UNIEXPERTS ACADEMY
ADVANCING KNOWLEDGE, EMPOWERING MINDS

Journal of Mechanical and Sustainability Engineering Technology

Journal homepage:
https://uniexpertsacademy.com/index.php/IJMSET/index
ISSN: 3083-8363

Evaluation Dye Penetration for Detecting Flaws in Aircraft Components

Nur Husnina Dayana Maulad Darahman[1], Eliza M.Yusup[1,*]

[1] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat Johor, MALAYSIA

ARTICLE INFO

Article history:
Received 17 August 2024
Received in revised form 04 March 2025
Accepted 04 March 2025
Available online 05 March 2025

Keywords:

Dye Penetrant Testing (DPT), Non-destructive testing (NDT), Dwell Time

ABSTRACT

Non-destructive methods are important in the maintenance of an aircraft due to their application and clear results. This study explores the efficacy of Dye Penetrant Testing in identifying defects or flaws in aircraft components such as propeller blades, bolts and nuts, modified exhaust engines, and towing bars. DPT is a non-destructive testing method to ensure the structural integrity and safety of aircraft by detecting surface-breaking flaws. This study compares three application methods of spraying, brushing, and clothing. These several methods are to determine the most effective technique for detecting defects such as cracks. The inspection results demonstrate that while spraying provides quick and uniform coverage, brushing provides only targeted areas and more controlled application, and clothing offers thorough surface contact. By comparing these several results, the spraying method concludes that the percentage of time is 28.3% and the cost effectiveness is about 32.1%, resulting in a lower percentage than the brushing and clothing methods. The study highlights the importance of dwell time in the penetrant process with a different method. To conclude, this research contributes to enhancing the aviation safety industry by optimising DPT techniques and providing an evaluation of cost-time effectiveness.

1. Introduction

Non-destructive testing (NDT) methods are used to assess the integrity of materials for surface or internal flaws. NDT techniques are used to monitor the compliance of aircraft components with airworthiness requirements throughout their lifecycle, from design and development to manufacturing and replacement. NDT is widely known for detecting cracks, flaws, incomplete or defective welds, and any other type of flaw that could lead to premature failure.

Dye penetrant testing (DPT), also known as liquid penetrant testing, is a widely used NDT method in the aerospace industry for detecting flaws in metal components. Additionally, DPT is a cost-effective and sensitive NDT method, making it ideal for inspecting large surface areas or large volumes of material. It is particularly well-suited for inspecting aircraft components, where it is the most sensitive and cost-effective method for detecting flaws [1]. Depending on the application, penetrant materials utilised, material, type of material being inspected, and kind of defect being

* *Corresponding author.*
E-mail address: elizay@gmail.com

inspected for, the inspection times change. Usually, minimum dwell durations span up to 30 minutes [2].

The purpose of this project is to detect flaws in aircraft components by using dye penetration. Aircraft components are habitually maintained to keep them operational, reliable, and to minimise flaws. This study investigates the comparison of several methods of DPT testing with different dwell times and the limitations of DPT in detecting flaws in aircraft components. Figure 1 is a procedure for DPT methods on the surface.

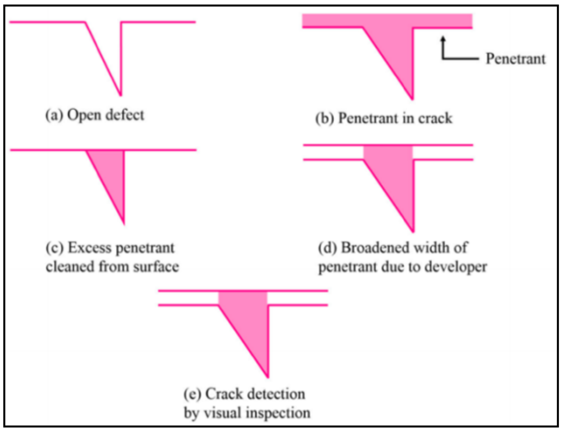

Fig 1 *DPT Procedure on the surface* [3]

1.2 Problem Statement

A previous study indicates that detecting small flaws using dye penetrant testing might be difficult to detect. False indications may occur due to excessive developer application or inadequate removal of excess penetrant. Moreover, prior studies stated that unidentified small flaws can lead to catastrophic failures in critical components [4]. Besides that, a study shows that the components must be cleaned after inspection to eliminate developer and other inspection material residues that might be damaging to the component's future operation or function. The main issue with penetrant testing is for the consumable to be properly applied to the sample. For better focusing on applying penetrant as well as the developer, the study using several methods such as spraying, brushing, and clothing and compared which method producing efficient and optimum results.

In addition, previous studies have shown that the complete cleaning of the material surface is an important step in penetrant testing. This is necessary to ensure that penetrant enters completely into potential surface gaps, which may otherwise be restricted by surface chemicals [5]. The residue from the penetrant procedure might be hazardous to the components as it accumulates residual layers of operation [6]. As supported by prior research, these residues may cause corrosion or other types of chemical deterioration, particularly when the component is exposed to hazardous conditions or corrosive chemicals.

1.3 Dye Penetration Testing

Penetration inspection capitalises on the natural collection of fluid around a discontinuity to produce a recognisable indicator of a fracture or other surface opening. Capillary motion draws the fluid to the discontinuity in comparison to its surroundings [7]. Penetrant examination reveals flaws such as surface cracks and porosity. Fatigue cracks, shrinkage cracks, shrinkage porosity, cold closure, grinding and heat treatment cracks, seams, laps, and rips can all create these flaws [6].

Previous research concluded that liquid penetrant testing is extensively used to maintain high reliability in aircraft manufacturing and maintenance and that this technology provides benefits such as flexibility and convenience of usage [8]. Additionally, engine components show wear, high temperature impacts on the mechanical characteristics of materials, fatigue, and erosion-corrosion damage [9]. Figure 2 indicates engine cylinder aircraft showing cracks detected by dye penetration, [9] and Figure 3 shows a DPT on the drain mast component or aircraft [8].

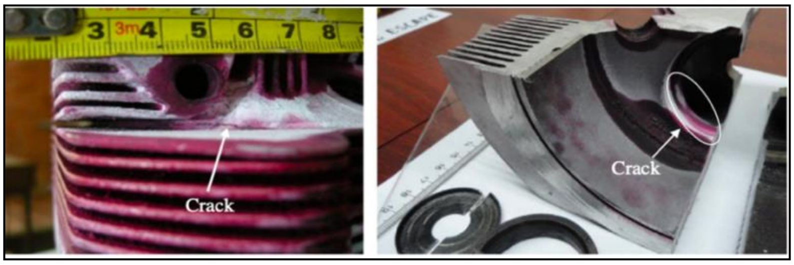

Fig 2 *Engine cylinder showing a crack* [9]

Fig 3 *DPT on drain mast component of aircraft* [8]

On top of that, other faults discovered include surface scratches and roughness, possibly resulting from collisions with other objects and ageing; porosity, presumably caused by corrosion; and a break in the metal bar caused by tensile stress fatigue. To summarise that, when the developer had been applied to the component, red dots on the surface exposed all of the flaws. Most of the components had complicated forms and/or tiny sizes, complicating inspection and demanding several test attempts before obtaining an adequate evaluation of their surface [6].

2. Methodology

The method of applying visible dye penetrants is very important because it can significantly influence the inspection's effectiveness. This inspection is conducted using several methods, such as spraying, brushing, and clothing application. Figure 4 shows the types of aircraft components.

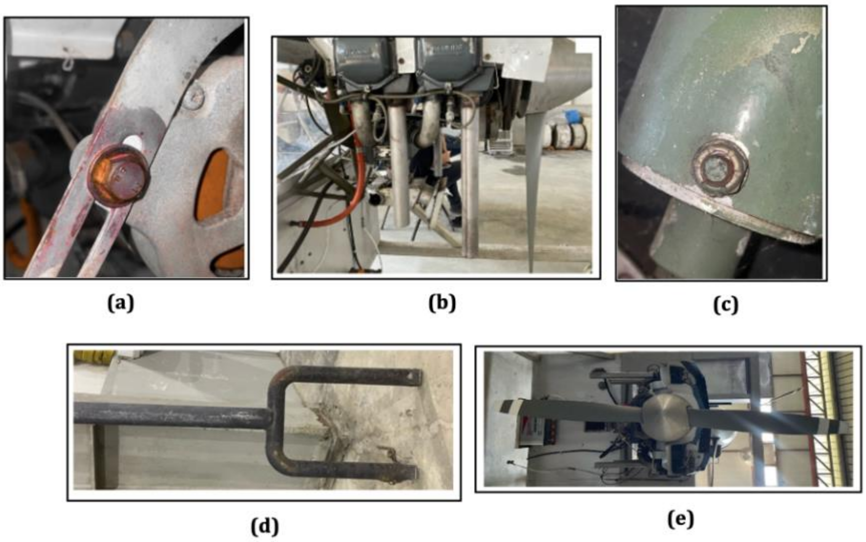

Fig 4 *Type of aircraft components (a) Uncoated Bolt and Nut; (b) Modified Exhaust Engine; (c) Coated Bolt and nut; (d) Towing Bar; (e) Propeller Blade*

2.1 Tools and Equipment

The utilisation of specific tools and equipment intended to enable the application, penetration, and evaluation of the penetrant substance is vital for the effectiveness of this inspection method. The penetrant is a low-viscosity liquid that can penetrate surface-breaking flaws. It is applied to the surface of the substance being examined. Apart from that, the developer is a white, powdery material that is applied following the penetrant. It draws the penetrant out of flaws, allowing them to be examined. These are used to completely clean the material's surface before applying the penetrant. The cleaner eliminates impurities from the inspection process, such as oil, grease, and grime. Shown in Figure 5 is a spray can of penetrant equipment.

Fig 5 *(a) Red Dye Penetrant; (b) Developer; (c) Cleaner Solvent*

For this study, to achieve precise results during inspection of dye penetration, is used brushes, tissues, rags, or cloths. Every tool has a specific purpose, which is to ensure effective performance and accuracy. Figure 6 shows a brush that is designed with synthetic filaments that are hollow and tapered. The amount of penetrant is sufficient when using this brush on the surface to be inspected.

The hollow structures match the penetrant substance, while the tapered features achieve precise and uniform application for thorough coverage over the entire surface.

Fig 6 *Hollow tapered synthetic filament brush*

Furthermore, the characteristics of the cloth are strieless, meaning it leaves behind no marks that can mask up the inspection process. Its superfiber composition ensures that it’s strong and durable, and it can withstand use without tearing. Moreover, it’s also got strong decontamination properties, leaving the surface free from any waste penetrant. The cloth is super soft to prevent any scratching or damage to the aircraft components. Figure 7 is a cloth for inspection of dye penetration.

Fig 7 *Cloth*

Based on Figure 8, it is a disposable glove, namely Natural Latex Disposable Gloves. These gloves have been used for dye penetration inspection, where it act as a barrier, protecting the inspector’s hand from direct contact with the dye penetration. The characteristics of this glove are its excellent tensile and tear resistance, less hand fatigue, ease of wear, and good resistance to diluted chemicals. This is to ensure the dye penetration inspection is not contaminated during the inspection process.

Fig 8 *Disposable Rubber Gloves*

In dye penetrant inspection, using tissue is essential for cleaning any excess dirt, oil, and other contaminants from the surface components before applying the penetrant. It is also used with cleaning solvent to effectively remove a waste penetrant from the aircraft surface components after the inspection process. Figure 9 is a multipurpose 2-ply kitchen towel that has strength when wet and is thick and of good absorbent quality, ensuring the surface is thoroughly cleaned without leaving any waste behind.

Fig 9 *Multipurpose 2-ply tissue*

2.2 Types of Aircraft Selection

Lake Renegade LA-2250 is manufactured with six amphibious utilities. This aircraft was designed with an amphibian complex design where landings and take-offs on both water and land are more complex. Figure 10 shows a Lake Renegade 250, whose features include a wing configuration, the empennage design, and the overall shape of the fuselage. Besides that, the unique design is that the pilot and passenger views are clear, but it also minimises the water splash when hitting the propeller during landing or takeoff on water. It has round tips, which contribute to aerodynamic efficiency. It is a four-cylinder in a horizontal position with a direct drive and an air-cooled engine [10]. Shown in Figure 11 are the parts of the Lycoming engine, which include a four-modified exhaust engine and a microfiber propeller blade.

Fig 10 *Lake Renegade LA-250 (a) Front View; (b) Side View*

(a) **(b)**

Fig 11 *Parts of Lycoming Engine; (a) Front View; (b) Side View*

3. Result and Discussion

The three methods of DPT application, which are spraying, brushing, and clothing, were compared. In order to understand the penetrant trend for each type of DPT method, the chapter presents the observations and results due to dwell time analysis. This chapter aims to identify the most effective DPT method for detecting flaws in aircraft components. The time durations for varying dwell times range from 10 to 20 minutes, which ensures the optimal dwell time for the aircraft components.

3.1 Spraying Method

Spraying application of visible dye penetrants is a common technique in DPI process, components providing a reliable and efficient for defect detection in various aircraft. Prior research stated that, it ensures a uniform and consistent layer through a surface area [11]. The penetrants will evenly flow across the surface of the aircraft throughout into any surface discontinuities. Shown in Figure 12 is a 15-minute dwell time for the propeller blade, and in Figure 13, it is a 10-minute dwell time for the modified exhaust engine, bolt and nut (uncoated and coated), and towing bar.

Figure 12 *Flaws on Propeller Blade*

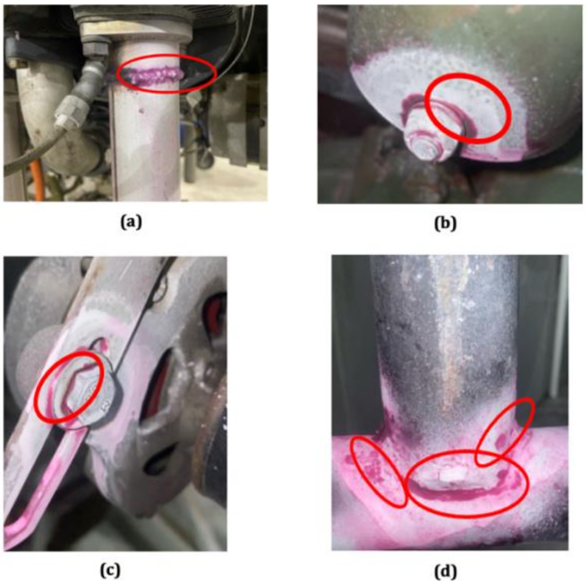

Fig 13 (*a) Modified Exhaust Engine; (b) Coated Bolt and Nut; (c) Uncoated Bolt And Nut; (d) Towing Bar*

3.2 Brushing Method

In comparison to the spraying method, which has a shorter dwell time of 15 minutes, it is faster and ensures equal coverage, but it may not penetrate as well into the defects as the brushing method. Overall, the precision offered by brushing is advantageous for localised defects or surface irregularities, which makes enhanced accuracy more efficient [12]. Shown in Figure 14 is a 20 minutes of dwell time of propeller blade and Figure 15 is a 15-minute dwell time of other aircraft components.

Fig 14 *Flaws detected on Propeller Blade*

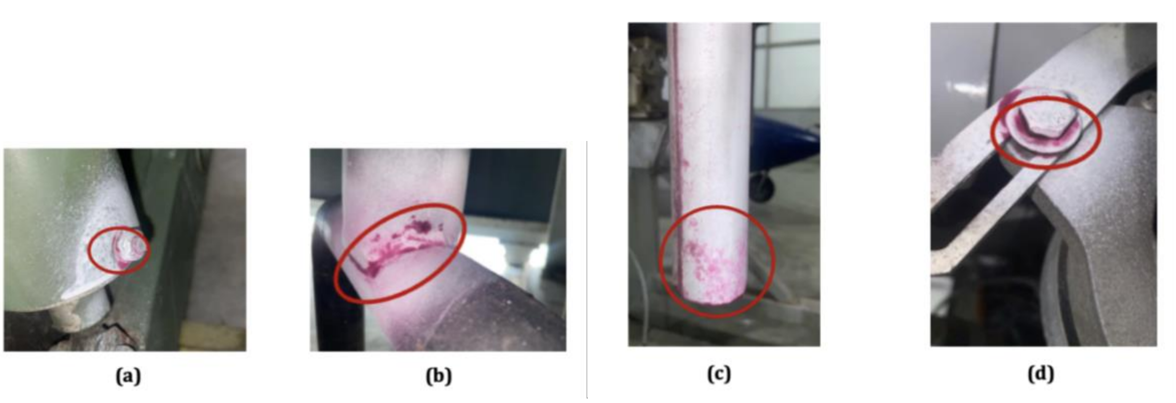

Fig 15 (*a) Coated Bolt and Nut; (b) Towing Bar; (c) Modified Exhaust Engine; (d) Uncoated Bolt and Nut*

3.3 Clothing Method

The clothing application might offer an uneven application because rubbing the penetrant by using cloth minimises the chance of dye reaching on potential defects. By applying a clothing technique, the penetrant viscosities might be affected because the amount of penetrant might absorb within the cloth texture. It is emphasized through previous research, a cloth texture can alter a liquid's properties [13]. As shown in Figure 16, the result of the dye penetrant is a 20-minute dwell time for each of the components.

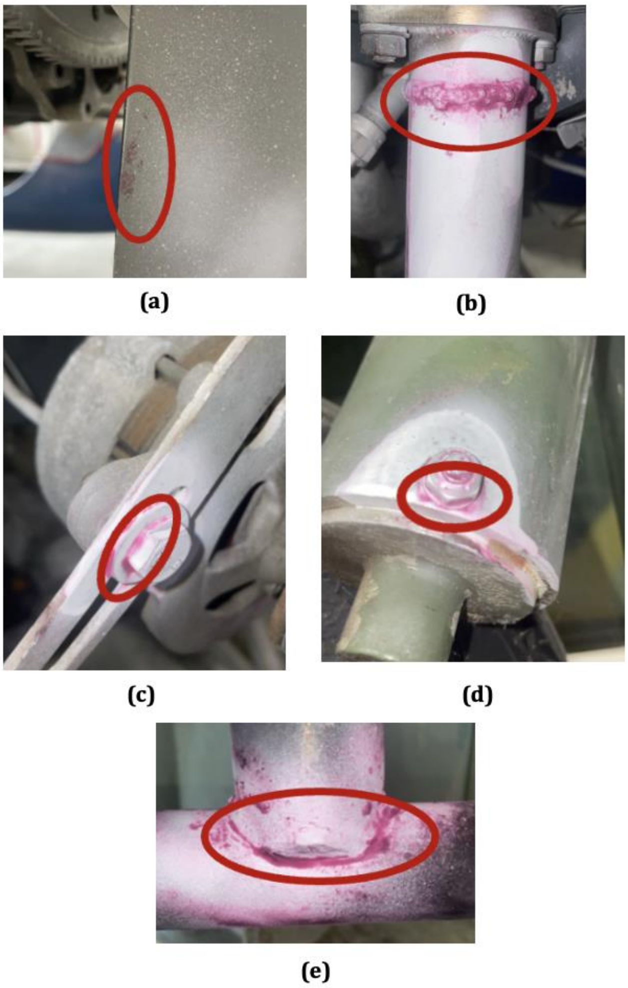

Fig 16 (*a) Propeller Blade; (b) Modified Exhaust Engine; (c) Uncoated Bolt and Nut; (d) Coated Bolt and Nut; (e) Towing Bar*

3.4 Dwell time

Based on the results of three different methods of DPT, it shows different dwell time each. For spraying and brushing methods, the dwell time is shorter compared with clothing methods. The reason is by spraying and brushing methods, the ample amount of red dye is applied to the sample. It indicates that the suction of red dye completely occurs as due to the capillary action. Through clothing methods, there is slight possibility that the red dye is absorbed by the cloth or tissue used as a medium in applying the dye. It prevents the dye from fully occupied and effect the efficiency of the suction during the capillary effect.

3.4 Evaluation of Cost and Time Effectiveness

The evaluation of cost and time effectiveness is essential to determining its optimisation throughout industrial applications. By computing the materials, labour, and equipment, as well as the time required for several methods, it can be shown which method is more reliable to use within the time consuming.

Spraying application is the most common method of Dye Penetration Inspection in NDT due to its speed and ease of use. As shown in Table 1, the time consumed for the spraying method. While spraying might offer a quick application process, it's important to consider its cost effectiveness for this multi-inspection inspection. The estimated inspection cost is about RM 68.00, as shown in Table 2. Previous studies have shown that the dye penetration method is a low-cost method compared to other NDT methods [8].

Table 1 *Time consumed for Spraying Method*

DESCRIPTION	TIME
Cleaning	5 min
Application of Penetrant	2 min
Dwelling Time	10 – 15 min
Cleaning	5 – 6 min
Application of Developer	2 min
Developer Time	10 – 15 min
Inspection Time	5 min
Post-cleaning	5 – 10 min
Minimum Total Time	44 min
Maximum Total Time	60 min
Total time consumed	**44 – 60 min**

Table 2 *Cost effectiveness of spray method*

Description	Cost (RM)
1 can of dye penetration	60.00
1 can of developer	
1 can of solvent cleaner	
Rubber Gloves	10.00
Tissue (2 packs)	
Clean Cloth	
Total Cost	**70.00**

In terms of time efficiency, the time consumed is 44 to 60 minutes. It is proven that the spraying method has quick coverage and even application of the penetrant, making it visible towards the penetrant. Meanwhile, regarding cost efficiency, the cost of the spray method is RM 68.00, which makes it an affordable option for conducting DPI. Previous studies highlight that spraying is effective in cost-time situations due to its faster application [11].

Table 3 *Time consumed by brushing method*

DESCRIPTION	TIME
Cleaning	5 min
Application of Penetrant	2 – 3 min
Dwelling Time	15 - 20 min
Cleaning	5 – 6 min
Application of Developer	2 min
Developer Time	15 - 20 min
Inspection Time	5 min
Post-cleaning	5 – 10 min
Minimum Total Time	52 min
Maximum Total Time	71 min
Total time consumed	**52 – 71 min**

Table 4 *Cost effectiveness of brush method*

Description	Cost (RM)
1 can of dye penetration	60.00
1 can of developer	
1 can of solvent cleaner	
Rubber Gloves	10.00
Tissue (2 packs)	
Clean Cloth	
Brush	
Total Cost	**70.00**

Brushing is a good alternative to spraying for DPI because it allows only targeted application to the surface components [12]. Furthermore, brushing can minimise wasted dye compared to spraying, which can lead to overspray. As shown in Table 3 and 4, the time consumed and cost effectiveness of using the brushing method. Compared to the spraying technique, it is slightly more time-consuming to conduct each inspection component. Moreover, brushers are generally inexpensive and reusable [12] so it do not cost a lot during the inspection, as shown in Table 4. By conducting the brushing method, it can mask up defects, especially on a rough surface such as a towing bar or modified exhaust engine, because the brush itself can wipe away the penetrant at a high interface contact pressure [12].

Table 5 *Time consumed for clothing method*

DESCRIPTION	**TIME**
Cleaning	5 min
Application of Penetrant	3 – 5 min
Dwelling Time	20 min
Cleaning	5 – 6 min
Application of Developer	2 – 5 min
Developer Time	20 min
Inspection Time	5 min
Post-cleaning	5 – 10 min
Minimum Total Time	65 min
Maximum Total Time	76 min
Total time consumed	**65 – 76 min**

Table 6 *Cost effectiveness of clothing method*

Description	Cost (RM)
1 can of dye penetration	60.00
1 can of developer	
1 can of solvent cleaner	
Rubber Gloves	14.00
Tissue (2 packs)	
Clean Cloth	
Cloth	
Total Cost	**74.00**

Meanwhile, clothing considers rubbing the saturated cloth to ensure good surface contact and dye penetration within the surface components. The Table 5 and Table 6 show the results of the time and cost effectiveness of the clothing method. The time is slightly higher compared to other techniques because clothing might seep away during the application and it takes a multiple time to applied the penetrant due to the amount of penetrant are not sufficient enough to be in contact through the aircraft components [14]. This is because clothing might absorb the penetrant onto the cloth while applying it to the surface components. In terms of cost effectiveness, it’s used a reusable cloth for applying penetrant and developer, resulting in a slightly higher cost than the spraying and brushing methods.

3.5 Comparison of Evaluation Effectiveness of cost-time

Shown in Table 7, the lowest amount of percentage of cost-time effectiveness is spraying method. This is the shortest time range among brushing and clothing methods. Spraying allows a straightforward application, which reduces the overall time required for each inspection of aircraft components. In addition, it can uniformly apply the penetrant, minimising reapplication of the penetrants. Apart from cost effectiveness, spraying is conducted in a precise amount of penetrant because it does not require additional equipment, such as brushes or reusable cloth.

Furthermore, table 7 shows that the percentage value of the brushing method is slightly higher than the spraying method and lower than the clothing method. The percentage of time effectiveness is a bit slower than the spraying method due to the need for more careful and targeted applications of the penetrant to a specific area, such as a towing bar, a modified exhaust engine, and both coated and uncoated bolts and nuts. The overall cost is higher due to the need for brushes, which are inexpensive and reusable but still add to the overall cost. In terms of applying the penetrant to the surface components, brushing can add to the waste of the penetrants, resulting in multiple applications in large areas such as propeller blades.

Moreover, the time-cost effectiveness of the clothing method is much higher than that of other methods. The percentage of time is higher due to the longer dwell time and developer time for each aircraft component to be inspected. This is because the cloth might absorb the penetrant while applying it to the surface. The rubbing application resulting from it can be time-consuming compared to spraying and brushing. As for the higher cost, it is due to the use of reusable cloth, which leads to a higher percentage of cost effectiveness.

Table 7 *Percentage of Time and Cost Effectiveness*

Application Method	Time Range (min)	Cost (RM)	Percentage of Time (Approx)	Percentage of Cost (Approx)
Spraying	44 – 60	68.00	28.3%	32.1%
Brushing	52 – 71	70.00	33.42%	33.0%
Clothing	65 – 76	74.00	38.3%	34.9%

4. Conclusion

The findings show that DPT is a crucial method for detecting surface defects in aircraft components. The sensitivity of DPT to detect flaws, such as cracks, ensures the structural integrity of aircraft parts. Among the different methods evaluated, the spraying method has the most consistent results in flaw detection, mainly for complex geometries such as propeller blades. The brushing and clothing methods showed variability in their performance, which indicates a need for precise control during application.

Moreover, the study also highlighted the dwell time effectiveness. An optimal dwell time is identified, and a longer dwell time generally increases defects. However, an excessive amount of dwell time somehow did not enhance the defects and could lead to false indications. Furthermore, the DPT limitations are consistent with detecting flaws on rough or textured surfaces. This result can be less efficient, reducing the reliability of the inspection of certain types of aircraft components.

An impact on aviation safety from this dye penetration inspection can prevent critical failures. Effective flaw detection can highlight the airworthiness and safety of aircraft, which reduces the risk of component failures during operation. This study also focuses on the economic aspects of DPT. It has been proven from cost-time effectiveness that the most common methods, such as spraying applications, have the most reliable performances in DPT. A recommendation that aligns with this inspection is to consider the surface smoothing technique by using light sanding to achieve a smooth surface, which can improve the ability of penetrants to detect the flaws accurately.

To conclude, DPT enhances the safety and reliability of aircraft components. The study highlights the proper application techniques and optimal dwell times to achieve results. Despite its limitations, DPT remains a valuable method to inspect in the aviation industry to ensure the continued safety and efficiency of aircraft operations.

Acknowledgement

The authors wish to extend their sincerest gratitude to the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia that has supported on the accomplishment of research activity.

References

[1] Fatma Nur Yiğit, Nurullah Keskinsoy, Türker Burak Güven, & Elif Eren Gültekin. (2021). Non destructive testing of aircraft wing with liquid penetrant method. *International Journal Of Aeronautics and Astronautics , 2(3)*, 56–60.
[2] Larson, B. (2002). *Study of the factors affecting the sensitivity of liquid penetrant inspections: review of literature published from 1970 to 1998*. Office of Aviation Research, US Federal Aviation Administration.
[3] Lu, Q. Y., & Wong, C. H. (2017). Applications of non-destructive testing techniques for post-process control of additively manufactured parts. *Virtual and Physical Prototyping*, *12*(4), 301-321.
[4] Prathi, H., Tamanam, S., Ganipisetty, V., & Burragalla, D. (2022, November). The NDT methods on the surface of rotating shafts. In *AIP Conference Proceedings* (Vol. 2648, No. 1). AIP Publishing.
[5] Kaiser, H., & Karbhari, V. M. (2001). *Quality and monitoring of structural rehabilitation measures*. USCD.
[6] Susilawati, S., Ardin, M. B., & Syarif, R. A. (2021). Material Screw Testing ON Tail Rotor Drive Using'D'Penetrant Testing Method. *VANOS Journal of Mechanical Engineering Education*, *6*(1).
[7] Raj, B., Jayakumar, T., & Thavasimuthu, M. (2002). *Practical non-destructive testing*. Woodhead Publishing.
[8] Berces, K. U. R. T., & TARHAN, C. Testing of Drain Mast Component Using Non- Destructive Testing Methods. European Journal of Science and Technology, (31), 852-860.
[9] Ortiz, A. F., Rodriguez, S. A., & Coronado, J. J. (2013). Failure analysis of the engine cylinder of a training aircraft. *Engineering Failure Analysis*, *35*, 686-691.
[10] Eshwar Kumar Munusamy, & Rahmat Mohsin. (2018). Anti-Knocking Characteristics Of Motor Gasoline Fuel In Reciprocating Lycoming O-320 Engine In Comparison To Aviation Gasoline Fuel. *Zibeline International Publications*, *2*(2). https://doi.org/10.26480/er.02.2018.01.07
[11] Mulder, R., Morshed, M. N., Seipel, S., Norén, U., Niit, E., & Nierstrasz, V. (2022). Study on hydraulic spray atomizing system as a new resource-efficient dyeing-finishing method for wool fabric. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-26172-4
[12] Ma, S., Zhang, X., Yu, B., & Zhou, F. (2019). Brushing up functional materials. NPG Asia Materials, 11(1). https://doi.org/10.1038/s41427-019-0121-2
[13] Ding, J., Kearney, J., Wang, H., Tian, T., Lin, T., & Wang, X. (2021). Competitive wetting: a new approach to prevent liquid penetration through porous materials with superior synergistic effect. Small, 17(49). https://doi.org/10.1002/smll.202103695
[14] Bormann, J. L., Acipayam, A. S. F., & Maibach, H. I. (2020). Percutaneous absorption of chemicals from fabric (textile). Journal of Applied Toxicology, 41(2), 194-202. https://doi.org/10.1002/jat.4077