Reliability Evaluations for the future of NDT/NDE4.0 in India

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Abstract

Usage of non-destructive testing or evaluation (NDT/E) techniques is widely accepted across various industries all over the world in order to maintain certain safety and quality standards. However, not many countries really perform the reliability evaluation of their NDT techniques. In this context, this article discusses the importance of reliability evaluations and state of reliability programs performed in India versus the reliability activities performed in the western countries. In addition, brief results from one of the POD programs carried out at DMRL are also presented for understanding the challenges involved in pursuing reliability programs in India. Moreover, remarks on the possible direction of POD especially under the context of transforming the industry towards NDE 4.0 were made.

Keywords: *NDT, Reliability, Probability of Detection, NDE 4.0.*

1. Motivation

Quality assurance approaches and in specific non-destructive testing or evaluation (NDT/E) methods are within the most unloved things within a modern production line or within maintenance operations. From a superficial point of view the feeling is understandable: It is impossible to imagine the world safety without the implementation of varied inspection protocols such as NDT. Specifically, in the case of NDT, there are a lot of costs (repair, scrapping, etc.) and in spite of which accidents happen day in and day out. Therefore, the perennial question which arises is "Why should anyone do NDT? ".

The answer is as easy as obvious: Because without NDT a modern world could not exists. A modern production company could not stand a chance and a modern infrastructure would break down may not be on day One. But it will fail all around the world. This is basically a question of luck and time. Annals of history do present the NDT community with worldwide examples indicating the importance of NDT [1].

Two accidents in aviation industry almost brought Malaysian Airlines to their knees [2]. Similarly, two incidents did cost Boeing almost $1 bn [3]. The Surfside accident in 2021 [4] at Florida, USA focused more on importance of testing in civil engineering. Amidst all these, 5 deadly accidents of MIG-21 in India within the last 1 and ½ years continuously haunts the regulators in terms of fleet reliability and maintenance [5].

Not in every accident NDT is the solution, but in a lot of it. It is the cheapest way to stay alive as a company and as a country. However, for this to happen, industry is often posed with an essential question: “How good is the method being used?” or more specifically: “How well does the NDT perform?”.

By choosing a possible answer to these intruding queries in a modern company/organization/facility, etc., there is a decent chance to transform a cost issue in to a treasure resulting in delivering a product which is competitive with the best technology companies in the world. Performance in NDT was defined with the term reliability: “the degree that an NDT system is capable of achieving its purpose regarding detection, characterization and false calls” [6].

And in all of them the discussion rather than being about an estimated magnitude of sizes, revolves around an objective which is aimed to determine probabilistic characteristic for a specific application. The most familiar one is the Probability of Detection. The only characteristic which allows estimating the capability of a system either to detect or not detect the critical defect in an application. No Thumb-rule, standard, has the power to evaluate the true status after NDT. Due to this characteristic, the switch from safe-life application approaches to slightly pragmatic damage tolerance models is possible, a movement, which allowed to save billions of dollars in just a decade. For the benefit of the user, in safe life approach, conservatively it is assumed that 1 in 1000 components may have a crack after its intended life, whereas in damage tolerance based approach, presence of undetectable crack is assumed and inspection intervals which are safe for detecting them is predicted.

However, this approach usually comes with a price:

a) Cost involved in learning the capabilities of the NDT application
b) Cost involved in assessing and discussing them in probabilistic terms
c) Finally, cost involved in thinking out of the typical technical box and the very basic need to start understanding statistics.

Therefore, in this article, an attempt is made to show this august NDT community, an ideology which is being practiced regularly in a large area of industrial sectors in Europe and the USA, for companies such as Porsche, Airbus, different Railway Companies in Europe (SBB, Deutsche Bahn, Trenitalia, etc) and which can pay rich dividends if implemented in India.

The authors would like to request the reader to just invest a paltry time for reading the article and further build up his/her own mind. This may be an essential approach as about 5 decades ago, the USA had an issue with their F-111 which is very similar with what being faced by India today with the MIG-21. Their solution was the reliability evaluation. Therefore, in a lot of quality issues – "reliable NDT" rather than "just NDT" is the solution.

2. Introduction

Ever since the start of industrial revolutions, non-destructive testing (NDT) techniques play a major role in terms of safety of the components, products or the complete assets of the industries. However, outcomes of any NDT technique have lot of uncertainties in providing consistent results. For example, when different numbers of flaws of same size are inspected, the NDT outcomes have different detection probabilities. Alternatively, repeated inspections of same flaw also do not provide consistent hit (detected) or miss (not detected) indications. Hence, it can be noted that the NDT outcomes are influenced by several uncertainties and are probabilistic in nature. This kind of probabilistic nature of NDT outcomes as well as its capability and reliability are well studied using probability of detection (POD) techniques.

These POD studies can be carried out using both non-parametric and parametric based approaches. The non-parametric POD approaches are based on binomial distributions for example, the 29/29 method [7] etc. However, these methods are highly dependent on very large number of sample sizes for obtaining reasonable confidence bounds on the POD curve. Under the absence of large number of samples, parametric based POD functions such as a log odds function or cumulative log normal distribution functions can be used [8]. However, these parametric methods are mainly divided in to two types, namely, the binary [8, 9] and the signal response [8] methods depending on the type of NDT outcome i.e., either qualitative or quantitative. In the case of NDT techniques producing qualitative outcome in terms of the binary responses such as the "1 or HIT" (defect detected) or "0 or MISS" (defect undetected) (in case of penetrant inspection, magnetic particle, etc.), HIT-MISS methods are used. In the case of NDT techniques producing quantitative outcome in terms of a signal response such as an amplitude (in case of Ultrasonic inspection) or volt (in case of eddy current inspection), â (signal response) vs. a (defect size) approaches are used. POD curves can be generated using either of the approaches i.e., hit-miss or signal response methods and the outcome of a POD curve is the $a_{90/95}$ (reliably detectable crack size with 90% probability and 95% confidence) value. This $a_{90/95}$ value helps in taking right decisions for approving components during inspection, identifying maintenance schedules, etc and is obtained from the intersection of the lower 95% confidence curve of the POD curve at 90% probability level as shown in Figure 1 [10].

2.1 Global (Western) Scenario towards POD Concepts

As part of the NASA space shuttle program and the US Air force programs for implementing damage tolerance concepts, initial reliability studies for understanding the probabilistic nature and capabilities of NDT techniques have been developed in the early 1970's. These reliability studies have been carried out using POD methods and are initially confined to the aviation industries. After the initial attempts on POD activity by NASA, several other POD related projects such as SISTAE [11], PICASSO [12], etc. were carried out in different industrial sectors. Apart from the aviation industry, these POD concepts were also well recognised for several other different fields of applications such as the nuclear, oil and gas, railways, automotives, civil engineering, etc. in the western countries. Eventually, this has led to the development of several standards and documents for carrying out POD studies for evaluating the capabilities of NDT techniques. Some of the most famous standards on POD concepts include, the Berens POD models from 1989 [8], MIL-HDBK 1823 [13] and 1823A [9], ENIQ reports [14], ASTM [15] standards, etc. By the year 2004, a dedicated group named as the model assisted POD (MAPOD) group came into existence for carrying out POD activities by using model-based methods. The major outcome of these POD studies is the a90/95 (detecting a flaw with 90% probability and 95% confidence) metric, which is typically used for the critical information under the damage tolerant concepts. In addition to the damage tolerant applications, this POD information is also used for qualifying NDT techniques, procedures, NDT inspection personnel, etc.

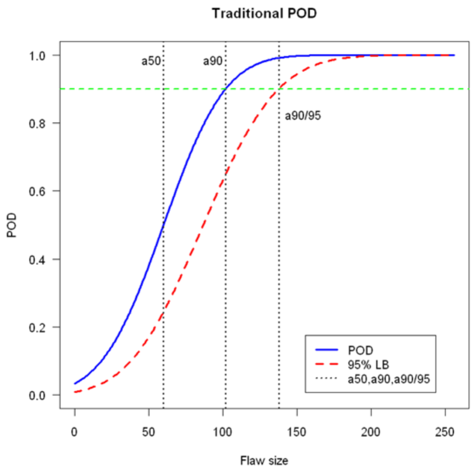

Fig.1: POD curve showing a_{50}, a_{90} and $a_{90/95}$ points [10]

2.2 Indian scenario towards POD concepts:

Even though Western countries were successful enough to generate POD curves for damage tolerance assessment from the early 1970's, no such effort was in place in India even till 2013. This can be either attributed mainly due to the limited understanding of the importance of POD studies or due to the lack of proper expertise in the field, specifically for generating POD curves. Further, these POD studies require huge number of representative samples and are considered to be laborious, time consuming and costly tasks. Considering the extreme importance of this procedure on life revision studies for aero platforms, in 2013, an indigenous effort was initiated at Defence Metallurgical Research Lab (DMRL), a R&D laboratory under the Defence Research and Development Organization for understanding the worldwide accepted and followed approaches for generating POD curves for the systems, equipment's and materials. The main goal of the exercise was to further extend it to techniques, equipment's and materials used within Indian Armed Forces.

During this initiative, several efforts have been carried out for estimating the POD of NDT techniques in terms of both experimental and model-based approaches. In addition, efforts have also been carried out in terms of estimating the remnant life calculations by using the POD information produced from these studies. Apart from many other challenges, these POD studies mainly rely on the representative samples comprising of laboratory generated fatigue cracks at DMRL mimicking those originating from the bolt hole locations of an aero-engine turbine disc. By using these representative cracks, POD of penetrant and eddy current inspection techniques have been estimated under the laboratory scenario [16]. In addition, proper statistical methodologies have also been well demonstrated using model-based procedures in the case of ultrasonic inspection technique. Parallelly and independently, around the same time, CNDE at IIT Madras have also initiated POD related projects which mainly confined to the development of model-based studies and in order to achieve this task ultrasonic testing was chosen as a representative metric [17].

Even though sporadic POD activities were initiated at DMRL and IIT Madras, the total amount of POD activity carried out in India was and still is in its infantry stage. This can be clearly observed from the number of total global publications on POD worldwide as shown in Figure 2 [18]. As shown in

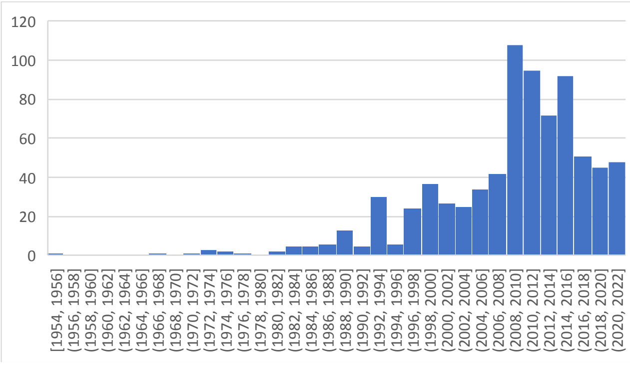

Fig.2: POD publications in the field of NDE [18]

Figure 2, the total number of publications accounts to approximately 800 amongst which the publications from India accounts to approximately 20 (from the POD activities carried out from both DMRL and IIT Madras). Moreover, to the best of authors knowledge, it is also observed that approximately from the last 1 year, new publications related to POD activity were missing from India.

Considering the severe importance of this activity in India, in the current paper, an attempt is made to briefly demonstrate the results obtained at DMRL on POD studies. This is also followed by the discussion on the importance of reliability evaluation for the future of NDT/E as well as NDE 4.0 in India.

3. Experimental POD efforts and results

One of the main requirements for any POD activity lies in the availability of representative samples with cracks or defect features. Initial studies in this direction directly dealt with failed components or components which are anticipated to fail shortly. These components gave the early studies luxury to have cracks and start the reliability assessment procedure.

3.1 Room Temperature Fatigue Cycling

Under the absence of such retired aero-engine components in India, specimens with representative defects were to be generated with morphological features being exactly similar to the defects originating in service. Therefore, the efforts at DMRL dealt with modifying the design present in Appendix F of MIL-HDBK 1823A (2009) standard [9] in a nickel based superalloy material. Using this design, fatigue cracks emanating from the bolt hole locations of a turbine disc was mimicked with a 3-point bend fatigue loading using the design mentioned above. Specific details of the specimen geometry, loading protocols adopted, etc., are all described in literature [19] The major outcome of this study is a demonstrable and repeatable procedure for generating representative fatigue cracks as observed in engines with identical morphological features such as crack tightness as low as 1 µm, crack tortuosity, trans-granular nature and multiple initiation sites of cracks (Figure 3), etc..

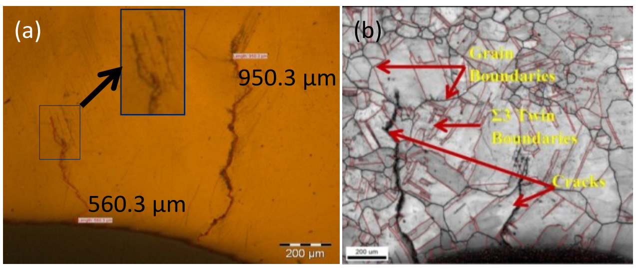

Fig. 3: (a) Micrographs of one of the room temperature tested samples with crack lengths indicated (0.95 mm and 0.56 mm) (b) its EBSD grain boundary map

In spite of this approach, several specific features such as in-situ crack oxidation could not be replicated as the testing was carried out at room temperature. This is essential as the engine operating at high temperatures undergoes predominant oxidation in fatigue cracks at high stress concentration locations of the turbine components. In order to circumvent these issues, attempts were carried out to exactly generate fatigue cracks with in-situ oxidation.

3.2 High Temperature Fatigue Cycling

This issue was addressed with the help of thermo-mechanical simulator Gleeble system present at DMRL. A notable outcome of this effort is its first-time demonstrability of the feasibility of generating these oxidized cracks. Considering the operating temperature of ~650oC, typically observed in an aeroengine, in-situ oxidized fatigue cracks were generated using Gleeble system. Detailed description of the procedure involved, load optimization, etc., are discussed in [16, 20]. Figure 4(a) shows a typical micrograph of one of the high temperature fatigue cracked samples showing crack initiation at the notch. Similar cracks initiating from the notch are observed in all the test specimens. From Figure 4(a), it can be observed that two cracks (shown in Figure inset 4(b)) are initiated from the notch location due to the stress concentration at the circular notch. In addition, it can also be observed that the crack surfaces are fully oxidized (shown in Figure insets 4(c) and (d)) due to the high temperature fatigue cycling in air environment. This results in the filling of crack widths with oxides as shown in Figure 4 (c) & (d).

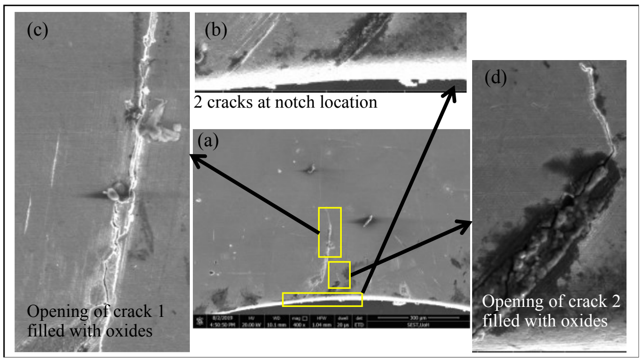

Fig.4: High temperature multiple fatigue cracks at (a) single notch location (b) crack 1 filled with oxides (c) crack 2 filled with oxides and (d) two cracks at notch location in zoomed view

This phenomenon of oxidation of nickel based superalloys at higher temperatures is similar to that of observed in literature [21]. Considering (a) log-normally distributed crack sizes (b) narrow, tortuous and multiple fatigue cracks at a location and (c) formation of oxides in the fatigue crack surfaces, observed from this study, it was concluded that the Gleeble® based novel methodology adopted for fatigue crack generation can produce fatigue cracks similar to that of expected from in-service conditions [22].

3.3 Statistical Analysis of NDT Inspection Data for Plotting POD Curves

Considering the fatigue cracks generated in room temperature and high temperature conditions, NDT inspection using fluorescent liquid penetrant technique (FLPT) and eddy current technique (ECT) (detailed procedure on FLPT and ECT inspection of fatigue cracks is provided in the reference) was carried out. In addition, different HIT/MISS based POD approaches [23] such as Type 1 (maximum flaw

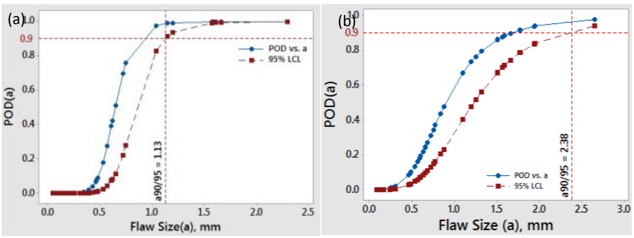

Fig.6: POD curves using different approaches for multiple cracks at a site for FLPT with (a) Type 1 and (b) Type 2 approaches indicating $a_{90/95}$ values.

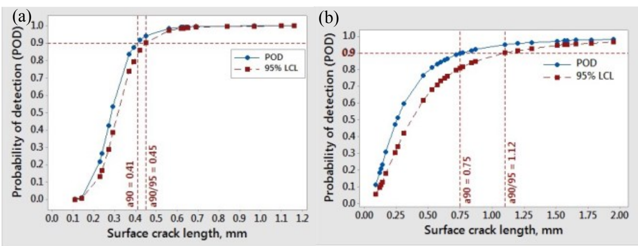

Fig. 5: POD vs. surface crack length for (a) oxidized cracks indicating a_{90} = 0.41 mm and $a_{90/95}$ = 0.45 mm (b) non-oxidized cracks indicating a_{90} = 0.75 mm and $a_{90/95}$ = 1.12 mm

size approach) and Type 2 (sum of flaw sizes approach) approaches were also developed and adopted for the FLPT HIT/MISS data of room temperature cracks. For all the HIT/MISS data obtained from FLPT inspection of room temperature cracks, the POD is estimated using log-odds distribution function (Detailed statistical procedure for HIT/MISS POD data is provided in reference). Figure 5 shows a typical POD curve plotted using Type 1 and Type 2 approaches for FLPT inspection of room temperature cracks data indicating $a_{90/95}$ values of 1.13 mm and 2.38 mm for Type 1 and Type 2 approaches, respectively.

Similar procedure for plotting POD curves was adopted for ECT results and as shown in Figures 6(a) & (b), $a_{90/95}$ values for ECT inspection of high temperature and room temperature surface crack length sizes are 0.45 mm and 1.12 mm, respectively. In all the cases, the $a_{90/95}$ values of high temperature cracks are sensitive compared to that of room temperature cracks due to the higher detectability of oxide cracks. Further, these $a_{90/95}$ values are incorporated into the damage tolerance based life calculations for estimating the remnant fatigue cycles the component which can withstand before failure.

3.4 Remnant life calculations using DT Methodology

Inspite of availability of several studies on generating POD curves for NDT techniques, the actual manifestation of this $a_{90/95}$ on the remnant life is not addressed in the open literature. Efforts were

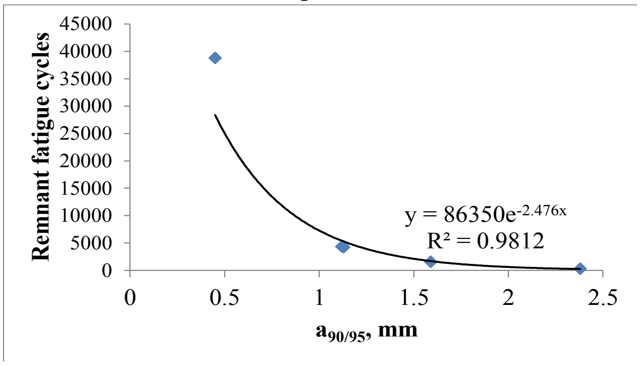

Fig.7: Effect of $a_{90/95}$ on remnant fatigue cycles

also made to demonstrate this significance and using three-point bend geometry as the candidate testing protocol and $a_{90/95}$ values generated, remnant life was estimated [20, 24]. Figure 7 shows the remnant fatigue cycles corresponding to different $a_{90/95}$ values of both the NDT techniques. From Figure 7, it can be observed that the remnant fatigue cycle decreases exponentially with an increase in the $a_{90/95}$ values.

The major challenge in POD curves is its superior dependence on material, geometry, defect characteristics, inspection technique, etc. This would result in re-generating POD curves, which are extremely laborious and cost-intensive. Due to this limitation, modeling approaches were also developed by simulating NDT process using physics based models for predicting NDT response [25]. The mentioned approach for generating cracks similar to that originating from bolt hole locations of an aero-engine turbine disk can be readily used by users working for aeroengine platforms. However, in case of users working for other platforms such as nuclear, space, similar programs can be initiated to first generate cracks and then establish POD curves.

4. Reliability Under the Context of NDE 4.0 in India

Even though very few POD activities have been carried out in India, it can be clearly noted that these

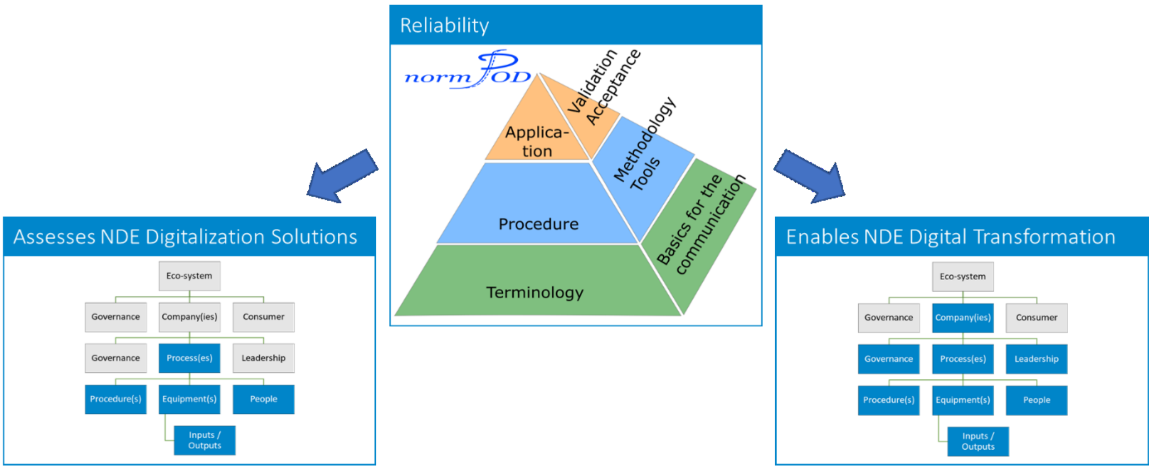

Fig. 8: Reliability is a Key-Success Factor for Both Faces of NDE 4.0

studies have not fully considered the different influences on the reliability estimation of NDT

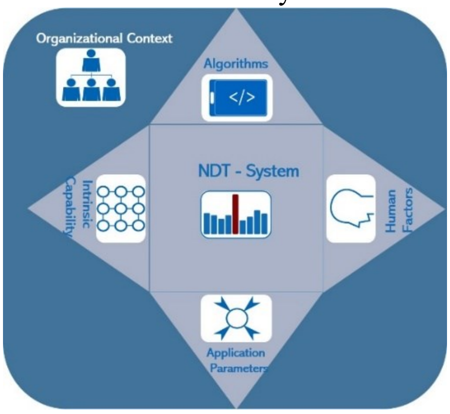

Fig. 9: Modular model under the context of NDE 4.0 [26]

techniques as explained from the modular model as shown in Figure 8. Hence, it can be noted that these POD studies can be brought to realistic scenarios only when all these different influences are considered. As shown by the modular system, the major sources of various influences can be broadly classified as (a) the intrinsic capability, (b) the application parameters, (c) the Human Factors in the organisation context as well as (d) the influence of algorithms under the context of NDE 4.0 [26].

NDE 4.0 is the confluence of the emerging technologies from the environment of Industry 4.0 with the physical inspection methods of non-destructive testing & evaluation as well as non-destructive sensors [27]. Depending on the informatization stage [28, 29] the use cases of NDE 4.0 can be divided into two groups as shown in Figure 9:

a) “Digitalization Solutions for NDE” or “Industry 4.0 for NDE”: Use of Emerging Technologies to "improve" NDT and NDE - e.g., the use of artificial intelligence for a more reliable classification of indications, the use of augmented reality for more intuitive visualization, or digital machine identification of a component and use of NDE workflow systems to ensure revision safe, audit-proof correlation of results.

b) “Digital Transformation of NDE Ecosystem” or “NDE for Industry 4.0”: Using NDE data which has got the real value to define may be in-terms of “Value Index” [30] to improve production, maintenance, and design of assets using cyber-physical loops and digital twins [31] - i.e., using NDE data for holistic predictive maintenance [32] or to use more accurate knowledge in a probabilistic fracture mechanics implementation, for example [33].

In the first use case group "Digitalization Solutions for NDE", the focus is on improving the reliability of the inspection and its documentation. However, such automated methods must be tested and certified before they can be used. The degree of improvement must be demonstrated. In the "Digital Transformation of NDE Ecosystem" use case group, the aim is to establish NDE as a data basis for engineering. Any data source has an inherent accuracy that should be included in the various approaches to transform data into knowledge [34]. Thus, the reliability information of data should be included in the metadata record that describes the actual measurement data. For NDE, this means that for a use of NDE data in digital twins and other data refinement methods, the reliability of the measurement method should be determined and transmitted as well. These approaches will lead to reliability assessment gaining importance - in classical NDE, in condition and structural health monitoring and more generally in sensor technology. More information on NDE 4.0 can be found in the books "Handbook of Nondestructive Evaluation 4.0" [35] and "The World of NDE 4.0" [36].

5. Closing Remarks

From the author's perspective, it is observed that Indian NDT community is highly involved in the development of new NDT techniques, new probes or new procedures for efficient NDT results. This is one way or the other very much beneficial for transformation to NDE 4.0 as the 4th generation of NDE is mainly based on the adaptation of several of the advanced technologies from the industry 4.0 such as the digital twin, automation, robotics, machine learning, artificial intelligence, etc. However, the biggest challenge lies with the qualification of new NDT techniques or methods or probes when planned for the actual industrial application. At present, most of the test systems are qualified based on several standards that are capable of technical justification or the POD based reliability methods. Hence, it is the need of the hour to qualify the test systems for the successful transformation to the NDE 4.0. ***In general, the transformation to NDE 4.0 is not an instant task and rather based on understanding the reliability of the existing systems.*** This will help in identifying the setbacks of the current techniques, methods or procedures and can be rectified by slowly adopting the industry 4.0 technologies eventually leading to the transformation of NDE 4.0 in the long run.

6. Way Ahead for the ISNT NDE Community

As mentioned earlier, studies in India have definitely showed the potential of Indian NDT community to gear up to the occasion of generating NDT reliability information by innovatively taking certain steps required for that. It is definitely agreed that the requirements for generating NDT reliability information for later use as transformation to NDE 4.0 is expensive, laborious and time consuming. However, as explained in the article, its impact on Indian community to catch the NDE 4.0 band wagon is itself a major boost for national level programs to be initiated. ISNT could take an active role in this direction and form task groups across organizations for initiating the discussion or generating test blocks with defects so as to use them for POD generation, etc.

Alternatively, services of consultant companies exclusively working on NDT or NDE reliability can be opted and with their help, enough leads into this fantastic area can be achieved.

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