developer layers one after one under visual examination. In this study, number of developer layers was chosen to be 1, 2, and 3. After 10 s of developing time, results were recorded.

For all the above-mentioned dwell times and number of developer layer variations, surface preparation and pre-clean processes were repeated totally 12 times. The same procedure was repeated for sample 2, sample 3 & sample 4. At the end of every penetrant test, detected indication lengths of each flaw were measured by using calibrated steel ruler and results were recorded as photographs in JPEG format. Then, weighting factors from 0 (No indication) to 5 (Very clear and bright indication) were assigned to data points by considering their indication lengths and acuity of color brightness in order to observe the obtained results comparatively. Then the data set was analyzed.

Part II**:** In this part, the physical properties; density, and viscosity of four visible penetrant samples were observed.

A pycnometer was used to determine the density of four visible penetrant samples. First, the pycnometer was cleaned with distilled water and dried completely. Then the weight of the empty pycnometer was measured using the electronic balance. Next, the pycnometer was filled with distilled water and the weight was measured. After that

pycnometer was dried completely and filled with sample 1, then the weight was measured. Again, pycnometer was cleaned and dried completely.

This same procedure was repeated for sample 2, sample 3 and sample 4. Room temperature was recorded. Finally, density of each sample at the corresponding was calculated using below equation [2].

$$\rho_L = \frac{m_L}{m_{H_2O}} \rho_{H_2O} \quad (1)$$

$V = Volume\ of\ the\ Pycnometer, m_{H_2O} = Mass\ of\ water, m_L = Mass\ of\ liquid,$
$\rho_{H_2O} = Density\ of\ water, \rho_L = Density\ of\ liquid$

Ubbelohde viscometer was used to determine the viscosity of the dye samples. First, the viscometer was cleaned using distilled water and then dried completely. After that, sample 1 was poured into the vertically fixed viscometer until it reaches the upper line of the reservoir. Then using a rubber suction valve, the sample was introduced to the measuring bulb through the capillary tube. Then the sample was allowed to travel back through the capillary tube to the reservoir, and the time taken by the sample to pass through two calibrated marks was measured. Finally, the viscometer was cleaned and dried.

The same procedure was repeated for sample 2, sample 3, and sample 4. Room temperature was measured. Finally, using the obtained results and the viscometer constant, the viscosity of each sample at the corresponding temperature was calculated. For a given glass capillary viscometer, the driving force is the hydrostatic pressure of the liquid column in the form of the mean pressure height. Considering the laminar flow within the capillary, Hagen-Poiseuille Law gives that,

$$\nu = \frac{\pi R^4 h g}{8LV} t \quad (2)$$

In addition to the flow time, equation 2 contains only constants and geometric details. So, for a given viscometer, that constant part can be summarized into one characteristic magnitude. Which is known as "Viscometer Constant" (K). This value is a determined value for each individual viscometer according to its type and size. So, the viscosity of a liquid can be calculate using the below equation. [1]

$$\nu = Kt \quad (3)$$

Results and Discussion

Weighted results were analyzed based on three variables; different dye penetrant samples, different number of developer layers & different dwell times.

The Figs. 1 and 2 show the results regarding the different dye penetrant samples on both test blocks. According to the results, each dye penetrant sample gives considerable fair results when it is used on test block 2, but there is a clear difference in the results from test block 1. For both test blocks, sample 4 gives the best results and sample 1 shows less detectability compared to others. When the defect is tight (very narrow opening), dye penetrants that elapsed their usable time tends to refrain penetrate into the flaw. Therefore, sample 1, 2 & 3 gives fewer defect detections compared to sample 4 when they are applied on block 1.

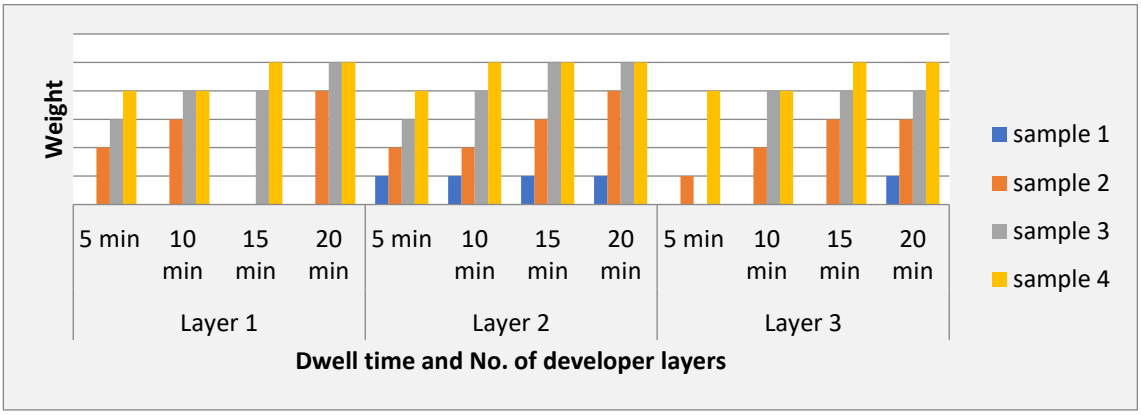

Figure 1. *Results for four dye penetrant samples from Flaw 1 of the test block 1.*

When considering the number of applied developer layers, double layers indicate high detectability of flaws in both test blocks than single developer layer or triple developer layers. The developer extracts the entrapped penetrant in the flaw and gives indications. When a single layer of developer is applied, it is not sufficient to bring back the entrapped penetrant back to the surface. Therefore, it gives less defect detection. When triple layers of developer are applied, thickness of the developer layer is considerably large and tends to mask the defects. Double layers' developer is sufficient and effective. But, when the defect width is larger, number of developer layers does not affect much on results.

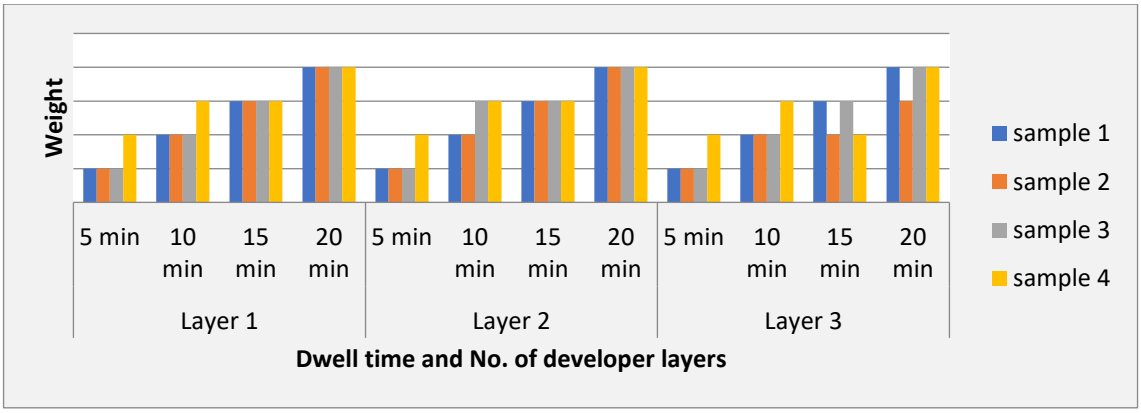

Figure 2*. Results for four dye penetrant samples from Flaw 2 of test block 2.*

An increase in dwell time has enhanced the defect detection capability in both test blocks. Dwell time is an important factor of PT because it allows the penetrant to be drawn into the defect. As per the both standard methodology given in the ASME Code and manufacturer's recommendations minimum dwell time is 5min, these experimental results indicate that the penetrant material getting aged, it is required to increase the dwell time respectively.

In the second part of this study, the density and viscosity of four dye penetrant samples were analyzed. When the density variation is considered, samples 1 and 2 have a density of 0.83×10^3 kg/m^3, and samples 3 and 4 have a density of 0.82×10^3 kg/m^3 at 31˚C. Both values are approximately close to the valve given in the manufacturer's specification (0.85×10^3 kg/m^3). In this experiment, densities of dye penetrants were measured to monitor the quality of the dye penetrants; In order to check whether these dye penetrant samples have been contaminated with the time. Contamination of a penetrant by another

liquid or any other means will change the surface tension and hence its penetration ability. Test results indicate that the dye penetrant samples were not contaminated.

According to the manufacture's specification viscosity of the solvent removable visible dye penetrant is $3.80\times82x10^{-6}$ m^2/s at 38˚C. The viscosity of penetrant sample 1, 2, 3 and 4 is found $2.15x10^{-6}$ m^2/s, $1.93x10^{-6}$ m^2/s, $1.82x10^{-6}$ m^2/s and $1.8x10^{-6}$ m^2/s respectively (at 31˚C). Although viscosity is decreasing with the increment of temperature, there is a possibility that exposure to heat can lead to increased viscosity. This means, increased heat or temperature can be caused to evaporate the volatile content in the dye penetrant and it results in high viscous dye penetrants [3]. Dye penetrant samples used in this project were stored in a normal storeroom without controlled temperature conditions prior to the experimental use. So, they had been exposed to different temperature and heat conditions over time and it can cause to change the volatile content, viscosity and the penetrability of the penetrant with their chemical ageing. Sample 1 has the largest time gap between its usable times, so it has exposed to heat than the other three samples; which explains its high viscosity compared to the three other samples. Improved storage conditions with controlled temperature can have positive impacts on the quality of dye penetrants.

Conclusion

The sensitivity and detectability of the penetrant will decrease with penetrant chemical aging, but considering flaw size and type, dye penetrants which have elapsed their usable time can be used utilizing increased dwell time and minimal number of developer layers. With the chemical aging of penetrant, density does not change significantly but viscosity can be changed with different thermal conditions and environmental impacts of storage facility.

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