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Reliability and sensitivity of magnetic particle nondestructive testing in detecting the surface cracks of welded components

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ABSTRACT

Defects generated during a welding process, specifically surface cracks, have a significant impact on the safety of welded components. Therefore, the detection of these types of defects has a considerable effect on avoiding the failure of the components. Since each nondestructive testing technique has its own limitations in defect detection, evaluating the detection properties of such techniques would be key for the inspectors of welded structures to possess a more proper technique selection. Moreover, the properties can be obtained from a number of maintenance and fracture control procedures such as the damage tolerance design technique. Reliability and sensitivity, as common tools, are extensively utilised to assess detection properties. Magnetic particle nondestructive testing is often used in the surface crack detection of welded components. To use this crack detection technique wisely, the properties have to be considered. However, to date, there has not been a comprehensive study on the reliability and sensitivity of the technique in detecting the surface cracks of welded components. To fill the gap, in this research, based on experiments and an analysis of the obtained data, the reliability and sensitivity of the technique in detecting the surface cracks of welded components are attained and presented.

1. Introduction

Welding procedures have the potential for generating a wide variety of defects in structures, which may cause the structures to be susceptible to fracture. In welded structures and components, fractures are capable of causing enormous loss of life and properties. To prevent such possible events, a number of maintenance and fracture control programs, such as damage tolerance design technique, have been employed by various industries and companies [1,2]. Since flaws are one of the main reasons for fractures, the characterisation of the flaws present in the structure is essential information for the abovementioned approaches, which have to be known and described in terms of shape, length and number.

The inspection procedure, as well as quality assurance, is used for defect characterisation by which the abovementioned maintenance and fracture control programs can be more

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effectively implemented. Nondestructive testing (NDT) techniques are among the most popular inspection methods. The main reason for their popularity lies in the fact that these methods do not affect the performance of the components, especially for critical applications such as power plants and pressure vessels [3]. For some techniques, the results of NDT depend on unstable parameters such as equipment quality, the emotional state of an operator, and defect shape and type. Thus, the characterisation of defects using NDT methods may vary. To address this and to quantify the results of NDT methods, sensitivity (detection capabilities) and reliability (probability of detection) are normally used [4,5] by conducting experiments and statistically analysing the results. Although experiment-based techniques are more common in obtaining sensitivity and reliability, some attempts using mathematical models and simulations such as the finite element [6–10], numerical model [11] and Monte Carlo simulation [12,13] have been reported.

Since reliability and sensitivity play a key role in inspection scheduling [14] and choosing a suitable nondestructive testing technique based on inspection objectives, several national institutes and programs (as examples: Advisory Group for Aerospace Research and Development (AGARD) [15], Nondestructive Testing Information Analysis Center (NTIAC) [16], Swedish Nuclear Power Inspectorate (SKI) [17], Materials and Manufacturing Directorate Air Force Research Laboratory [18], Air Vehicle Division of Defense Science and Technology Organisation [2]) along with international programs (for instance: Program for the Inspection of Steel Components (PISC) [19–21]) have made several attempts to report. Among researchers who have tried to report reliability or sensitivity of nondestructive testing methods, Lively and Aljundi, by conducting some experiments, reported the probability of detection of fluorescent penetrant testing (PT) in detecting low-cycle fatigue in plates of Inconel 718 [22]. In a similar way, the reliability and sensitivity of a liquid penetrant and an eddy current in detecting low-cycle fatigue cracks generated in compressor discs were studied by Simsir and Ankara [4]. The results revealed that the manual eddy current inspection method is more reliable and more sensitive than the liquid penetrant for that specific crack detection application.

Lately, the properties of visible liquid PT in detecting surface cracks of welded components in terms of sensitivity and reliability were studied by Zolfaghari and Kolahan [23]. According to the results, the probability of detection of cracks with a length equal to 3.37 mm is 90%. The reliability of automatic and manual ultrasonic NDT as the POD (probability of detection) in detecting the lack of penetration and lack of fusion of pipelines was reported in [24]. The ultrasonic techniques studied in the report were pulse-echo and TOFD (Time-of-Flight Diffraction), both manual and automatic. In other investigations, the detection features of an ultrasonically phased array [25,26], TOFD [27] and laser ultrasonics [28] as reliability assessments were studied by conducting some experiments. From other techniques, the reliability of eddy-current [29] and eddy current-induced thermography for the detection of small cracks [30] as well as vibrio thermography nondestructive evaluation in the crack detection of aircraft engine fan blades [31,32] were studied.

Magnetic particle nondestructive testing is extensively used in the surface crack detection of welded components. Once ferromagnetic components are placed in a magnetic field, the surface or subsurface discontinuities of the components perpendicular to the field generate a strong magnetic leakage field. The generated field is capable of attracting ferromagnetic particles, which could be wet or dry, onto the surface of the component to discontinuity locations. The aggregation of the particles creates indications at the locations

of the discontinuities [33]. Figure 1 shows the principles of magnetic particle testing (MT). Regarding the sensitivity and reliability of the method, Stadthaus et al. [34] evaluated the sensitivities of MT and PT. In the research, the determination of the visibility of indications generated once PT and MT are carried out on standard blocks encompassing natural and artificial defects was used to evaluate the sensitivity of the methods. In another investigation, the probability of detection for magnetic rubber inspections was assessed [35]. Burke and Ditchburn [36] attempted to present a comprehensive review of projects and studies carried out on the probability of detection for MT. Using the references, the coworkers presented the probability of detection for MT for detecting fatigue defects in high strength steels. The detection properties of the techniques depend on which kinds of defects are present, the procedure that generated them and the material. Therefore, the results may considerably change from one manufacturing process to another. Although the assessment of the detection properties of MT for detecting the surface cracks of welded components is an important topic, to date, there have been no specific and comprehensive investigations on this topic. In this paper, the detection abilities such as reliability and sensitivity are presented. Similar to the method described in [36], an approach was employed in this research to extract the reliability and the sensitivity by gathering two independent sets of data from a number of welded samples containing real surface cracks and then analysing the obtained data. The mentioned data include macroscopic assessments and inspection results of MT. Using the mh1823 POD software package [37], POD curves were drawn, and sensitivity analyses presented.

2. Detection properties in nondestructive testing

The detection properties of nondestructive testing techniques are generally described by two parameters: sensitivity and reliability. The sensitivity denotes the detection capabilities of the technique in terms of the detection rate, the smallest defect detected and the largest defect missed by the technique for a predetermined range of defect lengths. The reliability is defined as the probability of detecting defects by the technique and is typically calculated as a function of the defect length and drawn as a graph. The graph showing the function is called the POD. Moreover, the degree of confidence is utilised to consider the limitations in the number of the samples holding defects in calculating the probability of detection. By
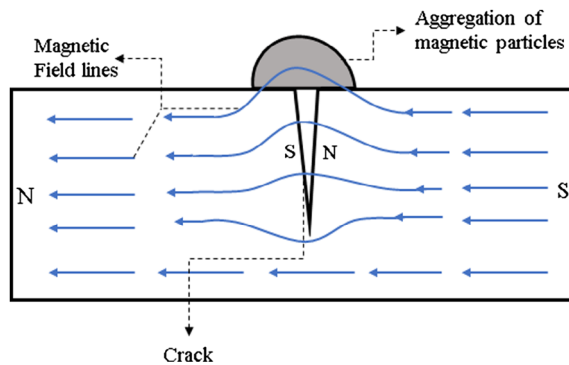

Figure 1. Principle of magnetic particles nondestructive testing.

the upper and lower boundary curves are depicted in Figure 1, and the POD confidence interval is illustrated. The most applicable parameters in the reliability assessment of NDT techniques are $a_{90/95}$, a_{90} and a_{50}.

The defect lengths that the nondestructive testing technique with a reliability assessment is capable of detecting with 50 and 90% probabilities are a_{90} and a_{50}, respectively. In the evaluation, the length of the defect with a 90% probability of detection and a 95% degree of confidence denotes $a_{90/95}$. The abovementioned POD graph shows the function called POD. Figure 2 illustrates an example of a POD graph for a nondestructive testing method. As shown in the graph, between a_1 and a_2, by increasing the defect length the probability also increases. The minimum value of defect length for which the probability of detection is zero is called a_1, while a_2 corresponds to the minimum defect length value for which the probability is one.

The signal response vs. flaw size (vs. a) and the binary data vs. flaw size (hit/miss vs. a) are the two main approaches to obtain the reliability and corresponding graph [23,38,39]. Due to the type of results in some nondestructive testing methods such as MT, the second approach is the only applicable method to acquire the reliability. In this approach, once a defect is found, the result associated with that defect is called a hit and is assigned the value 1. A defect that is missed is called a miss and is assigned a value of 0. In the case that the technique detects a defect in a specific location of a component but there is no defect in that position, it is named a false call. According to [23,39,40], the range of the lengths of defects under inspection was divided into length intervals called bins. The probability of detection for each bin is defined as the quantity of defects detected by nondestructive testing divided by the total number of defects in that range. Likewise, the false call rate can be defined as the number of false calls divided by the total number of defects in the entire range of defect lengths.

Regarding defects to be inspected to obtain the reliability and sensitivity parameters, two techniques of defect generation, artificial and natural, are introduced. In artificial flaw generation, a number of defects are fabricated by a manufacturing process such as electrical discharge machining [24,30]. Thus, the number of defects is known before employing nondestructive testing. In the second method, the components containing natural defects
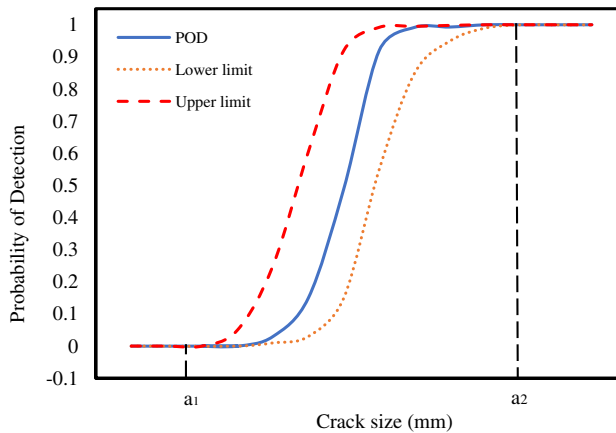

Figure 2. POD curve with confidence bounds.

created during manufacturing processes such as welding are considered to acquire the reliability. To obtain the real number of defects and characterisation, microscopic/macroscopic assessments or destructive evaluations are carried out [4,15,23,25]. Then, regardless which defect types described before are chosen, the components are inspected by means of the nondestructive testing technique to find defects. Consequently, there are two categories of detection results: the real number and characterisation of the defects and the results obtained by a nondestructive testing technique. The reliability (probability of detection) for each of the interval lengths of the defects (P_i) and the value of the center point of the length intervals (a_i) construct the (a_i, P_i) pairs. By extrapolating the pairs, the POD curve is obtained. From different equations describing the extrapolation, in the reliability assessment of nondestructive testing, the log-logistic distribution (Equation (1)) is the most consistent equation. β0 and β denote the location and slope parameter, respectively, and both are constant numbers.

$$P_i = \frac{\exp(\beta_0 + \beta_1 \ln(\alpha_i))}{1 + \exp(\beta_0 + \beta_1 \ln(\alpha_i))} \tag{1}$$

3. Experiments

In this study, the defects generated in a natural situation were chosen to obtain the sensitivity and reliability of magnetic particle nondestructive testing in the surface crack detection of welded components. The reason is that using realistic defects for inspection in nondestructive testing is better than using the artificial defects [4,23]. A total of 20 welded plates, 6 mm thick and Ck45 steel, containing surface cracks were chosen. This type of steel contained a medium content of carbon (as described in Table 1 in detail), and the welding procedure was MAG (Metal Active Gas). The experiments consisted of three main steps: microscopic assessments, nondestructive testing and statistical analysis.

3.1. Defect characterisation by microscopic evaluation

As previously described, to obtain the real number of cracks and lengths, a microscopic evaluation method was utilised. To accomplish this, images from the surfaces of the welded regions (×50 magnification) of the components were collected and analysed. After the images from surfaces of the welded regions of the components were collected and analysed, the number and lengths of the surface cracks were determined.

3.2. Defect characterisation by magnetic particle nondestructive testing

As described earlier, MT is based on the leakage of the magnetic flux applied on the surfaces of the components due to the presence of discontinuities. MT is performed with a wide range of techniques and methods, such as manually or fully automated methods, different types of electric currents (AC or DC) are applied to generate the magnetic field, various kinds of

Table 1. Chemical fractions of the material (wt.-%).

	%C	%Si	%Mn	%P	%S	%Cr
CK45	0.46	0.4	0.7	0.035	0.035	0.3

magnetic particles, and different methods used to transfer the particles to the surface of the components under inspection. In this study, manual nondestructive testing was employed, which generally included four stages.

3.2.1. Surface cleaning

Pollution such as oil, oxide particles, grease and scale may have negative effects on the aggregation of the particles and the inspection process. As a result, some cracks may not be detectable by nondestructive testing. Therefore, all contamination must be removed from the surface. To address that, prior to nondestructive testing, the surface is cleaned by various cleaners and techniques. In this study, after brushing, all pollution was cleaned using a liquid solvent.

3.2.2. Painting the surface

To increase the contrast between the indicators and background of the inspection area as well as to increase detectability, the surfaces are typically covered by a special white paint produced for this application. For this research, a white color was applied to the surface as a liquid spray (ARDROX (8901)).

3.2.3. Magnetisation

The magnetic field on the surface of each component is either generated directly by passing an electric current through the component or indirectly by placing the components in a magnetic field generated separately with external equipment. In this investigation, we used a magnetic yoke (PICO-MAG MY-100-NAWOO), by which an AC electric current was being employed, and the field was generated on the surface of each welded component.

3.2.4. Applying magnetic particles

Magnetic particles (visible or UV type) as dry or wet powders are employed on the surface for inspection by several techniques. In the research, a visible type of particles (ARDROX (800/3)-Chemetall) was transferred to the surface by spraying the liquid carrying the particles.

3.2.5. Indication evaluation

A higher aggregation of particles on the surface leads to visible marks as indicators of surface cracks. The indicator assessment condition differs based on the technique employed to assess the defects. In this study, the indications that appeared on the surface were evaluated under white light to find surface cracks.

3.3. Statistical analysis

Using the results obtained by the implementation of nondestructive testing and microscopic evaluation, the parameters of the sensitivity assessment and reliability, as well as the POD curve, were obtained.

4. Results and discussion

Figure 3 is a histogram representation of detection rate as a function of the subdivided defect lengths. For defect lengths in the range of 0–5 mm, the detection rates were calculated at intervals of 0.5 mm. According to the figure, the technique is not capable of finding any defects with a length of less than 1.5 mm. The rate for defect lengths between 1.5 and 2 mm reaches 33% and then for lengths between 2 and 2.5 mm attains 50%. Beyond the range of 0–2.5 mm, the method can find all defects. Table 2 shows the obtained parameters of the sensitivity analysis of the MT used in this study compared to similar previous investigations conducted by Fahr et al. [15] and NTIAC [16]. Fahr et al. [15] assessed the detection capabilities of fluorescent MT under ultraviolet light to reveal fatigue cracks created on the surface of the bolt holes of compressor discs. In a similar manner, the defect detection properties of nondestructive testing to find low-cycle fatigue cracks were described by NTIAC [16].

According to the table, the detection rate of the technique for the current study is 57%. The rate was between 19 and 69% in the NTIAC's research and 26 and 35% in Fahr's study. The discrepancy between the reported results is due to the method employed by the researchers (visible MT in the current study vs. fluorescent particle testing in other studies). Moreover, type of material, ranges of defect lengths under inspection, shapes of defects, equipment, and the level of the skill of the operator have considerable effects on the results in the table. Other parameters in the sensitivity analysis are the largest crack missed (a_L) and the smallest crack detected (a_s) by the technique. The present investigation shows that the largest defect missed was a crack with a 2.5 mm length. On the other hand, the smallest detected crack had a 1.6 mm length. These values have not been reported by NTIAC, but Fahr informed that a_L varied between 1.6 and 4.6 mm depending on the experimental condition. Therefore, a comprehensive comparison between the sensitivities of MT obtained in the current study and previous investigations are not possible.

As previously mentioned, the reliability of nondestructive testing techniques determines the POD of defects. Utilising the POD mh1823 software package [37], the POD curve of visible MT for detecting surface cracks in the welded regions with 95% confidence bounds was obtained, see Figure 4. Moreover, three important parameters in the reliability evaluation of NDT techniques including a_{50}, a_{90} and $a_{90/95}$ were found and presented [4].
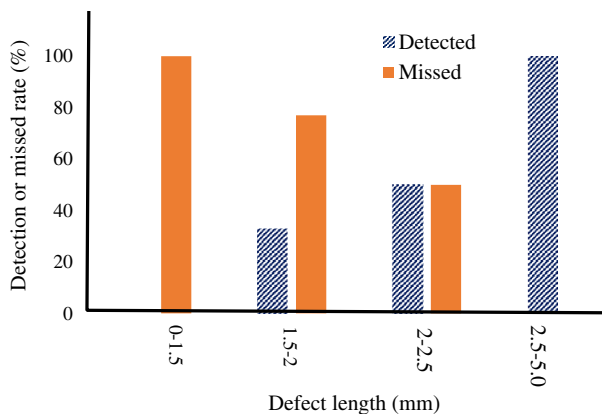

Figure 3. Detection and missed rate of the detects.

Table 2. Comparison between current study, Fahr et al. [15] and NTIAC [16] in reliability assessment of the nondestructive testing method.

	Detection rate (%)	False call rate (%)	Largest crack missed (a_l) (mm)	Smallest crack detected (a_s) (mm)	a_{50} (mm)	a_{90} (mm)	$a_{90/95}$ (mm)
Current study	57	7	2.5	1.6	1.9	2.5	3.8
NTIAC [16]	19–69	0–11.87	–	–	–	1.85–6.03	–
Fahr et al. [15]	26–35	0–10.5	1.6–4.6	–	–	–	1.9–3.7
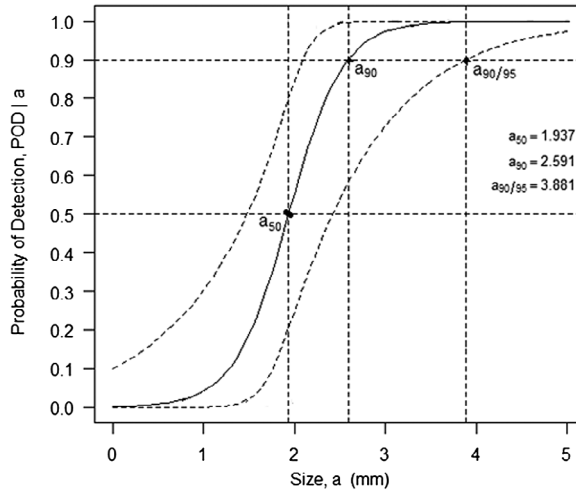
Figure 4. POD curve of visible magnetic particle nondestructive testing in detecting the surface cracks.

As described in Table 2, a_{50} is 1.9 mm, i.e. the technique can find defects of a 1.9 mm length with a 50% probability. Unlike the current study, the value of this parameter (a_{50}) was not reported in the previous investigations. The lengths relating to a 90% probability of defect detection reached 2.5 mm for the current research. NTIAC stated that this value that depends on the experimental conditions was between 1.85 and 6.03 mm. Thus, a_{90} based on the research explained in this paper is in the range of NTIAC's report (1.85–6.03 mm). Providing the average of the range considered as a basis for comparison (3.8 mm), the value of a_{90} based on two studies shows some deviations. According to another crucial parameter ($a_{90/95}$), the current study and Fahr's research demonstrate that the values of these parameters are 3.8 mm and 1.9–3.7 mm, respectively. The variation in the values reported for a_{90} and $a_{90/95}$ was due to the discrepancy in experimental conditions.

5. Conclusions

The present study provides a survey of the reliability and sensitivity analysis of visible magnetic particle nondestructive testing for detecting surface cracks of welded components. The sensitivity parameters of the technique obtained in this study were the detection rates at 0.5-mm intervals of the defect lengths, the largest crack missed (1.6 mm) and the

smallest crack detected (2.5 mm). For defects in the ranges of 1.5–2 and 2–2.5 mm, the rates were 33 and 50%, respectively. Beyond 2.5 mm, our technique was capable of detecting all defects. Moreover, the parameters of the reliability assessment of the nondestructive testing including a_{50} (1.9 mm), a_{90} (2.5 mm), and $a_{90/95}$ (3.8 mm) were obtained. In addition, the POD curve with upper and lower bounds as a function of the defect length was drawn. The results of this research could be used as a guide for people who are responsible for choosing the most suitable nondestructive testing technique. In addition, the results will be useful for designers and engineers responsible for planning the inspection procedure for welded structures.

Disclosure statement

No potential conflict of interest was reported by the authors.

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