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PROBABILITY OF DEFECTS DETECTION IN WELDED JOINTS USING THE MAGNETIC PARTICLE METHOD

The probability of defects detection (POD) is developed as an efficient tool to evaluate the detection capacity of non-destructive testing methods. An experimental study has been carried out applying the magnetic particle test method with an electromagnetic yoke on welded steel joints, which contained surface defects previously characterized in shape, size and location. The test conditions were varied, such as the type of magnetization current, and the type of magnetic particle. The probability of detecting defects in welded joints evaluated by the Hit/miss method increased with the size of the defect, independent of its shape factor. Smaller defects were likely to be detected with dry magnetic particles compared to wet fluorescent ones, a_{50} (2,118 mm < 2,469 mm), a_{90} (6,395 mm < 6,77 mm) and $a_{90/95}$ (12,12 mm < 12,19 mm).

Keywords: Magnetic particle testing (MT); probability of detection (POD); welding defects; detection capacity; non-destructive testing (NDT)

1. Introduction

Non-destructive testing (NDT) plays a fundamental role in the industry, as an effective means of evaluating the quality, operational safety and durability of products and structural components [1-3]. Allow timely detection of defects, thus ensuring that the functionality and reliability conditions of an industrial component meet the design specifications. In this context, the non-destructive magnetic particle testing (MT) method is useful for the detection of surface defects creating indications and thus revealing the defects [4-10].

The detection capacity is one of the reliability aspects of non-destructive testing methods and is quantified by the probability of detection (POD) [11,12]. Which is the probability that a given defect in a component can be detected using a specific inspection method [13-19]. In some recent investigations it is observed that the calculation of the POD obtained through software such as mh1823POD allows estimating the largest defect size that can go unnoticed by a certain non-destructive testing method [15], such as phased array ultrasound inspections [22], and visible magnetic particle inspections [23]. In addition, based on the POD results, the detection capacity of different NDT methods can be compared, such as acoustic emission, fluorescent penetrants and visual inspection [20]; and between the techniques of visible and fluorescent magnetic particles [2].

POD curves are tools that allow you to quantify the reliability and capability of inspection methods, compare inspection methods on the same material, qualify non-destructive testing procedures, and establish criteria in the acceptance of projects [15,21]. To estimate POD curves in non-destructive testing, there are two standard methods, the POD $\hat{a}$ versus a method and the POD hit/miss method, both with different requirements regarding the quality and quantity of the input data, as well as the to the method that can be applied [15,25]. The $\hat{a}$ versus a method is used for amplitude control data, which can take continuous values. These data are obtained mainly in eddy current and ultrasound tests. On the other hand, the hit/miss method is used for binary data, which contains detected or undetected defect information, these data are mainly obtained from liquid penetrant testing, magnetic particle testing or X-ray testing [15].

The key parameters or values of the POD curves, which are often used to evaluate the reliability of a given NDT method and to compare the inspection results obtained for the same data set, are:

– a_{50}, which is the length of the defect for a 50% probability of detection;

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– a_{90}, which is the length of the defect for a 90% probability of detection;
– $a_{90/95}$, which is the length of the defect for a 90% detection probability obtained with a 95% confidence level [15, 17,24].

The hit/miss Method takes into account that, once a defect is detected, 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. The case where the test detects a defect at a specific location on a component, but there is no defect at that position, is called a false call [15]. It is important to prepare the samples since they must contain defects that are as realistic as possible, with ideal dimensions, and in an adequate number to achieve the best estimate of the POD curves and their ranges trust [21]. The hit/miss method requires a minimum set of 60 representative defects, and inspection data (0 or 1) for each defect [15].

Binary data (hit/miss) are limited and discrete, since they can only take two values, 0 or 1, and the error associated with the observation and prediction of the model will be binomial. For this reason, generalized linear models (GLM) and a specific link function are used to generate the POD curve, which can be: logit function, probit function, cloglog function, or loglog function. In addition, a maximum likelihood fit to the data is used to estimate the parameters of the GLM model and obtain the shape of the curve. The corresponding confidence limits are obtained by the likelihood ratio method, varying the parameters of the POD model from their maximum values until reaching the chosen confidence interval [15,26].

In the present work, the logit link function has been used, which is defined as Eq. (1) [15].

$$POD = \frac{\exp\left(f\left(X\right)\right)}{1+\exp\left(f\left(X\right)\right)} \tag{1}$$

If $f(X)$ describes the POD as a function of the defect size, we have Eq. (2) that will allow obtaining the POD curves [15].

$$POD\left(a\right) = \frac{\exp\left(\beta_0+\beta_1\log\left(a\right)\right)}{1+\exp\left(\beta_0+\beta_1\log\left(a\right)\right)} \tag{2}$$

Where, $POD(a)$ is the probability of detection for a, a is the defect length, β_0 and β_1 are the model parameters.

Research reports show POD parameters in a wide range of values that differ from each other [2,23,27,28]. It has been said that the values of the POD parameters depend on the experimental conditions [15,16]. So expanding these studies by varying the test conditions and the characteristics of the defects of the test element contributes to improving the criteria for the selection of the procedure specifications of testing. The main objective of the study was to determine the detection capacity of defects in welded joints by quantifying the probability of detection using a yoke for the test of magnetic particles, visible dry and fluorescent wet, varying the type of magnetization current.

2. Materials and experimental methods

Twenty ASTM A36 structural steel groove and fillet welded specimens were available for butt joints and T-joints in sheets and pipes, marketed by flaw manufacturing technology, which can be seen in Fig. 1. Each specimen contained surface defects such

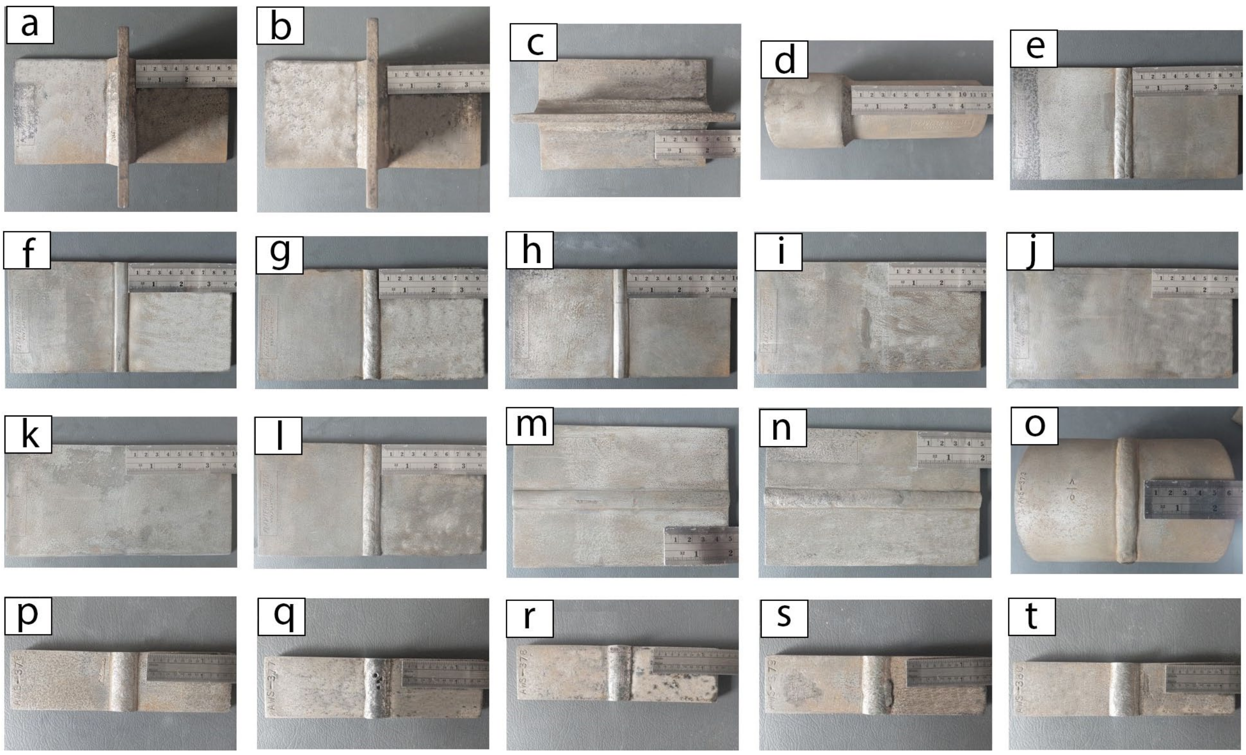

Fig. 1. Specimens fillet welded (a, b, c and d) and groove (e-t) of ASTM A36 steel

as cracks in HAZ, foot and root of welding, lack of fusion and porosities, which were characterized in shape, size and location.

For the verification of the sizes and location of the defects in the welded specimens, a UNITRON brand digital stereoscope was used, 63 defects were detected. The distribution of the number and size of the defects can be seen in Fig. 2.

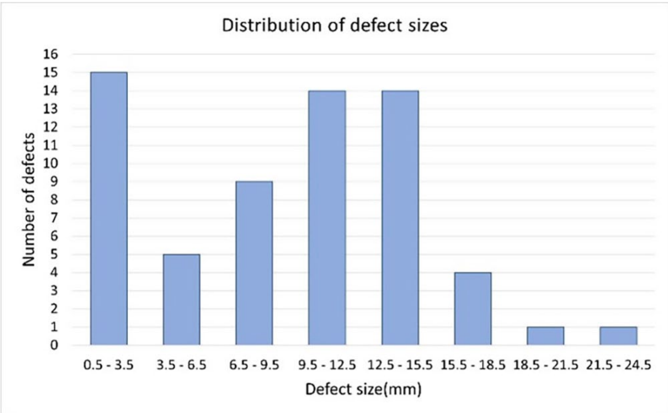

Fig. 2. Distribution of number and size of defects

The independent variables were the type of magnetization current, alternating (AC) and half-wave direct (HWDC) single phase-from rectified AC sources, and the type of magnetic particle, fluorescent wet and visible dry. The dependent variable was the probability of detecting defects. Four experimental runs with three repetitions were carried out, for which three NDT inspectors were required.

The test procedure was carried out in accordance with the standards and reference documents ASTM E709 [29], ASTM E3024 [30] y ASNT Level III Study Guide: Magnetic Particle Testing Method [10]. The weld surface, and the area adjacent to it (at least 1 inch), was prepared by mechanical cleaning (using a wire brush), and subsequently chemical cleaning with solvent. To induce magnetism in the piece, the indirect longitudinal magnetization technique was used with a MAGNAFLUX brand Y7 AC/DC electromagnetic yoke; Magnavis 8A oxide red magnetic particles with an average size of 80 microns for dry application and Magnaglo 14 AM fluorescent magnetic particles with an average size of 6 microns for wet application were used.

The pieces were evaluated under the appropriate lighting conditions. For the dry visible magnetic particle test, the minimum lighting level of 100 fc. (1076 lx) was verified using a MAGNAFLUX luxmeter in accordance with the ASTM E709 standard and for the wet fluorescent particle test, an ultraviolet light lamp was used. the minimum intensity of ultraviolet light of 1000 $\mu W/cm^2$ on the test surface was verified with a UVP J-221 brand black light meter, and with the lux meter, the maximum ambient white light of 2 fc. (21.5 lx) according to ASTM E709. The detected defects were photographically recorded and the dimensional verification was carried out with a digital vernier. The processing of the data obtained and the statistical analysis were carried out with the mh1823POD Software, available online [26], using the POD Hit/miss model to obtain the probability of defect detection (POD) curves. The input data was the size of each defect and the assigned numbers one (detected) and zero (not detected).

3. Results

The indications detected in the welded joints were framed and numbered in correlative order and photographically recorded for later evaluation as shown in Fig. 3 and 4.

The Fig. 3 shows indications detected with visible red magnetic particles: a) HAZ fissure at 1; b) standing crack in 1 and overlap in 2; c) lack of fusion in 1; d) standing crack in 1 and porosity in 2; e) HAZ fissure (root) in 1 and 2; f) longitudinal crack in weld metal at 1. And the Fig. 4 shows some indications detected with fluorescent magnetic particles seen under ultraviolet light: a) HAZ fissure at 1; b) longitudinal crack in 1 and 3, and transverse crack in 2; c) standing crack in 1; d) crack in HAZ of the weld root at 1; e) base metal laminations in 1 and 2; f) standing crack in 1 and porosity in 2.

For each test operating condition, the total number of detected defects was recorded and those that were not detected by arithmetic difference, as shown in TABLE 1.

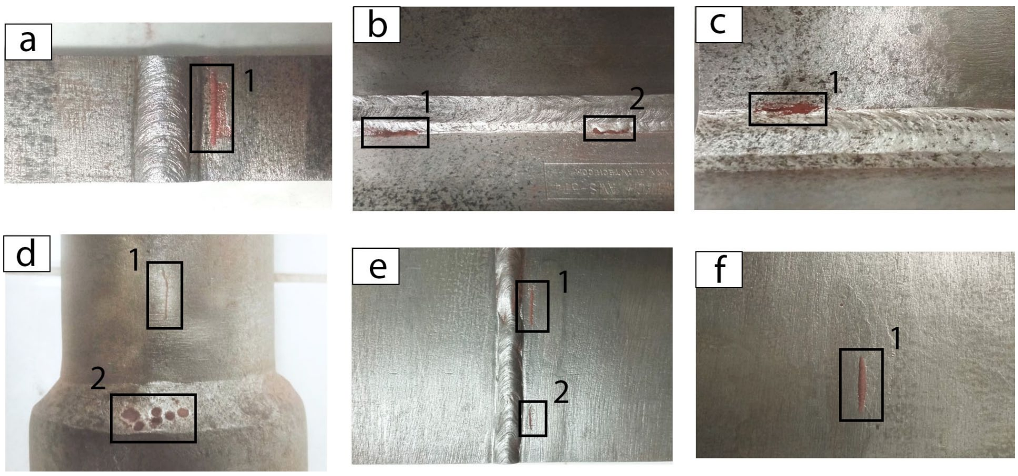

Fig. 3. Indications obtained from dry-applicable the visible magnetic particle tests

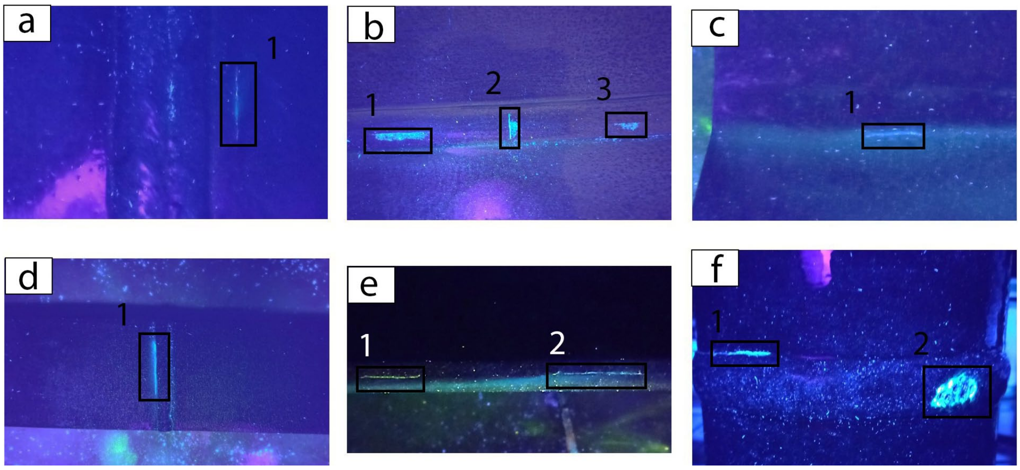

Fig. 4. Indications obtained from wet-applicable fluorescent magnetic particle tests

TABLE 1

Number of detected and undetected defects

Test operating conditions	Hit	Miss
AC and dry-applicable the visible magnetic particle	150	39
AC and wet-applicable fluorescent magnetic particle	147	42
HWDC and dry-applicable the visible magnetic particle	149	40
HWDC and wet-applicable fluorescent magnetic particle	147	42

The probability curves of defect's detection (POD) were obtained with 95% confidence limits and the parameters a_{50}, a_{90} and $a_{90/95}$ for each test condition, as shown in Figs. 5-8 and in TABLE 2.

A one-way analysis of variance was performed, using the DUNCAN test, processing the data in the SPSS program.

TABLE 2

Comparison of the POD parameters of the different tests

POD parameters	AC and dry particles	AC and fluorescent wet particles	HWDC and dry particles	HWDC and fluorescent wet particles
a_{50}	2,118 mm	2,469 mm	2,231 mm	2,469 mm
a_{90}	6,395 mm	6,77 mm	6,521 mm	6,77 mm
$a_{90/95}$	12,12 mm	12,19 mm	12,14 mm	12,19 mm

4. Discussion of experimental data

When magnetized with alternating current and by varying the type of magnetic particle, dry and then wet fluorescent, the POD parameters a_{50}, a_{90} and $a_{90/95}$ show significant differences, as detailed in TABLE 2, the lengths of defects and their probability of detection are a_{50} (2,118 mm < 2,469 mm),

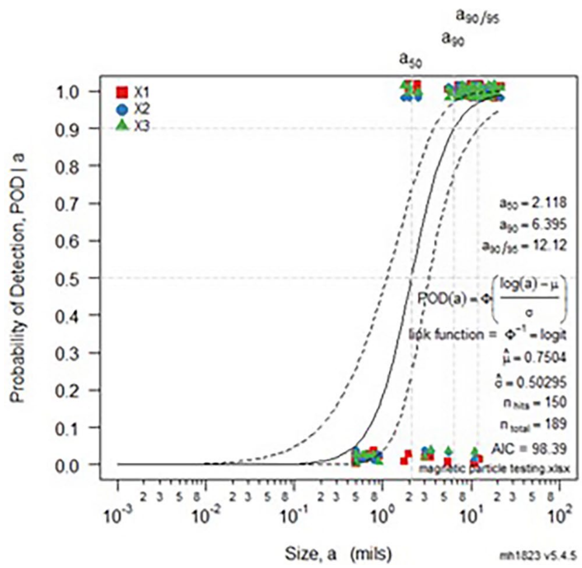

Fig. 5. POD curve of the tests with alternating current and dry particles

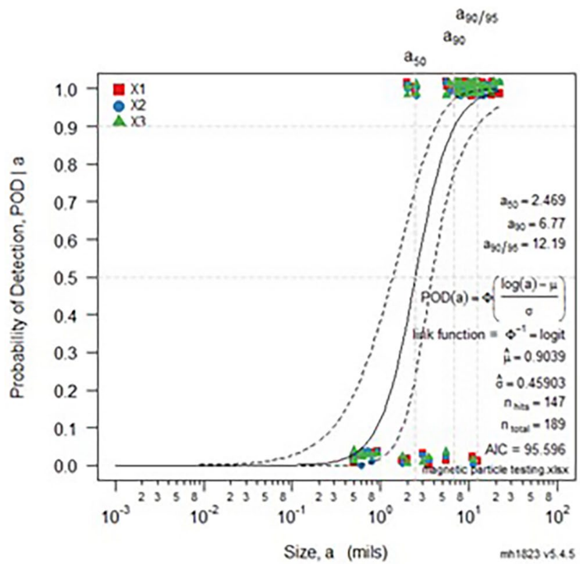

Fig. 6. POD curve of the tests with alternating current and fluorescent wet particles

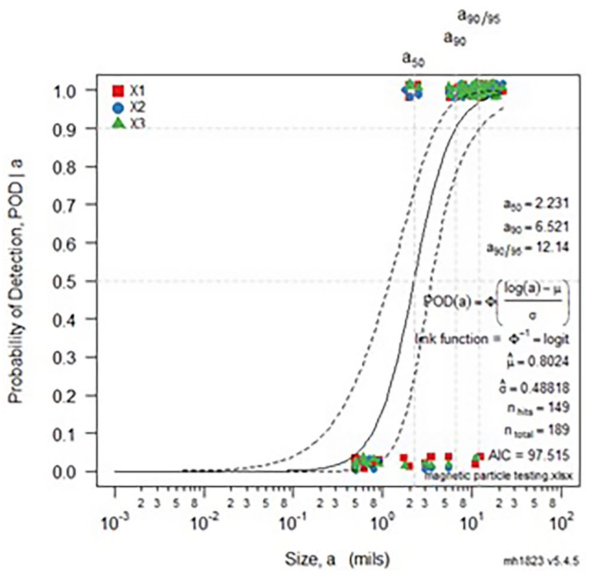

Fig. 7. POD curve of the tests with half-wave direct current and dry particles

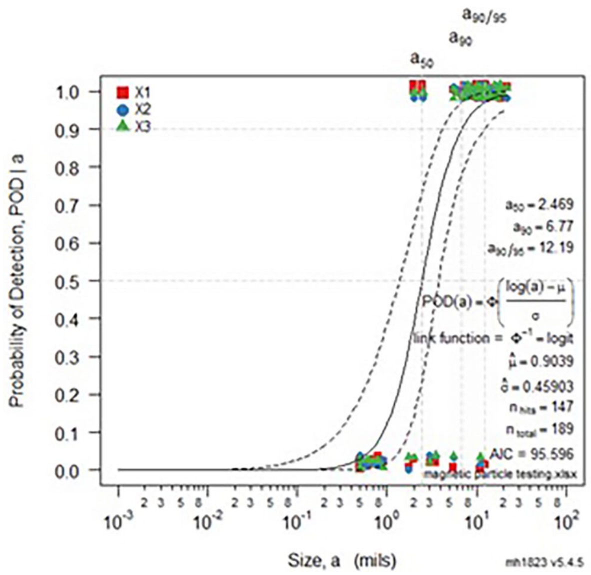

Fig. 8. POD curve of the tests with half-wave direct current and fluorescent wet particles

a_{90} (6,395 mm < 6,77 mm) and $a_{90/95}$ (12,12 mm < 12,19 mm). A similar effect occurs when magnetized with half-wave rectified direct current, the POD parameters are a_{50} (2,231 mm < 2,469 mm), a_{90} (6,521 mm < 6,77 mm) and $a_{90/95}$ (12,14 mm < 12,19 mm). From the analysis of variance ($P < 0.05$) it can be inferred that the type of magnetic particle turns out to be highly significant for the test, in fact with dry magnetic particles it is likely to detect smaller defects compared to wet fluorescent ones. It has been said that the wet fluorescent magnetic particles have greater sensitivity, since they are smaller than the dry ones and are suspended in a liquid medium, they have greater mobility capacity [10], however, they presented a strong adhesion to the test surface, causing a background that interferes with the formation and visibility of the indication, being less effective. In any case the method of particles in suspension is best for detecting fine or wide shallow flaws [2,10].

When the test is performed with dry magnetic particles, and the type of magnetization current is varied, from alternating to half-wave direct current, the POD parameters a_{50}, a_{90} and $a_{90/95}$ are statistically similar. As it was possible to detect longitudinal (cracks) and rounded (pores) defects as shown in Figs. 3 and 4, it can be inferred that the type of magnetic particle and size of the defect, independent of its shape factor in the test elements, affect the probability of the test method to detect defects.

The results obtained are a good guide for the magnetic particle inspection procedures in order to select the best parameters for the test procedure, and have a better evaluation with respect to the objective of the inspection. However, POD data cannot be generalized for every procedure or component, if any of the parameters or variables involved in the NDT process are altered (such as instruments, settings, the component to be inspected, types of defects, etc.), the POD data is expected to be different.

5. Conclusions

The probability of the magnetic particle test to detect defects in welded joints is affected by the size of the defect independent of its shape factor, a perceptible threshold size is glimpsed that defines the scope of the method, from this value the probability of detection increases with the size of the defect.

The probability of detection of welding defects is affected by the type of magnetic particle, regardless of the type of magnetization current, it is likely to detect smaller defects with dry magnetic particles because they present little adhesion to the test surface.

The POD parameters depend on the experimental conditions and cannot be generalized, it is suggested that future research consider modifying the magnetization method.

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REFERENCES

[1] P. Cawley, Non-destructive testing-current capabilities and future directions. P. I. Mech. Eng. L-J. Mat. **215** (4), 213-23 (2001). DOI: https://doi.org/10.1177/146442070121500403

[2] R. Fonseca, R. da Costa, S. Gomes, M. Ogawa, S. Peripolli, A. Badaro, R. de Oliveira, Study of Probability of the Detection of Defects in Welded Joints of the Techniques of Magnetic Particle and Penetrant Testing, (2014). https://www.ndt.net/search/docs.php3?id=15550

[3] R.A. Smith, Non-destructive testing (NDT) - Guidance document: an Introduction to NDT common methods. The British Institute of Non-Destructive Testing, (2015). https://www.bindt.org/admin/Downloads/Apprenticeship-Guidance-Document.pdf

[4] M. Pavlovic, C. Mueller, U. Ewert, U. Ronneteg, J. Pitkänen, C. Boller, Safe product design – the role of the NDT reliability analysis. Mater. Test. **55** (4), 270-275 (2013). DOI: https://doi.org/10.3139/120.110434

[5] M. Chang, A.K. Koul, P. Au, T. Terada, Damage tolerance of wrought alloy 718 Ni- Fe-base superalloy. J. Mater. Eng. Perform. **3**, 356-366 (1994). DOI: https://doi.org/10.1007/BF02645332

[6] Y. Zhang, D. You, X. Gao, N. Zhang, P.P. Gao, Welding defects detection based on deep learning with multiple optical sensors during disk laser welding of thick plates. J. Manuf. Syst. **51**, 87-94 (2019). DOI: https://doi.org/10.1016/j.jmsy.2019.02.004

[7] Y. Zhang, H. Zhang, J. Zhao, Z. Zhou, J. Wang, Review of non-destructive testing for remanufacturing of high-end equipment. Journal of Mechanical Engineering **49** (7), 80-90 (2013). DOI: https://doi.org/10.3901/JME.2013.07.080

[8] K. Ashok Reddy, Non-Destructive Testing, Evaluation of Stainless Steel Materials. Mater. Today-Proc. **4** (8), 7302-7312 (2017). DOI: https://doi.org/10.1016/j.matpr.2017.07.060

[9] J.R. Deepak, V.K. Bupesh Raja, D. Srikanth, H. Surendran, M.M. Nickolas, Non-destructive testing (NDT) techniques for low carbon steel welded joints: A review and experimental study. Mater. Today-Proc. **44**, 3732-3737 (2021). DOI: https://doi.org/10.1016/j.matpr.2020.11.578

[10] American Society for Nondestructive Testing, ASNT Level III Study Guide: Magnetic Particle Testing Method, 2nd Edition, (2013).

[11] A. Keprate, Probability of Detection: History, Development and Future. Pipeline Technology Journal. **8**, 41-45 (2016). https://www.researchgate.net/publication/299603630_Probability_of_Detection_History_Development_and_Future

[12] W.D. Rummel, A Path Forward for NDE Reliability. 5th European American Workshop on Reliability of NDE, Berlin, Germany, (2013). http://2013.nde-reliability.de/portals/nde-reliability2013/BB/lecture1.pdf

[13] B. Chapuis, P. Calmon, F. Jenson, Basics of Statistics for POD, in: Best Practices for the Use of Simulation in POD Curves Estimation. IIW Collection. Springer, Cham, (2018). DOI: https://doi.org/10.1007/978-3-319-62659-8_8

[14] N. Dominguez, C. Reboud, A. Dubois, F. Jenson, A new approach of confidence in POD determination using simulation. AIP. Conf. Proc. **1511**, 1749 (2013). DOI: https://doi.org/10.1063/1.4789252

[15] U.S. Department of Defense, MIL-HDBK-1823A: Nondestructive Evaluation System Reliability Assessment, Department of Defense Handbook, (2009).

[16] G.A. Georgiou, Probability of detection (POD) curves, Derivation, application and limitations, Jacobi Consulting Limited, Londres, (2006). https://www.hse.gov.uk/research/rrpdf/rr454.pdf

[17] A. Berens, NDE reliability data analysis, in: ASM metals handbook – nondestructive evaluation and quality control. ASM International **17**, 689-701 (1989).

[18] W.D. Rummel, Probability of detection as a quantitative measure of nondestructive testing end-to-end process capabilities. Mater. Eval. **56** (1), 29-35 (1998).

[19] B.G. Yee, F.H. Chang, J.C. Couchman, G.H. Lemon, P.F. Packman, Assessment of NDE Reliability Data, NASA CR-134991, National Aeronautics and Space Administration, (1976). https://ntrs.nasa.gov/citations/19760026437

[20] Y. Guo, F.R. Ruhge, Comparison of detection capability for acoustic thermography, visual inspection and fluorescent penetrant inspection on gas turbine components. AIP. Conf. Proc. **1096**, 1848-1854 (2009). DOI: https://doi.org/10.1063/1.3114183

[21] R.R.d. Silva, G.X. de Padua, Nondestructive Inspection Reliability: State of the Art, in: M. Omar (Ed.), Nondestructive Testing Methods and New Applications. IntechOpen (2012). DOI: https://doi.org/10.5772/37112

[22] J.H. Kurz, A. Juengert, S. Dugan, G. Dobmann, Probability of Detection (POD) determination using ultrasound phased array for considering NDT in probabilistic damage assessments, 18th World Conference on Non-destructive Testing, Durban, South Africa, (2012). https://www.ndt.net/search/docs.php3?id=12667

[23] A. Zolfaghari, A. Zolfaghari, F. Kolahan, Reliability and sensitivity of magnetic particle nondestructive testing in detecting the surface cracks of welded components. Nondestruct. Test. Eva. **33** (3), 290-300 (2018). DOI: https://doi.org/10.1080/10589759.2018.1428322

[24] M. Reseco, A. Hor, A. Rautureau, C. Bes, Implementation of a robust methodology to obtain the probability of detection (POD) curves in NDT: integration of human and ergonomic factors, French Confederation for Non-destructive Testing 2017, Strasbourg, France, (2017). https://www.ndt.net/search/docs.php3?id=21340

[25] I. Virkkunen, T. Koskinen, S. Papula, T. Sarikka, H. Hänninen, Comparison of â Versus a and Hit/Miss POD-Estimation Methods: A European Viewpoint. J. Nondestruct. Eval. **38**, 89 (2019). DOI: https://doi.org/10.1007/s10921-019-0628-z

[26] C. Annis, Statistical best-practices for building Probability of Detection (POD) models, R package mh1823 POD, version 5.4.5. (2018). https://statistical-engineering.com/

[27] W.D. Rummel, G.A. Matzkanin, Nondestructive evaluation (NDE) Capabilities Data Book, 3rd edition, Austin Texas: NTIAC, (1997). https://smartech.gatech.edu/bitstream/handle/1853/49124/[67].pdf

[28] A. Fahr, D. Forsyth, M. Bullock, W. Wallace. POD Assessment of NDI Procedures Using a Round Robin Test, AGARD-R-809. Advisory Group for Aerospace Research & Development, (1995). https://www.abbottaerospace.com/downloads/agard-r-809/

[29] American Society for Testing and Materials, ASTM E709: Standard Guide for Magnetic Particle Testing, (2021). DOI: https://doi.org/10.1520/E0709-21

[30] American Society for Testing and Materials, ASTM E3024: Standard Practice for Magnetic Particle Testing for General Industry, (2022). DOI: https://doi.org/10.1520/E3024_E3024M-22A