Human Factors and Ergonomics in Dye Penetrant and Magnetic Particles Nondestructive Inspection Methods

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Abstract- Dye Penetrant Inspection (DPI) and Magnetic Particles Inspection (MPI) are two of the most commonly used Non-Destructive Testing (NDT) techniques in industry. Both techniques do rely heavily on human judgment and visual capability to identify any faults or defects on the specimen at the end of the process. Despite the fact that human plays an important role on the reliability of the NDT test results, very little research work has been carried out to study the ergonomics and human factors in using these NDT methods. In this paper, several human factors which could affect the reliability of the tests are discussed and some recommendations are also provided to improve the tests.

Index Terms— Magnetic Particles Inspection, Dye Penetrant Inspection, Non-Destructive Testing, Ergonomics

I. INTRODUCTION

Non-destructive testing (NDT) is an examination or evaluation performed on a test object without changing or altering it in any way for determining the absence or presence of conditions or discontinuities that may have an effect on its usefulness or serviceability [1]. The number of NDT methods that can be used to inspect components and make measurements is large and continues to grow. Researchers keep on finding new ways of applying knowledge of physics, materials engineering, and other scientific disciplines to develop better NDT methods. However, very little research work has been carried out to study the ergonomics and human factors in using these NDT methods and equipment, and yet human is one of the important factors which could significantly affect the reliability of the test results. In order to investigating the ergonomic, safety and health problems in conducting these NDT methods, three NDT companies were visited in this study. During site visits, it was found that some of the NDT operators were not aware of their own personal safety and health. In this paper, two of the popular nondestructive inspection methods, viz dye penetrant inspection (DPI) and magnetic particles inspection (MPI) were selected for study and the related issues of ergonomics, safety and health were examined and discussed.

Basically, both the DPI and MPI have some similarities in operational and procedural aspects although their basic working principles are different. Unlike most of other popular NDT techniques, no electronic instruments are used to detect faults and defects with these two methods. Instead, these two methods rely heavily on the use of human visual abilities and cognitive decision process. Also it was noted that both methods involve spraying hazardous chemicals on the surface of the specimen prior to the human inspection task [2][3].

II. PRINCEPLES AND PROCEDURES

A. Dye Penetrant Inspection (DPI)

Dye penetrant inspection is a method for revealing surface cracks by using color dye. The technique is based on the ability of a liquid to be drawn into a ‘clean’ surface breaking flaw by capillary action [4][5]. Similar to magnetic particles inspection, the procedures of performing dye penetrant inspection begin with pre-cleaning of the surface of specimen with cleaner. Penetrant is then applied on the cleaned specimen so that its surface is covered with a layer of penetrant. The penetrant is allowed to remain on the surface for a sufficient time to allow penetrant to seep through the defects by capillary action. Generally, a 10-minute dwell time is sufficient on clean castings, welds, and most defects. The surface is then wiped clean with clean towel or cloth pre-moistened with cleaner or dye remover. After that, the surface is sprayed with developer to draw penetrant trapped in flaws back to the surface where it will be visible. The developer is allowed to stand on the part surface for an average of 20 minutes to permit the extraction of the trapped penetrant out of any surface flaws. Finally, the part is ready for inspection under appropriate lighting to detect the presence, location, and size of defect (Figure 1). After the inspection is completed, the part surface is cleaned thoroughly with cleaner or remover.

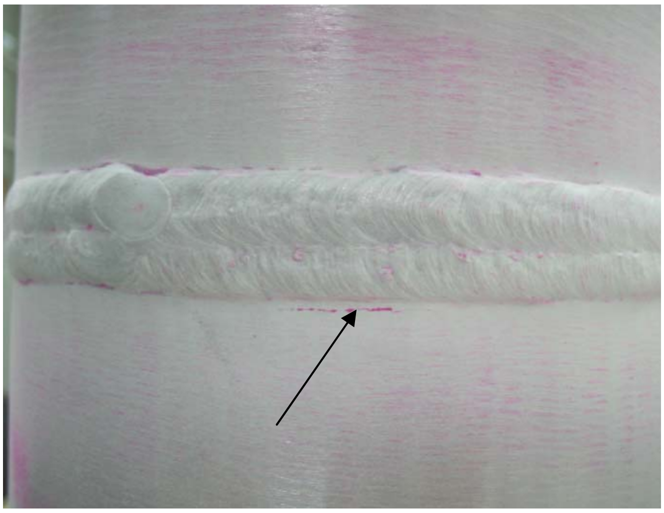


Figure 1: A crack (indicated by the arrow) was visualized with the DPI method

B. Magnetic Particles Inspection (MPI)

Magnetic particles inspection is a relatively simple technique and it can be considered as a combination of two nondestructive testing methods: magnetic flux leakage testing and visual inspection. Encountering a small air gap created by cracks on or near the surface (0 – 4 mm) of a magnetized component, magnetic field would spread out as the air cannot support as much magnetic flux per unit volume as the magnet can. When the flux spreads out, it appears to leak out of the material and is thus called a flux leakage field [6][7]. If iron particles are sprinkled on it, the particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect (Figure 2).

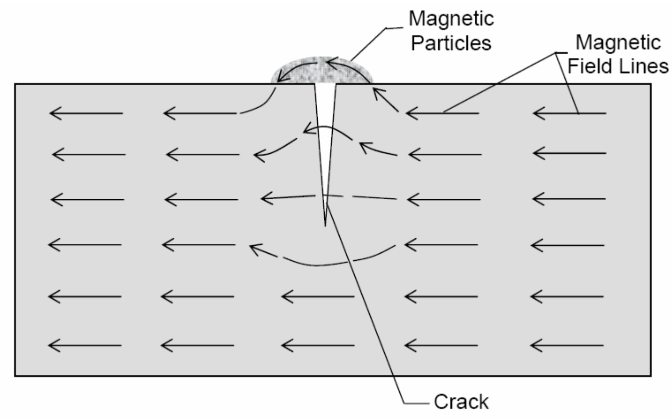


Figure 2: Working principle of MPI

The procedures of performing MPI involve pre-cleaning the surface of specimen with cleaner. The surface is then brushed with a wire brush (if necessary) and wiped off with purified wiping cloths (Figure 3a-3b). After cleaning, the surface is free of grease, oil and other moisture that could prevent the suspension† from wetting the surface and preventing the magnetic particles from moving freely. A layer of white contrast paint is then sprayed on the part surface to provide a better contrast for visualizing the position of faults (Figure 3c). After that, the part is magnetized with a pre-magnetized yoke (Figure 3d). While locating the yoke on the specimen, suspension of magnetic particles is gently sprayed or flowed over the surface, which is then blown to ensure the magnetic particles are evenly spread on the part surface (Figure 3e-3g). The part surface is then carefully inspected to look for areas where the magnetic particles are clustered. Surface discontinuities will produce a sharp indication (Figure 3h). The indications from subsurface flaws will be less defined and loose definition as depth increases. After inspection, the surface should be demagnetized and then cleaned again.

† The MPI suspension is a two-phase system comprising of finely divided magnetic particles dispersed in a vehicle, often a liquid petroleum distillate.

(a)

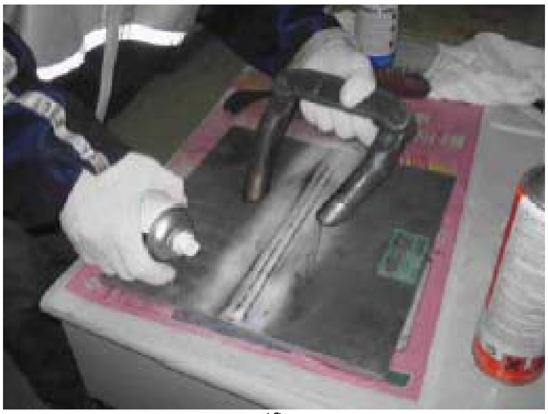
(b)

(c)

(d)

Figure 3a – 3d : Procedures of MPI

(e)



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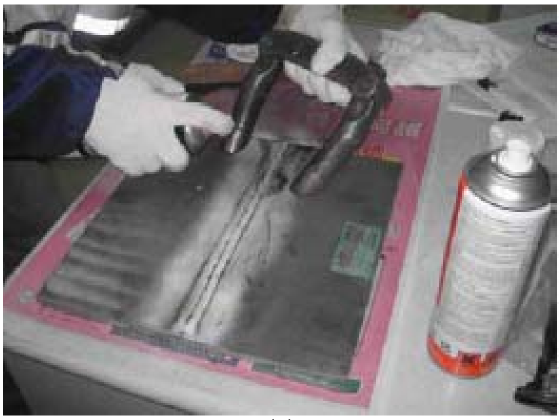

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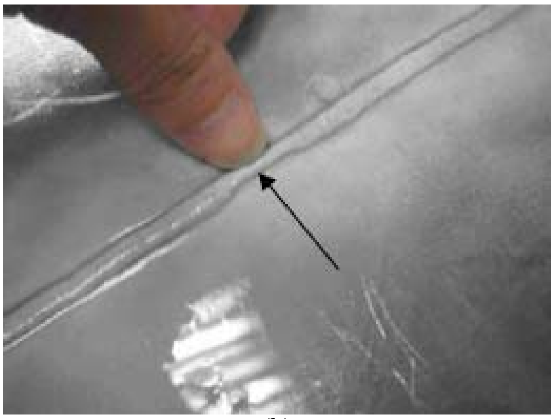

(h)

Figure 3e – 3h : Procedures of MPI

III. HUMAN ABILITIES AND SKILLS REQUIRED

A. Perceptual and Cognitive Abilities

The visual ability of inspectors is critical for identifying any defect in both magnetic particles and dye penetrant inspections. Their visual acuity should meet certain standard in order to perform the inspection tasks competently and properly. The European Standard EN473:1993[8], Qualification and Certification of NDT Personnel- General Principles, establishes a system for the qualification and certification of personnel who perform industrial NDT. According to EN473:1993[8], the inspectors shall provide evidence of satisfactory vision as determined by an oculist, optometrist or other medically recognized person in accordance with two requirements. Firstly, their near vision acuity shall permit reading a minimum of Jaeger number 1 (Snellen acuity of 20/15) or Times Roman N 4.5 or equivalent letters at not less than 30 cm with one or both eyes, either corrected or uncorrected. Also the verification of the visual acuity shall be done annually. In the NAS 410 [9], the Jaeger (J) number 1 criterion is also recommended for use for certification of operators for near-distance visual acuity, which is believed to be an important attribute for looking for a crack in NDT. Similarly, a recommended practice of Jaeger Number 2 or equivalent type and size letter at the distance designated on the chart but not less than 12 inches (30.5 cm) on a standard Jaeger test chart is proposed in SNT-TC-1A [10].

According to Hellier [1], the normal eye can distinguish a sharp image when the object being viewed subtends an arc of one-twelfth of a degree (5 minutes), which corresponds to a 20/20 Snellen acuity. At this condition, the thickness of the lines and spaces between the lines of the object subtend one minute of arc. It was also suggested that details of 1 minute of arc can be perceived by the human eye by other researchers [11] [12]. However, the authors believed that this measure of acuity, more precisely known as *minimum separable acuity*, may not be directly related to or useful for determining the suitability of operators for NDT tasks. Instead, *minimum perceptible acuity*, which is the ability to detect the presence of a spot or object from its background should be considered. It was reported by Hecht et al. [13] that the minimum perceptible acuity is of a value as high as 0.008 minutes of arc. Unfortunately, no other research was on the minimum perceptible acuity was reported.

The second requirement of human vision is that the color vision of inspectors shall be sufficient that they can distinguish and differentiate contrast between the colors used in the NDT method concerned as specified by the employer. It is obvious that the screening of operators based on the color vision requirement cannot be easily implemented as there is no specification of any color deficiency test recommended, and the employers may not have the sufficient knowledge and expertise in selection of the appropriated type of color vision test for recruitment of NDT operators. The Ishihara Compatible Pseudoisochromatic Plate (PIPIC) Color Vision Test 24 Plate edited by Dr. Waggoner [14] is a commonly used test of color vision. According to Wickens[15] , approximately seven percent of the male population is color deficient and are unable to discriminate certain hues from each other. Most prevalent is red-green color blindness in which the wavelengths of these two hues create identical sensations if they are of the same luminance intensity. However, it is difficult to precisely determine the type and degree of color deficiency of a person as there is wide variability within a class of color deficiency [12].

Apart from visual acuity and color vision mentioned in EN473:1993 [8], other visual characteristics of the operators such as contrast sensitivity and visual search abilities are also important factors. Contrast sensitivity may be defined as the reciprocal of the minimum contrast between a lighter and darker spatial area that can just be detected and become indistinguishable [15]. Since both MPI and DPI involve detecting the crack as a darker color indicator on a lighter background, operators' ability in contrast sensitivity is hence critical to the success and speed of the crack detection. Like visual acuity, contrast sensitivity decreases with ages of operators and may be required for consideration in selection test for operators.

For detecting the presence or absence of cracks, visual search is undertaken through a series of random or systematic eye fixations. A crack is usually first detected in the periphery with peripheral vision and then confirmed by foveal fixation. For a large product surface area, the peripheral vision is as important as foveal vision ability. Hence selection of NDT operators based on the area and shape of subjects' visual fields should also be seriously considered. A comprehensive visual field size and shape measurement software, Visual Lobe Measurement Software (VILOMS), developed by one of the authors [16] has been proved to be useful in predicting visual search speed of operators and may be helpful for screening NDT operators.

B. Physical Strength

In magnetic particles inspection, alternating current yokes have a lifting force of at least 4.5kg with 50-100mm spacing between legs, while direct current yokes and permanent magnets shall have a lifting force of at least 13.5kg with a 50-100mm spacing between legs; or 22.5kg with a 100 to 150mm spacing [4]. Therefore, during the magnetizing process, the arms of inspectors should have adequate lifting capability to separate the yoke from the part under inspection. Snook and Ciriello [17] provide information regarding what can be presumed to be suitable or unacceptable conditions for manual material activities in the United States. For lifting task, they suggested that the maximal acceptable lift weight, which accepted by 90% male industrial workers is 14kg and 17kg for a 51cm of vertical distance of lifting within the height of knuckle and shoulder in every 12 seconds and 60 seconds respectively. The data do not represent the capacity limits of individual. Instead, they represent the opinions of more than 100 experienced material handlers as to what they would do willingly and without overexertion.

C. Surface Preparation Technique

For clear indication of a crack with the MPI, if any, on a surface, concentration of magnetic particles in the suspension is a very important parameter which must be closely controlled. If there are insufficient particles in the suspension, no indications can be formed. However, too many particles may then give a high background that can mask small indications. The concentration is usually measured with the technique of settling test. The precipitate volume should be 0.15 to 0.3 mL per 100 mL for black oxide particles [4]. In DPI, removing of excess penetrant is the most delicate part of the inspection procedure. It is because this task requires the removal of all the excess penetrant on the surface without removing too much dye from the defects. Therefore, the inspector should have good skill in removing penetrant in order to visualize the defect successfully.

IV. ERGONOMICS, SAFETY AND HEALTH PROBLEMS

A. Illumination

Lighting can make details easier to see and colors easier to discriminate without producing discomfort or distraction [18]. Since both the MPI and DPI methods rely upon the inspectors to see the test indication, the lighting condition provided for these inspection tasks is extremely important. It does not only affect the sensitivity of the method but may also cause inspector fatigue if insufficient or too high level of illumination is provided at the workplace. Since lighting parameters can only affect the visual aspects of a task, the greater the contribution of vision to the performance of a task, the greater will be the effect of lighting on that task [12]. Obviously, NDT inspection tasks highly depend on vision for judgment of the presence of defect. If glare or reflections occur on the surface of the specimens, fatigue will quickly set in and lead to discomfort and decrease inspector performance as it prevents them from inspecting the specimens clearly. Glare is produced by brightness within the field of vision that is sufficiently greater than the luminance to which the eyes are adapted so as to cause annoyance, discomfort, or loss in visual performance and visibility [12].

B. Working Posture

Figure 4: Working posture of an inspector during performing DPI (Source: ETS-Testconsult Ltd.)

Figure 5: Working posture of an inspector during performing MPI (Source: ETS-Testconsult Ltd.)

The working posture of inspectors is usually determined by the actual location, size and mobility of the specimen. If the part being inspected is immovable, inspectors may need to adopt an uncomfortable working posture for performing the inspection tasks. As shown in Figure 4-5, inspectors have to squat down beside the specimen located in low position during performing MPI and DPI. Working with such kinds of improper postures may lead to different forms of musculoskeletal pains.

Hazardous ingredients	Potential health risks
Solvent based cleaner or remover ● light aliphatic solvent naphtha ● carbon dioxide propellant	● flammability ● flash fire ● mist or vapor may irritate the respiratory tract ● eye and skin irritation in case of liquid contact ● central nervous system (CNS) depression and target organ effects if overexposed ● slipping hazard if spilled
White contrast paint ● 2-propanone ● titanium oxide ● carbon dioxide propellant	● highly flammable ● cause sore throat, cough, confusion, headache, dizziness, drowsiness and unconsciousness in case of inhalation ● irritate skin by removing natural skin oils on long or repeated exposures ● eye redness, eye pain and blurred vision can be caused if eyes are exposed to it ● fast evaporating vapors can reach hazardous levels quickly in unventilated spaces
Magnetic particle suspension ● iron oxide, ● white mineral oil (petroleum) ● liquefied petroleum gasses ● isobutane	● extremely flammable aerosol ● bland oily liquid may irritate the skin ● isobutane vapors may cause dizziness and nausea in case of inhalation
Dye penetrant ● mineral oil ● phthalic esters ● liquefied petroleum gasses	● bland, oily liquid may irritate the skin and eyes ● burn vigorously if engulfed in fire ● extremely flammable
Developer ● 2-propanol ● 2-propanone ● isobutene ● talc	● flammable ● fast evaporating vapors can reach hazardous levels quickly in unventilated spaces ● irritate skin by removing natural skin oils on long or repeated exposures ● irritate eyes, but does not damage eye tissue ● dizziness and nausea if inhaled

Table 1: Summary of hazardous ingredients and potential health risks of chemicals used in MPI and DPI

The Rapid Upper Limb Assessment (RULA) method which was developed by McAtamney and Corlett [19][20] is a postural targeting method for estimating the risks of work-related upper limb disorders. A RULA assessment gives a quick and systematic assessment of the postural risks to a worker. For the working posture shown in Figure 5, the RULA score is 7, which means that the person is working in the worst posture with an immediate risk of injury from their work posture, and the reasons for this need to be investigated and changed immediately.

C. Potential Chemical Hazards

a. Dye penetrant inspection (DPI)

The chemicals involved in dye penetrant inspection (DPI) include cleaner, dye penetrant, and developer. The cleaner used in DPI is similar to that used in MPI. Dye penetrant may contain mineral oil, phthalic esters and liquefied petroleum gasses. The bland, oily liquid may irritate the skin and eyes. Although bulk material is difficult to ignite, it will burn vigorously if engulfed in fire. Aerosol is extremely flammable. The ingredients of developer may include 2-propanol, 2-propanone, isobutane, and talc. It is extremely flammable white liquid and aerosol. Its fast evaporating vapors can reach hazardous levels quickly in unventilated spaces. It can irritate skin by removing natural skin oils on long or repeated exposures. It can also irritate eyes, but does not damage eye tissue. Inhalation of this chemical may causes dizziness and nausea. A summary of hazardous ingredients and chemicals used in DPI and MPI and related health risks is shown in Table 1.

b. Magnetic particles inspection (MPI)

The chemicals involved in MPI include solvent based cleaner, contrast paint and magnetic particle suspension. In the course of operation, these chemical materials can have direct and unsafe effects on human operators (typical exposure to chemical solvents) or they can affect the environment in ways that are potentially hazardous [2][3]. A typical solvent based cleaner or remover in aerosol form may contain light aliphatic solvent naphtha and carbon dioxide propellant, which may cause flammability. Its vapor may cause flash fire. It would be harmful or fatal if swallowed. Mist or vapor may irritate the respiratory tract. Also, liquid contact may cause eye and skin irritation. Overexposure may cause central nervous system

(CNS) depression and target organ effects. Spills of the chemicals may create a slipping hazard.

White contrast paint may contain hazardous ingredients such as 2-propanone, titanium oxide and carbon dioxide propellant. 2-propanone is highly flammable, which may cause sore throat, cough, confusion, headache, dizziness, drowsiness and unconsciousness in case of inhalation. It can irritate skin by removing natural skin oils on long or repeated exposures. Furthermore, eye redness, eye pain and blurred vision can be caused if eyes are exposed to it. The fast evaporating vapors of white contrast paint can reach hazardous levels quickly in unventilated spaces. Magnetic particle suspension in general, contains iron oxide, white mineral oil (petroleum), liquefied petroleum gasses and isobutane. It is extremely flammable aerosol. The bland oily liquid may irritate the skin. In case of inhalation, isobutane vapors may cause dizziness and nausea [2][3].

V. CONCLUSIONS AND RECOMMENDATIONS

During task observation, it seems that the NDT operators were not aware of their personal safety and health. Although they have read the warning messages on the packages, they did not heed them. The employers should be responsible for providing a safe working environment, safety guide and protective equipment, etc.

Since, the position of the specimen being inspected is different for different cases, it is impossible to propose a standard working posture for the inspectors to follow. Instead, some guidelines can be recommended. Pheasant [21] suggested that inspectors should avoid forward inclination of the head, neck and trunk. Tasks which require the upper limbs to be used in a raised position should also be avoided. If it is possible, joints should be kept within the middle third of their range of motion. Also, twisted or asymmetrical postures should be avoided. As MPI involves a lifting task, job rotation is recommended in order to avoid muscular injury due to extensively lifting the yoke with high lifting weight as much as 22.5 kg.

For dye penetrant inspections, an illuminance level of 300 to 550 lx at the surface of the part is generally sufficient for gross defects where indication is large [6]. For extremely critical inspection, higher illuminance in the 1000 lx range is normally considered necessary. With visible magnetic particles, testing should not be attempted with less than 100 lx. Levels between 300 and 1,000 lx are best for most visible testing applications. Critical tests of small discontinuities may require 2,000 to 5,000 lx. However, it should be noted that extended testing at levels over 2,000 lx may produce eyestrain [4][6].

Recommendations of using chemical should also be given. When applying chemicals from aerosol cans, all inspectors must take very great care to protect not only their own well-being, but also that of their colleagues around them who may or may not be involved in the inspection task. When aerosols are used in an indoor workshop, care must be taken to ensure the local ventilation is adequate. There are occasions that the tasks must be carried out in the locations where the ventilation is poor, such as inside a vessel or pipe. In such circumstances, it would be advisable to supply the inspectors with independent air supply so as not to inhale the local atmosphere. The best form of this arrangement is the enclosed helmet variety which protects the head completely [5][7].

Apart from the issue of ventilation of the working environment, care must also be taken to avoid contact with eyes and skin during using the chemicals in NDT. Inspectors may wear protective goggles or glasses if necessary. It is also essential to avoid taking these chemicals into the mouth. If such chemicals get into the mouth accidentally, it should be washed out immediately with large quantity of water. Then medical treatment needs to be obtained directly afterward. In both MPI and DPI, most of the chemicals are applied by spray, frequently from aerosol cans. It is important to ensure that the spray nozzle is pointing away from the user or anyone else. Inspector may wear safety glasses to protect their eyes, and wear rubber gloves if hand exposure is unavoidable. When the chemicals are sprayed on site, inspectors are recommended to check the direction of the wind and avoid the possibility of sprayed chemicals being blown back over them if possible [4][6].

Furthermore, great care must be taken in handling and storage of the chemicals to avoid fire and explosive hazards, because most of the chemicals used in nondestructive test are flammable. Inspectors should be warned that no aerosol can ever be heated above 55^{o}C (130^{o}F). Stock of aerosol must be stored away from heat source. Also, chemicals must not be sprayed around arcs or flame in order to avoid ignition. If the chemical is accidentally release, sources of ignition should be turned off or removed first. The released chemicals should then be mopped up or swept up with absorbent [5].

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