Reliability and sensitivity of visible liquid penetrant NDT for inspection of welded components

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Welding, as an approach to join components, is used extensively by various industries. Generating several types of defects is one of the major weaknesses of the technique. Thus, inspection to detect the defects is normally considered as a stage of welding procedure. One of the main categories of the defects is surface cracks, which are found by nondestructive testing methods. However, visible liquid penetrant as a technique to reveal this kind of flaws is broadly used, the method capabilities in defect detection of welded components have not been comprehensively studied. In this paper, utilizing reliability and sensitivity concepts of nondestructive testing, its abilities in detecting of surface crack of welded joints are investigated. The results of the paper illustrate that the detection and missing rates are 52 % and 48 %. In addition, taking into account 95 % degree of confidence, probability of detection for defects with length equal to 3.73 mm is 90 %.

Article Information

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Disastrous failures in mechanical parts, due to some phenomena like fatigue and creep affecting the components, are feasible. The mentioned failures occasionally result in the loss of certain properties and can even lead to the loss of human lives. In order to prevent these types of undesirable events, some fracture control or maintenance procedures have been proposed and implemented in a wide range of industries [1].

Characterization of flaws existing in the components, especially the description of shapes, numbers and lengths is normally essential input data of the failure prevention approaches. To carry out the task, one of the major techniques which is employed to catch the aim, is the use of nondestructive testing (NDT) methods. The results of NDT are influenced by various factors such as skills and emotional mood of the operators, quality of inspection tools, environment conditions, types and shape of defects, and even the geometry and material of the components. As a result, detection and characterization of defects assisting these techniques may not be deterministic and inherits stochastic nature. For this reason, reliability (probability of detection) and sensitivity (detection capabilities) are utilized to quantify results of NDT methods [2]. Due to this importance, a number of researches have been implemented to determine the sensitivity and reliability of NDT techniques by conducting experiments or other approaches.

Fahr et al. [3] evaluated five common techniques of NDT in detecting low cycle fatigue of bolt holes generated in a disc engine. Few years later, Rummel and Matzkanin [4] published results of studies on the capabilities and probability of detection of seven nondestructive evaluation (NDE) methods on various materials and samples. In this area, a more comprehensive study is presented in [5-7] from a large scale research. In the investigation, twenty five teams from ten countries participated to assess efficiency of ultrasonic nondestructive testing and X-ray techniques in defect detection and characterization of stainless steel welds. As mentioned in the following as instances, other investigations were generally involved in a particular technique or material.

Based on the sensitivity and reliability assessment, Simsir and Ankara [2] made a comparison between two nondestructive methods, liquid penetrant testing (LPT) and eddy current. In another work, Stadthaus et al. [8] evaluated sensitivity of two techniques, penetrant and magnetic particles testing, using standard blocks containing natural and artificial defects and determining visibility of generated indications. Probability of detection of low cycle fatigue in plates of Inconel 718 utilizing fluorescent penetrant testing was obtained in [9]. Reliability of manual and automatic ultrasonic inspection was gained in defect detection of welds of pipes. The types of defects of the investigation were lack of fusion (LOF) and lack of penetration (LOP) [10]. Reliability of ultrasonic time of flight diffraction (TOFD) on inspection of complex geometry components [11] and phased array on a number of specimens with and without weld joint were also studied in [12, 13].

Weeks et al. [14] investigated the probability of detection of eddy current induced thermography in finding small cracks of special alloys. Owing to reducing cost of conducting experiments, some authors have even tried to calculate probability of detection (POD) using other approaches. For instance, by means of a proposed mathematical model, then combining the results of the model and Monte Carlo simulation and attempt to find probability of detection of automatic eddy current was made in [15, 16]. Likewise, in a similar manner, Carboni and Cantini [17] made an effort to determine reliability of ultrasonic inspection in railway axle evaluation.

In this paper, reliability and sensitivity analysis of visible liquid penetrant testing in detecting surface cracks of welded components are presented. To deal with this, the required data were gathered from inspections of some welded samples carrying natural surface cracks generated during welding procedure. The data contained two independent categories which were obtained separately, by macroscopic assessments and the results of the liquid penetrant testing. Utilizing the obtained data and mh1823 POD software package [18, 19], the probability of detection as POD curves were drawn and sensitivity analysis was made. According to the results, in the size range of 0 to 5 mm defect length, the probability of detection of the cracks with 2.58 mm length equal to 90 %. Considering 95 % degree of confidence, the corresponding length reaches 3.73 mm. The largest defect which could not be found by this technique is 2.2 mm, and the smallest one which was detected is 1.7 mm.

Reliability and sensitivity in nondestructive testing

As stated before, the results of a specific NDT method may vary due to diverse factors. Thus, concepts of sensitivity and reliability are normally used to cover the mentioned variations. Sensitivity describes detection capabilities and is normally evaluated by analysis of detection rates, the smallest defect which is detected by the technique, and the largest one that is not found. Reliability in nondestructive testing is defined as POD. It is typically determined as a function of defect length and is drawn as curves. Figure 1 shows an actual POD curve for instance. As seen, by increasing the length, the corresponding probability rises. Next and beforehand a particular value of the length, a_1 and a_2, the probability is between zero and one. In other words, the technique is able to find totally defects with a length larger than a_2 and does not detect any defects smaller than a_1.

There are two methodologies to determine POD curve. Building relationship between signal response and flaw size (â versus a), and constructing correlation between binary data and flaw sizes (hit/miss versus a) are the approaches. In the first approach, one of the technique outputs (â), the amplitude of the signals in ultrasonic nondestructive testing for example, is formulated as defect length (a) [19]. Another technique is based on binary response. According to that, when a specific defect with a particular length is detected, the result is defined as hit or it is described as miss or zero. When there is not any defect in a specific location of the component, but the NDT technique assumes existence of a defect there, it is defined as a false call. In this paper, owing to features of the results of penetrant nondestructive testing, the second technique was chosen to calculate POD curves.

Using the instructions stated in [19, 20], POD curve is obtained and drawn by hit/miss data gathered from a number of defects belonging to the defect length range. To carry out this, two methods may be typically used. In the first method, defects with known shape and length are inserted artificially in the components. Then, employing the nondestructive technique, all the defects are inspected to determine which ones are detected, and, therefore, hit/miss data constructed. In the second method, a variety of natural defects present in the components are precisely characterized by performing microscopic or destructive evaluations. Next, hit/miss data is created in the same way of the first method.

In the next stage, the range of defect lengths is divided into a number of intervals (a_i). The number of hit defects to total number of defects in each interval defines probability of detection of the NDT technique in the mentioned intervals (P_i). The obtained values and center point of the intervals are candidates of the whole intervals. Thus, the gathered hit/miss information yields a number of (a_i, P_i) pairs. Extrapolating the data attained as the pairs by the log-logistic distribution results in a functional form, as shown in Equation (1).

The equation describes the relationship between the probability of detection and defect length.

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

with P_i: probability of detection in the i^{th} interval of the length range, α_i: length of defect, β_0: location parameter (constant) and β_1: slope parameter (constant).

The mentioned distribution is the most consistent relationship in the POD calculation of NDT techniques. Using the relationship, the curve is drawn as depicted in Figure 1. In most applications of POD curves, degree of confidence is considered in the values which are obtained or drawn as POD curves by two bounds as shown in Figure 1. It is employed to involve limitation in the number of samples on predicting probability of detection. In the practical application of POD curves, the most important concept is $a_{90/95}$, which the researches carried out on reliability assessment of NDT techniques have made attempt to report it. By considering 95 % degree of confidence, it defines the length of the defect which the corresponding value of POD reaches 90 %. Other concepts, which have less degree of importance, are a_{50} and a_{90}, in which the probability of detection is equal to 50 % and 90 %, respectively.

Experimental procedure

Material and samples preparation. Some researchers have used the first method in obtaining the reliability of NDT techniques, artificial flaws, such as [10, 14], but others utilized the second one, realistic defects, like [2, 3, 13]. Since the shape and the situation of man-made flaws could be differed from realistic ones and then the corresponding results may be deviated, application of natural flaws is more accurate. In this study, the second method was chosen

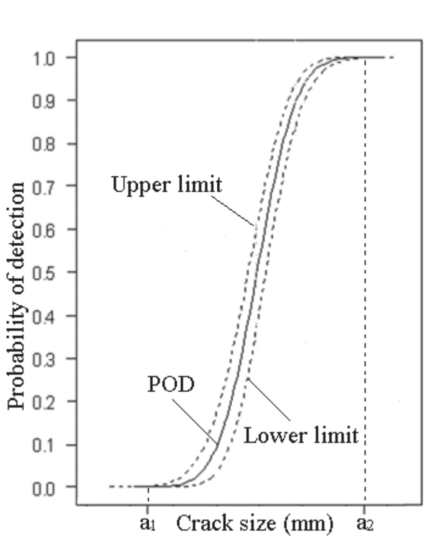

Figure 1: POD curve with upper and lower confidence limits

Figure 2: Welded specimen (left) and nonjoined samples (right)

to obtain sensitivity and reliability of liquid penetrant testing in detecting surface cracks. To deal with this, a total of twenty welded plates carrying defects were chosen. The plates were 6 mm thick and made of Ck45 steel, which is classified as medium-carbon steel and was fabricated by MAG (metal active gas) welding procedure. Chemical compositions of the samples as weight percentage (wt.-%) are given in Table 1 in detail. Figure 2 shows a welded specimen and nonjoined samples.

Surface crack description. The real number and length of surface cracks were determined using microscopic evaluation of the weld surfaces. To accomplish this, images from the weld surfaces of the components (in 50× magnification) were taken and the taken pictures were analyzed.

Liquid penetrant testing. Liquid penetrant testing (LPT) is an important method of nondestructive testing, which is normally used to detect surface cracks in a wide range of components and materials. The technique, as employed in this research, typically consists of four following main stages.

Surface preparing and cleaning. Surface of components may be covered with grease, oil, oxide particles, scale and so on. These kinds of materials might prevent the flow of liquid penetrant to surface cracks, therefore, may not be detectable by the technique. To cope with this problem, prior implementing the inspection, the surfaces of the components are cleaned by various methods from the mentioned substances. In this research, liquid solvent, which is a product of Magnaflux Company and are produced as Magnaflux (SKC-S cleaner/remover) brand, were applied to the surface by spraying.

Applying the liquid penetrant. The surfaces of the samples were covered by spraying the liquid penetrant (Magnaflux (SKL-SP2 penetrant)) in this stage of the inspection. Primary dwell time, the time to be passed to the penetrant flows into the cracks, was chosen to be twenty minutes. Then, excess penetrant was removed from the surfaces.

Utilizing of developer. Magnaflux (SKD-S2 developer) was applied to the surfaces to absorb the penetrant liquid trapped in the cracks and then inspection indications, which exhibit presence of cracks under the indication, appeared as a result. The mentioned indications exhibit presence of crack underneath the indication. Secondary dwell time, the time required which the developer has to remain on the component surfaces, was ten minutes.

Indications assessment. After passing the secondary dwell time, the indications showing surface cracks appeared. The surfaces of the samples were examined at room light to detect presence of surface cracks.

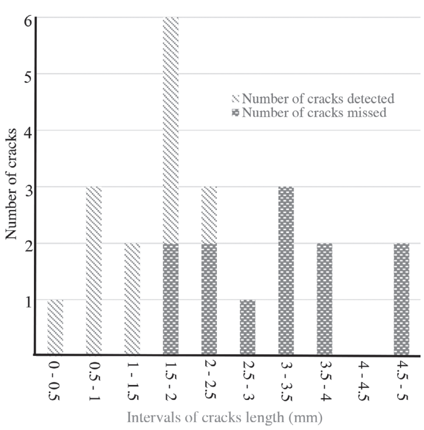

Figure 3: Histogram representation of the found defects in the length intervals

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

Table 1: Chemical composition of the investigated material (wt.-%)

Results and discussion

The obtained results of this paper, which is related to the surface crack detection capabilities of the welded joints by LPT, are shown in Table 2 and Figure 3. Moreover, the reliability and POD curves are depicted and indicated in Figure 4 and Table 3.

Table 2 shows the results regarding detection capabilities of LPT which have been measured in similar studies, including Simsir et al. [2] and Fahr et al. [3], in comparison with those found in this paper. Simsir et al. [2] and Fahr et al. [3] evaluated liquid penetrant testing in finding fatigue cracks generated naturally on the surface of bolt holes of compressor discs. As stated before, Lively and Aljundi [9] studied liquid penetrant testing on finding defects presented in Inconel 718 and only reported values of $a_{90/95}$. Due to not assessing the detection capabilities, the results of Lively's and Aljundi's study cannot be employed in the comparison.

According to the table, liquid penetrant testing is able to find twelve defects from 33 in total (52 %) by considering all the test conditions described before. The number and rate of defects, which is not able to be detected (missed defects), is 11 (48 %). In comparison with those found in Simsir et al. [2] and Fahr et al. [3], 81.2 % and (72 %-89 %), missing rate is larger. Furthermore, false call number (rate) of the current investigation which depends on inspection efficiency is larger than earlier studies.

The lengths of defects which are examined in this investigation are located at

	a_{50}	a_{90}	$a^{90/95}$
Current study (mm)	2.05	2.58	3.73
Fahr et. al [2] (mm)	–	–	1.90-3.60
Lively and Aljundi [9] (mm)	–	–	1.09-2.08

Table 3: Results of the POD calculation based on different studies

	Number of cracks detected		Number of missed cracks		False calls number		Largest crack missed (mm)	Smallest crack detected (mm)
	total	%	total	%	total	%		
Current study	12	52	11	48	1	4	2.2	1.7
Simsir et al. [2]	6	18.2	27	81.2	1	3.0	1.7	1.26
Fahr et. al [3]	–	11 - 26	–	72-89	–	0-2.6	–	–

Table 2: Comparison between the results found in the present research and previous studies

0-5 mm interval, but this size range (0-2.4 mm) was considered in Simsir's study. Because each study considered different defect lengths, discrepancy between results of detection/miss rates based on these researches has been observed. Due to the lack of reporting the size range in Fahr's study, no evaluation could be made regarding this subject. Furthermore, the method of LPT employed in this paper was visible, but the others used fluorescent type. These factors and differences in the shape of the defects, materials and even the skill of the inspector are able to influence the obtained results.

The largest cracks missed are 2.2 mm, and 1.7 mm in the current and Simsir's study, respectively. Moreover, Simsir's study was able to find cracks with a length of 1.26 mm, but this value was 1.7 mm in the present research. Therefore, neglecting the differences between the two studies, the smallest/largest crack detected is considered as a criterion to compare the techniques capabilities. The current study seems less meaningful than Simsir's in defect detection. Since any values related to these parameters were not reported in Fahr's research, it is not possible to compare it with the present study and Simsir's study.

For further evaluation, the detection results of the flaws are depicted as histograms in Figure 3. Using Figure 3, detection capabilities are determined as a function of the defect length. The size range was divided by 0.5 mm to construct intervals in the range. According to the figure, LPT is able to find 4 cracks from 6 cracks in the size range of 1.5-2 mm, thus, in this size range, detection rate is 67 %. The rate decreases and reaches 33 % in the size range of 2-2.5 mm.

Employing POD mh1823 software package [18], POD of liquid penetrant testing with 95 % confidence limit curves is shown in Figure 4. As shown in the figure, a_{50} and a_{90} are 2.05 mm and 2.58 mm, respectively. In other words, the probability of detecting defects with 2.05 mm and 2.58 mm in length are 50 % and 90 %, in turn. Considering upper bound of 95 % confidence, the length of defect relating to 90 % probability is increased and reaches 3.73 mm.

In reliability assessment of NDT techniques and application of the related results in design and maintenance of products, a90/95 is a crucial concept. Therefore, the researchers in this area have generally tried to report about it. As described in Table 3, $a_{90/95}$ was calculated to be between 1.90 mm and 3.60 mm in Fahr's study. However, due to differences in equipment, inspectors and vendors of the tools, the corresponding value in Lively's report varies in the size range of 1.09-2.08 mm (0.043-0.082 inch). It means that lower and upper bounds of $a_{90/95}$ in Fahr's research are larger than Lively's. As far as the centers of the stated ranges are considered instead of the whole ranges, value of $a_{90/95}$ based on Fahr's study is larger than Lively's and, as a result, Lively's inspection seems more accurate than Fahr's. Taking into account the current investigation, it is even larger than both studies and reaches 3.37 mm. The reason may relate on the factors affecting the results, so the method of LPT implementation seems to be the most effective one. Besides, the materials and inspection conditions as well as the defect shapes were different in the investigations, which have to be considered in the evaluation. Since $a_{90/95}$ has not been reported in Simsir's study, the comparison between the $a_{90/95}$ and the above-mentioned investigations based on this parameter is not possible. Furthermore, unlike the current study, a_{50} and a_{90} were not reported in the past attempts.

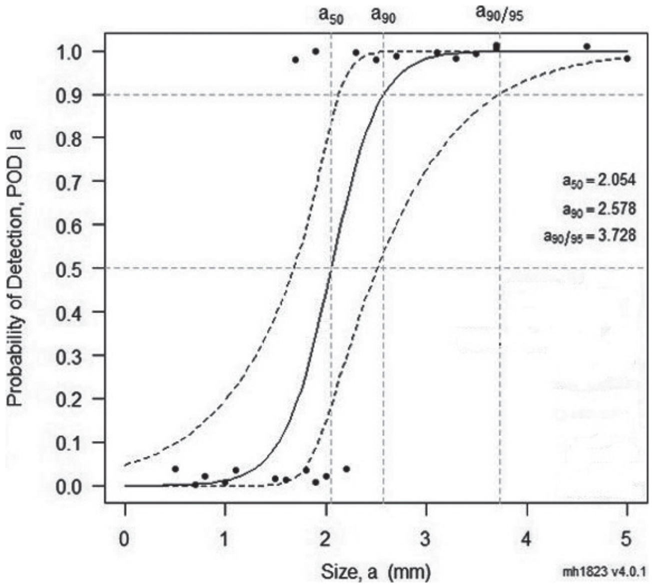

Figure 4: POD curve resulting from the present study

Conclusions

Sensitivity and reliability of liquid penetrant nondestructive testing (visible technique) in detecting of surface cracks of welded components were investigated. The main results of the investigation are listed below.

- The largest defect, which could not to be found by this technique, was 2.2 mm.
- The smallest length of the defects, which could be detected by this technique, was 1.7 mm.
- In the size range of 0-5 mm, detection and missing rate are 52 % and 48 %, respectively. Likewise, false call rate in defect detection was 4 %.
- For the cracks with length equal to 2.58 mm, the probability of detection is 90 %. Considering 95 % degree of confidence, the corresponding length reaches 3.73 mm.

These results can be considered as a good guidance for designer and engineers in order to make proper comparison between this technique under described situation and other techniques, and to have a better evaluation regarding the objective of the inspection. For instance, according to our aims, we have found that this technique is a suitable method for detecting surface cracks in welded parts in general applications.

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Abstract

Zuverlässigkeit und Sensibilität der zerstörungsfreien Farbeindringprüfung zur Inspektion von geschweißten Komponenten. Das Schweißen wird in vielen Industriezweigen breitflächig zum Verbinden von Komponenten eingesetzt. Eine der größten Schwachstellen dieser Technik besteht in der Erzeugung von verschiedenen Defektarten. Daher wird die Inspektion zur Detektierung solcher Defekte als ein fester Bestandteil der schweißtechnischen Fertigung allgemein berücksichtigt. Eine der Hauptkategorien schweißtechnisch bedingter Defekte sind Oberflächenrisse, die mit zerstörungsfreien Verfahren gefunden werden. Das Farbeindringverfahren wird zur Erkennung solcher Anrisse breitflächig angewandt, aber die Möglichkeiten dieses Verfahrens bezüglich der Erkennung von Defekten sind bisher nicht sehr umfangreich untersucht worden. In der diesem Beitrag zugrunde liegenden Studie wurden die Konzepte der Zuverlässigkeit und Sensibilität der zerstörungsfreien Prüfung nutzbar gemacht und ihre Möglichkeiten zur Erkennung von Oberflächenrissen in Schweißverbindungen untersucht. Die Ergebnisse dieser Studie verdeutlichen, dass die Erkennungsrate und die Nichterkennungsrate 52 bzw. 48 % betragen. Darüber hinaus beträgt, unter Berücksichtigung einer Zuverlässigkeit von 95 %, die Wahrscheinlichkeit der Fehlererkennung (Probability of Detection – POD) von Defekten mit einer Länge von 3,73 mm 90 %.

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